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Cross laminated plywood construction of a free-form roof

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Abstract

The paper discusses the design, fabrication and assembly of a free-form roof structure constructed using a hybrid method of cross-laminating structural plywood. The research outlined the roof's design, fabrication and engineering workflow within an integrated fabrication environment led by the architect in collaboration with the engineer. Such workflow constructed resilience in the design and manufacturing process. The digital fabrication of the structure was developed in a single parametric model informed through 3 sets of physical prototypes. By incorporating as-built site information through digital scans, the assembly process was enhanced with feedback to ensure precision in manufacturing, thereby demonstrating care in construction through digital technology.

Keywords: timber structure, integrated design and fabrication, cross-laminated, designing for assembly, plywood, digital fabrication, prototyping

1. Introduction

Structural plywood and Laminated Veneer Lumber (LVL) are common building materials in construction, typically used as bracing and beam, respectively [1]. In recent years, Cross Laminated Timber (CLT) as a structural wood panel has increased usage globally and in Australia [2]. This paper expands on the research on timber laminated panel systems using digital fabrication and robotics [3] to explore a hybrid fabrication method called Cross Laminated Plywood (CLP). The CLP forms a structural wood panel and is an alternative to CLT.

The paper outlined CLP's integrated design, fabrication, and assembly workflow for a house project with a free-form roof structure, see figure 1. The roof design had multiple performative requirements. It provided a flat roof deck as a private open space, addressed overlooking issues from neighbours and diffused sunlight to the interior, see figure 2. Structurally, the roof was designed to support a biodiverse brown roof. It consisted of a set of CLP rafter beams and bracing plates as the primary structure, sheathed with plywood, insulated, and topped with a brown roof build-up. Through prototyping and structural testing, design information and construction parameters were integrated into the computation model to manage the complex geometry and the fabrication workflow. The paper concludes with the assembly methods, including in-situ templating and digital scans to accurately position each roof beam within a +/-2mm tolerance on site.

The research's significance lies in manufacturing the CLP within a small-to-medium enterprise (SME) context to reduce the design-to-production supply chain. The fabrication methods are relevant during and after the COVID-19 pandemic, where construction is often delayed due to an extended production chain and lack of human resources in Australia. CLP fabrication and construction methods provide an alternative to CLT's large-scale production. The research highlights the need to integrate design, engineering and fabrication within a continuous construction ecology tested through a built project.

