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ASSESSMENT OF FLOOD AND WIND DRIVEN RAIN IMPACT ON MECHANICAL PROPERTIES OF HISTORIC BRICK MASONRY

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Abstract

As a result of increased rainfall and flooding the building fabric of historic structures in exposed areas are likely to be subject to higher and more sustained moisture content levels, along with experiencing an increased frequency and severity of wetting and drying cycles. This study aims to evaluate the impact of such cyclic wetting and drying on the mechanical behaviour of historic brick masonry. The reported results are obtained from a series of weathering and mechanical tests carried out on clay bricks and masonry specimens. The weathering test regime derives from analysis of observed weather data, combined with review of similar existing test protocols. Similarly, a modified mechanical test procedure is applied to simulate fatigue observed in the field. The results indicate that exposure to the weathering tests results in a reduction of masonry shear strength. This is discussed within the context of wider work carried out at a case study location, and highlights the value of designing a weathering regime that can more closely replicate the in-situ weathering processes. In this way the data collected in this experimental programme is shown to be suitable for use in contextual analysis of individual historic masonry case studies, with respect to climate change and the associated alteration of wetting regimes.

1. Introduction

Observations of changing trends in precipitation conditions are being regularly reported by the IPCC, with variance in precipitation conditions occurring at all geographical scales [1]. While some localised uncertainty does exist, one region of the globe has consistently exhibited a trend for increasing rainfall accumulations. Since the mid-20th cc. Europe has exhibited a consistently increasing trend in precipitation averages, contributed to by both seasonal conditions and extreme events [2]. Countries such as Norway and Poland have been shown to exhibit increases of up to 20% in daily precipitation totals [3,4]. Within the UK, total precipitation has been observed to increase between 10 and 50% in the second half of the 20th century [5]. In the future the "contrast in precipitation between (…) wet and dry seasons will increase", along with projected further increases in overall precipitation levels of up to 30%. Extreme rainfall events are already increasing in number [6] and projections indicate this trend will continue [7], which only contributes to an increased risk of flood occurrence. Quantitative data that informs on the mechanical resilience of masonry to these climate-induced moisture ingress processes is scarce, with only a limited number of numerical approaches having been published [8, 9]. Similarly, mechanical analysis of historic masonry in relation to these hazards is rarely studied, with any work that has focussed upon flood and wind driven rain impact on historic fabric assessing material decay through moisture ingress [10], salt movement [11] or drying regimes [12].

This study directly addresses this issue through the design and implementation of a series of tests intended to generate empirical data informing on the relationship between weathering conditions and mechanical response of historic masonry. The following section details the design of the new weathering test sequence and apparatus, in conjunction with a review of previous work. The remainder of the paper then sets out the detail of the test specimens used within this experimental programme, followed by the presentation of test results. Discussion of the findings focusses upon the value of the experimental data collected with regards informing upon the future protection and continued resilience of buildings on site, including their comparative use alongside monitoring data. The work was carried out as part of the Parnassus project (2010-2014, see www.ucl.ac.uk/Parnassus), which brought together laboratory, in-situ and numerical modelling investigations. Tewkesbury in Gloucestershire, England was one of the case study areas and is the main focus of this paper. Tewkesbury is an early medieval town located at the confluence of the River Avon and River Severn, and was chosen for its exposure extreme precipitation and to floods, with the latest events in July 2007 and May 2012 causing widespread damage. A 2001 study by Reynard et al. [13] has found that by 2050 the estimated increase in rainfall could cause an increase in flow for the River Severn in the range of 20%, significantly impacting on return periods of high flow events such as those leading to flooding of the site. These conclusions are in broad agreement with the findings of later work by Smith et al. (2014) [14], demonstrating that Tewkesbury constitutes a good location to study the impact of flood and rain on the historic built environment.

