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This article reports on the research and development of a radically simple new form of solid, dry-jointed construction made of expanded cork and engineered timber. It has outstanding whole life performance, and the potential to help sustain biodiverse landscapes, and create buildings with exceptionally low whole life carbon emissions. Building blocks made of cork forestry waste interlock for quick and easy assembly, creating buildings that are low-energy to inhabit and simple to disassemble at the end of the building's life for reuse. The project investigates an architectural language of cork stereotomy as a progressive reimagining of historic dry-stone construction. The research is architect-led and multidisciplinary, undertaken in three steps from 2014 to 2019. Step one was curiosity-driven research, hypothesising and making the Cork Casket. Step two involved detailed design hypotheses, extensive prototyping, and lab testing addressing structure, fire and weathertightness. The Cork Cabin was created and monitored, and the system design established. Step three created Cork House. As the first building of its type, it is permanent, replicable, and designed to fully meet local building codes. Its corbelled profile knits into its site, with sheltering interiors offering a rich sensory living environment. The research confirms the potential for such simple new forms of off-site plant-based construction to help address construction industry challenges relating to whole life environmental sustainability performance, complexity, quality, and productivity.

Introduction

There is increasing evidence and recognition that our planet is currently in a climate change and biodiversity loss emergency, caused predominantly by human activity.[1] The construction and operation of buildings makes a significant contribution to the damage that we are causing to life on our planet, including accounting for nearly 40% of energy-related carbon dioxide emissions in 2017.[2] The environmental impacts of a particular work of architecture can be determined and reduced by using a whole life approach, addressing each stage of a building's creation, use, and end of life. This approach is relatively uncommon in the UK at present. Design and regulatory efforts over the last couple of decades focused mainly on reducing operational energy and associated carbon emissions via reductions targets in building regulations, planning requirements, and sustainability assessment rating schemes.[3]

Areas receiving far less attention include reducing embodied carbon and biodiversity impacts in the materials used for building, simplifying forms and methods of

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construction to reduce unmanageable complexity in construction and in use, and design for disassembly to enable recovery of resources for reuse at end of building life. Consequently, there is significant scope to improve the environmental performance of our architecture by a process of incremental improvements. This entails evolving existing systems and practices with consideration of environmental performance at each stage of a building's life. At the same time, developments in engineered plant-based materials and digital design and fabrication workflows are opening up opportunities to develop radically new forms of component-based construction. The question therefore arises: What might be achieved by researching and developing new forms of construction using the first principles of environmental sustainability as the starting point? And what opportunities might this open up in relation to architectural form, language, and typology?

Research aims

This research aimed to develop a radically simple new form of construction made of expanded cork blocks and engineered timber, the Cork Construction Kit. This was to help address issues of global warming and biodiversity loss, using a material that can help to sustain existing biodiverse landscapes. Considering each stage in a building's lifecycle, the approach was to develop a system with exceptionally strong whole life performance.

The research was undertaken over five years, in three incremental steps with related methodologies and resources, and this article is structured in line with these three steps. Step 1 commenced in 2014 with curiosity regarding the potential of building with solid expanded cork, and the possible benefits. Initial design ideas and hypotheses progressed to simple prototyping and testing. These resulted in a very modest prototype building, the Cork Casket, in early 2015.

In 2015, Step 2 proceeded with in-depth research in developing the Cork Construction Kit, partly funded by Innovate UK and the Engineering and Physical Sciences Research Council (EPSRC). This involved a multidisciplinary team from industry and academia, with project partners: MPH Architects, The Bartlett School of Architecture UCL, the University of Bath, Amorim UK, and Ty-Mawr. Arup undertook structural and fire safety engineering, and a range of lab tests were undertaken by the University of Bath, and the Building Research Establishment (BRE). A carefully tailored research methodology was developed, and played a key part in enabling progression as there was no off-the-shelf methodology for this type of research. This article presents the methodology used, for those with a broader interest in ways to develop new forms of construction.

Step 3 commenced concurrent to the Cork Construction Kit research, leading to the completion of the Cork House, the first building of its type, in early 2019. Post-occupancy evaluation of the house has now commenced.

The cork oak and expanded cork

Cork is the outer bark of the cork oak tree, *Quercus suber*. It is harvested around once a decade in a unique process of stripping that does not harm the tree

Figure 1.
(top) Stripping cork from a tree in the Portuguese Montado, © Amorim; (bottom) waste cork manufactured into expanded cork billets at Amorim, Portugal, © Oliver Wilton and Matthew Barnett Howland

(Fig. 1). Cork oak landscapes have existed in the western Mediterranean Basin for millennia. Their gentle form of silvo-pastoral agriculture helps to prevent desertification and support biodiversity in these regions.[4]

After harvest, cork planks are stacked to dry before being used for a range of products. The finest cork is used for wine bottle stoppers, and the majority of the cork is then available for other uses. This is either waste from the bottle stopper industry or from cork oak forestry (Fig. 1). This cork is generally granulated and used to produce agglomerated products, some with added binders such as polyurethane.

Pure expanded cork agglomerate, utilised in this research, is 100% cork with no added ingredients. It is formed by heating cork granules in autoclaves using super-heated steam. This causes the granules to expand, blacken, and meld together. The suberin naturally present in the cork binds the granules together to form expanded cork billets. Amorim, the suppliers of expanded cork for this research, manufacture expanded cork (Fig. 1) using energy of which over 90% is derived from biomass waste. The Environmental Product Declaration for the product notes a negative Global Warming Potential. The methodology counts the atmospheric carbon locked into the cork for its lifetime, and this exceeds emissions due to manufacture.[5]

So, expanded cork is a remarkable, carbon-negative engineered plant-based material, made from cork waste. It is the original foam thermal insulation board, and is also used as acoustic insulation and for vibration damping, available in densities from 100 to 300 kg/m^3.[6] Thermal insulation board is the type identified for use here, ranging in density from approximately 115 to 160 kg/m^3, and available in sizes of up to 1000 × 500 mm, with thicknesses of up to 320 mm. It is a good thermal insulator, with a typical thermal conductivity of 0.04 W/mK.

Expanded cork is used increasingly as an external weathering surface, following the first such application in the Portugal Pavilion for Expo 2000 Hannover, by architects Álvaro Siza and Eduardo Souto de Moura. This Pavilion now serves as a community building in Coimbra, Portugal.[7]

Step 1 — the Cork Casket

The Cork Casket served as a prelude to the in-depth research that followed. This consisted of the design, construction, and rudimentary testing of a very small expanded cork and timber prototype building (approximately 1.50 × 2.00 m and 1.80 m tall). This work developed and tested a preliminary version of the form of construction under consideration. It served to sharpen the thinking on specific aims, objectives, and the general scope of the main research.