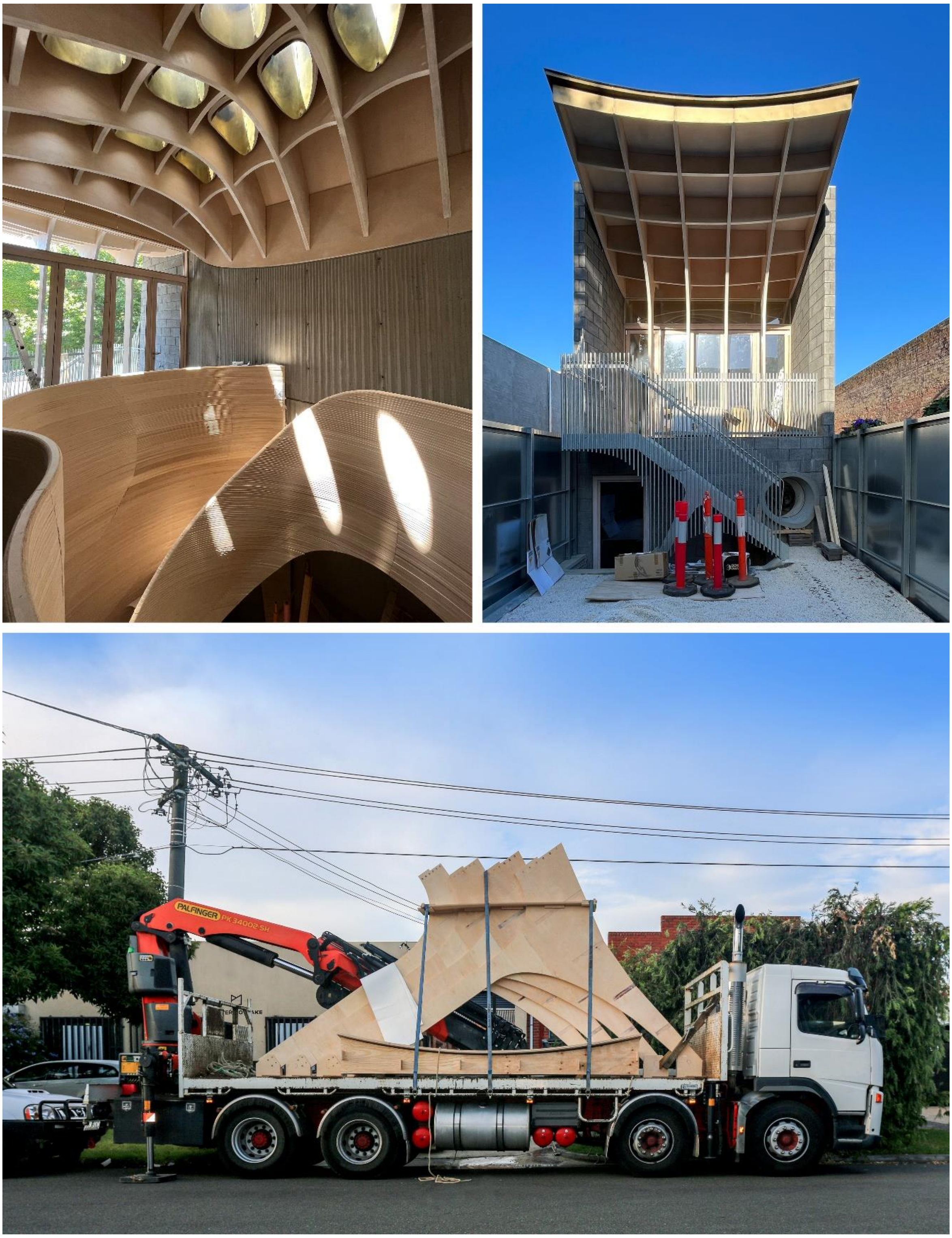

Figure 1. Top Left, the roof's soffit with skylights supported by the concrete boundary wall. Top Right, front elevation of the house with a cantilevered roof. Bottom, urban manufacturing facility of Power to Make. Image showing the loading of CLP roof rafters ready for site delivery.

2. Background

LVL is similar to plywood except that there is no cross-banding in LVL. CLT is fundamentally a large format plywood with individual layers between 12-45mm thick in three, five or seven layers [4]. The larger dimension of CLT over a standardise structural plywood sheet (typically of 2.4 x 1.2m) allows for its application as full-size wall, floor and linear components with the ability to bear load in and out of plane. Both CLT and plywood have high dimensional plane stability due to cross-layering. In CLT, a single layer is typically finger-jointed. The cross layering of lumber is quasi-rigidly connected using annular ringed shank nails or hardwood dowels [5].

Since its development in the 1990s, CLT has shaped building design. It challenges structure and superstructure design replacing concrete as the primary material. While solid timber construction has significantly accelerated in the past two decades, the first CLT building was not completed in Australia till 2012 [6]. In 2015, Australia produced its first CLT panel, and manufacturing plants were established in 2017 [7], [8]. Before this, most CLT panels are imported from New Zealand or Europe (using Spruce and Pine species).

2.1. Project background and fabrication context

The Northcote House by LLDS architects was designed in 2015-18, with construction commencing on site in 2019-2023. The roof design and fabrication result from an integrated collaboration between LLDS architects and TGA engineers, a specialist timber engineering practice based in Melbourne. While it is common for engineers to develop design and fabrication within the same environment (such as specialist fabricators in steel and timber), architecture practices are often removed from the fabrication environment. While significant efforts to bridge the gap exist through direct file-to-manufacturing in the past two decades, the integration is often only through data management and rarely through physical manufacturing [9], [10].

The significant difference in this project is the fabrication context. The architect operates a 500-square-meter fabrication workshop located within 7km of Melbourne CBD called Power to Make, specialising in timber joinery and architectural components, see figure 1. The practice operates its own CNC machinery, including a large format Computer Numeric Controlled (CNC) router (suitable for standard 1.2 x 2.4m plywood panel), a Kuka KR120 robotic arm, traditional woodwork and metalwork machinery.