2. Weathering regime design

The design of the weathering regime draws from various sources including observed climate data at the test site, contextual trends sourced from historic met office observations and long term conditions typical to the study area. The aim was to produce a set of test conditions that were robustly linked to the case study, using a methodology that could readily be transferred to another location if required. Prior to carrying out analysis of observed climate data, a review of existing test methods and standard protocols was completed, in order to generate a contextual picture of the range of flow rates currently being used to test for wind driven rain exposure. The empirical measure of wind driven rain (WDR) having first been proposed by Lacy (1977) [15] the relationship has since undergone a process of iteration [16] until its current accepted form [17]. The relationship describes the translation of rainfall into WDR using a vector relationship, taking account of wind speed to determine a rate of rainfall that would theoretically impact on a vertical façade of a building, typically given in mm/hour. This value therefore translates into a flow rate that could be specified in a test protocol assessing WDR impact. However, existing standards and literature discussing this have not typically applied this relationship to specify test flow rates. 3 British Standard procedures and few investigations carried out in the field of building conservation address WDR impact on building facades provide test flow rates (Table 1). However, correlation to climate conditions is not yet a common feature of such procedures.

Table 1: Flow Rates and Corresponding Rainfall Rates

Test	Flow Rate	Rainfall Rate	Test	Flow Rate	Rainfall Rate
[18]	1.5 L/min	15 mm/hour	[10]	1L/min	Not Correlated
[19]	2 L/min	21 mm/hour			
[20]	0.5 L/min	4 mm/hour	[21]	2L/test	

This investigation looks to build upon these existing protocols by developing a more explicit derivation of the flow rates used, such that confidence in the representation of the flow rates can be optimised. The strategy was to design a means of calculating flow rate applicable for a specific site, using a method that could be translated to other sites in order to similarly find representative values for those locations. This could then be applied in the laboratory to a construction system determined using assessment of buildings at the site, such that the impact (and hence risk) at the site could be determined (Figure **1**).

From the case study location of Tewkesbury a long term precipitation data set was obtained from the Met Office's MIDAS system, and this was used to determine the long term average daily precipitation total for the site, which was determined as 36 mm/day. This was then used in conjunction with the a 2m/s wind speed, specified as generating "wetting conditions" in BS 15927-3 [22] and input into the WDR equation to derive the average conditions for the site. This gave a daily total value, which was then required to be translated into a pattern of wetting and drying, the design of which was drawn from work at the Met Office [23] analysing the relationship between rainfall intensity and duration, and this was used to define the upper threshold for the flow rate used in the weathering procedure.

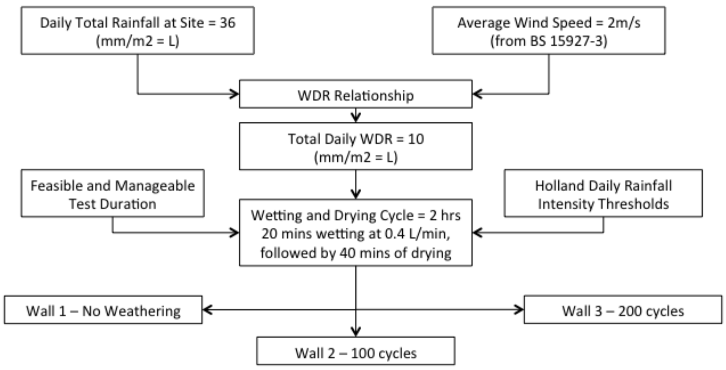

Figure 1: Route map demonstrating weathering sequence design process

To encourage wetting of the wall the water is dispersed at the slowest feasible rate to allow for the test length to remain feasible and for the continual 24 hr running of the test to be promoted. This ultimately produced a wetting-drying cycle of: 40 min of wetting, giving a flow rate of 0.4 L/min, followed by a 2 hr and 20 min period of drying. The water was applied to the face of the specimen using a spray nozzle from which a combination of air and water was dispersed, representative of the wetting by rain droplets carried horizontally by wind. Mechanical tests were carried out on individual specimens after 100 and 200 cycles respectively. After the first 100 cycles of the 200 cycle test the specimen was dried to original weight before a second run of cycles was implemented. The assessment carried out in order to determine the test flow rates demonstrates that the earlier test protocols have tended to overestimate the flow rates required to replicate these types of wetting events, although the decreasing trend in flow rate suggests that the validity of such procedures is gradually improving, to which end this sequence design also contributes.

