Strain in historic tapestries: An investigation on mechanical properties and hygroscopic simulation

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by

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Declaration

I, Pedro Josué Máximo Rocha, confirm that the work presented in this Thesis is my own.

Where information has been taken from other sources, I confirm that this has been properly referenced in this Thesis.
Abstract

Historic tapestries are artworks created by weavers, which are modified over time by damage and conservation interventions. Several projects have examined the mechanical and hygroscopic properties of tapestries (e.g. Bilson, Howell and Cooke, 1997, Lennard and Dulieu-Barton, 2014, Duffus et al. 2012 and Alsayednoor et al. 2019). However, these studies either used replica samples made of artificially aged materials or relied on a single technique to analyse the mechanical behaviour of limited set of samples. The two research approaches, produced limited conclusions because of the highly variable mechanical response of historic tapestries.

The current research is a collaboration between University College London (UCL), Historic Royal Palaces (HRP), and IBM Research. It adopts a multidisciplinary methodology that incorporates knowledge from engineering, heritage science and conservation. The main body of the thesis is an extensive experimental campaign, whose aim is to characterise the strain response of historic tapestries subjected to environmental changes. A questionnaire complements the research by understanding the influence current conservation techniques have in structural changing tapestries.

A comprehensive study of physical and mechanical properties of historic tapestries was carried out. Universal testing machine (UTM) systems and digital image correlation (DIC) have been used extensively for testing historic tapestry fragments. Both methods were used in combination, while quantifying the physical heterogeneity of each fragment tested. In a second stage, the performance of a historic tapestry in open display was studied. A complete historic tapestry was tested inside an environmental chamber under different environmental conditions. Full field strain and local displacements were measured with DIC and newly developed IBM sensors respectively. With the study of weaved features in the tested tapestries, DIC showed that mechanics and dispersion in tensile results can be explained. Results from hygroscopic experiments inside the chamber quantified strain variation when tapestries are exposed to indoor uncontrolled environments.
Impact statement

This collaborative doctorate research project was initiated and financially supported by Historic Royal Palaces (HRP) as part of a long-term research developing a science-based sustainable strategy for the protection of historic tapestries with a particular focus on the sixteenth century collection of Tudor tapestries displayed at Hampton Court Palace. The project benefited from accessing data and knowledge of previous research projects as well as the HRP collections and specialist staff. The clearly defined research questions, innovative methodology and carefully designed experimental work, resulted in several significant research outcomes.

The mechanics and hygroscopy of historic tapestries are subjects already established in the field of heritage science. This thesis provides a straightforward and reliable method for physical and structural characterisation of historic tapestries. This characterisation method makes use of tools and software commonly available to scientists. Furthermore, having this characterisation as background, the thesis explores methodologies to mechanically study tensile and hygroscopic strain behaviour using complementing methodologies and thus the ability to interrogate data in a more complete and holistic manner.

The main advantage of characterisation and testing methodologies developed is this research is the ability to understand how different heterogeneous tapestry structures behave when in open display supporting their own weight and exposed to indoor environmental changes. This research enables a better understanding on how differences and changes in a tapestry structure can affect its strain and degradation.

The experimental work assessed the impact of temperature and relative humidity fluctuations to the dimensional changes and the strain historic tapestries experience when on display. This information has direct impact on environmental standards and planning mitigation measures to manage any associated risk for these collections. Furthermore, this research had a global reach as the questionnaire results provided valuable information on tapestry conservation practices deployed across the globe identifying current common practices as well as deviations on methods used to provide structural support to historic tapestries. Another outcome of this research with immediate impact on tapestry conservation practices is the confirmation of the need to allow excess fabric for the support of the tapestry due to the maximum vertical displacement measured by the IBM sensors. Finally, this research has generated important data towards the development of a FEM model of a historic tapestry which would ultimately be used for testing further conservation practices. This work was not delivered as part of the project due to unforeseen conditions however, it can form an exciting future collaborative research opportunity.

The methods to assess and test tapestries were disseminated in talks and publications (Máximo Rocha, D’Ayala and Vlachou-mogire, 2018a, Máximo Rocha, D’Ayala and Vlachou-
Mogire, 2018b, Máximo Rocha, D’Ayala, et al., 2021 and Máximo Rocha, Takami, et al., 2021). These methods can be easily extended to other materials and objects whose structure and mechanics present a high degree of heterogeneity.
This endeavor would not have been possible without Prof Dina D’Ayala and Dr Constantina Vlachou-Mogire. I want to express my gratitude to these two supervisors not only for the academic dedication but specially to their support in challenging times. I am equally grateful to Dr Hector Altamirano-Medina for all his dedication to this project and support on the environmental chamber experiments.

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Words cannot express my gratitude to friends and family that never gave up in the challenging moments. To not mention all names in a long length of text a thank you to all that are always present. To these I dedicate this work. To the star that was once a weaver. To you.
List of Abbreviations and Acronyms

2D - Two Dimensional
3D - Three Dimensional
HCP - Hampton Court Palace
HRP - Historic Royal Palaces
IBM - International Business Machines Corporation
NIR - Near-infrared
RGB – Red-Green-Blue
RH – Relative humidity
T - Temperature
UCL – University College London
UK – United Kingdom
USA – United States of America
Glossary

Amorphous structure - In chemistry is a non-crystalline solid lacking a well-defined structure and thus not organized with ordered components.

Aune – French pre-revolutionary unit of measurement equivalent to approximately 119 cm under the reign of Francis I of France.

Crystalline structure – In chemistry is a solid that has a well-defined structure and thus regular ordered components joint by intermolecular forces.

Close Couching – Embroidering technique used to fix a thread on a surface of a material by stitching it at certain intervals with another thread through the material.

Denier – Unit for fineness measurement in textile fibres or yarns. A denier is the weight in grams of 9 meters of fibre or yarn.

Duite – Name given to the weaving procedure where in a single line of weaving the weft is interweaved with the front warps (half duite) and then folded back and interweaved with the back warps making the warp structure hidden.

Fibre – Filament of textile used to produce yarns.

Grab Test – Type of tensile test where the fabric have a length that extends beyond the jaw at the end of each clamp.

Historic Tapestries – Tapestries that are antique and thus experienced natural ageing processes and might or not have been subjected to restoration or conservation interventions.

Hygral Expansion – Reversible dimensional change in a fabric when there is a change in moisture content of its fibres.

Isoelectric Point – The pH level at which there is no electric charge in a molecule.

Loom – The instrument used to hold the warp threads under tension during the weaving process.

Relaxation Shrinkage – Irreversible dimensional change in a fabric when there is change in moisture contents of its fibres given certain conditions.

Selvedge – Finished edge of a fabric that has the function of stopping the fabric from fraying.

Slits – Empty space in the weave created by a stopping a row of weft threads in a single warp due to a colour change demanded by the design. A slit is stitched when the weaving is finished.

Split – Empty space in the weave created by the same reason as the slit although to create a shading effect it is leaved open when the weaving finishes and thus it is not stitched.

Tenacity – Measure of strength used in fibres and yarns. It is defined as the force at failure divided by the denier.

Tex - Unit for fineness measurement in textile fibres or yarns. A tex is the weight in grams of 1 meter of fibre or yarn.
Thread – Is a special kind of yarn. However, in weaving it refers to two or more yarns joined together in the bobbin to weave a single line on the weft.

Warp – The structure of threads in a loom which other threads (weft) pass over and under to make the weave.

Weft – The structure of threads created by passing weft threads over and under the warp to make the weave.

Yarn – Continuous length of interlocked fibres

Yarn Count – Measure for the fineness that is expressed n number of yarns per length unit.
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1.1 Motivation

Tapestries have been around for millennia, with the majority of these surviving artworks dating from the Middle Ages to the 18th century (Ackerman, 1933). Tapestries are handwoven using natural textiles and metallic threads which create a unified heterogeneous structure. Their artistic and historic value cemented their place as significant artworks and important role in world heritage.

Historically, when tapestry production and repair could still be supported by aristocracy, tapestries were used for many purposes from wall and furniture coverings, ceremonial decorations to wallpaper (Cavallo, 1993). Across the history of tapestries, these objects reflected the philosophy and ideals of the society of that time. Religious subjects, mythological stories, chivalry depictions and historical events were rendered in tapestries to convey a message that could be either political, religious or social. For this to be made, the most influential artists of the time worked in designing cartoons for tapestries that were then produced by experienced weavers that interpreted these cartoons. Artists such as Phidias, Da Vinci, Raphael, Mantegna, Le Brun, Boucher, Edward Burne-Jones, and many others produced cartoons for an art that sometimes implied colossal amounts of money when compared to painting commissions (Duffus, 2013). Nowadays, tapestries are regarded as precious artistic objects that need to be preserved for future generations to continue to enjoy and study these objects. However, many factors can lead tapestries into material damage, making their degradation a continued process dictated by the environmental conditions and mechanical forces that tapestry structures are subjected to. Because these objects are very fragile, damage can be produced by different mechanisms such as poor handling, light, dust deposition, pest infestations, stresses caused by their own weight as well as cycles of moisture adsorption and desorption (Fiette, 1997). As a result from the different damage mechanisms some of the biggest collections of tapestries reached our days reduced to a few examples (Turner, 2013). That is to say some important sets of tapestries were lost, such as the case of the famous “Armada” tapestries that perished in the Palace of Westminster’s fire of 1834 (Farrell, 2010), while others survived after passing through stages of extreme degradation such as the “Life of the Virgin” tapestries in Figure 1.1, which belonged to the Bayeux cathedral. Historic tapestries that managed to survive and reached to this date were mostly kept by the Church or belonged to important private collections, kept in storage for long times and only exhibited in special occasions (Jenny Band, 2006). In contrast with this, it is common practice nowadays to have tapestries in permanent open display in museums or other heritage institutions that are open to the public. Important historic tapestries are now permanently hung, and hence exposed to all sorts of chemical and physical mechanisms of possible degradation. In the worst cases...
tapestries kept being used as movable objects for display without particular consideration for the damage that loads and environmental conditions may produce on them. An extreme example of this is the Corpus Christi procession in Toledo, Spain, shown in Figure 1.2 where an important set of Brussels tapestries is temporarily displayed outdoor without much care for hanging conditions in full sunlight. A situation which contrasts with the need for preservation of these objects.


In response to the damage that tapestries undergo, the procedure of cutting off the damaged parts and replacing them by a new woven patch of tapestry was the most common restoration solution in the past. However, most of the conservators nowadays, without disregarding the rendered image, value the importance of the original material and hence the primary focus is now to consolidate torn areas of textile and prevent damage by providing structural support to allow these objects to continue to bear their own weight (Lennard, 2006d). This conservation philosophy, together with the current challenges imposed on these artworks, urges the need to understand historic materials to better protect them. As a consequence, since the 1930’s, the early conservation laboratories, connected to museums and academic institutions, started to look at tapestries from the point of view of material analysis (Conti, 1988). From this period onwards, the technical aspects imbedded in the artwork, began exercising a strong influence on the development of conservation techniques.
As a result, some scientific literature is available, reporting studies on tapestry materials and the effects of conservation procedures. However, the effects on the mechanics of hanging tapestries in terms of stress-strain behaviour are not yet fully understood (Duffus, 2013). At a time when tapestries that survived until the current day are permanently hanging in the most diverse conditions, to understand how these objects respond to their environment, it is necessary. This is what motivates this project, in exploring tensile mechanical properties of tapestries and studying which factors have an influence on strain. This can help to further understand the mechanical behaviour of tapestries exposed to their own weight when hanging as well as to cycles of moisture adsorption and desorption caused by environmental conditions.

The current research results from a collaboration between University College London (UCL), IBM and Historic Royal Palaces (HRP) and focuses on the Royal collection of Tudor tapestries in display at Hampton Court Palace. This collection includes the 16th century set “The Story of Abraham” attributed to Pieter Van Aelst (Campbell, 2002), the 17th century set “The Acts of the Apostles” designed by Raphael, the 18th century set “The History of Alexander” designed by Charles le Brun, three tapestries from the set “The Battle of Solebay” among other late gothic tapestries (Marillier, 1962), which makes this collection one of the world’s most important collection of tapestries. This collection of tapestries is now on open display in different rooms of Hampton Court palace and thus affected by the indoor environment and the permanent hanging which these tapestries are subjected to. The focus of this project is primarily on the Abraham series, but it aims to explore European tapestries from 16th to the 19th century. The availability to study this important collection of tapestries in the hope of enhancing the understanding of the physical phenomena that interacts with the materials that constitutes these objects and damages them, motivates a more in-depth research.
on this Heritage Science topic. The study on this very varied tapestry collection aims to produce results that are applicable beyond the given examples of tapestries displayed at Hampton Court.

1.2 Scope of the project

Extensive research in the areas of light degradation, ageing associated with different dyes and mordants as well as corrosion of metal threads was developed during the three-year project Monitoring of Damage in Historic Tapestries (MODHT) (Howell and Quye, 2009). On the other hand, past research in mechanics of historic tapestries shed light on the nature of individual fibres and threads in historic tapestries (Bilson, Howell and Cooke, 1997). Also studies on the woven structure mechanics, although scarce, evaluated tensile behaviour of historic tapestries and arrived to the conclusion that artificially aged samples are not fully representative of the level of degradation that can be found in historic weaving (Duffus, 2013). All these studies were of course limited by the fact that a tapestry is an artwork and given its value, sampling is very restricted and only used rarely in the case of loose threads that are hanging on the back of the tapestry. As follows, any destructive testing on originals is not conceivable and this is the reason which took researchers to apply alternatives to this by focusing their study on artificially aged samples and new woven tapestries (Hacke et al., 2009a, H. R. Williams, F. Lennard, D. Eastop, 2009, Duffus, 2013). Therefore, researchers focused on numerical approaches, producing FEM simulations, in an attempt to reproduce the effects of strain in tapestries. However these had severe limitations, as they either considered very simple modelling (Duffus, 2013) or several assumptions were made on the nature of conservation works and damaged areas without considering laboratorial tests in support of them (Alsayednoor et al., 2019). Notwithstanding, due to the extensive tapestry conservation history at Hampton Court Palace, the restoration processes used in the past collected a large number of fragments extracted from original tapestries. Although the original provenance of these fragments had been lost, they are now available as sacrificial fragments to conduct scientific research. The monitoring of indoor historic house environments is not new, however an in-depth tapestry oriented study of indoor environment conditions conducted by HRP since 2004. This indoor monitoring project developed by HRP, under the banner of “Tudor tapestries environmental protection project” proved to be an important step towards the implementation of state-of-the-art solutions that are able to protect these sensitive objects (Frame et al., 2018, Vlachou-Mogire et al., 2020). Furthermore, monitoring of tapestries vertical displacements using laser and magnetic sensors was also part of the programme developed by HRP (Frame et al., 2018). Another three-year project at the University of Southampton studied the monitoring of woven samples and in-situ tapestries using both optical fibre sensors and digital image correlation (DIC) and proved the usefulness and advantages that DIC have when compared with optical sensors (Lennard and Dulieu-Barton, 2014).
For this project, data gathered during the monitoring campaigns carried out by HRP, was made available and establishes a starting point on this research to understand mechanical degradation and strain processes in tapestry structures. Monitoring data to be used in this research is related to continuous recordings of temperature, relative humidity in the Great Hall of Hampton Court Palace during different times of the year.

The aim of this project is to further current understanding of the mechanical stress-strain behaviour in historic tapestries and to study the strain impact that historic tapestries experience when hanging in indoor environmental conditions. The main research questions that the project seeks to answer are:

1. What is the relationship between the environmental changes in humidity and temperature and strain in historic tapestries?
2. What are the most appropriate techniques to study this relationship?
3. Can environmental simulations inform the optimum environmental conditions for the protection of historic tapestries?
4. How can laboratory experiments inform current tapestry conservation methods, such as structural conservation stitching and lining?

Although the field of historic tapestry is quite vast, this research is focused on European tapestries that were produced to be hanged by their own weight. Historic European tapestries differ from others as they are weaved with specific techniques and materials explored in more depth in Chapter 2. This enables the research to narrow down to a specific type of tapestries and to orient the study towards similar tapestries to the ones in open display at Hampton Court Palace.

1.3 Objectives

The research project objectives are:

1. Test historic tapestries in controlled environment conditions.
2. Collect structural and tensile mechanical data from historic tapestries that can inform future computational simulations.
3. Collect conservation/restoration procedures currently in use that can inform about the impact these have on strain in historic tapestries.

Thus, the main objective of this research is to investigate the impact that environment impacts strain in tapestries. Due to lack of relevant understanding on the mechanics of historic tapestries, as discussed further in Chapter 2, the research of structural and mechanical properties in historic tapestries is also one of the main objectives in this research. DIC technique
was extensively used in this project, given its non-destructive nature and its proven efficiency in past studies. This technique enabled the study of strain displacements under moisture and under tensile testing.

To investigate the impact that environment has in historic tapestries, a finite element model (FEM) was planned to deliver one of the objectives of this project, which was modelling and simulation of a historic tapestry. FEM was chosen from different techniques as it can simulate a tapestry behaviour in a computational environment without the need to expose a historic tapestry to stress-strain cycles. The crisis of COVID-19 and delays in laboratory experiments made this objective not possible to be executed. Notwithstanding, the lack of structural and mechanical understanding of historic tapestries in the literature made the contribution given in this field relevant for future research in the area of simulation. The extensive data on tensile properties that was obtained was not previously available for historic tapestries. This data will enable researchers to create a more realistic FEM model that considers the specific properties of the materials used in the tapestry, such as the strength and elasticity of the woven fabric. With this more accurate model, it will be possible to simulate the behaviour of the tapestry under different conditions and to gain a deeper understanding of how it has aged over time. Ultimately, this will allow for better preservation strategies to be developed to ensure that these valuable cultural artworks are protected for future generations.

1.4 Thesis Structure

The current work is composed of eight chapters and twenty-eight appendices. Chapter 1 introduces the topic and explains the motivation for the research carried out. Chapter 2 reviews the current literature exploring the materials in a tapestry structure and the different damage processes that can affect these artworks. This review also discusses the different conservation strategies in use, including methods for displaying them. The scientific research in tapestries ends the literature review discussing the state-of-the art in heritage science applied to tapestries. Chapter 3 describes the methodology as a strategy followed to answer the research questions. This chapter explains how the various research tasks complement each others. Chapter 4 analyses the results of a survey in conservation strategies which characterises the state-of-the art in conservation of tapestries worldwide. Chapter 5 describes the tapestry fragments studied, and the methodology developed to physically assess tapestry structures which contain a high level of heterogeneity. This chapter shows how the quantification of the physical parameters was carried out. Chapter 6 reports the experimental campaign for the tensile strain characterisation on the historic tapestry fragments. Chapter 7 discusses the study of how the environmental conditions affect strain in historic tapestries when these objects are exposed to different levels of temperature and relative humidity. Chapter 8 presents a general discussion and conclusions on the strain in historic tapestries.
In addition, Appendix 1 reports a literature review of the history of tapestry use and manufacturing. Appendix 2 contains the questionnaire form created for the survey in Chapter 4. Appendix 3 reports the Historic Royal Palace’s standard system for condition assessment used in Chapter 5. Appendix 4 contains the structural and mechanical properties calculated for each fragment and sample area tested as a result of the assessment in Chapter 5 and experiments in Chapter 6. Appendices 5 to 8 are support images in the study of best calibration parameters for the DIC setup as used in historic tapestries in Chapter 6 and Chapter 7. Appendix 9 reports the strain evolution of tested sample 8 from fragment 503 until failure as discussed in Chapter 6. Appendix 10 shows the strain maps at 5 mm extension of the tested fragments in Chapter 6. Finally, Appendices 11 to 28 show the complete plots of environmental conditions, strain and displacement from the different experiments carried out in Chapter 7.
Chapter 2

Literature Review

2.1 Preamble

Most available literature on tapestries is related to the field of art history, however this review aims to go beyond that and explore research developed in the field of conservation, simulation, testing and hygroscopy of tapestries. Hence the review is articulated in the following topics: the definition and structure of a tapestry, the history of tapestry manufacture, damage and conservation methods, and conservation science including chemical studies, monitoring and testing and simulation of tapestries.

Considering strain characterisation in historic tapestries as the primary subject in this research, the understanding of tapestry as a structure is considered a key element of focus. The history of tapestry manufacture is hence meant to provide insight on how this art was developed and its evolutionary change in trends. Trends that changed the use and utility of tapestries across history that enable us to draw conclusions on how they were used as physical objects which resulted in their damage and current structural state. Furthermore, conservation and restoration procedures that were applied to these objects constitute a further change that drastically affects their physical structure and response. As different damage mechanisms can affect a tapestry, a section of this review investigates damage mechanisms that result from physical phenomena.

The section on heritage science aims to identify current scientific methods and techniques applied to the study of tapestry from a structural point of view. In this chapter, testing and simulation techniques have major importance since these are the subjects to explore in future experiments. This review wishes to explore how well the understanding of stress-strain behaviour is already known in tapestry structures as well as to identify the areas that still need investigation. Techniques to monitor displacements and strain in tapestries were also considered in this review.

2.2 Tapestry weaving and its structure

2.2.1 Definition

Following the most acknowledged definition, a tapestry is a hand woven textile that is produced in a loom using a simple technique of interweaving weft threads on the previously mounted warp thread structure until they are totally hidden (Lennard, 2006d). That is to say a tapestry structure is mainly characterised by being a plain weave, meaning that under a fixed warp system of yarns in a loom, a single weft yarn crosses the warp system by going over and
under adjacent warps. This interweaving of weft yarns is always done at right angles with the warp yarns (Cavallo, 1993) and after the weaving the weft yarns are beaten down until warp threads are hidden. On the contrary to the warp, the weft is interrupted at certain points in the structure (Bosworth and Caroline, 2006).

For purpose of this research are considered tapestries those objects that respond to this definition. Following this, other uses of tapestries such as carpets, on furniture, as book covers or clothing items (Cavallo, 1993), Turner, 2013, V&A, no date a, V&A, no date b) were excluded from the scope of this research. It is also important to clarify that some important artworks that were originally made to be displayed by hanging do not fall into the definition above and thus are not considered being a tapestry. To illustrate, this is the famous Bayeux tapestry which is not a handwoven textile but rather an embroidery and thus not considered a tapestry.

2.2.2 Structure of a Tapestry

The structure of a tapestry results from the processes of hand spinning threads, dying and weaving, resulting in a very complex self-supporting structure with textile threads held together by means of friction between them. A tapestry structure is an amalgamation of fibres, which combined result in yarns, which by themselves, when put together, are components of threads. Threads, when interweaved in a warp and weft basis, as explained above, form the complex structure of a tapestry which mechanically is dependent of each one of these single components but in the end, it works a whole unified composite structure.

A tapestry results from a very complex system of fibres, the smallest unit of its structure. For a tapestry measuring 6 m wide by 4 m high and assuming the wool fibre has 10 cm long it is estimated that 700 000 000 individual fibres compose that tapestry, there is an amount of 70 000 000 meters the total fibre length (Bilson, Howell and Cooke, 1997).

Individual fibres are different from each other depending on the material which they are made from. Fibres are spun to form yarns, which in turn are joint together to create threads to be used in the weaving process, thus creating a tapestry. Tapestries are not a single physical unit but rather an amalgamation of fibres held together only by the friction that exists between them (Bilson, Howell and Cooke, 1997). Figure 2.1 shows the cross section of a tapestry with the undyed warps sectioned in the perpendicular direction and the coloured crimped wefts running in the parallel direction. In this figure, the different fibres that compose each of the yarns and threads can be seen as the fundamental element of the structure that, when weaved, can give origin to a warp or weft yarn and thread.

As different levels of this complex structure can be studied from a mechanical point of view, there is the need to frame this complexity within the realm of the research that is to be conducted. Although all different levels within a tapestry structure contribute to the tapestry
behaviour, this research is interested in determining what features in the weaving of threads contribute to the general strain behaviour of a tapestry. In other words, the focus is on the response of the fabric as a whole, rather than individual fibres, yarns or threads although general knowledge on these elements remains important and was established through previous studies which focused on the different elements (McCullough, 2014, Kissi et al., 2017a, Hacke, 2006, Bilson, Howell and Cooke, 1997, Hearle, 2000, Susich and Backer, 1951, Wortmann and Zahn, 1994, and Garcia, Pailthorpe and Postle, 1994).

Figure 2.1 – Composite image of the cross section of a tapestry seen in the microscope with the warp threads sectioned perpendicularly.

A tapestry weave only diverge from simple plain weave because in tapestries the weft yarns do not go from selvedge to selvedge (Lennard, 2006d). Instead of this, weft yarns break or cross the warp at a certain points when a change in colour is needed for the design (Nutz and Ottino, 2013). Only the warp runs continuously from one selvedge to the other having as function the support of the weft threads (Lennard, 2006d). In a finished tapestry, only the weft threads are exposed forming the rendered image, on the contrary, the warp threads that are completely hidden by the weft structure. This justifies why the warp threads are always undyed and the weft threads are always dyed in different colours (Cavallo, 1993).

The detail in the design is given by the fineness in the weave which is defined as the number of warp/weft per cm length (Jobé, 1965b and Bosworth and Caroline, 2006). A higher amount of threads per cm gives the weaver the opportunity to create more details since more interruptions of the weft are available for the same area of fabric. Tapestries have usually the weft finer in terms of thread count than the warp (Cavallo, 1993) but of course a higher level of fineness in the warp threads also means higher level fineness on the weft. Fineness can be correlated with thickness also as this corresponds to the measurement of a tapestry’s cross section. Values for thickness changes according to the fineness of the tapestry as to finer tapestries corresponds a lower thickness and coarser tapestries corresponds a higher thickness.

In historic tapestries, each colour corresponds to a separate yarn (Bosworth and Caroline, 2006). Hence it its it’s the interruption of weft that gives way to a varied number of differences in the weave structure. It is a combination of interruption of weft threads that gives way to colour shading and different decorative techniques in the weaving, affecting also its structure (Bosworth and Caroline, 2006). Although they are structural, these different
techniques of interweaving threads have the objective of creating different effects with colours giving the material illusion of the object’s textures that they are portraying in a tapestry (Lennard, 2006d).

The most obvious of these different weaving structures is the slit. The slit is formed each time a horizontal line in the weaving is created by stopping a certain amount of weft threads in the same warp to start another series of weft threads of a different colour/material in the next warp. As observed as 1 in Figure 2.2, this change produces a hole in the weaving were a certain width in the textile is left without threads continuing to the next warp. This weaving technique can be stitched at the end or left without stitching to create a shadow effect which in this case is called split as shown as 2 in Figure 2.4. A split is then an open slit and the purpose of give tri-dimensionality to the design by creating shading effects. However, in most cases the effect of shadows in the design is woven and is independent of the splits (Columbus, 1973).

With time, material experiences wear and tear, a small cut or a stitched slit can develop into a larger split if the stitching weakens, resulting in a gap in the fabric’s structure and turning a simple slit into a split.

When in a tapestry slits appear in the weaving as steps, there is what authors call, “lazy lines” (Bilson, Howell and Cooke, 1997), which is shown as 4 in Figure 2.5. Lazy lines happen when there is a pattern woven diagonally creating a series of small slits which together form a weaving interruption connected only by the end warp of each slit when these interruptions in the weaving occur.

When change in colour happens on the direction of the warp, the weaving is continuous because this change does not imply any interruption of the weft since is by weaving another weft with a different colour on top of the already woven weft that this colour change is created. Although there is a colour change, the weaving is considered continuous and an example of this is given as 3 in Figure 2.4. To avoid slits, when a more subtle change in colour is possible by means of colour blending, a combination of interlocking techniques can be used to unite two different colours (Bosworth and Caroline, 2006). Colour blending is then produced by hatching which is the weaving in a comb-like teeth of continuous colours that interweave with each other and produce the illusion of a blended middle tone when seen from afar (Cavallo, 1993). Simple hatching is a more modern technique of colour blending and thus not found in the historic tapestries. However, it is the same principle, the weaver uses to create the dovetailing technique which creates an illusion of a soft change of sharp contours by doing what is shown below number 5 in Figure 2.5 (Cavallo, 1993).
Figure 2.2 – Detail of a tapestry: 1 – Stitched Slit, 6 – Hachure.

Figure 2.3 – Detail of a tapestry: 2 – Split.

Figure 2.4 – Detail of a tapestry: 3 – Colour change in warp direction, 6 – Hachure.

Figure 2.5 – Detail of a tapestry: 4 – Lazy lines, 5 – Dovetail, 6 – Hachure.
The dovetail technique is a variation of hatching technique since the principle is the same, the only difference being that in hatching the comb-like teeth is created considering several warps instead of one as it happens on the dovetail. The hachure is another way of blending colour by creating a comb-like teeth structure and although is a hatching technique by some authors (Cavallo, 1993 and Lennard, 2006d) the way of weaving differs from simple hatching since each tooth of the comb-like weaving is composed not by a single line of weft but with multiple lines diagonally composed: half duite lines giving further blending options as it can be seen as 6 in Figure 2.2, Figure 2.4 and Figure 2.5.

Other techniques of colour blending exist, however, as these are associated with contemporary tapestry manufacture, they are not considered. The techniques described above are related to the more traditional weaving of a tapestry.

Equally important are the 3 main parts of weaving that can be found in a tapestry. These 3 main parts can be observed in Figure 2.6. These are: the main section represented by A, the border represented with a B and the galloon represented as C in Figure 2.6. Both the main section and the border use the same technique of weft plain textile with interrupted weft, described above as tapestry. The galloon on the contrary is a simple weft plain textile, and the weft is not interrupted being this the reason when there is a fragment of the middle section or the border that fragment can still be considered a fragmentary tapestry while the galloon alone is not considered tapestry fragment because doesn’t fall on the definition given in 2.2.1. The galloon is attached to the weaved borders of the tapestry after the weaving is completed as a finish ticker border (Marko, 1987). The galloons have often darker colour than the rest of the
weaving (Lennard, 2006d) and are generally stiffer when compared with the main section and borders.

2.2.3 Making of a Tapestry

Tapestries are always the result of a collaborative process that results from the combination of skills of designers and weavers working to achieve the final weaved textile (Lennard, 2006d). To this three important factors are always present: money, time and skill (Breeze, 2000). The making of tapestries implies that these three factors are undertaken in what it is the making of a colossal artwork that needs to gather a large amount of resources.

The production of a tapestry always starts by the commissioning of the design that is going to be weaved. The design of a tapestry comprises a previous painted cartoon on paper or fabric that enabled weavers to have a full-scale model of the design. This cartoon was usually made from a previously designed sketch, whether made by the cartoon’s author or not (Cavallo, 1993). Yet, most of the times, rather than having an original design, tapestries followed existing drawings that were kept in stock for future use. The composition of cartoons would include designs taken from other contexts such as prints or paintings. As an example of this, ornamental tapestries used sometimes standard patterns used in embroideries (Cavallo, 1993).

Although the design of the cartoons might have been made by some very famous artist of the time (Guiffrey, 1886), the result was something that very depended on the interpretation and freedom that was given to the weavers. Throughout history of tapestry production, weavers had different levels of importance in the creative process of the final design and during medieval and renaissance periods their freedom in relation to the original painted cartoon was to the extent that they could interpret and change the original designs (Weigert, 1962). However, no matter the time when a tapestry is produced there is always some level of interpretation of the cartoon design, and colour by the weaver even in contemporary tapestry where weaving is almost dictated by the cartoon painter.

The main point of designing a tapestry was to produce a decorative object that could be adapted to various purposes of decoration with even some designers planning their design to be readable into sections in case the final work needed to be cut in smaller pieces (Cavallo, 1993).

After the cartoon is created the next step is to define a colour palette based on the cartoon and to dye with natural dyes and mordants, the weft yarns that are going to be used in the weaving process (Batcheller et al., 2006). In the medieval period, these were very limited. However, with the introduction of different shades and new colours from 16th century onwards, the possibilities of colour expanded. With the industrial revolution came the use of synthetic dyes but due to the high costs of production of tapestry in early 20th century, the number of colours available in the colour palette was reduced to make the weaving process less expensive.
and more efficient (Benson, 1936). Notwithstanding, the colour palette defines to a great extent the level of detail that a tapestry is going to have which also depends on the materials selected for the weft structure. Common tapestries were made of wool which was the standard material for weaving. However, the use of silk was also in place for better-quality tapestries. Extremely valuable tapestries also had the use of metal threads plated with silver or gold. During the golden period of tapestry weaving, high-quality wool was imported from England to the major European tapestry manufacturers while silk came from China or Italy (Batcheller et al., 2006). Metal threads were usually imported from Cyprus, Italy and the Middle east (Batcheller et al., 2006 and Hacke, 2006) and were wound in a S or Z direction around the main core fibre yarn which usually was made of silk (Batcheller et al., 2006). Since the 19th century, cotton and linen were also introduced in weaving.

After cartoon preparation and decision on the properties of the tapestry such as the materials, the thickness of yarns and consequently the spacing between them which is known as the fineness of a tapestry, there is the need for the weaving to occur. The basis of textile work is always the mechanical union between threads without having to use chemical agents to obtain the final work (López, 2015). In tapestries, this mechanical union is made by interweaving of threads that constitute the weft and warp directions.

There are two main types of loom which support the two main weaving processes, variants of the same technique: the high warp loom or haute lisse in Figure 2.7 in which the warp structure is mounted in a vertical position and the low warp loom or basse lisse in Figure 2.8 where the warp is on the horizontal position (Thomson, 1973). During traditional manufacture, the weavers preform their work always from the back of the tapestry (Bosworth and Caroline, 2006), which with the high warp loom implies having a mirror reflecting the front of the tapestry and having the cartoon on the back of the weaver, which can be used to
check the work when needed. Alternatively, the weaver can always step in the back of the loom and see how the work is progressing. As for the low warp the weaver can only see the work once it is finished (Breeze, 2000). In the low warp technique the tapestry is going to be a mirror of the cartoon and will appear flipped horizontally in relation with the cartoon once the work is finished (Weigert, 1962). Moreover, the weaving is traditionally made sideways so that when finished it is turned to be hung with the warps in the horizontal direction (Bosworth and Caroline, 2006) except for modern weaving in which the warp might be hung in the vertical direction.

The first step in tapestry manufacture is to mount the undyed warp threads between two rollers which according to the fineness of the weaving will be more or less close together. The warp is divided into two different planes, the one that is in front, and the one that goes in the back, passing in the front and the back of the rollers alternatively. As weaving proceeds, finished sections are rolled back, exposing the sections of the support warp structure still to be weaved (Weigert, 1962). The warp threads are under high tension during the weaving process in order to keep them straight throughout the whole process (Bosworth and Caroline, 2006).

Before the weaving to start, the weaver transfers the contours of the cartoon to the warp structure of the tapestry. This contour serves as a guide for the weaver to have an idea of the image drawn in the cartoon. The cartoon is however never discarded as is always present being placed behind the weaver in high-warp loom or placed underneath in the case of the low warp loom (Weigert, 1962).

During weaving, the weaver takes the weft over and under the warp yarns stopping and changing the weft colour when the cartoon requires. This process of taking the weft over and under the warp is made of two stages and is called duite. In the first stage, the weaver takes the weft thread from left to right under and over a sequence of warp yarns so that the weft threads are hiding the warp yarns they went over. Then he takes the same weft thread and passes over the warp yarns to which it went under in the first stage, thus making sure all warp threads are hidden by the weft (Weigert, 1962). After a duite, the weft threads are beaten down or with using a bobbin or using a comb to make the weft threads hide the warp and making the weaving structurally sound. The process of making a duite stops in the warp yarns where according to the cartoon its colour is not necessary anymore and thus a new colour needs to start. This makes the weft to be interrupted according to the image rendered (Nutz and Ottino, 2013).

To make this passage of the weft under and over the warp with the bobbin, in the case of high warp loom there is the need to pull out on the overhead strings attached to each warp thread to open the shed for the weft to pass as Figure 2.7 shows (Breeze, 2000). In the case of the low-warp loom the shed is controlled through pedals in the loom and the weaver can always use both hands to pass the bobbin through, which makes the process faster (Breeze, 2000).
When the weaving finishes, the last step is to give more strength to the fabric by stitching the open spaces in the weaving caused by continuous interruption of threads known as slits (Breeze, 2000).

Due to the tension to which the warps are exposed to during the weaving process, when a tapestry is taken out of the loom there is always shrinkage occurring specially in the warp’s direction (Breeze, 2000).

By looking at the whole process of making a tapestry, it is understandable that the price of a tapestry is greatly influenced by the level of weaving detail which is produced by increasing the fineness. Detailed tapestries are finer and thus have a bigger yarn count. Materials used such as silk and metal threads and a larger number of colours also increases the price of a tapestry (Cavallo, 1993) and although some materials such as silk were extremely expensive in the past, this also applies to contemporary tapestry.

2.2.4 Fibre and Yarn Properties
2.2.4.1 Introduction

Textile industry produced an accelerated research on the previous decades that transformed a field that was in the hands of artisans into a science-based industry (Taylor, 1990). The areas of research in textile industry are very extensive but this section only aims to focus on the mechanics of fibres that more usually constitute tapestries and their change with environmental conditions.

Having into account a large range of studies in historic tapestries, it is quite clear that wool, silk and metal threads are the main materials present in a tapestry structure (Marko, 1987, Maes, 1987, Hutchison, 1987, De boeck et al., 1987, Kusch, 2006, and Degano, Łucejko and Colombini, 2011). Yet, aside from these materials there are some cases mentioned in the literature (Brutillot, 1987 and Rogerson and Garside, 2006) where linen and cotton were also applied in the weaving process or even in further restoration works (Dolcini, 1987) and their occurrence are more common from 19th century onwards. However, for the largest amount of tapestries that are considered being historic belonging to the golden age of European tapestry manufactory, the main materials present in their structure is wool, silk and metal threads (Lennard, 2006c) and are mainly on these that the following review is focused. In regard to metallic threads, these are made by wrapping a metal band onto a core usually made of silk and thus their mechanics are expected to match the behaviour of silk core instead of metal. Cotton is briefly considered also as some 19th century tapestries contain this material on the warp (Baumgarten, 1897). Therefore, the main materials considered in this section are wool and silk and cotton.
2.2.4.2 Chemical composition and mechanical properties

Fibres as yarn components are the smallest component unit of a tapestry. These fibres have different characteristics that influence their mechanical properties which in turn influence the mechanical behaviour of the textile (Susich and Zagieboylo, 1953). This is not the same as saying that fibre mechanics are the same as yarn and woven fabrics since yarns and woven textiles have a higher level of complexity that needs to be considered. Yet, any change in the fibre structure will impact textile behaviour and both wool and silk woven fabrics, and it is important to bear in mind that each material have a different fibre structure (Chen and Hearle, 2010). Both wool and silk are natural protein fibres, however while silk is composed of a continuous filament produced by the larva of insects, wool is made of keratin, a protein polymer that in tapestries usually comes from sheep (Hatch, 1993). Characteristics of silk and wool fibres can present some differences according to climatic conditions at time of growth, plant variety or breed of sheep whether is silk or wool respectively (Taylor, 1990). Silk is much finer when compared with wool, with values of fineness that can rise to around 3 denier (grams per 9 Km of yarn) when compared with around 11 denier in the case of wool (Taylor, 1990). Cotton is a natural fibre that grows on the surface of seed in pods from the Gossypium plant (Taylor, 1990).

When comparing the mechanics of wool fibre to wool yarn the former can withstand more stress than the latter which also has a lower initial modulus. The stress-strain curve of the wool fibre also has an initial flat portion which is justified by the amount of crimp that a single wool fibre has (Susich and Zagieboylo, 1953). Crimp can be defined as the waviness in the weft threads and yarns, which occur during the weaving process because of the tension in the loom. This waviness on the weft threads can be seen in Figure 2.1. The crimp percentage of a yarn or thread can be calculated by measuring its length in a relaxed state, and then measuring the length of the same length of yarn after it has been straightened under tension (Duffus, 2013).

Silk fibres behave differently from other protein fibres such is the case of wool. Silk fibres can withstand higher stresses but have less extensibility at break when compared with wool. These mechanical differences are justified in the literature by the distinct polymer structure of each fibre (Susich and Zagieboylo, 1953). The polymer structure can be oriented in more or less parallel direction which gives way to two different polymer orientations: amorphous and crystalline orientation. While the amorphous polymers have a random distribution and thus are weaker and more susceptible to water absorption, the crystalline polymers have a parallel orientation thus being stronger and less absorbent (Gohl and Vilensky, 1980). One of the major differences between wool and silk fibres is that while wool fibres are crimped three dimensionally having an amorphous structure, those of the silk have a high degree of crystallinity and high degree of orientation (Susich and Zagieboylo, 1953). This crimp on the wool gives a very open yarn structure when fibres are combined together which enables the retention of heat (Hatch, 1993).
Mechanical studies on tensile properties of wool and silk fibres can be found in the literature (Morton and Hearle, 1962). Silk fibres when tested have an average strength of 700 MPa when compared to an average of 220 MPa to the case of wool fibres. Elastic modulus of silk is also higher when compared with the wool fibre (Susich and Zagieboylo, 1953). Cotton fibres tend to have much less elongation when compared to silk and a strength between that of wool and silk (Susich and Backer, 1951). Table 2.1 summarises mechanical properties found in two cited works in the literature with values given by the authors (Susich and Zagieboylo, 1953 and Morton and Hearle, 1962).

A yarn is formed by a larger number of textile fibres twisted together. For yarns to be spun it is necessary that fibres are fine and long compared with their thickness form them to grip each other when twisted in a yarn (Taylor, 1990).

Stress relaxation and creep behaviour are other parameters to consider when studying wool and silk yarns. Creep is the response of the yarn whereby, after a force is applied, and an initial elastic extension is obtained, sustained application of the initial load would cause further deformation without load increase (Saville, 1999). Pure woven wool fabrics when compared with blended fabrics have already proved to have a higher tendency of creep, stretching after a force has been applied but they also have more ability for relaxation by recovering when this force ceases (Manich et al., 2006). On tapestries this is an observation that has been done already for a tapestry that was for the first time hung (Lennard et al., 2011). Furthermore, the weaved structure behaviour of a tapestry depends on the individual behaviour of each one of its components and from a hygroscopic point of view it is among other things because of the different materials that each component is made of (Lennard et al., 2011).

Tapestries result in a very complex system in mechanical terms whereby swelling, hygral expansion, relaxation shrinkage, exposure to different pH, cycles of temperature and relative humidity will have an influence on the behaviour of any textile fabric. Tensile behaviour of tapestry threads and woven samples are further discussed in chapter 2.7.4 of the review.

<table>
<thead>
<tr>
<th>Mechanical Properties</th>
<th>Wool fibre</th>
<th>Wool yarn</th>
<th>Silk fibre</th>
<th>Silk yarn</th>
<th>Cotton fibre</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breaking Strength</td>
<td>1.44 (g./gx.) (1)</td>
<td>1.12 (g./gx.) (1)</td>
<td>0.38 (N/tex) (2)</td>
<td>4.89 (g./gx.) (1)</td>
<td>0.19 to 0.45 (N/tex) (2)</td>
</tr>
<tr>
<td>Elongation at break</td>
<td>31.0% (1)</td>
<td>33.2% (1)</td>
<td>23.4% (2)</td>
<td>21.8% (1)</td>
<td>5.6% to 6.8% (2)</td>
</tr>
<tr>
<td>Wet Breaking Strength</td>
<td>0.96 (g./gx.) (1)</td>
<td>0.72 (g./gx.) (1)</td>
<td>-</td>
<td>4.27 (g./gx.) (1)</td>
<td>-</td>
</tr>
<tr>
<td>Wet Elongation at break</td>
<td>45.0% (1)</td>
<td>49.0% (1)</td>
<td>-</td>
<td>33.1% (1)</td>
<td>-</td>
</tr>
<tr>
<td>Initial Modulus</td>
<td>2.1 to 3.0 (N/tex) (2)</td>
<td>-</td>
<td>7.3 (N/tex) (2)</td>
<td>-</td>
<td>3.9 to 7.3 (N/tex) (2)</td>
</tr>
</tbody>
</table>

Table 2.1 - Mechanical properties of fibres and yarns with values extracted from literature: (1) (Susich and Zagieboylo, 1953) and (2) (Morton and Hearle, 1962).
2.2.4.3 Impact of moisture

The crimp on wool fibres is also what explains the reason wool fibres although acting as a repellent when in contact with liquid water, can absorb and hold internally huge quantities of water (Hatch, 1993). On the contrary, silk fibres given their crystallinity and high degree of orientation are always expected to have a lower degree of swelling when compared with wool. This relationship with water at a fibre level impacts the dimensional stability of textiles when they are exposed to environmental changes with different levels of moisture. This dimensional stability is affected mainly by the mechanisms of hygral expansion, and relaxation shrinkage (Hatch, 1993).

In a woven fabric, hygral expansion can be defined as the dimensional expansion or contraction caused by moisture absorption which straightens or contracts the crimped yarns (Saville, 1999). Hygral expansion is a reversible phenomenon (Cook and Fleischfresser, 1986) and the changes due to water absorbed in the textile is a crimp dependent property (Garcia, Pailthorpe and Postle, 1994). On the other hand, relaxation shrinkage is a dimensional change when a textile that had a previous tension applied to it relaxes in the presence of water (Saville, 1999), this is the change that happens to a textile when there is the release of strains set up during spinning, weaving and finishing processes (Hunter and Fan, 2004).

Important changes in textile properties occur when these are in the presence of water (Susich and Zagieboylo, 1953 and Fu, Porter and Shao, 2009) and this is the reason standard environmental conditions during laboratory tests were defined since early studies (Morton and Hearle, 1962). British standard EN ISO 139:2005+A1:2011 defines this environmental conditions as 65%±4% of relative humidity 20°C±2°C of temperature (British standards, 2011).

All fibres swell with increasing levels of moisture. Cotton, for example, swells much more than wool and silk. Cotton swells up to over 40% of its original cross-sectional area. The same values for wool and silk are of approximately 25% and 20% respectively (Saville, 1999). The values for longitudinal swelling along the textile fibres are lower. Thus for cotton this is 0.1% and for silk approximately 1.5% (Saville, 1999). However, this swelling is not always correlated with the amount of moisture absorbed. Cotton’s absorption at a relative humidity of 65% and temperature of 20°C accounts for less than 9% of its dry weight when compared to 10% for silk and approximately 17% for wool (Taylor, 1990).

With moisture, cotton becomes stronger while silk and wool reduce their strength depending on different levels of temperature and relative humidity (Taylor, 1990).

At standard environmental conditions, as stated in EN ISO 139:2005+A1:2011, the strength of cotton is comparable to silk (Taylor, 1990). However, cotton’s extension at break is of approximately 10% while for silk this is approximately 20% and 40% for wool (Taylor,
Previous studies, though, attributed lower levels of strength to cotton when compared with silk (Susich and Backer, 1951).

Past research (Susich and Zagieboylo, 1953) compared fibre stress-strain behaviour of wool and silk under standard wet conditions after swelling in water for 1 hour. Their conclusions were that with swelling in water, there is a general increase of extensibility and decrease in breaking strength. Silk is more resilient to wetting than wool, as its wet strength at break decreased to approximately 80% compared with a decrease to 60% of wool in relation to the original behaviour at standard environmental conditions. When wet, both materials increase their extensibility by having longer elongation values at break (Susich and Zagieboylo, 1953) (Pérez-Rigueiro et al., 2000). Not only the strength at break in both silk and wool decreases but also their yield points, and young moduli (Susich and Zagieboylo, 1953). This decrease in modulus and strength at break can also be found in more recent studies both for the case of wool (Abbott, Temin and Park, 1968) and for silk fibres (Pérez-Rigueiro et al., 2000). It can be concluded that when wet, any applied force will produce greater elongations on both materials. It is also interesting to notice that for the case of silk fibres when wet during cyclic testing the elastic region stops of being defined as by a straight line, a fact that is attributed to the breaking of hydrogen bonding in the presence of water that allows creep and stress relaxation (Pérez-Rigueiro et al., 2000). Figure 2.9 and Figure 2.10 show the impact that moisture has in textile mechanics by comparing the mechanics of dry fibres with the mechanics of wet fibres (Susich and Zagieboylo, 1953).

Figure 2.9 - Stress-strain curves for dry fibres. (Susich and Zagieboylo, 1953).

Figure 2.10 - Stress-strain curves for wet fibers. (Susich and Zagieboylo, 1953).
Furthermore, the combined effect of relative humidity with temperature affects textile fibres depending on the range of these two different parameters (Pérez-Rigueiro et al., 2000 and (Fu, Porter and Shao, 2009). For instance, with silk fibres from Antheraea pernyi species at an indoor temperature of 25°C, the modulus decreases from 11.8 GPa at 10% RH to 8.5 GPa at 70% RH and to only 3GPa at 90%RH (Fu, Porter and Shao, 2009). Also, for silk fibres of the same species at 25°C, there is a transition point at 70% RH in which the elastic modulus decreases abruptly. As expected, these transition points for RH decrease with the rise of temperature, which means that the modulus can decrease in the same way with a high relative humidity at a low temperature or with a low relative humidity at a high temperature (Fu, Porter and Shao, 2009). For wool, heating fibres in the presence of moisture cause changes in their properties, which are usually studied as part of short time heating treatments above 100 °C to increase stiffness and strength of wool (Watt, 1975). Notwithstanding, long exposures to temperatures above 100 °C are damaging to wool fibres. Studies which compare transition points of RH with decrease of elastic modulus were not found in the literature for the case of wool. From the studies mentioned, it can be concluded that the behaviour of modern fibres is well explored in the literature. The same is not verified for historic tapestry fibres. Although these findings can give a possible indication of the behaviour of historic fibres, it is known that historic tapestry fibres may have been subjected to various manufacturing processes with dyes, mordants, and also exposure to ageing processes. Similarly to what was detected for tensile mechanics of tapestries (Duffus, 2013), the damage that historic fibres may have suffered over time might result in heterogeneity in their behaviour when exposed to moisture. Also, the influence of fibre crystallinity and the different ways water can bind to macromolecules are critical factors in the behaviour of textile fibres (Morton and Hearle, 1962). Degradation of these fibres can lead to changes in crystallinity and water binding properties, which can impact their overall performance and behaviour. These processes provide researchers with an explanation of how historic tapestries might behave differently in the presence of water when compared to modern textiles.

2.2.4.4 – Impact of pH

Another parameter that can modify the mechanical response of textile fibres is the pH they are exposed to. Tensile properties change with a change in pH. A study on wool plain weave fabrics concluded that from pH 7.2 to 4.8 there was an increase of 1% of the extensibility values under a low load of 490 N/m (Li, Rex and Wang, 2007). Granted that this is a value given for a low load test, this initial extensibility can be related with the initial crimp in a wool fabric since this is the main property that is being tested under a low load (Susich and Zagieboylo, 1953). Another research studied the relationship between wool fabric tensile properties and different pH values (pH 2.1; pH 4.8; pH7.2) of solutions to which wool was exposed during relaxation periods. First, this study concluded that the values of hygral expansion and shrinkage depend on the pH of the solution in which wool was relaxed. The
minimum value of relaxation shrinkage coincides with the maximum of hygral expansion at pH 4.8 (Li, Rex and Wang, 2007), which is the isoelectric point of wool (Speakman and Stott, 1934) where swelling of moisture is reduced to a minimum. Lower swelling of the fibres produces a lower level of swelling shrinkage and consequently gives the higher value for hygral expansion.

