Understanding the challenges of circular economy construction through full-scale prototyping

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Abstract: Applying the Circular Economy paradigm in the built environment requires buildings to be designed for deconstruction and material recovery. Achieving circularity is complicated by the fact that requirements for deconstruction are at odds with most current mainstream construction techniques. The widespread adoption of single-use fixings, adhesives and composite materials mean that it is rarely economically or technically feasible to recover materials. To address this issue a highly modified structural timber framing solution has been designed that separates traditionally dependant layers of a buildings weather resistant envelope. As part of evaluating the viability of this modified framing solution a full-scale building prototype was constructed. The prototype adopted an entirely modular, prefabricated light-weight structural frame with provision for the reversible fixing of structural cavity battens, cladding, purlins and internal linings. Experimental thermally modified plywood cladding materials, using a bespoke concealed bracket, were also designed and deployed. The design-build process worked effectively to highlight limitations within the proposed circular building system, however it was observed that many of the issues found could have been identified using detailed BIM modelling (down to a fixing level).

Keywords: Circular Economy; Design for Deconstruction; Circular Construction; Construction.

1. Introduction

Separating modern construction practices from the environmental destruction caused by unmitigated material extraction, consumption and disposal remains a significant challenge for the building industry. In recent years the *Circular Economy* has been touted as a framework for transitioning away from a linear consumption model towards waste-free and restorative industrial practices. As such, under the theoretical framework of circularity, this paper documents an attempt to translate best practice theoretical circular design recommendations into the real world. A 'full-scale' design-build project undertaken in late 2019 has been documented and critiqued with the aim of generating insights useful to those developing circular building systems and products. The paper documents the technical features

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of this prototype and critically reflects on the circular, economic and constructability performance of the completed building.

2. Background

2.1 The Circular Economy

In the late 1960’s there was a growing sentiment that the impact of modern human activities on the environment was unsustainable. Buckminster Fuller’s seminal book ‘*Operating Manual for a Spaceship Earth*’ in 1969, followed closely by Barry Commoner’s essay ‘*The Closing Circle*’ in 1971, outlined an industrial complex held by society that was incompatible with natural processes. Commoner theorized that unlike humans, nature operates as a closed system, an ‘ecosphere’ governed by laws in which waste and pollution becomes fuel and food for another natural process (1971, p. 33-48). Commoner outlined four distinct laws that allow the ecosphere to proposer:

- Everything is connected to everything else.
- Everything must go somewhere.
- Nature knows best.
- There is no such thing as a free lunch.

Commoner suggested that for humans to limit their impact on the environment they would need to operate within the bounds of these ecosphere requirements rather than operating in a linear manner. Commoner’s insights formed the basis of the Industrial Ecology movement, as well as the notion of ‘Cradle-to-Cradle’ and the ‘Product-Life Factor’ (Evan, 1974; Sahay, 2006, p. 215; Stahel, 1981 and 1982). The popularity of these ideas in academic and government organizations grew significantly throughout the 1990’s and early 2000 with the Chinese government being the first to pass such ideas into law in 2009 (Matthews and Tan, 2016). It was at this point the many different proposals for operating our economic and industrial systems in a way that emulates that of nature were captured under the broader umbrella term of *circularity* (the circular economy) (Geissdoerfer et al, 2017). Stewarded by the Ellen MacArthur Foundation circularity is today described as “…an economy based on the principles of designing out waste and pollution, keeping products and materials in use, and regenerating natural systems” (MacArthur Foundation, 2020). From Barry Commoner’s four laws of ecology in the 1970’s to today’s multi-national circular economy foundations and policy, c*ircularity* is widely recognized as the preeminent holistic framework for addressing climate change (Baker-Brown, 2017; MacArthur Foundation, 2020; Babbitt et al, 2018).