3. Laboratory programme

3.1. Specimen design and initial testing

Three masonry specimens were constructed using the reclaimed bricks and fresh non-hydraulic lime mortar. Among the reclaimed bricks available on the market, older, narrower, less dense and more absorbent bricks were chosen for being more vulnerable from the perspective of the test programme. The brick type selected was manufactured in Bridgwater, Somerset in the early 19^{th} cc, with average dimensions 230 x 105 x 65 mm, and an average dry density of 1600 kg/m^3. A test to determine the initial rate of absorption was carried out in accordance with BS EN 772-11 [24], and the specimens were found to have an average absorption of 16%. These bricks have therefore been classified as Category II, HD, Group 1 clay units of low durability [25, 26].

In order to determine compressive strength of whole bricks testing of a sample of 12 bricks was carried out in accordance with [25]. The loading rate was 3600 N/second, with capping provided by dense engineering cork to ensure even loading across the surface of the brick. The sample yielded an average compressive strength of 25.2 MPa, and a standard deviation of 2.4 MPa.

The mortar was a non-hydraulic mix, selected as a representation of the historic air lime typically used in historic masonry within the UK during the 13^{th} to 17^{th} cc [27], presenting an opportunity to study a mortar especially vulnerable to exposure to moisture due to its inherent softness and high absorption [28]. The mortar used had a traditional 3:1 ratio of aggregate to lime, mixed with pure lime putty and a combination of both sharp and soft sand. The masonry specimens were of dimension 490 x 390 x 120 mm thick, constructed of a total of 12 bricks laid in a stretcher bond, with a single skin of masonry (Figure 2 left). The bricks were laid wet with a 10mm mortar bed and the wallettes were cured for a total of 18 months prior to testing to ensure the maximum strengthening of the mortar and bonding. Three specimens were constructed in total; one specimen was tested unweathered to produce a datum. The 2nd and 3rd specimens were tested following 100 and 200 cycles of weathering respectively (Figure 1).

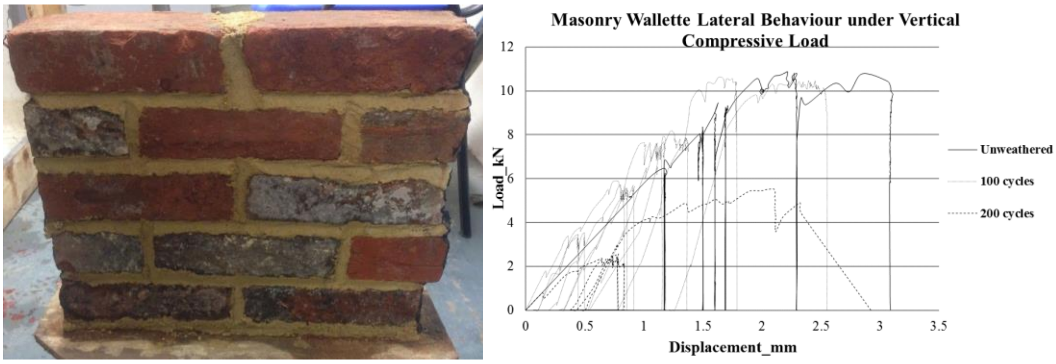

Figure 2: Masonry wallette specimen (left) and comparative assessment of weathered and unweathered masonry wallettes (right)