2.2. Roof design

Two 150mm thick concrete walls on the site's boundary support the timber roof. At its thickest point, the roof is 3 meters deep and tapered to the cantilever edge of 205mm. The roof was designed as a trafficable landscape (live load of 3kPa). It functioned as a brown roof that contributes to the site's biodiversity (500kg/m2), shedding water to the edge gutters, and the symmetrical apex is used to block views from the neighbouring buildings. Figure 2 illustrates the geometric parameters used to set up the roof design. The underside of the roof is an exposed waffled (or coffered) structure that gives the main living area of the house its dramatic volumetric form. It is defined by a centrally located parabolic curve which blends into the two (short) parameter straight edges, see figure 2A. The two straight edges interface with the opening of the façade identified as Beam 1 and 15; Beam 1 is conditioned by the concrete beam that ties the two concrete walls together; Beam 15 is required to interface with the entrance door.

The roof consisted of 19 rafter beams and 76 bracing plates. It was designed to be assembled in two phases. The first phase is from Beam 1 to Beam 15; see figure 2. The second phase forms the cantilever roof from Beam 16 to Beam 19; see Figure 2. Two waling plates designed with mortises were anchor-bolted to the concrete walls to receive the primary beams. The area covered by Beam 1 to 15 forms the main roof over the interior. Beam 15 marks the transition between inside and outside. After Beam 15, the primary beams changed orientation from north-south to east-west and cantilevered out to form the overhanging roof. These east-west beams rested on the first-floor slab for two reasons. First, it ties the uplift forces of the cantilever roof to the first-floor slab. Second, the depth of these beams acts as vertical brise soleil and privacy screening from the street.

Thirteen cone-shaped roof lights in the coffered roof structure draw daylight to the interior, see figure 2b. The depth of the coffered soffit is driven by the need to (1) diffuse daylight during winter and (2) block direct sunlight during summer. The roof light's fabrication detail is outside the scope of this paper.