Considering what was said before on the increase of 1% extensibility when pH decreased from 7.2 to 4.8 under a low load, considering pH 4.8 being the value where minimum relaxation shrinkage and maximum hygral expansion exists for wool it can be extrapolated that reduced swelling at this level allows yarn crimp to increase (Li, Rex and Wang, 2007) making the wool more amorphous.

In silk, the isoelectric point can change between pH of 3.5 and 5.2 (Zhuang et al., 2015), however, the relationship between this and changes in physical and mechanical properties was not found in literature.

### 2.2.5 Summary

Section 2.2 gave an insight on the definition and on the components of a tapestry and how these components are joint together in the manufacture process in order to create a tapestry. It also explored main features present in fibres and yarns of wool and silk that are the main materials used in tapestry production. The main conclusions can be taken:

- A tapestry is composed of a non-continuous weft structure weaved at right angles with the continuous warp which is hidden and support the weft.
- Multiple techniques to interrupt the weft exist being the most common the slits, splits, hachure, dovetail and lazy lines.
- A tapestry is usually composed of a main section, border and a galloon which is usually stiffer and frames the tapestry.
- The manufacture of a tapestry defines physical properties that are going to be present during its lifecycle, including the materials present, the existent and type of weft interruptions and fineness and thickness. A thread is made by yarns placed together which, by their turn, are made by fibres that were spun.
- The mechanical and hygroscopic behaviour of wool and silk fibres can be explained by their polymer structure. Silk fibres as crystalline polymers are stiffer and can withstand more stresses than wool, which is an amorphous polymer. Wool fibres have more extensibility than silk.
• Wool as an amorphous polymer can absorb more quantity of water when compared with silk. Wool can also retain heat because of its open yarn structure. Wool is also prone to creep and relaxation behaviour.

• The presence of water increases the extensibility and reduces the breaking strength and modulus for the case of silk and wool, being silk more resilient to these changes than wool.

• pH can also influence the swelling of moisture. With wool swelling is minimum at a pH 4.8 and increases at pH of 7.2 which coincides with the average pH of air in museum indoor environments.

2.3 History of European Tapestry and Damage

2.3.1 Tapestry in the history of art

This section presents a brief description of the history of tapestry making, its use and evolutionary artistic progress in the history of art. Because tapestries are above everything, important artworks, their history in art is their most studied field that can be found in the literature. Because of this, an extensive review was made on the history of tapestry and this detailed review is presented in Appendix 1. This chapter summarises the review presented in Appendix 1, specially focusing on general historic aspects that explain the uses, materials and manufacture locations of these objects.

Tapestry weaving is a very ancient art and examples of tapestries are known since prehistory. The ancient civilisations of Egypt, Mesopotamia, Greece and Rome have weaved tapestries on smaller and larger scales (Weigert, 1962 and Sakamoto, 2001). However, after the fall of the Roman empire, it was only in the 11th century that tapestry weaving became again an important form of artistic expression in Europe (Baumgarten, 1897). Although the earliest tapestries that have survived are from Germany and date from the 11th to the 13th century, it was only towards the end of the 13th century that the industry was being expanded to cities such as Paris, Arras, Valenciennes and Lille.

On the 14th century, Arras, Paris, and Brussels became the most important centres for tapestry manufacture. In this initial phase of European tapestry development, Arras became so important because of the exceptional quality of the metallic thread tapestries that all tapestries using metallic threads were being called as Arras no matter where they were being produced (Guiffrey, 1886). Owners of tapestries used to transport these objects everywhere they went, as it was very common the middle ages for nobility to travel along different properties they owned. Tapestries were the ideal objects for an easy transportation and could quickly decorate an interior space and provide instant thermal insulation to the bare walls of the architecture.
characteristic of the medieval period. In church interiors, tapestries were also used for acoustic reasons (Verlet, 1965).

During the renaissance, the character of tapestries as precious household objects was maintained. However, with the artistic and social development of the renaissance, tapestries became progressively a way to public display wealth and power, which created rivalry between royals who owned them (Jenny Band, 2006 and Campbell, 2002). Tapestries were used during occasions where the showing off status was needed, from coronation ceremonies, state entries of royals in cities, festivals and religious processions (Cavallo, 1993). In the renaissance the technique of interweaving different threads was perfected (Breeze, 2000). Adding to the fact that the leading painters of this time were producing cartoons to tapestries, this is the golden period of tapestry manufacture (Muntz, 1881, Campbell, 2002). It was also in this period that the industry expanded to the Italian Peninsula, which is justified by the role that Italy was having during the renaissance period. Cities such as Florence, Ferrara, Mantua, Milan, Venice and Genoa created their own workshops with the help of Flemish immigrants that were leaving Flanders because of a period of crisis and protestant persecution (Guiffrey, 1886). Notwithstanding, not only Italy benefited with the immigration of experienced Flemish weavers but also in other countries, a fact that contributed to the creation of national workshops in the 16th and 17th centuries (Baumgarten, 1897).

During the baroque period on the 17th and 18th centuries, another golden period came to tapestry manufacture, which updated the art of weaving to the contemporary style in use mainly in France. Brussels fell into decline due to the mass immigration of its weavers and thus numerous centres for tapestry manufacture continued to be funded in countries such as France, Germany, England, Spain and Portugal. The geographic evolution of tapestry manufacture in Europe across the centuries is presented in Figure 2.11. French tapestry made at Gobelins and Beauvais workshops under the reign of Louis XIV and Louis XV became the main artistic current influencing trends in style and technique (Guiffrey, 1886). One of the main changes from the 17th to the 18th century is that the size of tapestries reduced as an adaptation to the smaller room sizes of this period. Another important feature on the baroque tapestries is that weavers increasingly pursued the imitation of canvas painting and for this the artists Oudry and Boucher with the aid of chemists created a colour palette with thousands of colours each one with 12 different shades (Baumgarten, 1897). However, this came with the disadvantage that numerous colours were chemically unstable, and the sets of this period degraded quickly. The 18th century is also known for being the century when the use of metallic threads ended (Champeaux, 1871).

After the rococo period in France, tapestry felt into decay because successors of artists were not as good in design and the change of trends in the 19th century placed the art of tapestry apart from the contemporary art market. Most of the productions in this century were only revivals of what had been done in the baroque era. With the invention of the Jacquard loom, the production of replica tapestries using industrial mechanical processes started thus
introducing a pressure to an artistic tradition that was already in decline (O’Mahony, 2016). The interest by handwoven textiles decreased and with the change in artistic trends in the 19th century together with the lack of money for maintenance and restoration, tapestries were left abandoned in attics and barns or renegaded to be used as wallpapers in which paintings were hung. In some extreme cases, tapestries were being adapted as furniture coverings and even carpets (Montebello, 1993, Baumgarten, 1897).

In the 20th century, some modernist movements tried to update the art of weaving to the modern artistic movements and to cheaper and quicker processes of manufacture (Jobé, 1965b, O’Mahony, 2016). Contemporary tapestry in the 21st century still faces similar challenges regarding cost-time challenges and textile industrialisation procedures that came since the invention of the automatic loom in the 19th century. Despite this, there are still many individual weavers and tapestry workshops that continue to practise the art of handwoven tapestry.

Figure 2.11 – European Centres for tapestry production.
2.3.2 History of Damage

Damage is always a hard definition to attribute to any kind of artwork, and to define its boundaries can lead to very complex discussions on the topic. However, it can be seen as harm that impairs the function, value, or usefulness of an object. For the case of tapestries within this research, any change that decreases the usefulness as a tapestry or impair tapestries as decorative artworks is understood as damage.

As in any object, from the moment that the first tapestries were hung, damage was present. Damage is caused mainly because the object is exposed to natural conditions such as environmental conditions and physical forces. Under these circumstances, damage can never be stopped nor cannot be avoided but in most cases can be delayed and mitigated, and tapestries can be restored or conserved.

Along the history of tapestries, damage was always present and as tapestries are very fragile objects, damage is an important piece in the puzzle of history of tapestries and serves as an alert to the importance of studying conservation and best conditions to preserve the few examples that reached our days.

Damage on tapestries before the middle ages is very difficult to trace but given that only small fragmentary pieces survived and the fact that most of them if not every existing fragment were found in burials this means that all other tapestries that were used for decorative purposes were for some reason lost. This shows how fragile and prone to damage these objects are.

During the middle ages, the nomadic life of tapestries has created so much damage that only a few examples before the 15th century survived (Guiffrey, 1886). Guiffrey explains the large dimensions of medieval tapestries were one of the main drivers of so much degradation (Guiffrey, 1886). The 14th century tapestry depicting the battle of Roosebeke weaved by Michel Bernard is reported to have measured 56×7.25 aunes which is roughly equivalent to 66.6×8.6 meters. Ironically, it is also been reported to have been in a ruined state just a few years after being weaved and it was necessary for the restorer Nicholas d’Inchy to cut the original piece in small fragments to reduce its size to decrease the loads it was subjected to (Guiffrey, 1886). Furthermore, in the middle ages, to cope with the nomadic life and damage created by poor conditions of storage and handling, these objects were experiencing there were weavers whose main task was the restoration of tapestries. Their main restoration procedures were dividing these pieces in smaller fragments, restoring the damaged areas by reweaving them and even replacing sound areas where the tapestry owner desired changes (Guiffrey, 1886). Reweaving was the main practice to preserve these objects (Fryman, 2011) as they were valued not as historic artefacts but as artworks who existed to decorate and tell a narrative.

In the middle ages hanging tapestries by using nails or hooks was a very common practice and these were transported along with the tapestries every time that nobles travelled.
for the tapestries to be ready to hang as soon as they arrived to their destination (Guiffrey, 1886). Of course, that at that time the practice of hanging a tapestry with nails was not seen as damaging, but the effects of this are documented by the constant need that tapestries at this time needed to be restored.

With the change of trends in the end of the 18th century, the manufacture of tapestries reduced substantially and some of the best sets of tapestries were being used in permanent display as wallpapers to hung paintings or even burned to extract its precious metal threads (J. Band, 2006 and Campbell, 2002).

From 18th century to mid-19th century, history of tapestries is full of incidents and neglect that made these valuable artworks to fall into oblivion and be cast aside by public opinion, in contrast to what happened in the history of painting (Baumgarten, 1897). The practice of cutting tapestries into small pieces to fit as wallpapers in certain walls or in order to update their use in the household, give us a grasp of what was happening to these objects when by some reason stopped being evaluated by their artistic importance and started to be seen as mundane objects. Some tapestries were being used as carpets, wallpapers, lining furniture material and even as sailing fabric for boats. Their use as source of material extraction can be seen in the same way as monuments of ancient roman empire were seen in the medieval times, as a source of material extraction to fill the needs of an impoverished and dilapidated aristocracy especially after the French revolution. In a similar way, many tapestries were being ripped of their borders to be used as ornamentation for modern curtains or cut in small pieces to be used as upholstery material or to serve as repairing and filling material for other tapestries (Böttiger, 1937).

As their use was purely decorative sometimes to decorate a room in a palace they were being cut in pieces to fit door frames while the empty spaces in the wall were covered with diverse pieces that resulted from this practice of cutting big tapestries (Böttiger, 1937). Once again, this is a practice that became more common from 18th century onwards when the big dimensions of interior spaces were reduced and became more intimate (Baumgarten, 1897). To add to all this damage going on after the golden age of tapestry manufacture, the practice of extracting golden threads can be also found in the literature, a practice where the owners of metallic threads tapestries where patiently removing these threads because of their value. In other situation there was even massive burning of tapestries in times of economic strife such as during the French revolution just to extract metal threads within them. However, and not only revolutionaries were doing this, but also important manufactures such as Gobelins (Böttiger, 1937). In a more recent history, the loss of tapestries because of looting and bombardments in the second world war is also a major event and hundreds of tapestries figure in the list of artworks lost during this period (Lost Art-Datenbank, 2019). Fire is also a hazard that leads to the destruction of several sets of tapestries across history, such is the famous armada tapestries that used to be hung in the old Westminster palace (Farrell, 2010).
Although tapestry is one of the strongest weaves, their display and handling leads to a loss of structural integrity over time (Breeze, 2000). This makes the mitigation of damage mechanisms and conservation very important practices to keep the endurance of the tapestries that remained intact and reached our days.

2.3.3 Summary

Chapter 2.3 is divided into two parts which presented the history of tapestry in the history of damage in tapestries. The following conclusions are taken:

- European tapestry has its origins in ancient civilisations but reached an important artistic developed that goes from the middle ages until the baroque period. The style and technique suffered some changes, being the baroque tapestries characterised by the use of an extensive colour palette and a closer imitation of painting canvas.

- Tapestries were damaged in the middle ages to a great extent due to their use. The use of nails and hooks to hang tapestries, their nomadic life associated with the need of reshaping a tapestry to a new environment by cutting the original tapestry into pieces and even changing their original design with reweaving are among the main factors that lead to loss of these artworks in the middle ages.

- The 19th century is another wave for the loss of major sets of tapestries, since with a change in trends these objects started being used as wallpapers, carpets, furniture materials source of metal extraction and any other use that could be given from the materials they were made of.

- The history of tapestry serves as an alert to how fragile these objects are and the importance of keeping the remaining examples of this art in a good state of preservation.

2.4 Damage Parameters

A tapestry is an interwoven work of art, where the wefts that produce the image are held together because of the warp structure but are usually also supporting their own weight. It has a remarkable difference when compared with a painting on canvas because in a tapestry is the woven structure that creates and supports the rendered image. When exposed to any damage mechanism, given this interdependent structure, not only the design suffers, but also its structure becomes affected (Lennard, 2006d).

In an assessment of tapestries in Hampton Court in 1997, it was verified that the damage found by order of frequency were: opening of slits due to threads failure, degradation of silk
areas, and pests damage (Bilson, Howell and Cooke, 1997). These areas of damage were spread to the entire tapestry with more occurrence of damage in silk areas of tapestries. Although the authors did not attribute this damage to hanging stresses, areas of silk on top edge were opening up more than areas below (Bilson, Howell and Cooke, 1997), which is an indication that stress must have been contributing to further damage.

Damage mechanisms are activated when tapestries are exposed to environmental conditions on display or in storage. These mechanisms depend on a huge amount of parameters such as the type of fibres (Graaff and Boersma, 1997), dyes (Hacke, 2006), previous conservation procedures (Lennard, 2006b) and even the type of weaving (Hacke, 2006). The tapestry characteristics and current conservation conditions give way to more or less chemical and physical stability, which affect aging processes that the materials experience.

Structural damage result either as a cause of chemical degradation or of direct damaging by physical forces applied on the tapestry. However, these distinct processes are always dependent on each other.

Regarding chemical stability, these are mainly related with two factors being the first the dying process used in tapestry threads and the second the type of materials that constitute the tapestry which commonly are silk and/or wool. Silk is usually much more chemically unstable being susceptible to fading and degradation (Graaff and Boersma, 1997). Medieval and Renaissance tapestries are comparatively more stable with regards to dyes, as a limited range of vegetable dyes were utilized that did not react with wool fibers. The only exception to this was the production of black and dark brown colors, which were created through iron oxidation, leading to fiber degradation. (Pow, 1970). By contrast, when in the baroque period the reproduction into a tapestry of oil paintings acquired interest, the number of colours increased exponentially (Weigert, 1962). This increase in the number of colours available came with the cost of them being more chemically unstable, which caused tapestries produced from the baroque period onwards to become very often more degraded than medieval tapestries (Pow, 1970). Furthermore, with silk becoming more accessible after renaissance (Turner, 2013) this chemically unstable material was used more than before also contributing to the degradation in tapestries from this period onwards (Pow, 1970).

The main damage mechanisms that affect tapestries are light, dust, relative humidity, temperature, pests and mechanical damage (Frame et al., 2018, Langley and Sanders, 2006 and Holc, 2006).

Since tapestries are sensitive to light conditions, the study of light impact on fibres is also one of the major topics covered by conservation scientists (Frame et al., 2018 and Hacke, 2006). Computational light simulations considering the exhibition of tapestries in historic building environments are studied in order to find the best conditions that serve the conservation of these objects (Balocco and Frangioni, 2010).
Solutions to protect tapestries from light damage include managing of exhibition period during the year, use of curtains or other filters for UV transmission control and the use of special wall show-cases with fibre optic lighting and climate control system (Frame et al., 2018 and Balocco and Frangioni, 2010). For a long time, light was considered the most damage factor for tapestries (Hacke, 2006). However, this idea changed when during the monitoring damage in historic tapestries project (MODHT) it was detected that some fibres from the back of the tapestries that were not exposed to light had the same level of fibre damage as fibres in the front of the tapestries (Hacke et al., 2009b). This brought the idea that other damage mechanisms could be as important as light in damaging historic tapestries.

Relative humidity and temperature are usually not by themselves the direct cause of damage but their fluctuation causes chemical and physical damage and because of this, their study is of major importance (Hacke, 2006 and Duffus, 2013). Nevertheless, in extreme conditions of moisture and temperature, direct damage to tapestries can happen. An example of this is reported whereby tapestries soaked water from the walls they were attached to and, because of very cold winter temperatures, the water turned into ice, causing physical damage (Maes, 1987). Here the damage did not come directly from the high level of moisture or due to the cold temperatures, but rather to the joint effect of factors that further led to mechanical damage. This is somehow different to what happens when due to moisture adsorption a tapestry increases its weight in cycles, introducing a change in weight that makes the stress increase in the tapestry structure.

When tapestries are in open display, they easily gain dust by being exposed to indoor environment (Frame et al., 2018). Dust also spreads through a tapestry structure due to the practice of rolling tapestries on themselves, loose fibres and dust often accumulate both on front and reverse, also making loose threads to get dispersed through the entire tapestry (Breeze, 2000).

The presence of pests and rodents in the indoor environment can also lead to missing areas in the textile, since these can sometimes feed on textile materials (Langley and Sanders, 2006).

The literature on mechanical damage related to historic woven textiles is much scarcer when compared with research developed by textile industry in the later years regarding wear and tear. However, some examples of conservation studies give some insight into this matter.

Mechanical damage can be a direct effect of wear and tear or can be part of a more complex process which involves chemical degradation. As an example, the opening of the stitches in the slits results sometimes from the chemical degradation of stitches used which become loose. This opening of the stitches results then in a physical damage phenomena causing high strains in the ends of the gapping slit (Graaff and Boersma, 1997).
Mechanical damage can also be produced by piercing nails into tapestries or by the use of damaging hanging techniques, such as hooks (Cavallo, 1993, Columbus, 1973, and Böttiger, 1937). As immediate damage examples are fibres that are broken in this piercing process, with some old tapestries being reported as having big holes in their structure caused by these hanging methods (Böttiger, 1937). However, other damage can also happen if these nails are used for hanging purposes, since this is expected to create areas of extreme stress concentrations. Furthermore, there is a display option that considers the stretching of tapestries on frames for exhibition in order to keep them flat. Such a technique restrains the tapestry not enabling it to react to dimensional changes (Columbus, 1973).

Damage is also reported to have happened due to conservation approaches in areas of lining where the stitches were producing stresses to an extent where these were pulling the weaved tapestry and thus making holes in it (Langley and Sanders, 2006). Also, localised stresses can be induced by the use of repair patches if they are different in terms of stiffness of the woven tapestry and thus have been reported by conservators as pulling and pucking some original areas of the weave (Graaff and Boersma, 1997). Pull and pucker being defined in conservation practice as the undulating effect in the weave caused by the fabric contraction into wrinkles as high strain applies to the weave.

Physical damage caused by hanging and conservation techniques is further explored ahead in this review over the next chapter.

In summary, the main conclusions that can be taken from this chapter are:

- The main damage mechanisms in historic tapestries are light, dust, relative humidity, temperature, pests and mechanical damage. Temperature and relative humidity do not produce direct damage, but their fluctuation can activate damage by other processes.

- Chemical damage is usually associated with the dying process used which can be chemically unstable or not and the materials in use in the tapestry that can be more or less reactive according to certain conditions such as the case of interaction between wool and black or brown historic dyes.

- Mechanical damage can occur due to wear and tear and to physical damage, such as piercing or restraining a tapestry’s natural movement using a frame. Mechanical damage due to stress development caused by conservation treatments or activated by other damage mechanisms can also be present in a tapestry.
2.5 Tapestry Conservation

2.5.1 Introduction

Conservation results from a direct response to damage and the human will to preserve artworks and it is because of this that historic tapestries still exist reached our days (López, 2015). The concept of conservation had however evolved and changed according to the change in trends and values across their history (Shephard, 2006).

Since the early times of tapestry manufacture, cleaning and maintenance was needed and in order to update tapestries and to keep them with a new appearance, alterations and restorations were always in place (Guiffrey, 1886). Restoration/conservation processes are seen as tools to keep the monetary and artistic value of the object updated (Bosworth and Caroline, 2006). Furthermore, when deterioration was so high that their use as hanging textiles was at risk, conservation was required to keep these objects hanging on open display and thus continuing to have their function (Conti, 1988). We can consider that if change and damage is intrinsic to an object its restoration and conservation as part of the process to readapt and update that object to its new status is also an intrinsic process to the artwork.

Restoration and conservation processes both consider change to the current state of the object. On the contrary to paintings, where the paint layers and canvas are two independent structures, in tapestries it is the structure of warp and weft that forms the rendered image. Because of this, any change produced during a restoration/conservation procedure implies a change in the rendered image, establishing tapestries as a distinct branch in conservation (Lennard, 2006d). This means that after any process of change a tapestry undergoes, its structure changes and thus it is expected its response when submitted to physical forces and environmental conditions to change as well. It is important to note that conservation treatments change the structure of a tapestry, leading to a direct impact on strain. Therefore, the impact of conservation treatments on tapestry structure and subsequent strain is an essential consideration for this project.

2.5.2 Evolution of Tapestry Conservation

Historically, tapestries were restored with the reweaving technique, which was considered in the past as the main process that could enable both aesthetic values to be preserved and to make tapestries structurally sound again. In this method the section of damage was cut out, new warps were added, and wefts were reweaved. Furthermore, in the past even some modifications to the original design would be considered if the owner wanted these changes for decorative purposes or for tapestries to gain more value, which in some cases resulted in adding marks of famous tapestry ateliers (Guiffrey, 1886). Before the 20th century, we can also find examples of tapestries that were being cut into patches to restore other tapestries, by replacing areas where loss of material was present or to apply them as lining
material (Breeze, 2000). These tapestries that were being cut had less value than the one to be repaired most of the times because some irreparable damage must have been already present on them (López, 2015). A practice that lead to the destruction and loss of various tapestries to ensure that others were in an acceptable condition for display (Hayward and Marko, 2006). If the material was damaged by discolouration there was also the option to use *potomage*, a technique to update the colours of a tapestry by painting its threads (Böttiger, 1937 and J. Band, 2006). This was a practice where further damage was created if not by chemical reaction of the added paint layer, because of the increased stiffness created by paint material in certain areas of the structure. Although maintenance of tapestries in the past also considered dry cleaning and washing, these were roughly cleaned without clear scientific knowledge of damaging processes that could be initiated when some practices were put in place (Breeze, 2000).

The concept of tapestry restoration before the 20th century included already structural consolidation in its meaning. However, this concept of restoration changed when some restorers started to place more value in the remaining original material than in the physical appearance that certain areas of a tapestry would acquire if they were rewoven with new threads (Bosworth and Caroline, 2006).

Restoration of tapestries started to be criticised because of many past interventions that were damaging to the original structure (Böttiger, 1937) because most of the times were performed by restorers who did not fully understood the principles of a textile woven structure and the science behind damage and thus disregarded any mechanical aspects in favour of aesthetics. The aesthetics that were considered in restoration processes were mainly to make the tapestry look new again by recreating areas of loss (Breeze, 2000). However, this damage created by reweaving is relatively recent, when tapestries started to be conserved by weavers and conservators who have no understanding about skilful weaving, the quality of restoration decayed. Historically, the reweaving present in old restorations is done to an extent that is not always recognisable as an area of restoration (Marko, 2006). An undetectable restoration is something expected especially in those cases where the same weavers that weaved the tapestries were restoring them with the same original materials and techniques (Guiffrey, 1886). Historically, this was very common since reweaving was done by the same studios that were producing tapestries and weavers were using the same technologies and proficiency either for manufacture of new tapestries or restoration of the old ones (Guiffrey, 1886), a practice which produced in most of the cases restorations that were unrecognisable (Marko, 2006). This approach changed with the industrial revolution as new materials and synthetic dyes were introduced in restoration (Barnett et al., 2006). These new restoration materials were degraded faster than the original work, making restoration areas more noticeable and aesthetically unpleasant (Lennard, 2006d). Furthermore, weaving of new tapestries decreased in the 19th century, which lead to loss of knowledge on weaving techniques (Baumgarten, 1897). Under these circumstances, during the 19th century the loss of weaving techniques took restoration to some shocking cases where tapestries were cut to amend others (Böttiger, 1937) and some very
bad restorations were in progress (Smith, 1984). The practice of reweaving, however, appears to have continued its development in France with more quality when compared to the rest of the world, perhaps because of longer weaving tradition, and by the existence of experienced repairers of tapestries (Breeze, 2000).

In early 20th century, the expert in tapestries and managing director of William and Morris, Marillier (Marillier, 1962), described the state in which he found tapestries in England as an amalgamation of woven patches that were randomly sewed together to fill spaces of damage in the original tapestries. Back then, as explained above, the solution for someone experienced in weaving procedures was to repair these tapestries by removing these patches that did not belong to the original work and to reweave the damaged structure. However, it is also important to account that, at the beginning of the 20th century, Marillier already defended a strong position that the original material should not be destroyed in the restoration process (Breeze, 2000). If by following this process with areas of repair that will not be distinguishable from the original weaving can be perceived as a lack of conservation ethics then one must admit that this was a great improvement when compared to what was practiced in UK before by cutting other tapestries and randomly sewing them together to replace areas of extensive damage (Breeze, 2000).

Nonetheless, while conservation ideals were already gaining favour, in some countries, restoration by reweaving remained the main approach until the end of the 20th century. As for the case of the UK in the early 20th century, the use of repair with patches and non-specialised needle workers seems to have been in place (Breeze, 2000). The best example of restoration of tapestries in this period in UK seems to have happened in the case of Hampton Court Palace, where reweaving was the main method used to conserve these objects. Here the tapestry collection was being restored under direction of Marillier from 1912 to 1946 when ministry took over the direction of works. It was only after the last restorer retired in 1979 that the practice changed to a conservation approach (Delmarcel, 1999 and Asai, 2007).

It was also at the end of 19th, beginning of the 20th century that conservation science in tapestries started to gain relevance, with John Böttiger developing a series of scientific studies to determine the ideal conditions to store and hang tapestries (Böttiger, 1937). In 1889 Böttiger oversaw the care of the Swedish royal collection of tapestries which he described as being in a dilapidated state with tapestries cut into pieces spread for the various royal residences and others in a fragmentary state which had the function of serving as repair material for other tapestries and even to serve as rugs in the royal palace. His work with this collection was focused on creating an inventory, and the reconstruction of tapestries from common fragments that had survived. After having created a restoration atelier and created a storage room, he focused his attention on the multiple factors that can damage tapestries and studied them in a scientific approach which paved the way for future research to come in this field (Böttiger, 1937). As a conservator, he is mainly known to have introduced vacuum cleaning on tapestries (Breeze, 2000), however, his research went further by studying the influences of temperature...
and relative humidity, light and a lining and hanging systems (Böttiger, 1937). All these studies, although primitive when compared to the technologies available today to study physical and chemical degradation of materials brought awareness that wool and silk were different materials that were differently affected by the surrounding environment aging at different speeds, with silk being much more vulnerable (Böttiger, 1937).

In the beginning of 20th century, European experienced restorers were being taken to US to work in tapestry restoration (Breeze, 2000) which kept being considered as the main treatment to apply to a tapestry. It was only in the last quarter of the 20th century that restoration processes were being replaced by the conservation philosophy ( Getty, 1987 and J. Band, 2006), a fact that was clear having into account the amount of conferences being held in Europe and US which favoured this ideology (Breeze, 2000). Not disregarding the fact that many restoration techniques are seen today as inappropriate, it is important to remind that it was because of this process of restoration that the examples of historic tapestries we have today survived (Fiette, 1997). However, considering the costs involved when reweaving as well as the disregard of original work conservation is currently the new ideology of tapestry treatment to follow. It is important to note in tapestry conservation, reweaving is considered a restoration method, while other methods that preserve the original materials and do not involve reweaving areas of loss are seen by conservators as conservation techniques.

Also, in the last quarter of the 20th century that American conservators started to deviate from the European tapestry conservation techniques. In published works of this period is noticeable the use of full support lining by the English conservators in contrast with localized patches being used elsewhere and more specifically vertical straps in the case of US. The trend of escape from full restoration methods involving reweaving was also more noticeable in the US (Breeze, 2000).

The use of straps, which are strips of fabric stitched to the back of the tapestries, appears to be used in a great extend in US from 1970’s onwards. This system was introduced by Josep Columbus that passed this tradition to Kajitani which worked oriented many conservators. However, in a survey done in US in 2000 it was verified that some conservators raised doubts and do not fully understand the mechanical aspects of strapping a tapestry (Breeze, 2000). The same survey showed some aspects about restoration by reweaving, which currently is considered one of the most controversial issues in tapestry conservation (Breeze, 2000). In this survey, few conservators answered that never used considered restoration in their studios, however other few answered that they almost always used restoration procedures, which shows that restoration, although controversial could still be often found in US 20 years ago (Breeze, 2000). It is interesting also that one respondent raised budget as the factors for not use restoration repairs since these are clearly more expensive (Breeze, 2000).

From 1980 to 2000s, there has been increasing discussion among conservators in Europe and US regarding techniques in use for conserving tapestries (Breeze, 2000). In Italy,
the debate on a more scientific conservation methods for tapestries started in 1981 with the congress Tecniche di Conservazione degli Arrazi (Kusch, 2006). Conservation principles differ from pure restoration since it includes professionally trained conservators supporting areas of degradation and restoring the visual aspect with replacement of losses but without effort to bring the tapestry back to its original state (Breeze, 2000 and Adelson, 1994).

Conservation of tapestries is seen as structural stabilisation of the textile material which can either be or not followed by procedures that help the aspect of the tapestry to resemble how it was before and thus making the rendered image readable. The aim is to provide structural stability for the tapestry to continue to bear its own weight. Nonetheless, the clarity of the design is also considered an important factor for readability and decorative purposes (Lennard, 2006d and Bosworth and Caroline, 2006) and conservation methods include re-warp and weft replacement but always using daring technique which makes repairs visible from close examination (Adelson, 1994). The idea that any intervention needs to be identifiable from the original material is clearly opposed to what happened at the beginning of the 20th century in tapestry restoration. Conservators try to apply their methodologies in a way that areas of conservation are clearly identified and will not be mistaken for the original in a closer look (Smith, 1984). On the other hand, conservation needs to enhance the aesthetics and structural recovery of the piece being conserved. Furthermore, the concept of reversibility gains relevancy under conservation philosophy (López, 2015). This concept of reversibility results from two different assumptions: the first one is that there are imperfections in restoration treatments which can in a long-term cause damage to the objects, and the second is the consideration of artworks not only by their aesthetic value but also as cultural documents which authenticity needs to be kept (López, 2015).

The concept of reversibility is a major concern for conservation, but it is not always applicable in textiles due to inherent difficulties in this area of conservation. This is the reason that the idea of minimum intervention is many times highlighted (Lennard, 2006d and Bilson, Howell and Cooke, 1997). This concern that some conservation work needs to carry some consideration for the reversibility of the work done is one of the major topics that can be found in the literature (Maes De Wit, 2006, Wild and Brutillot, 2006, Kusch, 2006 and Smith, 1984).

Replacement of the original galloons is also part of the restoration/conservation processes that tapestries went through in the past and this is perhaps the only accepted practice of replacement nowadays. Since galloons are considered as the outer border of tapestries and are almost always not original, their replacement when damaged is still accepted (Marko, 2006).

Current conservation is also interested in optimisation of its techniques, meaning that it always aims to achieve the maximum conservation effects with minimal use of resources (Duffus, 2013). It is also the duty of the conservator to maintain the equilibrium between ethics, necessities and action, an equilibrium to which a budget available for an intervention always
needs to be considered (López, 2015). However, several differences in conservation methods between the UK and USA were detected in a survey by Duffus, where different conservation aims and ideas proved to be contrasting (Duffus, 2013).

Currently, in the UK alone, over 3 million pounds are spent every year to conserve historic tapestries (Alsayednoor et al., 2019, and Lithgow, 2013). A number that is influenced most of the times by decisions based on the experience of conservators rather than on scientific evidence for which treatments are the best and the more cost-effective methods to preserve these historic objects.

Furthermore, it is important to understand the performance of conservation methods and their impact on a tapestry structure since, when one conservation process is initiated is usually impossible to go back. If a tapestry is being restored by reweaving, visual impact will be evident if the work is changed to minimal conservation as well as if a tapestry is receiving full support lining would be difficult to go back and start reweave some areas with the lining fabric attached (Breeze, 2000). Thus, there needs to be an understanding of the impact of mechanical behaviour that each conservation method brings. However, before understanding scientific methods that can give better light on the understanding of the behaviour of these objects, it is worth to review the most well-known conservation techniques.

The next sections discuss the main techniques in more detail and are related to what is currently in use nowadays but never placing apart past conservation/restoration procedures, which are still present nowadays in the structure of tapestries restored in the past. Five major areas of conservation techniques that are more commonly used in tapestries are reviewed in the following sections, these are: cleaning, reweaving, lining, conservation stitching and adhesive supports (Lennard, 2006d and Hillyer, Tinker and Singer, 1997). Although some of these processes can overlap in many conservation situations, they always produce some structural change in a tapestry and for this reason, it is important to consider them in more detail by understanding what these methods imply in terms of modifying the original tapestry structure.

2.5.3 Current Tapestry Conservation Methods

Tapestry conservation is a relatively new profession that has developed from the basis of tapestry restoration (Howell, 2009). While in tapestry restoration, the removal of original damaged areas is the practice, in conservation there is an effort to maintain the historic material considering a minimal intervention (Howell, 2009). However, these two different approaches can sometimes overlap and depend on different practices and conservation techniques in use in different studios (Smith, 1984). The following subsections: cleaning, reweaving, lining system, conservation stitching, and adhesive support aim to provide an insight of current methods used to clean and preserve tapestries. Although nowadays there is a strong concern on the
preservation of the original material, reweaving might as well be in use by some conservation studios (Breeze, 2000) and thus was included in this review.

2.5.3.1 Cleaning

Cleaning of a tapestry consists in the removal of soiling dust that makes the rendered image unclear and disfigured, and the fibres dehydrated and stiff (Kusch, 2006 and Howell, 2006). The removal of deposited soiling in the weave is important because dust causes the pH of threads to decrease to very low and damaging levels (Lennard, 2006d).

Cleaning is one of those conservation procedures that always had its role in the conservation of tapestries. Yet, in similarity with other conservation procedures, it had a significant development through history. Because of its similarities with domestic laundry, the cleaning of tapestries had always the risk of falling into a simplistic approach (Howell, 2006). In the past, the cleaning of tapestries was done by beating them in order to remove dust. Another practice very common from the seventeenth century onwards was the use of crumbled bread to brush across the surface of a tapestry to collect particles of dust (Lennard, 2006b and Fryman, 2011). The removal of dust by gently brushing the dust was already an improvement of this rudimentary technique (Hayward, 2006). However, these practices became very criticised by conservators in early 20th century when the first vacuum cleaners became more common (Breeze, 2000). The use of vacuum cleaners produced a responsible novel approach to the cleaning of tapestries (Böttiger, 1937). Still, inappropriate cleaning solutions were being used, and when compared with modern conservation approaches, old cleaning methods seem to be extreme in terms of mechanical actions and chemical reactions that the threads were being submitted to (Lennard, 2006d). The second half of the 20th century saw the implementation of wet cleaning into tapestry conservation (Kusch, 2006) and some conservation studios have now facilities designed to carry out immersion cleaning (Lennard, 2006d).

After the meeting at institute Royal du Patrimoine Artistique in Brussels in 1987 the main modern conservation thoughts on the cleaning of tapestries have been summarised (Masschelein-Kleiner, 1987). In the first instance an in-depth study regarding the fibres, dyes, metallic threads and finishing needs to be considered because of chemically unstable dyes and the fragility of threads. The main concern fall usually on the dye-bleeding process that can happen during wet cleaning and thus makes the testing of threads to colorfastness a necessity (Howell, 2006 and Columbus, 1973). In the second place, the benefits of cleaning should be compared with possible disadvantages to the textile that comes with this procedure. If, after this, cleaning is to be considered, a suction method should be the first approach rather than wet cleaning (Masschelein-Kleiner, 1987). However, when the acidity of the object justifies, there is usually the need for wet cleaning the tapestry to reduce this acidity that can be very damaging to the object (Howell, 2006).
Conservation cleaning of tapestries can then be made dry or wet cleaning with water or solvent. Solvents are used numerous times to remove adhesives or paints that exist in tapestries due to rudimentary conservation works performed in the past (Lennard, 2006b). Solvents are also used when tapestry cannot be cleaned with water as it happens on 19th century tapestries that have warps made of cotton which can shrink significantly (Lennard, 2006b).

When vacuum dry cleaning is in place, a screen is usually used to cover the tapestry for the tapestry to be vacuumed through the screening and thus avoiding mechanical damage on the weaved structure (Columbus, 1973). A vacuum cleaning can also be done in a wetting process, which can use water or other solvents and aerosols. This process it’s more problematic when lining by stripes are applied because the cleaning on a vacuum suction table brings differential areas for dust removal because areas with strips of fabric are more difficult to remove dirt (Wild and Brutillot, 2006). It is because of this that the removal of patches is important because these can trap soil during the cleaning process (Columbus, 1973). Furthermore, the use of solvents is commonly done using vacuum suction table in order to make the solvent pass through the textile rather than in an immersive method (Lennard, 2006b). In the aerosol suction method, the tapestry is gradually wetted in a system that mixes water, detergent and air using suction underneath the tapestry to extract particles of dust that becomes released from the fabric thus avoiding dust re-deposition (Wit, 2006).

Wet cleaning is seen as the most efficient method to remove deposited soil from the tapestries (Lennard, 2006b). However, some considerations must be taken when wet cleaning is the option. The water is usually demineralised and used at room temperature (De boeck et al., 1987 and Howell, 2006). This water should be pure or have a small amount of detergent used and chemical additives should only be considered if used consciously (Masschelein-Kleiner, 1987). Wet cleaning can be done or by a spray of water or by full immersion (Cussell, 2006a) or even considering both as it happens in the textile conservation studios in Historic Royal Palaces. When full immersion is not done, wet cleaning usually consists of gently rubbing sponges into the tapestry in order to soak the dirt attached to it (De boeck et al., 1987).

Before wet cleaning it is usual to remove lining or patches stitched in the back of the tapestry (Kusch, 2006). As explained above, it is also very important to conduct tests to see if it is safe to undertake full cleaning and the type of cleaning to undertake which usually has to do with the fact that dyes used in threads are water soluble (Kusch, 2006). When different materials exist in the same tapestry is also important to investigate if immersion in water will not produce differential shrinkage (Kusch, 2006). One of the main concerns is also to minimize the movement in the weaved wet fabric, thus reducing any physical forces applied in the tapestry (Lennard, 2006d).

To wet clean wool and silk is usually easier than other textile materials because these materials both have a protein structure chemically similar which usually makes a neutral or slightly acid cleaning solution work very well (Howell, 2006). However, due to the
extensibility of wool when compared with silk, it is verified that wool tapestries tend to shrink more after wet cleaning when compared with silk weaving (Howell, 2006). For more modern tapestries that have linen on their warp structure, cleaning is more challenging because with the contact with water damaged, linen can become heavily damaged (Wild and Brutillot, 2006). It is also a problem for modern tapestries that are made with cotton warps since this material tends to shrink exponentially when in contact with water (Lennard, 2006d).

The drying of tapestries after wet cleaning is a very sensitive in terms of mechanical stresses, since historic tapestries can increase seven to eight times their initial weight. It is then important that stress is reduced to a minimum, and this is the main reason usually tapestries lie flat during the drying process (Howell, 2006).

2.5.3.2 Reweaving

Reweaving is the process of replacing areas of original weaved threads which have been damaged or are not fit to use anymore. This is the method considered for restoration of tapestries and was used since there are accounts on the restoration of tapestries (Guiffrey, 1886).

In this process the warps need to have some tension as it happens during weaving, for this to be achieved, conservators used weights attached to these warps in order to produce tension (Columbus, 1973) or alternatively a frame-type structure to hold warp threads under tension. The conservator then removes the damaged weft threads to reweave them. There are cases where areas are so damaged that weft does not exist anymore or even the warp is lost. In these cases, a new warp must be placed where the old was and this process is called rewarping which is done prior to reweaving or any other process of structural consolidation. For reweaving, the weft threads are interwoven with the warp, a process that can be done with the use of a needle (Cussell, 2006b).

Reweaving is most of the times seen as the opposite of conservation since here the original threads are replaced while conservation considers the structural stabilisation of the original threads. For this reason, this technique is not seen nowadays as ethical since consideration for original material doesn’t exist (Columbus, 1973). Furthermore reweaving is considered to be extremely time consuming when compared to other conservation techniques (Columbus, 1973).

Notwithstanding, reweaving can be also seen from a conservation point of view as for the case of a tapestry conserved in Boston museum (Smith, 1984) where a woven patch was produced to be added to a lost area in the structure. This was done always considering ideas of reversibility and the final aspect of the image, which did not look like original material. For this to be achieved a separated woven patch was created and then attached at the back of the original tapestry by stitching the warps of both the woven patch and the tapestry.
2.5.3.3 Lining System

Since the 13th century that lining is mentioned for the case of tapestries (Guiffrey, 1886) and until the present day, tapestries were lined and relined across their history (J. Band, 2006). In 1547 inventory, three quarters of Henry VIII tapestries are reported to have been lined with 86% of these being fully lined (Hayward, 2006).

The process of lining consists in the application of physical support, so they acquire a double utility by protecting the back of textile and by reducing stresses during hanging (Bilson, Howell and Cooke, 1997). Lining is seen as part of consolidation process of the degraded weaved structure (Maes De Wit, 2006) and a way that conservators use to ensure an even distribution of loads in the textiles. However, lining is not used only as a weight distribution, but is also used as a protective back to the tapestry abrasion onto the wall (Harper and Thompson, 2006) and a dust barrier (Marko, 2006). To line a tapestry is a long process in terms of time and needs a considerable investment of money and people specialised to do this task, but it is a very important process since it ensures the longevity of tapestries (Hayward, 2006). Every time a tapestry is conserved, the old linings are usually very degraded and thus are removed and replaced by a new linings (Hayward and Marko, 2006).

Once the process of attaching a lining fabric to the back of a tapestry will increase the weight of a tapestry, the material considered for this must be light (Wild and Brutillot, 2006). Lining can be either done with linen or cotton, however the former seems to be more used in conservation than the latter (Hayward and Marko, 2006). Linen is considered as the best material for lining because it’s more compatible with the weaved structure of a tapestry in terms of deformations due to moisture adsorption. Linen absorbs and releases moisture more quickly than cotton, thus behaving similarly to what happens to the weaved structure of a tapestry (Hayward and Marko, 2006). However, the density and the type of stitching used in lining must also be considered. In extreme cases, lining can be stitched so tight that with time starts to show creases that result from restraining tapestry movement (Brutillot, 1987). To go around this, conservators can add extra areas of fabric, leaving the lining loose and thus anticipating future differential changes in dimensions of the tapestry when it absorbs and releases moisture (Marko, 2006).

Historically, lining could also be done by employing patches of weaved fragments that have been removed from other tapestries. These patches were coming from less valuable sacrificial tapestries or from areas which have been reweaved but this is not done anymore (Hayward and Marko, 2006).

There are two main methods of lining in tapestry conservation: the American and the English method. Joseph Columbus in US used supporting straps spaced 18cm apart on the back of the tapestry before attaching the dust cover. His method of repairing by spaced straps of
lining became a standard method for conserving tapestries in US since then and he is considered the father of tapestry conservation in US (Columbus, 1973). Aligned with this, there is also the practice of applying only necessary lining which considers patches that act as bridges between sound areas and areas of silk that are profoundly damaged. The reasoning behind the partial linings is the belief that objects can be exhibited in a sound condition and thus minimising the budget in conserving them, a technique that ensures minimum intervention (Bilson, Howell and Cooke, 1997).

This contrasts with the UK approach to lining, where the tendency is always to give tapestries a full lining support (Bosworth and Caroline, 2006). Furthermore, partial lining can always be converted into full linings by adding fabric or placing a full lining on top of them, which seems to be the treatment that is followed in UK each time a tapestry is partially lined (Marko, 2006).

The process of preparing linen for lining consists in washing to scour, removing any kind of coating finishes and pre-shrink the fabric (Hayward, 2006). This process frequently resorts to boiling water (Maes De Wit, 2006) and it seems to have been the same process used to prepare lining for historic tapestries in the past (Hayward, 2006). After this initial preparation, the conservator fixes the lining to the tapestry using stitches in the vertical direction of the tapestry (Maes De Wit, 2006). This stitching uses the warp structure to attach stitches at certain spaced intervals (Cussell, 2006b). The stitching of the lining to the tapestry is done by creating a grid of fixating stitches which will be more or less dense, depending on the importance of the tapestry and the level of damage that is present. The result is a system of short lines of stitching staggered in rows systematically (Wild and Brutillot, 2006). The material used for stitching is usually cotton since is stronger when compared with other threads (Maes De Wit, 2006).

On top of this lining, it is often employed a protective lining cover to protect the lining of tapestries from dust at their back (Bosworth and Caroline, 2006). When employed, this lining is loose since it doesn’t give any structural support but rather a protection. For this reason, this cover should be lightweight and repellent of dust, such as cotton sateen (Barnett et al., 2006).

2.5.3.4 Conservation stitching

The technique of conservation stitching or couching have been in use since 1960’s when conservators started to consider the attachment of the lining to the tapestry as a way of distributing the weight of a tapestry hanging by its own weight (Columbus, 1973).

Couching technique as the aim to hold the tapestry fabric to the lining fabric at the back. This procedure helps to support areas of weaved threads that are damaged or weak onto patches or full lining support while recreating the design (Lennard, 2006d).
Yarns used for stitching aim compatibility with the weaved structure and, for this reason in wool areas, wool is usually used. As for the case of silk, since this material can easily become degraded, other threads are usually considered being the cotton those that can combine strength, durability and a shiny appearance blending with silk without having much visual impact (Columbus, 1973). Polyester threads can also be used since this material is strong and durable. However, if fine polyester is used, damage can be created on the warps which do not happen with thicker polyester threads. Yet, as thicker as threads become, more visual impact is created into the weaving structure (Columbus, 1973). Similar considerations for threads are used in the case of slit stitching when conservators decide to close the open slits during conservation works (Columbus, 1973).

To implement conservation stitching, vertical lies of running stitches equally spaced are considered (Marko, 1987). If a tapestry is too weak and damaged, these lines will be less spaced than if the tapestry is in sound condition (Boswrth, 2006). A variation that can also be done depending on damage and restoration present in each area inside the same tapestry (Shephard, 2006). The implementation on the vertical direction is done because warps are used to stitch the tapestry to the lining since these are the stronger than the crimped wefts (Columbus, 1973).

Stitching is done over one warp and under another number of warps sequentially. The number of warps under depends on the conservators that need to consider the level of damage and costs present in a specific tapestry conservation task. Couching technique can also incorporate some work with the damaged warp threads in order to enhance the rendered image in the tapestry by matching colours of the damaged areas (Columbus, 1973 and Boswrth, 2006). To redefine the design, colour matched stitching is done to infill areas of loss in the tapestry structure (Lennard and Harper, 2006). In terms of visual impact, threads are usually selected matching the colour of surrounding areas (Columbus, 1973) and even the missing weft threads in case the tapestry is showing only the bare warps (Lennard, 2006d). But of course this option for colour matching will depend on each conservator and on the design and damage that is present in each tapestry (Gill, 2006).

Aligned with modern conservation philosophy, conservation stitching is made to be seen by the viewer in a closer inspection (Lennard, 2006a) and requires from the conservator a great amount of experience and technique to be able to subtly recreate the image keeping the stitching visible at the same time (Lennard, 2006d). Some conservators, however, criticise this method because it resembles embroidery rather than weaving (Maes De Wit, 2006).

2.5.3.5 Adhesive support

Historically, starch and modified starch and animal glue were used to attach support materials to damaged areas in textiles (Timar-Balazsy and Eastop, 1998). Since second world war synthetic resins were becoming more common on conservation (Lodewijks, 1964), and in
the 1950’s thermoplastic adhesives were introduced in the field of textile conservation as a method to support fragile areas on textiles (Hillyer, Tinker and Singer, 1997).

During the early years of the second half of 20th century, the use of adhesives as a consolidation method for woven structures on tapestries seem to have been used in some cases (Marko, 1978 and Hayward and Marko, 2006). These adhesive treatments were applied in the back of the tapestries to glue a textile supporting structure that could be either a nylon net (Marko, 1978), polyester or silk crepeline (Timar-Balazsy and Eastop, 1998). This treatment can be applied first, considering small patches to the most degraded areas, followed by a main piece of net that covered all the surface in the tapestry (Marko, 1978). To apply these support fabric structures, an adhesive coating was placed on the supporting fabric to form a thin film after which was softened in a process that usually was done with a heating technique before contact was made with the damaged textile structure (Timar-Balazsy and Eastop, 1998). In a more intrusive technique, where costs compared with traditional conservation approaches is significantly reduced, the tapestry is impregnated with a resin (Lodewijks, 1964).

Of course, the objective of conservators was to use adhesive treatments in a way that no change was produced in the structure and appearance (Lodewijks, 1964). However, this was not what was verified. Not disregarding the chemical effects that the adhesive must have created, the use of such technique restrains the textile that is always expanding and retracting due to moisture adsorption cycles, this textile will be submitted to a high variety of stresses that can lead to damage. As observed by Marko (Marko, 1978), one of these textiles have degraded in just a couple of years after an adhesive treatment been applied to it. The 16th century tapestry in cause presented large areas were the weft break with areas where the weft have disintegrated completely in the front of the tapestry. These treatments often increase the stiffness of the treated areas (Timar-Balazsy and Eastop, 1998), and there have been cases where the whole object was very inflexible resembling a “piece of card” and was very dusty since no lining was applied (Marko, 1978). To add to this, the contact areas between the net and the tapestry had different areas of adhesion, varying the amount of adhesive applied with even some areas presenting bubbles where no contact between the tapestry and the net was provided (Marko, 1978). The use of net in textiles is also reported as a support method that distorts and stretches (Hillyer, Tinker and Singer, 1997), a factor that in early conservation of tapestries must have been amplified by the insufficient knowledge on application techniques and the objects interaction with environmental conditions (Pretzel, 1997). Moreover, with aging, the mechanical properties of the adhesives will change, and having into account that this change will not be uniform across the whole surface of adhesion at same time, differential strain areas will be created as the tapestry expands and retracts with changes in environmental conditions (Timar-Balazsy and Eastop, 1998).