Design and fabrication of a range of prototype assemblies was undertaken to investigate possibilities, and to become acquainted with the material first-hand (Fig. 2). Options investigated included interlocking cork blocks, cork with timber dowels to locate each block, and the use of lime mortar to bond each block course to the next.

The Cork Casket was built on a raised timber and plywood deck using rectangular cork wall blocks and corbelled cork roof blocks profiled to aid rainwater shedding. The blocks were slotted to take timber dowels, locating each block relative to the next, and delineating areas for the application of lime mortar between each course. This was fairly easy to assemble (Fig. 2), but rather time consuming due to the number of components and the application of lime mortar. The advantages with this form of cork construction include simple machining of the cork blocks with conventional woodworking tools, and low cork wastage from machining. The lime mortar offered some confidence that this relatively light form of construction would not simply get blown away. Disadvantages include the use of dowels and mortar with the cork blocks adding complexity and cost, and increasing construction time. Finally, the resulting composite structure is not easy to disassemble for re-use of the components.

Field testing revealed that the structure leaked, in part due to a design defect. This resulted in rainwater that passed down through perpendicular roof joints being retained within the roof structure in the area delineated by the timber dowels, before eventually leaking into the interior. Simple thermal and humidity

Figure 2 (opposite).
(left) Preliminary material, forming and assembly investigations; (right) constructing the Cork Casket,

monitoring of the Cork Casket was undertaken. A comparable structure of a similar geometry was then made with PIR insulation of the same u-value. The Cork Casket was a little cooler, perhaps due to higher air-permeability of the material, and some quality issues with the mortar application. The Cork Casket was more thermally stable than the PIR one, with less diurnal temperature fluctuation. This resulted in an improved internal thermal environment despite the similar u-value. It was thought to be potentially due to the thermal inertia characteristics of expanded cork as a hygroscopic material.

The Cork Casket work gave a feel for the character of the material, and one way to assemble it into a building. It also illustrated how a couple of decisions relating to certain aspects of assembly and building performance could rapidly turn a simple system into a rather complex one, incorporating numerous timber dowels and lime mortar. It was also fiddly to assemble, with unanticipated defects, and not easy to disassemble. This informed the decision to resolutely pursue the development of a very simple system of dry assembled cork block walls and corbelled roofs. We aimed to determine how much complexity could be removed by cork playing multiple roles in the system. We knew that it would be simple to then augment the core system if wished, for example by adding linings to change the visual appearance of a living room, or to strengthen the fire performance of a party wall.

Step 2 — developing the Cork Construction Kit

Hypothesis and methodology

Development of the Cork Construction Kit began in earnest in 2015. The aim to develop a simple, high performance, dry-jointed form of construction was formulated following consideration of certain historical and contemporary forms of construction. Examples of historical dry-stone construction, some dating back millennia, still resonate today for reasons including their stone stereotomy, simple, readily appreciable assembly, sheltering forms that relate directly to their compression structures, and longevity. Dating from the thirteenth century BC, the Lion Gate in Mycenae, Greece (Fig. 3) is constructed of monolithic stone, corbelled above its stone lintel and relieving triangle.

Current forms of construction typically involve more material and constructional complexity as an approach to delivering tailored performance benefits on multiple fronts. These include structure, durability, weathertightness, thermal performance, fire performance, appearance, cost, etc. For example, the timber-framed wall with brick outer leaf (Fig. 3) is an extensively used and well-regarded form of construction. It is cost-effective in delivering the desired performance in a relatively modest wall thickness, with a resilient brick weathering face. Constituents might typically include a timber frame as structure, foam plastic boards as thermal insulation, plastic vapour and breather membranes, painted plasterboard lining, an air cavity with steel cavity wall ties, and bricks and mortar external leaf. This complexity gives a viable form of construction with a level of in-use performance deemed to be satisfactory, but it can be relatively high in embodied carbon. It can also provide barriers to strong

whole life performance relating to construction, maintenance, adaptation, and disassembly for resource reuse at the end of the building's lifespan.

The Cork Construction Kit aims to deliver a simple form of solid cork construction that meets or exceeds all contemporary performance requirements, whilst avoiding the use of complex layered, aggregated construction. This is in order to deliver outstanding whole life performance and a distinctively tailored architectural language based on cork stereotomy (Fig. 3).

The hypothesis is that a simple assembly of dry-jointed cork blocks, augmented with engineered timber components, will be able to deliver a contemporary level of performance. The detailed roles of the materials and components in the delivery of the overarching system performance were developed over the duration of the research via an iterative process of design proposition, critical analysis, and reflection. Using cycles of hypothesis, test, evaluation, and reflection, we addressed matters including block geometry and fabrication, structural performance, weathertightness, and fire safety performance.

Project and risk management of the research was relatively involved, requiring frequent review and careful judgements leading to some resequencing of particular clusters of work. This was partly because there is no readily available methodology for developing new forms of construction such as this. Another reason is the complex, transdisciplinary, sometimes competing, interconnectedness of considerations for this sort of research. We needed to address a range of chicken-and-egg scenarios to carefully determine the optimal sequence for undertaking the evolving range of necessary tasks. Aspects of the methodology will be familiar to many building design team members as in places it resembles an extended architecture design methodology, focusing on notions of a building. The work extends further backwards and forwards (than is currently the norm) in terms of lifecycle considerations. It also addresses material science and formulation, manufacturing methods, indeterminacy regarding the role of the building component in the broader system that decreases as the work progresses, system standardisation, applicability for a family of building types, the need for a gradation in the means of production as the body of work progresses, etc.

Figure 3 (opposite).
(top left) Wilhelm Dörpfeld and Heinrich Schliemann at the Lion Gate of Mycenae, Greece (thirteenth century BC), 1884–1885, © Heritage Image Partnership Ltd / Alamy Stock Photo; (top right) contemporary timber frame wall with brick outer leaf, drawn by Kasia Skorkowska-Wilton; (bottom left) contemporary construction typically incorporates many elements and layers in order to deliver the desired performance, © Oliver Wilton and Matthew Barnett Howland; (bottom right) the hypothesis for the Cork Construction Kit is that it will deliver this performance with far less complexity, © Oliver Wilton and Matthew Barnett Howland

Preliminary research

The hypothesis for the ultra-simple building envelope asked a lot from expanded cork blocks in areas where its performance was undetermined from over a century of past use. Areas of unknown performance included weathertightness, structure, and some aspects of fire performance. Also, a more intimate knowledge of its machining characteristics was needed to better understand what viable forms it might be shaped into to serve as the building blocks of the system.

Expanded cork is simple and easy to machine using woodworking tools. Initial block prototyping investigated a range of preliminary system designs using block forms giving an interlocking, tongue and groove geometric fit from one block to the next (Fig. 4). This is a little like simple LEGO® bricks: the Lego Group initially made timber toy construction blocks before moving on to plastics.[8] The use of tongue and groove profiles in prototype blocks was also deployed with the aim of improving weathertightness performance.