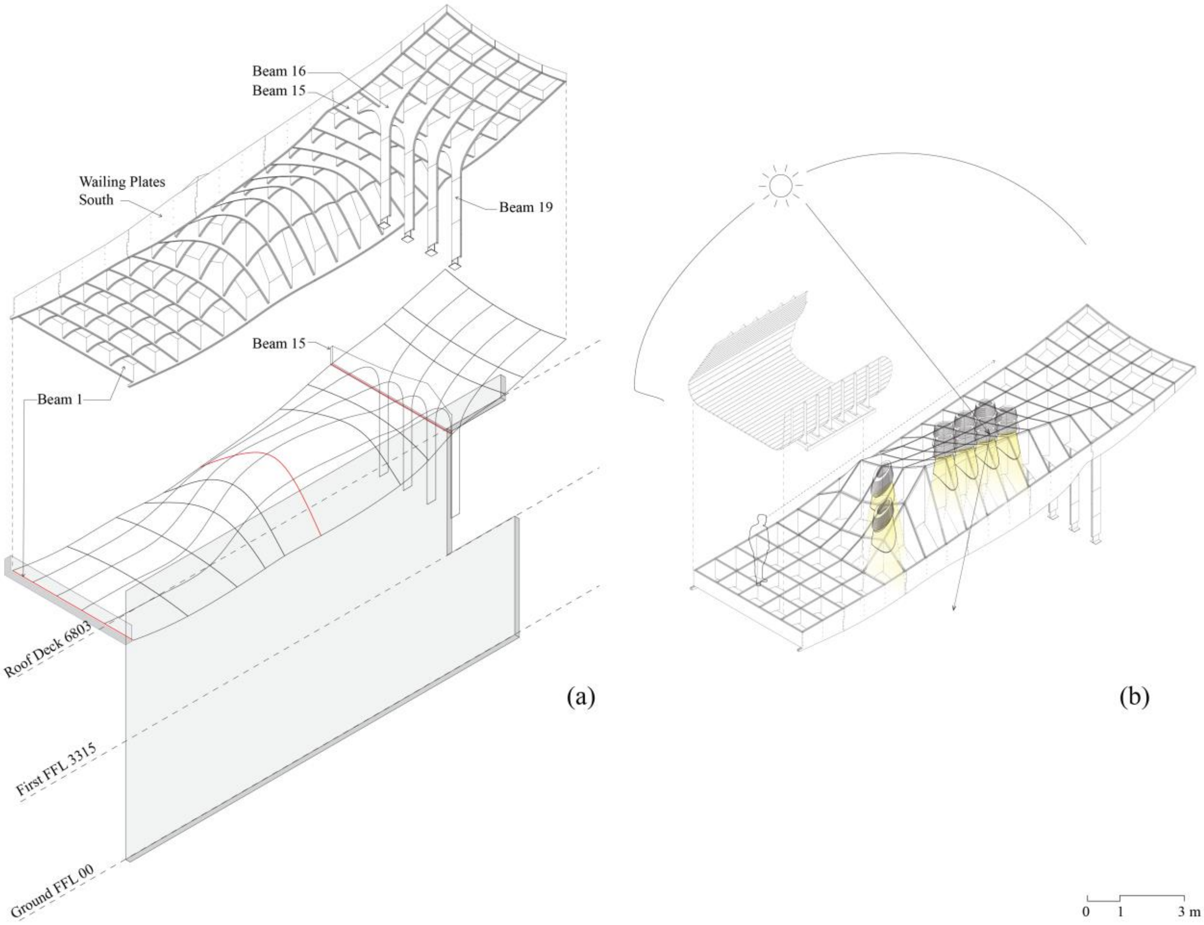

Figure 2. Left, (a) worm-eye isometric view of roof indicating the interior geometry parameters. Right, (b) isometric view of the roof illustrating the exterior requirements that shaped the roof design, including the 13 roof lights that bring diffuse lighting to the interior.

2.3. Motivations to reduce supply chain

During the schematic design phase in 2015, the nearest CLT supplier was based in New Zealand. The design team consciously shifted away from CLT, motivated by the need to reduce the roof's supply chain and the transportation cost (and carbon footprint). Two other design alternatives were considered, including (1) using LVL as a beam and rafter to construct a portal frame structure with plywood gussets or (2) constructing the roof using plywood-stressed skin panels [1]. The design team rejected these options as the width of the rafter will increase significantly from 54mm to 150mm. Further motivation to reduce the supply chain comes from the design team to integrate the design and fabrication of the roof structure within the manufacturing facilities of Power to Make. The workshop setup allows the design team to develop three sets of prototypes with the engineers. The testing and prototypes subsequently led to Power to Make fabricating and assembling the CLP onsite with the assistance of a licensed builder.

Reducing the supply chain has other implications. For example, the design team can monitor and control the cost of the CLP through its design. In-house production also allows the team to manage the quality of the finish, especially when the entire interior surfaces are visual. Structural plywood comes in five veneer grades (A, S, B, C and D), and the appearance can be further specified with ten different combinations of grading to the facing and back veneer (AA, AB, AC, AD, BB, BC, BD, CC, CD and DD). The structural plywood used in the project was specially pressed with the grain running along the panel's length and a BB/BB-facing veneer. The COVID-19 pandemic hit in January 2020 in Australia, halting all global supply chains. The roof was manufactured at Power to Make between March – August 2020, and installation on site commenced later that year.

3. Cross laminated plywood (CLP)

Standard plywood sheets come in 2400 x 1200mm. Each roof beam and bracing plate are glue laminated like a CLT - comprised of three layers of 18mm birch plywood laminated using structural polyurethane adhesive at 4MPA or a minimum of 500 PSI. Each layer was designed to be staggered vertically and horizontally, so there was no continuous joint line across the entire panel. Similar to CLT fabrication, each layer was edge-jointed with finger joint, L ≥ 45mm, to reduce resistances and bend out of plane. The finger joints were CNC milled with 0.1mm tolerance.

The architects decided to use European Birch plywood as it was the most economical and dimensionally stable (compared to Hooped pine) in Australia. TGA engineers converted data for structural plywood performance certified to AS/NZS 2269.0:2012, in an equivalent of F17 grade timber to satisfy the Building Code Australia (Class 1) and simulated plate displacement and stress calculation analysis, see figure 3.

The main advantage of CLP is (1) it can be locally manufactured using a standard CNC router and (2) a single person can manually handle the standard-size plywood sheet. In this project, the authors fabricated the CLP under the guidance of TGA engineers. The largest panel fabricated was nominally 3.63m x 3m. In practice, the panel size is only limited by the constraints of the lifting equipment in the manufacturing facilities.