After much debate due to negative experiences using adhesives (Timar-Balazsy and Eastop, 1998), in the end of the 20th century this practice was infrequent. After many iterations of success and failures many conservators were feeling that there was not enough information
on the use of adhesives on textiles which reflected on concern of reversibility and the response that synthetic modern materials cause in terms of performance and compatibility with historic textiles (Hillyer, Tinker and Singer, 1997). Although at the end of the 20th century experimental lead research was informing textile conservators on the role of adhesives in textiles structures (Pretzel, 1997), its use was already scarce (Hillyer, Tinker and Singer, 1997).

Nowadays it is considered that any type of adhesive can cause staining, embrittlement of the tapestry fibres. Because of this, any type of adhesive must be removed from the tapestry structure when possible, which is usually done with solvents when the colours are not fugitive or there is risk of compromising metal threads (Lennard, 2006b). A solution of using solvents can take the form of simple spot cleaning to total immersion on solvent depending on tapestry properties and where this technique is being applied (Lennard, 2006b). Not disregarding that adhesive techniques are not considered anymore in tapestry conservation by known conservators (Lennard, 2006b), nothing prevents other conservators from using this technique as well as the existence of this conservation method in tapestries treated in the past.

2.5.4 Summary

This chapter reviewed the origin and the concepts behind conservation and the main methods in use, the following can be summarised:

- Reweaving remained for centuries the main method for the preservation of tapestries. It was only in the last quarter of the 20th century that this practice changed to conservation due to a better scientific understanding of historic materials which started in the early 20th century.
- Conservation is characterised by the concepts of structural stabilisation, reversibility, minimum intervention and clarity of the design but without the work to resemble the original weaving.
- In relation to cleaning, the first approach to take should be suction. However, because of the high level of acidity in the tapestry, wet cleaning is numerous times considered. Other solvents than water can be used specially if the objective is to remove paint or adhesives attached to the tapestry. Solvents other than water must be used in tapestries made with linen and cotton because these materials can get damaged and shrink exponentially. However, it is also reported that in water cleaning areas of wool tend to shrink more when compared with areas of silk.
- Reweaving considers the removal and replacement of original material, which is not considered an ethical technique to be used. However, some cases are in the literature where both reweaving and conservation principles were applied.
• Lining is the application of a physical support in the back of the tapestry that protects the textile and distributes the weight of a tapestry through its surface. In lining conservation stitching or couching introduces stitches connecting the lining support to the tapestry warp. These stitches made of wool, cotton or polyester are applied at certain intervals, defined by the conservators. Conservation in USA deviates from the practice in UK especially when considering support lining. In UK, a full lining support is considered which is clearly opposite to the use of support lining strips as it is more common in USA. After lining it is current practice to add a dust protective cover.

• Adhesives to consolidate areas of damage in tapestries proved to have bad results in the past and thus they are not in use anymore. Some tapestries can however still have adhesives present in their structure because of past conservation interventions.

2.6 Methods of Displaying Tapestries

Hanging is the process of suspending tapestries to exhibit them. This can be done using different ways of fixating a tapestry into a wall. In the past it was very common to nail tapestries of to use hooks to fix tapestries into the walls. Although the use of nails and hooks is mentioned in the literature since the 13th century (Guiffrey, 1886), it was still very common in the 1970's (Reeves, 1973) and this practice of hanging tapestries can still be found in some historic houses (Hutton, Lennard and Marko, 2006).

On a paper from 1973, Reeves (Reeves, 1973) describes 6 methods for hanging tapestries that were very usual at the time when the paper was published. In the first of these methods was the most archaic for hanging tapestries (Guiffrey, 1886), here nails are inserted in the tapestry structure, attaching it to the wall. Although the author pointed this as a bad method for hanging, the localised stresses that this method supposedly produces are not mentioned and only the damage created by nails because of its insertion on tapestry structure is considered (Reeves, 1973). In this method, the stress concentrations must have been similar to what is represented in Figure 2.12. The second method described was the sewing of rings on the top of the tapestry and then slip the rings over an auxiliary structure attached to the wall made by nails or a rod (Reeves, 1973) as shown in Figure 2.13. This method is also considered bad by some authors but not due to any localised stresses but because the appearance of the tapestry which appears with a draped effect (Reeves, 1973). However, more recent studies acknowledge the fact that to hang a tapestry from nails, hooks or rods lead to damage along the top edges of the tapestry (Marko, 2006). Notwithstanding, the use of rings and nails was still a very common method until 20th century (Bilson, Howell and Cooke, 1997 and Reeves, 1973).
The third method of hanging described by Reeves consists in creating a sleeve and insert a rod inside the sleeve. The rod will then be fixed to the wall using some support technique. The fourth hanging method was described by the sewing of a tape to the upper part of the tapestry leaving the bottom of this tape free to be nailed to a board attached to the wall using any support technique (Reeves, 1973). The fifth method of hanging a tapestry is to use a Velcro strip that is composed of two complementary strips one sewed to the back of the tapestry and another attached to the wall. These strips, a male and a female when pressed against each other are capable of holding the tapestry (Reeves, 1973). These three last methods are the ones considered to create an even distribution across the top edge in a way that localised stress and strains are avoided (Marko, 2006). In addition to these methods, a technique to distribute the weight of the tapestry in a more uniform way across the structure is the use of support lining (Finch, 1987). When support lining is used together with a Velcro strip, the Velcro needs to be attached onto the lining before lining process to start (Maes De Wit, 2006). This Velcro strip is sometimes not directly attached onto the tapestry lining, but considers another strip of fabric which is by its turn attached to the tapestry (Wild and Brutillot, 2006). This Velcro strip varies its height depending on the conservation studio applying it but standard dimension can go from 5 cm to 10 cm (Barnett et al., 2006).

Another method of hanging a tapestry would be to mount and frame the tapestry which is known by restricting tapestries from movement, placing them under great amount of stress (Reeves, 1973). This type of hanging was a very popular technique of displaying tapestries in the 17th and 18th century (Shephard, 2006) and consisted in creating a frame applying tension on all sides of the tapestry to make it completely flat (Marko, 2006).

As a variant for these hanging methods, there is the inclined plane. This is not a method for hanging since the different described methods for hanging are still valid in combination with this method if the object is displayed in an inclined plane rather than in vertical hanging. Some museums in Manheim and Munich use this method for display their tapestries in an inclined plane (Wild and Brutillot, 2006). This is also something used in Palazzo Vecchio in Florence were there are wall show-cases that can be lifted during the night period to enable a stress relaxation period for tapestries in slope angles higher than 10-15° (Balocco and Frangioni, 2010). In a research by Brutillot it was concluded that elongations of the fibres were inexistent after 30 years of exhibition in inclined planes(Wild and Brutillot, 2006). A theoretical analysis of the efficacy of sloping board was further explored by heritage scientists which concluded that if minimal friction is present in small slopes from the vertical, there is no noticeable reductions in strain (Costantini et al., 2020). The same team of scientists later concluded that if friction forces are present on a vertical plane, a tapestry is well supported and there is no benefit in providing small slope in an inclined plane (Lennard, Costantini and Harrison, 2021). Another technique used in the past to protect tapestries hanging was the use of lesser valuable tapestries to be placed as a cover with the higher valuable tapestries underneath protecting them from light, smoke and dust deposition (Frame et al., 2018).
2.7 Scientific and technical approaches for the conservation of tapestries

2.7.1 Introduction

In the early 20th century when the first steps towards a more scientific approach on managing tapestry collections started, the monitoring of environmental conditions was already present (Böttiger, 1937). However, it was not until the 80’s that a more serious systematic research on the science behind physical phenomena affecting tapestries and its monitoring became an field of study in heritage science (Getty, 1987). In the 90’s research in chemistry of conservation treatments and mechanical aspects of tapestry materials became a field of study (Garcia, Pailthorpe and Postle, 1994, Pretzel, 1997 and Bilson, Howell and Cooke, 1997). In the first decades of the 21st century extensive chemistry studies on the impact of dyes, mordants, ageing, cleaning procedures were done. (Hacke, 2006 and Howell, Mitchell and Carr, 2007). Moreover, some research regarding the study of tapestry mechanics and hygroscopic behaviour was also present and studies in the literature can also be found (Duffus, 2013, Lennard et al., 2011 and Bratasz et al., 2014). This chapter takes into consideration the research developed in the scientific areas of chemistry, physics and engineering to support conservation of historic tapestries.
2.7.2 Chemical Studies in Tapestries

The study of chemical degradation in tapestry materials is not part of the current research. Nonetheless, given the extensive research on this area, it is important to have a general literature review on the projects and contributions that were most relevant in this field and that can bring understanding on the nature of chemical degradation that induce changes in textile mechanics. The importance of this research to the study of mechanics in historic tapestries results from the fact that chemical damage can in some cases play an important role in the stiffness and strength of wool and silk (Bilson, Howell and Cooke, 1997).

Chemical compounds of tapestries include both organic protein fibres of wool and silk and inorganic materials of silver and gold metal threads (Kissi et al., 2017). These compounds are subjected to change due to chemical reactions with other compounds that ultimately produce change in material behaviour and appearance. The study of chemical degradation in tapestries has already a long history and already in the 80’s the oxidative processes have been attributed to changes that cause degradation in textile fibres (Bresee and Goodyear, 1986).

An early study on tensile properties of tapestry threads by Howell (Bilson, Howell and Cooke, 1997) verified colour dependent tensile properties in historic tapestry threads suggesting that the dying process could have produced differential damage and thus affected the strength of dyed threads.

The research on the chemical effects of dying proceed with the project monitoring of damage in historic tapestries (MODHT) from 2003 to 2005 and gave way to a considerable amount of research in the nature of chemical degradation that triggers structural damage in tapestry structures (Quye et al., 2009, Hacke, 2006 and Odlyha, Theodorakopoulos and Campana, 2007). In the past there was the assumption that light was the major cause of degradation for historic tapestries (Timar-Balazsy and Eastop, 1998). Thus the main objectives of MODHT project was to study damage in light aged tapestries and the development of microanalytical techniques to study tapestry fibres (Hacke, 2006). In the MODHT project model tapestries were manufactured, accelerated aged by light and then analysed (Hacke et al., 2009a). The analysis concluded that discolouration happens to a faster rate than fibre damage for the case of wool and in fact fibre damage was much more associated with type of dye and mordants used in the dyeing process than with light exposure. Silk is different, because its degradation is more influenced to the light ageing than by the dyeing process. Furthermore, this research also proved that silk degrades faster than wool and thus, with time, end up weaker (Hacke et al., 2009b). The MODHT brought another interesting conclusion when comparing model tapestries with fibres from the reverse of historic tapestries that still had preserved much of their colour but were in an advanced level of degradation (Hacke et al., 2009b). It was already well known that exposure to sunlight can lead wool and silk to discolouration (photo-yellowing) and to loss of strength (photo-tendering) but the MODHT project proved that tapestries were very degraded by comparing with damage produced by artificially ageing.
Damage in textile fibres was not only associated to loss of stiffness but also to the type of dyes and mordants used (Odlyha et al., 2005). In relation with metallic threads, no difference in the silk core yarns was detected in relation to the composition of the metal strip. Also, no significant difference was observed when comparing the degradation of these silk core yarns with other historic silk yarns (Hacke et al., 2009b).

Batcheller (Batcheller et al., 2006) studied new wool dyed with traditional processes to verify if natural dying processes have any influence on fibre loss. This research concluded that the removal of covalently surface lipid from wool fibres are a result of natural dying processes and that this can result in light ageing (Batcheller et al., 2006). The same study concluded that dyeing processes significantly affect initial tensile properties of wool. However, these same dying processes are independent of the process of degradation due to ageing. It also concluded that Weld which is used in great quantities to produce yellows, greenweed which is also used for yellows and gall which is used to produce red and darker colours were the dying components that proved to reduce initial tensile strength of wool (Hacke, 2006). This was an important step in the study of tapestries because confirmed the hypothesis, already suggested in previous research (Bilson, Howell and Cooke, 1997), that yellow dyed threads have less strength when compared with other threads.

More recently, McCullough’s (McCullough, 2014) developed a near-infrared spectroscopy (NIR) technique to predict the hidden chemical damage in tapestries. This study was followed by Kissi (Kissi et al., 2017) in 2017, who developed this method of identifying areas of non-visible damage by using (NIR) and comparing it with multivariate PLS models of measured cystine oxidation products of tapestries historic wools, establishing a relationship with embrittlement and fibre loss that are related with cystine oxidation (Kissi et al., 2017).

From the reviewed chemistry studies made in historic tapestries, of which the collection of tapestries housed at HRP represent a crucial part, it can be concluded that non-visible chemical damage is present in tapestries and that this is dependent at least in part on the dyeing and finishing processes that each colour weft thread received. Other damaging chemical processes can be triggered by light and dust as already mentioned above on chapter 2.4.

2.7.3 Hygroscopic Studies

This section discusses hygroscopic studies, which are investigations that focus on how materials respond to changes in humidity or moisture levels in the surrounding environment. Böttiger in charge of the royal collection of tapestries in Sweden initiated the practice of measuring T and RH conditions to which tapestries were exposed in open display (Böttiger, 1937). To these two parameters light levels were added to the monitoring conditions that were in place for tapestry collections during 20th century (Kajitani, 1987).
More recently, an important monitoring campaign has been taken place in Hampton Court palace under the banner of the “Tudor tapestry environmental protection project”. This project started in 2012 and is an ongoing project that aims to use monitoring to identify the drivers of degradation to which the tapestries exhibited in Hampton Court are exposed to (Frame et al., 2018). In a first phase, the effect of T and RH in tapestry deformation was monitored with a laser sensor measuring the distance from the floor to the edge of the tapestry each 10 min. It was verified that when RH changed, the edge distance to the floor also changed. Results for this monitoring can be seen in Figure 2.14. This was followed by a more in-depth full-scale monitoring of T and RH which resulted in the removal of radiators from the Great Hall. Monitoring on the number of lux-hours in HRP also resulted in changes being made into the glazing system at the Great Watching chamber with the objective of reducing damage by light exposition of tapestries in open display. Dust monitoring also produced mitigating measures in terms of spaces where visitors pause or walk since it was found that dust deposition was correlated with the number of visitors (Frame et al., 2018). Strain monitoring of one tapestry was also carried out by HRP and is presented below on the following chapters.

![Figure 2.14 – Tapestry movement in relationship with change in RH (Frame et al., 2018).](image)

DIC strain monitoring is also in use in a newly created tapestry since 2009 with the objective of study the life-cycle of tapestries since the time they are first hung (H. R. Williams, F. Lennard, D. Eastop, 2009). Another monitoring campaign was done by Khennouf in an historic tapestry using DIC to monitor strain during 48h (Khennouf et al., 2010). This study proved that even with small changes of less than 6% in RH it is possible to quantify longitudinal strain that follows a decrease or increase in RH. Furthermore, the same research group also used DIC to monitor a 16th century tapestry in Hardwick Hall, however to process the strain maps was impossible at that time since because of demanding computational requirements (Lennard and Dulieu-Barton, 2014).
2.7.4 Testing and Simulation of Tapestries

This section discusses the methods for simulating tapestry mechanical behaviour which can be found in the literature. Due to the scarcity of research directly relating to historic tapestry structures this also comprises research in similar structures such as woven fabrics.

Veit separates simulations in: simulations using computers and simulations using real samples which can be destructive or non-destructive (Veit, 2012). From the first category this section discusses the use of FEM in tapestry structures, while from the second, several methods of mechanical testing in woven structures are exemplified.

2.7.4.1 Physical testing of historic tapestries

A study by Bilson, Howell and Cooke on the collection of Hampton Court Palace developed a mathematical model to calculate weights that single threads were bearing given different structural conditions. In this study, published in 1997, the team created a mathematical calculation taking into account individual properties of weft yarns to conclude on the weight a tapestry was able to support (Bilson, Howell and Cooke, 1997). The mathematical model for the calculation of the ultimate load for a tapestry based on the tensile strength of individual weft yarns is the first structural approach that can be found in the literature for tapestries and although very simple, it marks the beginning of the study of modelling in tapestry structures. In the calculations done it was important the distinction made between degraded wool threads and silk. However, the calculations were done considering single weft threads tested in direct tension and without counting for with the complexity of a weaved area. Slits were also considered in this study, as being just an interruption of threads (Bilson, Howell and Cooke, 1997) and not with all the complexity and all heterogeneity that exists in a tapestry weave to create the rendered image. This model assumes a perfect elastic behaviour until failure of threads. (Bilson, Howell and Cooke, 1997).

In terms of tensile tests, the results for this study are presented in Figure 2.15 where the breaking loads for different wool colours are compared with silk degraded yarns and in Figure 2.16 which presents breaking loads for continuous weaving, slits and splits. It was concluded that blue wool yarns are in average two times stronger than yellow yarns, which are two times stronger than silk yarns. In terms of continuous weaved areas are stronger as stitched slits areas being splits much weaker. After testing areas of woven fabric these however showed to be weaker than what was predicted by the model (Bilson, Howell and Cooke, 1997).

The conclusions of this study were that although there are areas of silk not capable to hold any stress, in overall sound textiles the ultimate capacity is much greater than the forces they are subjected by hanging and thus this do not cause any major risk, suggesting deterioration by stress exposure is not a problem (Bilson, Howell and Cooke, 1997). However further in-depth research developed by the European project MODHT showed that tapestries
are much more fragile than what was previously thought (McCullough, 2014) which brought some uncertainties to what was known about the mechanics of historic tapestries. Also, as mentioned above, Hacke’s research (Hacke, 2006) brought more insights into the relationship between chemical and physical degradation of these objects which justified the fact that yellow wool threads sampled from historic tapestries were having less strength when compared with blue wool (Bilson, Howell and Cooke, 1997) as reviewed on chapter 2.7.2.

To test different tapestry conservation techniques, a research done by Asai (Asai et al., 2008) explored the effects of reinforcing artificially damaged areas of new woven tapestry samples with conservation stitching techniques. Samples were tested under an applied load in a universal testing machine. This study concluded that maximum intervention using stabilizing lines of stitches, close couching and a support fabric proved to be more beneficial in producing less deformations. However some considerations on cost-time efficiency, that are very important for these decisions as pointed out by past research (Bilson, Howell and Cooke, 1997) need to be taken into account and thus the use of stabilising lines alone was suggested as good option of intervention when the tapestry required a full structural support. It was also suggested that using conservation stitching to prevent damage in a sound area will only produce minimal effects (Asai et al., 2008). This study was the first to test different conservation techniques of couching and although done in a control new woven tapestry it came out with the conclusion that as more stitching is applied, less deformations will be produced in that area, but more costs and time are required. However, these conclusions left open the discussion on whether the reinforcement is beneficial for heterogeneous areas surrounding areas of conserved damage or not.
Figure 2.17 – Asai tested samples: 1- Control sample, 2- Damaged sample, 3- Minimum intervention, 4- Maximum intervention, 5- secondary minimum intervention, 6- conservation stitching without lining applied (Asai et al., 2008).

Work by Duffus in 2013 tested historic weave along with artificially aged samples and came out with the conclusion that the historic weave was much more degraded when compared with artificially aged samples as shown in Figure 2.18 (Duffus, 2013). Because of this there was the suggestion for future research to test only historic weaved materials if conclusions on the mechanics of weaved structure were to be taken. This research further validates the observations made by conservators regarding the vulnerability of silk to damage caused by significant changes in mechanics, as it demonstrates (see Figure 2.19) the significant impact of such changes on silk. Furthermore, this research tested 10 samples of historic tapestry weft and the results can be seen on Figure 2.20.

Another research developed on historic textiles aimed to determine water vapour adsorption, moisture dimensional response and tensile behaviour (Bratasz et al., 2014). To this date, this was the most comprehensive research in hygroscopic behaviour in historic textiles was developed by Bratasz in 2014 (Bratasz et al., 2014). In this study hysteresis phenomena were verified during adsorption and desorption as at any given value of RH, moisture content during desorption was higher than during adsorption. The swelling of fibres attributed as the reason for this (Bratasz et al., 2014) This study tested 2 samples of 18th century historic tapestries in the weft direction which at failure presented a load of 6.3 and 5.0 KN/m and and extension of 12.8% and 25% respectively. Further tensile tests on historic textiles proved that strain increases with decrease in rates of loading (Bratasz et al., 2014).

A more recent research by Alsayednoor (Alsayednoor et al., 2019) tested 7 historic tapestries to extract their behaviour for modelling purposes. The results are presented in Figure 2.21. Since these results were expressed in different units than other research, if one considers a thickness of 2 mm for previous tests done by Duffus (Duffus, 2013), the values of stress for both studies at 10% strain are at the same level of magnitude. These studies give a good starting point to the study of mechanics in tapestries and the general understanding on modelling of historic tapestries. However, the fact that only very scarce information on the material properties and the variation that can be found on different tapestries exists, the current models draw only general conclusions related with the factors that affect tapestries behaviour when hanging. Higher stress concentrations towards the top of the tapestry as well as uniform stress
distribution given a uniform support at the top in a simple uniform weave is both commented in the cited studies (Duffus, 2013 and Alsayednoor et al., 2019).

Figure 2.18 - Comparison of historic and artificially aged woven weft and warp tapestry fabric by Duffus (Duffus, 2013).

Figure 2.19 – Comparison of un-aged and aged silk woven tapestry fabric by Duffus (Duffus, 2013).

Figure 2.20 – Tensile tests on woven samples of historic tapestries by Duffus (Duffus, 2013).
Not many studies can be found on mechanical analysis of tapestries and the few available are based on new woven samples (Asai et al., 2008) or artificially aged (Duffus, 2013) which are not representative of the complexity of historic tapestries structure. Furthermore it is suggested in the literature that to deepen the study of conservation stitching in historic tapestries, there is the need to use historic samples that are already naturally degraded and thus are representative of the historic material (Duffus, 2013). On the other hand, there is extensive research done in new textile fibres and yarns as reviewed previously in chapter 2.2.4 where silk yarns are always stiffer and brittle than wool (Susich and Backer, 1951) but tests in historic material seem to contradict this because the effects of aging and damage (Alsayednoor et al., 2019).

2.7.4.2 Methods of analysis of deformations

Methods for analysing deformations by monitoring strain in tapestry structures can be divided into two main categories: the point strain measurement and the whole field strain measurement (Dulieu-Barton et al., 2005). Point strain measurements are those that monitor strain at certain points in a tapestry and can be applied in a single point or as a mesh through the tapestry structure. On the other hand, full field strain measurements aim to give an overall image of the strain in the tapestry. Both categories have their own specific methods with different characteristics. Both methods have been suggested in the literature for monitoring tapestries and analysis of deformations in the form of optical sensors, digital image correlation (DIC) and 3D photogrammetry (Ye et al., 2009).
2.7.4.2.1 Point strain measurements

Resistance strain gauges is a method to measure deformations in artworks, however they produce local reinforcement of the structure that they are attached to, locally modifying material properties and thus giving inaccurate results (Dulieu-Barton et al., 2005).

Optical fibre sensors can be either fibre Bragg grating sensors (FBG) or extrinsic Fabry-Perot interferometer (EFPI), these sensors cause much less impact since they can even be embedded in some materials (Dulieu-Barton et al., 2005). These sensors however have some disadvantages, while the FBG sensors are affected by temperature variations, EFPI are difficult to manufacture and to calibrate. Furthermore, these kind of sensors cannot be applied to every work of art, when an optical sensor is stiffer than the artwork it can cause reinforcement leading to inaccurate readings and even produce damage in the object (Dulieu-Barton et al., 2005). Past studies on tapestry structures considered FBG sensors and came out with the conclusion that FBG could be used to monitor textiles (Ye et al., 2009). However, their level of stiffening which is dependent on the method used to bound the sensors is always something to consider.

The main limitation for point strain measurements is the attachment to the surface since the sensor needs to be bond in a way that experiences the same level of the strain as the object, because of this the nature of the adhesive must be such that it is thin and strong enough to transfer the load from the object to the gauge behaving in the same way as the object (Dulieu-Barton et al., 2005). Innovative strain sensors were built to reduce to a minimum level the attachment of the sensor to the artwork. This is the case of tri-axial strain sensors developed by IBM (Sloan et al., 2014). IBM tri-axial strain sensors use receptors that attach to the object with the use of a simple magnet, thus reducing stiffening effect on the object. These receptors measure displacements in microns taking as reference another magnet in a fixed position which is not in contact with the artwork. These sensors were successfully tested for wood objects (Schrott et al., 2014) and applied to an extensive 2 years monitoring project to one tapestry from the set of tapestries Story of Abraham (Frame et al., 2018) employing a grid of 20 sensors. These IBM strain sensors were also selected to be used in the current research and are further presented.

2.7.4.2.2 Full field strain Measurements

Full field strain measurements usually use imaging techniques where non-contact with the object is assured.

Photographic techniques are perhaps the simplest approach to full strain monitoring. These techniques make use of photographs taken before and after a deformation by correlating both images to get results. Sometimes a grid is needed in the object for a correlation to be made. This is similar to what is considered when using 3D photogrammetry with digital image
correlation to monitor deformations in textiles since past research needed to consider the use of grids to monitor changes in displacements (Ye et al., 2009).

In the literature, 3D modelling techniques such as photogrammetry to assess structural damage and displacements in buildings is already a very studied topic (Armesto et al., 2008). Yet, in other studies the application of 3D modelling to works of art such as paintings (Guidi et al., 2004) exists and explore how 3D scanning technology can be used to achieve a quantitative measurement of the deformation happening in the painting adoration of the magi by Leonardo Da Vinci (Guidi et al., 2004). The study performed a quantitative analysis of painting deformation in respect with a planar reference. This was done with generated 3D models of the object using a range camera. With this technology, there is the possibility of comparing two different 3D models in order to evaluate deformations along a certain period of time due to environmental parameters such as humidity and temperature (Guidi et al., 2004).

To apply 3D modelling in metrology, there are currently two common ways to obtain geometric tri-dimensional information on assets. These are photogrammetry and laser scanning. In these two different methods a point cloud is created which can then be used to generate a mesh or to be used as it is since working with point cloud can make the process more straightforward and cheaper. Photogrammetry enables the creation of a point cloud or 3D mesh from a set of pictures that share same features overlapping in the image area. Point coordinates of an object are obtained from overlapping images after having camera position and orientations known (Yastikli, 2007). For obtaining a 3D model using photogrammetry there is 3 main steps to consider: data collection, data processing, restitution and 3D modelling (Arias et al., 2007). Photogrammetry already proved its application in historic embroidery textile where it was used to capture its geometry and produce a 3D printed replica of it. With less than a 561 photos in a fabric approximately 1 m² was possible an accuracy showing details of textile threads (Angheluta and Radvan, 2017).

Laser scanners produce automatically 3D coordinates of the scanned objects after calculating the distance between laser and object (Yastikli, 2007). Point cloud data taken from laser scanning is similar with photogrammetry that offers information of defined 3D points by giving values of their coordinates as well as RGB colour values. However for the case of laser scanning, data produced often also includes values for intensity (Höfle and Pfeifer, 2007). These intensity values correspond to the energy of the echo that is backscattered from the emitted signal which is the energy reflected by the object’s surface (Guarnieri et al., 2017a and Pfeifer et al., 2007). Since materials have different reflectance properties the resulting intensity is different, and materials can be identified. Although intensity levels can be exploited for registration or classification of surface material properties, they are frequently used only for visualisation purposes (Pfeifer et al., 2007). Notwithstanding, research that extrapolate intensity values collected during laser surveying campaigns can be found in the literature (Höfle and Pfeifer, 2007).
Although 3D modelling techniques were used to capture the shape of textiles as explained above, the monitoring of textiles using only 3D modelling is rare and apart from the references showed above no other works were found in the literature.

Digital image correlation (DIC) is an optical-numerical full strain measurement technique for displacements (Lecompte et al., 2006). This is a non-contact method for measuring displacement either qualitatively by giving the spatial strain distribution or quantitatively giving strain values as results (Daggumati et al., 2011). This technique consists in taking a series of digital images when an object is going through some kind of mechanical transformation and then using an image correlation algorithm with support of an appropriate software (Sutton et al., 2008).

DIC as the name indicates is a procedure where a sequence of images, captured using a static camera system, are correlated with a reference image (Pierce et al., 2015) giving as output full-field measurements (Sutton et al., 2008). Since this technique works by tracking and comparing features on the surface of the object, it is usual for samples to require a painted pattern on them which is known as speckle pattern (Lecompte et al., 2006). Usually textiles have enough features for DIC to work without this pattern (Pierce et al., 2015). One of the advantages of using DIC is that both a qualitatively study as well as a quantitative study of mechanical behaviour of an object that has complex heterogeneous fields can be obtained (Lecompte et al., 2006).

In each photo taken, each picture stores a grey value related with the light reflected by the surface of the tested specimen. (Lecompte et al., 2006). This is the pixel signature to which a collection of signatures forms a subset. The subset size varies as well as the step size which is the number of pixels over which there is shifting with another subset on both vertical and horizontal directions. The software calculates differences between centre of each subset to build the entire displacement field, a process that can only be done if a unique signature is guaranteed by a non-repetitive high contrast pattern. Being this pattern the reason why speckle pattern is usually applied in any DIC measurement (Lecompte et al., 2006).

The main feature of DIC is the measurement of heterogeneous strain fields when an object is deformed (Lagattu, Brillaud and Lafarie-Frenot, 2004). DIC already proved to be a good technique to map the high strain values given in-plane deformations (Lagattu, Brillaud and Lafarie-Frenot, 2004). However, Out-of-plane movement is always important to consider when DIC is being used. It is known that the process of using a single camera 2D DIC is sensitive to out-of-plane movement by presenting in-plane strain errors which are bigger as the camera gets close to the object (Sutton et al., 2008). It is equally important to consider an optimised subset size which is dependent on the user preference and where a balance from resolution and accuracy needs to be studied and it is dependent on the experiment being performed (Alsayednoor et al., 2019). For these reasons, the position of the camera and the setup of the experiment is very important to consider for the reduction of any type of noise that
can be produced. This method can also be used to measure 3D deformation when a system of 2 cameras is used and thus the out-of-plane movement instead of being a noise value is quantified as displacement (Daggumati et al., 2011).

To measure the impact of different speckle patterns a study by Lecompte developed a comparison of patterns under the same numerically controlled deformation which eliminated any interferences that could come from experimental set-up and optics. This proved that size of the speckles used in the speckle pattern in combination with different pixels subsets can have influence on the accuracy of the measurements (Lecompte et al., 2006). In line with research on the influence of speckle patterns, DIC research on tapestries was developed by Alsayednoor where DIC performance was evaluated by comparing an optimised speckle pattern with the rendered woven pattern of a tapestry (Alsayednoor et al., 2019). This study in order to compare the same deformation on the speckle pattern and image of the tapestry built a FEM simulation of a tapestry hanging by its own weight in order to project, by using interpolating functions, both the speckle and tapestry images according to the given FEM deformation extracted from the simulation. By using this technique, the researchers were able to compare noise in the deformations obtained with using a speckle pattern and rendered image of the tapestry with the deformation given by FEM model. Furthermore, the influence of subset size both on speckle pattern and tapestry image were assessed. It was concluded that results using tapestry image in DIC were encouraging when compared to the real deformation (Alsayednoor et al., 2019). The main drawback of this study is the fact that deformations are compared in the perfect conditions of a computer simulation which doesn’t correspond to the real conditions of monitoring where noise caused by vibrations and by light changes on the de-crimping of the woven threads produce changes on the weft woven pattern when a tapestry is experiencing deformation. A recent research project (Nwanoro, Harrison and Lennard, 2022) investigated the accuracy and reliability of the digital image correlation (DIC) technique when used to measure strain fields in tapestry materials. The authors used synthetic deformation fields generated through finite element analysis to evaluate the influence of various factors on the accuracy of the DIC measurements. The paper concludes that the accuracy of DIC measurements is dependent on the load/deformation level, and care should be taken when using tapestry inherent features as tracking information in DIC analysis. With this methodology, it was verified that when compared with direct correlation with the reference image, incremental correlation was found to introduce accumulated error and is less reliable when considering low strains. However, as mentioned above, a computational simulation does not seem to correspond to the real conditions of monitoring a tapestry as light will change on the de-crimping of the woven threads when the tapestry deforms. Furthermore, the authors recommend an iterative approach to determine the optimum DIC parameters, which means these parameters still needs to be tested in a case-by-case basis.

A major project implementing DIC in tapestry structures was developed by Lennard (Lennard et al., 2008, Lennard et al., 2011 and Lennard and Dulieu-Barton, 2014). This project
aimed to prove the implementation of DIC on tapestries and used optical fibre sensors to validate this methodology. It was showed that DIC could produce strain map of selected areas in tapestries and that areas of slits considered as areas of imminent damage could be detected by the presence of higher strains. It was also concluded that as RH increases the strain rises since tapestries gain weight by absorbing moisture (H. R. Williams, F. Lennard, D. Eastop, 2009).

The influence of RH was first explored by Khennouf (Khennouf et al., 2010) by capturing strain using DIC in an area of 12 by 9 cm of an historic tapestry in situ. In a period of 48 hours after being exposed to uncontrolled environmental conditions it was verified that a variation of 6% RH had an impact on 0.06% strain. Figure 2.22 show the recorded values for temperature, relative humidity and strain in this experiment. Although no information on the tapestry or the area in the tapestry this experiment was done is available in the literature, the general behaviour can be observed on Figure Figure 2.22. It is clear that vertical strain increases when relative humidity increases and vice-versa.

![Figure 2.22 – Test on a historic tapestry in situ by Khennouf (Lennard and Dulieu-Barton, 2014).](image)

Relative humidity effect was also investigated by Lennard using a new woven strip where a load of 40 N was applied while the sample was exposed to uncontrolled in-situ conditions(Lennard and Dulieu-Barton, 2014). It was verified that for an increase from 30% to 35% RH the vertical strain increased 150%. However, as temperature also decreased these values need to be taken with caution as absolute humidity changes.

In terms of strain in micro-structure of textiles, a study by Daggumati used DIC to investigate the damage initiation on a satin weave composite. This study concluded that maximum longitudinal strains happened on the centre of the weft yarns at the yarn crimp location and that this location was the same as the damage initiation zone (Daggumati et al., 2011). This research suggests that for a textile fabric, the centre of crimp locations where weft
threads interweave with the warp corresponds to the maximum longitudinal strains, (centre of weft yarn) these areas were immediately followed by an area of minimum longitudinal strain where the transition between the load bearing warp intersects with the weft. As for the transverse strain in the centre of the weft it has a slight positive value, however the other areas seem to be under negative strain. Furthermore, still focused on the micro-structure of textiles it was showed that crack initiation in the fabric happens where there is a local point of high strain in the longitudinal direction when compared to the value of the average tensile strain (Daggumati et al., 2011).

Since deformation of objects need to happen during measurements, in many studies these deformations are induced in the objects by heating or changing RH levels or even applying loads to the object changing a simple monitoring system to a physical simulation (Dulieu-Barton et al., 2005).

A more recent research from the same group (Lennard, Costantini and Harrison, 2022) presented a study on the effectiveness of stitching techniques used to secure woven tapestries to fabric supports, with the aid of DIC. The study found that stitching support reduces deformation and strain caused by damage, and a full fabric support provides better overall support for weak areas. The authors suggest that DIC could be used to optimise the amount of stitching needed for a successful support treatment. This study proved with scientific evidence what the conservation community already observed using tapestry stitching and support fabric to reduce strain in damaged areas. Yet, due to the high level of heterogeneity, it lacked a more in-depth study of material analysis in relation to the physical properties of tapestries and stitching materials and techniques being tested and their respective response.

\[2.7.4.3\text{ FEM}\]

Finite Element Modeling (FEM) is a numerical method that analyses complex structures. It involves dividing a complex object or system into smaller, finite elements and then using mathematical equations to model and analyse how the individual elements behave under different conditions. The use of FEM in the study of artworks is an approach that helps to bring knowledge for predicting the magnitude and distribution of actions that these objects are submitted due to the conservation/restoration works that were applied on these objects (Colville, Kilpatrick and Mecklenburg, 1982) or due to their unique structure (Duffus, 2013 and Alsayednoor et al., 2019). However, in comparison with other areas that have used FEM as simulation method, its use in artworks is very limited (Conde-Carnero et al., 2016a and Guarnieri et al., 2017a). Furthermore, most of FEM modelling that can be found in the area of conservation and study of artworks belong to research done in oil paintings (Arroyo, 2013). However, its importance is evident since choices made for conservation of tapestries and hanging techniques are being made based on practical experience rather than scientific knowledge related with study strain and computational modelling (Alsayednoor et al., 2019).
Research that used FEM for the study of canvas paintings always had the study of mechanical properties of these artworks as background (Arroyo, 2013). Also, to build inputs in FEM on the actions of environmental conditions in the mechanical behaviour of canvas paintings research was developed. The understanding on how objects react and change their material properties according to different levels of RH were successfully used as input in the modelling of canvas (Colville, Kilpatrick and Mecklenburg, 1982). Experiments are usually done to validate and optimize FEM until a satisfactory model is built (Arroyo, 2013). It is recognized that the success of such procedures will depend both on the accuracy of quantification of mechanical properties of materials as well as on the mathematical model (Colville, Kilpatrick and Mecklenburg, 1982).

For the case of tapestries, FEM was introduced for the first time in a research by Duffus on 2013. This research aimed to study the role that slits and different materials can have in stress states in a tapestry structure (Duffus, 2013). This research produced a 2D membrane and with the measured tensile properties of poison ratio, elastic modulus and density created a hanging simulation of a tapestry for 3 different scenarios: unaged wool tapestry, unaged wool/silk tapestry and for an historic tapestry which is showed in Figure 2.23. However, the influence that drapery, conservation stitching as well as complex shapes of different materials, weaving procedures have on an historic tapestry were not considered. Also, the model applied was an elastic model which doesn’t correspond to the real behaviour a weaved structure experiences when hanging (Bratasz et al., 2014). More recently, as an upgrade to this solution, a research to model the behaviour of tapestries was developed by Alsayednoor (Alsayednoor et al., 2019).

This research also considered a 2D membrane to model a tapestry hanging by its weight and slits were modelled as empty spaces in the mesh. However, in comparison with previous research, introduced a more complex situation by considering tapestry material as being hyperelastic material. Also, the model considered stitched slits by assigning lower stiffness properties and patches by assigning higher stiffness properties respectively the half and double of the assigned stiffness for normal areas (Alsayednoor et al., 2019). Two example scenarios of this model can be seen in Figure 2.24. This model constitutes an improvement to previous work but made some assumptions that didn’t match the reality of what is found in a tapestry structure. Firstly, stitched slits were modelled as linear areas in the mesh were the contours created by colour change in the tapestry existed, which as seen above in the previous sections, doesn’t always correspond to the presence of slits. Colour changes only correspond to slits when threads change in the horizontal direction of hanging and even on this situation not all of them are stitched. Furthermore, patches and stitched slits were modelled based on assumptions of their stiffness without mechanical tests to inform their real behaviour. Considering also that there was no distinction of materials in previous research on FEM, results must then be interpreted carefully since these are still behind to what it is the behaviour of an historic tapestry structure.
It can also be observed that modelling done in the past didn’t considered the effect of the draping weave on tapestries, which can only be considered if 3D modelling is implemented and will be of major importance since these textiles do not usually hang in a straight line (Duffus, 2013).

When working with FEM there its always necessary to consider how to define the 3D mesh to consider. Most FEM modelling software available enables to transform a NURBS model into a volumetric mesh (Gonizzi Barsanti and Guidi, 2018) or even to directly draw this volumetric mesh directly in the software (Duffus, 2013). There are several studies in the literature that have used laser scanning or photogrammetry point clouds to create the necessary geometry for a FEM analysis (Gonizzi Barsanti and Guidi, 2018 and Guarnieri et al., 2017a).

Yet, not neglecting the increasing importance and use that point clouds bring for cultural heritage assets in terms of recording, mapping, documentation, representation and preservation (Remondino, 2011 and Yastikli, 2007) in relation with FEM there is no automatic robust process to transform them in solid volumetric models ready to be used in a FEM software (Conde-Carnero et al., 2016). Because of this, different methods are applied for converting point clouds into solid FEM models.

There are 2 main processes used to obtain the geometry for FEM analysis from point cloud data (Gonizzi Barsanti and Guidi, 2018): To create a mesh from point cloud and then use it as a starting point to the 3D volumetric model or the creation of volumetric model directly from the point cloud.

Figure 2.23 – Model of a historic tapestry with slits made with wool created by Duffus in 2013 (Duffus, 2013).

Figure 2.24 – Model made by Alsayednoor (Alsayednoor et al., 2019) of vertical strains in a tapestry made with homogeneous materials and having: a) stitched slits, b) patch restorations.
An approach following the first of these processes would be to create a new model in CAD following the geometry of the acquired point cloud data. Some examples of this approach can be found in the literature, such as the case study of structural analysis for the façade of villa Rivedin-Bolasco (Guarnieri et al., 2017), the viaduct of Ourille (Conde-Carnero et al., 2016), Fillaboa bridge (Kyosev, 2012). This approach comprises always the simplification of the raw point cloud data as well as importing it into a CAD software and decimating the point cloud in order to redraw a simplified model of the structural features (Guarnieri et al., 2017 and Conde-Carnero et al., 2016a).

In a study by Barsanti and Guidi the second of these processes is further explained. Here, the use of photogrammetry and laser scanning to capture cultural heritage assets for finite element analysis is discussed (Gonizzi Barsanti and Guidi, 2018). In this study the initial complex mesh was reduced by a retopology process in Zbrush software and then converted into a NURBS before finally import into a FEM software.

Alternatively, after acquiring dimensions from the point cloud data or by any other process, the model can be draw directly into the software as already mentioned above (Duffus, 2013).

2.7.5 Summary

Conservation science applied to the study of tapestries is an extensive area as the literature review in this chapter shows. The main conclusions that can be taken and considered for the aim of this project are:

- Chemical degradation affects textile fibres and thus mechanical properties are influenced by this. Although light was considered during many years the main damaging factor, research proved that dying processes can considerably affect the mechanics of textile fibres and thus colour information can also inform the mechanics of a tapestry.

- Monitoring of the environmental conditions and their impact on the displacements in tapestries is considered nowadays as a source of valuable information that informs on the level of changes tapestries go in certain conditions.

- Tensile tests done in past research for historic silk show the great amount of damage this material has. With the natural ageing, historic silk, on the contrary of new silk, is weaker than wool. Tensile testing of woven samples also show the difference when considering aged samples with historic material where the latter is always much weaker.
Deformation monitoring can be done using point strain measurements or full field strain measurements. For the first case localised sensors can be placed on objects, however considerations on localised strengthening needs to be considered. Full field measurements can use multiple techniques including 3D modelling techniques and digital image correlation (DIC). DIC was successfully applied in the past to monitor strain development in tapestry structures and can provide both qualitative spatial strain distribution as well as quantitative results.

Not many studies in FEM are applied to tapestries. However, this technique has proved its usefulness in past research to create a simplified model of a tapestry. For better FEM of historic tapestries, it is necessary to have an improved physical and mechanical characterisation of historic tapestries that will inform the best input values for the mechanical properties to consider.

2.8 Discussion and Conclusion

Along this chapter of literary review, the topics covered were very vast and thus detailed conclusions were given at the end of each subchapter. General conclusions that are important to retain for the development of the methodology can be taken.

First, on the review of section 2.2 it became clear that a tapestry structure is composed of different weaved sections which count with multiple techniques of interweaving threads. These threads are commonly made of wool or silk, but they can also be made of metal and cotton or linen. This material and structural heterogeneity means that different sections in a tapestry have different hygroscopic and mechanical responses to physical conditions.

Sections 2.3 and 2.4 introduced damage as another parameter contributing for the heterogeneity in the case of historic tapestries. Damage can take the forms of either mechanical damage but also chemical processes that produce weakening of tapestry threads and thus modify the mechanics of tapestry. Section 2.5 is a literature review of conservation and adds to the understanding of how these tapestry structures might have been modified with conservation interventions which created their current condition. It becomes clear that when studying a historic tapestry structure, there is the need to first understand all the factors that make the tapestry unique which is clearly different from studying a homogeneous new material.

Section 2.6 was a short review on the different methods for hanging tapestries and the most important conclusion remark was that each method produces different mechanical responses from the tapestry since distribution of weight across the tapestry differs.

Finally, section 2.7 presented a review on the scientific and technical approaches that have contributed to the understanding of conservation of tapestries. The main conclusions extracted from this chapter are the scientific techniques being developed and applied to the
understanding of tapestries, their challenges and achievements. Research on chemistry proved that not only light is a damaging factor but also dying processes used to create the different colours in a tapestry. Tensile testing of historic tapestry yarns proved that blue wool yarns were stronger than yellow wool yarns. Moreover, across the literature it is verified that historic wool yarns are stronger than historic silk yarns given the advanced state of degradation of silk. Monitoring of tapestries in terms of light, dust, temperature, moisture and deformations is an area of study that became more holistic in recent years. Furthermore, strain measurements in tapestries is an area of increasing interest and in the last years DIC as imaging technique proved its applicability in capturing strain distribution in tapestry surfaces and thus constitutes an area under development. FEM modelling applied to tapestries can be found in two different research studies. However, given the complexity of historic tapestries these models are still limited due to the reduced number of historic samples tested which resulted in assumptions of mechanical parameters as inputs without fully characterize them.

As a summary, strain research in historic tapestry materials, already brought some light into this topic. As it was shown in section 2.7.4 Testing and Simulation of Tapestries strain development phenomena in tapestries and the way this impacts the structural stability of these objects by modelling their behaviour was carried out in some research projects (Duffus, 2013 and Alsayednoor et al., 2019). In spite of limitations as testing new tapestries materials, which exhibit behaviour different from the mechanics of historic tapestries (Duffus, 2013), past projects brought some insights into the nature of strain behaviour of historic textiles.

First, research by Howell has suggested that there might have been a relationship between colour of yarns and their strength. Adding to this, this research proved that historic wool has more strength than historic silk (Bilson, Howell and Cooke, 1997), which is exactly the opposite when considering new wool and silk as seen on section 2.2.4.

As in section 2.7.4 further tensile tests done for the context of modelling proved that historic samples usually break at around 20% strain (Duffus, 2013). Tensile behaviour is very heterogeneous and the force applied to cause a strain of 10% can change between 0.1 and almost 1.5 MPa (Alsayednoor et al., 2019).

As discussed above, the study of strain using optical fibre sensors and full field strain measurements was initiated by a research group in Southampton (Lennard et al., 2008, Lennard et al., 2011 and Lennard and Dulieu-Barton, 2014). This group produced a workflow that enabled the applicability of DIC on tapestry materials without the use of a speckle pattern. Strain studies on tapestries using DIC proceeded with research in Glasgow where researchers were able to compare noise in the deformations obtained using an optimised speckle pattern and comparing with a rendered image of a tapestry. A research that fed into a FEM model (Alsayednoor et al., 2019).

However, due to limitations on characterising historic tapestry materials, a complete comparison between tensile mechanics and weave structure was never carried out in the
literature (Duffus et al., 2012 and Alsayednoor et al., 2019). Considering the high level of heterogeneity as seen in section 2.2.2 the relationship between mechanics and structure could perhaps explain the reasons of different mechanical and hygroscopic properties. Furthermore, most of past research relied on one single technique for analysing the mechanical behaviour of tapestries. This produced limited conclusions which left a space for future research to compare results from different strain assessment techniques side by side and further investigate diverging mechanical and hygroscopic behaviours. Given the lack of systematic characterisation of physical properties of tapestries being studied, it was essential to conduct a comprehensive assessment of materials to be tested as the starting point. In this project, only historic tapestries were used as modern tapestries are substantially different. To analyse the tensile behaviour of the tapestries, tensile testing was considered, as literature has proven this to be an important method. Additionally, digital image correlation was selected as it can provide a strain field instead of single local readings and further explain deviations in material behaviour. The selection of these tools was based on their suitability and effectiveness in addressing the research questions and obtaining the required data.
3.1 General considerations

Investigation of strain in historic tapestries is a very complex procedure requiring the understanding of different aspects and properties. The statement “Strain in historic tapestries” implies that these objects are exposed to strain development processes related to either storage or display conditions. Free hanging display submits a tapestry to strains caused by its own weight and moisture fluctuations. On the other hand, under the most common cases of storage where is rolled into a supportive structure, a tapestry does not have to support its own weight but is still might be affected by strain variations caused by moisture or by natural expansion of the supporting structure the tapestry is rolled into. In this study only the technique of display by hanging is considered and with this, all environmental and physical aspects that can have an influence on strain development.

Tapestries on open display are under an active state of strain generated by gravity and modified by environmental conditions. As introduced in Chapter 1, this study stems from four key research questions: I) what is the relationship between environmental changes in humidity and temperature and the strain in historic tapestries? II) what are the most appropriate techniques to study this relationship? III) can environmental simulations inform the optimum environmental conditions for the protection of historic tapestries? IV) how can laboratory experiments inform current tapestry conservation methods, such as structural conservation stitching and lining?

This will include an in-depth study of stress-strain properties of historic tapestries materials as the tensile behaviour of these aged objects is not yet fully understood (Duffus, 2013). As conservation can change the weight distribution and restrain the tapestry fabric, the study of tapestry conservation procedures deployed across the world is also crucial to draw a full picture of the expected strain response of these objects.

Initial development of this methodology included a numerical modelling stage whereby, after gathering mechanical and hygroscopic data from experimental work, a FEM model would be produced. However, due to delays in accessing instrumentation and COVID-19, the modelling part was not accomplished. Nonetheless, the work developed on the correlation between mechanical and structural heterogeneity as well as the hygroscopic behaviour of tapestries feeds into the knowledge gaps identified in the last section of chapter 2. Furthermore, the results attained and the databank produced in the present study represent a unique foundation for the development of future computational models.
While past studies have attempted to characterise the mechanical characteristics of historic tapestry by applying either tensile testing or DIC (Duffus, 2013, Lennard et al., 2011 and Costantini, 2021), a substantial novelty of the present study is the systematic correlation of the two techniques, applied to the whole range of structural properties that historical tapestries weave contain. This is critical as tensile testing provides direct quantification of strain assessment but can only be used on small samples in laboratory conditions, while DIC, if properly calibrated, can be used while the tapestries are on display. Furthermore, the present study integrates these two techniques with state-of-the-art sensors manufactured by IBM to locally measure strain as explained in section 3.7.

The current methodology proposes a multidisciplinary approach to the study of historic tapestry structures. It is known that given their nature, the only similarity that different tapestries share is their weft faced discontinuous interweaved structure. Anything else such as fineness, colours, materials used, and designs where these discontinuities happen is specific to the individual tapestry design and craft. To this adds the fact that historic tapestries have acquired some level of degradation by aging. To assume this as a datum is where this research deviates from previous studies. Previous research projects tried in different ways to replicate degradation of historic tapestries by considering artificial ageing. Yet it was shown that tapestries behave very differently even when compared with a new woven artificially aged tapestry (Duffus, 2013). Thus, historic tapestry structures are the main input in the methodology of this project and the only object of study that is going to be tested and analysed throughout the project.