2.2 Circularity, the Construction Industry, and the Impact

Almost every construction practice that we adopt today is incompatible with circularity. The unilateral adoption of low-cost composite materials, irreversible chemical connections and fixings that inherently damage the materials they intersect is alarming (Storey et al, 2005). These practices mean that today the building and construction sector is responsible for more than forty percent of the world’s waste (Inglis, 2007; EPA, 2016). Reducing this vast volume of waste materials prevents a spiral of environmentally harmful human behavior (Ajayi et al, 2015; MfE, 1997; Kennedy, 2007; Braungart and McDonough, 2002; Baker-Brown, 2017; Inglis, 2007). Ensuring that building materials normally sent to landfill are instead either reused or reprocessed reduces the demand for new materials (Allwood et al, 2011; Broadbent, 2016). This leads to significantly reduced carbon emissions, as materials already processed into useful products often require less energy to re-process into another useful product (Russell, 1983; Schmidheiny and Stigson, 2000). Furthermore, a weaker demand for raw materials leads to less ecologically destructive bi-products that come from material extraction. These include habitat destruction, biodiversity loss, dust pollution, soil erosion, soil nutrient deficiency, sulphur dioxide pollution production, eutrophication and soil subsidence (Wood et al, 2000). Such negative environmental changes also occur at the point where waste building materials are deposited (Rabl et al, 2008). Collectively, the environmental side-effects of unmitigated material extraction and landfilling impact the food supply, security, health and diversity of our people and natural ecosystems (Sun et al, 2017). Addressing the issue of building waste is therefore an essential step in reducing the impact of modern construction practices on the environment and ensuring ongoing prosperity for our global communities.

2.3 Research Approach

Principles of circularity have been translated into tangible architecture in the past. Kieran Timberlake's 2006 Loblolly House is one of the earliest modern technical examples in which principles of circularity were applied to the way in which different materials were assembled. Two further significant experiments in technical circularity came in 2016 with the construction of the ICEHouse (Innovation in the Circular Economy) by McDonough and Partners and the ARUP Circular House by ARUP Consultants International. These buildings all achieved varying degrees of tangible circularity (see Finch, 2019) with a common technical design characteristic of using a structural metal frame to which building envelope and partitioning layers were bolted too. The result is an inherently carbon intensive construction assembly that restricts users ability to modify parts easily and comes with an inflated price-tag (Alcorn, 2010; Finch, 2019). To achieve circularity of a technical nature without the associated carbon and economic costs the authors of this paper designed a research programme focused around the use of engineered timber products. The ambition of the study being to test whether it was viable (economically and technically) to design a circular economy compatible building using such materials. The project began in 2017 and the prototype reported upon in this paper was the first major real-world test of the proposed engineered timber circular construction approach.

To locate the work alongside concurrent research a literature review was completed prior to undertaken design experiments. This review identified that a large segment of existing studdies outlined a consistent set of design principles governing the implementation of circularity in buildings (Brand, 1994; Durmisevic and Brouwer, 2002; Webster and Costello, 2005; Crowther, 1997–05; Storey et al, 2005; van de Westerlo et al, 2012; Nakajima and Russell, 2014; Beurskens et al, 2016) (refer specifically to Finch et al, 2019 for the complete list). After reviewing these guidelines, alongside further attempts at building to circular specifications, a series of preliminary design experiments were undertaken (Finch, 2019). These experiments centered on digital three-dimensional modeling of possible modular geometries based on the limitations of engineered wood products and known fabrication methods. Simulation modeling of structural loads was also undertaken to preemptively eliminate structurally inadequate options. Together with the review of literature these processes formed the basis for real- world prototyping and testing.

3. Early Stage Prototyping

The prototypes material and construction specification followed strict circular economy design guidelines based on literature. As the implementation of these ideas were largely untested at scale smaller elements were prefabricated and assembled in workshop conditions prior to undertaking full- scale fabrication. These tests examined any tolerance, durability and/or assembly constraints of the proposed system. Initial testing focused on verifying the structural and assembly capabilities of the modular structural frame before expanding to test the assembly parameters of the cladding and roofing assemblies. The critical learnings/observations from these tests largely related to 'ease-of-assembly' (and disassembly) issues existing within the proposed construction methods. Substituting nail and screw fixing methods with more durable reversable and non-damaging bolted, or clip connections is generally more labour intensive as a single part is often being replaced with two or more separate fixing components. To counteract the implications of slower fixing installation the proposed circular building system attempted to ensure that a bolted (or multi-part) fixing was always at least duel purpose. In this case a bolt connecting the structural cavity batten to the modular frame also acted to secure parts of that frame in place (figure 1). The smaller prototyping tests revealed that while this was feasible there was additional time costs associated with aligning the elements, effectively counteracting the efficiency of a single fixing.

