LAMINATED NODES FOR A ROUND TIMBER STRUCTURE

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ABSTRACT: This research investigates the design and fabrication of a laminated timber node connection in a branched roundwood structure. The node was designed using parametric modelling and digital fabrication to resolve complex 3-dimensional non-coplanar connections between round timber members in a columnar frame structure, designed and fabricated to be realized in 1:1 exhibition pavilion[4]. Using bespoke laminations of LVL billets arranged in an optimized 3-dimensional layup, the node design investigates novel techniques to maximize the billet overlap for structural integrity while minimizing the amount of timber wastage. A key innovation in the node design was the sophisticated 3-dimensional resolution of the non-coplanar mitring of branch arms, resulting in a semi rigid connection with a high degree of moment resistance, but also an elegant expression of the timber grain in the node, as it maintains tangential direction corresponding to the intersecting round timber member.

KEYWORDS: Laminated timber node, round timber structures, parametric timber design, digital timber fabrication

1 – INTRODUCTION

Branched structures involving node connections where three or more members intersect in a 3-dimensional configuration, can exhibit geometries that are described as non-coplanar, where one of the members' axis is on an alternate plane to the other two. This is typical of 3-dimensional branching structures where for example, a single base column branches to support a volumetric space frame canopy. The node connection in this type of structure typically relies on a custom fabricated steel connection where the intersecting geometries are resolved through angled and rotated steel plates. This research investigates an alternative to steel connections, by developing a node constructed primarily from engineered timber, in this case, laminated LVL.

2 – BACKGROUND

The node design research was part of a larger project entitled 'Forest to Fibre, Fibre to Building' that investigated the design of roundwood branched structures, where the structural geometry utilises an Inventory Constrained design process combined with CEM form finding [1], that is intended to utilise the most efficient arrangement of a given timber inventory, in this case three specifically selected trees in a statically equilibrated structure [2]. As part of this project, the development of a bespoke laminated LVL node was an integral part that both resolved the structural criteria, being semi-rigid, but also utilised under-valued timber by employing LVL manufactured from low diameter log veneer.

The 'Forest to Fibre, Fibre to Building' project investigated the novel application of roundwood thinning from a hardwood plantation forest on Kabi Kabi and Butchulla country, just inland of Hervey Bay, Queensland, Australia. Over the past two decades the Fraser Coast Regional Council has been reforesting farm land with local native hardwood species such as Spotted Gum (Corymbia Maculata). Since the early 2000s, the council began irrigating these trees with recycled treated effluent to reduce the negative impacts of discharge into creeks, rivers and the ocean, protecting the World Heritage K'Gari (Fraser Island) and surrounding marine environments of the Great Barrier Reef. Drip irrigated trees have been

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[4] The pavilion was exhibited as part of the exhibition at: https://www.slq.qld.gov.au/blog/forest-fibre-building and Forest to Fibre: FCRC Hardwood Plantations – Hervey Bay Regional Gallery

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planted over 526 hectares. These trees have now reached an age where the plantation needs to be thinned out to allow healthier trees to reach their potential and grow to a size suited to traditional timber milling processes. In this process, small diameter trees are felled and are usually treated as a by-product with only marginal value[3], being used for firewood or pulp, though they do have some structural value, albeit in thin roundwood logs[4]. Given the logs are of marginal value when felled, and due to their small diameter, a key objective of the project was to minimise the amount of log processing involved, and to utilise as much of the available fibre in the log as possible, both for retaining viable structural fibre, as well as maximising the sequestered carbon locked up in the structure.

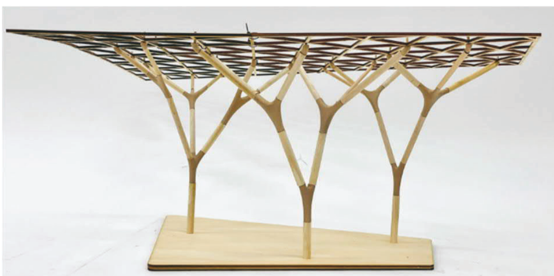

Figure 1. A model of the pavilion, made of 3D printed nodes, laser cut canopy and dowel members.