Keeping this highly heterogeneous structure into account, the initial step in this research is to find a method of characterising and quantifying structural differences in tapestries that can further help to interpret results of other methods used to study and quantify strain states. Techniques of mechanical characterisation such as Digital image correlation (DIC), tensile testing and sensing are then considered as ways of quantifying and characterising mechanical behaviour on these objects. However, since all samples of historic tapestries will be different, the characterisation of their differences is essential to support the mechanical analysis. Because tapestries are displayed by hanging under tension, tensile behaviour is considered the primary mechanical characterisation. Mechanical properties compared with the structural individual characteristics in each studied tapestry, will help the study of the strain state in these objects. Furthermore, a series of hygroscopic tests are carried out to identify changes in the strain field that tapestries experience when environmental conditions change, and they absorb or lose moisture. The following methodology constitutes a holistic approach to the understanding of historic tapestries structure and its level of heterogeneity.

This chapter presents the methodology developed for the current research. An overview of the methodology in Section 3.2 is followed by an expanded description of the main tasks to be accomplished. For these different tasks a further detailed methodology that contains all aspects related with equipment setup, calibration and processing is included in Sections 3.3
Survey, 3.4 Historic tapestry fragments selection, 3.5 Tensile strain characterization, 3.6 Digital image correlation methodology and 3.7 Hygroscopic experiments. Section 3.8 draws some concluding remarks on the overall methodology of the study.

3.2 Overview of methodology

Considering the different stages of the methodology, Figure 3.1 presents these graphically in a diagram that summarises the work paths to the output of the study. In Figure 3.1 in yellow are highlighted a number of main tasks, composed of smaller steps, which contribute to the main outputs. The approach adopted is to use multiple techniques which are complimentary to each other. This can be better exemplified by dividing this methodology into the following main tasks described below.
Figure 3.1 - Diagram with tasks to be followed on the methodology of the current research project.
Task 1: Survey of conservation strategies. Previous surveys have been carried out across the US and Europe (Breeze, 2000 and Duffus, 2013) and their conclusions were summarised in Section 2.5. Tapestry conservation techniques have evolved over the last decades due to improved scientific understanding of techniques and materials used to the conservation of artworks. Thus, a follow-up survey was conducted as part of this research to gather information on what techniques are presently used and the reasoning behind conservation decision making. In particular, it is important to ascertain conservators’ preference towards either restraining a tapestry movement or let it expand when on open display. The investigation of structural changes to a tapestry following conservation, can then be compared to results extracted from experimental work to inform on best practices. Without a clear understanding of the conservation processes applied to tapestries, it would not be possible to provide sound advice based solely on the results obtained from mechanical and hygroscopic tests. This task consists of the creation of a questionnaire, the selection of textile conservation workshops to whom the questionnaire is administered, and the analysis of the collected responses. Section 3.3 Survey explores the methodology used on implementing the survey described in this task.

Task 2: Selection of historic fragments for testing and their physical assessment. For the purposes of this research items from the HRP Historic Tapestry Fragments Archive housed at the Heritage Science Laboratory were used. The fragments were removed as part of past restoration practices taken place over the 100 years long history of tapestry restoration at Hampton Court Palace however, there is no associated information on the tapestries these fragments originated from. Furthermore, it is important to highlight that this approach has not been used at the current Textile Conservation Studio over the last four decades where modern tapestry conservation methodologies have been spearheaded by scientific research including this project.

This task considers firstly the required physical characteristics for the selection of the historic tapestry fragments representing a wide range of tapestry qualities and structural characteristics. These samples are selected from the fragments, ensuring that the high level of heterogeneity in tapestry structures is represented in this selection including specific features of the weave. Variation in terms of fineness, materials, weaving patterns and slits and splits are considered. This selection will be also critical for task 3 as the same samples will be used for mechanical testing requiring significant test repetitions. A second constraint for the selection is that fragments should be not smaller than 80×80 mm which is determined by the testing apparatus used for task 3.

The second stage in this task is the physical assessment of the selected fragments and samples. This brings a novel approach into studying historic tapestries in a holistic manner in relation to their structural features. The focus is on quantification of different structural
properties that makes each fragment and subsequently each sample area unique. For this, thickness is initially evaluated with a calliper since this has a direct impact on the mechanical calculations. Fineness, which given the way tapestries are made, is assumed to be directly related with thickness is also considered by an assessment using microscopy. Other properties that have shown significant impact on the behaviour of tapestries and therefore are quantified in this study are the amount of different materials namely wool and silk, the existence of slits and splits and the predominant colour of each sample. Different imaging techniques within the ImageJ software are used to this end. This heterogeneity will then be compared with results from tensile tests obtained from implementing task 4 and conclusions on different mechanical behaviour drawn taking into account each individual weaved structure.

Furthermore, this task considers the study of mass gain by water absorption by building a small environmental chamber inside a scale and measuring moisture content on 5 samples extracted from 5 fragments of historic tapestry samples exposed to different RH levels. The objective is to compare mass increase with strain levels by using results of experimental data of tasks 3 to estimate much mass increase is present on the experiments of task 4. A detailed methodology is presented in section 3.4.

Taking into account previous studies in mechanics of woven tapestries discussed in section 2.7.3, this aims to be the most extensive and representative sample characterization to date, considering the large number of selected historic weaved tapestries. Given the complexity of this task, its detailed methodology is discussed in depth in Chapter 5.

Task 3: Mechanical testing of historic samples. For the delivery of this task two concurrent activities are taking place tensile testing and Digital Image Correlation (DIC). The first considers the tensile testing of selected areas for each fragment and requires further mechanical calculations for the stresses and strain to be extracted. DIC takes place at same time of the Instron mechanical tests, capturing a series of photographs during testing. DIC output is further analysed using specific DIC software package, whereby strain states can be obtained and mechanical properties that are strain dependant extracted. This is the first time, to our knowledge, that these two complementary methods of analysis have been used together to reach conclusions on the features affecting the stress state of historic tapestries and their stress-strain curves. Section 3.5 describes the methodology on the tensile strain characterization using the Instron tensile tester. Section 3.6 contains a detailed methodology for the DIC technique used.

Task 4: Hygroscopic experiments on a historic tapestry. The objectives of this task are to get a deep understanding on how a tapestry structures absorb moisture, the time it requires for a tapestry weave to stabilise from changes in RH levels and the associated quantity of water that a tapestry can absorb. As main object of study, this task considers the testing of an historic tapestry hanging by a Velcro strip as it is usual in current conservation practice display. This is carried out by simulating inside the internal environmental chamber of the laboratory of the
Institute of Environmental Design and Engineering at UCL Here East, a range of T and RH conditions found when tapestries are in open display inside of a historic house or palace. DIC and IBM sensors are considered in these experiments to record the variation in strain field caused by the variation in moisture content of the tapestry. IBM sensors were developed by IBM research and their use in historic tapestries result from a partnership between HRP and IBM. These sensors are made of a chip with a variable resistor composed of a Giant Magnetic Resistance (GMR) material. As displacements are measured using magnets, there is no structural reinforcement as in the more common transducer sensors (Schrott et al., 2014). IBM sensors are very accurate being able to measure displacements of microns at discrete points over the textile, while DIC is able to capture the full strain field in a selected area. This is the first time that a complete non-fragmentary historic tapestry is tested in a controlled environment and thus this investigation aims to also understand the role that different parts of the weave in a hanging tapestry have in moisture adsorption.

Section 3.7 Hygroscopic experiments explores in detail the methodology used in this task.

3.3 Survey

This section explains the methodology followed for Task 1 described in section 3.2.

The current survey on conservation aims to investigate four key research questions on conservation methods currently in use:

- What are the types of structural supports, stitching and techniques in use?
- What are the conservation materials considered nowadays in tapestry conservation?
- Is conservation restraining the weaved structure?
- What are the main reasons behind conservators decisions?

A multiple answer questionnaire cannot account for a full picture of the conservation work that is done manually and is very dependent on the responder. To overcome this, visits to tapestry conservation studios were planned to gain better understanding of the conservation alterations that are being made to these objects and in which way conservation techniques change the structure of tapestries. However, due to Covid-19 these visits had to be cancelled.

The survey is based on a multiple answer questionnaire structured into six distinct sections that aim to target different conservation topics while answering the research questions: general questions, type of support, stitching methods, materials for stitching, conservation studio history and general comments. The objective is to understand the extent of use of given conservation methods and techniques in terms of types, materials and density of support fabric and stitching. The reasons for conservators actions are explored in ranking based questions.
Open questions provide space for conservators to better explain their conservation methods. Some questions are related to the rationale conservators follow for certain treatment decisions. These questions touch on the concept of levels of damage which can differ among different conservators. However, this does not influence decision making based on the criteria each conservator attributes to different levels of damage. What changes is the classification of levels of damage and not the decision once these levels are defined. Hence, these questions evaluate the rationale for choice of treatment and not thresholds on levels of damage. The full questionnaire sheet is presented in the Appendix 2.

The survey is targeted at textile conservation studios across the globe that currently work on historic tapestries. As different schools in conservation of historic tapestries are to be identified, the aim was to target the highest number of participants and countries as possible.

The questionnaire developed in this study is largely adapted from the questionnaire formulated by Duffus (Duffus, 2013), mentioned in section 2.5 Tapestry Conservation, having included a number of new multiple answer questions, to enable a quick interpretation and to limit open ended questions. Multiple answer questions help with processing results and organise common views that otherwise would be scattered. However, space at the end of most questions and at the end of the questionnaire was considered for conservators who wished to further explain, comment or give an alternate answer on any question of the questionnaire. In order to deepen the understanding of conservation techniques described in the questionnaire some visits to conservation studios had been planned. However, these visits were not carried out due to Covid-19 pandemic.

This questionnaire was developed in collaboration with the conservation and science teams at Historic Royal Palaces and was conceived as an online questionnaire. After gathering the contact information of previous respondents on Duffus questionnaire, and a complimentary extensive search which resulted in a total of 152 textile conservation studios both in the private and public sectors the questionnaire was administered by email and was available from July 2019 to February 2020. From 152 conservation studios contacted, 44 answered, of which 40 were complete answers, for a participation rate of 29%. Figure 3.2 and Figure 3.3 show a map with the geographic distribution of the studios contacted for the survey and a map for the studios that responded, respectively.

For the questionnaire to meet an ethical approval from UCL the responses needed to be anonymised. Because of this, although personal questions were asked to the participants to ensure no duplication of answers, these were not included in the analysis. Answers from the same studio were treated as a single answer. For this, when more than one answer was received from the same studio, conservators were asked to submit a single answer.
The questionnaire is structured in five different sections, besides the initial 3 question on personal information as it is presented in Table 3.1.

<table>
<thead>
<tr>
<th>Section</th>
<th>Questions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st Section</td>
<td>• Studio capacity</td>
</tr>
<tr>
<td></td>
<td>• Rationale for support</td>
</tr>
<tr>
<td>2nd Section</td>
<td>• Type of support and rationale</td>
</tr>
<tr>
<td></td>
<td>• Material for support and rationale</td>
</tr>
<tr>
<td></td>
<td>• Amount of excess fabric and rationale</td>
</tr>
<tr>
<td>3rd Section</td>
<td>• Stitching characterisation on support fabric</td>
</tr>
<tr>
<td></td>
<td>• Type and distance for stitching</td>
</tr>
<tr>
<td></td>
<td>• Type and distance for stitching in damaged areas</td>
</tr>
<tr>
<td></td>
<td>• Materials used for stitching</td>
</tr>
<tr>
<td></td>
<td>• Rationale behind Stitching</td>
</tr>
<tr>
<td></td>
<td>• History of conservation practices</td>
</tr>
<tr>
<td>4th Section</td>
<td>• Open comments</td>
</tr>
</tbody>
</table>

From the literature, it is known that a difference in conservation techniques exists between the US and UK (Breeze, 2000 & Duffus, 2013). However, not much is known about conservation procedures outside these centres. It was then important to analyse results considering geographic regions based on the number of answers obtained in the hope of clarifying the existence of other possible conservation schools. Therefore, 6 different
geographic regions were selected based on the number of answers and location. Given the differences in conservation between the American and English method both the USA and UK were analysed individually. Although no distinction was made in a previous questionnaire on American methods of conservation (Breeze, 2000), Canada was considered individually for the analysis as having 4 respondents could have a great influence in the results when compared with the 6 respondents from USA and there is no previous indication that these two countries still share a common method of conservation. Europe was considered as a whole geographic region as there was not a significant number of answers that would enable its separation into countries. Yet, for countries with 3 or more respondents such is the case of Germany, Sweden, Switzerland and Italy special attention on the analysis was given to verify consistency of conservation methods in the mentioned countries. As culturally and geographically distinct Japan and Australia were considered as separate regions in the analysis, as shown by colour grouping in Figure 3.4. Results of the survey are presented in Chapter 4.

![Figure 3.4 – Map representing geographic regions considered for the analysis.](image)

<table>
<thead>
<tr>
<th>Country</th>
<th>Number of participant studios</th>
</tr>
</thead>
<tbody>
<tr>
<td>UK</td>
<td>10</td>
</tr>
<tr>
<td>USA</td>
<td>6</td>
</tr>
<tr>
<td>Canada</td>
<td>4</td>
</tr>
<tr>
<td>Czech Republic</td>
<td>1</td>
</tr>
<tr>
<td>Estonia</td>
<td>1</td>
</tr>
<tr>
<td>Netherlands</td>
<td>1</td>
</tr>
<tr>
<td>Germany</td>
<td>3</td>
</tr>
<tr>
<td>Sweden</td>
<td>3</td>
</tr>
<tr>
<td>Belgium</td>
<td>1</td>
</tr>
<tr>
<td>Spain</td>
<td>2</td>
</tr>
<tr>
<td>Switzerland</td>
<td>5</td>
</tr>
<tr>
<td>Italy</td>
<td>3</td>
</tr>
<tr>
<td>France</td>
<td>2</td>
</tr>
<tr>
<td>Japan</td>
<td>1</td>
</tr>
<tr>
<td>Australia</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 3.2 - Number of participant studios per geographic region.

### 3.4 Selection and structural characterisation of historic fragments and sample areas

This section explains the methodology followed for Task 2 described in section 3.2. The section provides the general methodology in terms of equipment and materials used for the selection and structural characterisation of historic fragments and sample areas. However due to the complexity of the process of creating a novel systematic structural characterisation...
for historic fragments this is further explained and developed in Chapter 5 where results of this assessment are also discussed.

This selection and structural characterisation aimed to provide the base material for further mechanical tests reported in Chapter 6.

### 3.4.1 Historic tapestry fragments selection

From the collection of historic tapestry fragments at Hampton, thirty were selected considering a good coverage on different materials and fineness. Due to the dimension of the jaws on Instron tensile tester, only fragments with more than 80 mm length and width were considered in the selection.

In each one of the selected fragments, 5 sample areas (76 mm × 80 mm) were selected for repeatability when testing each fragment. These areas were selected to have as much variability as possible in terms of structural features. This selection process and its limitations is further explained in section 5.1.

### 3.4.2 Structural characterisation of historic fragments and sample areas

Structural characterisation aimed to characterise historic fragments and sample areas in terms of fineness, thickness, materials, slits and splits, condition and colour.

To measure thickness a digital calliper HITEC 101-45 with 0.01 mm of precision was used. The calliper was opened and closed for 30±5 seconds in 5 locations on the warp and 5 on the weft. In each location, the 3 measurements were made and the results averaged. The average of the total 10 locations was then calculated as the tapestry thickness. The use of a calliper was dictated by instrument availability and this method is known to be pressure dependent. To minimise the effect of this dependency, all measurements were made by the same person in the same conditions.

Fineness was evaluated by using a microscopic technique. Although the concept of fineness was not developed in this study, the method and calculation of fineness using a microscope was implemented and is described. A Dino-Lite microscope setup to 34 times magnification was used to measure 12 locations across the tapestry surface. In each location two measurements on the warp and two on the weft were made. In each measurement the distance along a certain number of threads was recorded and fineness calculated according to

Equation 3.1. Results for the warp and weft direction were then averaged.
Material assessment relied on a more complex process of image capture and post processing on Photoshop software (Adobe, 2012) and calculation on ImageJ software. Initially, a photograph was taken in the parallel direction to the tapestry plane. Then a visual assessment for fibre identification was carried out with a microscopic analysis. This was followed by post-processing on Photoshop where colour from wool areas was systematically removed. In ImageJ the coloured areas on the image were selected and the ratio between the overall area and silk areas taken as in Equation 3.2.

\[
\% \text{Silk} = \frac{\text{Area Coloured}}{\text{Total Area}}
\]

Equation 3.2

The number of slits and splits was assessed using the same photographs used for material assessment. The length of each slit and split was measured and its sum was divided by the width of each fragment 76mm.

Equation 3.3 was applied to calculate slits and splits ratio.

\[
S = \left( \sum_1^n W \right) / 76
\]

Equation 3.3

Condition rating was assessed by conservators at Hampton Court Palace and considered 3 distinct parameters: condition, stability and treatment priority. Each one of these parameters is evaluated qualitatively following a sheet that classifies these parameters into 4 distinct levels from 1 to 4, being 1 the highest level and 4 the lowest. Results are then averaged and a condition ratio attributed to each tapestry.

Colour analysis used the same photographs used in the previous material analysis. Colour correction was carried out by using a plugin developed for ImageJ (Haeghen, 2009). Colour scale was separated into 5 equal ranges and the percentage of pixels that composed each range quantified under ImageJ software.

This structural characterisation is unprecedented in the study of tapestry materials and because of this, details on the methodology are further given in Chapter 5.

### 3.4.3 Hygroscopic characterisation of historic fragments

An experiment with the objective of quantifying the amount of mass gain that a woven sample from an historic tapestry can have when exposed to certain levels of relative humidity was developed. This was a semi-destructive analysis since implied cutting 5 samples from 2 fragments of historic tapestry galloon and from 3 historic tapestry fragments, residuals of past
restoration procedures. Gallon are outer borders that are attached to a tapestry as explained in section 2.2.2., always woven with a single colour and, as external borders of tapestries, usually stiffer than the tapestry weave. However, the middle section of a gallon is weaved as the tapestry, with the same materials and techniques, except that it doesn’t have interruption in the weft. The two gallons were made entirely of wool both on the warp and weft directions. Samples from fragment 33 had wool and silk in its constitution while fragments 62 and 170 were also entirely made of wool.

Having 2 gallons and 3 tapestries available for testing, 5 sets with 5 samples each were tested in this experiment. Samples of 3×3 cm from the middle section of the gallons and 1.5×1.5 cm from the fragments were cut off with a scissor. Difference in sizes from tapestry to gallons was considered due to the smaller amount of material available on tapestry fragments. This ensured that tapestry fragments could be used in repetition of future tensile experiments if necessary. Table 3.3 summarises the physical properties of the samples studied in a range between 30 to 80 % of relative humidity with increments of 10% RH.

<table>
<thead>
<tr>
<th>Samples</th>
<th>Galloon 1</th>
<th>Galloon 2</th>
<th>Tapestry 33</th>
<th>Tapestry 62</th>
<th>Tapestry 170</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dimensions</strong></td>
<td>3×3 cm</td>
<td>3×3 cm</td>
<td>1.5×1.5 cm</td>
<td>1.5×1.5 cm</td>
<td>1.5×1.5 cm</td>
</tr>
<tr>
<td><strong>Colour</strong></td>
<td>Faded Blue</td>
<td>Green/Blue</td>
<td>Green/Yellow</td>
<td>Yellow</td>
<td>Brown</td>
</tr>
<tr>
<td><strong>Provenance</strong></td>
<td>Gallon from one of the sides of a tapestry, given its weft direction</td>
<td>Gallon from the upper or lower end of a tapestry, given its weft direction</td>
<td>Middle section</td>
<td>Middle section</td>
<td>Possibly from a border</td>
</tr>
<tr>
<td><strong>Thickness</strong></td>
<td>1.6 ± 0.1 mm</td>
<td>1.7 ± 0.1 mm</td>
<td>1.6 ± 0.1 mm</td>
<td>2.8 ± 0.2 mm</td>
<td>1.2 ± 0.0 mm</td>
</tr>
<tr>
<td><strong>Fineness (Approx.)</strong></td>
<td>11.5 weft/cm</td>
<td>9.1 weft/cm</td>
<td>10.1 weft/cm</td>
<td>7.5 weft/cm</td>
<td>14.4 weft/cm</td>
</tr>
</tbody>
</table>

Table 3.3 - Properties of gallons and tapestry samples tested.

To obtain the mass of a sample at different levels of RH the apparatus of the experiment as shown in Figure 3.5, consisted of a relative humidity generator connected to a precision scale to create the desirable environment on the scale and thus creating a small environmental cabinet over the scale. To set up the experiment, a v-Gen relative humidity generator was connected to a gas source supply of compressed air, where a pressure of 1 Bar was applied to create a stable air flow from the rotameter (air flow regulator). The air flow was set up to 100 cm³/min of air. An external water reservoir was connected to the RH generator via a flexible tube. The equipment was setup to work in the manual mode with air flow forward. The air flow exit was then connected to the precision balance as can be observed in Figure 3.6. The scale used was a Mettler Toledo XS205 with a precision of 0.1 mg. The scale was then sealed with
parafilm to create a microenvironment with the scale within allowing the environment to stabilise. The temperature was stable and constant set at 25°C ± 1.5 °C.

Initial preliminary tests consisted in placing one sample at a time inside the conditioned scale until equilibrium to the desired RH was reached. However, this process entailed a period of 10 hours for each sample. To shorten the time all samples were placed on the scale plate until equilibrium was reached. Then the environment was opened, and each sample was weighted individually by removing them sequentially with a tweezer and placing each in the internal base of the scale, to avoid moisture loss during this process. Samples were considered to be in equilibrium when the weight variation was less than 0.01%, over 5 minutes, as recommended by Bratasz et al. (2014). At the end of the measurements all samples were again placed on the balance plate and their mass measured again to verify how much mass was being lost by opening the scale chamber. Then another increment of RH was generated.

To control the desired relative humidity, the dew point of the RH value at ambient temperature should be calculated. For that a psychrometric chart was used and the dew points entered in the controller of the RH generator. A HOBO data logger was placed inside the scale chamber with the samples as shown in Figure 3.6. This logger was used to measure the real temperature and relative humidity inside the chamber. Furthermore, this enabled to see if condensations inside the connection tube were occurring since this is very frequent for high levels of relative humidity.

To obtain the dry mass, an oven was used to remove moisture from samples. To measure their weight avoiding samples to absorb moisture, they were carried in plastic bags to the scale. Oven temperature was set to 40°C for 30 min due to lab restrictions although the recommended temperature to dry should be 105 °C ± 2°C (Bratasz et al., 2014). Because of
these laboratory restrictions, these values need to be regarded carefully as there might have been some moisture still present on the samples.

All samples have small variations on their weight with a standard deviation of 34.8 mg for galloons and 15.0 mg for tapestry samples. Moisture content was calculated according with the equation (Saville, 1999):

\[
\text{Moisture Content(\%)} = \frac{W}{D + W} \times 100
\]

where D is the dry oven weight and W is the weight of absorbed water.

### 3.5 Tensile strain characterization

This section explains the methodology followed for Task 3 described in section 3.2. This includes the detailed methodology used in the different parameters that contribute to the strain characterisation of tapestry fragments: tensile tests, linear modulus and crimp calculations.

As seen in section 2.7.4.1 past research did not consider three important points for the characterisation of woven tapestry mechanics. First of all, the heterogeneity across the tapestry woven structure was not quantified and correlated with tensile behaviour. Secondly, there was not a good range of samples considered for repeatability of experiments. Also although there was a qualitative interpretation of the several stages of tensile stress-strain curves, a quantitative approach separating crimp from elastic stage was never done before for the case of woven tapestries. These three points make the following methodology to diverge from past studies. The survey explored in section 3.3 informs on the possible changes that tested fragments might have due to conservation together with the physical assessment described in task 2 will inform interpretation of results from tensile tests.

#### 3.5.1 Tensile tests

Historic fragments selected in task 2 are the object of the tensile mechanical characterisation. Contrary to modern tapestries, since historic tapestries are always hanged in the weft direction, this results in tensile stress caused by its own weight in this direction. Therefore, the weft threads are selected for monaxial tensile testing, to define the tapestries stress-strain behaviour. Although the full characterisation of stress-strain curves under tensile action is critical to understand the strain development in tapestry, the actual weight a tapestry is subjected to when hanging is of crucial importance. As presented in section 2.7.3 a monitoring campaign in Hampton Court Palace detected a change of 6.5 mm in the length of a tapestry for 30% change in RH. Considering the tapestry measures 4.5 m length this is equivalent to around 0.15% strain.
As explained in the literature review in section 2.7.3, environmental conditions can play an important role on how textiles behave mechanically and therefore, conditioning of samples prior to any test was undertaken for 24 hours before being tested. Fragments were placed on a table exposed to the lab environmental conditions to assure that conditioning was consistent across all selected fragments and that at the moment of testing, fragments were in equilibrium with the environment. Tensile tests were then performed in the constant environmental conditions of 25.0±2.0 °C for temperature and 45.0±4.0% RH.

Given the variability across the various historic fragments in terms of materials, weaving and ageing, homogeneity across the tests is assured by having consistency in the testing conditions across all sample areas. Selected samples were tested using a UTM Instron 3365. The precision of the load cell used in the Instron tensile tester was ± 0.25N and ± 0.12 mm. To better hold the samples avoiding slippage during tests, serrated jaws were used in the holding grips of the Instron. However, since serrated jaws can also produce local damage in the tapestries, protective adhesive tape was used on each jaw. Samples were mounted in relaxation state with weft treads running perpendicular to the edges of the jaws. Before closing the jaws, the fragments were carefully adjusted to ensure that the test matched the sample areas selected in Task 2. Some adjustments were done to ensure a reduced amount of slack. The closure of the jaws was ensured by pressure controlled grips. Tensile tests were conducted in displacement control at a rate of 2 mm/min. Extension rates for tensile tests on historic tapestries found in literature are as high as 200 mm/min (Duffus, 2013), however this rate is not representative of the rate of load uptake that a tapestry will experience by being hanged. Notwithstanding, a past study done on rugs proved that there was not much difference when comparing tests done at 200 mm/min and 2 mm/min (Bratasz et al., 2014). Furthermore, the rate of 2 mm/min for testing textiles seems to be favoured by more studies (Bratasz et al., 2014). The Instron tensile tester in these conditions had a measurement accuracy of 0.25 N for loading and 0.12 mm for extension.

In literature (Bratasz et al., 2014) most load-strain curves for fabrics display the load in units of kN/m. This is mainly due to difficulties in quantifying accurately the cross section of textile samples due to thickness varying considerably during the test and locally through the width of the specimen. However, when comparing sample results from different fragments, with different thickness, it is essential to have a parameter independent of size. Hence the cross-sectional area was computed taking as reference the thickness of each fragment measured in a relaxed state. Results are then presented in stress units of MPa. When calculating stress-strain curves, the slack in specimens was not removed because doing so may have introduced errors in interpretation by obscuring any potential transition from the slack to the crimp stage. Additionally, manually deleting the initial part of each graph would be subjective and prone to human error. Finally, the slack usually accounts for only a small area in strain, typically less than 0.2% and always less than 1%, making it negligible in the overall analysis of the material properties as it was further verified during the experiments.
3.5.2 Linear modulus and crimp calculation

To study strain in a tapestry there is the need to consider the whole tensile behaviour since different regions of the textile might be in different state of stress. For instance the portion of weft threads close to the top of the tapestry, because they support the whole weight will be in a different state of the stress-strain curve than the portions at the bottom which support little weight. For a clear definition of the different phases of tensile behaviour for the tested fragments it is important to characterise them using a rigorous approach to determine the relationship between strain and stress, and identify the transition between the phases. Past approaches used simple regression analysis to identify only the linear phase (Duffus, 2013), which was not suitable for this study given the wide range of behaviour for the specimens, as can be seen in Appendix 4. Therefore, a MATLAB program was developed to accurately identify the extent of the linear stage and the corresponding value of the elastic modulus, between the end of crimp stage and the initiation of fibres/yarn breaking stage.

The assumption underlining the analysis of the curves performed with the support of an algorithm coded in MATLAB, is that each curve has a linear portion that can be identified by determining the change in tangent between two adjacent section of the curve. In order to determine this, a representative step length of the curve needs to be established. Before doing so, the test data needs to be cleaned from noise, and this is accomplished by using a moving average of 10 consecutive points, so that each point on the curve represent one second of testing.

The Elastic modulus is defined as the slope of the linear zone in a stress-strain curve (ASTM, 2010) and for the calculation in MATLAB this was considered as the slope of the tangent between 2 points of the load-strain curve resulting from the averaging operation. A region of linearity is defined when the error in the moving average for the modulus over 15 points in consecutive intervals was less than 1%. Notwithstanding that a 1% difference can be very restrictive, for fragments with a long crimp behaviour, the assumptions on point of moving average and error where the results of optimisation over a large range of possible values, as they provided the most consistent results across the whole sample.

Breaking of yarns was identified by a portion of the curve where the tangent had a negative slope, corresponding to failure of several fibres, yarns or threads. The value of strain which identified the transition between the crimp zone to the linear zone was recorded as the maximum crimp strain. Results for these calculations are further discussed in Chapter 6.
3.6 Digital image correlation

Digital Image Correlation (DIC) was employed as a tool to identify the strain field in two phases of the study, Task 3 and Task 4, as described in section 3.2. This section introduces the details of the procedure developed for the tensile tests on historic fragments, using a one camera system. The differences between this and the two cameras system employed during hygroscopic experiments are further discussed in section 3.7.4.

DIC measurements are based usually on a speckle pattern, which is a heterogeneous non-repetitive pattern painted on the surface of the sample being tested, so that the software can identify the location of matching features captured at different times during testing. However, in the case of historic tapestries, this is not possible as the sprayed speckles would damage the tapestry surface. The speckled pattern needs to be installed normally because stress tests are carried out on elements of homogeneous material with blank surfaces without particular features and thus the relative displacement among points in the structure cannot be identified by an imaging software. This is not the case for tapestries, as the different rendered images they portray, and their crimped woven wefts threads made of multiple yarns prove sufficiently capable of producing a pattern that can be identified under DIC (Lennard et al., 2011). The drawback is that in comparison to a speckle pattern, a tapestry rendered image can produce more background noise (Alsayednoor et al., 2019) because the pixel signature is fuzzier. However, in this study, in agreement with similar studies (Lennard et al., 2008 & Khennouf et al., 2010), the tapestry image is used as pattern for the pixel signatures.

In the application of DIC in Task 3, images were captured by a single camera, making this an in-plane 2D analysis. Therefore attention was paid to the effects of out-of-plane displacements when designing the experiment. It is known that background noise is proportional to $\Delta Z/Z$, where $\Delta Z$ is the out-of-plane translation displacement and $Z$ the distance from the object to the pin hole of the camera (Sutton et al., 2008). This means that if the camera is too close to the tapestry sample more background noise will be produced by out-of-plane displacements. On the other hand, the image resolution decreases with the distance between camera and testing sample. Therefore the camera was set up at 1.00 m distance from the testing rig. Furthermore, image acquisition had to take into account multiple factors such as the image format, light conditions, equipment set up as well as external circumstances, such as vibrations that could generate background noise.
The setup of the camera for DIC measurements is shown in Figure 3.7: a DSLR camera Canon EOS 700D with an ISO 100 is used to take pictures at the beginning and for every 1 mm of extension of the tested sample. To avoid vibrations, the camera is set on a tripod and each photograph is captured manually using the remote control of EOS Utility software. Each set of pictures is then imported to DIC software Davis 8 from LaVision (LaVision, 2017) whose user interface can be seen in Figure 3.8.

DIC analysis carried out during tensile experiments considers an incremental correlation using the option “sum of differentials” in Davis software. Incremental correlation was used as in preliminary tests proved to provide better results matching images. This is the opposite of what Nwanoro et al., 2022 used and this suggests that testing DIC in woven materials exposed to real environmental conditions of light is different from testing an image of a tapestry in a computational generated image of a deformation (Nwanoro, Harrison and Lennard, 2022). This means that displacement is calculated incrementally from the previous image rather than from the initial image. This was done since calculating the differential between the current frame and the initial image caused errors due to the large deformations produced during tensile testing, especially in the latter phases. Yet, it is important to notice that, by considering this incremental correlation between two successive frames there might be less accuracy as errors in each couple of frames measures will sum up (Ghani, 2016). On the other hand, because deformations are not small compared with the size of the sample, from a structural mechanics theory point of view, it is correct to consider the updated configuration of the sample, in a Lagrangian sense, rather than the undeformed state.

To improve accuracy an initial calibration of the DIC correlation was carried out to inform the best values for the parameters considered and their validity over the full range of images captured. Initial results of this calibration were used to set up DIC settings that were used in the experimental method. These are then described in this section as DIC settings are part of the method and not the object of study. Past studies considered the influence of the
subset size parameter (Alsayednoor et al., 2019). In addition also the influence of different image formats, pixel steps, and computational time required were considered in the present application.

Since pixel information has great impact on image processing, different digital image formats were tested. As explained in section 2.7.4.2.2, each pixel in the picture stores a grey value, relating to light reflected by the surface of the woven sample. Each one of these grey values composes the pixel signature, which is organised into subsets corresponding to an assemblage of pixel signatures. To generate the full displacement map, the software calculates differences between the centre of each subset. Therefore, it is expected that larger number of pixels will produce more accurate results. The step-size is the distance in pixels considered to compare different pixel subsets and the lower this value is the more accurate results are expected. Additionally, as pixel signatures are dependent on the shade of grey each pixel has, two different picture formats, TIFF and JPEG with different number of shades of grey were compared.

To assess the influence of the shade of grey contained in each format, pictures of sample 1 of fragment 44, were saved in RAW as well as in JPEG for each mm extension. RAW pictures were converted into TIFF and then into black and white using respectively dcraw (Coffin, 2018) and Adobe Photoshop CS6 (Adobe, 2012). On TIFF images, 65536 shades of grey were present while on the imported JPEG there were only 255 shades of grey. Figure 3.9 and Figure 3.10 show a comparison between two strain maps, one processed with JPEG format and the other with TIFF, respectively. For reference, an extension of 1 mm is equivalent to approximately 1.3% strain and 10 mm to approximately 13% strain.

![Figure 3.9 - Vertical strain at 3 mm extension of sample 1 from fragment 44 processed from a JPEG image.](image1)

![Figure 3.10 - Vertical strain at 3 mm extension of sample 1 from fragment 44 processed from a TIFF image.](image2)

The colours shown represent the strain maps calculated by DIC. It was verified that at all levels of extensions the results were very similar between both formats. More examples are provided in Appendix 5 for different extensions of the same sample.
Figure 3.11 show the differences in strain between JPEG and TIFF format when analysing the strain in the same sample area. It is shown that the difference increases with increasing extension as JPEG image having less levels of grey will sum more noise in the overall correlation process. Although the strain maps have similar appearance as shown in Figure 3.9 and Figure 3.10, for the TIFF image, the time taken converting the RAW picture into TIFF and removing its colour in DIC for a picture with 65536 levels of grey was in average 8 times greater than the time needed for the 255 levels of grey in the JPEG picture, which amounts to 2 min for a set of 10 pictures. For this reason, considering that differences in strain were lower than 0.014% for 8 mm extensions, the JPEG format was chosen for DIC processing.

Since hundreds of images need processing, the computational time required to process images with different subset and step sizes was evaluated. The results are obtained by processing a set of 10 DIC images of a tensile test whereby each picture represents 1 mm extension. Figure 3.12 shows an evident increase in time with an increase in subset size. The same can be noticed when the step size decreases since the software needs to compare subsets which overlap a smaller number of pixels. The difference in time is more noticeable when step size increases from 4 to 8 pixels than from 8 to 16 pixels, indicating that step size has greater influence than subset size. Parameters from previous research in DIC were not used. It was necessary to test the subset and step size as contrary to a deformed image of a tapestry used in previous studies (Nwanoro, Harrison and Lennard, 2022), this research used real conditions of light to test a real woven sample of a tapestry.

As external factors such as natural vibrations and light cause impact on measurements a preliminary DIC test was carried out to assess the best set of values for the processing parameters. The trade-off is between noise and resolution. To address noise, two photos were recorded for one sample, number 5 from fragment 137, in the Instron jaws, before starting the
test. As the sample is held in a steady position, the “strain” measured represents noise extracted from comparing these two pictures and constitutes the base error in the measurements. Figure 3.13, Figure 3.14 and Figure 3.15 show that noise decreases with increasing subset and step size. It is important to note that by using the incremental correlation, this error will sum up as the number of pictures increase. Thus, having a higher level of accuracy does not mean a higher level of precision.

To address resolution a second set of tests was performed for the same sample 5 of fragment 137 comparing strain maps at an extension of 5 mm, (see Figure 3.16, Figure 3.17 and Figure 3.18). The resolution decreases sharply with increase of subset and step size. Therefore an intermediate subset size of 31 pixels and step size of 8 seems to produce sufficiently low noise and acceptable resolution. This is confirmed by the capture of the accurate strain field around the area of open slits marked with the number 1 as shown on Figure 3.17, corresponding to a retraction of the textile immediately below and above. This effect of open slits on strain field in textiles, was demonstrated in a recent study by Alsayednoor et al., (2019). A complete set of images for different subsets and step sizes for different extensions on sample 5 of fragment 137 are included in Appendix 6 and 7. Appendix 8 shows an extra example for sample 5 of fragment 44 where DIC software could not process pictures to a subset size of 15 pixels.
In summary small subsets have higher resolution and are more detailed but also have errors due to the correlation technique used. On the other hand large subsets have less resolution but also less noise and to a certain extent are more accurate but all this at the cost of having a high computation time and a strain map which is more blurred when compared with smaller subsets, which is something that also needs to be considered when processing hundreds of pictures from different samples tested in each fragment. In conclusion a subset of 31 pixels with a step size of 8 pixels was considered as the configuration producing best results in terms of mapping the strain and thus was the setup considered for all further DIC analysis. On one hand this configuration gives a clear sharp strain map while maintaining a low level of background noise. On the other hand, the computational time required for processing is around 60 seconds for correlating 10 pictures which is a very good time when compared with other options available.

For each correlation, strain distribution on both vertical and horizontal directions were extracted. When a tensile force is applied in the vertical direction, the vertical and horizontal strain maps help to identify how tapestries behave in the direction of the action and in the perpendicular direction to it, bringing new light into Poisson effect experienced by tapestries. Results for DIC investigation on tapestry fragments are further discussed in Chapter 6.

### 3.7 Hygroscopic experiments

The objective of the hygroscopic experiments is to determine the response of a tapestry in extreme indoor conditions. These required the selection of an appropriate specimen, the development of a novel experimental setup together with choices of appropriate sensors and measuring equipment (Máximo Rocha, D’Ayala and Vlachou-Mogire, 2018). This section presents first the selection of the specimen, then the setup of the experiment in terms of
equipment, material and methods. The specific approach developed for the DIC data capture and processing is then discussed and finally, the setup of a set of IBM sensors and their data processing procedure is presented. The diverse data generated enables a comprehensive characterisation of the hygroscopic response of a historic tapestry without causing damage to the artefact.

### 3.7.1 Tapestry selection and characterisation

Tapestries on display in Hampton Court Palace are too valuable to be exposed to any kind of lab testing. Thus, the purchase of a tapestry from an antiques dealer to be used as testing specimen was considered. After a thorough search under a restricted budget, a tapestry from an art dealer was selected and bought in May 2019. Information given by the dealer stated that the artefact was a 19th century Aubusson French tapestry from around 1850s. However, an investigation with conservators and the science team in HRP was carried out to confirm this and to prove its utility in the planned lab tests.

A visual investigation on the artistic skill and depiction in the tapestry provided some initial insight. The tapestry depicts a common 18th century scene while showing a more simplistic and less skilled approach in the depiction of characters, especially around the faces (Baumgarten, 1897), which given its simplistic weaving can be dated to the middle of 19th century as suggested by the evidence in section 2.3.

A visual inspection revealed further details about the tapestry structure. Initially, conservators suspected that the piece was machine made however this was disregarded after looking at the stitching of the slits and of dovetail and hachure techniques only used in hand woven tapestries as highlighted in section 2.2. Conservators noticed how the front of the tapestry was faded compared to its back as shown in Figure 3.19 A and B. Moreover, the stitches for the slits are faded to the same extent as the front of the tapestry. This indicate the stitching as original. The level of fading, together with the fact that there is neither apparent conservation work on damaged areas nor any lining support or dust cover, confirms the hypothesis that this tapestry has aged without undergoing any change. This tapestry measures 1.58 m per 1.02 m and weights 1.37 Kg. It has an area of approximately 1.6 m² and a thickness of 1.9 mm.
In terms of materials in the weft, larger areas of silk, especially on the sky area, where identified from visual inspection. A visual assessment under a magnifier (Figure 3.19 C) and under a Dino-lite microscope revealed that most colour tones are present for both wool and silk threads, which makes necessary a more in-depth assessment to fully identify the materials. Given the uncertainty of material in the warp, an electronic microscopic analysis for fibre identification was carried out. Textile fibres from the warp, one from the selvage and the other from an area of damaged exposed warp were sampled and proved to be cotton.

Considering the weaving and material properties, this piece is comparable to fragment 158, among the ones tested, whose mechanical characteristics are presented in section 6.2 Tensile tests. Although the presence of the cotton warp differentiate substantially this specimen from historic tapestries produced before the 19th century, its good state of conservation, free from intervention and material additions, and the presence of wool and silk in the weft, make this tapestry suitable for the objectives of the hygroscopic tests.

Similarly to the process of material assessment explained in above for task 2 for tapestry fragments, this tapestry was quantified and its materials mapped. In the current case, due to the tapestry dimensions, the challenge was to take a high resolution picture to the entire tapestry surface that could follow the same method as applied before for the single fragments. This picture needed to be taken parallel to the surface for distortions to be reduced to a minimum. It was also necessary to have a sufficient resolution that enabled the visual differentiation of silk from wool. As the tapestry was too large for a single photo to have the desired resolution, a composite image was created from 40 detailed photos taken parallel to the tapestry surface while hanging from its Velcro strip stitched across its top border. This was done using a camera Canon EOS 700D with an ISO 100 taking each detailed picture in a defined grid of 40 squares parallel to the tapestry surface. These pictures were then merged using Adobe Photoshop CS6.
(Adobe, 2012) and distortion resulting from the process was corrected by comparing the composite photo with a lower resolution photo taken to the entire tapestry in parallel to the tapestry surface. Results from this assessment are shown in Chapter 7.

As the DIC system has limitations in terms of field-of-view, a smaller area was considered for analysis, as shown in Figure 3.20. This area measures approximately 588 mm per 183 mm as per DIC software DaVis 8.4.0. A number of reasons made this area ideal for strain analysis. Firstly, every weaving technique described in section 2.2.2 is present. It also shows the presence of both silk, wool and mixed sections and a good number of slits. This area also includes the only damaged section present on the tapestry. In this section of the tapestry most slits are stitched. Break in weaving is represented in Figure 3.20 C in blue and this corresponds to two small areas which were identified as damage.

Figure 3.20 – Detail of area for DIC strain analysis with areas selected for detail analysis as 1, 2 and 3: A - Material assessment, B – Slits assessment.

Three small areas represented in Figure 3.20 as 1, 2 and 3 were selected for strain computation under DIC and further investigation on the material influence for strain. All areas have the same approximate dimensions of 67 mm per 72 mm as measured on the DIC software DaVis 8.4.0. As shown in B, while the weft in area 1 is made of 100% wool, the weft in area 2 corresponds to 100% of silk. The weft in area 3 is measured as 51% silk and 49% wool.
3.7.2 Experimental logistics

The environmental chamber used in these experiments is a newly built equipment and thus a set of preliminary experiments to optimise its use, including mitigation measures, were undertaken. While the measurement systems have different levels of accuracy that need to be considered, the biggest challenge with the environmental chamber is the movement caused by airflow inside the chamber. This can cause out of plane displacements of the hanging tapestry of some centimetres, which could cause malfunctioning of the IBM sensors. Therefore the solution is to mount a wire system that can hold the tapestry in its plane during testing and thus restricting out-of-plane movement. DIC measurements will also detect movement from airflow, however by restricting the out-of-plane movement with the wire system this should also be brought under control. Due to the failure implementing load cells in this task the mass gain method was used to estimate mass increase.

The chamber used was a JTS model WTH35/-20/+70/F4T with a temperature range of +10°C to +40°C +/- 1.0°C and humidity range of 10% to 98% +/- 3%. In the first place, the connection of the indoor chamber with the external chamber was sealed with tape as showed in Figure 3.21 C-2. This was because a smoke test proved insufficient insulation in the panels separating the two chambers.

Ventilation in the chamber is necessary to ensure homogenous moisture and temperature diffusion, however these had only a choice of two speeds, low or high, and tests considering the tapestry hanging inside the chamber were carried out to evaluate its impact. It was demonstrated that ventilation would cause the tapestry to have considerable out-of-plane displacements causing IBM sensors to disconnect and DIC readings to have extra noise. Therefore the chamber ventilation was set up on the low level option. Furthermore, as the chamber also has an oxygen intake ventilation system for experiments with human subjects these were obstructed as shown in Figure 3.21 C-3.

For the tapestry to hang inside the chamber a frame was designed and custom built taking into account two requirements: it needed to be made with a non-magnetic material as magnetism would interfere with the IBM sensors and it needed to be able to accommodate all three sets of required equipment for the experiments. The frame was designed as shown in Figure 3.21 A with sufficient depth to accommodate shelves where each IBM mote signal transmitter could lay behind the tapestry. The height and width of the frame was established as large enough to be able to hang the tapestry. A hanging bar with Velcro attached to it and connected to another bar via a load cell was built (indicated with 3 in Figure 3.21 A and B). The frame was placed against the wall of the chamber as DIC system has a limited field-of-view and thus it was necessary to have sufficient distance that would capture the area selected for analysis. High levels of RH are always a concern when it comes to electronic equipment. Therefore, all equipment related to DIC processing, including the laptop, was set outside the
chamber via a chamber connection to the exterior that was insulated to prevent air leak. The same connection was also used to externalise the load cell cables, as shown in Figure 3.22 B.

![Figure 3.21 - Experimental apparatus of hygroscopic experiments inside the environmental chamber: A – Experimental design featuring the frame (1), IBM sensor location (2), Tapestry hanging bar connected to a load cell; B – Frame built in place with same elements as in A (1-3); C – Interior of environmental chamber with tapestry hanging in place featuring chamber ventilators (1), insulation tape used for door gaps (2), insulation used on oxygen intake (3).]

### 3.7.3 Experimental programme

The programme established for environmental experiments was divided into three phases as depicted in Table 3.4.

The first phase experiments were characterised as a prolonged exposition to certain conditions of RH and T while observing change in strain to establish the time taken by the tapestry to reach equilibrium with the environment. These experiments had the aim of understanding the chamber performance and precision of DIC measurements so that the whole set up could be accurately calibrated for the tapestry characterisation tests. Three changes in environmental conditions were considered, all at the same temperature of 25°C. In the first change the RH decreased from 45% to 30%, in the second there was an increase from 30% to 90% and in the last change there was a decrease from 90% to 45%. Each one of these experiments were repeated twice. The higher level of 90% RH could not be reached in one of the experiments because the chamber stabilised the RH at the lower level of 80%. This is the reason in the first repetition, 80% is the value represented in Table 3.4. The extreme values used in this study were intended to test the limits of where a tapestry could go in terms of strain. This phase made use of the DIC for results discussion.

The second phase of the program is composed of shorter experiments were the duration of each change is based on the time of equilibrium as established in the first phase of
experimentation. The second phase experiments had the objective of establishing the behaviour of the tapestry when exposed to consecutive cycles of change in RH. This phase includes a preliminary experiment used as a reference to be repeated in the cycle experiments. The duration of each plateau was of 4 hours and thus a change from 45% to 30% followed by a rise to 80% and then again back to 45% took a total of 12 hours. The reason the cyclic experiments used a minimum RH of 40% instead of the initially determined 30% in the preliminary experiment was because during the set time interval the chamber could not reach the lower RH. Each one of these cycles was repeated four times, however, the last cycle was stopped at slightly different times due to restricted use of the lab during Covid-19 pandemic. This phase made use of both DIC and IBM sensors.

![Table 3.4 - Environmental chamber experimental program.](image)

The third phase of experimentation relies on real condition testing using monitored data of variation of temperature and RH for selected days in Hampton Court Palace. This testing was divided on the real-time simulation of a summer and winter days. The objective was to observe the general performance of the tapestry under real conditions as verified in Hampton Court. For the summer season, 1 day was tested while for the winter season, 2 consecutive days were considered. This experimental phase made use of both DIC system and IBM sensors.

All environmental changes considered were setup in the chamber as immediate changes. Therefore, the time elapsed between the initial and the set condition, is a direct function of the chamber’s time to respond to each change of setting. This was established to simplify the experiment by avoiding tapestry to have relaxation periods over changes between levels of RH and T.
3.7.4 Digital image correlation system calibration and processing

A two-camera stereoscopic DIC system was setup inside the chamber and calibrated to record the tapestry area showed above in Figure 3.20. The system uses 2 cameras with macro lenses mounted on a tripod and aligned to capture the defined region of interest. The system is calibrated with a Type31 calibration plate as shown in Figure 3.22 A. Figure 3.22 B shows the camera calibration being performed on the laptop installed outside the chamber. Each camera has a resolution of 4032 per 2688 pixels and 4095 levels of grey. With this resolution, each pixel measures 9 µm. Similarly to what was considered previously in section 3.6 Digital image correlation, the tapestry pattern was considered sufficient for the application of DIC. In this application a subset size of 64 pixels and a step size of 8 pixels where chosen as the best option, upon a sensitivity analysis similar to the one discussed in section 3.6 Digital image correlation. In contrast with the procedure considered previously, for all experiments, each image is being compared with the first image of the set and thus values of strain result from this direct comparison and not from the sum of successive images. This minimise errors as explained on section 3.6 Digital image correlation. A correlation relative to the first image was possible in the hygroscopic experiments as the tapestry is subjected to much smaller displacements when compared to the tensile tests. The average vertical and horizontal strains for each region of interest were computed on the Davis 8.4.0 DIC software from LaVision. This calculation results from differentiating displacement maps calculated during correlation.

The images recorded by the DIC system were acquired continuously as the tapestry was exposed to environmental conditioning. In the first phase of tests, for quick changes in RH and T the acquisition was setup at intervals of 5 min for the period of one hour, and afterwards 10 min. In the second and third phases images were acquired every 5 minutes throughout the test. For the relaxation experiments, the images in the initial hour were acquired every 1 minute being followed by acquisition every 10 minutes for the following hours.
3.7.5 IBM magnetic sensors setup and processing

Local displacements were measured using sixteen magnetic sensors developed by IBM, placed in specific areas of the tapestry as represented in Figure 3.23 A. These sensors were used as they are capable of measuring local displacements with precision on the order of the micrometre without producing the effects of local stiffening over larger areas induced by strain gauges (Sloan et al., 2014). A local monitoring of high precision is important to give some insight as to the tapestry’s behaviour at the level of the yarn.