Early investigations regarding the use of cork-to-cork compression joints, following the principle of cork wine stoppers, were not pursued further. The conclusion was that this might cause ripping in the assembled cork block structures over time, as compression in one part can put another part in tension. This made assembly more challenging, due to the need to pre-compress certain areas and it caused the blocks to tear during disassembly.

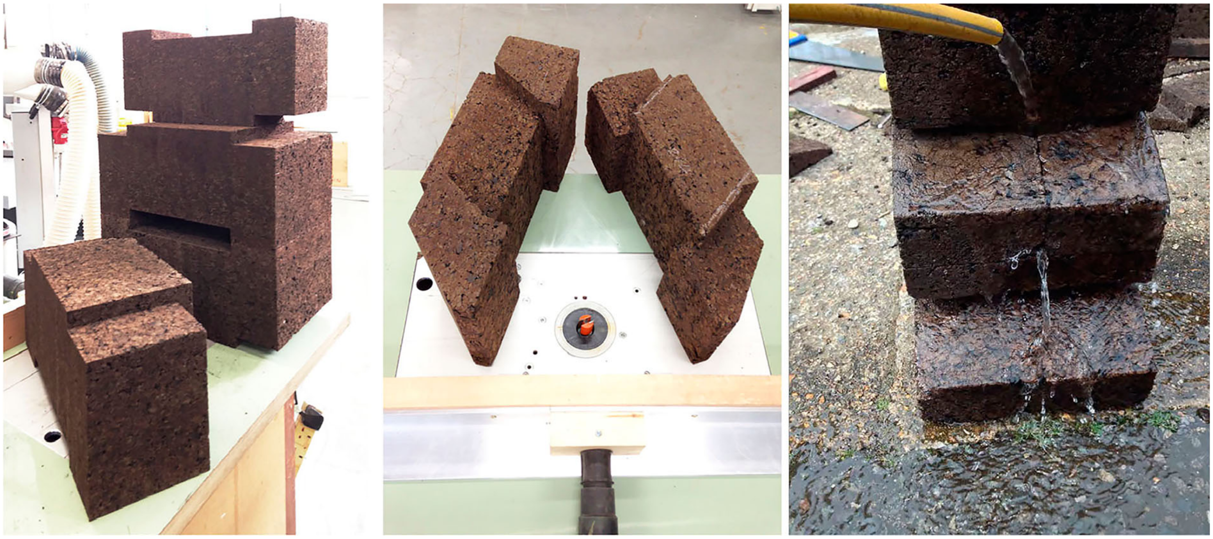

Figure 4.
(left) Tongue and groove interlock tests; (middle) prototype roof blocks; (right) rudimentary weathertightness testing,
© Oliver Wilton and Matthew Barnett Howland

Preliminary block assemblies were subjected to some very rudimentary structural and weathertightness tests. The simple tongue and groove geometry worked well in locating one cork block relative to another. The springiness, surface roughness and non-slip character of cork gives a friction joint when two parts are connected. The conclusion was that the intended approach might be viable, with no insurmountable issues identified, and an idea of key risks emerged.

Material selection

When considering expanded cork as a structural building envelope, advantages include its good thermal and acoustic insulation performance, relative chemical stability, negative Global Warming Potential, and ability to contribute to high indoor air quality. Its Euroclass E fire rating indicates the need for careful fire safety strategy development, to be informed by further fire characterisation work. The material is relatively lightweight and friable for a structural building material. Initial work with Amorim investigated the viability of producing higher density expanded cork blocks specifically for the project.

The density of expanded cork is varied during manufacture by altering the volume of cork granules added to the autoclave, and the pressure exerted by the autoclave during 'cooking'. A range of test billets were produced by Amorim at up to 300 mm thick and with densities of up to 230 kg/m^3. Quality control proved to be challenging, with large cracks to some test blocks indicating potential manufacturing limits in terms of block thickness and density. This was especially in relation to heat dissipation which is achieved via the injection of water into the core of the blocks immediately after the steam-cooking process. Indeed, the whole 'recipe' and 'cooking' process of the cork blocks is relatively complex, with variable relationships between granule size and quality, heat, pressure and volume, and the resultant density, cohesion, and consistency of the blocks.

By this time, work on structural characterisation and design by the University of Bath and Arup indicated that a standard formulation of cork may be suitable for the intended use. Utilising a new formulation would have meant no established characteristics. This would generate much additional lab work compared with using an existing material. In addition, the construction kit is intended to be available for use by other architects, with incremental uptake in its use, starting with pilot projects. The ready, off-the-shelf availability of the cork used is key to the initial viability of the construction kit, as this needs to be simple to order, with an acceptable lead time and cost. With these considerations, a standard facing grade of expanded cork was selected with a density range of 140–160 kg/m^3. With a maximum available board thickness of 220 mm, the maximum billet weight is approximately 17 kg.

Timber complements cork in the construction kit, extending the palette of forestry products. The cork blocks work in compression, with timber used elsewhere (including CLT floor and timber ring beams and lintels), and for weatherboarding on the roof. Upon advice from Arup, all timber integrated within the depth of the solid cork is acetylated in order to give suitable rot resistance.

Block geometry and robotic cork milling

The geometries for a family of cork construction kit blocks were developed and machined from trimmed billets of the maximum available size, 1,000 × 500 × 220 mm. This two-stage forming process was adopted following some preliminary research on the potential for more intricate block shaping during a one-stage autoclave forming process. It concluded that the autoclave process cannot be used to intricately shape blocks in the way that this work requires. Large block sizes were selected in order to minimise the number of parts in the kit, the amount of machining, and the number of joints in assemblies. The tongue and groove profiles were retained and evolved to give a suitable balance of structural fit and material efficiency. Slots were incorporated into the block designs in order to provide air pressure equalisation and drainage, making block geometries relatively complex. A lot was being asked of the blocks in their contribution to overall system performance. This relative geometric complexity was the result, or the price for keeping the system simple as a whole. This is especially the case in relation to the roof blocks, which incorporated an offset between the underside and the top of the blocks to achieve an interlocking corbelled structure.

This design approach resulted in many unique block types being required to form a complete cork building envelope. Using traditional woodworking tools was sufficient for the early studies, but a different approach was now called for. The cork block geometry was such that numerous jigs would be required to guide the tools for accurate shaping of each block type. The time taken to fabricate each block manually would have been prohibitive, both during system development and later during system application.