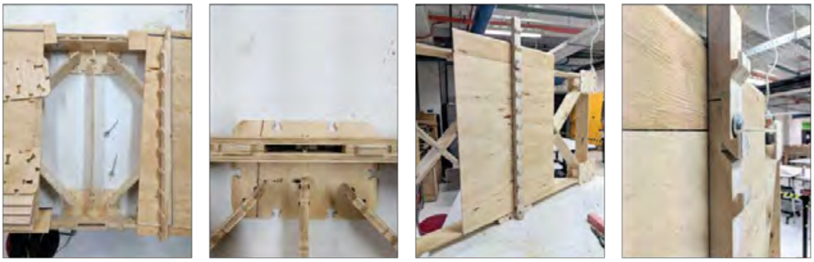

Figure 1. Early Stage 'mock-up' tests (from left to right: Frame Parts (tolerance test), Structural Cavity Batten Fixing, Rigid Air Barrier Testing, integrated weatherboard fixing).

4. Prefabrication and Construction

4.1 Foundations and the Structural Frame

The process of construction adopted by this prototype replicated conventional build methods. Prefabricated timber parts were transported to site and assembled into frames after completion of the foundation structure, with the walls then raised and bolted to that sub-floor system. Roof panels were then lifted into place before building wraps being applied and roofing materials installed. The major differentiating factor compared with conventional construction were the materials being specified at each stage and their fixing methodologies. The sub-floor system was conventional in many respects for a building of this size. Macrocarpa bearers supported by pre-cast concrete foundation slabs were installed first and anchored to the ground using steel rods. The assembly, although not as quickly recoverable as screw piles (which would be the mainstream recommended approach) was identified as low carbon, durable and entirely reusable. The modular plywood structural system forming the floor (also used for the walls and roof) was then bolted through dowel nuts into the Macrocarpa bearers (figure 2). The modular structural walls were then assembled as whole-wall-panels and stood vertically. Mortise and tenons notched into the ends of each wall panel secured separate wall elements together. A dowel nut and bolt were also used at 1200mm centres to prevent the assembly separating over time. This assembly approach differs significantly from conventional methods that would rely on skew nailing dimensional timber members. Finally, the spanning roof structure was assembled into 840mm wide panels and lifted into place to align with protruding tenons positioned at the top of each wall. If desired it would have been possible to adopt a more contemporary prefabrication approach and completely assemble/clad wall panels off-site in factory conditions. Such an approach was not deemed necessary for this test building given the structures scale and the projects ambitions.