The sensors’ receptors measure changes in magnetic field as a small magnet attached to the tapestry surface moves together with the tapestry (Sloan et al., 2014). The sensors are fixed to the tapestry weaved surface, while the receptors are static fixed to an independent structure. This magnetic electric potential difference measured as a voltage is then converted into displacement according to a sensor calibration relationship developed by IBM and shown in Equation 3.5 where A is the voltage read by the sensors:

$$D = \left( (A - 8388608) \times \frac{2800}{16777216} \right) \times 125$$

Equation 3.5
The linear relationship shown in Equation 3.5. is valid for distances between magnet and receptor in the range of 10000 to 25000 micrometres. Therefore the initial position of the magnets is such that the distance from the receptor is the mean point of the range. The measurement is unidirectional and since the interest was to measure displacements in the vertical direction, the receptor and sensors were aligned vertically. Because the magnets need to be in the same vertical plane as the receptors in order to correctly measure vertical displacement and the ventilation in the chamber could cause out-of-plane displacements a wire system to hold the tapestry in plane was added to the frame as shown in Figure 3.24 D.

One row of sensors is placed close to the top border of the tapestry and one closer to the lower border. Two middle rows of sensors are placed to coincide with the central area within the tapestry’s border considered for DIC analysis as shown in Figure 3.23 A. A vertical alignment of the sensors was ensured by placing vertical metallic bars to the hanging frame, to obtain a reliable vertical alignment of the measured displacement. The vertical bars hold the sensor receptors in place as shown in Figure 3.24 B. The sensor receptors were fixed with Velcro to the vertical metallic bars and their connection wires attached with tape to these same bars as Figure 3.24 A shows. Each row of 4 sensors was connected to the respective motes that transmit the signal to an IBM gateway receptor via a communication antenna. This gateway receptor was placed outside the chamber and connected to a RaspberryPi device that collects data at intervals of 1 minute and stored these data in JSON files for each 15 min of recording. A python code was developed to read batches of JSON files in a folder, process and store data in spreadsheets organising measurements by date and time, for analysis and plotting. Such processing included conversion of the electric signal into micrometres. To calculate the change
in position of the sensor, and therefore the elongation or contraction of the tapestry, consecutive data values were subtracted from the initial reading position.

Figure 3.24 – Experimental apparatus of IBM sensor system: A – Back of the tapestry hanging in the frame with sensor receptors and magnets attached to its surface, B – Detail showing one IBM sensor receptor attached to the frame with a white round magnet attached to the tapestry surface, C – IBM Motes placed on the back of the tapestry during experiments, D – Wire system holding the tapestry on plane.

A second Python code was also developed to eliminate noise from the signal. This code applied as a filter a moving average to a number of displacement values calculated with the conversion explained above. Moving average was used as it is a simple method that is computationally inexpensive and can easily smooth out fluctuations in the data and highlight long-term trends when compared to other methods. The number of calculated displacement values considered for the moving average depended on the level of noise. To evaluate this, for the first 120 minutes of each experiment the standard deviation of the measurement was calculated. This first 120 minutes were always considered as this corresponds to a plateau of displacement values where displacements in theory are zero as there were no changes in the environment. Prior to the initial 120 minutes the tapestry had been in equilibrium with environmental conditions for more than 4 hours at the standard conditions of 45% RH and 25°C. If the standard deviation was lower than 5 microns, no data cleaning was considered for the sensor movement. When the value of standard deviation was between 5 and 10 microns a moving average was applied to 6 consecutive readings. If the standard deviation was between 10 and 50 microns, an interval of 10 readings was considered and for values of the standard deviation above 50, an interval of 12 readings was chosen. Moreover, spikes in displacement data were detected immediately after each change in RH. As data for RH in both environmental chamber and the IBM motes didn’t show any exponential change in moisture, these spikes were treated as outliers and thus replaced by a linear interpolation between points before and after them. As shown in Figure 3.23 B, a reduction in voltage represents an increase in distance between the magnet and the sensor receptor as the magnetic field becomes weaker. As IBM magnets were placed above the receptor as shown in Figure 3.24 B, a reduction in distance
between magnet and receptor as the tapestry absorbs moisture means an elongation of the fibre at that particular vertical coordinate of the tapestry, and where therefore inverted.

3.8 Conclusion

In the methodology described along this chapter some final remarks related to changes in experimentation must be stated. First of all, in spite an initial consideration to use load cells to measure the increase in weight, this is something that was not done. The programming and setup of the load cells overlapped with Covid-19 lockdown periods and thus it was impossible to pursue their use. During Covid-19 lockdown some magnets on the IBM sensors got detached from their casing but it was not possible to replace them as the labs were shut down. For these reasons, not all data from the IBM sensors are included in the section of results and discussion.

As seen in this chapter, this is a multidisciplinary methodology that gathers knowledge from different areas including conservation of tapestries, heritage science, material mechanics and hygroscopy.

Considering the tasks mentioned above, the current methodology is very dependent on the availability of historic tapestry material for testing and techniques that rely on sensors that are externally provided and not commercially available. This means that all these tasks are considered as part of a collaborative process with all partners involved in the project. With the investigation of strain in historic tapestries occupying the centre point to which every task in the project converges to, the aim of this methodology is to investigate tapestries tensile strain mechanics and hygroscopic strain when these objects are exposed to the environment while in open display.

The novelty throughout all proposed tasks is the fact that only historic fragments and tapestries are the only object of study. Although actions are put in place to work around the highly heterogeneity of these objects, it is important to always have this considered since some unexpected behaviour, either mechanical or hygroscopic can happen because of parameters that were not assessed like the case of chemical deterioration.

It is also important to consider that by studying a fragment from a tapestry will not fully inform on the behaviour of the full tapestry the fragment was extracted from. Tapestries can be very different in terms of weaving and materials depending on the area of the surface is considered for study. Notwithstanding, several fragments from different areas are considered in this study which enables at least to have an overview of a whole range of very diverse tapestries. Only one historic tapestry was tested during the hygroscopic experiments developed in task 4. It is expected that there might be variations in terms of hygroscopic behaviours across different tapestries. Notwithstanding, a characterization of this tapestry’s properties using the methodology described in task 2 was done so that results can be better interpreted and analysed.
Differently from previous literature where a full physical properties assessment was not considered for strain analysis (Lennard et al., 2011, Duffus, 2013 and Bratasz et al., 2014), this methodology considers a holistic approach to tackle material heterogeneity. This constitutes a novelty in heritage science applied to the study of historic tapestries. The development of such methodology can then be applied in future research to interpret mechanic and hygroscopic behaviour in historic materials.

The survey on task 1 is explored in chapter 4. The fragment selection and physical assessment of samples on task 2 is part of chapter 5. Task 3 on mechanical testing of historic tapestries is explored in chapter 6. Hygroscopic experiments making up task 4 account for chapter 7.
Chapter 4

*Conservation Strategies Survey*

4.1 Introduction

The following survey is an investigation of conservation interventions and the important changes they produce to a tapestry structure. In the literature on Chapter 2, different conservation interventions were discussed. Some of these interventions such as reweaving are seen by numerous conservators as obsolete, while others, such as the use of straps or full support fabric, have divided conservators into two schools of conservation, the US and UK. Two past surveys exist on this subject, one about north American conservation techniques by Breeze in 2000 (Breeze, 2000) and the second more general in 2013 by Duffus (Duffus, 2013). The motivation for this survey is that the distinction in schools of conservation is not clearly perceivable from the past surveys available as one focuses only in north American studios, while the other does not differentiate answers between geographic locations. It is important to understand how different conservation schools influence structural changes in a tapestry weave by producing restraints through the different techniques in use. The understanding of how conservation methods change a tapestry’s strain field will enable a better understanding of the structural changes. This aims to help the structural characterisation of fragments and tapestries tested within this study. Results from further tensile and hygroscopic tests can then be interpreted with a new light regarding conclusions extracted from this survey, such as treatment for slits and restraining of the tapestry fabric.

The American method is famous for its use of straps as a lining for structural support and stabilisation while the English method focus on a full lining. These differences are evident when comparing the two previous surveys (Breeze, 2000, Duffus, 2013). Although the questionnaire analysis made by Duffus don’t differentiate answers among countries, the low percentage of 10% using strap method among conservators reflects a divergence in tapestry conservation outside US (Duffus, 2013). Duffus questionnaire had a special attention to aspects related to tapestry support systems which had the aim of informing FEM modelling by providing a picture of the global practice of tapestry conservation. However, given that conservation practices are always changing and evolving because of new techniques, materials and better scientific understanding, and the fact that 10 years have elapsed since the study conducted by Duffus, it was deemed necessary to undertake a new questionnaire-based survey of the tapestry conservation industry oriented to determine the popularity of current support systems and conservation procedures which alter the structure of historic tapestries.

To evaluate the differences from different conservation schools across the globe, this survey considers an analysis based on the different participating regions. Hence, this survey aims to be more informative when compared with past surveys by exploring different
conservation methods worldwide and investigating the existing schools of tapestry conservations. This will give a better overview of tapestry conservation across the globe which might be compromised by the high amount of existing literature focusing on conservation in US and UK.

As shown in section 3.3, the survey is divided in 5 sections: the first section aims to understand the reason why conservators provide support for tapestries and how large their studios are. The second section aims to understand the type of support provided. The third section targets stitching techniques and materials used in conservation. The fourth section explores changes in conservation practices. The fifth section provides an open comment space so that any detail or opinion could be explained. The full questionnaire form is shown in Appendix 2.

4.2 Analysis

4.2.1 Introduction

The survey takes a novel approach analysing data by comparing the chosen geographic regions and plotting the number of answers for each given option. The analysis differs from Duffus questionnaire (Duffus, 2013) as this only evaluated the percentage of answers each option had. Three different types of questions exist in the questionnaire: multiple answer questions, questions with score attribution system to parameters and open questions. Multiple answer questions were processed by plotting the number of answers each obtained in each geographic region. Therefore not only the most popular answer is clear but also a comparison between geographic regions can be established. For the score attribution questions, the analysis was done separating different regions and calculating the percentage of each score attributed to each parameter. As for the open questions, these were used to better understand if conservators were adding any other changes on the tapestry weave and to verify if there were any more options that were not listed in the multiple questions. Open answers are integrated into the discussion rather than in the analysis.

4.2.2 Section 1 - General Questions

The chart in Figure 4.1 represents the average number of tapestries that are conserved each year by the respondents. Two respondents who said that no tapestries were currently being conserved at their studio were included in the following analysis, as it is assumed that they had applied their methods before and will employ them again in the near future.
Most tapestry conservation studios conserve only 1 tapestry each year. In general terms around 60% of textile conservation studios have a capacity for conserving between 1 and 2 tapestries each year. Notwithstanding, in Europe, 3 tapestry conservation studios have the capacity of conserving more than 5 tapestries each year which count for around 7% of the total studios.

Respondents who answered that the number of tapestries conserved was very dependent in terms of schedules, exhibitions, and type of intervention without giving further indication of the average number of tapestries conserved are included as “unknown”.

Figure 4.2 represents the main reasons conservators consider when they apply a support fabric to the back of the tapestry.
Respondents from UK, US, Europe consider similar level of importance for strengthening, distribution of load and support display as these are the main reasons for adding support fabric. Yet, in Europe, the strengthening and stabilising is around 10% higher than distribution of load and support for display while UK and specially US have a more even distribution of these three factors.

Respondents from Japan consider a similar level of importance across all factors while the one from Australia indicates only Strengthening and Stabilising.

4.2.3 Section 2 - Type of Support

The questions and processed answers related to the type of support are shown in Figure 4.3.

Methods in use by different conservation schools can be identified in Figure 4.3. The differences between US and UK are shown in Figure 4.3 a). Overall, full support is the main method of support used in UK, by 7 respondents against 1 respondent using patches and 2 patches together with full support. The answers from US showed a distinct approach with 3 respondents using straps and 1 respondent using patches together with full support and 1 other respondent using overall full support. This showed that as in the literature on the past surveys, strap method is more used when comparing to full support method extensively in use in UK. In Europe use of patches together with full support is the common solution as 8 respondents
prefer this method, while 4 prefer full support, 2 use only patches and 1 uses straps. Notwithstanding, it is important to note that 3 of 4 respondents that use overall full support in Europe belong to major public institutions.

Canada is more familiar with the British method as 2 respondents use overall full support in comparison with 1 that uses patches together with full support. Australia uses the patch technique, bringing this method overall to the same level of importance as straps, with 4 international respondents each. Furthermore, by looking at all answers the 2 most used techniques are the overall full support and patches and full support.

Among respondents that answered “other”, another conservation school was identified in Sweden, whereby all answers by 3 conservators considered a solution of patches with straps. This solution was also noted by one respondent in US. Other solutions included full support in the top third of the tapestry and reweaving instead of adding fabric to the tapestry structure.

In terms of materials used, as shown on Figure 4.3 c), linen is the most used material as support fabric. Linen is the only material used as support fabric in UK while cotton is the only in use in Canada. In US cotton is the most common with 4 respondents preferring it to linen, used by 2 respondents. This clearly shows again a division between American and UK practices. Europe has a preference for linen however cotton and a mix of linen and cotton is also used by some conservators. Yet, linen is the only material in use in south Europe by Italian and Spanish conservators. Other materials in use include a mix of linen, cotton and silk depending on whether the support type is patches, strips and/or full support.

When asked about excess fabric on the back support an extra 0.8 to 1 cm per 20 cm of fabric is the favorite support excess among 12 conservators. From these 12 conservators, 6 were answers from UK. However, 7 conservators don’t use excess fabric, a trend that is more related to European studios as 4 respondents are from Europe being 3 of these German studios. Answers from Canada and US are very disparate. However, 4 American conservators use more than 1cm extra fabric per 20cm.

The dependence of the amount of excess fabric on the tapestry characteristics is considered by 5 conservators. The large number of conservators who answered “other” justified their answer by saying that it varies depending on whether it is an upper or bottom part. Conservators consider more fabric in the upper parts and then reduce the excess as they reach the bottom parts. This is clearly dictated by the mechanic response of the tapestry hanging in vertical display. Other conservators also justified their option as they add excess fabric both on horizontal and vertical directions with one answer considering excess just on the horizontal direction. Decisions for choosing the amount of excess fabric rely on experience acquired through the years. As shown on Figure 4.3 f), a majority of 24 conservators use the amount of excess fabric they learned to use or during training or by the studio experience acquired over the years. Only 5 conservators make their decisions based on experimental results either acquired from research or hanging tests. One conservator described the procedure for the tests
where the tapestry is hung for a certain period to stretch it before cutting to size the back cover which is then stitched to the tapestry. Conservators who answered “other” justified this option by saying that more than one of the mentioned factors are taken into account.

Answers for the reasons of selecting a type of support fabric on Figure 4.3 d), indicate that most conservators acknowledge the importance of allowing the fabric to change its dimensions. However, one conservator in Europe considers a tapestry needs to have its movement restricted by the support fabric. Material longevity also plays an important role but has less than half of answers when compared to the level of importance.

As for the choice of support method on Figure 4.3 b), most of the conservators seem to agree that the extent of damage is the most important factor as this factor has the biggest percentage of importance in every country except Japan which considers all factors with the same importance. The level of importance attributed to extent of damage ranges from 28% to 46% across all geographic regions. In UK, US, Canada and Europe the other factors such as time, cost, material availability and facilities available share a fairly similar level of importance. For the case of Australia, time is the second most important factor. Other factors pointed by conservators were the type of deterioration, the physical properties of the tapestry such as weight and size, the quality of the tapestry fabric, planned handling and presentation of the tapestry, length of display, visual compensation of areas of loss.
Figure 4.3 – Graphs representing answers related with support fabric: a) Type of fabric support used on the different geographic regions; b) Factors for choosing type of support fabric per country; c) Material used as support fabric in different geographic regions; d) Reasons for using a specific material as support fabric, e) Excess support fabric added to allow ease. f) Reasons for choosing a specific amount of excess on the support fabric.
4.2.4 Section 3 - Stitching Methods

Section 3 explores stitching methods in use to attach the support fabric and provide support on weak areas. The questions and processed answers are showed in Figure 4.4.

Figure 4.4a clearly shows that conservators in UK are divided between the use of running and zig-zag stitch. A division which is less pronounced in the case of US which had the double of answers in favour of the zig zag stitch. Zig-zag stitch is also the stitch used by the respondent from Japan. Europe and Canada are very keen on the use of running stitch as all respondents chose this option to stitch support fabric to the back of the tapestry which again show the differences between these and the US and UK schools of conservation.

While evaluating the distances of stitching runs as shown in Figure 4.4 b) it is clear that conservators in US and Europe are more conservative than conservators in UK. Conservators in UK prefer a distance of 20 cm while in Europe the most used distance is 15 cm. In US smaller distances of 8 to 10 cm are more used and no answer on 20 cm was given which seems to reflect the use of straps as conservation method. Equally important is the distance as dependent on the tapestry characteristics which is not considered by any of conservators in UK.

The favoured length of stitch as shown in Figure 4.4 c) is 1.5 to 2 cm for all regions except Canada that is divided between this option and a length dependent on the tapestry characteristics. The second most used length for stitches is from 2 to 3 cm being followed by the dependence on tapestry characteristics. Smaller lengths of 1 cm and 1 to 1.5 cm are only in use in Europe where some studios show to be more conservative. These stitches are usually done in the weft direction as it is the most favorable direction to attach the support fabric to the back of the tapestry according to answers in Figure 4.4 d). However, many conservators are also in favour of the warp direction for the stitching of support fabric. Indeed, while UK and Europe show a preference of the weft direction, the US and Canada favour the warp direction which makes this a clear division between the two continents.

As shown in Figure 4.4 e), to add strength to weak areas, couching is favored by conservators in UK while in US a combination of couching and running stitch was the most common answer. In Europe a combination of running stitch and couching is also the most used technique with more conservators using this than the sum of the conservators using either one of these techniques individually. Yet, all German conservators use couching as stitching method showing similarity with UK. In Canada 2 conservators use the running stitch and 2 a combination of couching and running stitch.

For areas severely damaged, as shown in Figure 4.4 g), although couching is still favored by conservators in UK, in US running stitch was the most common answer. In Europe couching and a combination of running stitch and couching is still the most used technique with 7 respondents although many chose couching when compared with answers for damaged
areas. Similarly to damaged areas, all German conservators use couching technique for stitching. In Canada 2 conservators use couching and 2 others running stitch which is also different when compared to the stitch used in weak areas as 2 were in favor of the combination of both techniques.

In terms of distance between stitching rows in weak areas (Figure 4.4f), in UK a space of 0.5 and 1 cm on stitching rows is favoured having both options the same number of answers. For the case of US the smaller distance of 0.5 cm is favoured with 4 answers against 1 for 1 cm distance. In contrast, for Europe 1 cm is favoured by 9 conservators being followed by 5 that use 0.5 cm distance. However 1 conservator use 1 to 2 cm distance and 2 other conservators 2 to 3 cm distance. In Canada 1 cm is more used. Yet 0.5 cm and more than 3 cm is used by one conservator each.

As expected, in general terms the answers to a severely damaged areas are more conservative than the answers of weak areas as it can be observed in Figure 4.4 h). Conservators in UK and US agree with a distance of 0.5 cm between stitching rows. For Europe 0.5 cm is favoured by 8 conservators being followed by 6 that use 1 cm distance. However, 1 conservator uses 1 to 2 cm distance and 2 other conservators 2 to 3 cm distance, the same as in weak areas. In Canada the answers are divided between 0.5 cm and 1 cm distance between stitching rows.

On the open question in the stitching techniques section, most conservators answering referred to the importance that damaged areas and the tapestry characteristics have when deciding the stitching method and material in relation to both attaching the support fabric and to repair-stitching degraded areas. However, one conservator stated that no decision making in terms of support system and stitching is done on the basis of the tapestry conditions, which makes the suggestion that this studio has a very well established protocol which is followed in every tapestry conserved. A second conservator mentioned client specifications and budget affecting distance between stitching rows.

One conservator said the aim with stitching is to make a bridge from weakened areas to stronger areas and all the distances between stitching lines and the length of these lines are dictated by the conservation state of the object.

Special attention to stitch loose warps to the support fabric was mentioned by two conservators. they indicated that warp threads that are uncovered because of damaged weft are sewn in separately from the support fabric with stitching lines following the twist of the warp thread.

The avoiding of knots was also mentioned by one conservator who leaves the end of the sewing threads open. As alternative stitching methods one conservator reported the use of darning stitch, another conservator weft faced couching mimicking the weave and another conservator the use of brick couching, instead of the options that were given in the questionnaire.
For severely damaged areas conservators also stated the use of individual support fabrics or base grills stitched with running or couch stitching before applying the full back support. Slits were also mentioned to be areas where particular attention to restriction is given by one conservator. There was one conservator that reported the use of adhesives considering lining seals on conservation work.

Reweaving was also highlighted by two conservators one in US and one in Canada. The conservator in US uses reweaving after stitching down loosed warps on the support fabric. The conservator in Canada usually reweaves areas of missing weft and justifies this option because of stress avoidance due to differential stretching of different materials and also because the area stays more homogeneous and in the same place when the tapestry is rolled in storage.
Figure 4.4 - Graphs representing answers related with stitching methods section: a) Stitching technique used to attach support fabric to the tapestry; b) Distance apart used for stitches to attach a support fabric to the back of the tapestry; c) Length of stitch used to attach the support fabric; d) Direction of stitch used to attach the support fabric. e) Stitching technique used to add strength to weak areas in the tapestry. f) Distance between stitching rows to add strength to weak areas in the tapestry. g) Stitching technique used to add strength to severely degraded areas in the tapestry. h) Distance between stitching rows to add strength in severely damaged areas in the tapestry.
4.2.5. Section 3 - Materials for Stitching

The questions and processed answers for section 5 of the survey are showed in Figure 4.5. In terms of stitching materials, cotton is in general the most used material as it can be observed in Figure 4.5 a), b) and c). However, depending on the tapestry section the stitching is used for, some important regional differences could be identified.

Cotton is the favourite material in US, Europe and Canada to attach the support fabric. This is in clear contrast with UK as polyester is the choice by most conservators. European conservators also use a mix of cotton and polyester and 2 reported using silk to stitch the support fabric. The answers as “other” reported that the choice of material depends on the tapestry being conserved. Also, a mix of silk and cotton was reported by two European conservators.

To stitch silk areas, cotton is the favourite among conservators with 16 respondents using this material. However, silk also plays an important role among European and Canadian conservators. The most used material in Europe is silk with 8 respondents using silk against 6 who use cotton. The same trend was verified in Canada as 3 conservators use silk with only one using cotton. This material is not in use by conservators in US and UK. Respondents of “other” said that they can use either cotton or silk depending on the tapestry features, such as fineness.

To stitch wool areas cotton is again the favourite among conservators with 12 respondents using this material. In similarity with silk areas, wool here also plays an important role among conservators. For the case of UK, wool is the favourite stitching material with 4 answers to this option. Canada is divided between the use of cotton and wool with 2 respondents for either option. While a mix of polyester and wool is the second most used solution in UK, for the case of Europe it is silk. Respondents who answered “other” justified that usually a mix of wool with cotton or polyester thread is used. Also, the choice of material might depend on the tapestry condition. Only Japan considers all the factors equally important. Notwithstanding, tradition and experience also play an important role in conservators decision. Conservators that mentioned “other” referred to the importance of physical and chemical properties of the thread, compatibility with the original tapestry threads and the avoidance of natural threads because of pests.
4.2.6 Section 4 - Conservation Studio History

The factors that most contributed for the conservation approaches in the different studios are represented in Figure 4.6. Tradition and current research are the factors that more contribute to conservation approaches according to conservators from all regions except for Japan that attributes the same level of importance to tradition, cost and current research.
Figure 4.6 - Graph representing factors affecting conservation approach used per country.

4.2.7 Section 5 - General Comments

This section summarises the answers received on the open question where conservators where asked about general comments on the survey.

A conservator mentioned reweaving might happen after stitching loose warps to the support fabric. It was stressed that some options for the treatment applied need to consider the hanging method and thus are dependent on this. The conservator that mentioned this exemplified with a case where the tapestry is hanging not only by the top border but by the lateral and top borders which would change the practice consideration in terms of the amount of excess fabric considered.

Mentioned by 3 conservators was the fact that no definite answer could be given to some questions, their choices would depend on the tapestry characteristics.

One conservator showed some concerns about the opinion shared by some curators that tapestries have faded and degraded as much as they could be and thus no more damaged would occur and hence no need for conservation.

A conservator in Italy mentioned the importance of restoration by reweaving some areas which are considered important to the image of the tapestry. This conservator also uses conservation methods for structural stabilization of the tapestry.
Another conservator mentioned that the reason used for the strips method is that of weight reduction. This conservator mounts a sleeve on the top back of the tapestry to insert an aluminium bar for hanging purposes. Also mentioned by another conservator was the fact that full backings are a problem for historians that are trying to study a tapestry in terms of its original colour by observing back threads and taking samples for aging properties characterization. It was also mentioned the lack of reversibility when using full backings.

One European conservator gave a full insight on his conservation method whereby patches are used to repair weak areas of the tapestry before a full lining is installed. All stitching is done using running stitches and the chosen material for patches and lining needs to be stiff but not as stiff as the weave as this is believed to cause damage due to deformation restrictions in the historic fabric.

In a very large collection of tapestries in UK a conservator said that due to costs a remedial repair is often done before full conservation be considered.

4.3 Comparison with past questionnaires

Two surveys on tapestry conservation methods were identified in section 4.1 one related to the conservation method in North America (Breeze, 2000) and other with a more international overview (Duffus, 2013).

The American survey dates from 2000 and got 16 respondents across the United States and Canada which summarised the North American conservation practice of tapestries (Breeze, 2000). This survey covered several stages of tapestry conservation from documentation, fibre testing, cleaning, drying, slits, restoration, the use of adhesives, strapping, hanging and maintenance. The answers stressed the importance that cost and time had in tapestry conservation practices. It was also evident the desire of keeping the tapestry legible and then using restoration practices in opposition to structural stabilisation. Technology available in each studio and training of conservators was also pointed as main factors that determine the preference of one method when compared to another. Breeze’s survey clearly outlines that the use of straps across the USA became common among conservators who worked with Kajitani in the 70s which is known as the first conservator to use the strap method (Breeze, 2000). In terms of stitching used, herringbone stitch was common among 9 of the respondents to attach the straps to the tapestry. Other 3 used running stitches. Cotton was the material used for the straps by all respondents on this questionnaire. Full lining was rare in the reported questionnaire and the use dust cover was reported by 50% of the respondents. Cotton was also the only material reported for straps being used by 12 of the respondents that answered, three of them using cotton tape for straps. Cotton was also the only material reported to be used in dust cover and in the threads to stitch the straps to the back of the tapestry. For stitching areas of silk and wool it has been reported that 5 use cotton exclusively, 8 use wool for wool areas and 3 silk for silk areas.
When comparing Breeze’s survey on American methods with the current one conducted 20 years later, some similarities and changes on the American approach can be identified. First of all, after analysing answers of question 6 related with the type of support it is evident that the strap method is still largely in use by conservators in US. Considering Breeze survey also considered Canada, it is surprising that no conservator in Canada reported this method in the current survey as their preference goes towards full support. Also there were 3 conservators in US from a total of 6 reporting alternative methods than the use of straps. On question 8 of the current questionnaire it is showed that cotton is still largely used as support fabric for US and Canada. Yet one conservator in US reported the use of linen. As for the stitching of the support fabric in the current questionnaire around 50% of conservators in US and Canada reported the use of running stitch, which is a higher percentage than 19% as it was detected in Breeze’s questionnaire.

In terms of stitching material for the lining method Cotton is still largely used by American conservators with only 2 out of 7 answering alternative materials. To stitch areas of wool the current questionnaire shows what appears to be a shift from wool to Cotton by the American conservators as 4 reported the use of cotton and 3 the use of wool inverting the trend verified on Breeze’s questionnaire. As for silk areas the trend seems to be relatively the same as reported on the American questionnaire as 3 conservators in Canada use silk for silk areas and 5 from US and Canada use cotton.

The international survey collected in 2009 (Duffus, 2013) presented a more general overview on worldwide conservation practices. As the current survey is based on this, it is worth to compare side by side the changes verified in some conservation approaches although no separation on geographic regions was considered in the analysis by Duffus. In terms of capacity by tapestry conservation studios the studios conserving 1 or less tapestries each year seems to have been increasing from 35% to around 45% in the current questionnaire. On the other hand, studios conserving 3 or more tapestries decreased from 52% to 20% in the current questionnaire. This suggests that less tapestries are being onserved when compared to 10 years ago.

On question 6 of the current survey it is evident that there was a slight increase on the use of full support in relation with full and patch. In the current survey a considerable amount of respondents use other techniques which is not verified on Duffus survey. However, this is perhaps because in the current survey there is a higher number of conservators that answered. In relation with reasons to select a specific type of fabric on question 9, conservators were more keen to justify their option regarding the freedom of movement a specific fabric gives to the tapestry with only one respondent justifying his choice because it restricts the tapestry. This is in clear contrast with the previous Duffus questionnaire where 30% of respondents were using a fabric to restrict the movement. It is however curious that not a big difference in both questionnaires was reported on the question relating with the material used for the support fabric. When asked the amount of extra material conservators used to allow ease on the support
fabric, 50% of conservators applied no excess fabric as reported on Duffus’ survey. A number that is reduced to around 18% in the current survey. This shows that over a period of 10 years conservators are more keen to use extra support fabric to allow tapestries to expand.

On the questions regarding stitching, the novelty that comes with this current survey was on the extended answer that a high percentage of conservators said it was all dependent on the tapestry characteristics and level of damage. Removing this option from the answers the other relative percentages were similar in terms of distance apart from stitching and length of stitches. However, it was interesting to see that some conservators stitch on the warp direction and not on the weft as seen on the analysis of question 15. A fact that goes against Duffus questionnaire were all conservators said they used the weft direction. This suggests that since the last survey, conservators have been experimenting on applying conservation stitches in the warp direction and thus using weft threads as support for stitches.

In terms of stitching material to attach the support fabric, when comparing the current survey to Duffus, the percentage of cotton increased from 30% to 46% and polyester decreased from 30% to 19%. For stitching silk areas the percentage of silk in the current survey decreased from 41% to 29%. The same trend is also true for the case of stitching wool areas with wool threads which experienced a reduction from 33% to 24%.

4.4 Conclusion

Along this questionnaire the following conclusions can be drawn:

The idea that straps and full lining are the most common methods of conservation proved to be true for the case of US and UK. However when conducting a worldwide questionnaire it becomes clear that patches with full support are the second most important conservation method after the full lining as showed on the answers of question 6.

It was also showed that Sweden has its own approach to lining by considering the use of patches together with straps.

Although considered by many conservators a technique used only in the past, reweaving areas of loss was stressed out by 3 conservators, one in a major Italian institution and other two in Canada and US.

In terms of material for support fabric, it was shown that while cotton is more used in US, linen is more used in UK. Although there is a division in Europe between several materials for support fabric, linen was identified as being largely in use in south European countries such as Spain and Italy. In terms of excess fabric for the support, answers on question 10 proved that in Germany this is something not considered. This is something that is clearly different from other conservation practices which seems to indicate that Germany has its own approach to tapestry conservation.
In terms of stitching to attach the support fabric, running stitch is consistently used by Canada and Europe. When considering the distance apart and length of stitching lines, conservation studios in UK seem to follow a well-established protocol as none of the conservators answered that this depends on the tapestry characteristics. In terms of direction for stitching, US and Canada are quite distinct from other geographic regions as they favour the warp direction.

Areas of damage sometimes receive special attention by conservators, to add strength in these areas couching is largely used by conservators in UK while for Europe and US a combination of couching and running stitch is used. However, if the damage is severe, there is a higher amount of conservators use couching and reduce the distance between stitching.

In terms of stitching material, it has been showed that cotton is the most used material to attach the support fabric in Europe, US and Canada. However, conservators in UK prefer the use of polyester. For stitch silk areas, silk is sometimes used but cotton is favoured among conservators. The same happens with areas of wool since wool is used by some conservators but the most used materials is still cotton.

When comparing the current survey to Breeze’s done 20 years ago the biggest shift in American conservation is that now Canadian conservators prefer the use of full support instead of the strap method.

The comparison of the current survey with Duffus also brings important conclusions on the evolution of tapestry conservation. There is the suggestion that less tapestries are being conserved now when comparing the capacity of different conservation studios. Conservators nowadays seem to be more prone to use extra fabric to allow tapestry to have more freedom of movement when compared to 10 years ago. However what is perhaps more noticeable is that conservators also seem to be experimenting on applying conservation stitches in the warp direction rather than the weft which clearly contrasts with Duffus questionnaire where all conservators considered the weft direction.
Chapter 5  
*Physical assessment and structural characterisation*

### 5.1 Historic Tapestry Fragments Selection

The removal of patches of damaged original areas in tapestries was a common practice in the past as already mentioned above in section 2.5.3. In this restoration practice, woven patches of historic material were being removed and replaced by newly woven sections (Shephard, 2006). When this didn’t happen extremely damaged tapestries were being cut to serve as repair sections on other similar areas that belong to other tapestries (Böttiger, 1937). This restoration practices enabled Historic Royal Palaces (HRP) to gather a collection of fragments that were originally removed from different historic tapestries throughout countless restoration interventions in the past. This collection composed of fragments with different designs and structural features is itself of historic value and was generously made available for mechanical tests during this research.

From a vast number of fragments available, 33 were selected based on considerations of their physical properties and size. Fragments from the galloons were excluded from mechanical testing due to their dimensions. On the other hand, although weaved galloons are very structurally homogeneous and thus expected to have different mechanical behaviour when compared with other sections from tapestries, they were considered for the case of hygroscopic experiments as they are made with same materials.

Past studies considered destructive sampling of historic tapestry fragments (Duffus, 2013). However, given the historic rarity of these samples and since cutting these fragments for sampling would constrain further testing to their newly defined dimensions, this was not considered. Therefore, grab tests (BSI, 2014) were considered as a way for testing fragments without having to cut them for sampling. For the grab tests, dimensions of fragments are

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*Figure 5.1 – Historic tapestry fragments on HRP collection.*  
*Figure 5.2 – Detail of fragment 157.*
dependent on the jaws of the Instron tensile tester which measure 76 mm width. With this required parameter, fragments that were smaller than 90 mm in width were excluded. Another factor of exclusion was hugely damaged fragments with substantial areas of loss that were under acceptable dimensions but totally degraded that could not be considered anymore to be part of a weaved tapestry. Selected fragments can be seen scattered on the table at HRP lab in Figure 5.1 with an example of one of these fragments in Figure 5.2.

A dimension of 80 mm in length was selected for samples to be tested on the Instron tensile tester. As a result, 5 sampled areas were selected for physical characterisation in each fragment to have enough representative repetitions. The criterion by which such area were selected is that they should show as much variability as it is present in the fragments in terms of weaving features. By variability its understood variance in terms of presence of slits, heterogeneity in design patterns and different degrees of physical damage when this was detectable. As shown in Figure 5.3, some sample areas were selected as much apart from each other as possible while others were inevitably overlapping. Figure 5.4 shows an example were all areas overlap.

![Figure 5.3 – Sample areas selected for testing in fragment 60.](image1)

![Figure 5.4 – Sample areas selected for testing in fragment 146.](image2)

In an ideal experimental setting, homogeneous samples with same dimensions and properties would be tested for their mechanical and hygroscopic properties to understand and characterise the behaviour of the material under study. Nevertheless, in the study of historic tapestries, this becomes one of the main challenges of this research. Not only testing new homogeneous samples will lead to wrong estimations of the behaviour of tapestry material (Duffus, 2013), but also there is a need to always keep in mind that tapestries are highly heterogeneous surfaces (Lennard, 2006d). As can be seen in Figure 5.1 and Figure 5.2, fragments in this research have a very heterogeneous structure and to identify different properties that can impact on their mechanical behaviour a structural assessment was carried out prior to the tensile testing. By structural assessment is implicit the evaluation of properties that are part of the weaved structure and that will serve to help to establish differences between the fragments, in other words what makes them heterogeneous. Considering this, there was the
need to extract all the possible structural characteristics that could have influence on the mechanical and hygroscopic properties. The characteristics that were quantified were: thickness, fineness, material, slits, condition rating and colour. As discussed in section 2.2 Tapestry weaving and its structure they can completely define the physical structure of a tapestry in terms of dimensions, materiality, colour and damage. The results of this assessment are presented in the sections composing this chapter.

5.2 Thickness and Fineness

Thickness and fineness, defined in section 2.2 Tapestry weaving and its structure, are characteristics whose influence and importance when conducting mechanical tests are immediately evident. Thickness depends directly on the number of yarns used in each thread. The coarser the tapestry, more weft yarns will be needed for each thread and consequently the threads of the warp will be coarser to serve as support structure. In other words, a coarser thicker weft structure will need a similarly coarser warp structure to support the first. The coarser the tapestry threads, the greater the distance between the centre of weft threads packed together to hide the warps. Thus, a coarser weave leads to a coarser structure with lower levels of fineness which is assumed to be inversely proportional to the thickness of the tapestry. For tapestries to be comparable thickness is an important parameter to be quantified since the load capacity of a tapestry will be proportional to its thickness. The current standard for measuring thickness of textiles considers the application of a presser-foot with a recommended pressure of 1 ±0.01 KPa (British standards BS EN ISO 5084:1997, 1997) However, since this equipment was not available, a calliper was used instead. The use of the calliper provided enough precision for thickness measurements without causing any damage to the tapestries being measured. It is also a method that can be replicated in case conservators want to follow the assessment workflow developed in this project.

To assess thickness in each fragment, a digital calliper HITEC 101-45 with 0.01 mm of precision was used. After closing the calliper jaws and setting the reading to 0 the jaws were open and then closed sequentially on each measurement point dispersed around the fragment as showed on Figure 5.6. A period of 30±5 seconds was given after closing the jaws and before reading each measurement in accordance with the current standard (British standards BS EN ISO 5084:1997, 1997). Each one of these points were measured 3 times and the results were then averaged.
For the assessment of fineness, a series of microscopic images were recorded and measured using the software associated with the microscope. The microscope in use was a Dino-lite microscope setup to a magnification of 34 times. Measurements were taken following a template created for this purpose as shown on Figure 5.7. This template is composed of 12 measurement areas where the Dino-lite microscope was used to capture the required images. This template was created considering the dimensions established for further mechanical tests. As shown in Figure 5.7 it evenly distributes 12 areas of measurement across the sample area. The location on the fragment where the template was assigned to is related to the sample areas selected for further testing. The recorded images were imported into Dino-lite software and two measurements in mm in the warp and weft direction, were taken for each one of the images as shown in Figure 5.8.

A total of 24 measurements for each direction were taken across a certain amount of warp and weft threads. These measurements were then divided by the number of threads.
considered and the measurements for each direction averaged so a fineness for both warp and weft direction in each one of the fragments was established.

The distribution of fineness values for this assessment is summarised in Figure 5.9 and further presented in Figure 5.10. All values for each fragment are further presented in Appendix 4. The interquartile range in Figure 5.9 for the weft fineness goes from 8 to around 11 threads/cm. The range on the warp varies from 4 to around 6 threads/cm. It is then noticeable that in general weft direction is finer than warp direction as also shown in Figure 5.10 and previously reported in section 2.2. Weft fineness can have more variation when compared to warp as values have a wider range.

![Box Plot showing the distribution of fineness on the wrap and weft of the fragments assessed.](image)

![Graph showing fineness distribution in analysed fragments.](image)
The distribution of thickness values for this assessment is presented in Figure 5.11. It is shown that thickness can change from 1.2 mm to almost 3 mm. Although greater thickness is associated with coarser tapestries and thus lower levels of fineness, this relationship is not always linear. As example when comparing values of thickness and fineness for fragment 501, it can be observed that although this fragment presents the lowest thickness measurement, it does not correspond to the highest level of fineness.

Figure 5.11 - Graph showing thickness distribution in analysed fragments.

Figure 5.12 shows a correlation matrix comparing variables of fineness in warp and weft and thickness values.

The correlation coefficient of 0.91 suggests that there is a strong positive relationship between the thickness and fineness in the warp direction. As expected and given a negative value of correlation coefficient, as thickness increases, the fineness decreases. The other correlations shown coefficients of 0.56 and 0.61 which are moderate correlations. However, given the weaving process described in Chapter 2, it is known that, to some extent, fineness in the weft depends on the fineness in the warp. Since fine weaving also uses finner threads, thickness is also a dependent variable.
Figure 5.12 – Correlation matrix showing correlation coefficients plotting fineness for warp and weft against thickness.

5.3 Material Assessment

Tapestries usually include the use of silk together with wool in the weft direction. As already identified in the literature review in Chapter 2, although it may be true that silk and wool are both natural protein fibres, these two fibre materials are very different regarding mechanical and hygroscopic properties. Material distribution in each sample is then a crucial property to assess when working with a high level of heterogeneity across the different weaved samples in each fragment. While the warp is consistently made of wool in all chosen fragments, the weft material varies considerably from fragment to fragment. Therefore the material analysis was only considered in the weft direction in terms of the percentage of each material present.
To assess the weaving materials, a picture taken in a parallel direction to the tapestry plane of each sample area was used to quantify the percentage of silk and wool that exists in each mix-material sample to be used in further mechanical testing. This process considers 3 distinct phases where microscopic analysis and imaging process converge. In the first phase, visual inspection was followed by a microscopic analysis to detect in each sample which areas were made with wool threads and which were made with silk. Microscopic analysis was a way to double check what was already verified under visual inspection since the different colours with shiny effects of the silk threads can be easily distinguished by a thorough inspection. However, there are always cases such as the one shown in Figure 5.13 where silk areas are identical in colour with the wool threads and thus a detailed analysis is needed under the microscope to assess the presence of the two materials. Their fibre structure can be easily differentiated under the microscope since silk fibres are notoriously finer when compared with wool. After this microscope assessment where areas of wool and silk have been clearly distinguished, Photoshop software (Adobe, 2012) was used to manually remove the colour of wool areas, leaving only silk with their original colour as shown in Figure 5.14. The next process was to import this new wool de-saturated image into ImageJ software as shown in Figure 5.15. The next step was to select only the coloured areas of the image which corresponded to the silk areas. This was done by selecting only the saturated areas by applying a colour threshold as shown in . The next step was to measure the number of pixels in the areas selected. With this done the percentage of silk was calculated considering the initial number of pixels in the entire image and the selected pixels for the coloured areas. The area of wool was calculated by subtracting the area calculated for silk.
Figure 5.16 highlights some small portions between the coloured wefts that are not picked up but on the other hand this is somehow compensated by residual areas of colour that are picked up in the selection. Of course, this process is dependent on the level of saturation selected in the colour threshold as showed on the right window in Figure 5.16. Notwithstanding this, several saturation levels randomly selected for the case of the sample presented above show that an average deviation of only 1% in percentage of silk was obtained, therefore determining the threshold of accuracy of this method.

All values for silk and wool proportion assessed with this procedure in each sample are reported in Appendix 4. The graph in Figure 5.17 shows the material distribution across different samples analysed. It is observed that only samples from fragment 143 have 100% of silk on their weft. More than 50% of silk is also attributed to samples from fragments 146 and 154. The other fragments always have a smaller percentage of silk and thus it is observed that in general wool as a weft material is more abundant when compared to silk.
5.4 Slits and splits

Presence and number of slits is another parameter considered when assessing properties for analysing tapestry samples. Slit is the name given to the empty space in the weaving when there is a colour change as explained in chapter 2.2.3. Whether considering a slit or a split, there is a need to quantify their occurrence in the samples since any kind of discontinuity in the weaving is expected to affect the behaviour of the samples.

Although a detailed assessment was done by conservators to distinguish slits from splits in the original tapestry weaving, for this research slits were considered the ones stitched and splits the ones that are loosed. Since fragments are historic, some of the slits were already open as stitches degraded with time and this was the main reasoning behind this consideration. This was particularly important for the DIC analysis were this division in slits and splits helps to understand the strain maps obtained.

The number of slits and splits respectively, were assessed taking into consideration sample pictures taken in a parallel direction to the sample plane. This pictures not only considered the sample area to be used in further testing but also a photo target with a measurement ruler was recorded in this pictures as can be seen in Figure 5.18. The criteria for an interruption on the weaving to be considered a slit/split was that it must have more than 2 interrupted weft threads. Figure 5.18 shows examples of slits and splits and interruptions that

![Material distribution across samples analysed](image)

**Figure 5.17** – Stacked column graph showing the material distribution of wool and silk in all samples analysed in each fragment.
were not considered in the assessment because they do not comply with the established criteria. For the assessment of slits and splits, the length of the horizontal projection was considered as the best measurement method. A virtual ruler was superposed to the pictures of the samples and used for measuring of the horizontal projection of both slits and splits, as shown in Figure 5.19.

![Figure 5.18 – Picture of sample 5 of fragment 32 recorded with the use of a photo target.](image1)

![Figure 5.19 - Picture of sample 5 of fragment 32 after being edited for slits/splits measurement.](image2)

After measuring slits and splits in each sample, the ratio for each one was calculated using the following formula:

\[ S = \frac{\Sigma W}{76} \]

In this formula, \( S \) is the slit/splits ratio, \( W \) the width of slits in mm, \( n \) is the number of slits measured and 76 is the width of each sample in mm.

All values for slits/splits ratio calculated by this method in each sample are presented in Appendix 4. The graph in Figure 5.20 shows the distribution of slits ratio across the different fragments analysed. A good distribution across samples is shown and values for slits ratio range from 0 to almost 4. Samples that show no value have no slits in their weaved structure. A slit ratio of 1 means the sum of all slit widths is the same as the width of the sample.
5.5 Condition Rating

One important characteristic that is expected to have great impact on historic tapestry’s mechanical response is the chemical and physical damage experienced in their structure. Yet, damage can be extremely difficult to classify without an in depth chemical and physical assessment. This would require a thorough study and high amount of time and resources to achieve since damage rating on tapestries based purely on scientific quantitative methods is something that has never been done before and thus there is no straight approach through metrology that can easily be applied when compared with other property assessment methods.

The assessment carried out replicate the process used in studios prior to decide on the conservation strategy. This was carried out with the support of the tapestry conservators at HCP.

Age was initially discussed as a possible indicator to assess degradation since it is known that with ageing, the change of mechanic properties is something that intensifies (Duffus, 2013). However, dating any object precisely would require chemical analysis and would be subjected to certain levels of uncertainty given the nature of tapestry manufactory and restorations processes. To illustrate this issue, a wool warp from 17th century could be dated but it could happen that this was a latter restoration addition into an earlier tapestry fragment resulting from a re-warping process that would lead into incoherent information. This classification according to age would therefore not be reliable. Moreover, there is another and more important aspect to consider which is the different rate of degradation that different tapestries are subjected to. Firstly, different materials age differently and even considering fragments made entirely of wool, they could have different dyes and mordants applied that will
change differently with time. Secondly, ageing is also related with environmental factors. Depending on its history of exposure to different environmental agent, different ageing processes will take place which ends up in a woven structure that is the result of a combination of damaging factors. As an example, a tapestry that would have been stored during centuries being exhibited only in special occasions could not be compared with another tapestry that was in permanent display and was submitted not only to environmental degradation but also to major restoration processes.

To account for damage, present in the sample areas selected for testing, resulted from years of exposure to environmental, support and storage conditions, a condition rating was defined and carried out. This condition rating has followed an approach already established by experienced conservators in the textile conservation studio of HCP and is a qualitative method where physical damage is assessed according to a set of parameters established by the conservators. It is a purely qualitative assessment in a way that no measurement of any kind is performed on the tapestry samples. However, this is also the same procedure that conservators commonly use to assess the condition of areas of tapestries to identify if they need repair and the level of repair they need.

The assessment was carried out by the conservators Emma Henni and Mika Takami in HCP science laboratory (Figure 5.21). In this assessment, 3 different parameters are evaluated, these are: condition, stability and treatment priority. All these are classified according to a scale that goes from 1 to 4 always considering 1 as the more favourable situation and 4 the least favourable as shown in Appendix 3. By following this conservation condition rating, on the first parameter, condition, the amount of damage and loss of original material is considered. Equally important is the presence of light degraded areas as well as disfiguration of the rendered image. A tapestry rated with 1 would have little or no apparent damage while a tapestry rated with 4 will have major damages presenting significant losses of original or added material. The second parameter relates with stability, where conservators after a careful examination of the material try to predict when damage is going to happen. A rating of 1 here would be the condition not expected to deteriorate within more than 10 years and a rating of 4 would be saying that the change in condition will likely to happen within 1 year. The last parameter assesses the priority that should be given to treat that object and ranges from simple monitoring and maintenance on a rating of 1 to extensive conservation due to structural vulnerability on level 4.

An overall rating for each fragment is derived by taking the average of the 3 parameters evaluated during the condition rating. In the case of a real tapestry to be conserved it is this overall rating that help conservators to decide whether the object needs only maintenance, stabilizing or full conservation treatment.
Figure 5.21 - Conservators on HCP assessing the condition of sample areas selected for testing.

All values for condition ratio assessed by this method in each sample are presented in Appendix 4. The graph in Figure 5.22 shows the distribution of condition ratio across the samples from different fragments. Although, the value of condition ratio goes from 1 to 4, the highest level of condition ratio was 3. This shows that even the samples that present more damage, with a ratio of 3, are not in a condition that present significant losses of material and extreme structural vulnerability. This could have been the case as these fragments were removed from the original tapestries for restoration purposes in the past. However, higher levels of 4 would limit the research as further tensile tests aimed to be representative of different conservation conditions that can be found in tapestries in open display. Furthermore, a good distribution exists in levels from 1 to 3 which proves there is a good range in the current set of fragments.
Figure 5.23 presents a correlation matrix that shows the correlation coefficients between different variables, and from this analysis, several properties can be assessed. According to the correlation matrix, the results show that the percentage of silk used in tapestry manufacture is moderately correlated with fineness and thickness. This is consistent with what is mentioned in the literature in Chapter 2, as silk is often used in more expensive tapestries that are finer and have more detail.

The only other moderate correlation that is shown in the matrix is related to the variables of slits and splits, which are related to the condition of the tapestry. The higher the level of splits, the higher the condition ratio, which corresponds to more damage. This seems to indicate that samples that are more damaged were more exposed to mechanical stresses, and thus stitches broke, originating splits.
Figure 5.23 - Correlation matrix showing correlation coefficients plotting different physical properties assessed.
5.6 Colour Analysis

Colour was considered a parameter for analysis. This not only this will complete the physical characterization of samples but also research a method to quantify colour as this parameter was discussed in previous research. (Bilson, Howell and Cooke, 1997). To analyse the colour of each sample the pictures taken of each testing sample were used. For colour comparison, these pictures were colour corrected by using the colour bar in the photo target as shown in Figure 5.18 which enabled to uniformize colour. This colour correction was done using a plugin developed for ImageJ (Haeghen, 2009). After colour correction, each picture was cropped using ImageJ and the colour hue was divided into 5 equal ranges as shown in Figure 5.24. The first colour range considers hue values from 0 to 37 plus the last 14 values in order to pick all the reds. The other colour ranges start from hue value 38 and each range covers 51 values. Thus, the second colour range termed in this study as yellows goes from 38 to 88 colour hue. The third range termed as greens goes from 88 to 139 colour hue. The fourth range termed as blues goes from 139 to 190. The fifth colour range termed as pinks goes from 190 to 241 The percentage of pixels that belongs to each colour range is calculated by selecting these pixels using a colour threshold on ImageJ as shown in Figure 5.25.

