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BIO-MATERIALITY

THE ROLE OF ROBOTIC MILLING IN THE RESEARCH AND DEVELOPMENT OF THE CORK CONSTRUCTION KIT

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Aims and Objectives

The aim of this research was to develop a viable robotic cork milling method that could contribute to the development of the Cork Construction Kit, a radically simple new form of cork and timber construction developed under a broader research project and subsequently refined further and used in Cork House, the first of its type.

Research Context

Cork is the outer bark of *Quercus suber*, the cork oak tree, harvested around once a decade using traditional methods in a process that does not harm the tree. It has been used in construction for several millennia, including documented use as a roofing material in Roman times (Pereira, 2007). The material used in this research is pure expanded cork agglomerate (expanded cork), accidently invented by John Smith in New York and patented in 1891 (Thomas, 1928; Smith, 1891). Expanded cork was widely used in construction in the 20th century, mostly as thermal insulation board, and has been resurgent in recent years, in part due to its strong environmental sustainability profile and also its rich experiential character when used as an internal or external finish.

The specific material used for this work is manufactured by research partner Amorim in Portugal using granulated cork, the by-product from forestry and other cork industries, which is cooked with pressurised steam in autoclaves at around 350°C using heat from waste biomass (Fig. 2). The result is a 100% plant-based cork billet with a very particular combination of properties, bonded with the suberin resin naturally present in the cork. It is thermally insulative (its principle use is as an insulation board), vapour permeable, aromatic, and has some load bearing capacity, as indicated by some of its historical uses, for example self-supporting partitions (Thomas, 1928). It is also carbon-negative owing to the absorption of atmospheric carbon during the growth of the tree bark (refer to Environmental Product Declaration number DAP 002:2016 for specific figures).

Due to its particular combination of properties, expanded cork was identified as a suitable material for use in the development of a radically simple new form of construction, the Cork Construction Kit. This combines large format monolithic cork blocks with engineered timber and aims to fulfil all of the performance requirements of the contemporary building envelope and deliver exceptional whole life performance. The aim was that the interlocking

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cork block assemblies, dry jointed with no glue or mortar, would provide structural enclosure, thermal and acoustic insulation, and rain and air tightness. This work was undertaken in three interrelated and overlapping stages, with initial hypothesising and prototyping being undertaken from 2014 to 2015, the major research project being undertaken from 2015 to 2018 and Cork House being constructed from 2017 to the start of 2019.

Initial prototyping work undertaken at The Bartlett utilised traditional woodworking machine tools to shape the cork billets into blocks of relatively simple geometry, which slotted and locked together when combined with timber profiles. Expanded cork is relatively straight-forward to machine using these tools. This initial system utilised lime mortar to bond each course of cork blocks together to form walls and a corbelled roof in a construction method that had some similarities with traditional masonry and was used to make a very small first prototype building in late 2014, the Cork Casket.

Work was undertaken in 2015 with research partners to develop a custom grade of expanded cork for use in the project. A range of sample blocks of differing densities was produced by Amorim. Alongside existing production grade samples, these were all characterised using lab tests at the University of Bath and were then reviewed by Arup. The outcome was that an existing grade of cork, MD Façade, was selected due to its suitable characteristics and because of the broader applicability benefits for the system of using a readily available product that did not require a special production run to manufacture. MD Façade has a density of around 150kg/m^2, with cork granules selected with care in order to give a good quality surface finish.

The Reasons for Selecting Robotic Milling and the Questions Arising

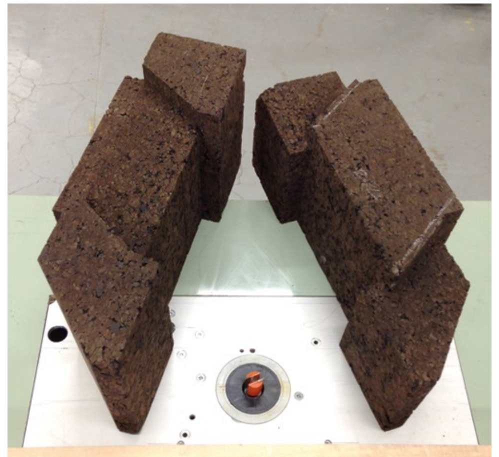
Evaluation of the system used in the Cork Casket determined that the timber profiles and lime mortar used to connect the cork blocks were building in unnecessary technical challenges and significant whole life complexity to the structure. A decision was made to pursue the development of a simpler form of wall and roof assembly using only expanded cork blocks, without any additional elements. Tongue and grooved block geometries were developed that interlocked in plan and section with an interference fit, a bit like a giant plant-based toy construction kit. The development of a dry-jointed assembly method was of particular interest in relation to ease of assembly, and ease of disassembly enabling ready recovery of the blocks at the end of a building's life. Initial block prototypes cut using a table saw and spindle moulder showed promise (Fig. 3).