Prior to testing of the masonry specimens using the weathering sequence, individual bricks were exposed to the same weathering process. It was intended to also undertake the same tests on prisms of the mortar, however unfortunately the samples collapsed during the weathering process. Although this therefore did not yield any data for the analysis, their collapse is in itself a finding of the vulnerability assessment. The cyclic weathering of the bricks was an enhanced test, in that each brick was fully submerged for a period of 40 min, before being dried in the oven for 2 hr and 20 min at 40°. On average the moisture content reached after 40 min of submersion was 6% and after drying the bricks were returned to their original weight. It is appreciated a higher amplitude of fluctuation of moisture is likely to have occurred than through exposure to spray at 0.4 L/min, however the same frequency of cycling was maintained. Three cycles were completed in a day, and overnight the bricks were maintained at ambient temperature and humidity. A total of 50 cycles were completed before compression testing.

Six specimens were tested in compression according to [25] in a dry state following the cyclic weathering, producing an average compressive strength of 26.9 MPa and a standard deviation of 1.5 MPa. This finding would suggest that the cyclic weathering of the bricks had no impact upon their strength, assuming that the small increase in average strength exhibited is statistically insignificant. Testing after higher numbers of cycles may induce a more significant loss, and verification of this should form the focus of future work. This finding is also considered with testing carried out elsewhere in the Parnassus project [29], which assesses the impact of prolonged exposure to moisture on bricks and demonstrates that on average up to 43% of strength can be lost in bricks tested wet after 72 hours of submersion, where moisture content is determined by weight increase. Testing of bricks in this way is more representative of flood events or prolonged saturation due to capillary rise and highlights that this hazard may prove to be more significant for bricks than the WDR simulated by the cyclic weathering.

3.2. Masonry testing

The three masonry specimens were subject to the weathering sequence as in Figure 1, and then were dried to their original weight prior to testing under combined compression and lateral loading. This was to simulate the loading that an infill panel in a timber frame is likely to experience during a WDR event, when wind loading of the frame could potentially set up a racking process. This is reflected in the test procedure used for the masonry specimens, which takes reference from the standard test for determining racking strength of timber frames [30]. For each specimen a lateral load was cycled incrementally up to failure, in stages of 2.5kN. The load was applied for 300+/-60 seconds, and at each level the load cycle was repeated 3 times.

A vertical uniformly distributed load of 5+/-0.5kN was applied, inducing a vertical compressive stress in the material of approximately 0.1 MPa, a value selected to represent loading of exposed on-site structures of similar construction. The displacement in the specimen was measured both vertically and laterally, in accordance with [31]. This was carried out with LVDT transducers mounted at fixed positions on the test rig frame and attached to the face of the masonry using brackets, which were screwed and glued into the bricks.

For each test the maximum lateral load that was withstood prior to failure was recorded, meanwhile Figure 2 (right) shows the lateral load-displacement relationship for the each of the three specimens. Shear strength was calculated in accordance with [26] and the results are displayed in Table 2 below. The maximum lateral loads withstood by the unweathered specimen and the specimen exposed to 100 cycles of wetting and drying are very similar. The shear strength reduction of the 100 cycled specimen is also very small at only 6.7%; meanwhile the 200-cycle specimen suffered a far greater loss of strength, representing a 51% reduction, by far the greatest impact of the test.

Table 2: Strength and stiffness characteristics of weathered and unweathered wallettes

	Unweathered	**100 cycles**	**200 cycles**
F_{max} (kN)	10.8	10.6	4.2
Shear Strength, S (MPa)	0.105	0.098	0.051
Loss of S (%)	-	6.7	51

The failure mode of all the specimens was similar, with a diagonal path of failure developing entirely at the interface between the mortar and brick, travelling from the load point at mid-height on the left of the specimen towards the base of the specimen on the right hand side, (Figure). In the case of the unweathered specimen initial cracks were observed after 2.5kN of lateral load application, whilst by 10kN substantial cracking existed across the whole sample of masonry were mobilised against one another. The 100-cycle specimen maintained a relatively intact façade until 5kN of lateral load whilst mobilisation occurred at a similar load of 10.5kN. The 200 cycles specimen exhibited initial cracking at 2.5kN, with a complete crack network across the masonry face established by 5.5kN of load.