![Figure 5.24 – Colour parameters in ImageJ applied to sample 1 of fragment 32 used to divide the colour of each image into 5 equally spaced colour ranges.](image)

![Figure 5.25 – Colour selection on sample 1 of fragment 32 in the 3rd colour range from 88 to 139 in the hue value.](image)
The percentage of pixels that fall into each colour range defined are presented in Appendix 4 for each sample of the tested fragments. Figure 5.26 shows the distribution of these colour ranges across all the samples for each fragment. It is clear that from the percentage of pixels, the first two colour ranges, more related with red, yellow, and greens are dominant across all samples with the exception of sample 60 that has substantially more blue areas. This indicates that the fragments selected for testing are limited for complete colour comparison because they lack areas of blue and pink that are more related with colour range 4 and 5.

It is important to state that this method chosen for colour quantification aimed at creating a more quantitative approach rather than qualitative visual inspection of each sample. This however has the drawback of results extracted by splitting colour into hues not being necessarily comparable to colour of dyes used for threads. This can be observed in the different divisions of colour in Figure 5.24 as for example greens are split between the second and third divisions and yellows are all contained in the second division. However, having this in consideration this method can help to define boundaries in a colour range and calculate the percentage of pixels within a colour range. As an example sample 1 of fragment 32 in Figure 5.25 is shown in the graph of Figure 5.26 as containing a considerable amount of pixels in the second and third ranges.

![Graph showing % of pixels across different colour ranges](image)

**Figure 5.26** - % of pixels across the different colour ranges for each sample analysed in each fragment.

### 5.7 Mass Gain by Water Absorption

As explained in the methodology of section 3.4.3, 5 samples from 2 fragments of historic tapestry galloon and from 3 historic tapestry fragments were exposed to steps of 10%
RH changes in a range from 30% to 80% RH. These samples had their mass measured at each interval of RH. From the fragments considered in previous assessments, samples from fragment 33, 62 and 170 were tested as these fragments had considered dimensions to allow destructive sampling.

This physical hygroscopic property differs from the previous structural properties assessed along this chapter as it is not a structural property. Because of its destructive sampling only 3 fragments and 2 galloons were tested. Because of its character restricted to only 3 fragments used in previous structural characterization, all results are presented in this section instead of in Appendix.

Figure 5.27 shows the average value, over the five samples, of moisture content for the 2 galloons and the 3 tapestry fragments.

It is observed that all values for moisture absorption on the tapestry fragments are superior to the water absorbed by galloons. It is known that galloons are usually replaced when they became old and thus it is assumed that these galloons are less aged and damaged that tapestry samples and this behaviour has partially to do with the good conditions when compared to the aged weaving of the tapestries. The ageing of these samples usually causes fibres to become looser which in the case of wool increases the already naturally open structure.
This is what is suggested by looking at results from these tests, however in a structure that is highly heterogeneous other parameters will certainly have their influence. Differences in moisture content between tapestries seem to be associated with condition. A correlation matrix similar to Figure 5.23 was not done in this case as there are only three values for the condition variable. This does not give enough variability in the data to properly assess the strength of the relationships between the variables in this case. When comparing results from Figure 5.27 to the same samples in Figure 5.22 it is observed that condition ratio for tapestry fragments 33, 62 and 170 are 3, 2 and 1 respectively. This means that the more damaged tapestries tend to absorb less water. This suggests that as tapestries begin to lose weft threads and get more dirt in their structure, they also get more impermeable. As shown in Figure 5.17, tapestry fragment 33 also has a small percentage of silk. As silk is known to absorb less than wool, this might be another factor that justifies the lower levels of moisture content in fragment 33 when compared to the other fragments.

Both galloons had very similar behaviour in terms of moisture adsorption having galloon 2 almost always 2% of moisture content more when compared to galloon 1. At 30% relative humidity, the moisture content was 2.1% and 3.9% for galloon 1 and 2 respectively. At 80% relative humidity, values of moisture content were 7.5% and 8.4% for galloon 1 and 2 respectively. This means that considering moisture absorption to be linear, as it is suggested in Figure 5.27 for each 10% increase in relative humidity, the moisture content will increase 1%.

As for the results on tapestry samples, a non-linear behaviour is suggested by the logarithmic regression fit to the tapestry samples on Figure 5.27. All values for moisture content are higher when compared with the galloons, being their increase rate also higher. This increase has averages of 1.6%, 1.9% and 2.2% for tapestries 33, 62 and 170 respectively.

Comparing these results with a previous study (Bratasz et al., 2014) it seems that galloon samples absorb 5% less of water at 80% RH when compared with a wool fabric tested in the literature. However, at 80% RH sample 62 has a moisture content of 14.4% which is very similar to moisture content found in the literature for wool fabrics (Bratasz et al., 2014). Once again, this can be due to multiple factors but it can be verified that tapestry samples were absorbing similar amounts of water to what can be found in the literature, although samples tested in the literature were not part of an original historic tapestry.

As general conclusion for a tapestry in an environment in which RH changes from 30% to 80%, an increase in mass from 4.5% to 11% is expected. Taking this into account and considering the average weight of a tapestry considering a set of 10 tapestries as measured by Duffus in HCP to be 58Kg (Duffus, 2013), this means an increase in mass up to approximately 6.4Kg when RH changes from 30% to 80% in a wool tapestry. Considering samples from fragment 33 that is composed by a mix of wool and silk the mass increase will be around 4.6 Kg for a tapestry of 58Kg when the RH changes from 30% to 80%. Taking into account that the average area of the set measured by Duffus (Duffus, 2013) is 26 m², this results in a mass
increase of approximately 0.18 Kg per meter square. Silk weaved areas are expected to absorb less moisture due to their fibre crystallinity and high degree of orientation (Susich and Zagieboylo, 1953) as explained in 2.2.4.2 and this might explain the reason that samples from tapestry 33 always have less moisture content when compared with the other tapestries tested.

Nevertheless, results from this experiment need to be interpreted carefully, since during the experiments it was observed that samples immediately started to lose moisture during the opening of the scale chamber. Equally, moisture adsorption happened during transportation from the oven dry conditioning to the scale.

Figure 5.28 shows the average of 3 samples from galloon 2 that were tested in a first phase from 30% to 80% RH and in a second phase from 80% to 30% RH, thus testing the extent of hysteresis associated with the dynamic hygroscopic equilibrium of tapestry with the environment. It is known that a material can be in equilibrium, having different levels of moisture content given the same level of RH. This test was performed for galloon 2 only, given lab limitations since it required scale to be used continuously for a 2-day period for samples to fully reach equilibrium given the slow rate to which the humidifier was working.

It can be observed that the difference in values in average for the same level of RH was 1% higher for the case of desorption when compared to adsorption. Values in the literature (Bratasz et al., 2014) have higher differences for lower RH values. Again, these results must be interpreted with some caution because the experiments needed to be stopped during night at a RH of 80% due to lab restrictions.

![Figure 5.28 - Average value for 3 tested samples of their moisture content and their relationship with the % of RH.](image-url)
5.8 Conclusions

This chapter established the structural characterisation of the fragments and sample areas selected for further experimental testing. The methodology developed for the structural characterisation regarding thickness, fineness, material, slits and splits, condition rating and colour analysis is by itself an achievement since in the literature the heterogeneity of historic tapestries is mentioned several times but without many efforts to fully characterise this heterogeneity. Information gathered in relation to each one of the parameters assessed for sample areas and their respective fragments are given in Appendix 4.

From 33 fragments assessed, the fineness on the weft can go from 6.9 to 15 threads/cm and on the warp from 3.3 to 8.1 threads/cm being the average values 9.8 and 5.2 threads/cm on the warp and the weft respectively. In terms of thickness, the average for the same 33 fragments is 2.1 mm and the range changes from 1.2 to 2.9 mm from the finest to the thickest respectively. As an example, the sacrifice of Isaac has 8 warps per cm (Campbell, 2002), which falls on the range of the finest tapestry fragments available for testing. The condition ratio average is 2, the medium level of damage. Across the fragments conservators found some tapestries which they considered damaged while other were in good condition which makes this a good sampling for further research on them.

In terms of material percentage, samples entirely made of wool and samples entirely made of silk exist however the mixed samples usually have lower percentages of silk being the average value for silk percentage only 27%. The colour analysis also revealed that colour across most of fragments fall on the first and second colour ranges which are more related with red, yellow and green colour which can be a limitation if a comparison of breaking strength of blue areas when compared with yellow areas is carried out as it has been suggested in the literature (Bilson, Howell and Cooke, 1997).

As results of hygroscopic experiments carried out, when considering an increase in moisture from 30% to 80% RH at the temperature of 25°C the mass increase is between 8% and 11% in a historic tapestry and around 5% in a gallo. While moisture content increases linearly for the case of galloons a non-linear logarithmic increase is suggested for the case of historic tapestries.

The assessment method presented has its challenges as discussed along the current chapter. However, it focuses on a systematic quantitative assessment of structural properties that are not found in past research apart from some indications to the fineness and thickness of tapestries and samples. To have a full structural characterisation of tapestries prior to testing gives more space to critical assessment of heterogeneity in these artworks. As shown, even assumptions from the literature that thickness and fineness in tapestries share a linear relationship proved not to be necessarily true. This characterisation can then be applied to
tapestries in future research and its methods applied to other cultural heritage objects that are often very heterogenous in their structure.

This structural assessment enabled the establishment of a categorisation of physical properties that can then be compared side by side with tensile mechanics of the same samples used in further tests in Chapter 6. This enabled a process to target heterogeneity in the hope that some of the material properties assessed might answer differential mechanical behaviour within the samples tested in Chapter 7. Results form mass gain by water absorption experiments can be compared with hygroscopic experiments on Chapter 7. This enables the consideration of mass increase when tapestries are hanging in open display exposed to different levels of RH.
Chapter 6

Tensile strain characterisation in historic tapestries

6.1 Preamble

This chapter discusses the experiments carried out regarding task 3 from the methodology presented in Chapter 3. As discussed previously in section 2.7.3, past research was more focused on mechanical aspects of individual yarns and fibres, and the studies that explored the mechanics of weaved samples both using tensile testing and DIC analysis had a limited range of samples and didn’t consider a holistic assessment for the structural characterisation as performed in this study and reported in Chapter 5. Thus, the object of study in this chapter is the selection of fragments and sample areas presented on the previous chapter which aims to give a better understanding on the mechanical and hygroscopic properties of historic tapestries. With the comparison of differences in the structure of each sample, this investigation aims to verify the level of impact that structural differences have on the mechanical response of tapestries when these are on open display. This chapter also aims to identify different phases in the stress-strain curves using a quantitative approach not found in the literature. The influence in stress-strain curves that different materials and anomalies in the weft produces is also included. Consistency and inconsistency in the tensile tests is also a subject of this research.

This chapter is divided in 5 sections. Section 6.2 presents the tensile tests done on the selected samples. Section 6.3 presents the linear modulus and crimp calculations from tensile raw data presented on section 6.2. Section 6.4 discusses the results of data extracted using DIC during tensile experiments presented on chapter 6.2. Section 6.5 is a conclusion of results of this chapter.

6.2 Tensile tests Results

Tensile tests on sample areas from fragments selected for testing were carried out in the weft direction using a UTM Instron 3365 as shown in Figure 6.1. These are the same sample areas for which structural assessment was carried out as reported in Chapter 5. The interpretation of differential mechanical behaviour in the different tests relies on material properties assessed in Chapter 5.

From each fragment, 5 sample areas were tested with the exception of fragments 501 and 503 where 7 and 8 sample areas were tested respectively. Only fragments 501 and 503 were tested until failure. Figure 6.2 and Figure 6.3 show an example of a before and after tensile testing until failure of sample 7 from fragment 503.
Figure 6.1 Sample 3 of fragment 150 mounted in the Instron tensile tester.

Figure 6.2 – Sample 7 from fragment 503 prior to test.

Figure 6.3 – Sample 7 of fragment 503 being tested to failure.

Figure 6.4 shows the results of two tensile tests performed on two different sample areas of fragment 503. These two sample areas were tested until failure to determine a complete tensile test material stress curve. Both samples are very homogeneous and entirely made of wool.

As a first observation on the shape of stress-strain curves it can be seen that they follow the standard tensile behaviour that characterises other woven textiles tests found in literature (Bratasz et al., 2014). This behaviour is composed of four different stages represented in Figure 6.4 with A, B, C and D. Initially represented by A in Figure 6.4 there is a zone where the samples are adjusting to the pulling grips and that is commonly known as “slack”. In tested samples of Figure 6.4, this is a very subtle change that happens before 1 % strain and thus not very noticeable. After this primary stage, the weft threads are aligned with the pulling grip and they start to lose their crimp by becoming more and more stretched as the strain increases. This region represented by B in Figure 6.4 is characterised of being mainly curvilinear and corresponds to the transition from a relaxed into a stretched state of the weft threads. This curvilinear region is placed in the stress-strain curves between the end of the slack region up to a stage where the woven structure starts to behave in a more linear way. In the linear zone, C in Figure 6.4, the woven textile, having its weft threads under tension and without crimp, behaves as an elastic material until its weft thread structure starts to fail. On sample 8 it is noticeable a non-linear zone after this elastic region, however this is also the point where some textile fibres started to fail. This is followed by a region of sequential failure, D in Figure 6.4, of threads starting for a strain value of around18% and 20% and stress values of about 6 MPa.
and 5.5 MPa for samples 7 and 8 respectively. A picture of sample 7 taken at failure can be seen in Figure 6.3. It is important to observe that although both samples belong to the same tapestry fragment and can be considered very homogeneous in terms of material and structure, differences can be noticed when comparing their tensile curves. The stress-strain curve of sample 7 is stiffer and shows less crimp in its interweaved structure than the one of sample 8.

![Stress-strain curve](image)

**Figure 6.4 -** Tensile test of samples 7 and 8 from fragment 503 until failure showing the different regions on the stress-strain curves: A – slack, B – crimp region, C – linear region, D – sequential failure.

To take into account such variability for fragments with homogeneous structure, i.e. samples for which the weft is entirely in silk or in wool and do not present any kind of design pattern, change in colour or weaving interruptions either in the form of slits or splits, representative curves are obtained by averaging three stress strain curves obtained from testing different patches. Such average curves are shown in Figure 6.5 for 5 different tapestry fragments tested until 11% strain. This value for maximum 11% strain was chosen as a limit for all other tensile tests done. This limit was chosen based on data provided by testing until failure the two samples from fragment 503 showed on Figure 6.4. This strain value has shown to be a good value since both the crimp and elastic zones are visible in the stress-strain curve and it is also still far from failure as discussed above. Furthermore, considering the example of Elymas tapestry from the royal collection that measures around 7 m length and weighs 80 kg (Duffus, 2013), considering a thickness between 1 and 2 mm, the tapestry is still in the early stages of crimp between 1% and 2% strain when in open display. Thus, the study of crimp
region is of higher importance in this research. To visually represent the dispersion of the data around the average of tensile data, the standard deviation was included in graphs where an average value was given. Shaded areas in tensile graphs represent plus or minus the standard deviations calculated from the average. Fragment 44, 502 and 503 are homogeneous wool and, 501 and 143 are homogeneous silk. The three wool fragments, represented in blue in Figure 6.5, show remarkably little variance, when compared to the two tested areas of fragment 503 shown in Figure 6.4.

![Figure 6.5 - Average of 3 tensile tests from homogeneous wool and homogeneous silk fragments.](image)

On the other hand, for silk fragments, represented in red, the difference between them is very significant with fragment 501 being much stiffer than fragment 143. This is a very noticeable difference although these fragments have identical values of fineness at 10.8 and 10.2 threads/cm in the weft direction and thicknesses of 1.3 and 1.2 mm for fragments 143 and 501 respectively.

Although fragment 501 has a very similar behaviour to wool when compared with 143, this suggests that silk fragments have more crimp and are less stiff when compared with wool. As mentioned above in chapter 2.7.4, although for the tests of single new yarns, silk has showed to be stiffer when compared with wool these results seem to go against what is commonly observed in previous tests. Yet, this difference in stiffness between wool and silk seems to suggest that silk in the case of historic tapestries is already very degraded. As mentioned in chapter 2.4, silk in historic tapestries tend to degrade more easily and quickly than wool and in fact in many cases silk in tapestries reached to our days in a very degraded state, a fact that has been proved in previous research for single yarns of historic tapestries (Bilson, Howell and Cooke, 1997).
Figure 6.6 shows the average of 3 sample areas from 3 different fragments that are thought to belong to the same original tapestry, given the identical design pattern. It is interesting to see this variance on samples that were originally part of the same tapestry and compare them with the variance observed for the wool fragments from different tapestries in Figure 6.5. It is true all 3 fragments in Figure 6.6 seem to follow the same non-linear behaviour until approximately 4% strain. After this they start to show some variation and at 11% strain, stress ranges between 0.65 and 0.75 MPa, equalling the variability of wool fragments in Figure 6.5. This variance in the same tapestry can be explained by 3 different phenomena. First, it can be that slightly different weaving structures produce these small differences. Second, these differences might have to do with the crimp zone which seems to be longer on sample 73. Different cycles of stress-strain might have removed crimp in some areas of the weft that were more exposed to higher forces. Since top areas of tapestry have higher stresses, and fragment 71 seems to have less crimp, it is possible that this fragment was placed at higher levels in the tapestry than 72 and 73, respectively. Another factor that can explain this is that these fragments although belonging originally to the same tapestry might have experienced different damaging processes. As already mentioned in the review, they might have been used to restore other tapestries and provide support on the back of other more valuable tapestries as it was very common in the past. These might have caused them to experience different levels of strain a fact that is supported by the slightly different levels of thickness varying from 2.7 mm on fragment 71, 2.6 mm on fragment 72 and 2.5 mm on fragment 73. This very small difference, having into account that the same level of thickness should have been common throughout the all tapestry, could be a suggestion that fibre loss due to damage is slightly higher on fragment 73 followed by fragment 72. Condition ratio on these fragments is the same except for a sample on fragment 73 which conservator considered more damaged than the others as shown in Figure 5.22. However, it could have happened that these different fragments were exposed to slightly different damaging conditions. This is also supported by the fact that fragment 73 is the less stiff of all fragments followed by fragment 72. Also, it is important to consider that although for stress calculation the thickness was considered to be the same during all phases of the test, this is a simplification and thickness changes during de-crimping stage being a function of strain. The variance in stress-strain curves of Figure 6.6 from samples of the same tapestry is also justified by the subsequent calculus of the Young modulus in section 6.3 Linear modulus and crimp calculations, and shown in the Appendix 4, which supports the interpretation described in the current section.
Figure 6.6 - Average of 3 tensile tests from 3 heterogeneous wool fragments that originally seem to have belonged to the same tapestry.

Another observation that is worth to emphasise when comparing different fragments is given on Figure 6.7 and Figure 6.8. As mentioned in the previous chapter, when fragments are very small, only a sample area with or without small variations could be selected and considered for 5 or 3 repetitions, depending on the test, to produce an average stress-strain curve comparable to the others. However, little is known of the extent that tapestries can be tested without creating damage and this is something that was verified by comparing the examples of fragment 32 and 146. Figure 6.7 shows 5 tested samples from fragment 32. This is a heterogeneous wool fragment where samples 1 to 4 perfectly overlap the test area which includes splits. Sample 5 only partially overlap and includes a slit. It is noticeable that by testing this fragment repeatedly until 7% strain there is a decrease in stiffness from sample 1 to sample 4, although this does not occur for the initial 2% strain. This can be explained by repeatedly testing the same area all over again during 4 tests separated 24 hours from each other. However, as the drop in capacity is localised and the following stress-strain curve is parallel to the previous branch, this detects the opening of a split, rather than failure of weft. Similarly, in sample 5, the stitched slit occupies a great length of the sample (confirmed by its slit ratio in Appendix 4) and there is evidence that the force being applied was going to the stitches and thus what is actually being tested as a higher contribution of the stitches and not much on the weaved weft threads.

On the other hand, fragment 146, had also 5 samples over the same area, and the stress-strain curves are shown in Figure 6.8. When comparing this with fragment 32, it is noticeable that degradation by cyclic loading of the sample is not so apparent, and only the stress-strain
sample 3 seems to deviate from the others. However, the splits ratio on these samples are much lower when compared with splits ratio on samples 1 to 4 in fragment 32. This would suggest that fragments with a higher number of breaks in weave, either stitched slits or splits are more prone to concentration of load path that reduce the apparent stiffness of the weave.

Moreover, it is noticeable that fragment 32 is stiffer when compared with 146. Yet, an important observation must be done since fragment 146 is composed of wool and silk and fragment 32 is entirely made of wool the conclusion taken by analysing Figure 6.5 supports this idea.

As already mentioned, silk fragments have more crimp and are less stiff in comparison with fragments that are made of wool which tend to be stiff and have less crimp. Yet, this needs to be considered in more depth. Figure 6.9 shows tensile test average of 3 samples from each one of 33 fragments tested up to 11% strain and gives a general overview of silk samples compared with wool samples. Fragments made entirely of wool are represented in blue, yellow corresponds to fragments that have are a mix between wool and silk and in red fragment 143, the only made entirely of silk. The only 100% silk sample has indeed more crimp and less stiffness than most whole wool samples, however, some of the latter and some mix wool-silk fragments have significantly lower stiffness. Of course, many other factors will have their
influence on the behaviour of these fragments and further investigation is needed to bring some light into the structural aspects that impact tapestries tensile behaviour. Figure 6.9 also show a very substantial range of behaviours when fragments from different tapestries are tested using the same consistent procedure.

Figure 6.9 - Average of stress-strain curves from 3 tested samples on each one of the 33 fragments.

Considering only the wool fragments represented in blue in Figure 6.9 and comparing them with the colour analysis done in section 5.6 it is interesting to observe that wool fragments 44, 502 and 503 are the most stiffer and they have colour hue range 2 predominance as defined in Figure 5.26. The hue ranges as can be seen in Figure 5.24 and colour range of 2 is associated with light yellow and green colours. The other wool fragments have all a predominance of colour range 1 associated with reds and yellows. The exceptions to this are fragments 32, 130, 62, 68 that also have a predominance of a hue colour range 2. This supports the hypothesis that colour is having influence in the tensile behaviour of tapestries since most of tapestries associated with red-yellow tones proved to be less stiff when compared with tapestries that are associated with yellow-green tones. However, due to the fact that blue fragments are very scarce, a good analysis to colour influence and its comparison with the previous study (Bilson, Howell and Cooke, 1997) is not possible since blue tones are more related with the defined hue ranges 3 and 4 in Chapter 5. Notwithstanding, it is important to remark that stiffer fragments 44, 502 and 503 that have a hue colour range 2 more associated with greens are believed to be from areas in a tapestry depicting the sky. If this is true these fragments might have been blue in the past before colour fading happened which suggests that their stiffness are associated with their colour. No conclusions can be taken in relation with fragments that contain silk in the
selected fragments since almost every silk presents cream tones which is associate with hue colour range 1 as defined in section 5.6.

6.3 Linear modulus and crimp calculations

While past research described historic tapestries behaviour having a slack, crimp phase followed by an elastic zone until the sample finally breaks (Bratasz et al., 2014), more recent studies described as a highly non-linear behaviour (Alsayednoor et al., 2019) but none had sufficient analytical support to define how these structures behave and the separation between linear and non-linear phase if this is indeed happening. It is important also to understand if all tapestries behave in the same manner and if linearity and non-linearity are linked with certain structural differences such as the occurrence of slits.

Tapestries are mechanically different when compared with other textiles (Bratasz et al., 2014) and the elastic modulus can be very challenging to define. In the first place what is being tested is a composite structure and not the material itself such as the silk and wool individual threads. Also, the high level of heterogeneity that can be found on tested samples of tapestries produces a more complex situation since diverse response is observed on different areas of the same tapestry being tested. In other words, following the 3-phase behaviour for tapestries described above, this implies that, while some areas of the tapestry are already responding with the stiffness observed in the linear range, other portions could be still in the de-crimping stage. This happens as different threads have individual mechanical behaviour depending on factors such as material and condition. Therefore, it is important to quantify quantitatively the behaviour of tapestries and reach a method that will enable to characterise all tapestry samples tested using the same parameters in a systematic approach. For this, a mathematical approach was used as previously described in section 3.5.2. A region of linearity was defined if the moving average for the modulus over 15 points in consecutive intervals differed less than 1%. Breaking of yarns was defined by points where the tangent to the curve had a negative slope. The breaking of yarns is distinguished by a negative slope rather than a reduction in modulus, as a decrease in modulus can occur without the yarn breaking, whereas a negative slope has been consistently observed to correspond to a break in yarns. An example of points calculated using the method is given in Figure 6.5 and Figure 6.6. The graphs in Figure 6.5 and Figure 6.6 represent points of linearity and points where threads break for the same averages showed in Figure 6.10 and Figure 6.11 respectively. In these graphs points where linearity occur are represented with red dots and with blue dots are represented points of breaking threads.
In Figure 6.10, it can be observed that for the green curves representing wool fragments show a clearly different analysis of linearity when compared to silk fragments represented by the blue curves. Wool fragments consistently show points of linearity from 5 % strain onwards. In the silk fragments linearity do not happen as curves do not show points of linearity. However, a breaking thread is shown on fragment 143 at around 2% strain, in a fragment that do not have any stitched slits.

After analysing the data extracted, the results show that the de-crimping phase and elastic behaviour can sometimes happen simultaneously. This is believed to happen because some samples had breakage of threads while in early stages of the testing. Because threads break at early stages of testing, it can be concluded that either these are very warn out fragments that have already permanent deformations and thus lost most of their crimp or this indicates an area where stitched slits were present and thus these threads do not have crimp. However, in samples that do not have slits, the first justification seems to be the most plausible. The fact that some threads break at early stages also indicates that different threads in the same sample experience different mechanical behaviour and what is quantified in stress-strain curves is their joint contribution as an average mechanical response.

It was interesting to observe in Figure 6.11 that even fragments taken from same tapestry such is the case for fragments 71, 72 and 73 can have differences in crimp. While fragments 71 and 72 start their linear stage at approximately 7%, fragment 73 only presents some linearity at approximately 8.5% strain. This analysis made possible a more quantitative approach to crimp that was already explored above for these fragments in Figure 6.6. After analysing all samples, the values for the linear phase after de-crimping are presented in
Appendix 4, and can be observed that the modulus changes considerably from fragment to fragment with average values ranging from 29 KPa to 324 KPa for fragments 156 and 44 respectively. In some samples an initial linear phase before the de-crimping was observed. This linearity can be seen on Figure 6.10 for the wool samples represented by the green curves and the values for the respective modulus can be very low when compared to modulus calculated in the linear phase after de-crimping. As an example, 9 KPa is the average modulus for fragment 142. The de-crimping process is presented in the form of a strain value at the end of the crimp phase in Appendix 4. This enables an attribution of a crimp value for every woven sample, facilitating their subsequent analysis in conjunction with other mechanical properties.

To conclude, this calculation results from a mathematical approach that defines linearity in the stress-strain curve. This is something that was never done before for the case of tapestries. Although this results from the assumption that a change in 1% of modulus when comparing a moving average of 15 points in consecutive intervals defines linearity.

A recent research (Costantini, 2021) analysed seven different historic tapestry fragments and provided values for their Young’s modulus. While this research offers valuable information about these woven samples, direct comparisons with this work cannot be established due to considerable differences in extension rates of mechanical tests. Additionally, the method of calculating Young’s modulus used in Costantini, 2021a was the same as in previous research, offering no novelty in terms of methodology. Previous authors relied on a visual identification of the linear part of the graph and identified the slope in this region to determine the Young’s modulus. However, this project went further by creating a workflow that automatically extracted the Young’s modulus, thus avoiding human errors in identifying which areas were linear and which were not. This improved methodology provides more accurate and reliable results for the determination of Young’s modulus in historic woven samples.

All results calculated and extracted from mechanical tests are further presented in Appendix 4 for all samples tested.

Figure 6.12 shows correlation tables for calculated values of end of crimp in % of strain and linear modulus against different physical properties previously assessed. From Figure 6.12, the end of crimp does not have a significant correlation with any of the physical properties assessed. The exception is the ratio of splits with a correlation coefficient of 0.37, suggesting a weak correlation. Figure 6.12 shows that there is a moderate correlation coefficient between the linear modulus and the properties of warp fineness, thickness, and condition ratio. This shows that there is some dependence of the modulus on the condition of the tapestry, but it is important to note that a moderate correlation coefficient is not enough to draw any definitive conclusions. Furthermore, there is a strong positive correlation between the % of silk and the linear modulus, with a correlation coefficient of 0.68. This suggests that the material in the
weft of tapestries has a significant impact on the linear elasticity of tapestries when they are under an applied tension.

Tapestries are known to be very heterogeneous, meaning that they have a wide range of structural properties that can affect their mechanics. While Figure 6.12 shows that the material used in tapestries’ weft can significantly affect their elastic modulus, it is important to note that other factors such as the tapestries’ condition and the presence of splits in the weave can also have an impact in the mechanics. Therefore, it is essential to conduct a case-by-case study to determine which structural properties are most influential in a particular tapestry. To further investigate how the structure affects the strain in tapestries, the next section uses digital image correlation.

![Figure 6.12 - Correlation tables showing correlation coefficients plotting End of Crimp values extracted in % and Linear Elastic Modulus against physical properties previously assessed.](image)

### 6.4 Digital Image Correlation Results

Digital image correlation (DIC) is used to determine the deformation of each sample of each fragment as it undergoes tensile testing, as specified in section 3.6. The main objective of employing DIC to measure deformations, is to improve the understanding of the deformation that samples undergo and provide correlation between constitution and pattern of the samples and the dispersion of load-strain curves for tensile tests, reported in section 6.3.

Table 6.1 shows the strain evolution in both vertical and horizontal direction when a tensile force is applied in the vertical direction of the weft threads for sample 7 of fragment
503 in the test until failure, as shown in Figure 6.4. As a first observation, strain maps in the vertical direction are always positive in % strain and in the horizontal direction are mostly negative. This is in accordance with the Poisson effect since when there is an extension in one direction, the other tends to shrink. However, it is important to have in mind that to an extent this cannot be compared with the Poisson ratio that is commonly tested and found in other materials since in this case it is not the material being tested but the composite structure that results from the interweaving of wool threads. This is the main reason why some areas in the horizontal direction show a small expansion when vertically they are also expanding. These vertical bands of positive and negative strain were first detected in a study using newly woven tapestry samples (H. R. Williams, F. Lennard, D. Eastop, 2009). In the current research, these vertical bands were identified as undulations in the tapestry that with the vertical strain become flattened and thus constitutes an out-of-plane change. Although out-of-plane movement was identified in later stages of tensile test, a relative sliding between weft and warp threads when friction is overcome by the applied load appears to be the origin of this in early stages.
Table 6.1 – Strain evolution in the vertical direction EY and in the horizontal direction EX when a tensile vertical force is applied on sample 7 from fragment 503 until failure. Sample had a fineness of 8.2 and 6.3 threads per cm in the weft and warp respectively, a thickness of 1.6 mm, made entirely of wool, no slits or splits, a condition ratio of 1.7 and with more than 80% of pixels falling on the second range of colour hue.

<table>
<thead>
<tr>
<th>503-7</th>
<th>2 mm</th>
<th>4 mm</th>
<th>6 mm</th>
<th>10 mm</th>
<th>14 mm</th>
<th>24 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>EY</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>EX</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
<td><img src="image9.png" alt="Image" /></td>
<td><img src="image10.png" alt="Image" /></td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
</tr>
</tbody>
</table>
What is perhaps more important in the strain maps of these tests up to failure is to observe the area that failed during testing. Firstly, the area where failure occurs is the area that from the beginning of testing shows to have the highest strains in the vertical direction. The same occurs for sample 8 of the same fragment, as showed in Appendix 9, where in a test until failure, the two small areas that break show higher vertical strains in early stages. This proves the applicability of DIC to monitor tapestries, as it can give an insight on the more fragile areas of the weaving that with time will start to fail. Furthermore, the area where the sample failed is of high importance. As shown by the comparison of Figure 6.2 and Figure 6.3 the area where weft threads fail is where a slightly different weaving is present. This weaving seems to be slightly stiffer when compared to the other weaving and this shows that even in a very homogeneous fragment, the slightest difference in the weft structure can produce differential strains and thus lead to damage propagation in that area. In this case the stiffer area takes initially more load because has less crimp. Observing the evolution of vertical strain, shows that this follows a very homogeneous strain distribution with the exception for the areas where the weaving has small alterations, such as the portion that eventually fails. It is also important to consider that the DIC in use is a 2D technique and thus the analysis must be restrained to low levels of strain before the sample starts to fail since after this phase a higher amount of out-of-plane displacements is in place as Figure 6.13 shows for the latter stage of tensile testing at 24 mm extension. For sample 7 failure starts at around 15% strain as it can be observed from stress-strain curves in Figure 6.4, corresponding to around 12 mm extension. By observing the vertical and horizontal strain maps for 14 mm extension on Table 6.1, a higher amount of negative strain above 9% starts to become more evident from this extension onwards. However, this represents the out-of-plane movement when the samples are under a high amount of stress and thus gives way to a warping effect.

![3D model of sample 7 from fragment 503 during the last stage of tensile testing showing out-of-plane deformations.](image)

Figure 6.13 – 3D model of sample 7 from fragment 503 during the last stage of tensile testing showing out-of-plane deformations.
Similar conclusions to early detection of the area of failure and higher strains being present on areas of heterogeneity can be drawn for the failure test of sample 8 as presented in Appendix 9.

Table 6.2—Maps at 10% nominal strain for the vertical direction of 3 tested sample areas in each one of fragments 71, 72 and 73. Fragments made entirely of wool without slits and a very high percentage of pixels falling into the first range of the colour hue.

<table>
<thead>
<tr>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>71</td>
<td>72</td>
<td>73</td>
</tr>
</tbody>
</table>

Table 6.2 shows the vertical strain maps of tested samples from fragments 71, 72 and 73 when the nominal strain is at 10%. Values exceeding 10% are indicated in red, using the same colour as the 10% values. These are the same fragments whose tensile stress-strain curve are presented in Figure 6.6. It is noticeable that strain tends to be higher on areas where design pattern changes. These lines where high strain occur, are related to the weaving itself in particular to interruption of weft due to colour change. These interruptions cause weakness in the weaved fabric. As it can be observed all areas are very heterogeneous having almost always a cross rendered pattern that is easily identifiable as lines of higher strain in red on the strain maps. The lower zone on sample 1 of fragment 71 presents an area where the strain become more homogeneous, a feature that seems to explain, at least partially the reason why the behaviour of fragment 1 is stiffer when compared with the others in Figure 6.6. Sample 3 of fragment 72 also presents in the lower part an area which is more homogeneous when compared
to the other cross-shape patterns. However, this area is not homogeneous in strain behaviour as sample 1 of fragment 71 and this can be explained by a small area of damage that appears to cause negative strain in the lower part of this sample. By observing sample 1 of fragments 72 and 73 there are also areas of negative strain, which are more noticeable on fragment 73. These negative strains seem to be produced by relaxation of these areas. Relaxation in these areas suggest that when the sample is under extension, the sample experiences localised compression or buckling. When a tapestry sample is pulled under tension, the individual threads within the sample can buckle or deform, thus showing a negative strain under DIC. As already mentioned above for the case of fragment 503, these areas where negative strain starts to develop on the vertical strain maps are associated with out-of-plane displacements that start to appear in advanced stages of the tensile testing due to heterogeneity in the weaving.

Table 6.3 shows the vertical strain maps at 6.25% nominal strain for 5 tested samples of fragments 32 and 146, whose stress-strain curves are reported in Figure 6.7 and Figure 6.8 respectively. These strain maps provide further support to the preliminary conclusions reached by analysing the stress-strain curves of these fragments. Sample 5 of fragment 32 (see also Figure 5.18) has an important stitched slit on the lower part. This is subjected to large displacements and it can be seen already open at a strain of 6.25%. Hence the hypothesis formulated in relation to the stress-strain curves that slits and change in weft threads, are taking the majority of applied strain can be confirmed by the comparison of strain maps for the samples of fragment 32. The other hypothesis for repeated cycle behaviour on fragment 32 can also be observed by analysing the evolution of strain maps when comparing samples 1 to 4 sequentially. DIC images show that by testing the exact same area repeatedly, slits become more open each time. In particular, the slit on the upper left corner appears substantially more open in sample 3 and 4 when compared with samples 1 and 2. This opening of the slit is marked by the kink in the stress-strain curve of sample 3 at around 3% strain and at around 2% for sample 4 (Figure 6.7).

Table 6.3 – Maps at 6.25% nominal strain for the vertical direction in 5 tested sample areas in each one of fragments 32 and 146. Samples from fragment 32 contain a much higher slit ratio than samples from fragment 146.
On the other hand, samples from fragment 146 seem to have a very consistent behaviour by showing no relevant differences when comparing the same tested area of samples 1 to 5. This is confirmed by the curves in Figure 6.8. This indicates that no relaxation was caused by the sequential test of the same area for all samples in this fragment. It is worth to analyse these strain maps by comparing these with the Figure 5.4 representing the area being tested in the samples of fragment 146. Once again in this fragment it seems that areas, where there are changes in weft threads to create the design pattern, are subject to higher strains. Yet, the most remarkable area with higher strain that crosses the central area of these samples is an area where a damage by folding was present in the textile. Although not clearly seen in the images, this area had a permanent fold which does explain the reason why neutral strains appear in the middle of this zone in the strain maps and also provides a possible explanation of the generally less stiff behaviour when compared with fragment 32 when comparing the stress-strain graphs (see Figure 6.7 and Figure 6.8). If an area in the textile is damaged with a wrinkle by folding the textile weaving, this means that the textile has already a 3D out-of-plane deformation and this is what causes the line across the strain maps that seems to have very weakly positive strain. The areas in beige and yellow in this fragment shown in Figure 5.4 are all made of silk, which it is assumed to be in general less stiff when compared with wool areas as already explained above in section 6.2. Silk areas here show in general higher strains when compared to wool areas.

Table 6.4 shows the vertical and horizontal strain maps extracted from the tensile tests of different fragments at 5 mm extension which corresponds to a nominal strain of 6.25%. For each one of the fragments the sample area presented is the one which was found to be more representative of their behaviour. Samples in Table 6.4 are organised in descending order of stiffness as determined by the tensile tests in Figure 6.9. A complete comparison of the most representative samples from each one of the fragments presented in Figure 6.9 is given in appendix 10, also by descending order of stiffness.

As a first observation, it is clear that to homogeneous weaving corresponds homogeneous strain distribution. This homogeneity can be identified in fragments 502, and 170 in Table 6.4.

Similar observation can be drawn for fragments 44, 503, 501 and 143 which are the most homogeneous amongst all fragment tested. Fragment 170 shows that even in homogeneous fragments minimal change in weaving can produce higher relative displacements. In the case of fragment 44 and 170 the red lines on vertical strain represent a strain higher than 8% and correspond to the lines where weavers changed the weft thread. This discontinuity is sufficient to produce higher relative displacements. The same was verified for the case of fragment 501, however in this case the change in threads that produced higher displacements are due to change in colours/materials to produce the desired patterns. Small areas of damage on fragment 143 also show the same kind of behaviour in a fragment that is very homogeneous. For these samples to areas of high relative vertical displacement correspond
equally higher negative strains in the horizontal strain maps which correspond to contraction in this direction. Fragments 154, 158, 139, 146, 71, 72, 73, 132, 54, 156, 119 and 60 show the same behaviour of higher strains where there is a colour change as described. However, these fragments also show that for horizontal changes in threads there is no strain increase because in this case, to change colour horizontally, the weaving is not interrupted. Weft threads ran continuously from one jaw to the other in the described areas and thus no influence on strain is measured.

For fragment 154 in Table 6.4 as long as the colour change is horizontal the behaviour presents some homogeneity but when they diverge at the top, the strain is more heterogeneous. A slight degree of higher strains is also found on its silk weft structure where the yellow threads are, but this is perhaps related with these being made of silk. A similar evidence of slightly higher strain at the location of silk threads is visible for fragments 150, 146 and 33 where silk areas are found with strains higher than 6% and wool areas between 2% and 4%.

Fragment 139 in Table 6.4 also have straight lines of weft threads changing horizontally its colour as 170 but its behaviour is not as homogeneous because presents an area of damage on the upper part in the middle of the yellow line and during the condition assessment by conservators was classified with a rate of 2 which is more damaged than the rate of 1 attributed to 170. With this fragment it can be seen that damage can modify the strain behaviour on both vertical and horizontal directions of a fragment that otherwise would have had a more homogeneous strain distribution. The influence of damage was also observed on fragment 131, which is also very homogenous in its weaving without having any slit but a small damage with exposed warps in the centre right area of the sample. An area in the centre tends to show horizontal contraction when the sample is pulled vertically. A closer look to the test sample suggests that this generated by the tension being applied to the red weft threads which are continuous between the jaws of the Instron leaving the area of brown threads in the middle unstretched leading to this apparent contraction. As for the vertical direction this does not seem to have any major implication since no strain patterns in the vertical direction suggest this structural influence.

The fragments 146, 71, 73, 132, 156 119 and 60 discussed above are not governed by vertical stripes of pattern change but by changes in patterns that occur diagonally where weft threads are interrupted, and other weft threads start with a different colour. Similarly to what happens on the more homogeneous samples where there was the necessity of changing thread, these areas of change behave on the same manner. However, in these samples, because the changes are higher in number for a design pattern to be built, these colour changes which correspond to changes in weft correspond to areas where high vertical strains of more than 6% are present and thus the design of the tapestry clearly appear drawn as high strains on vertical strain maps. Fragments 150, 147, 32, 33, 72, 137, 138, 77, 130, 76, 128, 62, 68, 142 and 157 clearly have their strain defined by the heterogeneity present on their structure. This heterogeneity is reflected by higher strains where the structure presents differences and it is
more related with weft interruptions for colour change as well as the presence of slits and different materials. In these samples strain behaviour is governed by the design pattern they have which clearly shows higher strains of vertical strain map where some interruption on the weft occurs. The horizontal strain seems in general to be less affected by the heterogeneity in the structure. However, it is also on areas where there is change in the weft structure that the higher horizontal strains are concentrated. Heterogeneity in the weave of these sample are related with change in material as it can be seen on fragment 33, change in weft due to design patterns as it is for the case of 138, presence of slits as it is for fragment 130, open slits as in the example of fragment 68 and extensive areas of damage as in fragment 77.

On fragment 157 in Table 6.4, colour changes created using the hachure technique as described on chapter 2.2.2 show small gradations of brown change through its surface which correspond to changes and interruptions on the weft threads that clearly correspond to higher vertical strains on this sample. Fragment 147 in Table 6.4 is the perfect example of a fragment characterised by its slits. This fragment has a high number of slits crossing the tested sample more than once and the behaviour that results from this is a high concentration of strain around areas of slits. This suggests that what is being tested in this fragment is only the stitches rather than the weave which explains the reason why in spite of having the same material without change in design pattern its stiffness is very low in comparison with homogenous samples that doesn’t present slits.
Table 6.4 - Stain maps at 5 mm extension in the vertical direction EY and in the horizontal direction EX when a tensile vertical force is applied on tested samples.

<table>
<thead>
<tr>
<th>Test Sample</th>
<th>44-2</th>
<th>502-1</th>
<th>503-2</th>
<th>170-2</th>
<th>150-3</th>
<th>501-2</th>
<th>154-3</th>
<th>158-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strain EY</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
</tr>
<tr>
<td>Strain EX</td>
<td><img src="image9.png" alt="Image" /></td>
<td><img src="image10.png" alt="Image" /></td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
<td><img src="image13.png" alt="Image" /></td>
<td><img src="image14.png" alt="Image" /></td>
<td><img src="image15.png" alt="Image" /></td>
<td><img src="image16.png" alt="Image" /></td>
</tr>
<tr>
<td>Test Sample</td>
<td>137-3</td>
<td>138-1</td>
<td>73-1</td>
<td>132-2</td>
<td>54-2</td>
<td>156-2</td>
<td>119-4</td>
<td>77-1</td>
</tr>
<tr>
<td>-------------</td>
<td>-------</td>
<td>-------</td>
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<td>-------</td>
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<td>-------</td>
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<td>------</td>
</tr>
</tbody>
</table>
6.5 Conclusions

After extensive testing and interpretation of results, it has been shown that the consideration of the weaved structure in tapestries is crucial to understand their mechanical behaviour. This chapter has shown the successful application of a mathematical method to calculate linear modulus and crimp. The application of DIC to visualise strain maps was also shown to be important to further understand differential behaviour by comparing tensile test results with strain maps. Not only tensile test conclusions were based on strain maps extracted from DIC but also the interpretation of DIC strain maps takes into consideration the 4 distinct stages of tensile behaviour. All the assessments and experiments including structural characterization, tensile test and DIC proved to complement each other and constitutes a holistic methodology to study the mechanics of non-homegenous historic tapestries.

In terms of tensile properties of historic tapestries, it was shown that tensile behaviour proved to be similar to what was previously mentioned in literature composed of 4 stages (Bratasz et al., 2014): slack, crimp, linear and sequential failure. When compared with wool, silk fragments have more crimp and are less stiff.

Historic tapestries present differential mechanical behaviour that can be detected either in homogenous wool, silk areas or in fragments extracted from same tapestry. Differences of behaviour in homogeneous areas are greater for homogeneous silk.

Damage by cyclic fatigue was associated with areas of slits as force applied was directed at the stitches as verified in Figure 6.7 and Table 6.3. This was verified under DIC as these areas had more strain because stitched threads take initially more load as they have less crimp.

This analysis on DIC concluded some important aspects of historic tapestries when a tensile force is applied. First, it is clear that different areas of a tapestry will contribute more than others in terms of strain when a tensile force is applied. In a tapestry, areas where an interruption of any kind is detected either by damage, change in threads or presence of slits always show more relative displacement comparing with more homogeneous areas. As seen in DIC analysis, areas of weft interruption always present vertical strains higher than 6% when compared with more homogeneous areas that show in average strains between 3% and 4%. Secondly, areas of homogeneous weaving showed a respective homogeneous strain, which is the same behaviour shown by areas where colour changes horizontally. Finally, it was shown that DIC can be used to detect areas of different structural properties that present higher strains even in the early stages of tensile testing. This then gives an insight on fragile areas of the weaving that with time can lead to damage propagation.

In a larger scale tapestry, it is expected that all cases presented by Table 6.1 to be present to a greater or lesser extent. However, the structural characteristics towards the top of the tapestry are expected to produce a greater impact on strain since during hanging these areas are
supporting the weight of the areas bellow them. Also, the use of DIC in a full-scale tapestry would detect the impact produced by the galloons on a tapestry that could not be tested in the smaller fragments. The different areas in a tapestry are expected to produce differential impact on strain as suggested by the smaller scale tensile tests in this chapter. The impact on strain caused by environmental changes is expected to produce lower strain levels than tensile tests until 11% strain. The impact of environmental changes is then studied over the next chapter. This aims to explore strain levels present in tapestries in open display exposed to normal environmental fluctuations as detected in HRP.
Chapter 7

*Environmental impact on the strain of historic tapestries*

7.1 Preamble

This chapter discusses the experiments carried out regarding task 4 from the methodology presented in Chapter 3. The object of research in this chapter is the impact that environmental conditions of temperature and humidity have in a historic tapestry. The environmental impact on the strain in historic tapestries was studied through a series of hygroscopic experiments. These experiments aimed to study the levels of strain historic tapestries are subjected to in real hanging conditions. For this, a tapestry was hung inside an environmental chamber where different conditions of temperature and relative humidity were tested, and the tapestry movements quantified using DIC and the novel magnetic sensors developed by IBM as shown in section 3.7.5.

As discussed previously in section 2.7.4.2.2 DIC has been used in past research to record strain of tapestries exposed to environmental changes. Past work proved the importance that DIC can have in the study of strain in historic tapestries materials. Not only areas of higher strain could be detected since the initial stages of tensile tests as shown in Chapter 6, but also areas of differential strain in slits were detected on monitoring campaigns in the past (H. R. Williams, F. Lennard, D. Eastop, 2009 and Costantini, 2021a). It was also proven that with an increase in RH strain tends to increase (Lennard and Dulieu-Barton, 2014). Variations of 5% RH in the environment produced a variation of around 0.06% strain (H. R. Williams, F. Lennard, D. Eastop, 2009). However, past studies have several limitations to understand the nature of influence that environmental conditions have on strain in historic tapestries. While past studies do not characterise the weaved structure under analysis, it is known that historic tapestries offer high level of heterogeneity. In addition, tensile tests in Chapter 6 proved that structural heterogeneity has a great influence in mechanical behaviour of tapestries. Subsequently, very few moisture experiments exist and these study only small changes in RH levels which is limiting for the full understanding of strain variation caused by different ranges of RH and temperature. It is also important to consider that past studies only tend to look at vertical strain in the weft direction, rather than considering the bi-dimensional state of strain tapestry are subjected to.

The following experimental campaign results from two main research questions that take in consideration not only the strain quantification and study when a tapestry is exposed to different environmental conditions but also the challenges of running an experiment with a historic tapestry inside a controlled environment for the first time.

The research questions formulated are:
Is it possible to measure tapestry deformation using DIC and IBM magnetic sensors inside an environmental chamber given all experimental conditions? Can we quantify strain changes with enough precision?

How does the variation in the strain field correlates to the absorption and desorption of water vapour? How is this affected by the tapestry fabric?

The first research question aims to explore the applicability of environmental chamber testing using a full tapestry hanging conditioned to different levels of temperature and RH. This considers not only the applicability of DIC and validation of IBM magnetic sensors monitoring a historic tapestry but also the experimental conditions in terms of ventilation, light, equipment setup and calibration.

The second research question concentrates on the study of strain in historic tapestries. This aims not only to verify expansion and shrinkage processes but also to quantify strain at different levels of RH and study the tapestry behaviour. Tapestry structural heterogeneity proved to influence strain distribution on tensile tests of Chapter 6. As different textile materials have unique properties, it is important to study their effect on the strain field as tapestries absorb moisture. Equally important is to quantify the time of absorption and desorption given defined levels of RH and to investigate if the tapestry returns to the same position for tested levels of RH or if permanent deformations occur.

This chapter is divided in 3 sections. Section 7.2 presents hygroscopic results from the experiments carried out. Section 7.3 is a discussion of the experiments and conclusions of this chapter.

7.2 Experiment Results

7.2.1 Results Introduction

This section aims to discuss results in each experimental phase as described in section 3.7. Each subsection is related to a different phase of experiments as previously described in Table 3.4 in section 3.7.3. In the appendix 11 to 26 are complete graphs of measured environmental conditions, strains and displacements. The area of analysis for this section is described in detail in section 3.7.1 and illustrated in Figure 3.20.

