EXPERIMENTS IN TIMBER SPACE FRAME DESIGN

Fabrication, Construction and Structural Performance

GERARD FINCH¹, GUY MARRIAGE², ANTONY PELOSI³ and MORTEN GJERDE⁴
¹,²,³,⁴Victoria University of Wellington
¹,²,³,⁴[ged.finch|guy.marriage|antony.pelosi|
morten.gjerde]@vuw.ac.nz

Abstract. Digital fabrication makes it possible to create precise and replicable components from engineered timber products. Coupled with strategic design, these tools can be leveraged to produce intelligent and informed jointing conditions that facilitate material arrangements of unprecedented efficiency and strength. This project builds on an existing body of knowledge in the field of digital wood design and fabrication to examine the design, fabrication and structural capabilities of massively modulated plywood space frames. The practice based research finds that while the geometry of a timber space frame is of excellent strength the detailing of joints and overall structural rigidity is a key concern.

Keywords. CAD / CAM; Digital Wood Design.

1. Introduction

This paper documents and reflects upon a new type of timber space frame design that takes advantage of sheet plywood and computer aided manufacturing processes (CAD/CAM - milling). The scope of this paper is limited to the design, fabrication and structural performance of this new type of space frame. Documented in conjunction with this space frame concept is the design research methodology adopted. This method is of particular interest as the research straddles both scientific experimental and action based research techniques.

2. Background

In recent years there has been a significant increase in the development of innovative timber-based solutions in the construction sector. These range from new timber products (Cross Laminated Timber, Glue Laminated Timber), new environmentally friendly treatment technologies (Timber Acetylation) and the recent use of robotics in prefabricated timber construction processes (Harris, 2015; Alexander, 2007; Parvin, 2013; Chapman et al, 2014; Marriage, 2016). One category where innovation has been particularly concentrated is in the use of structural timber sheet materials and computer numerically controlled (CNC)
fabrication to produce prefabricated structural building elements (Albright et al, 2017). This approach was pioneered by Lawrence Sass (2006) in the Instant House project in 2005 (Figure 1). Using plywood sheets and a CNC router, all the components in the Instant House were designed to inherently fit together with friction joints and integrated mortise and tenons. Consequently, the project used only a single material, eliminated all secondary fixings, could be built with only four tools, and was entirely ‘digital’ in its conception (Sass, 2006). This project has inspired a range of industrialized solutions based on the same ideas, including the WikiHouse and the Facit Homes System (also Figure 1) (Parvin, 2013; Albright et al, 2017). Both use end-to-end digital design and fabrication processes, and a similar ‘stressed skin’ structural configuration. The Facit approach has been the most successful of these solutions in terms of real-world implementation with over 40 homes built throughout the United Kingdom (Facit, 2018).

Although intelligent in their fabrication, these solutions have not offered any advancements in architectural form or structural efficiency. The stressed skin panel based approach that these systems use dates back to the 1960s where plywood, and sometimes asbestos cement sheets, were fixed to conventional dressed dimensional timber members (Bell, 2009; Holden, 2018). And while the formal characteristics of houses have changed since that time, a home built using the Facit system and a home built using conventional platform framing today are virtually indistinguishable. There have, however, been other developments based on the same technology and ideas that have pushed the formal attributes of architecture and sought more intelligent structural configurations. The notable example of this endeavor is Click-Raft; a laterally stable plywood wall and flooring product designed by Chris Moller (2006-present) (Figure 2). Click-Raft stands out from other solutions by gaining its lateral strength from curved plywood members that exert internal tension against other curved members (Marriage, 2016). The result is an elegant lattice structure comprised of sinusoidally curved members with robust physical attributes. A positive consequence of achieving lateral stability without the need of a rigidly fixed lining/sheet material is that the visual qualities of the structure can remain exposed. This leads to greater material efficiency and cost savings as there is no need to use two layers of sheet materials to line a wall as is common in both the WikiHouse and Facit Home solutions.
Inspired by Click-Raft’s ambitious use of a non-orthogonal structural language, and the use of engineered timber products to achieve this, the following research reports on experiments with another alternative geometry: space frames. The research asks if there are structural, material efficiency and/or architectural advantages when digitally fabricated engineered timber space frames are adopted. The motivation for selecting the space-frame geometry comes from William McDonough’s Innovation for the Circularity Economy (ICE) House and its WonderFrame structural aluminum space frame (2016) (Figure 3). The formal structural ideas were also influenced by work of Pei-Shan Chen regarding 1.5-Layer Space Frames (2014) (Figure 3 right). Together with the emerging popularity of diagrid solutions these are intelligent structural formal arrangements that have the potential for more efficient material use, more resilient structural characteristics, the potential for total end-of-life material recovery, and outstanding aesthetic qualities versus conventional structural elements (Chen, 2014). The research hypothesized that timber space frames, like Click-Raft, would have structural advantages over conventional construction systems that utilise CNC and plywood products (i.e., stressed skin panels - WikiHouse and Facit Homes). And, unlike Click-Raft, it was predicted that a timber space frame could be freely modulated for a diverse range of span requirements and not limited by the size of the plywood sheet product. If proved to be accurate, digitally fabricated timber space frames could represent a highly intelligent and informed architectural solution.
3. Experiential Action Research Methodology