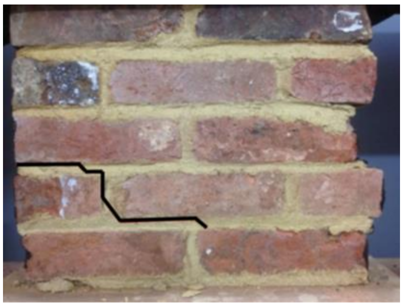

Figure 3: Failed masonry wallette showing location and extent of shear crack

4. Discussion

The data collected from these tests, along with visual evidence of the failure mechanism in the masonry, suggests that the difference in impact between the 100 cycle test and 200 cycle test is significant. The drying that occurred between the first and second 100 cycles in the 200 cycle test is likely to have contributed to this, although some alteration of the bonding of the masonry did occur after 100 cycles, as is demonstrated by the changing crack pattern. The fact that this decay did not occur after cyclic testing of the bricks suggest that the loss of strength exhibited by the masonry is almost exclusively as a result of loss of bond strength and reduction in strength of the mortar itself. A shear strength test tends to highlight loss of capacity in the mortar bonds, which supports the theory that the mortar is the material that has suffered most from the wetting and drying regime, as the wetting and drying cycle of the mortar is likely to be of greater amplitude than in the bricks, considering this is the preferential route for moisture ingress.

The results of the prolonged wetting and cyclic wetting tests on bricks demonstrate the different impacts of different weathering conditions, and highlight that brick does exhibit varying degrees of recoverability when exposed to these types of climate events. The results suggest that the hazard posed by wind driven rain to bricks is considerably less than that posed by flooding and saturation of this material, i.e. cyclic wetting is less hazardous than prolonged wetting. The result is a positive finding from the perspective of cultural heritage preservation, as it means that those climate events that instigate a wetting and drying cycle in the material, which are considerably more frequent than floods, are less damaging, and hence the risk is lower. The findings should be validated through further testing of different examples of historic brick however, as they are can be highly varied in terms of physical and chemical composition. Furthermore, significantly higher numbers of wetting and drying cycles may induce a loss, however further testing on this individual material is beyond the scope of this investigation.

This study showed that wetting and drying can be critical to masonry with historic bricks as it induces high levels of shear strength reduction after 200 cycles. Tests on individual materials showed that bricks are comparatively resilient to this impact, whilst the mortar suffered most from this weathering regime, which is in line with previous studies [32]. The fact that the reduction in shear strength is only 7% for the first 100 cycles in contrast to 51% after another 100 cycles shows that the rate of the strength reduction greatly increases after a relatively flat initial variation.

A monitoring system was implemented on the façades of a number of buildings studies as part of the Parnassus project, with a range of indoor, outdoor and in-wall temperature (T) and relative humidity (RH) sensors, in conjunction with rain gauges and anemometers, with the aim of quantifying the hygrothermal loading to which they were exposed [33,34]. The data obtained from monitoring was further analysed in order to understand how the findings of this lab test scheme translate into the actual buildings that have been studied in Tewkesbury. In one year from May 2011 to May 2012, on the most exposed southwest façade of one of the case study buildings in Tewkesbury, Abbey Mill, a Grade II listed, 4 storey brick masonry building from the late 18th century, there has been one episode of WDR exposure that lasted equal to or longer than 40 min, which is the wetting duration used in the lab tests. Therefore, one can conclude that cyclic wetting and drying as defined by the lab tests is not a frequent action affecting the building under investigation.