1. View of Cork House from the garden, 2019. Image: David Grandorge.

2. Freshly cooked expanded cork billets emerging from the autoclave at Amorim, Portugal, 2015. Image: Matthew Barnett Howland and Oliver Wilton.

3. Interlocking tongue and groove roof blocks fabricated with a spindle moulder and table saw, The Bartlett, 2015. Image: Matthew Barnett Howland and Oliver Wilton.

4. Left, model of early Cork Cabin design in SolidWorks. Right, roof block toolpath development in PowerMill Robot. 2015. Images: Matthew Barnett Howland and Oliver Wilton.



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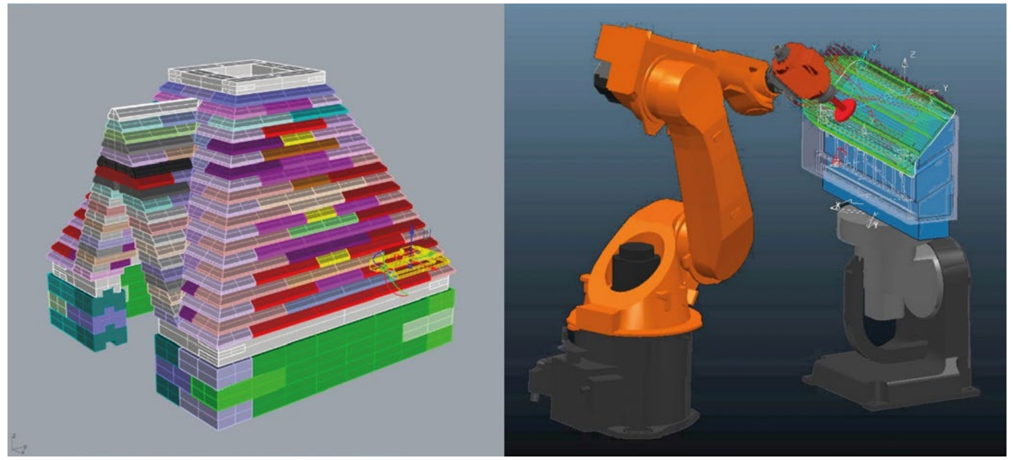

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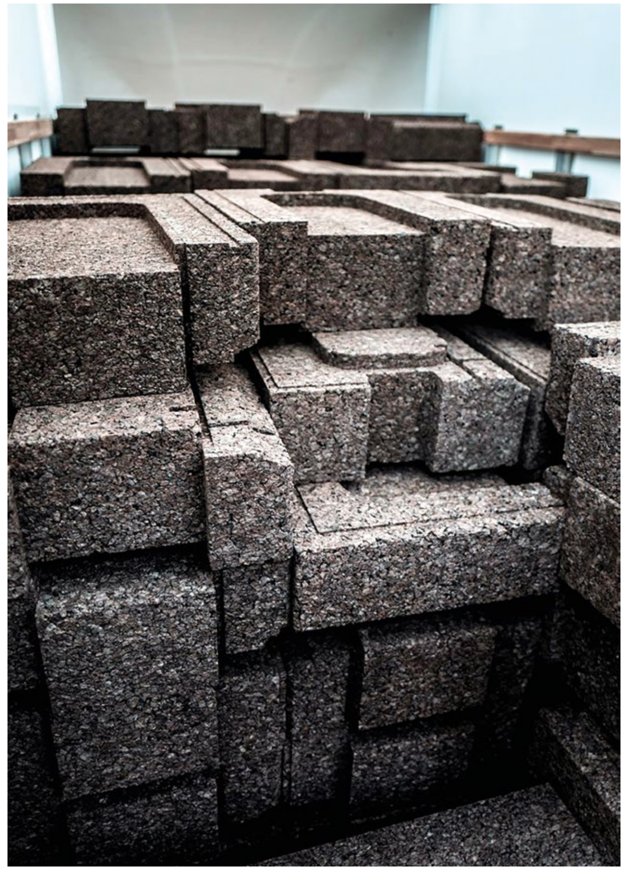