3 – PROJECT DESCRIPTION

The project investigates the objective of maximising the use of the marginal roundwood resource, via three strategies: firstly, utilising as much of the length of a given felled log as possible; secondly, minimising the amount of fibre removed around the outer (sapwood) layer of the log[5] and; thirdly, where sapwood material is removed, identifying opportunities for its use in engineered timber products that are integrally designed to be part of the structural system.

To use as much of the length of the log as possible, the research proposed an analysis and inventory constrained design methodology that allowed the research team to walk through the forest, scan and digitally identify individual trees, and interpret how that particular log would be optimally assigned to branches of a given structure[1]. This technique employed static analysis utilising CEM form-finding processes, where live data from the analyses was sent immediately back to a forester who then cut the specific lengths (plus some tolerance) ready for transportation.

Figure 2. A selected felled log being sawn into specific lengths, directly in the forest.

Upon transporting to Brisbane, Australia, the logs were then processed with minimal fibre removed, in the process of them being peeled into 'true round' members. This was undertaken principally for reasons of manufacturing standardisation, providing a cylindrical member allowing for connections designed with greater geometric precision. It also created a more aesthetically desirable end result which would support a higher perception of value and uptake in industry. The intention of the design proposal was that the veneers peeled from the outside of logs would also be able to be glued into LVL elements which could in turn be used in the fabrication of the node connections[6].

4 – DESIGN PROCESS

4.1 NODE GEOMETRY

The Inventory Constrained design and CEM form finding design process resulted in an optimised but asymmetric and non-uniform structure where the branches within the structure vary in both diameter and length, and intersect at a range of irregular angles that are dependent upon their optimised equilibrated geometric configuration.[1] This

5 Being Spotted Gum, the sapwood does have recognised structural capacity, but is susceptible to the Lyctus Borer and weathering, so must be treated accordingly if used in external applications.

6 Whilst this is technical possible, the time constraints of the pavilion project pre-determined that off-the-shelf LVL products were required to be used. It is also acknowledged that the initial peeling involves debarking resulting in discontinuous veneer as a result of irregular log profiles. It would be necessary for additional veneer to be peeled from the log and set aside for incorporation into an LVL member.

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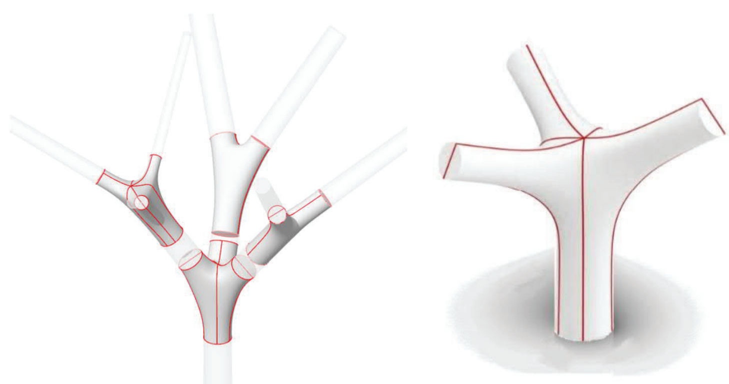
results in frequent instances where nodes are non-coplanar. The nodes for the branched columnar structure had two key geometric challenges to resolve. Firstly, the non-coplanar intersection geometry of four centreline axes[7], representing the centrelines of the converging roundwood members; secondly, the intersecting roundwood members were of varying diameters, due to the overall design optimisation process whereby each given segment of the log was only peeled to an optimal thickness to achieve the true-round profile.