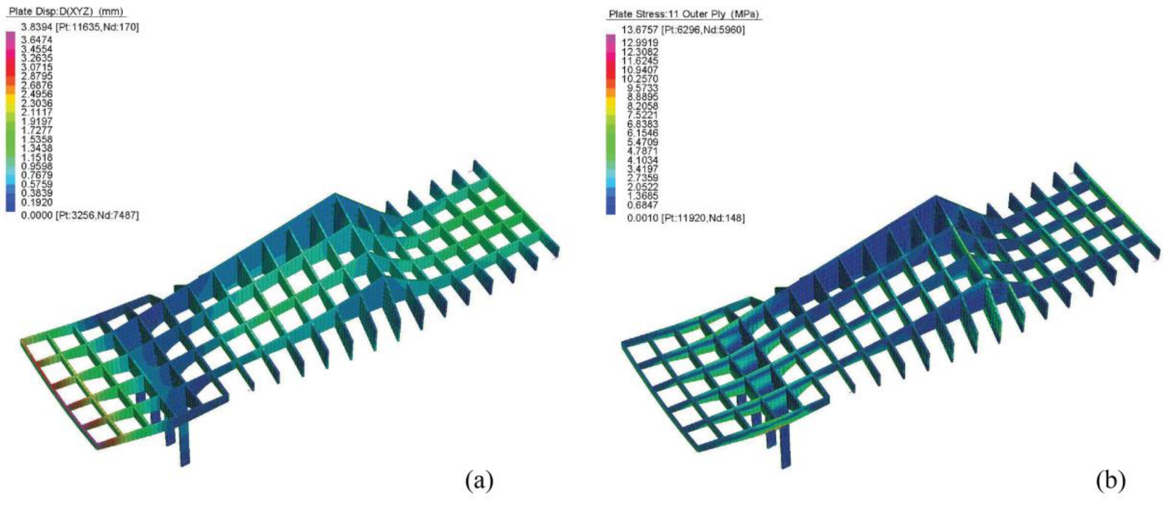

Figure 3. (a) Plate displacement analysis of 3-layer CLP. (b) Stress displacement analysis of 3-layer CLP. Image by TGA engineers.

3.1. Engineering and design feedback

The roof design evolved over two years, from initial sketch design to fabrication. To be resilient to the data updates and design changes, LLDS developed a single parametric model that processes the design constraints, detailing, engineering inputs, fabrication and assembly information into a continuous workflow using Grasshopper 3D, see figure 4. The roof design was denoted by a set of base parameters, including a base grid, a collection of input curves and a surface (figure 4a). The input curves and surface respond to the criteria outlined in section 2.2. The model was evaluated through two sets of analysis: the minimal structural depth provided by the engineer (figure 4b) and the planarisation of the sheathing panels, refer to section 4.2. Rooflight detailing and its distributions were separately developed and integrated into the model (figure 4c). The structural members were separated into their assembly sequenced, and construction detail (figure 4c:11, 12 and 13) was added to the modelling, further expanded in section 4.1. The data was then checked against the as-build information (figure 4d:15); refer to section 5.1. The splitting of the CLP into its layers and joints was automated for CNC fabrication (figure 4d). The model enables LLDS to incrementally build design knowledge as the research team understands the roof's limitations and opportunities. In this instance, care in construction was created through the feedback system embedded in the parametric model, designed as an open system.