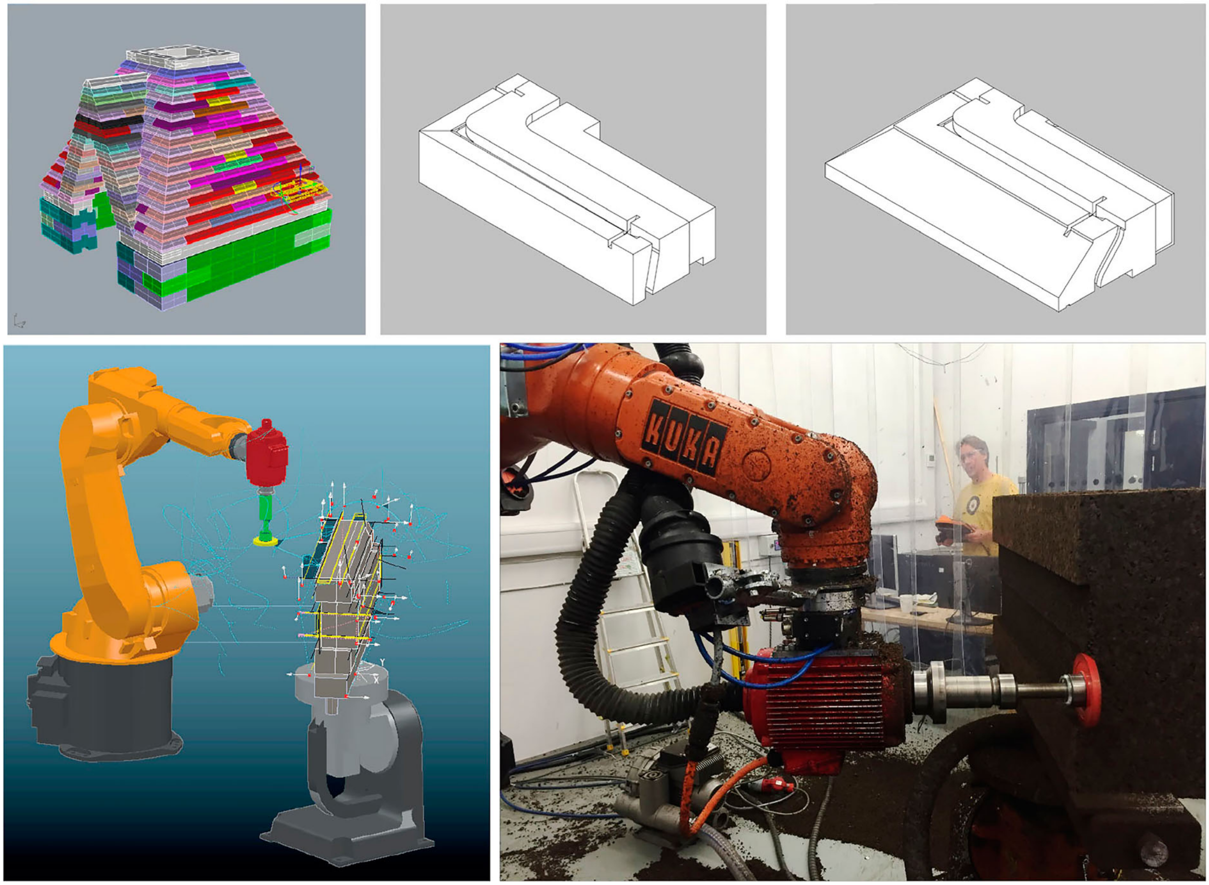

Figure 5.
Robotic milling workflow. (top left) Initial Cork Cabin design assembly; (top right) wall and roof cork block designs; (bottom left) determining toolpaths with PowerMill Robot; (bottom right) robotic milling of a cork wall block, © Oliver Wilton and Matthew Barnett Howland

Fabrication options were reviewed with Peter Scully, Director of B-made, The Bartlett workshops, where all prototypes were fabricated. Robotic milling was identified as being well suited to shaping multiple cork block types simply and quickly. A tailored cork milling method was developed specifically to do this (Fig. 5). This involved the use of a 6-axis Kuka KR60 HA industrial robot with 2-axis positioner. During milling, each cork block is held in place by a bespoke vacuum box on the positioner. This rotates to give the robot arm free access to mill five of the six block faces. The cork is milled to shape with a 125 mm diameter by 14 mm thick cutter connected with a bespoke spindle to a milling end effector on the robot. The need for multiple cutter geometries was designed out to avoid the need to manually change cutters which would have slowed the process down and added extra calibration challenges. The resulting configuration is able to mill large volumes of cork relatively rapidly. A target time of ten minutes of milling per block was set, and this was achieved for some wall block types further to considerable work in developing the setup. Roof blocks took closer to fifteen minutes.

The workflow for the robotic milling started with developing the block designs. These were modelled in *SolidWorks*. Their geometries were evolved to allow cutting with the single 125 mm diameter by 14 mm thick cutter. An early version of the Cork Cabin, a small prototype building, was first modelled in *SolidWorks*. A 1:5 scale physical constructional model was then created as a design development tool, partly to gain a fuller understanding of the assembly dynamics of the system, and partly to assure that there were no parts of the Cork Cabin that were impossible to assemble. Block geometries were exported to *PowerMill Robot* for toolpath development and milling. Some technical compatibility and control challenges arose and several workflows were tested. These included using *Rhino* and *Grasshopper* codes developed in-house to generate tool paths and transitions.

Developing the robotic milling workflow proved to be a relatively in-depth exercise, proceeding more slowly than anticipated. Significant work was required on robot calibration to deliver satisfactory tolerances. The system design required relatively high tolerance milling, circa ±0.5 mm, to give a satisfactory block-to-block fit. In addition, toolpath generation with the available software gave some unpredictable toolpaths, with transitions not always proving simple to control. There was a balance to be struck between the speed of the robot arm, the cutter's RPM, and the quality of surface finish. These issues were addressed and robotic milling was used to fabricate all subsequent blocks for the Cork Construction Kit research, including the Cork Cabin.

The use of robotic milling lowered the fabrication barriers to the development of the system and enabled the use of relatively complex block geometries. These allow the blocks to play a sophisticated role in the system performance, which in turn helps to keep the construction kit simple by avoiding the need to introduce other components and assemblies to augment performance on specific fronts.

Structural design and testing

There are limited historical examples of cork planks playing a structural role in walls, and expanded cork blocks have previously been used for internal self-supporting partitions.[9] In recent years, expanded cork has been used structurally in a number of small temporary pavilions. But its suitability for primary structural use in a permanent building was undetermined at the outset of the research. This raised the question: is expanded cork suitable for use as primary structure in a permanent building? It is clearly relatively weak for a structural material. But we posit that it is strong enough to act as a compression structure when used in large volumes as the principal building material.

As the work progressed, the structural design hypothesis was developed in detail with Andrew Lawrence and Gavin Maloney of Advanced Technology and Research at Arup. It was also informed by a range of detailed lab testing and structural characterisation work led by Professor Pete Walker at the University of Bath. The initial structural characterisation gave sufficient confidence to proceed in detail with the selected grade of expanded cork. Material testing proceeded to address compression, shear and creep characteristics, and other matters including coefficient of friction, and linear moisture shrinkage. Further work as the design progressed included structural testing of a prototype cork wall, including vertical, in-plane and out of plane lateral load tests.