To understand if timber space frames have the hypothesized advantages outlined above it was necessary to design, develop, build, test and evaluate a potential version of a space frame. And, in order to achieve this, an experiential action research methodology was adopted. This research approach is based on “a spiral of cycles of action and research consisting of four major moments: plan, act, observe, and reflect” (Zuber-Skerritt, 1992). This is a ready-made scaffold for a “systematic research method... ...easily understood and adopted by designers...” (Swann, 2002, p. 61). An action research methodology was also deemed appropriate as it accounted for both how the timber space frame was to be realised (designed), and the consequences (performance) of the frame once applied (Kock, 2017). Within this methodology an iterative design process reflecting the four stages of action research was carried out. The basis for this was to reflect upon examples from both space frame design (Chen, 2013) and digital wood system design (McDonough, 2016; Albright et al, 2017). Initial ideas were modeled in a digital environment (Rhinoceros 3D), fabricated at a small scale (laser cut from medium density fiber board), assembled and reflected upon. Initial reflections were based on functional constraints such as ease of assembly and structural functionality. Upon multiple cycles of reflection and redesign the process was completed again, however, this time fabricated at full scale using CNC router fabrication and 18mm plywood. Following the action research methodology, reflections were again made and a further developed solution was fabricated. Throughout this development process quantifiable information was recorded to facilitate an empirical performance assessment, fulfilling the ‘experimental’ aspect of this action research methodology. Due to resource limitations the research spiral has been put on hold after ten iterations and two full scale fabrication cycles. However as sections 4-6 will indicate, there is the potential to continue the action research spiral in search of a more developed design output.

The experiential action research methodology outlined above is a subjective and intuitive process. Tacit knowledge, rather than empirical information, directed many of the design decisions required to build the timber space frame. For example, the length of a module is based on the most efficient nesting configuration when the components for the system are layed out onto a standard plywood sheet. This is achieved by constantly working between the assembled
system and the nested components in the design phase - dynamically evaluating how objects can be changed to get better material efficiency. Similarly, in the ‘current’ iteration, the way in which two identically shaped plates lock all the components together at each node through the use of a single bolt is informed by a drive for simplicity and elegance, rather than pure structural performance. Simplicity ensures the design is more appropriate for rapid on-site assembly by low-skilled labor. Hence, it is not expected that another architect or engineer tasked with the same challenge would achieve the same design.

4. Design and Fabrication of Timber Space Frames

The principal goal of the timber space frame was to provide an efficient and modular horizontal spanning structural element. As part of this design brief the aim was to also use as few different parts as possible, to produce as little waste in fabrication as possible and to aid in overall constructional simplicity. This aim produced a series of iterative explorations in which auxiliary elements were integrated, optimised and/or discarded from the developing solution. Through these iterations the most significant changes focused on optimising the node of the space frame. In conventional space frame designs the nodal point is almost always a high strength steel. This is because compression and tension forces converge at nodal points, putting a large degree of strain on the point (Lan, 1999) and steel is an affordable material that can cope with these complex forces (Ramaswamy et al, 2002). Steel is also selected due to its ability to be easily cast into a nodal form that enables it to receive members from many different directions (Ali et al, 2013). Consequently, to achieve an efficient and elegant nodal connection using only CNC cut sheet material is challenging. Figure 4 and 5 documents the process of refinement undertaken to ensure that the timber-only space frame nodal design meets the aforementioned design criteria.