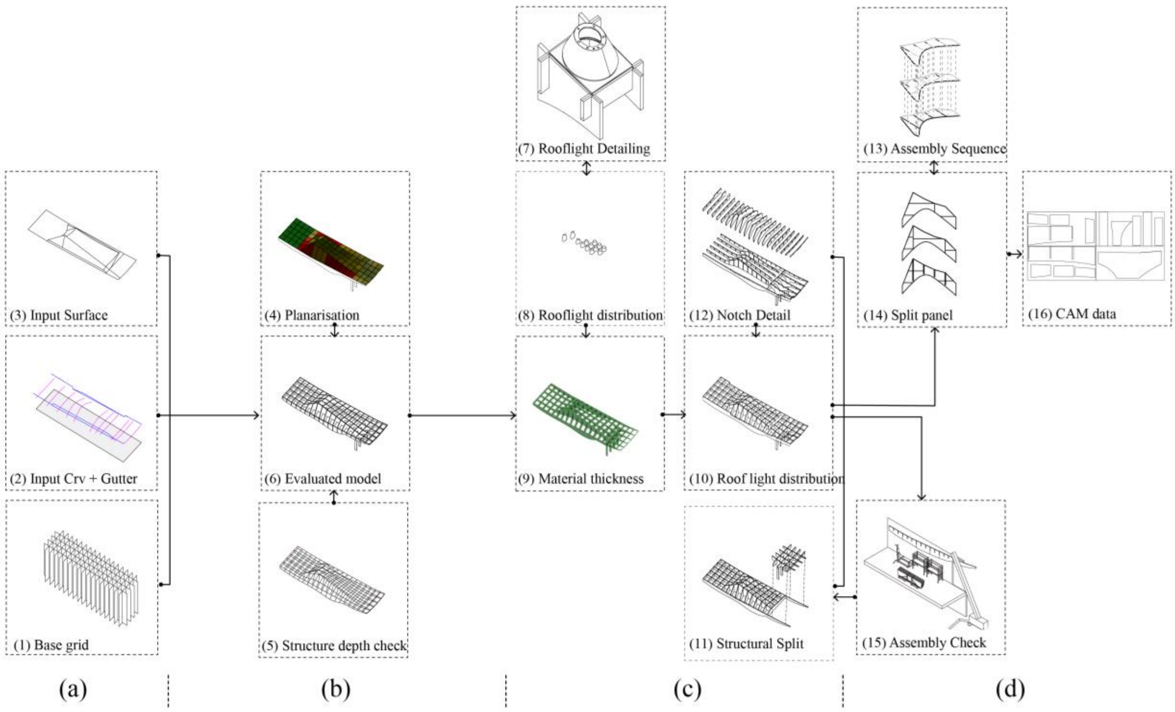

Figure 4. Integrated parametric design workflow. (a) Design input and criteria used to shape the roof geometry. (b) Evaluation of material and engineering requirements. (c) Inclusion of details developed through prototyping and construction sequencing. (d) Automation of fabrication information.

4. Learning from prototyping

Three prototypes are developed: (1) a 1m long junction with the 3-layer CLP composition, (2) a 1:1 prototype of a typical cell with a roof light and (3) a full-scale CLP Beam 1 for point load testing by TGA engineers. The purpose of these prototypes was to understand the fabrication sequence and technique of the CLP. Critically, the development led to Power to Make fabricating all the beams and plates in-house.

4.1. Prototype 1: fixing and lamination

Prototype 1 allowed LLDS to test the finger joints' tolerance, lamination techniques, and the junction between the beam and the bracing plate, see figure 5. The engineer specified 120mm long annular ringed shank nail to be screwed into the junction at a 45-degree angle, leaving little room for errors. Any deviation by +/- 3 degrees will cause the screws to penetrate the plywood on the other side. A jig was designed to hold the screw at the correct angle. The screw hole positions were CNC piloted with an asymmetrical ellipse, used as a guide to orientate the screw fixing. It was pocketed so the fixing can be concealed with a plug. All the above are visual considerations.

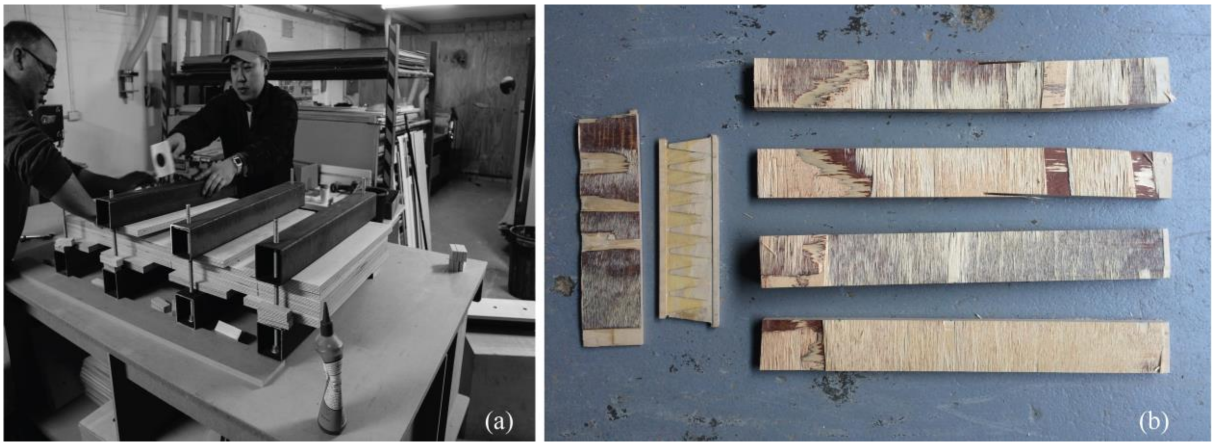

Figure 5. Left, lamination of prototype 1 illustrating the clamping device. Right, a splitted CLP demonstrates the glue bond quality between plywood layers.