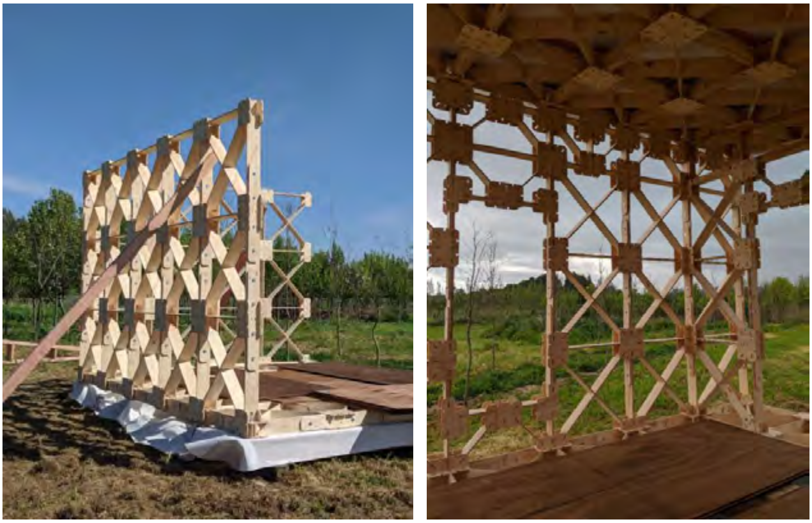

Figure 2. Wall Frame and Sub-Floor during Assembly

4.2 Weather Barrier Layers

Completion of the structural frame was followed by the installation of weather barrier layers. Due to a series of material and financial limitations a conventional synthetic building wrap was adopted for use in the prototype. The rationale for this was based on prioritizing the testing of the overall assembly under the assumption that this wrap would not affect the circularity of other building components. At the time it was hypothesized that a rigid air barrier would be a more circular solution as it could be modulated based on the same conditions as the structural frame. It was found, however, that no material was available that could fulfill this role while operating under circular economy material specification rules. Common rigid barrier products available in New Zealand rely on either chemical preservatives in timber substrates or inert carbon intensive materials such as Fibre Cement (Finch, 2019). Fixing specifications of these rigid layers also typically clash with circular economy requirements. The advantage of the building wrap in this instance was that being a pure polypropylene material both offcuts and the product as a whole at the end of its life could be recycled in a high-value manner (Thermakraft, 2019). Where the wrap failed to meet circular criteria however was when construction tapes were used to seal seams and openings. Deconstruction in the form of separating the tape from the wrap and frame at end-of-life leaves contaminates both on the frame and on the polypropylene material – effectively compromising the recycling process (note that these issues will be addressed in further research and prototypes). Consequently a breathable non-woven thermally bonded polypropylene ('building wrap') enclosed the entire structure (including below the modular floor and over the modular structural roof frame).

A further compromise was made in the material specification of structural timber battens. The modular structural frame acted as a self-braced anchor for linings and cladding materials. To prevent damaging fixings entering this frame a structural timber batten was specified on the outside of the building wrap to which cladding products could be fixed. This practice of fixing a batten to create a void between cladding materials and the structural frame fulfilled a dual purpose as this configuration is considered best practice from a durability perspective as it ensures the cladding materials can dry out easily (Finch, 2019). This batten was factory profiled to include holes down one face that corresponded with mounting points in the modular frame (figure 3). 60mm M8 Stainless Steel bolts were then used to fix this batten to the frame at 600mm centers in an easily demountable manner. The bolts were fixed into insert nuts pre-positioned in the face-plates that connected structural members together. Ideally this timber batten would have been a durable natural timber (i.e. Douglas fir) or a naturally persevered softwood timber (i.e. Abodo or Accoya) to meet the durability specification required by the building code and circular design ambitions. All options were priced out with the cheapest circular specification (Abodo profiled 40mm square lengths) coming in at three times the cost of pressure treated pine. Given the quantities of batten needed and the small size of the build it was decided to specify the treated pine. It was noted that this specification would not limit one's ability to deconstruct the building, only the potential for any damaged parts of this member to be discarded safely.

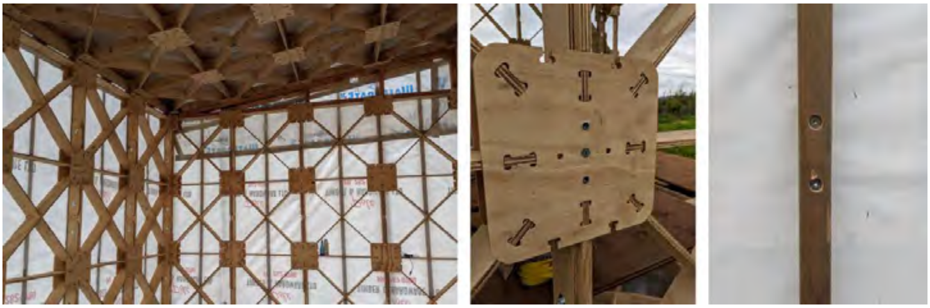

Figure 3. Synthetic Building Wrap (non-woven thermally bonded polypropylene) over the modular frame (left), the cavity batten mounding points (middle) and the batten installed (right).

4.3 Cladding and Linings

Over the structural batten was fixed an experimental modular cladding solution centred on a thermally modified plywood material (figure 4). This material is reported to achieve a 15 year durability specification from a softwood based timber without any chemical preservatives. After the lifespan of the cladding the materials can be resurfaced and reused or returned to the earth without any negative side- effects. To complete the circular nature of this bespoke cladding a shingle pattern was created. Circular economy guidelines recommend the use of smaller and more modular components in buildings as they are easier to handle, less prone to damage and simple to fit into a reuse situation (Crowther, 2005; Durmisevic and Brouwer, 2002). The adopted cladding follows this guide and required only three standard parts to enclose the building. The base shingle specification was a 595mm square panel cut from standard sized plywood sheets (resulting in negligible wastage of <1% per sheet). These panels were fixed to the structural battens using a self-aligning galvanised bracket and 50mm long stainless steel screws. The overlapping nature of the singles meant that no corking/sealant was required and the overall assembly used approximately 60% less fixings then normally required.