The structural design focused on single-storey building applications. The structure consists of 480 mm thick cork walls, giving a high level of thermal insulation, built off of a raised timber floor structure. A timber ring beam at eaves level laterally supports the roof and walls, carrying wind loads back to lateral walls. This beam changes profile at openings to serve as a lintel. The roof is solid corbelled cork blocks, giving pitched roof or truncated pyramid forms, with intermediate horizontal timbers to resist wind loads. The roof is topped with a rooflight, giving some additional weight at the top.

The corbelled roof was developed due to an interest in this type of legible compression structure, which can be assembled with no falsework, and in the sheltering internal room forms that it creates. This is a relatively elaborate part of the construction kit, which can also be used with simpler pitched roof forms or as a wall-only system with a more conventional timber-framed roof.

Preliminary work was undertaken on developing the kit for use in two-storey buildings to increase applicability. The indication is that compressive strength would be sufficient, with some preliminary approaches identified to address creep and shear performance.

Fire safety design and testing

In common with many plant-based materials, expanded cork has relatively poor fire resistance. It has a Euroclass E fire rating, and is often used today within forms of construction that include covering layers to improve fire safety performance. This somewhat resembles the typical approach for structural timber framing, utilising elements such as plasterboard linings and brick external leaves to help deliver satisfactory fire resistance. Expanded cork is also used as an external weathering finish with no added treatments. Under this use, attention to spread of flame and other fire safety matters is needed.

Fire safety design was one of the key areas of research during the development of the construction kit. The aim to utilise cork structurally with no external or internal treatments or linings presented a number of issues requiring careful attention. Arup were the fire safety consultant for the research. Initial flammability and spread of flame testing on expanded cork was undertaken by the BRE Centre for Fire Safety Engineering at the University of Edinburgh. This informed the development of the system design, with sample panels then being tested at BRE, Watford.

Testing of sample inclined cork roof panels to 'BS 476 Part 3: 2004 incorporating amendments A1: 2006 and A2: 2007 — External fire exposure to roofs' gave results on preliminary ignition, spread of flame, and penetration testing. This established a designation of EXT.S.AB indicating that the panel had not been penetrated by fire within sixty minutes (Fig. 6), and that spread of flame was not more than 533 mm. The testing also resulted in a classification to 'EN 13501-5: 2005 incorporating amendment A1: 2009 — Fire classification of construction products and building elements' of B_{ROOF}(t4), indicating a fire penetration time of equal to or greater than sixty minutes.

The designations resulting from the lab tests inform the fire safety design for specific applications of the construction kit, as for other forms of construction. In

Figure 6.
Sample roof panel laid horizontally immediately after fire penetration testing, with charring indicating the visible extent of fire penetration, © Matthew Barnett Howland

practice, a small ancillary building, such as a home office, in a relatively fire-safe location away from site boundaries may not require further fire safety elements to be incorporated, while other building types or locations typically will. For a typical house, the cork walls to the interior will need to be treated with a suitable fire retardant. They could be lined, or a sprinkler system could be introduced to provide satisfactory internal spread of flame characteristics. Where a building is in close proximity to a boundary, the relevant cork wall faces will need to be treated with a fire retardant, or suitably clad. The research focus was on the application of the construction system in single-storey buildings. Preliminary investigations regarding the applicability to two-storey buildings identified the need for further lab tests on wall performance.

Weathertightness design and testing

Expanded cork has been used as an external weathering surface for nearly twenty years. As such, its suitability and resilience for this application is becoming relatively well established. Beyond this, the construction kit also requires expanded cork to stop rain penetration into a building, and to act as an air permeability barrier, neither of which it has historically done.

Cork as a material is relatively water-impermeable and airtight. But expanded cork blocks include fissures and voids between the expanded granules, typically around 16% in 130 kg/m^3 cork. These can potentially give routes to enable water and air to pass through a block.[10] Some rudimentary early material testing was inconclusive. Since it did not rule out the feasibility of expanded cork acting as a watertight and airtight barrier in a building envelope, the research proceeded with the aim of further testing this.

Design proceeded on the assumption that the cork blocks would be sufficiently airtight, with the dry joints being vulnerable to air leakage. This would be especially the case for the perpendicular joints that would not be compressed by gravity. For this reason, easily removable foam airtightness tape is fitted at block-to-block joints on the interior face of walls and roofs. This approach was later put to the test with an air permeability test on the Cork Cabin.

In addition to the preliminary testing, initial research regarding rainwater penetration included observations on site visits and anecdotal information from various parties. These indicated that where expanded cork was used as an external facing material, rainwater tended to permeate an outer zone, no deeper than 100 mm, and dried out fairly quickly after rainfall. The design and shaping of the cork blocks aim to stop rainwater penetration through the dry joints using stepped profiles, air pressure equalisation slots, and drainage channels. The air pressure equalisation slots are intended to balance air pressure within the joint, and to give no suction of rainwater into the joint, externally. The airtightness tape also reduces the potential for wind pressure differentials causing rainwater suction. The drainage channels are intended to drain any water passing in through joints back to the outer face. The initial system design did not attempt to counter water penetration directly through the material itself.

Following on from rudimentary testing, wall and roof sample panels were produced and tested in accordance with 'CEN FprEN 15601:2012 — Hygrothermal performance of buildings' at BRE, Watford. More specifically, we carried out a Type B test, designed to simulate the worst combination of wind and rain conditions likely to occur in Northern Europe during any fifty-year period. This is implemented at BRE with the use of a wind tunnel to direct sprayed water on to the sample, which is mounted on a suction box to simulate differential wind pressure. A sparge bar at the top of the sample is used to simulate water run-off from further up the building envelope (Fig. 7). The test resulted in no water leakage through the wall, including at a high air pressure factor of over 275 Pa. The roof test panel started to leak water at a pressure factor of under 60 Pa. It reached a leakage of 10 g/m^2/5mins at 68 Pa, with leakage increasing further under higher pressure factors. Water was observed passing through some blocks that had become saturated, and also through certain joints. These identified areas for design revision.

Subsequent to the roof panel test, the roof system was developed further to improve rain penetration performance. The revised design included changes to roof block geometries. Cedar weatherboarding was added to inclined external

Figure 7.
(top left) Wall panel under wind-driven rain testing; (bottom left) testing the first roof panel, which leaked; (right) testing the second roof panel, which didn't leak. Water shedding from timber weatherboards is visible, © Oliver Wilton and Matthew Barnett Howland

block faces to shed rainwater, and prevent it from gradually saturating cork blocks from above during periods of prolonged heavy rain. The weatherboarding is screw-fixed into insulation plugs in the cork to retain a relative ease of disassembly. A panel fabricated to the revised design was tested to the same rain penetration standard by BRE (Fig. 7). This time, the result was no water leakage, including at a high-pressure factor of over 175 Pa.