7.2.2 Phase 1 Experiments

As explained about the experimental program in section 3.7.3, this first phase of experiments had as primary objective to test the chamber and tapestry performance for adjustments to be made prior to further experimentation. Two repetitions of each change in environmental conditions were performed to verify the performance of the tapestry in each
experiment. Figure 7.1 shows extracts of the first repetition experiments during the first 4-hour period after each change in environmental conditions started. The full experiments are shown in appendices 11, 13 and 15. Extracts of the second repetition are shown in Figure 7.2. Full experiments are shown in appendices 12, 14 and 16.

An overall look into the changes for vertical and horizontal strain as levels of moisture change, proves that these are directly correlated as a decrease in RH makes the level of strain to decrease and vice versa. This means that the tapestry absorbs moisture with an increase in RH. With moisture absorption, in the vertical direction, the tapestry gains weight and thus the strain increases making the tapestry to expand as the length of weft yarns increase. In the horizontal direction, the inverse should happen. However, this is not the case, and it can be explained due to the swelling of the fibres in the presence of moisture. When considering that the warp in the horizontal direction is made of cotton while the weft is woven with silk and wool it is suggested that the swelling for cotton has more importance than the possible contraction caused by an expansion in the vertical direction. Indeed, with moisture, as stated in section 2.2.4.3, cotton tends to swell approximately two times more than wool and silk. The inverse of this happens when tapestry releases moisture to the environment as RH decreases, since vertical and horizontal strain both decreases. In Figure 7.1 it was also shown the strain responds to any disturbance in terms of T and RH of the environmental chamber. This situation is very clear between hour 2 and 4 in Figure 7.1 A and at hour 2 in Figure 7.1 B. In both situations, there is a return to the trend when the oscillation in environmental conditions stops.

In terms of strain magnitude, vertical strain has a decrease of approximately 0.15% when RH changes from 45% to 30%. When the RH increases from 30% to 80% the increase in vertical strain is of approximately 0.45%. A decrease of approximately 0.25% is obtained after the RH decreases again from 80 to 45%. The second repetition, in Figure 7.2, shows slightly lower levels of decrease and increase in vertical strain. These levels of strain are almost always 0.05% lower than in the first cycle. In terms of horizontal strain, although the behaviour is the same as already discussed, the values for decrease and increase are lower when compared with the vertical strain. When a change from 45% to 30% RH happens, the reduction in horizontal strain is approximately 0.06% for the first repetition as shown in Figure 7.1A and of 0.02% for the second repetition in Figure 7.2A. For the increase in RH from 30% to 80% RH, horizontal strain increases approximately 0.15% in the first repetition, as shown in Figure 7.1B. With the second repetition, in Figure 7.2B, the increase in RH reaches 90% despite controls having been set at 80%. The increase in strain is of approximately 0.3% showing a non-linear behaviour for large values of RH. The decrease from 80% to 45% RH in the first repetition in Figure 7.1C produces a change of approximately 0.1%, while for the second repetition in Figure 7.2C, this change is less than 0.02%, although the initial level of RH in the second repetition was 90%.

First, it can be concluded that vertical strain is much more affected by moisture changes than horizontal strain. This is expected to happen as vertical strain has the influence of
displacements caused by fibre swelling and by weight increase due to increase in moisture content. For horizontal strain this is not the case, this direction has the impact of Poisson effect since when the vertical direction expands the horizontal direction tends to contract. However as mentioned above this suggests that the swelling of cotton warp is more important when compared to the swelling of wool and silk.

An analysis of how different materials contribute to strain changes was carried out by studying strain extracted from areas of the tapestry with different content of silk and wool as presented in section 3.7.1. The last two plots of Figure 7.1 and Figure 7.2 show strain calculated in these areas. Silk areas seem to have greater influence on strain when compared with wool areas. Indeed, across all the plots in Figure 7.1, silk areas almost always show a greater increase or decrease when compared with wool. The exception to this is the vertical strain during absorption where wool seems to play the most important role. Another observation can be drawn for the horizontal strain during desorption from 80% to 45%. Here wool seems to produce a slight increase in strain, while all other areas show a clear strain decrease.

This initial experiment with two repetitions had as primary objective the evaluation of tapestries performance during a chamber test. It is seen that the time lag for tapestries to equilibrate after the chamber starts changing environmental conditions at different levels of RH is never longer than 3 hours. With this, further experimentation could proceed considering the time of 3 hours for the strain to equilibrate after the starting of each experimental conditioning.
Figure 7.1 – Phase 1 experiments, extracts from the first repetition of the following experiments: A – Desorption from 45% to 30% RH, B – Absorption from 30% to 80%, C – Desorption from 80% to 45%.
Figure 7.2 – Phase 1 experiments, extracts from the second repetition of the following experiments: A – Desorption from 45% to 30% RH, B – Absorption from 30% to 45% and then 90%, C – Desorption from 90% to 45%.
7.2.3 Phase 2 Experiments

The second phase of experiments considers cyclic testing to understand the performance of a tapestry when exposed to continuous cycles of moisture absorption and desorption. A testing period of 4 hours at each level of conditioning of temperature and RH was considered, as shown in Figure 7.3 for the preliminary experiment for this phase.

After the preliminary experiment, tests with 4 cycles of the same environmental fluctuations were carried out and results of strain computed by the DIC as well as displacements calculated from magnetic IBM sensors can be observed in Figure 7.4. IBM sensors 77-2, 77-3 are located in areas of silk, sensors 60-3 and 60-4 are located in areas of wool and sensors 77-1, 60-2 are in mix areas. While Figure 7.4A shows the results for the cycles run at a constant temperature of 15 ℃, Figure 7.4B shows the results for the same cycles of RH fluctuation run at a constant temperature of 25℃.
Figure 7.4 – Phase 2 cyclic experiments considering stages of absorption and desorption: A – Constant temperature of 15°C, B – Constant temperature of 25°C.
In terms of the control of the environmental parameters, the temperature level remained very stable during the tests, only displaying minor disturbances when RH is subjected to change. In terms of RH however, for the first experiment at a temperature of 15°C, shown in Figure 7.4A, the lowest level the chamber could achieve was 55% RH, notwithstanding a target of minimum RH at 45% had been set. Because of this, a period of 8 hours at 55% RH was recorded (Figure 7.4A). For the case of the second experiment at 25°C T, the minimum set RH of 40% could be achieved in the first cycle. However, in the following cycles the attained minimum drifted to 45% RH as shown in Figure 7.4B. Conversely to relative humidity, absolute moisture describes the actual amount of moisture in the air regardless of the temperature or saturation level. To visualise both of these variables, absolute moisture was calculated from Equation 7.1 to better interpret and homogenise results from these two sets of cycles:

\[
\text{Absolute Moisture (grams/m}^3) = \frac{6.112 \times e^{\frac{17.67 \times T}{T+245.85}} \times rh \times 2.1674}{273.15+T}
\]

Equation 7.1

The strain computed from DIC at constant temperature of 25°C is shown in Figure 7.3B and Figure 7.4B for both preliminary and cyclic experiments. In terms of vertical strain, in Figure 7.3B, a drop of more than 0.05% when the RH changes from 45% to 30% and an increase of around 0.3% strain when the RH increases from 35% to 80% are comparable to the levels observed in phase 1 experiments. When the level of RH drops again from 80% to 45% the drop in vertical strain is of around 0.2%, also being comparable to the same levels observed in phase 1 experiments. In terms of horizontal strain, it can be observed that this is much less affected by changes in RH when compared with the vertical strain as, for example, the maximum increase in vertical strain is almost three times greater than the horizontal strain increase (see Figure 7.3B). In terms of values, an increase of around 0.2% when RH changes from 35 to 80% and a decrease of less than 0.1% when RH changes from 80 to 40% is also comparable to what was verified before in phase 1 experiments. According to Costantini, 2021a, strain values cannot be directly compared as the tests in the current project, as shown in the experiments above, were conducted under controlled conditions using an environmental chamber, ensuring that the temperature remained very stable. However, the current project has shown that there was a similar change in strain of 0.25% with an RH increased from 40% to 80% (see Figure 7.3B). This is comparable to the findings of Constantini, which showed a similar value for vertical strain increase when RH increased from 40% to 60%. It should be noted that in the research by Constantini, horizontal strains were found to have a bigger increase for a smaller change in RH levels. Nevertheless, the influence of changes in temperature for this research cannot be neglected.
Strains computed from the experiment at 15°C temperature are shown in Figure 7.4A. This experiment shows smaller strain variation when compared with experiments at 25°C. In the vertical strain, increases of approximately 0.15% were observed in all cycles when RH changed from 55% to 80%. Changes of the same magnitude but with negative sign are observed when RH returns to 55%. For the horizontal strain, the general behaviour seems to be the inverse for what is detected in the other experiments. Here an increase in moisture causes a slight decrease in horizontal strain, while a decrease in moisture slightly increases the horizontal strain. The magnitude of these changes is residual when compared to the values observed for the same levels of RH in the experiment at 25°C.

It was not possible to establish a clear correlation between different levels of moisture and their corresponding strain values as done in previous studies (Costantini, 2021). This is because the current research was conducted under more controlled conditions, where the change from one level to another of relative humidity (RH) occurred in a more abrupt manner, leading to drastic changes in strain values. If the change in RH had been more gradual over time, each point recorded would have captured an incremental increase in strain for each single level of RH, enabling the extraction of a correlation between moisture levels and strain values. Nevertheless, plotting strain values against absolute moisture and separating the data into the different cycles can enhance the understanding of the current phenomena. Changes in strain when compared with the experiment at 25°C can be explained by observing the variation in absolute moisture in both experiments. As shown in Figure 7.5, the absolute moisture increases from 7 g/m³ to around 10 g/m³ during the experiment at 15°C. The total increase in the experiment at 25°C is from around 9 g/m³ to 18 g/m³. At higher temperatures at the same levels of RH, the air contains more moisture, which makes the tapestry to absorb more water justifying the reason the cyclic experiment at 25°C presents more strain. However, the relationship between strain and absolute moisture is not linear, as it can be concluded from Figure 7.5. In the experiment at 15°C (Figure 7.5A), to a change of 3 g/m³ in absolute moisture corresponds a change of 0.15% strain. In the experiment at 25°C (Figure 7.5B), for a change in absolute moisture three times bigger, the strain change not even doubles, to only 0.25%. A possible explanation for this might be the influence that temperature have in the amount of water fabrics can absorb.

Figure 7.5 shows that for all cycles of moisture absorption in both experiments, most of the strain occurs for the initial small increase in moisture. It is shown that in all cases there is a drop in strain before the last increase in moisture. For the 25°C experiment (Figure 7.5B) the cycles increase in area, suggesting that absorption and desorption increase with cycles, while for the 15°C the inverse is observed.
One more observation can be made on the strain computed from DIC in both experiments. It became noticeable that after a first peak of strain at 4 hours’ time stamp there was a reduction of strain with time in the following 4 hours. This is more noticeable in experiment at 25°C in Figure 7.4B. In the first cycle, when the vertical strain increases after a maximum strain peak, a long-term reduction of 0.05% is observed. Although this strain peak and reduction seem to become smaller after each cycle, they are always present. The same happens for horizontal strain, yet in this case it is more attenuated. This might be attributed to the de-crimping of textile fibres. As seen in section 2.2.4 Fibre and Yarn Properties in the literature, the longitudinal swelling of textile fibres is much lower than its cross-sectional area swelling. However, it is suggested that there is an initial longitudinal swelling, along the length of the fibres and this is what is reflected in the strain peaks of DIC measurements. It is suggested that water particles, initially distributed along the longitudinal direction are then internally absorbed, occupying the intermolecular spaces along the fibres width (Saville, 1999). This increases the tapestry volume by increasing the cross-sectional area of the fibres and thus slightly reducing their length again. This phenomenon would then be related with crimp in each textile fibre.

The last 2 plots of Figure 7.4A and B show the IBM sensor measured displacements for cyclic experiments done at temperatures of both 15°C and 25°C respectively. As a first observation, all IBM sensors recorded displacements with the same behavioural patterns that can be seen in the vertical strain computed with DIC. A rise in moisture means a decrease in the distance of the magnet and receptor as tapestry expands vertically and moves downwards. The sign of IBM displacements was inverted though for consistency with DIC results. In terms of magnitude, for the experiment at 15°C, there is a change in around 0.05 mm as the levels of RH increase and decrease from 55% to 80% corresponding to an absolute moisture change from 7 g/m³ to 10.3 g/m³ respectively. As the levels of absolute moisture were higher in the
experiment at 25°C, greater displacements were recorded by the sensors. To an increase from 40% to 80% RH corresponding to 9.27 g/m$^3$ to 18.47 g/m$^3$ of absolute moisture, a movement of approximately 0.10 mm was recorded.

In both experiments, although most of the sensors tend to follow the same level of displacements, some variations could be detected. In the desorption stage on the last cycle of experiment at 15°C sensors 77-3 and 60-2 show a decrease of 0.025 mm displacement in comparison with the previous cycles. In the same cycle sensor 60-3 show a lower decrease of the same value when compared with the previous cycles. In the experiment at 25°C temperature, it is sensor 77-1 that seems to show higher displacements across all the cycles. Sensor 60-4 also shows some deviation when compared with the other sensors in the experiment at 25°C temperature. These variations in displacements do not seem to be related with material distribution across tapestry surface as the sensors indicated are from areas of wool, silk and mix. It is then suggested that these can be justified by different weave patterns and their differential displacements. However, this would need further testing on specific weaving patterns to be able to further conclude the reason for differential displacements.
Figure 7.6 – Contribution of different materials to strain: A – Experiment at constant temperature of 15°C, B – Experiment at constant temperature of 25°C.
An investigation on the influence of the material of the tapestry on the strain computed with the DIC is presented in Figure 7.6A and B for the cyclic experiments at temperature of 15°C and 25°C respectively.

The vertical strain in the experiment at 15°C temperature suggests that silk areas show different behaviour than mixed areas and areas of wool. Silk areas show slightly higher strains of more than 0.02% during absorption of moisture and less strain decrease during desorption. As wool and mixed areas decrease around 0.15% during desorption, silk decreases only approximately 0.1%. However, the same cannot be concluded for the experiment at 25°C temperature as all materials seem to have the same values of strain. For the horizontal strain, wool shows an inverse behaviour when compared to the areas of silk and mix material. When the tapestry absorbs moisture wool shows strain reduction. The opposite happens when the tapestry is under desorption. This is very clear on experiment at 25°C (Figure 7.6B) after an initial period of strain increase during absorption in the first cycle. This trend is also in the second and third cycles for experiment at 15°C showed in Figure 7.6A. Yet, the signal for strain in this experiment is very noisy when compared to the experiment at 25°C and thus the behaviour is not that evident. For both experiments, the horizontal strain of silk always shows higher increases and decreases when compared with mixed areas. Nevertheless, there is a big initial jump in silk areas for the experiment at 25°C temperature as shown in Figure 7.6B.

Experiments in Phase 1 showed that a period of 3 hours was necessary for the tapestry to equilibrate after the start of environmental conditioning in the chamber. However, a more detailed study on this was carried out to investigate the time that the tapestry takes to reach an equilibrium after the chamber stabilises at certain conditions. For this an investigation on the first three cycles for each one of phase 2 experiments was considered. Figure 7.7 shows a table with time in minutes for each variable to equilibrate after environmental conditions measured by the chamber reached an equilibrium. Each value results from an average of three, considering the first three cycles of experimentation. This investigation on the tapestry equilibrium is based on RH measured by IBM motes behind the tapestry, strain from the DIC and also the IBM sensors measurements. Conclusions for this study results from zoomed time frames of interest already presented in Figure 7.4 and Figure 7.6. A visual representation with the zoomed plot of the first cycle in each experiment is presented in Appendix 17 to 26.

According to the value of RH recorded on the mote 60 and 77 (see Figure 7.7) is possible to evaluate the buffer effect that a tapestry creates. This is based on the time lag for stabilisation of the RH measured by the motes behind the tapestry, amounting several minutes. For the experiment at 25°C temperature, the IBM motes were stabilising after approximately 50 minutes for absorption and 30 minutes for desorption. On the case of the experiment at 15°C temperature, IBM motes took around 40 minutes to equilibrate for both absorption and desorption. However, it is important to note that the largest portion of RH change in the back of the tapestry was immediate and closely followed the RH of the chamber. These values for
time lag reflect mainly residual changes in RH. Therefore the following observations on lag for the strain measurement refer to the value of RH stabilised at the chamber controls.

<table>
<thead>
<tr>
<th>Phase 2 Experiments - Constant Temperatures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature 15°C</td>
</tr>
<tr>
<td>-------------------</td>
</tr>
<tr>
<td>Absorption</td>
</tr>
<tr>
<td>RH Mote 60</td>
</tr>
<tr>
<td>RH Mote 77</td>
</tr>
<tr>
<td>Vertical Strain</td>
</tr>
<tr>
<td>Horizontal Strain</td>
</tr>
<tr>
<td>Vertical Strain - Wool</td>
</tr>
<tr>
<td>Vertical Strain - Mix</td>
</tr>
<tr>
<td>Vertical Strain - Silk</td>
</tr>
<tr>
<td>Horizontal Strain - Wool</td>
</tr>
<tr>
<td>Horizontal Strain - Mix</td>
</tr>
<tr>
<td>Horizontal Strain - Silk</td>
</tr>
<tr>
<td>Sensor 60-2</td>
</tr>
<tr>
<td>Sensor 60-3</td>
</tr>
<tr>
<td>Sensor 60-4</td>
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<tr>
<td>Sensor 77-1</td>
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<tr>
<td>Sensor 77-2</td>
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<tr>
<td>Sensor 77-3</td>
</tr>
</tbody>
</table>

Figure 7.7 - Table with time lag in minutes after RH of the chamber was stable.

On the absorption of experiment at 25°C temperature, as shown in Figure 7.7, the general vertical and horizontal strain computed from DIC shows a period of around 35 minutes to reach an equilibrium after stabilised environmental conditions. However, after this there is also a slow change in horizontal strain as there is an increase of around 0.025% in a period of around 60 minutes. This time for equilibrium in vertical strains is the same across different areas of materials. As for the horizontal strain, the different areas of materials reflect the longer time for change until equilibrium that is also observed in the general horizontal strain when compared to the vertical. As for IBM sensors, the time for equilibrium in displacement readings is variable depending on the sensors. The time for sensors 60-2, 60-3 and sensor 77-3 to equilibrate is similar to the time observed on the DIC strain. However, the time for the sensors 60-3, 77-1 and 77-2 to reach a stable value is longer and can be compared to the time for horizontal strain in areas of mix and silk to equilibrate. One possible explanation for sensors 77-1 and 77-2 to equilibrate over a longer period is the area of the tapestry where they are. This area has in general more wool content which it is known to take more water content than silk and thus takes more time to equilibrate. Yet, the same is not verified under DIC results for the wool area in the vertical direction. The reason the strain in areas of mix and silk take more time to equilibrate in the horizontal direction might be because as silk tends to absorb less water than wool. Because of this, it gives a protective layer to the cotton warp, which takes more time to reach an equilibrium.
On the desorption of experiment at 25°C temperature as shown in Figure 7.7, the general vertical and horizontal strain computed from DIC takes 53 and 43 minutes respectively to equilibrate. A similar time to equilibrium is also present for the strain of silk and mix areas. However, here in the case of desorption, wool takes more than 60 minutes before becoming stable as it releases moisture. IBM sensors 60-2 and 60-3 show a time of around 30 minutes to stabilise after the environmental conditions are in equilibrium. Sensor 60-4 shows in average a time lag of 43 minutes before reaching a stable level. Sensors from mote 77 take more than 50 minutes to equilibrate. However, similarly to the response of all other sensors, approximately 80% of their displacement occurs in the first 30 minutes. Sensors 77 that take more time to release moisture are located above sensors 60. Sensors 77 however are more related with silk areas which judging by DIC results should take less time to equilibrate. However, differences in the weave might explain this.

In Figure 7.7 DIC strain for absorption in the experiment at 15°C temperature, takes 43 and 33 minutes to reach an equilibrium for vertical and horizontal directions respectively. These times are comparable with times that different material areas take to reach an equilibrium. The time for IBM sensors to stabilise after the RH is stable also corresponds to 35 minutes for sensors from mote 60 and shorter times for sensors from mote 77.

On desorption of experiment at 15°C temperature, the strain computed with DIC takes in general almost always around 60 minutes to equilibrate after the RH value was stable. This time was the same for the different materials in the horizontal direction. Materials on the vertical direction seem to take even more time to equilibrate. In most cases, this corresponds to an increase of approximately double the time when compared to the time DIC takes to equilibrate under absorption. The same was true for IBM sensors on mote 77. However, IBM sensors 60-2 and 60-3 showed slightly shorter times when compared to absorption. In general, desorption is longer than absorption as textiles take more time to release than to absorb moisture. The fact that equilibrium under desorption in the experiment at 25°C is shorter when compared to the experiment at 15°C indicates the role that temperature has accelerating the process.
A representation of the vertical and horizontal strain maps computed with the DIC during the experiment at 25°C is shown in Figure 7.8. Here two phases are represented, one at hour 7 of experiment after the tapestry equilibrates having absorbed water at 80% RH, the equivalent to 20 g/m³ of absolute moisture. The other phase at hour 14 after the tapestry equilibrates as it loses water vapour at 40% RH, the equivalent to approximately 10 g/m³ of absolute moisture. While Figure 7.8A and B shows the vertical strain after absorption and desorption respectively, Figure 7.8C and D shows the horizontal strain also after absorption and desorption respectively. On the vertical strain in Figure 7.8A, it can be observed that strain during absorption is mostly positive, as tapestry absorbs water and elongates. On the other hand, Figure 7.8B shows the inverse as tapestry contracts with the release of moisture the strain is mostly negative. Horizontal strain on Figure 7.8D show two vertical bands of strain concentration on areas made of silk during desorption. Figure 7.8B and D show that wool tends to have different behaviour when compared to other areas as already seen in Figure 7.6. Wool shows contraction in the horizontal direction after absorption. On the other hand, wool shows expansion in horizontal direction after desorption.

As for the area of damage, this seems to produce a great impact on the horizontal strain as positive strain shows an expansion of this area and suggests a possible explanation for the vertical band shown on the horizontal map of desorption. For the case of vertical strain maps, the damage produces local negative strain when the tapestry elongates due to the water absorption (Figure 7.8A) and positive strain when the tapestry contracts due to water desorption. However, it is important to exercise caution when interpreting high strain areas, as higher strains can sometimes be erroneous. As noted in previous research applying DIC to a
tapestry image, erroneous areas of high strain were apparent in the DIC measurements (Nwanoro, Harrison and Lennard, 2022). In practice, this means that when using DIC settings, it may be difficult to distinguish between real and erroneous regions of high strain with certainty, and the results can only suggest “probable” regions of high strain.

7.2.4 Phase 3 Experiments

The previous test considered cycles of extreme RH conditions at typical indoor temperature levels, to understand the response of the tapestry over a wide range of moisture load. This section studies the performance of the tapestry in real environmental conditions. Figure 7.9 shows the simulation of conditions of temperature and RH recorded in the Great Hall of Hampton Court palace on a summer day and two consecutive winter days (Figure 7.9 A and B respectively). This figure also shows the strain computed on DIC as well as IBM sensor displacements for each experiment.

As a first observation on strain, it is evident that in these experiments the signal is rather noisy when compared with the previous experiments. This might have to do with the fact that in this case both temperature and RH were changing at lower levels. Therefore, it is suggested that there is a continuum contraction and release of the fibres which explains the noisy signal. Another more plausible explanation is that, the continuum small changes in both environmental parameters required the chamber’s controls to be constantly using ventilation for keeping conditions at the desired levels which causes relative movement on the tapestry and thus noise in signal. This phenomenon does not occur when monitoring tapestries in indoor environments, as there is no airflow to induce vibrations that can interfere with the measurements (Costantini, 2021). Despite this, the strain follows quite accurately the variation of absolute moisture in both experiments.
Figure 7.9 – Experiments simulating real conditions in Great Hall of Hampton Court Palace: A – Summer Day, B – Two consecutive Winter days.

In terms of magnitude, strain in these tests is comparable to the previous experiments already discussed. As an example, this is very evident in the simulation of winter days in Figure 7.9B, where an increase from 40% to 50% RH from hour 32 to hour 40, corresponds an increase of around 0.10% vertical strain. The corresponding change in horizontal strain is not that evident as the signal is very noisy in this direction. However, an observation on the signal for the displacements in IBM sensors is more promising than past experiments, as in here displacement mimics quite accurately the variation in RH. It is shown that for small displacements IBM is more accurate than DIC. In general terms, all sensors from IBM seem to show the same value for displacements except for sensor 60-1 that in both experiments showed relatively higher displacements in the order of 0.1 mm in the most extreme cases.
An analysis on the material influence in strain behaviour can be drawn from Figure 7.10 that shows the contribution of different materials to the overall vertical and horizontal strain.

Similarly, to what happens on the general strain for the real conditions testing, the strain in vertical direction is less noisy when compared with the horizontal strain. In these experiments on testing real internal conditions in HCP the difference in strain of different materials is very subtle when compared with results from cyclic experiments showed above in Figure 7.6. Yet these tests simulating real conditions have much less RH variation when compared with the previous tests.

With this analysis it was clear that IBM sensors can capture lower changes in the tapestry movement but not the current DIC setup. The level of noise is high and thus DIC could not capture small strain changes.

7.3 Environmental Experiments Discussion and Conclusions

The analysis of strain and displacements calculated from both DIC, and IBM sensors respectively proved that it is possible to simulate different environmental scenarios of temperature and relative humidity and measure the changes in strain of a historic tapestry. It was the first time that a complete historic tapestry was hung and conditioned inside an environmental chamber and its hygroscopic behaviour quantified under defined environmental conditions of temperature and RH. Using DIC together with IBM sensors inside an
environmental chamber posed many challenges as each system possesses its own requirements and limitations. The chamber required to be constantly running its fans that generate an air current for the chamber to operate. At the same time, the tapestry as a textile is very sensitive to air movement which limits its use using DIC. The same is true for the IBM sensor receptors as in these required to be in the same plane as the magnets. The solution for this was to use the wire system as described above on the methodology on Chapter 3.

In terms of precision DIC could measure changes in strain on the order of 0.01% and IBM sensors displacements on the order of the micrometre (Sloan et al., 2014). However, when analysing results from DIC strain during the cyclic (phase 2) and summer/winter days (phase 3) experiments, it was clear that the level of noise was different between them. This is because while simulating a continuous change in environmental conditions, as it was the case for the experiments on phase 3, the chamber needs to be continuously using its fans which interfere with the tapestry movement creating more noise on DIC data. Noise that can also be associated with a continuum contraction and release of the fibres. Notwithstanding, DIC brings the advantage of computing a full strain map of the area of analysis as shown in Figure 7.8. This strain map has the advantage of providing information about strain in damage and reinforced areas that point measurements cannot give. However, as magnetic sensors are independent of any imaging setup, assuming that there is not out-of-plane displacements, they can provide clean data even when there are small movements caused by ventilation. In real conditions, the challenge would be to keep the tapestry in the same plane. As tapestries tend to show what is known in conservation as “the drapery effect” (Reeves, 1973), the challenge for monitoring a tapestry in situ using IBM sensors would be the changes in out-of-plane created by this phenomenon. However, while past research used in situ monitoring (Khennouf et al., 2010), the approach of using DIC is not always practical in the context of museums and historic houses where minimal visual interference is required, and the camera system must be positioned at a specific distance in front of the tapestry. Also DIC requires minimal interference which might invalidate its use if visitors cause vibrations.

In relation to the tapestry behaviour when there is a change in environmental conditions, the experiments have shown that with water vapour absorption the tapestry expands and with desorption of water vapour the tapestry contracts. The rate of strain was shown to be dependent on the absolute moisture in the air at a given time. However, the results suggest that this relationship is not linear as cyclic experiments on phase 2 at 25℃ temperature showed that a decrease from 45% to 40% RH is proportionally more significant than a decrease from 80% to 45% RH. It is important to consider that two different phenomena are contributing to strain. First there is the influence of weight increase caused by water absorption which produces a force that elongates the tapestry in the hanging direction because of a tensile force. Secondly, there is the strain produced by fibre swelling due water intake. The fact that load cells were not setup because of Covid-19 pandemic created the limitation of understanding how much weight tapestries were gaining with water intake. Experiments at 25℃ have shown that strain in the
horizontal direction produced a behaviour with the same sign as the vertical, having a lower values. In Chapter 6 it was shown that as a tensile force causes expansion in the weft direction, the warp direction tends to shrink. This shows the important role that the swelling of fibres have in the horizontal strain due to the high levels of absolute moisture in experiments at 25 °C when compared to the experiment at 15°C. Indeed, in the experiment at 15°C lower levels of absolute moisture, produced less cotton swelling in the horizontal direction and this is the reason why the behaviour of horizontal strain was the opposite compared to the experiment at 25°C. The reason why vertical strain was always higher in values than horizontal strain was due to the strong component of weight increase. This analysis also reflects the high levels of cotton swelling in the warp direction and different materials hygroscopic properties, as mentioned in section 2.2.4.

Considering experiments on phase 3 with the simulation of winter and summer days, it was shown that in real conditions, the changes in RH are more modest than the ones simulated during cycles on phase 2 experiments. Consequently, the strain changes are reduced when compared to extreme changes simulated during cyclic experiments. Notwithstanding, as it was observed during cyclic experiments, a small change in lower levels of RH can still cause noticeable effects on the strain as suggested by the vertical strain increase during the simulation of the winter days.

In terms of materials, the cyclic experiment at 15°C temperature in Figure 7.6 suggested that silk areas take a higher amount of vertical strain when compared with wool. Considering only the weight component of strain, it is understandable that silk presents more strain than wool in the vertical direction. As it was explained before in Chapter 2 and verified by the tensile tests Chapter 6, silk is more sensitive to damage than wool and thus is usually less stiff after ageing. If silk areas are less stiff, these take more strain as same force will produce higher displacements. This same phenomenon is suggested by the vertical strain map after adsorption in Figure 7.8 A as silk sky area takes more strain when compared, for example, with area of wool in the lower right corner where trees are depicted. However, the same was not evident when considering the plots for each material area in the experiment at 25°C shown in Figure 7.6. This can be explained by the fact that here the swelling of the fibres has a more important role due to the higher level of absolute moisture. It is known from the literature in Chapter 2 that textile fibres reduce their young modulus when exposed to moisture. Liquid water makes the strength at break to decrease by 80% and 60% for new silk and wool respectively, while extensibility increases. Water vapour is also known to decrease the Young modulus in Antheraea Pernyi species of silk, particularly after the transition point that in silk happens at 25°C and 70% RH (Fu, Porter and Shao, 2009). With this, it is suggested that changes at higher RH levels would cause more impact on the strain than lower levels. However, the experiments seem to suggest the opposite, especially by observing the strain variation from 45% to 40% on the cyclic experiment at 25°C temperature. This suggests that at lower RH levels, the hygral contraction phenomenon has a higher contribution than at higher levels. If this is the case hygral
contraction seems to have a more important effect on strain than weight increase. However, further tests would be needed to deepen the study of the two components contributing to strain or at least a complementary study done on weight increase in tapestry materials.

Also important of note is the fact that cyclic experiments suggest that the tapestry returns to the initial position after desorption. If this is true, no permanent deformation is occurring as the tapestry absorbs moisture at 80% RH in both experiments at 15°C and 25°C. However, is important to consider that inside the range of historic tapestries, this is a relatively new tapestry from the 19th century. Also, excluding the damage area detected on the silk, the tapestry is in fairly good condition. In this tapestry, even silk which is known to be chemically unstable (Graaff and Boersma, 1997) presented a good conservation state on visual inspection when compared to other tapestries. These hygroscopic experiments never reached higher levels of strain, such as 11% as discussed previously in Chapter 6 when assessing load cycles during tensile testing. If an aged medieval tapestry was considered for environmental conditioning, perhaps results would differ, and this is something to be considered in future research. It would also be important to run similar cyclic experiments considering a higher number of cycles to further study permanent deformations.

Considering the general vertical and horizontal directions, on both experiments in Figure 7.7 it was shown that the time for the tapestry to reach an equilibrium during desorption was longer than during absorption by a ratio of approximately 1.5. This means that the tapestry takes 50% more the time to release water from its fibres by drying than to absorb. For the case of experiment at 25°C temperature, considering the vertical direction, the difference between both phenomena was of 21 minutes more, while on the experiment at 15°C this difference was 19 minutes more. However, in the experiment at 15°C the time the tapestry took to equilibrate at certain selected areas was longer. It is interesting this is the result because on the experiment at 25°C temperature, the absolute moisture was higher when compared with the experiment at 15°C. Despite more moisture being absorbed by the tapestry in the experiment at 25°C, it is known that higher temperatures speed up the time of drying textiles.

Experiment at 25°C showed that wool takes more time to reach an equilibrium during desorption when compared with silk. This seems to be related with the fact that wool fibres are crimped and have a more amorphous structure able to hold more quantities of water, as explained on the review in Chapter 2.

When studying the time to reach an equilibrium, it is important to consider that a microclimate on the back side of the tapestries might be influential. A closer observation of Figure 7.7 show that sensors from IBM register a delayed stabilisation of RH in comparison with the chamber sensor. This suggests that a microclimate exists behind tapestries. The results showed RH levels measured by the motes placed in the back of the tapestry took more time to stabilise when reaching an equilibrium. This was more noticeable during the absorption in the experiment at 25°C where a lag of more than 50 minutes was identified as showed on the Figure
7.7. Yet, as mentioned above, this delay in time is to a residual change in RH. However, the fact that the chamber was with ventilation continuously running and that the frame structure was very open suggests that this differential microclimate effect is stronger when tapestries are hanging on open display attached to a wall. More studies are needed to understand relationship of microclimate and buffer effect, especially in tapestries where two protective layers of fabric exist mentioned in the survey of Chapter 4 and referred in literature as lining and dust cover in Chapter 2. These layers have different levels of fineness than the tapestry and are generally made of different materials which adds to the complexity of the hygroscopic studies in tapestries.

As for the strain maps on Figure 7.8, it is important to note that a much larger section of a tapestry was under analysis when compared to the strain maps obtained on the tensile tests on Chapter 6. However, despite less detail and precision in the strain maps obtained in the hygroscopic tests, some considerations must be drawn. First, the presence of diversified number of characteristics such as damage, slits, mix of materials are present in the tapestry used for hygroscopic experiments to a less or higher extent. In both horizontal strain maps on absorption desorption in Figure 7.8 C and D respectively, the vertical strain bands previously detected in past experiments until failure in chapter 6 were again quite evident. In this case the vertical bands of high horizontal strains seem to coincide with the vertical areas of alignment where the sensors are placed and with the area of damage as showed on Figure 7.8. In the vertical strain in Figure 7.8, the same zones related with the sensors and damage areas presented a difference in concentration of strain. Areas where IBM sensors are placed show higher positive and negative strain which seems to be associated with the local small reinforcement these sensors produce.

Due to lack of material to absorb and desorb water, the damage area produces negative strains after water adsorption, as shown in Figure 7.8A, and positive strains after water desorption as shown in Figure 7.8B.

The vertical strain maps from the tensile experiment until failure in chapter 6 also proved that areas with initial higher strain were the first to fail. If the same can be applied in the current experiment, for the vertical strain in Figure 7.8 A, after excluding areas of abnormal strain because of IBM sensors and Damage, there are some important high strains in the upper left corner of the section considered for analysis. Comparing these with the tapestry characterisation done in Figure 3.20 of Chapter 3, the areas showing higher vertical strain in the upper left of Figure 7.8 A are related with areas where the weave presents change in material and presents slits. Thus, there is the suggestion that these correspond to the most fragile areas in the tapestry’s area of analysis, and they would be the first to fail if tensile test until failure was performed. Observations on the strain maps of tensile tests in tapestry fragments in Chapter 6, proved that, in homogeneous areas, strain was homogeneous. Areas where there were slits or a change in pattern or material, the weft interruption in the weave caused sufficient local weakness for the strain to be concentrated in these areas. In the hygroscopic environmental
experiments, the strain maps showed a similar behaviour for areas of silk, as these very homogeneous proved to have homogenous strain distribution. Wool and mixed areas, where more changes in weave were mapped, showed a more heterogeneous strain distribution.

To summarise in conclusion:

• It was proved that both DIC and IBM sensors can be used inside an environmental chamber to measure strain and punctual deformations in a tapestry structure. Although both systems complemented each other, considering in situ experiments the requirements of each one of these equipment systems need to be considered. Also, IBM proved to be more suitable to low changes in RH when compared to DIC that produced more noisy results.

• Areas of high strain concentration were successfully mapped using DIC processing.

• The results suggest that strain in tapestries quickly adapts and equilibrates to the changes in the environment. This means that tapestries quickly absorb and release water vapour, changing and reaching a weight equilibrium to any fluctuation in RH.

• Desorption takes more time than adsorption and this is dependent on the temperature to which tapestries are exposed. Higher temperatures accelerate the time for desorption to take place.

• The absorption phase corresponds to an expansion recorded by positive strains while the desorption phase corresponds to a shrinking reflected by the negative strains. The absorption phase is faster than the desorption phase by a ratio of 1.5.

• In the absorption phase, after an initial strain increase, there is a small strain reduction in time which is suggested to be related to the crimped threads. Experiments indicate that tapestries expand after a longitudinal swelling of the textile fibres. Water particles are then internally absorbed occupying the intermolecular spaces of the fibres and thus increasing the cross-sectional area of the fibres. This consequently makes the tapestry to contract.

• It is seen that wool and silk have substantially different behaviour as far as horizontal strains are concerned. Therefore, the overall strain distribution on a tapestry surface will be highly influenced by the material distribution and mix.

• Homogeneous areas in terms of weave and materials showed more homogeneous behaviour when compared with areas of structural heterogeneity.

• In open display conditions, it is expected that a microclimate in the space between the tapestry and the wall exists. This microclimate reflects the buffer effect that tapestries produce. Experiments proved that even in a high ventilated open space,
the environment in the area behind the tapestry, takes more time to equilibrate than the environment in front of the tapestry.
Chapter 8

General Discussion and Conclusions

8.1 Main Achievements

Previous chapters discussed and concluded each single task of the methodology presented in Chapter 3. It is then worth to go back to the initial research questions formulated in Chapter 1 and summarise results and conclusions obtained in the several stages of this research. The research questions that this research considered were:

1. What is the relationship between the environmental changes in humidity and temperature and strain in historic tapestries?

2. What are the most appropriate analytical techniques to study this relationship?

3. Can environmental simulations inform the optimum environmental conditions for the protection of historic tapestries?

4. How can laboratory experiments inform current tapestry conservation methods, such as structural conservation stitching and lining?

The relationship between environmental changes and strain has been studied in Chapter 7. It was shown that the changing environmental conditions produce strain changes in historic tapestries. While an increase in moisture causes the tapestry to expand, a decrease causes a contraction. This phenomenon proved to be more evident in the vertical direction rather than the horizontal. It is suggested that when tapestries absorb moisture, after an initial vertical expansion, there is a small contraction in time. It is suggested that crimp in tapestry fibres explain this phenomenon. Tapestries have an initial expansion after longitudinal swelling of fibres that is reflected in the vertical direction. After this, in time water particles migrate to the intermolecular spaces in the crimped fibres resulting in an increase of their cross-sectional area. This, in turns, causes a small contraction in the vertical direction. It is important to note that this particular phenomenon has been detected for the first time using an environmental chamber, as previous research studies have typically relied on in-situ monitoring (Khennouf et al., 2010 and Costantini, 2021). The use of an environmental chamber allows for precise control over temperature and relative humidity levels in a stable environment over time, which provides an accurate representation of the phenomenon, detectable by DIC. This level of control is not always possible in natural settings, which made the environmental chamber an invaluable tool to quantify the extent of this phenomenon, across the range of environmental conditions considered.

In terms of magnitude, the maximum vertical strain increase verified on the experiments in Chapter 7 was of approximately 0.3% when the tapestry was exposed to a change from 40%
to 80% RH at a temperature of 25°C. A value that is reduced to half if considering a change from 55% to 80% RH at a temperature of 15°C as verified in the hygroscopic experiments of Chapter 7. The highest displacement recorded by IBM sensors was around 0.2 mm. This is in the same order of magnitude of what has been verified in monitoring tapestries at HCP (Frame et al., 2018). As seen in Figure 2.14, the monitoring of a tapestry from the series of Abraham in HCP was showing a change of 6.5 mm when the RH changed from around 35% to 67% at a temperature averaging 20°C. However, it is important to note that while in HCP monitoring, a laser was measuring changes in the bottom part of a tapestry (Frame et al., 2018), in the hygroscopic experiments of Chapter 7 the strain was measured on the middle section of a much smaller tapestry. As tapestry from the series of Abraham measures an average height of 5 meters (Royal Collection Trust, 2019) it is expected to proportionally have more displacements than a tapestry that has a height of 1.58 meters. Yet, the physical assessment of tapestries in Chapter 3, proved that tapestries are very heterogeneous structures which suggest differential hygroscopic behaviour when comparing different tapestries. Moreover, tapestries from the Abraham series belong to a 16th century set and thus were already subjected to numerous conservation changes throughout their history, as discussed in the literature and during the conservation strategies survey in Chapter 2 and Chapter 4, respectively.

The hygroscopic experiments in Chapter 7 showed that the time lag for the tapestry to equilibrate to a given environmental change is not uniform across the tapestry surface. It is clear that experiments of Chapter 7 proved the time lag for desorption to be higher than the time lag during adsorption by a ratio of 1.5. Experiments at 25°C temperature where the absolute moisture was higher showed differential times for wool areas to reach an equilibrium during desorption when compared with silk or areas of mix.

The magnitude of strain changes is dependent on the moisture absorbed and can be divided into two different components: strain caused by hygral expansion and strain caused by weight increase. As an example, taking into account tensile characterisation across 33 historic tapestry fragments presented in Chapter 6 in Figure 6.9, and comparing results with strain and mass changes obtained during hygroscopic experiments in Chapter 7 and Chapter 5, an interpretation on the origin of this strain can be drawn.

Considering the results in section 5.7 for mass gain experiments, it is shown that an increase from 45% to 80% RH can cause a change in moisture content of approximately 4% to 8% in fragments 33 and 170, respectively. As the tapestry tested in Chapter 7 has a weight of 1.37 kg at 45% RH and 25°C temperature, this means an increase in mass of around 0.05 Kg to 0.11 Kg.

Considering this tapestry has a width of 1.02 meters and a thickness of 1.9 mm, its cross-sectional area is $19.38 \times 10^{-4}$ m$^2$, the tapestry weight at 45% RH and 25°C temperature produces a force of 706.9 Kg/m$^2$. Considering an increase of 0.11 kg when the tapestry absorbs moisture at 80% RH, this means a force increase to 763.7 Kg/m$^2$. Converting this to Pa,
multiplying by 9.81, the differences between 45% and 80% RH are 6935 Pa and 7492 Pa. A change from approximately 6.9 Kpa to 7.5 Kpa can be compared to the tensile test results in Figure 6.9 of Chapter 6 for the 33 fragments tested. Figure 8.1 shows a zoom in a region of interest from the stress-strain results in tensile tests discussed in relation to Figure 6.9 in Chapter 6. From these stress-strain curves, the difference in strain when the stress increases from 6.9 Kpa to 7.5 Kpa was calculated. The average difference in strain was of 0.020% with a minimum strain of 0.003% verified in fragment 502 and a maximum of 0.104% verified in fragment 157. This strain values can then be compared to the values obtained during the hygroscopic experiments reported in Chapter 7. In the experiment at 25°C temperature, an increase in the vertical strain of approximately 0.3% was shown when the RH changed from 40% to 80%. Taking into account all previous calculations for the average strain due to weight increase being 0.020%, there is the suggestion that tensile force cause by weight increase only has a small contribution to strain, in this case of 6.7%. The contribution to vertical strain from the swelling of the fibres would then be 93.3%. However, considering the highest strain value of 0.104% for fragment 157, this contribution can be up to 35%. This example should be taken with caution as the stress-strain curves shown in Figure 8.1 are still in the early ranges of strain corresponding to the transition between the slack and crimp phase as discussed in Chapter 6 and shown in Figure 6.4. Yet, this example can give an idea of the strain impact that moisture and changing loads cause in a tapestry.
This research also envisioned to investigate the most appropriate techniques to study the relationship between strain and environmental conditions. Chapter 3 described the methodology developed to interpret mechanical and hygroscopic tests. In Chapter 5, a quantitative method to evaluate the structure of a tapestry was developed. Chapter 6 managed to evaluate the tensile strain of historic tapestries using an UTM complemented with DIC. Chapter 7 tested a full historic tapestry inside a controlled environmental chamber using both DIC and IBM displacement sensors.

Each technique explored in this research had its advantages and challenges. The methodology developed in Chapter 3 could have been more complete as a set of load cells were planned to be used in the tapestry tested in the hygroscopic tests of Chapter 7. This was not carried out due to lab closures during the Covid-19 pandemic. Yet, it presents a holistic methodology that considers the use of multiple techniques to extract conclusions from experiments carried out.

A complete physical and structural characterisation presented in Chapter 5 proved crucial to interpret experimental results. As historic tapestries are extremely heterogeneous, it is important to first understand their structure to further interrogate their strain changes. This
is one of the main outcomes of this thesis, as it goes beyond qualitative approaches taken in the past.

Results from physical and structural characterisation were used to interpret results of Chapter 6. The application of DIC together with tensile testing has proved important for interpretation of results. The holistic approach of considering both methods and interpreting results in the light of the different structural features explained the dispersion of stress-strain curves of different tested fragments, changes after cyclic testing, strain distribution and location of breaking points in the weave.

A mathematical approach to calculate crimp and linear modulus was applied to different samples. However, as described in 3.5.2, the definition of the different stress-strain phases and areas of linearity is based in the assumption that a region of linearity is defined when the error in the moving average for the modulus over 15 points in consecutive intervals was less than 1%. Changing the number of points or the tolerance value and results would be different. Notwithstanding, this is still considered better than a purely qualitative approach and future research can apply the same calculations with consistency.

In the hygroscopic tests of Chapter 7, DIC and IBM sensors proved to complement each other. In situ application of these techniques will have its challenges. For the application of DIC, it is required that a camera stand is placed in front of a tapestry. To small changes in environmental conditions, typical of indoor environments, this technique might produce a considerable amount of noise and thus conclusions should be taken with caution. As for IBM sensors, their application proved to be more suitable for small changes in the environment that consequently produce low strain response. However, these sensors require that the tapestry does not present a large amount of out-of-plane displacements, as this would stop readings given the characteristics of this monitoring system. Furthermore, DIC can provide a full strain map of a selected area, while sensors only provide specific point measurements. DIC is dependent on imaging conditions, such as light, lenses, and distance from the tapestry surface. One system cannot replace the other, but both should be used considering their advantages and limitations.

To determine the optimum environmental conditions for the protection of tapestries, it is implied further research in hygroscopy that considers a whole range of historic tapestries. Future research might consider repeating the methodology applied in Chapter 7 for a significant range of historic tapestries and analysing their strain behaviour. Not only can this bring a new light into the diverging results for a range of historic tapestries, but also a new understanding of structural properties that influence hygroscopic behaviour. Similarly to what was done in this thesis in Chapter 6 for different results of stress-strain curves, the same could be done for different hygroscopic behaviour comparing results with a full physical and structural assessment of the tapestries as developed along Chapter 5.
Notwithstanding, to answer the third research question, Chapter 7 proved that environmental simulations can inform on best practices to protect historic tapestries. To avoid strain, lower temperatures are desirable when compared to higher temperatures. Hygroscopic tests in Chapter 7 have shown that lower strains are associated with lower temperatures. As for the same RH, there is a lower level of absolute moisture in the air. Changes of RH in lower temperatures make tapestries to absorb and desorb less amount of water particles and thus limits changes in strain. Nevertheless, it was also shown that strain has a non-linear relationship to the absolute moisture in the air. Lower increments in RH at lower levels of 40% to 50% RH, seem to have more impact on strain than proportionally higher levels. It is then important to limit changes in RH even at lower levels if strain levels are meant to be kept low.

The amount of strain desirable in a tapestry depends also on the type of conservation methods and the amount of restraint these treatments bring to the tapestry.

Chapter 4 shown that the use of patches to reinforce areas of damage is a very popular alternative to straps in conservation. Tensile tests in Chapter 6 proved that any difference in the weave produces a differential strain in the woven fabric. Areas of stitched slits have shown more strain when a tensile force is applied. It is then expected that stitches used to attach patches will produce non-uniform strain across a tapestry.

In clear opposition to what was initially thought, reweaving areas of loss is still a method currently in use outside UK. This method is expected to consolidate the fabric as it replicates the area that has been lost. However, the behaviour of historic and new material together in the same woven section is something worth to investigate in future research. It is known that new material is going to show different behaviour. Yet, the extent of differential strain this produces is unknown.

As seen in Chapter 4, the use of support fabric introduces a new fabric, usually linen or cotton, in the back of a tapestry. This produces an increase in weight and the interaction between this support fabric and the tapestry is not fully understood. However, conservators generally use an excess fabric to allow tapestry to move without being restrained if this fabric experiences differential strain when compared to the historic weave.

As presented in Chapter 4, from the conservators that consider excess fabric to let the tapestry to expand, most conservators use 0.8 cm per each 20 cm. Some conservators mentioned even a lower excess of 0.7 cm per each 20 cm. Considering the strain measured in the tapestry tested in Chapter 7, some conclusions can be drawn. The maximum vertical displacement measured by IBM sensors in the tapestry tested from 40% to 80% RH at a temperature of 25°C, was around 0.2 mm. Assuming sensor 60-2 was at a distance of around 70 cm from the Velcro hanging in the tapestry’s top, this represents a movement of 0.06 mm per each 20 cm. The excess fabric considered by conservators is more than enough, even in an extreme example. However, excess fabric is not considered in Germany. This shows tapestries might experience differential strain compared to the support fabric. It is expected points of
concentrated strain where the fabric attaches to the historic weave as it was observed for stitched slits in tensile tests of Chapter 6.

Changes in conservation practice were also stated in the survey of Chapter 4. When compared to a survey carried out 20 years ago (Breeze, 2000), a shift in conservation practice was shown in Canada towards full support instead of the use of straps. The current survey also shown that conservators consider more excess fabric to allow tapestries to have more freedom of movement than when compared to a survey run 10 years ago (Duffus et al., 2012). This is seen as a positive change, as considering Chapter 6, it is suggested that areas of high strain concentration because of heterogeneity or restricted weave are being avoided. However, experimentation of new techniques where conservators apply conservation stitches in the weft rather than in the warp is worrying. Not only weft threads are part of the tapestry image, but are also structurally weaker when compared to the warp. As seen in the review of Chapter 2 and quantified in Chapter 5, weft presents slits, splits, changes in colour, weave and materials that originate points of high strain as shown in tensile testing of Chapter 6.

8.2 Relevance to Conservation

This project has significant relevance to conservation as it provides important insights into the behaviour and degradation of tapestries when exposed to environmental changes and strain. The research outcomes directly apply to tapestry conservation practices and data gathered from experimental results can inform the development of environmental standards and mitigation measures to manage the associated risks.