Additionally, it is important to note that during the design process there were many competing factors that made development challenging. For example, modifications to the size of plywood components and the overall structural module directly affected the nesting efficiency of plywood components. This mandated a compromise between the ideal form of components and the quantity of CNC waste produced. For this reason the final design presented here should not be seen as a perfect optimisation. Instead the design represents one of the many possible rationalizations of a functional plywood space frame.

Figure 4. Authors nodal design iterations. Iterations focus on (from left to right) a first embodiment of key ideas, a reduction in the number of fixings per node, simplification of the number of different pieces per node and material efficiency/CNC fabrication time.
Figure 5. Ten design iteration cycles undertaken by the author. The first five iterations (top) are conceptual in purpose - quickly testing general ideas i.e. the efficient modulation of the members on a plywood sheet. The last five (bottom) begin to detail and resolve key issues and involve more subtle changes (as per fig. 5).

Again, the aim of this study was to follow the CAD/CAM processes of projects such as the WikiHouse and Facit homes. As such, fabrication of the timber Space Frame assemblies rely on CNC routing technologies to create intricate jointing details, which in-turn enable engineered timber sheet products to be organised into a three dimensional structural matrix. This is best demonstrated in the node design and construction. The final space frame presented in this paper (3DX 1.6) (Figure 6) requires only two identical, highly optimised, plywood plates to connect the eight individual converging members. A single 120mm bolt between the two plates locks the node together and facilitates rapid and hassle-free assembly (Figure 4 - right and Figure 6).

Figure 6. Axonometric drawing and full scale of final prototype of timber space frame concept (version 3DX 1.6) (authors image).
5. Quantifiable Performance Assessment Methods

Alongside the design component of the action research methodology are scientific experimental assessment methods that were followed to produce quantifiable metrics. This information was used to objectively assess the benefits of timber space frames in comparison with other solutions designed to do a similar job. Quantifiable metrics also allow other experts to understand the performance of the solution(s) and adopt aspects of the design in their own work.

5.1. GENERAL PERFORMANCE MEASURES

As a basis for comparison against other solutions system weight, material cost and CNC cutting time (if any) were recorded for a one way floor spanning 2.4m and running 4m in length. Values for other systems were then calculated for the same area based on literature and building code guides (NZS3604).

Table 1. Quantity of materials (Weight & Volume), Cost, and CNC Cost of different structural flooring solutions.

<table>
<thead>
<tr>
<th>System Description</th>
<th>Weight: (kg)</th>
<th>Material Cost: (NZS)</th>
<th>CNC Cost: (NZS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid Timber Joists</td>
<td>82.1</td>
<td>$294.24</td>
<td>N/A - Costs to trim joists unknown.</td>
</tr>
<tr>
<td>Timber 'I' beams</td>
<td>74.4</td>
<td>$298.32</td>
<td>N/A - Costs to trim and fix I-Beams unknown.</td>
</tr>
<tr>
<td>Space-frame 18mm</td>
<td>96.5</td>
<td>$279.23</td>
<td>$987.18</td>
</tr>
<tr>
<td>Space-frame 12mm</td>
<td>64.3</td>
<td>$161.28</td>
<td>$658.12</td>
</tr>
<tr>
<td>WikiHouse Ren (4.3)</td>
<td>377.9</td>
<td>$1,084.69</td>
<td>$1,211.03</td>
</tr>
<tr>
<td>X-Frame 9</td>
<td>148.6</td>
<td>$907.37</td>
<td>$1,368.60</td>
</tr>
<tr>
<td>Click-Raft</td>
<td>105.1</td>
<td>$266.50</td>
<td>$445.71</td>
</tr>
</tbody>
</table>

Universal Notes: Floor area; 2.4 x 4m - No surface finish - structure only - no fixings.