The Cork Cabin

The Cork Cabin is a small single-room prototype building that was made to test the developing construction kit. This work proceeded to test the system as a whole. It was carried out in parallel with the lab test work addressing particular aspects of system performance, as the research was sequenced to carefully address a range of intertwined issues. Upon completion, the cabin performance was then monitored for twelve months, through the seasons.

Figure 8.
(top) Cabin roof assembled to check fit at The Bartlett then disassembled for transport to site; (bottom) Cabin assembly on site, © Oliver Wilton and Matthew Barnett Howland

Prior to fabrication, the cabin design went through a number of iterations, which related to developing the block designs and the overall building form. An initial design had a more complex building geometry (Fig. 5) than was needed for testing general applications of the system. This was simplified to reduce the number of unique block types needed. The corbelled roof also required rationalisation to minimise the number of block types whilst maintaining sufficient horizontal offsets between perpendicular joints to maintain structural integrity and weathertightness.

Each cork block was robotically milled at The Bartlett. A total of 202 blocks were used to build the cabin. This comprised ten generic block types, with forty-four unique block geometries in total (twelve for the walls and thirty-two for the roof), each weighing a maximum of 15 kg, depending on size. The blocks were fabricated in two batches (first the wall, and then the roof). These batches were each assembled at The Bartlett prior to disassembly and transportation to site in Berkshire (Fig. 8). This assembly work was undertaken to ensure sufficient milling tolerances to give satisfactory block interlocking. It also served to identify any other assembly issues for rectification prior to transport to site. Finally, this was a test and confirmation that the system was indeed as simple and easy to disassemble as had been intended, to allow component reuse at the end of the building's life.

Milling the cork blocks generated significant volumes of expanded cork granules as a by-product. These have a range of established uses including loose fill insulation, and being added to screed. Project partner Ty-Mawr already utilise granulated cork in some of their products. They used some of the by-product to produce experimental lime plaster and lime mortar floor mixes, and to compress to form cork fuel briquettes.

The on-site cabin assembly sequence started with the cork walls built off of a raised CLT platform supported by a timber perimeter beam (Fig. 8). The CLT was supplied in strips of approximately 90 kg in order to enable manual assembly with no lifting gear. Assembly of the cork blocks proceeded as intended, and was pleasingly straightforward. It was relatively easy to do as a one-person operation, by carefully locating each block before firmly pushing it into place. Final positioning was done with the aid of a timber mallet, due to the relatively snug bock-to-block fit. A ratchet strap was used to encircle the wall as it was built up course by course. This strap was needed to keep the blocks in place, and prevent them from nudging apart horizontally. It also prevented perpendicular joints from opening up during assembly. The strap was removed after the fitting of the timber ring beam at eaves level that locks the wall assembly. As well as transferring lateral loads to perpendicular walls in the completed structure, the ring beam also acts as a geometric control point at the head of the wall, locking blocks into position by limiting the length of each wall run to that intended, preventing perpendicular joints from opening up over time.

The corbelled roof was simple to assemble block by block, working from a suitable scaffold platform, with no additional support needed for the corbelled structure during assembly. These blocks do not tend to nudge apart horizontally during assembly because of the way their weight acts on the inclined structure. This makes the roofs slightly easier to assemble than the walls. The timber trimming beams at the head of the truncated pyramidal roof support the glazed aluminium rooflight. They also act as a geometric control point for the roof block structure. The rooflight contributes to the weighing down of the finished structure.

The completed Cork Cabin was photographed in spring 2018, around six months after completion (Fig. 9). The photograph shows the weathered cork surface which silvers naturally, somewhat similar to timber. It becomes much lighter than the dark brown colour of freshly manufactured blocks. Situated next to the Cork Cabin in the photograph is the Cork Casket, the preliminary cork prototype building made around three years earlier during Step 1. As the cork blocks silver, they take on an appearance more similar to stone or concrete. It is easy to see why cork has long been used to make architectural models of stone buildings, some of which can be seen today in the newly recreated model room of the Soane Museum.[11]

Figure 9.
Cork Cabin on site, around six months after completion, with Cork Casket standing adjacent,
© Oliver Wilton and Matthew Barnett Howland

The completed cabin was tested for air permeability, with a result of 8.53 $m^3/h.m^2$ at an imposed pressure differential of 50 Pa. This surpasses the current UK Building Regulations threshold. The use of a thermal camera to survey the cabin during positive and negative pressurisation revealed areas of significant air leakage. These included cork-to-timber joints around the eaves beams, and internal cork-to-cork corners. These were all areas where foam tape was not utilised. This informed system design adjustments, including using foam airtightness tape at the internal faces on all joints (which is easy to remove during disassembly).

The cabin was then monitored through the seasons, including visual inspections to ascertain the general performance of the building envelope. A weather station and temperature and humidity data loggers were also used in the cabin and within the depth of the cork building envelope to ascertain performance.

After some months the cabin roof started to leak water. The extent of this was limited, and it occurred only through certain blocks on a specific elevation. But it indicated a variation in water permeability between blocks. This is easily understood as a result of variations in localised block density due to the manufacturing process, and a variation in site conditions regarding aspect, prevailing wind, and overshadowing by tree canopies. This leakage concurred with the rain penetration lab testing of the unclad cork roof sample. The system was developed in response to this, including the incorporation of timber weatherboarding to inclined roof block faces (Fig. 7). The Cork Cabin roof was subsequently retrofitted with weatherboarding, after which it stopped leaking.

The resultant system

The result of this work is the development of the Cork Construction Kit to the point where it is sufficiently defined and standardised. Levels of uncertainty are reduced and the system de-risked to the point where it is suitable for application to pilot construction projects. The range of lab testing undertaken has characterised the material and system sufficiently to enable a range of single-storey applications in relatively low-density contexts. Exploitation planning has identified these as including small ancillary buildings such as home offices and summer houses, dwelling houses, school classrooms, and community buildings. Further research, lab testing, and design development on structural and fire safety matters would enable the development of the system for two-storey, and higher-density applications.

Step 3 — the Cork House

The Cork House was completed at the start of 2019. It is the first building of its type. Sited within the curtilage of a Grade II listed mill house on a small island in the Thames, it is a permanent building with solid structural cork walls and roof, designed to fully meet relevant building codes. It utilises an evolved version of the Cork Construction Kit, augmented to address particular site conditions. This was a rare and ideal opportunity to put the newly researched and developed form of construction to the test on a modestly scaled live building project.

Design

The house is carefully tailored to its site, nestled within its own walled garden. It has a simple linear plan laid out with its back to a brick garden wall. It is formed of five structural bays, each with its own truncated pyramid roof topped with a skylight (Fig. 10). An open bay at the south end acts as a gateway into the garden and an open antechamber to the house. The house is built on a raised CLT deck with cork insulation to the underside. This rests on perimeter timber beams that are supported on steel screw pile foundations, resulting in an entirely cement-free building. The piles are simply screwed into the ground, and are easy to remove at the end of the building's life by unscrewing.