A key aspect of CLP is the lamination techniques, particularly the consistent pressure required during the pressing process, as this needs to be proportional to the timber properties [11]. The engineer split the prototype with a chisel as a visual check. The glue is stronger than the timber, so the split did not yield a clean surface. Instead, it revealed the ply of each layer. Figure 5 illustrates the outcome, which indicates the lamination process was adequate.

4.2. Prototype 2: active bending

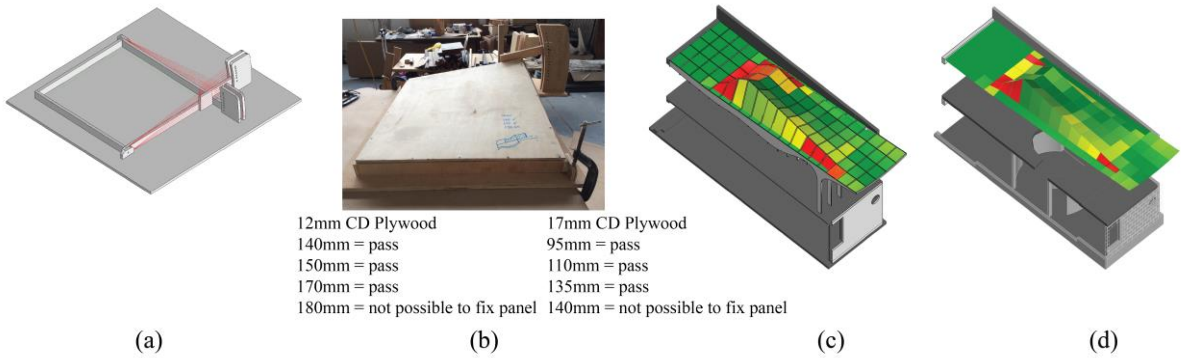

Figure 6. (a) Device used for testing the warp property of plywood. (b) Physical testing of plywood. (c) Roof model correlating sheathing geometry to plywood warp property. Red indicates the surface warp is out of range, and the dark green panel is flat. (d) The roof model was optimised to reduce the number of extremely warp panels to 8.

The second prototype is an entire roof cell with a roof light detail. This prototype illustrates the complexity of the sheathing to the roof. As the roof was subdivided into square cells (730 x 730mm), 75% of the 95 sheathing panels were doubly curved hyperbolic surfaces. Triangulating the sheathing panel into a planar surface was not an option without introducing another complicated structure to the cell and impacting the interior's visual quality.

LLDS developed a simple device to test the bending capacity of 12mm and 17mm plywood, see figure 6a & b. The physical tests provided data as input to the parametric model of the roof, see figure 6c. After several modifications to the surface geometry, the number of panels outside the active bending capacity of the plywood was reduced from 18 to 8 panels with the most extreme curvature, see figure 6d. These panels are kerf and laminated separately. This results in all the sheathing panels being CNC milled and brought to the site, which speeds up the installation process.

4.3. Prototype 3: point load and deflection

The third prototype is a full-length beam, laminated with all the details captured in Prototype 1. LLDS designed a bespoke, flexible table clamp system to provide even compression pressure across the beam surface, see figure 8. The 3.63m long beam was point-load tested at the TGA workshop. It was designed to take up to 30kN. The result indicates the beam deflected by 21mm at 65.7kN (6.7 tonnes) with visible tear to the plywood core, see figure 7. The beam outperforms the design by over 200%.