No blocking, no flooring included, no labour included, cost includes GST, no fixings.

All costs from Burning New Zealand dated 26/11/2018 excluding I Beams (cost from STEICO, 2018).

Calculated based on average area of timber required for all components for 1m2 of effective area.

6mm per CNC Pass, 35mm per second cut speed, $150 per hour of CNC cutting.

The results from this measured analysis suggest that the proposed plywood space-frame solution is lighter and therefore more economical in respect to materials then all other solutions presented in this comparison. The more efficient
triangulated spanning geometry adopted within the frame is the key basis for this efficiency benefit (Chen, 2014). Compared with the WikiHouse system, a plywood space-frame structure is far more intelligent and informed. However, a consequence of this triangulated configuration of structural elements is the need for the more intricate shaping of components. This results in longer CNC routing times and increased costs in fabrication. And because of this, even with the material savings offered the 12mm iteration, the Spaceframe is more expensive than Mollers Click-Raft system. Other advantages of Click-Raft, based on the authors observations, are that it produces less waste when being routed and is less complex to assemble than a space-frame. Yet the expandability of a plywood space-frame is potentially far greater than Click-Raft given that it can modulate in any direction without the need for additional timber members. This is a benefit thats practical advantages are difficult to quantify but could ultimately lower the cost of the system over a larger span.

5.2. STRUCTURAL PERFORMANCE MEASURES

Structural performance of the designed timber space frame included the destructive bend testing of a full scale frame specimen (Figure 6). From this test the deflection under a given load was calculated to identity the maximum potential weight that the system could support. Two structural tests were conducted each using a different structural plywood product. This is important to test as the performance of the frame was expected to differ significantly between different grades of timber. Results are reported in Figure 8.

The structural test was designed to work within the constraints of the accessible equipment. As such the effective spanning length was limited to 2000mm and a uniformly distributed load was ‘simulated’ through two evenly distributed contact points. The frame was fixed at one end and let to slide at the other so as to not gain any additional strength through the bending frame itself. The key area of interest during the structural test was the level of deflection found in the system at residential and light commercial floor loads. This was observed by plotting the
displacement of the beam against the load acting upon it (Figure 7). To make this relatable to building code performance the load was reported in kiloPascals (kPa). The displacement was measured at the bottom central node of the system using a laser measuring device mounted to the overhead bending rig.

![Figure 8. Load displacement results from test (authors image).](image)

The load deflection curve indicates that for a domestic floor loading of 1.5kPa and the tests span (2.0m) the plywood truss is operating close to the maximum permissible level of deflection (1/400) (5mm out of a maximum of 5.125mm). At this level the occupant of the space would be able to feel the structural members deflecting when moving about in the space, suggesting that more rigid nodal connections are required. That said, these tests indicate that the structure is at no risk of total failure when used in residential and light commercial buildings. Notably, the 13 ply Birch plywood offers a safety factor of five, further confirming that it is the stiffness of the structure, rather than its overall strength that is a concern.

6. **Future Research**

The geometry conceived and tested in this research presents a multitude of challenges to conventional construction techniques, especially at the domestic scale. Integrating such a complex geometry into other building elements could prove to be a significant barrier to real-world implementation. Lining, insulating, designing it to be pitched and ensuring it can support a range of services are all challenges that need to be looked at. The authors are also interested in how the system could be further optimised for structural efficiency, and how the system could be designed to assemble into a slim structural wall when required, all while using the same pieces.
7. Conclusions

The research documented in this paper is directly inspired by the work of Facit Homes, WikiHouse and Click-Raft. These solutions’ ability to take a technology and distill it down into tangible systems have led to a new approach to construction. Based on this intent the research sought to explore alternative geometries that could offer further structural and economic efficiencies while still using the same simple materials and technology. Through an action design research methodology a lightweight timber space-frame was conceived and evaluated. The study found that while a plywood space-frame is indeed possible and has weight advantages, the current nodal designs allow levels of deflection that exceed building code regulations. That said, compared with the WikiHouse solution, plywood space-frames are a far more intelligent approach to horizontal plywood-only structural systems.

References