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5. Cork Cabin blocks being transported from The Bartlett to the site in Eton, UK, 2016. Image: Magnus Dennis.

Using traditional machine tools has the advantage of maximising broader applicability, with the potential for the cork block system to be readily machined by any joinery workshop. However, while there is a simplicity in asking one material to perform all of the functions of a building envelope, as design hypotheses developed so the resultant block geometries became more complex due to the multiple roles required from the blocks, and this in turn was time consuming to manually machine. Also, in order to give a positive connection and to meet the hypotheses for a dry-jointed system with air and rain-tightness, relatively low tolerance machining was needed in the region of +/-0.5mm to give a satisfactory interference fit between blocks. Accounting for these matters, proceeding with the current tools was deemed unviable as it was too time consuming – potentially over an hour to machine each full-size block even when using a range of jigs – and with too high a risk of unacceptable resultant block tolerances.

With these challenges in mind, the robotic cell was identified as being well placed to play host for design development, as an unfinished machine awaiting purpose. Whilst the research and design of the Cork Construction Kit was in its plastic phase, the specifics of the manufacturing process evolved concurrently with the component design. This enabled a gradual reduction in uncertainty for local and global design decision-making relating to fabrication. It presented procedural constraints and opportunities that could have only occurred in a manufacturing process whose particular attributes were open to change, allowing design and fabrication processes to co-evolve. This activity was made possible by access to The Bartlett's robotics facilities, and the work proceeded to address the following questions:

- What robotic milling set-up is suitable for milling large format 1000 x 500 x 220mm expanded cork billets into tongue and grooved blocks of the required geometries?
- What design and fabrication workflow will be effective for this?
- Is it possible to cut all blocks with a single cutter in order to minimise cutting time (using an industrial robot with no automatic cutter changer)?
- If so, then how will this constrain and inform block geometry, and what will the resultant milling time per block be?

The Robotic Milling Method and Its Influence on Design Development

A tailored robotic milling method was developed to cut the expanded cork billets into the blocks for the construction kit, with a target cutting time of 10 minutes per block. The method utilised a six-axis Kuka KR60 HA industrial robot with a high-volume cutter held by a bespoke spindle in a milling end effector. Cork billets were held in place by a bespoke vacuum bed fitted to a two-axis positioner. The vacuum bed was designed to hold both full size 1000 x 500 x 220mm billets and also those of shorter lengths from which shorter modules of the wall and roof blocks were milled. The cork proved to be relatively simple to mill, with cutter speed and rpm adjusted to higher speeds when removing bulk cork to form the block and to lower speeds for finer cutting of the finished block surfaces.

The design and fabrication workflow utilised SolidWorks modelling of blocks and assemblies as part of the design development process, in combination with hand sketching and scaled physical prototyping including creating a 1:5 constructional model of the second prototype building, Cork Cabin. Individual block geometries were then

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exported from SolidWorks to PowerMill Robot to generate cutting paths (Fig. 4). Some challenges were encountered in controlling transitions between cuts with this set up, and the use of Rhino with Grasshopper using a script developed in-house to generate the g-code was also trialled. Another challenge that emerged was some initial off-tolerance block cutting and this was eventually identified as being caused by insufficient calibration of the robot, with this particular application requiring a high calibration accuracy due to the tolerances needed to give a satisfactory block-to-block interference fit.