The methodologies developed in this research allow for a better understanding of how tapestries with different structural properties behave when in open display, supporting their weight and exposed to indoor environmental changes. This understanding is critical to maintaining the structural integrity of tapestries and ensuring their longevity. The research also highlights the need to allow excess fabric for the support of tapestries to prevent excessive strain that can cause further degradation.

The survey conducted as part of this project provides valuable information on the current conservation practices deployed across the globe, identifying common practices and deviations in the methods used to provide structural support to historic tapestries. This information can be used to further develop best practices for tapestry conservation that are effective across different regions and conservation schools. The comparison of this survey with two past surveys on the same topic, one covering only North America (Breeze, 2000) and the other not specifying regional areas (Duffus et al., 2012), further strengthens the relevance of this project by providing a comprehensive overview of the conservation practices used across the globe. This research can further assist conservators in evaluating differences and identifying...
the most effective conservation practices which ultimately can lead to standardising conservation protocols to preserve tapestry collections.

The findings of this project can be generalized to large tapestries, in the care of the Historic Royal Palaces collection, as the principles of tapestry structure remain the same regardless of the size of the tapestry. As shown in this project, strain behaviour might differ because of several factors as it is the case of damage which might be difficult to identify. However, if larger tapestries are characterised according to the method developed in this project to identify their unique structural properties, comparisons to similar fragments can be made. By following the method developed in this project and exercising caution when comparing tapestries, conservation practitioners can better understand the structural behaviour of larger tapestries and develop effective preservation strategies.

While the specific results may vary for different tapestries, the methodologies and insights gained from this research can apply to other tapestry collections and provide valuable information for conservation practices.

8.3 Future research recommendations

As research in heritage science continues to expand, it is important to identify areas that require further investigation. By identifying the gaps in the current research, future researchers can focus their efforts on developing innovative approaches to address these gaps. In this way, the following recommendations serve as a guide for future heritage science researchers or using similar tools.

First, tests considering different conservation approaches can be conducted in future research to evaluate mechanical behaviour of different conservation methods. If tapestry samples and conservation interventions are tensile tested following the methods used in Chapter 6, results can be interrogated in the light of physical and structural characterisation as established in Chapter 5. A definite answer to the performance of conservation methods and their impact on tensile strain can then be established.

Although the environmental experiments provided a first test on a full historic tapestry inside an environmental chamber, future research would bring new understanding on the different conservation methods explored on the survey of Chapter 4. The tapestry tested was a 19th century tapestry that has never been conserved. To have this tapestry conserved by repairing the damages and attaching a support fabric would inform on the conservation impact on strain by comparing with results obtained in current research. Moreover, the testing of a significant range of historic tapestries as it was done with the fragments in Chapter 6 would provide better conclusions on the different hygroscopic behaviours across tapestries with different structural features and conservation methods applied. Several questions remain to be answered on how conservation interventions affect the strain behaviour when tapestries are
hanging on open display. Further investigation on the role of galloons, backing support, dust covers, different stitching and materials in use by conservators is needed to acquire a better understanding of the impact of conservation.

Similarly to other literature studies in section 2.7.4.3, future research might also consider the development of a more accurate FEM model of a tapestry on open display. Past studies did not have available a good input dataset of mechanical properties of historic tapestry materials. Thus, several assumptions about tapestry mechanics were made to model and simulate historic tapestries. The current research provides a new dataset with a detailed physical, structural and mechanical characterisation of several samples across 33 fragments tested, and establish the correlation among these parameters. Strain maps extracted from DIC can be used for calibration of a FEM model and thus contribute to the development of a more accurate method for modelling tapestries. If the same methodology of structural characterisation and testing developed along Chapter 5 and Chapter 6 is applied to different conservation methods, a simulation of a whole scale tapestry with different conservation methods can then be produced and further interrogated.
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Appendix 1 – Literature Review on the History of Tapestry

1.1 Introduction

This section presents a brief description of the history of tapestry making, its use and evolutionary artistic progress in the history of art. Because tapestries are above everything, important artworks, their history in the context of art is their most studied field that can be found in the literature. History of tapestry is then presented with special regards to medieval era, renaissance, baroque, 19th century and onwards always considering the importance tapestries played in European society and the value which they were attributed through time. Tapestries in the broader sense are part of an international culture of weaving and although they have an important role in many world cultures such is the case of kesi textiles in China, kelim rugs in Middle East and Navajo weavings in America, these examples are not considered in this brief description since the focus of this project is in European tapestries. The history of European tapestry is then discussed by framing this topic with the influences that gave origin to this art, the golden age of tapestry that goes from medieval to baroque period and then the most recent examples of this art from 19th century onwards.

1.2 Prehistory and Antiquity

As part of human cultural heritage, weaving is one of the earliest primitive arts and its history was defined by the use of natural raw materials such as wool, silk, flax and cotton (Taylor, 1990). Because of the availability of these materials together with the human need to produce textiles, it is believed that since an early stage of civilization the weaving of tapestries existed. Weft plain weave is the most simple weave and it thought that earliest humans have evolved the weft plain weave to tapestry technique with interruption of weft threads in order to produce textiles with different patterns as early as the first wall paintings start to appear during pre-history (Baumgarten, 1897).

Tapestries are very fragile compared with other objects made with more durable materials and because of this the most ancient works were lost and only fragmentary tapestries from Egypt or Roman Coptic period survived and reached our age. Notwithstanding, there is some knowledge related with ancient tapestry production that resulted from archaeology. In Egypt for example the tomb of Khnumhotep II at Beni Hasan cemetery from the 20th century BC depicts women weaving in an upright loom which had already the elements that can be commonly found on the current high warp looms (Baumgarten, 1897). However, apart from some fragments found on the tombs of Thutmosis IV and Tutankhamun there is scant information from tapestries in ancient Egypt (Weigert, 1962).

The Roman author Pliny wrote about the importance that Babylon played in ancient times regarding the weaving of tapestries making this artworks in vogue during ancient times
Tapestries in Babylon acquired such an importance in terms of quality due to colour blending and quality of materials employed that in antiquity tapestries acquired the name of “Babylonians” (Baumgarten, 1897). Tapestries from Nineveh and Babylon acquired such an important status (Weigert, 1962) that Romans were paying huge fortunes to acquire them with the emperor Nero acquiring one of these works from Babylon at an expense of four million sesterces. Archeologic evidence shows that in the Middle East during classical times, tapestries were not only used as wall hanging but also as part of high status garments for high rank society to wear (Sakamoto, 2001) thus showing that in classical antiquity tapestries were most likely employed for the various functions that a textile can have.

In ancient Greece the weaving of tapestries seems to have had a great importance of a household practice lead by women as many depictions of weight looms exist from Greek times. Some classical stories on mythology such as Penelope’s loom in the myth of Odysseus and the myth of Athena and Arachne also suggest the strong influence that tapestry weaving had in Greek society. It appears that there were also great sets of tapestries in ancient Greece since literature refers that tapestries designed by Phidias were used to decorate the Parthenon (Weigert, 1962). Influence from the oriental tapestries were also incorporated into the Greek world tapestries after conquests of Alexander (Weigert, 1962).

Depictions in wall paintings such as the ones in the Hypogeum of the Aurelii and in the frieze of forum Nerva in Rome which depicts the myth of Arachne are also proof of the living art of tapestry during roman times (Rogers, 2001). A large number of Coptic fragments exists from the romanisation period in Egypt which are usually found in burials and served as garment decorations. However, in a similar way to other examples from antiquity, the Copts also had manufacture of larger tapestries (Weigert, 1962).

In terms of design for tapestries in the antiquity the few fragments, descriptions and most important pictorial art from different civilisations that still exists give precious information on how major works of tapestry from this period looked like. Tapestries followed similar styles of other artworks that exist from Greco-Roman cultures and characteristics like the colour scheme, shading and figure poses that are commonly found in paintings and mosaics from this period seemed to have been also followed by tapestry weavers (Sakamoto, 2001). Babylonian tapestry seem to have had colour scheme with blue and white colours (Baumgarten, 1897), which also seem to correspond to the same colour scheme found on glazed tiles from the ancient city.

Taking into account the description of the tapestry designs on Ovid’s story of Arachne, mythological scenes involving the story of Gods are likely to have been part of tapestries from this period (Ovid, 1986). However, more mundane scenes are also existed judging by the name of Nero’s already mentioned tapestry being “Triclinaria Babylonica” (Baumgarten, 1897).
Coptic fragments of tapestries that exist show an evolution of design that starts with mythological subjects from classical antiquity acquiring in the 4th century an oriental influence and the change to Christian subjects (Weigert, 1962).

In terms of manufacture process, it is believed that the two-beam vertical loom started to replace the warp-weighted loom from the first and second centuries onwards. Yet, it seems that these two existed simultaneously during a period in the roman empire (Rogers, 2001). Tapestries produced in these looms in classical antiquity are somehow different in their structure from modern age tapestries since they had the weft weaved diagonally across the warp (Sakamoto, 2001). In terms of materials, tapestries from his period seem to share many similarities even considering the use of metallic threads. The use of golden threads had similar characteristics known to us today since they were made of a gold strip with a core thread made of other material (silk, wool, linen) as reported by archaeological findings (Giner, 2001). Apart from this not much information exists on ancient tapestries and after the fall of roman empire the art of weaving seem to have been almost lost (Baumgarten, 1897).

1.3 Middle Ages

The middle ages saw the Arab invasion of Egypt in 640 in which the Coptic tapestries experienced a transition period for adaptation to tastes of Arabs. In the second half of 9th century during Tulunid dynasty tapestries were being produced in wool with very stylized designs which was followed by an increased use of silk under Fatimids from the 10th to 11th centuries (Weigert, 1962). Nevertheless, in spite of tapestry production before 11th century being more documented by existence of fragments when compared to other locations which used to belong to the roman empire, weaving was not exclusive of the Islamic world in this period and some tapestries from the Viking era are also been preserved (Jamtli, no date) (Dimand, 1923). Besides Medieval bobbins dating from the 10th century onwards in northern and central Europe suggest that tapestry manufacture was in place in various centres during this period (Nutz and Ottino, 2013).

Muslim golden age of tapestry manufacture came to an end when the crusades started, and in this period works of weaving made in the Islamic world were being brought and assimilated in central Europe. It is also believed that weaving at a larger scale entered Europe from the Iberian peninsula because Islamic world encompassed part of that peninsula during middle ages (Weigert, 1962).

Much of what is known from these early medieval European tapestries and their manufacture is given by descriptions, illustrations or archaeological artefacts (Nutz and Ottino, 2013). Many written documents from the 9th, 10th and 11th centuries mention the word tapestries. However, there is no certainty that these were actual tapestries since during medieval
era this definition was broader encompassing for instance the case of the famous Bayeux tapestry that is in fact an embroidered cloth (Guiffrey, 1886).

The cloth of St. Gereon is an example of an early 11th century fragmentary tapestry probably made in Cologne, Germany and presents similarities in design with illuminated manuscripts, assumed to have had a great influence on tapestry design during this period (Baumgarten, 1897). The oldest pieces of tapestries that survive are from 12th century Germany and belong to the collection of the Halberstadt Cathedral. Among the collection of 12th century tapestries found in Halberstadt, there is the Twelve Apostles, St. George killing the dragon, Charlemagne and a tapestry representing Abraham (Baumgarten, 1897). They all show strong Romanesque features and prove that already in the 12th century there must have been considerable production of tapestries, although mostly associated with religious institutions (Baumgarten, 1897). The same trend is verified for the 13th century, where the only tapestry known which survived to our days was made by the nuns of Quedlinburg Abbey in Germany and represents the marriage of Mercury and Philology (Baumgarten, 1897). By the end of the 13th century tapestry manufacture was being developed in Paris, Arras, Valenciennes and Lille with the high warp loom being used as a new technique replacing the low warp loom (Guiffrey, 1886).

At the beginning of 14th century tapestries were being woven in a small industrial scale at Paris and Arras, a production that quickly grew after 1350 (Nutz and Ottino, 2013). Important members of the nobility had a great impact in the development of these centres since they were spending high sums of money to request various kinds of tapestries for their own use as well as to be used as international gifts for allied countries or as part of war negotiations with enemy states. This practice of using objects was also a way to spread their popularity to centres that previously didn’t have tradition of weaving tapestries (Guiffrey, 1886). The larger tapestry collectors of this initial industrialisation period of European tapestry were: Mahaut Countess of Artois, Louis I Duke of Anjou, Philip the Bold duke of Burgundy and Charles V of France (Guiffrey, 1886).

In the second half of the 14th century the cities of Paris, Arras and Brussels became the most important centres for tapestry weaving. It is from the reign of Charles V onwards that the history of tapestry making can be traced with accuracy due to the official archives preserved (Baumgarten, 1897).

The most important weaver of the 14th century was Nicholas Bataille who was working in Paris together with Jacques Dourdin. Bataille produced more than 250 metal thread tapestries for the Duke of Burgundy and with Dourdin was supplying the king, the royal family and foreign sovereigns. Despite the importance of Paris in the 14th century, it was in this period that the Flemish town of Arras became the most important centre for tapestry weaving. Arras was so important at that time that sets of high-quality metal thread tapestries no matter where they were being produced they were being called pieces of Arras as a reference to this city.
status (Baumgarten, 1897). Also because of this, the word arazzo persist in Italian, to describe these artefacts.

Medieval interiors were scarcely furnished, and the owners of these artworks travelled from one property to the other carrying furnishings with them. Tapestries played an important role in this nomadic attitude since they were easily stored and transported (Cavallo, 1993) Also, these objects could be easily loaded on wagons which after the arrival to a certain stop were unloaded, unrolled and hung with nails made specifically to hung them, thus quickly creating a colourful room decoration. (Verlet, 1965) (Cavallo, 1993). To place tapestries it was very common to adjust them to the dimensions of the room where they were hanged temporarily (Verlet, 1965). Records show that some tapestry owners were even using their tapestries to decorate their chariots and barges (Cavallo, 1993). It is this nomadic life of tapestries during the middle ages that is thought to have created so much damage to these objects to a point that only few examples before the 15th century survived (Guiffrey, 1886). As for church interiors tapestries were sometimes hung in the choir area for improving the acoustics of the space, a practice that can be found in France and Germany like for example in chaise-Dieu abbey (Verlet, 1965).

Paris had its importance reduced in the 15th century when Arras became a true metropolis for the production of tapestries (Guiffrey, 1886). In 1466 the house of burgundy and king of France started to purchase tapestries from Brussels which testifies the importance that Brussels was stating to acquire in the second half of 15th century (Baumgarten, 1897). However, not only Arras and Brussels were producing tapestries in this golden age. In Flanders many cities such as Lille, Bruges and Tournai had their own centres of manufacture (Baumgarten, 1897). Throughout Europe, small tapestry production was in place in the castles of the minor nobility (Nutz and Ottino, 2013) and even in Buda tapestry weaving had its place (Guiffrey, 1886). Furthermore, the period that goes from 1420 to the end of the 15th century saw the creation of tapestry manufacturers in the Italian cities of Ferrara, Urbino, Mantua, Venice and the regions of Tuscany and Umbria started to build their own tapestry ateliers with weavers that were coming from the Flemish towns. Yet, in spite of the weavers in Italy being Flemish, Italian artists were designing the cartoons for the tapestries which produced important changes in this art. Cosimo Tura, Andrea Mantegna and Da Vinci were producing cartoons at this time which introduced the Renaissance style in tapestry weaving (Baumgarten, 1897).

At this time, to control the production of tapestries, strict rules were applied to the different workshops. In Brussels for example only one apprentice that was not the child of the weaver could learn this art. To be accepted into a workshop, there was the need to have 3 years experience to work in the city and every tapestry needed to be examined before being sold (Baumgarten, 1897).

The 15th century is considered to be a golden age for tapestries, and in the city of Arras alone worked 59 master weavers supervising thousands of other weavers which produced
tapestries to fulfil all demands coming from Europe. This art expanded to all corners of continental Europe and British Isles because of tapestry imports from France and Flanders (Baumgarten, 1897). It was in this century that these artworks became so important that tapestry hangings were placed everywhere were public display of ostentation was required. From processions of kings, emperors and popes to the canonisation of saints, royal entrances into cities, banquets and marriages these items were used to show power and wealth. Even in war these objects had their place as a way of providing comfort for the nobility in the battlefield (Baumgarten, 1897).

The end of this golden age with Arras as the centre of tapestry came in the aftermath of the Burgundian wars when Louis XI took the city in 1477 and expelled its inhabitants 2 years later. After this, the hegemony of tapestry manufacture was assumed by Brussels (Muntz, 1881).

Different themes could be depicted in these objects with religious, mythological, country scenes and greenery being the most popular and contemporary subjects, while battles and jousts were less depicted subjects. The presence of coats of arms in early tapestries was something popular and is now very useful to date objects since no signatures or marks were used in tapestries before 16th century (Guiffrey, 1886).

In religious environments, tapestries served as devotional objects or as visual lessons of the bible for illiterate people (Cavallo, 1993). This is the reason why scenes of the new testament were far more used once they were more known and easily identified by the people in the church (Verlet, 1965). However, non-religious themes were much more often depicted in tapestries and this was due to the building construction of the medieval period. Religious buildings were more and more incorporating larger windows while domestic architecture was fortified having small windows and openings. The huge bare walls were then exposed and needed to be covered (Verlet, 1965). Under domestic use tapestries were meant to cover the entire walls being interrupted only by fireplaces and light openings (Cavallo, 1993). In Palazzo Davanzati, Florence there is a painted wall that simulates the old tapestries that were once hung there. This need to cover entire walls led to the production of huge sets of tapestries of several meters in length. On the other hand, since most medieval furniture didn’t had upholstery, many tapestries were being used for seat, tables and bed covers as well as cushions (Cavallo, 1993).

Artistically, tapestries in this period were extremely rich in details and full of characters and although they usually portrayed ancient stories such as biblical passages, characters are usually dressed in contemporary clothes. Ceramic painting and medieval manuscripts are believed to have had a huge influence in the way tapestries were rendered since characters in medieval tapestries are most of the times portrayed with the use of contours of the figures. This way of using contours for figures was also present in early renaissance works and in some cases was still being used in 18th century. In terms of colour, medieval tapestries had a limited amount of colours being, red, blue yellow and green the main in use with just few shades for
each colour (Breeze, 2000). As backgrounds the use of mille-fleurs was very common (Verlet, 1965). Borders in medieval tapestries are characterised by having floral motifs and animals with angels often depicted in case of the upper borders (Guiffrey, 1886). To import materials in medieval times was extremely expensive but due to the importance of these textiles, weavers in the 14th century were already using silk and metal threads coming from the orient (Guiffrey, 1886).

1.4 The Renaissance

The end of medieval traditions and beginning of renaissance period in tapestries is related with the ruin of Arras ateliers in 1477 (Guiffrey, 1886). However, the change from medieval to renaissance style in tapestries happened gradually from early 16th century onwards with the weaving of the Acts of the Apostles around the year 1520 being considered a landmark of this change in style (Cavallo, 1993).

The 16th century with the renaissance period saw many changes in the art of tapestry. These changes were more related with the design and subjects depicted rather than a change in material or procedures or the use of these objects. The subjects of medieval knighthood were replaced by mythological scenes and allegories which together with religious scenes summarises almost everything that was being produced in this time (Baumgarten, 1897). In terms of colours, tapestries of Brussels were the first to have pink and light blue colours. At some point in this period, black colour was forbidden and replaced with dark brown and blue because to achieve dark colour there was the need to use iron-oxide which caused accelerated decay. This era is also known for the huge amount of metal threads used in some of the high standard tapestries being produced as well as for the high quality in the hachure technique with was perfected during this time enabling a better interlinking between different colours (Breeze, 2000).

These objects continued to be used for public display the wealth and power of their patrons and in a similar way to what was happening in the previous centuries in France and Flanders now it was in Italy that important families were investing money by commissioning tapestries to decorate their residences and show their status. The Medici in Florence, the Gonzaga family in Mantua, the doges of Venice and Pope Leo X were very important to the spread of this art and its development in the Italian peninsula (Baumgarten, 1897). Also the rivalry between kings for the possession of these precious fabrics reached its peak in the 16th century (Marillier, 1962) where the king of France, Francis I, Charles V and king of England Henry VIII were the perfect examples of this competition (Baumgarten, 1897) (J. Band, 2006) (Campbell, 2002).

In the 16th century many examples of using tapestries as a public display of wealth can be cited. The coronation ceremony of several queens of France including Eleanor of Austria in
1530, Catherine de Medici in 1549 and Elizabeth of Austria in 1571 used tapestries as part of the decoration (Godefroy, 1619). State entries of royals in cities were always an occasion for public display tapestries (Cavallo, 1993). In the entry in Paris of Henry II (1549) and Charles IX (1571) tapestries had a major role in the decoration of the ceremonies (Cavallo, 1993)(Godefroy, 1619). Similarly, tapestries were also hung in the streets for special occasions such as festivals and processions (Montebello, 1993), a costume that was still used in France until mid-20th century (Kagan, 2015). Furthermore, important meetings between royals were always an opportunity in showing of their wealth. This I what happened in the meeting between Henry VIII and Francis I in 1520 that became known as the cloth of gold and that took place in a series of improvised structures that relied specially in tapestries and other furnishings (Hall, 1548). Henry VIII inherited tapestries from his predecessors, however he also gathered tapestries from the spoils of the monasteries and also incorporated the possessions from Cardinal Wolsey after his death (Marillier, 1962). He became one of the biggest collectors of his time together with the Dukes of Burgundy, Austrian Emperors, Kings of Spain and King of France (Marillier, 1962). A remarkable example of tapestries being used as objects to impose religious ideals is given by the example of The Story of Abraham which was commissioned by Henry VIII with the objective to impose is status as the head of the church of England (Campbell, 2002).

In the 16th century the most notorious artists were producing cartoons for tapestries. While in Italy there was Raphael, Giulio Romano, Bronzino, Andrea del Sarto, Titian and Paolo Veronese in Flanders Bernard Van Orley and Michiel Coxie were producing the cartoons for the most exquisite tapestries. It was in early 16th century that the medieval style of tapestries changed when in 1515 pope Leo XIII commissioned a set of tapestries to hang on the newly finished Sistine chapel. The set of tapestries was the act of the Apostles and for the designing the cartoon Raphael was in charge with the weaving being produced by the Flemish Pieter Coecke van Aelst which finished this gigantic work in only 4 years. The intervention by Raphael changed forever the style of tapestries. The borders were designed as if represented windows decorated with the cupids and flowers. The nude was presented on the tapestries for the first time and the compositions become freer and simpler in terms of ornamentation. The background figures and extensive ornamentation gave way to sky areas where the simulation of light falling onto the characters was represented. This new style of composition was much criticised since the tapestry was treated as if it was a fresco (Baumgarten, 1897).

The second half of 16th century saw the decline of Brussels prosperity in tapestry production since the persecutions of protestants and internal crisis lead to a decadent artistic taste. In this period instead of borders with flowers and fruits, pumpkins onions and carrots mixed with allegory figures was being used (Baumgarten, 1897). With the decadence of Brussels other places enjoyed the opportunity to expand or create tapestry workshops. In Italy, Ferrara, Milan, Mantua, Venice, Genoa and most importantly Florence saw the creation of their workshops. In Florence, Cosimo I created the famous Arazzeria Medicea which lasted until the
18th century. These centres of Italian production counted with Flemish weavers imported to produce these exquisite textiles. Jean Rost and Nicholas Karcher brought their expertise to Florence and collaborations with Bronzino and Salviati produced the most remarkable tapestries of this period. While Bronzino designed the Story of Joseph, Salviati created the History of Alexander and Story of Lucrezia (Baumgarten, 1897) (Balocco and Frangioni, 2010).

In England until the middle of 16th century most tapestries were woven in the European continental centres of tapestry manufactory. However due to an increasing demand, Flemish immigrants were already working in London as tapestry restorers during this century and some minor tapestry production is suggested to have happened (Turner, 2013).

1.5 Baroque

The 17th century is a very important century in the development of tapestry manufacture because of the many changes happening after the decline of Brussels as the centre of tapestry production. The trend of creating local tapestry manufacture centres was intensified by the various royal courts in Europe and due to the emigration of the weavers from Flanders this state of things created many high-quality workshops throughout Europe. This was also one of the reasons that enabled the creation of Gobelins tapestry manufactory in Paris which since its creation stood as the most important centre until 20th century (Baumgarten, 1897).

It was when the two Flemish weavers Marc de Comans and François de la Planche came to work in Paris that tapestry in this city was revitalised once again (Champeaux, 1871). The King of France Henry IV set up a series of measures to protect and boost the production and commerce of French tapestries. The most drastic measure was to forbid the commerce of tapestries that weren’t produced in France. The king also gave many incentives apprentices to establish a solid industry of tapestry (Baumgarten, 1897). Marc de Comans and François de la Planche establish themselves in Gobelins in 1630 where they produced some of the most important tapestries of this period. However, it was only in 1662 Louis XIV established The Manufacture of Gobelins and charged Le Brun to design cartoons for tapestries. The most famous sets from Gobelins in this period were The Acts of the Apostles by Raphael, The Story of Alexander, The Elements, The Seasons by Le Brun, The Story of Alexander and The Castles of France by Vander Meulen and Le Brun and The Story of Moses by Poussin (Guiffrey, 1886). In terms of weaving, although the baroque is more associated with the imitation of oil painting in the warp and weft, Charles le Brun is known to have given huge freedom to the weavers once they could add or remove figures or modifying groups according to their will (O’Mahony, 2016).

Towards the last quarter of the 17th century the manufacture of Beauvais became increasingly important also when Gobelins felt in a period of lack of investment, the tapestry
industry in this city flourished. In the rest of Europe only Italy lost some of the importance it played in the preceding century (Guiffrey, 1886). Tapestry workshops were being created in many countries due to the emigration from Flandres which continued. In Munich a workshop was established by Maximilian I and in England James I established Mortlake workshop in 1619 which initiated the most remarkable period for tapestry production in England. Also, it implemented the system of marks in England which enables nowadays the attribution of tapestries produced in the British Isles (Turner, 2013).

During the 17th century Le Brun in Paris and Rubens in Brussels were the most important artists designing cartoons for tapestries. However, names such as Poussin, Guyot, Coypel and Jordaens had a major role in redefining tapestry in the 17th century (Baumgarten, 1897).

The 18th century marks a new era for tapestry as the architecture changes from the big sumptuous rooms of Louis XIV style to the smaller and intimate rooms that were part of Louis XV style. The solemnity that were sets such as the history of Alexander are replaced by more simple and mundane themes such as “Adventures of Don Quixote”. Distant and idealistic places were portrayed into tapestry. Chinese and Indian scenes, Russian festivals, and the bohemian life all have space in the new style of tapestries which aligned perfectly with Rococo style of this period. This new style in tapestries is more reflected in the “Pastoral” themed tapestries where Sheppard’s are represented in an idealistic world much connected with the spirit of Rococo (Baumgarten, 1897).

Furniture became much appreciated and tapestries applied as upholstery and coverings were very much appreciated and valuable when compared with the big sets that were in vogue in the previous century. For these furniture coverings, pastorals, mythological scenes and landscapes were used.

This new style was particularly strong in the Beauvais manufactory which assumed a quite relevant status in the course of the 18th century (Baumgarten, 1897) and as immediate successors of Le Brun, Boucher and Oudry renew this art adapting to the fashionable style of this century (Guiffrey, 1886).

In Paris at Gobelins, Boucher was producing the cartoons for the most famous sets of this period such as Neptune and Amymoné, Venus and Vulcan, Psyche and Amor, The Fortune Teller. This was the century where the tapestry was emulating the work of painted canvas to an extreme and Oudry and Boucher were very known artists associated with this. Oudry and Boucher are also known to create with the aid of chemists thousands of colours each one with 12 different shades (Baumgarten, 1897). Because colours were chemically unstable they begun to fade and this resulted in the most vibrant tapestries of this period to be many times known nowadays by the colour loss more than by the themes they portray. Not only Oudry and Boucher, but also Audran, Cozette became so influent that they were still being used as models.
for the 19th century tapestry manufacture in France and the other countries that followed the French tradition of design including the USA. Tapestry however felt into an age of decadence since the followers of artists mentioned above were not as good in design and in weaving as their predecessors. The 18th century was also the period where the use of gold and silver threads felt into disuse and stopped being used in tapestry manufacture (Champeaux, 1871). Towards the end of this century the last workshops in Brussels closed and for the case of Lille workshops French revolution marked the end of the production. Only the city of Tournai continued to produce in a smaller scale tapestries after the 18th century (Champeaux, 1871).

1.6 The 19th Century

With the French revolution and the end of the elite of aristocracy, tapestry felt into complete decay with Brussels not having a single workshop of production and Gobelins continuing to produce in a state of decadence as a simple small manufactory. Cheap substitutes for tapestries as painted textiles and paper hangings and machine-made textiles took place of tapestries. The invention of Jacquard loom and its implementation into producing replica tapestries by mechanical processes produced the loss of the weaving tradition (O’Mahony, 2016).

Without money and availability of workshops for restoration, tapestries were left abandoned in attics, barns or renegaded to be used as wallpapers in which paintings hung or to serve as mere furniture coverings or even as carpets (Montebello, 1993) (Baumgarten, 1897). The dispersion of important tapestries left many sets of tapestries divided and even lost (Böttiger, 1937). An example of this is Henry VIII’s set of History of Julius Caesar that went missing in this period and nowadays constitutes an example of a set only known by documentation and surviving dispersed tapestries made or inspired on the same cartoon designs which gives an idea of how this set might have looked like (Campbell, 1998).

However, towards the end of 19th century a revival of tapestry took place, with important collections being restored and increasing interest by the public collections and the new industrial bourgeoisie wanting to acquire these precious textiles of the past (Böttiger, 1937).

In this period Gobelins and Beauvais counted with 80 persons working. Private establishments at Aubusson had 100 weavers and some small ateliers in Neuilly also existed (Böttiger, 1937). The last decades of the 19th century counted with the opening of some tapestry workshops as a revival of this art was taking place. In Rome the atelier San Michele reopened by Giuseppe Printo. Ziesch opened an atelier in Berlin, Baumgarten created a workshop in US and in the UK, the Royal Windsor Tapestry Works and William and Morris were created (Baumgarten, 1897).
1.7 The 20th and 21st Century

With the high industrialisation and increase in economic power in the US towards the end of the 19th century and the beginning of the 20th, many European tapestry collection were sold to US were rich industrialists started to buy from European aristocrats in need of money (Breeze, 2000).

In early 20th century, weaving practice was taught in emerging modernist schools as it’s the case of the textile workshops in Bahaus school (O’Mahony, 2016) first located in Weimar and then in Dessau. It is interesting to notice in the beginning of modernism the shift from an art that was historically led by men to a women’s leading craft. In France Aubusson had in the beginning of the century an already mix-gendered practice which was somehow contrasting with the policies of Bahaus school that sectorized women to the learning of this craft (O’Mahony, 2016).

Tapestry centres in France were directly affected by the impact of first world war and the economic crisis on the 1930s which threatened the centres of tapestry manufactories. As follows, these centres needed to readapt. For this, an adoption of modern motifs and the modernisation and in updating the production process took place (O’Mahony, 2016), making the economic aspects to be the main concern of the development of this art.

After the second world war there was a wave of public commissions taking place such is the case of Christ in Glory tapestry for Coventry cathedral (O’Mahony, 2016). Furthermore, in 1960’s a mid-century revival was taking place in France with the painter Jean Lurçat and the weaver François Tabard producing some of the most famous 20th century tapestries (Jobé, 1965). Lurçat became the major figure in redefining the art of tapestry and adapting weaving to modern standards. To adapt the art of weaving to more cheap standards, he campaigned for a new movement of weaving production. This movement transformed a very slow and expensive process in a more cheap and fast by limiting the fineness to 13 threads per cm and narrowing down the colour range from thousands of shades to 40 (O’Mahony, 2016). This process is considered both as a panacea for an industry that could end as well as the limitation of weavers artistic expression since they were now under the aesthetic control of designers colour choose instead of a free interpretation (O’Mahony, 2016). Yet, Lurçat is seen as the figure that removed the importance of the weaver as an artist and brought it to the simple artisan that executes the work of the cartoon painter (O’Mahony, 2016). Weavers started to lose power over design and free interpretation, a fact that became more common in modern times. The weaver became no longer in power of make changes and free interpret the cartoon. This change in design of tapestries and the way cartoon painters dictate their wish to put their artworks into a weaving tapestry brought with it new ways of designing a tapestry which in some contemporary cases simulate watercolour effect, brushstrokes or collage techniques commonly done by artists (Chris Ofili: The Caged Bird’s Song, 2018).
Tapestries with cartoons designed by Picasso, Braque, Matisse were being produced in the 20th century (Benson, 1936).

Nowadays, some hanging textiles are being produced with digitally designed files that are then machine woven (O’Mahony, 2016), however in a similar way to what happened with the advent of the Jacquard loom in the 19th century these cannot be considered as tapestries if there is not the handcrafting involved in the process.

In 2009 the intangible heritage statues was granted to Aubusson weaving by UNESCO (O’Mahony, 2016).
Appendix 2 – Questionnaire Form

Personal Details
1. Current place of work

2. Email Address

3. Name

General Questions
4. How many tapestries are conserved at your studio per year?
   - None
   - 1
   - 2
   - 3
   - 4
   - 5
   - Other

Other

General Questions

5. A support fabric is often applied to tapestries using a variety of methods. This is usually to add additional support in weakened areas of the tapestry whether through natural material deterioration, insect damage or strain. What would you say are the main reasons you would apply a support fabric? (more than one answer can be selected)

- Strengthening/stabilising areas of weakness due to material deterioration
- Distribution of load
- Support for display
- Preventive strengthening for the future when tapestry cannot support its own weight
- Facilitate safe handling
- Other

Type of Support

6. Which is the most common type of fabric support that you use to apply to the back of the tapestry?

- Overall full support
- Patches
- Patches and full support both
- Straps
- Other

Type of Support

7. What are the major factors affecting your choice of fabric support method? Please rate the following factors on a scale of 1 to 5 (1 - not very important, 5 - very important)

<table>
<thead>
<tr>
<th>Factor</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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</thead>
<tbody>
<tr>
<td>Extent of damage</td>
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<td>Time</td>
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<td>Cost</td>
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<td>Material availability</td>
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<td>Facilities available</td>
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<td>Other</td>
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</table>
8. If you answered other please specify

Fabrics
9. Which type of material do you most commonly use for support fabric?
   - Linen 100%
   - Cotton 100%
   - Linen and Cotton (mixed)
   - Other

Fabrics
10. What are your reasons for using this type of support fabric?
   - Tradition
   - Material Longevity
   - It allows the tapestry to change dimensions with the environmental conditions as it responds faster/at a similar rate to the tapestry
   - It restricts the movement of the tapestry as the fabric does not respond to changes in the environmental conditions
   - Not sure
   - Other

Amount of Fabric
11. When applying a structural support to the back of tapestry, how much excess of support fabric do you add to allow ease?
   - No excess
   - 1 cm per 25 cm
   - 1.5 cm per 20 cm
   - 2 cm per 20 cm
   - More than 2 cm per 20 cm
   - Other

Amount of Fabric
12. How do you determine the amount of excess you answered in question 7?
Stitching Methods

13. Which of the following stitching techniques do you use to attach a support fabric to the back of tapestry?
   - Running stitch
   - Zig-zag stitch
   - Herringbone stitch

14. What is the distance apart?
   - 8-10 cm
   - 15 cm
   - 20 cm
   - Other

15. What is the Length of stitch?
   - 1.5 to 2 cm
   - 2 to 3 cm
   - Other

16. What is the direction?
   - Weft
   - Warp

Stitching Methods

17. Which of the following stitching techniques do you usually use to add strength to weak areas in the tapestry?
Couching
Running stitch
Couching and running stitch combined
Herringbone stitch
No stitching added to strengthen weak areas

18. **Distance between the stitching rows**
- 0.5 cm
- 1 cm
- 1.5 cm
- 2 to 3 cm
- More than 3 cm

**Stitching Methods**

19. **If there is a severely degraded area in the tapestry, which of the following stitching techniques do you use to strengthen the area?**
- Couching
- Running stitch
- No stitching
- Couching and running stitch combined
- Herringbone stitch
- No stitching added to strengthen weak areas

20. **Distance between the stitching rows**
- 0.5 cm
- 1 cm
- 1.5 cm
21. Please feel free to provide more information about the choice and method of stitching you use to strengthen weak areas

Materials for Stitching

22. Which of the following type of threads do you use to attach a support fabric to the back of tapestry?

- Polyester
- Cotton
- Cotton/Polyester
- Silk
- Other

Materials for Stitching

23. For stitching silk areas, what type of thread do you use?

- Polyester
- Cotton
- Cotton/Polyester
- Silk
- Wool
- Polyester & Silk
- Polyester & Wool
- Other

Materials for Stitching

24. For stitching wool areas, what type of thread do you use?

- Polyester
- Cotton
- Cotton/Polyester
- Silk
- Wool
Materials for Stitching

25. What are the major factors affecting your choice of stitching thread? Please rate the following factors on a scale of 1 to 5 (1 - not very important, 5 - very important)

<table>
<thead>
<tr>
<th>Factor</th>
<th>1</th>
<th>2</th>
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<tbody>
<tr>
<td>Aesthetics</td>
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<td>Mechanical strength of thread</td>
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<td>Ageing properties of thread</td>
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<td>Cost</td>
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<td>Availability</td>
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<td>Tradition/Experience using this thread</td>
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<td>Other</td>
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26. If other, please specify

History

27. What factors have contributed to the conservation approach in your current workplace? Please rate the following factors on a scale of 1 to 5 (1 - not very important, 5 - very important)
<table>
<thead>
<tr>
<th>Question</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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</thead>
<tbody>
<tr>
<td>Tradition</td>
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<tr>
<td>Current research</td>
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<tr>
<td>Material availability</td>
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<td>Cost</td>
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<td>Dictated by owner/curator</td>
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<tr>
<td>Restrictions due to resources (e.g. time, conservators and space)</td>
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<tr>
<td>Other</td>
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</table>

28. **If other, please specify**

General Comments

29. **If you have any other thoughts or comments, please describe them**

If you feel you want to add anything else to your answer in this questionnaire please feel free to contact me by email: pedro.rocha.16@ucl.ac.uk
Appendix 3 - Historic Royal Palaces’ standard system for scoring the condition, stability and priority of object treatment as used for condition rating of fragments in the current research.

### Condition Code

<table>
<thead>
<tr>
<th>Condition Code C</th>
<th>1 Excellent</th>
<th>2 Good</th>
<th>3 Fair</th>
<th>4 Poor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Definition</strong></td>
<td>Little or no damage evident</td>
<td>Minor amount of damage and/or loss of original and added material, or with light discoloration or accretions.</td>
<td>Noticeable damage and loss and appears disfigured with visible accretions</td>
<td>Considerable and/or significant loss of original or added material or major damage/breakage or disfigurement. May be endangering other objects and surfaces.</td>
</tr>
</tbody>
</table>

### Stability Code

<table>
<thead>
<tr>
<th>Stability Code S</th>
<th>1 Stable</th>
<th>2 Potentially unstable</th>
<th>3 Unstable/Steady deterioration</th>
<th>4 Highly unstable</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Definition</strong></td>
<td>Condition not expected to deteriorate within the next 10+ years</td>
<td>Condition not expected to deteriorate within next 5-10 years</td>
<td>Change in condition likely to be evident between 1-5 years</td>
<td>Change in condition likely to be evident within 1 year</td>
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</tbody>
</table>
## Treatment Priority

<table>
<thead>
<tr>
<th>Treatment Priority</th>
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<td>Conservation treatment necessary to avoid further deterioration, loss or undesirable strain on an object &amp;/or loss of significance (evidential or artistic). Minimal to medium conservation needs.</td>
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<td>Conservation treatment required to prevent significant deterioration in condition of object &amp;/or loss of significance (evidential or artistic value). This may include structural vulnerability, risk of total loss of entire object or part of object, or risk of accident to visitors/users. Extensive conservation needs for either short or long term display.</td>
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Appendix 4 – Structural and mechanical properties calculated for each fragment and sample area tested.

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<th>Condition Ratio</th>
<th>Initial Linear Modulus (kPa)</th>
<th>Strain at the End of Crimp Phase (%)</th>
<th>Final Calculated Linear Modulus Elastic (kPa)</th>
<th>Strain at First Fibres Breaking (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>503</td>
<td>0.8</td>
<td>1.6</td>
<td>19.9</td>
<td>0</td>
<td>0.00</td>
<td>0</td>
<td>78</td>
<td>3.79</td>
<td>293</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>77.6</td>
<td>0</td>
<td>0.00</td>
<td>0</td>
<td>85</td>
<td>2.74</td>
<td>236</td>
<td>-</td>
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<td></td>
<td></td>
<td>32.1</td>
<td>0</td>
<td>0.00</td>
<td>0</td>
<td>98</td>
<td>3.17</td>
<td>166</td>
<td>4.82</td>
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<td>69.9</td>
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<td>35.7</td>
<td>0</td>
<td>0.00</td>
<td>0</td>
<td>77</td>
<td>2.08</td>
<td>156</td>
<td>8.44</td>
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<tr>
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<td>0</td>
<td>0.00</td>
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<td>Failed Test</td>
<td>Failed Test</td>
<td>Failed Test</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td></td>
<td>56.5</td>
<td>0</td>
<td>0.00</td>
<td>1.7</td>
<td>121</td>
<td>7.35</td>
<td>451</td>
<td>10.61</td>
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</tbody>
</table>

272
Appendix 5 - Comparison of strain maps between JPEG and TIFF image formats for the tensile test of sample 1 from fragment 44.

<table>
<thead>
<tr>
<th>Extensions</th>
<th>0 mm</th>
<th>1 mm</th>
<th>3 mm</th>
<th>6 mm</th>
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</thead>
<tbody>
<tr>
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<td><img src="image1" alt="JPEG 0 mm" /> <img src="image2" alt="JPEG 1 mm" /> <img src="image3" alt="JPEG 3 mm" /> <img src="image4" alt="JPEG 6 mm" /></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>TIFF</td>
<td><img src="image5" alt="TIFF 0 mm" /> <img src="image6" alt="TIFF 1 mm" /> <img src="image7" alt="TIFF 3 mm" /> <img src="image8" alt="TIFF 6 mm" /></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix 6 - DIC subset and step size analysis of sample 5 from fragment 137 at 0 mm extension before tensile testing.

<table>
<thead>
<tr>
<th>Step Size</th>
<th>15</th>
<th>21</th>
<th>31</th>
<th>61</th>
<th>121</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td><img src="image1" alt="Subset Size 15" /></td>
<td><img src="image2" alt="Subset Size 21" /></td>
<td><img src="image3" alt="Subset Size 31" /></td>
<td><img src="image4" alt="Subset Size 61" /></td>
<td><img src="image5" alt="Subset Size 121" /></td>
</tr>
<tr>
<td>8</td>
<td><img src="image1" alt="Subset Size 15" /></td>
<td><img src="image2" alt="Subset Size 21" /></td>
<td><img src="image3" alt="Subset Size 31" /></td>
<td><img src="image4" alt="Subset Size 61" /></td>
<td><img src="image5" alt="Subset Size 121" /></td>
</tr>
<tr>
<td>16</td>
<td><img src="image1" alt="Subset Size 15" /></td>
<td><img src="image2" alt="Subset Size 21" /></td>
<td><img src="image3" alt="Subset Size 31" /></td>
<td><img src="image4" alt="Subset Size 61" /></td>
<td><img src="image5" alt="Subset Size 121" /></td>
</tr>
</tbody>
</table>
Appendix 7 - DIC subset and step size analysis of sample 5 from fragment 137 at 5 mm extension under tensile testing.

<table>
<thead>
<tr>
<th>Subset Size</th>
<th>15</th>
<th>21</th>
<th>31</th>
<th>61</th>
<th>121</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
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<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
</tr>
<tr>
<td>8</td>
<td><img src="image6.png" alt="Image" /></td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
<td><img src="image9.png" alt="Image" /></td>
<td><img src="image10.png" alt="Image" /></td>
</tr>
<tr>
<td>16</td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
<td><img src="image13.png" alt="Image" /></td>
<td><img src="image14.png" alt="Image" /></td>
<td><img src="image15.png" alt="Image" /></td>
</tr>
</tbody>
</table>
Appendix 8 - DIC subset and step size analysis of sample 5 from fragment 44 at 5 mm extension under tensile testing.

<table>
<thead>
<tr>
<th>Step Size</th>
<th>Subset Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>15</td>
</tr>
<tr>
<td>8</td>
<td>21</td>
</tr>
<tr>
<td>16</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>61</td>
</tr>
<tr>
<td></td>
<td>121</td>
</tr>
</tbody>
</table>

![ Subset Size Analysis ]
Appendix 9 - Stain evolution in the vertical direction $E_Y$ and in the horizontal direction $E_X$ when a tensile vertical force is applied on sample 8 from fragment 503 until failure.

<table>
<thead>
<tr>
<th></th>
<th>2 mm</th>
<th>4 mm</th>
<th>6 mm</th>
<th>10 mm</th>
<th>14 mm</th>
<th>24 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_Y$</td>
<td><img src="image1" alt="Image" /></td>
<td><img src="image2" alt="Image" /></td>
<td><img src="image3" alt="Image" /></td>
<td><img src="image4" alt="Image" /></td>
<td><img src="image5" alt="Image" /></td>
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</tr>
<tr>
<td>$E_X$</td>
<td><img src="image7" alt="Image" /></td>
<td><img src="image8" alt="Image" /></td>
<td><img src="image9" alt="Image" /></td>
<td><img src="image10" alt="Image" /></td>
<td><img src="image11" alt="Image" /></td>
<td><img src="image12" alt="Image" /></td>
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</tbody>
</table>
Appendix 10 - Stain maps at 5 mm extension in the vertical direction EY and in the horizontal direction EX when a tensile vertical force is applied on tested samples.

<table>
<thead>
<tr>
<th>Test Sample</th>
<th>Strain EY</th>
<th>Strain EX</th>
</tr>
</thead>
<tbody>
<tr>
<td>44-2</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>502-1</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>503-2</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>170-2</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>150-3</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>501-2</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>154-3</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>158-3</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>Test Sample</td>
<td>Strain EY</td>
<td>Strain EX</td>
</tr>
<tr>
<td>-------------</td>
<td>----------</td>
<td>-----------</td>
</tr>
<tr>
<td>32-2</td>
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<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>139-1</td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td>146-3</td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>71-2</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
</tr>
<tr>
<td>131-3</td>
<td><img src="image9.png" alt="Image" /></td>
<td><img src="image10.png" alt="Image" /></td>
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<td>33-2</td>
<td><img src="image11.png" alt="Image" /></td>
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</tr>
<tr>
<td>143-2</td>
<td><img src="image13.png" alt="Image" /></td>
<td><img src="image14.png" alt="Image" /></td>
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<tr>
<td>72-3</td>
<td><img src="image15.png" alt="Image" /></td>
<td><img src="image16.png" alt="Image" /></td>
</tr>
<tr>
<td>Test Sample</td>
<td>Strain EY</td>
<td>Strain EX</td>
</tr>
<tr>
<td>-------------</td>
<td>----------</td>
<td>----------</td>
</tr>
<tr>
<td>137-3</td>
<td><img src="image1" alt="Image" /></td>
<td><img src="image2" alt="Image" /></td>
</tr>
<tr>
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<td>73-1</td>
<td><img src="image5" alt="Image" /></td>
<td><img src="image6" alt="Image" /></td>
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<tr>
<td>132-2</td>
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<td><img src="image8" alt="Image" /></td>
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<tr>
<td>54-2</td>
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<td><img src="image10" alt="Image" /></td>
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<tr>
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<td><img src="image12" alt="Image" /></td>
</tr>
<tr>
<td>119-4</td>
<td><img src="image13" alt="Image" /></td>
<td><img src="image14" alt="Image" /></td>
</tr>
<tr>
<td>77-1</td>
<td><img src="image15" alt="Image" /></td>
<td><img src="image16" alt="Image" /></td>
</tr>
</tbody>
</table>
Appendix 11 - Phase 1 Experiments: Desorption from 45% to 30% RH, 1st repetition.
Appendix 12 - Phase 1 Experiments: Desorption from 45% to 30% RH, 2nd repetition.
Appendix 13 - Phase 1 Experiments: Absorption from 30% to 80% RH, 1st repetition.
Appendix 14 - Phase 1 Experiments: Absorption from 30% to 45 and then 90% RH, 2nd repetition. Followed by desorption to 45% RH.
Appendix 15 - Phase 1 Experiments: Desorption from 80% to 45% RH, 1st repetition.
Appendix 16 - Phase 1 Experiments: Desorption from 90% to 45 RH, 2nd repetition.
Appendix 17 - Phase 2 Experiment at 25°C: Absorption from 40% to 80% RH, environmental conditions inside the environmental chamber, RH read from sensors in IBM motes and strain computed from DIC.
Appendix 18 - Phase 2 Experiment at 25°C: Absorption from 40% to 80% RH, environmental conditions inside the environmental chamber, strain computed from DIC and strain computed from DIC in selected areas for different materials.
Appendix 19 - Phase 2 Experiment at 25°C: Absorption from 40% to 80% RH, environmental conditions inside the environmental chamber, RH read from sensors in IBM motes, strain computed from DIC and displacements calculated from IBM sensors.
Appendix 20 - Phase 2 Experiment at 25°C: Desorption from 80% to 45% RH, environmental conditions inside the environmental chamber, RH read from sensors in IBM motes and strain computed from DIC.
Appendix 21 - Phase 2 Experiment at 25℃: Desorption from 80% to 45% RH, environmental conditions inside the environmental chamber, strain computed from DIC and strain computed from DIC in selected areas for different materials.
Appendix 22 - Phase 2 Experiment at 25°C: Desorption from 80% to 45% RH, environmental conditions inside the environmental chamber and displacements calculated from IBM sensors.
Appendix 23 - Phase 2 Experiment at 15°C: Absorption from 55% to 80% RH, environmental conditions inside the environmental chamber, RH read from sensors in IBM motes and strain computed from DIC.
Appendix 24 - Phase 2 Experiment at 15°C: Absorption from 55% to 80% RH, environmental conditions inside the environmental chamber, strain computed from DIC and strain computed from DIC in selected areas for different materials.
Appendix 25 - Phase 2 Experiment at 15°C: Absorption from 55% to 80% RH, environmental conditions inside the environmental chamber, RH read from sensors in IBM motes, strain computed from DIC and displacements calculated from IBM sensors.
Appendix 26 - Phase 2 Experiment at 15°C: Desorption from 80% to 55% RH, environmental inside the environmental chamber, RH read from sensors in IBM motes and strain computed from DIC.
Appendix 27 - Phase 2 Experiment at 15°C: Desorption from 80% to 55% RH, environmental conditions inside the environmental chamber, strain computed from DIC and strain computed from DIC in selected areas for different materials.
Appendix 28 - Phase 2 Experiment at 15°C: Desorption from 80% to 55% RH, environmental conditions inside the environmental chamber, RH read from sensors in IBM motes, strain computed from DIC and displacements calculated from IBM sensors.