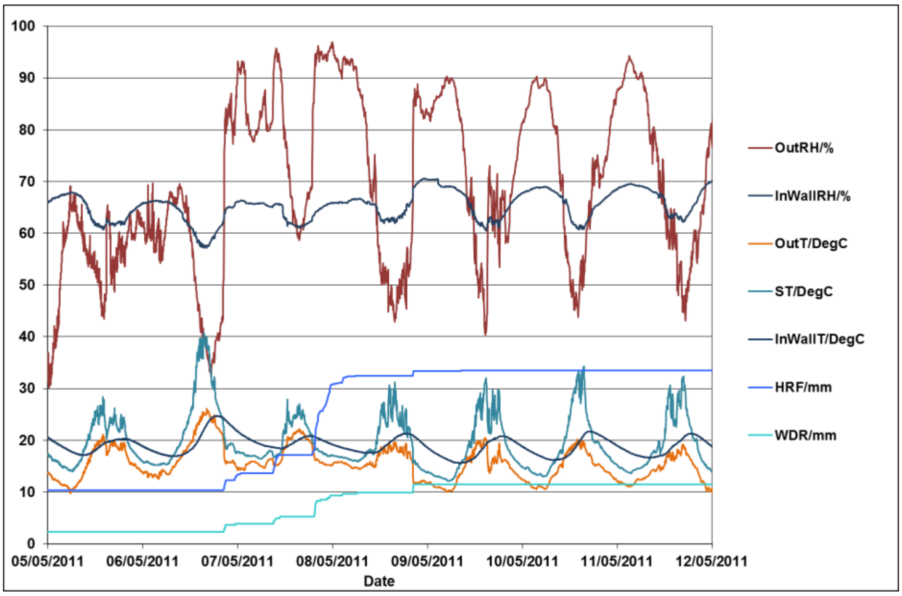

Figure 3: Monitoring results for a week between 05-12 May 2011 (ST and HRF stands for Surface Temperature and Horizontal Rain Fall, respectively)

Further, as seen from Figure 3 during this precipitation episode the outdoor RH values rise considerably, while for the in-wall RH the associated increase is around 5% from approximately the maximum value of 65% to 70%. On the other hand, it can be also seen the both the peaks and the nadirs of the outdoor RH and T fluctuations are followed by in-wall fluctuations almost without any time lag, but with a lesser degree of fluctuation. Therefore, the case study building can be said to be considerably resilient to cyclic wetting and drying action not only because of the rarity of such phenomenon, but also because of the intrinsic material properties that result in the dissipation of the extent of outdoor fluctuations.

5. Conclusions

The results show that the experimental weathering regime used here can result in significant degradation in the shear strength of the masonry, and that mortar is particularly vulnerable against this action. On-site monitoring showed that in one year, between May 2011 and May 2012, only one precipitation episode that produced wind driven exposure comparable to the wetting action defined by the testing programme. Whilst variation in the annual climate conditions must be considered, it is a fair conclusion that the building could have been exposed to more than 200 such cycles in its lifetime of approximately 300 years. As such the exposed and non-refurbished sections would have undergone shear strength degradation of the scale quantified by these experimental tests.

However it is currently uncertain how much the strength reduction indicated by the experimental tests is dependent on the length of the drying periods. In the experimental tests this period was less than three hours, while the data collected during the monitoring period suggest that on-site conditions can extend drying conditions up to a year. In this respect shear strength degradation on site may follow a different pattern of loss, and the effect of drying conditions needs to also be quantified before a complete appreciation of the weathering impact can be achieved.

This study aims at understanding the response of historic brick and masonry specimens to a series of weathering and mechanical tests within the context of wider work carried out at a case study location. The work highlights the value of designing a weathering regime that can more closely replicate the weathering processes taking place in-situ. In this way the data collected in this experimental programme is shown to be suitable for use in contextual analysis of individual historic masonry case studies, with respect to climate change impact and the associated alteration of wetting regimes. Despite the limited correlations made here, the difference between the weathering sequences used for testing purposes and observed on-site has be quantified for future work.

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