All blocks were cut with a single, high-volume, 125mm diameter by 14mm thick cutter in order to keep fabrication as quick and simple as possible, using the available robot that did not have a tool autochanger. The use of this configuration with the single cutter was enabled by developing the design of the cork blocks to fit within this particular set of geometric parameters, allowing the cutter geometry to play a role in determining the final block geometries for the construction kit. This was a negotiated outcome between what was desirable and what was possible under the chosen constraints, with the possible range of cutting geometries sitting alongside other constraints, considerations and strategies when designing the blocks. Other considerations for each block and its contribution to the construction kit, and buildings made with it, included the need for sufficient airtightness and rain tightness, a suitable structural block-to-block interlock, and block geometries that allowed them to be combined into assemblies in all cases.

The resultant milling process enabled the cork blocks to be formed in around 10 to 15 minutes cutting time for a wall block and 15 to 20 minutes for a roof block. During milling, up to around 20% of the cork billet is cut away while forming a roof block, less for a wall block. So, the milling process generated large quantities of cork granules as by-product, requiring a suitable enclosure for the robot and regular clean ups between milling blocks. As part of the broader work, an investigation was undertaken by research partner Ty Mawr into using these granules for a range of purposes. This included use as an additive to lime mortar to give texture and improve insulation level (something they already use cork granules for), for more novel cork granule and lime formulations including a form of Terrazzo, and to form cork fuel briquettes for use in their on-site biomass boiler.

Contribution to the Broader Research

The robotic milling process was used to fabricate all 202 cork blocks for the prototype Cork Cabin, including 10 different types, some with multiple lengths. It was also used to fabricate all blocks for subsequent lab tests, including wall and roof assemblies subjected to structural, fire and rain tightness testing. The cabin walls and roof were assembled at The Bartlett after fabrication, to ensure the assembly was correct, before being disassembled and shipped to site in Berkshire for re-assembly. This also served to test and demonstrate the readiness of the system for disassembly, a key part of the design allowing the cork blocks to be readily recovered for re-use at the end of the building's life.

6. Cork Cabin being assembled on site in Eton, UK, 2017. Image: Matthew Barnett Howland and Oliver Wilton.

7. The last roof block in a course ready to be pressed into place on Cork House, demonstrating the interference fit using no glue or mortar, Eton, UK, 2018. Image: Matthew Barnet Howland and Oliver Wilton.

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The cabin was assembled on site by hand, with no glue or mortar (Fig. 6). The CLT floor plate was laid within the bolted oak ring beam and raised off the ground on wheels. Cork block walls were laid on the floor platform, acting in structural compression and capped by oak eave-beams that take lateral loading. The corbelled cork block roof was built off this, also acting in compression. The completed structure is capped by a rooflight, mounted on a timber ring beam, which lets in daylight and also adds some weight to the top of the structure, acting a bit like a giant paperweight. The completed cabin was then subjected to air tightness testing and temperature and humidity monitoring over several months, which informed further design development of the construction kit.

At this point in 2017, the Cork Construction Kit was sufficiently developed and de-risked to apply an evolved version to its first live architecture project – Cork House. Options were appraised for fabricating the cork blocks required for the house design. These included robot-assisted self-build, where an industrial robot similar to that used to fabricate the cabin would be installed on site for the duration of the project, with cork billets shipped from Amorim in Portugal direct to site for fabrication in the correct sequence and then assembly. There are a number of interesting aspects to this, including the potential to evolve self-build and also to broaden the applicability of the construction kit by reducing cost. Robot-assisted self-build was ultimately not selected in this instance for reasons including the prohibitive cost of installing 3-phase power on this particular site, necessary for the specific robot that was available.

The 1268 cork blocks used in Cork House were milled on a large format five-axis CNC machine with automatic tool changer by Wup Doodle. The blocks were then transported to site for assembly by hand with no glue or mortar. This was a relatively clean and simple exercise, with each block weighing around 12 to 13kg and being easy to manipulate. The house was completed in early 2019 (Fig. 7) and post-occupancy evaluation is now commencing.

Conclusion

Robotic milling has played a key role in enabling this research to directly address its key aims. It has lowered the barriers to developing this uncommonly simple plant-based form of construction, developed to fully meet contemporary building performance standards, while delivering outstanding whole life performance. This is an example of work combining historical and emerging methods to form a tailored research, design and making methodology that uses digital tools to serve broader architectural, habitation and environmental sustainability aims, with their use enabling and also subtly informing the resultant architectural language.

Acknowledgements

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