The walls and roof are made with 1268 interlocking pure expanded cork blocks, with careful integration of timber eaves beams and lintels, and cedar weather boarding to the roof. Windows and doors are to a bespoke design in acetylated timber, giving long life and low maintenance. Gutters and downpipes are formed from untreated copper, with sympathetic weathering characteristics, long life, and minimal maintenance requirements.

The interiors provide a rich, protective, tactile and sensually evocative environment. The end bays function as chambers for the bedroom and bathroom. The

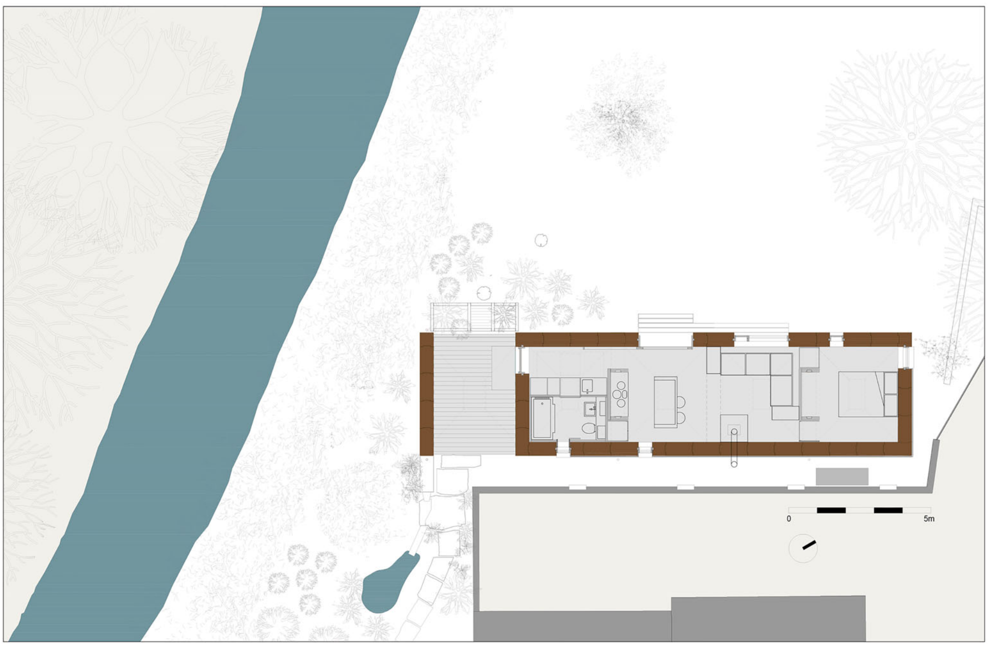
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Figure 10 (opposite).
Long section, plan and elevation of the Cork House, © Oliver Wilton and Matthew Barnett Howland

central bays provide living accommodation opening onto the garden. Skylights cast daylight into the spaces below and also open in summer to provide cooling stack ventilation. Interior fittings extend the material palette with oak, pine triply, untreated brass, and wool.

The structural strategy, developed with Arup, utilises the cork walls and roof as simple compression structures built off of the floor beams and CLT deck. Eaves beams take lateral loads, mainly wind loading to the main facades and roof, back to lateral walls. The interior is relatively open plan, with no lateral cork walls. The central truncated pyramids are supported on lateral timber beams. Two structural CLT wardrobes transfer lateral wind loads down from the lateral beams to the CLT floor structure.

The fire strategy, also developed with Arup, incorporates a sprinkler system to the interior to give the necessary internal spread of flame performance. An alternative would have been to line the cork or treat it with fire retardant. For this project, the intention was to deploy the cork wall system in its simplest form, and not to chemically treat the cork blocks which may affect indoor air quality. It would also contaminate them in relation to possible future uses after the end of building life. Externally, where the building is located close to the site boundary to the north and east, these façades are clad in cedar weather boarding treated with fire retardant to give the necessary spread of flame performance. Cork blocks of simpler geometry are used in these walls as the timber rainscreen prevents rainwater penetration.

The house is heated by a wood-burning stove, utilising a plentiful supply of logs from pruning the numerous trees on the site as a part of their regular maintenance. A gas condensing boiler provides hot water, and electricity use is partly offset by an on-site photovoltaic array. Building services cables and pipes utilise simple services ducts within the CLT floor and structural wardrobes, giving easy access. Copper sprinkler pipes are face fixed to the corbelled cork roof forms.

Fabrication and assembly

A range of fabrication options was considered for shaping the cork billets into the building blocks for the house. A feasibility study was undertaken on using robot-assisted self-build, whereby an industrial robot would be temporarily installed at the construction site and the cork billets delivered from Amorim Portugal directly to site for robotic milling and then assembly. It was attractive to think that the digital workflow used to fabricate the Cork Cabin blocks could lend itself to this application. It could potentially reduce the financial costs of using the system by removing an intermediate specialist contractor and associated transport costs. This arrangement could be well suited to an enthusiastic self-builder prepared to undergo training to operate the robot. This option was not implemented for a number of practical reasons, including the need to install a 3-phase electricity supply at the site to power the type of robot that the workflow had been developed for.

In the end, fabrication of the blocks was undertaken by Wup Doodle Ltd using a large 5-axis CNC milling machine (Fig. 11). Milling cork in this way did present some challenges to be overcome but this type of milling is relatively well

Figure 11.
(top, from left to right) Model of corner wall block profiled to accept door frame, CNC milling a block, wall blocks on site ready for assembly; (bottom) assembling the walls and roof, © Matthew Barnett Howland

established and widely available in the UK compared to large format milling of biomaterials using a robot arm. This is comparatively slower, less well developed and currently not commonly available in industry. Using 5-axis CNC milling increases the applicability of the Cork Construction Kit and gives the potential to scale up its use now in the UK, with sufficient capacity already in place in industry to do this.

The cork billets were milled and then transported to site in batches in the correct sequence for assembly (Fig. 11). Assembly of the cork block system on site was a relatively simple manual operation undertaken by one or two people. The walls were mostly assembled working directly off of the CLT floor deck, and the roof was assembled from a scaffold platform. No falsework was needed to support it during construction (Fig. 11).

Some challenges faced during construction included the receipt of some blocks milled out of tolerance. These required some remedial work on site. Another problem was the tendency for the wall blocks to spread out horizontally course by course as the walls were assembled. As a result, they were too long when they got to the timber ring beams at eaves level. Ratchet straps were used to nudge and hold walls to their correct geometries prior to fitting the ring beams, timber window, and door sub-frames, which locked the geometries. Overall, the system demonstrated itself to be suitable for assembly by general builders with no specialist expertise, and by enthusiast self-builders.