The building's interior was insulated using a wool blend insulation and lined with prefabricated modulated panels fixed using a reversible pressure-clip mechanism (figure 4). The choice of woolen insulation was motivated by the local supply of the material, the take-back scheme operated by the manufacturer and the materials hydrophilic capabilities. Given that the prototypes wall assembly did not include a vapor barrier it was deemed essential that there be a material in the wall cavity capable of managing moisture vapor. According to the manufacture (TerraLana, 2020) the wool fibers will absorb moisture vapor and release it back over time when the relatively humidity drops. This action prevents the build-up of condensation on the inside of the building wrap and thus prolongs the life of the building. The prefabricated plywood linings covering this insulation used a 2-part male/female pressure clip. Installation of these clips was accelerated by the prepositioned holes in the modular framing system that corresponded with pre-routed holes in the rear of each lining (figure 4).

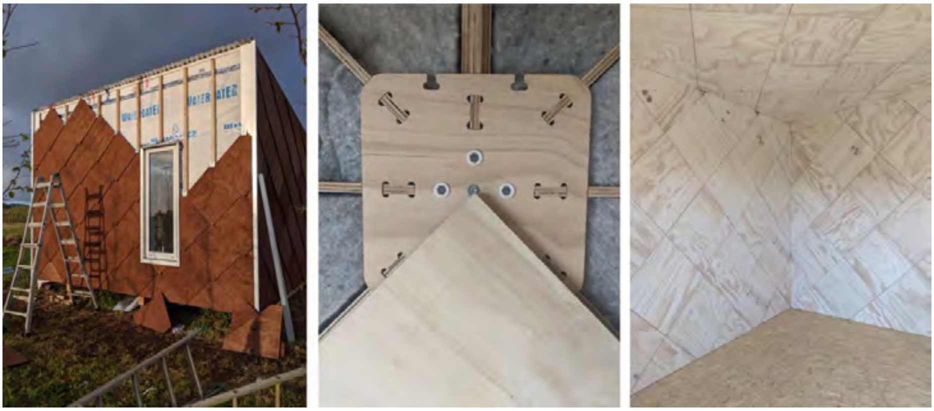

Figure 4. Installation of the Thermally Modified Plywood Cladding (left), a close up image of the pressure clip receptacle used for the internal linings (centre) and the finished lined interior (right).

6. Conclusions

Through prototyping this research explored the technical challenges of achieving a circular economy building with timber as the base structural material. The ten square meter prototype building allowed a series of hypothesized circular building solutions to be examined and evaluated in 'real-world' use case. As a result of this process a series of key learnings were identified and used as the parameters to improve the circular building approach.

Undertaking a physical full-scale test of the proposed circular building system was viewed at the time as a necessary step in validating the proposed research ideas. On reflection, however, learnings and outcomes gained from the build process could have been equally identified through a thorough prosecution of a digital 3D model. This observation came post construction when documentation of failures identified during the build process were being produced. It was found that all issues noted during construction could have been flagged by simply 'deconstructing' the digital model. The one area where this observation did not apply was to issues of material capabilities (such as plywood parts warping/twisting due to exposure to moisture and thermally modified timber failing to hold short screws).

In future research there is the opportunity to lean further towards natural building methods (adobe, earth, timber post and beam, straw-bale etc) to achieve circularity. This research acknowledges the importance of such techniques and applauds their efforts. The methods adopted in this research attempted to blend natural building techniques with economical materials and scalable techniques and the result is a somewhat compromised version of circular construction. In the context of the 21st century matching ecological practices with economical drivers (both time and cost) will continue to challenge the implementation of circularity in buildings. Alongside this there is also an equal opportunity to lean towards more technical pursuits. Additive manufacturing on a building scale is emerging as a viable method of construction and there may be ecologically sensitive printable materials that allow for circular construction methods.

Physical construction processes revealed that although the standardised structural parts works effectively to create whole of wall panels a better approach would be a modification that allowed wall panels of a standard manageable width to be created and then joined to create longer wall sections. It was also identified that the modular structural system needed to be capable of further redundancies. The process of adding blocking to support cavity battens at their base or at corners introduced major contaminates to the system and slowed construction down. For those conducting research in this field the authors recommend conducting detailed reviews of complete virtual models before building. Finally the authors hope that findings from this field-study are useful for researchers and practitioners alike when aiming to create circular economy compatible buildings.

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