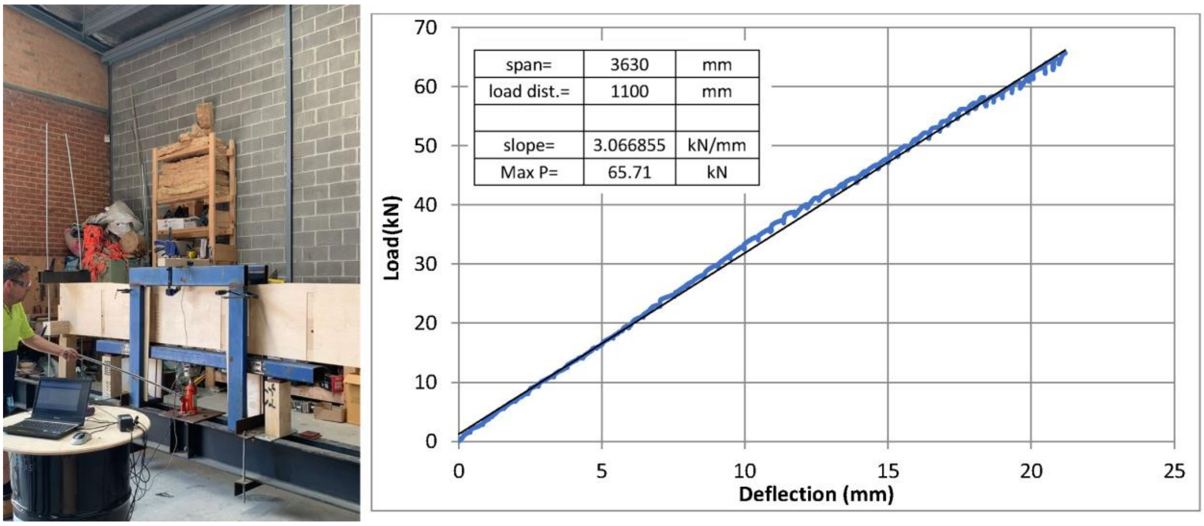

Figure 7. Left, point load deflection testing at TGA workshop. Right, load–deflection curve indicates the beam outperforms the design deflection by over 200%.

5. Assembly of the CLP roof

The authors installed the CLP roof structure with assistance from a registered builder. Before the final wailing plates were delivered to the site, LLDS architects produced a full-scale template of the waling plate in MDF. The templating process was critical as it allowed a final check on the wailing plates' alignment using laser levels and for the anchor bolt holes to be pre-drilled. Each wailing plate comprises five segments with a notch joint between each panel. Four segments were fully anchored to the concrete wall to receive Beam 1 to 15. The last segment was supported with 1/3 of its length fixed to the concrete wall (supported by a concealed steel bracket) and the rest cantilevering.

5.1. Site feedback

Once the final wailing plates were installed, the site was digitally scanned with a Z+F IMAGER 5016 terrestrial laser scanner with a maximum of 160m reach and a resolution of 0.8mm. A series of sections were extracted from the point clouds to check the as-built against the digital model, see figure 8. The scan data were used to (1) adjust the CNC fabrication information of the beams and (2) allowed Power to Make to trim the tenon ends of the beams to ensure the entire structure would fit before delivery to the site. With the scanning technique, LLDS comfortably work to a tolerance of +/- 2mm, just enough for the beam to wiggle into the mortise with a snug fit. The authors used this incremental construction technique in the concrete package previously published in another article [12].

Once all Beam 1 to 15 were installed, the bracing plates followed. The beam and bracing plates were mechanically screw-fixed at a diagonal per the prototype. The jig for the screw fixing and the pocketing to orientate the screw become useful onsite. The same operation applies to the second installation phase for the cantilever roof.

Figure 8. Top Left, clamping device developed by Power to Make. Top Center, Installation of the roof beam on site. Top Right, Installation of sheathing panels, showing both the pre-curved panels and active bending of the sheathing onsite. Bottom, point cloud of as-built concrete walls checked against the digital model of the roof.

6. Conclusion

The paper outlined the design and fabrication of a free-form roof using an integrated design and fabrication workflow, embedding architectural practice within a fabrication environment in collaboration with engineering. The research used CLT fabrication techniques to explore an alternative method using structural plywood as lumber layers, called CLP. CLP is designed to be manufactured within an SME context and to reduce the supply chain. Through 3 sets of prototypes, the design and engineering information was integrated within a single parametric model, allowing resilience in the design and manufacturing process. As-built site information was looped back into the fabrication data to ensure precision in site assembly, demonstrating care in construction.

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