Whole life carbon assessment

The house was carefully designed to have outstanding whole life performance. We intended to use the construction kit in the simplest form applicable to the site, to test and demonstrate what it could do. Lifetime carbon emissions are one key aspect of whole life performance. Sturgis Carbon Profiling LLP (SCP) undertook a whole life carbon assessment of the Cork House to BS EN 15978. The assessment estimates the whole life carbon emissions for the house, based on a sixty-year lifespan, at 618 $kgCO_2e/m^2$ GIA, the lowest of any building ever assessed by SCP. This includes 286 $kgCO_2e/m^2$ of embodied carbon over the lifespan of the building. The house is embodied carbon negative at completion, –18 $kgCO_2e/m^2$, due to the atmospheric carbon stored in the cork and timber. Embodied carbon then gradually accrues over its life as services, and other features are renewed. The 333 $kgCO_2e/m^2$ of operational carbon relates mainly to electricity use, with the on-site PV array reducing carbon here. The use of logs from on-site tree maintenance to heat the building is near carbon neutral, as this forms part of a natural carbon cycle of atmospheric CO_2 absorbed by trees during growth and then in due course re-emitted to the atmosphere, in this case via combustion.

It is interesting to compare the figures for the Cork House to those for the reference projects included in the SCP study. The whole life carbon for the Cork House is less than one-sixth of that for a typical new-build house at 4110 $kgCO_2e/m^2$, around one-third of that for the reference timber frame Passivhaus with no renewables at 1830 $kgCO_2e/m^2$, and under half that for the reference zero operational carbon building at 1500 $kgCO_2e/m^2$, all of which relates to embodied carbon. These comparisons underline the need for a whole life carbon approach when assessing relative merits, and total carbon impacts associated with a building.

Furthermore, all whole life carbon is not equal. For new buildings, there is a case for prioritising embodied carbon reduction, such as by locking carbon into the building structure in the way that the Cork House does. This delivers the carbon reduction at the start of the building's lifespan, helping to contribute to urgently needed carbon reductions now (to help limiting global warming to 1.5°C),[12] as compared to rather less certain operational carbon reductions over the coming decades (if the building remains operational and performing as predicted over this period, and subject to the rate of decarbonisation of the UK electricity grid).

Completion, inhabitation and post-occupancy evaluation

The photographs of the finished house are taken several months after completion. Externally, the cork is starting to weather and silver, along with the cedar weather boarding to the roof (Fig. 12). As the photographs suggest, it is a unique work of architecture, owing both to the use of the cork system and its careful tailoring to its site. Visiting the house in person is a far richer and more evocative experience than conveyed in the photographs, due to the tactility, aroma, and calm acoustics provided by the sheltering cork compression

Figure 12.
(top and bottom left) The finished Cork House, photographer Ricky Jones, © Matthew Barnett Howland; (bottom right) thermal image of an interior wall and roof area during negative air pressurisation. Dark tones indicate areas of air leakage, © Oliver Wilton

structures. These are all legible and readily understood when inhabiting the building.

The house was air permeability tested at completion and gave a result of 5.64 $m^3/h.m^2$ at an imposed pressure differential of 50 Pa. This is significantly less permeable than the Cork Cabin. It indicates that design changes, including better eaves beam integration, have led to improved airtightness performance, and a little over half the maximum permitted by the current UK Building Regulations. The use of a thermal camera to survey the house during negative pressurisation revealed areas of air leakage that could be reduced. These included areas around the sliding glazed timber door, and some cork-to-timber joints (Fig. 12).

At the time of writing, the house is performing as intended overall. It is watertight, and also warm in winter during the internal fit-out, despite very limited heating. Detailed post-occupancy evaluation has started, including thermal and humidity monitoring that commenced in July 2019, and runs for a minimum of twelve months.

Whilst the Cork House is the result of significant in-depth technical research, it also has a unique character, and a simple, compelling, overarching narrative that is easily understood and enjoyed by anybody. This makes it of relatively broad interest and relevance, and dissemination is currently underway via the architectural and mainstream press in the UK and internationally. The house has attracted a multitude of visits both during construction and after completion. Visitors came to experience the building and learn about its cork form of construction, how the building was made, and its whole life performance. There has been an enthusiastic response from visitors ranging from school children to students in further and higher education, members of the public, academics, architects, and other construction industry professionals.

Conclusions

An interest in developing a new form of construction from environmental sustainability first principles, with consideration of each stage in a building's lifecycle, has led to the development of the Cork Construction Kit. This uses interlocking expanded cork blocks, made with cork oak forestry waste, and timber to create a radically simple new building system. It is dry jointed and easy to assemble. The system can be used to create buildings that are delightful to inhabit, and low energy in use. At the end of building's life disassembly is simple, enabling the components to be reused or recycled.

The research that commenced with rudimentary curiosity-driven investigations has progressed to the construction of the Cork House, a live architectural project and the first deployment of the new system. The research has also incorporated significant in-depth technical research, with a range of lab testing that contributes to a fuller characterisation of expanded cork in construction. The next step is to proceed with detailed post-occupancy evaluation of the Cork House, to gain a fuller understanding of the in-use performance of the system. Some further pilot projects are also intended. Further research that could expand the applicability and scalability of the Cork Construction Kit includes:

- More detailed system standardisation and work to optimise the block fabrication workflow.
- Development of roof weatherboarding integration for pitched roofs, and development of other roof types.
- In-depth exploitation planning and a programme of market engagement.
- Further structural design development and lab testing with the aim of establishing a viable two-storey variant of the system.
- Further fire safety design development and lab testing with the aim of establishing viability for two-storey use and higher density uses including fire-compartmented buildings and terraced housing.

The research is also concerned with stripping away material and constructional complexity from building. In this respect it can be seen relative to the work of certain architects with an interest in the architectural possibilities of simple, solid, low-carbon construction. These include Gilles Perraudin with his remarkable work in solid stone, including the Wine Museum in Patrimonio, Corsica, 2011, and Social Housing in Zac Monges, Toulouse, France, 2013.[13] The rammed earth projects of Martin Rauch also have some commonality of approach, including Lehmhaus Rauch (with Roger Boltshauser) in Schlins, Austria, 2009.[14] In the UK, the Architecture Archive, Somerset, 2014, designed by Hugh Strange is a notable reference project, with its solid CLT walls and roof.[15] In common with these projects, the construction kit delivers a radically simple building envelope. This has the potential to reduce complexity in the construction process, with potential benefits relating to organisational and technical risk, productivity, and quality.

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Step 3 — The Cork House. Architectural design of the Cork House is by Matthew Barnett Howland with Dido Milne and Oliver Wilton, with structure and fire safety engineering by Arup. The clients are Matthew Barnett Howland and Dido Milne. The construction project manager is Matthew Barnett Howland. CNC milling of the cork blocks is by Wup Doodle Ltd.

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