The intersecting geometries of the non-coplanar nodes were resolved through a process of mediating convergent centreline vectors, using parametric NURBS modelling utilising Rhino and Grasshopper[1]. In this strategy, the centreline axis of each convergent branch represented the centreline of a peeled roundwood member. From the intersection point of these axes, a parametrically defined offset length was applied that represents the junction between the end of the peeled roundwood member and the end the 'node arm'. At this junction, the given diameter of the joining roundwood member was ascribed to the diameter of the adjacent node arm. The solid geometry for each of the node arms was then lofted from its circular base at the end the node arm, along the axis of the member toward the common intersection point. The mediation of the geometry about the centre point was parametrically controlled to allow manipulation of the smoothness of the fileting geometry.

A series of planes were then established that were common to both the primary supporting node arm, (the lowermost arm) which is the more vertical and loadbearing member of the node, and each of the departing (uppermost) node arms. This results in generating, for a 3-way node with four intersecting members, three planes that bisect each pair of interesting node arms. The result is that each of the uppermost node arms are bisected longitudinally into two equal parts, and the lowermost branch is bisected three times, resulting in six parts[8]. This can be seen in Figure 3 and Figure 4.

The reason for the bisection of the node into a series of smaller parts is twofold. Firstly, if a node in this application were to be created from a single block of engineered timber, given the range of variation with the intersecting node geometries in the overall structure, the size of the bounding volume that would cater for all of the node configurations would become overly cumbersome and materially wasteful. Secondly, due to the orthotropic nature of the base timber block, it would be suited to only a limited range of intersecting geometries before shear or bending failure would occur. For this reason, a custom lamination process that involves 3-dimnesional mitring of the LVL branch arms was pursued.



(a) *(b)*

Figure 3. (a) A cluster of 2-way coplanar and 3-way non-coplanar nodes and their intersection with roundwood branch members. (b) An isolated example of a 3-way node. Note the red lines represent the planes of bisection.

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[7] The typical nodes of the structure were a 3-way node, consisting of four intersecting members, but some 2-way nodes, consisting of 3 intersecting members were also present. As a result of CEM modelling, the 3-dimensional, equilibrated branch bifurcation resulted in some of the upper level 2-way nodes also presenting non-coplanar geometries.

8 The lowermost branch is bisected three times, into 6 parts, consisting of three pairs of equally sized parts.

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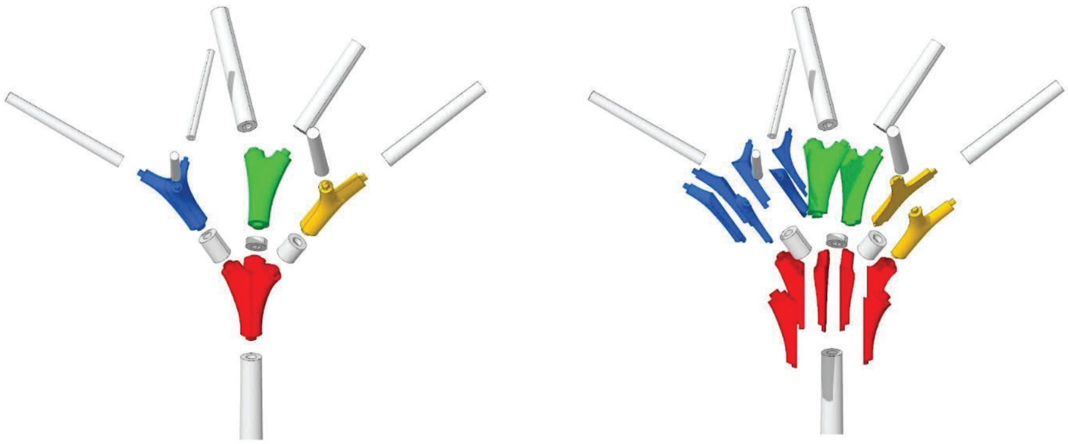


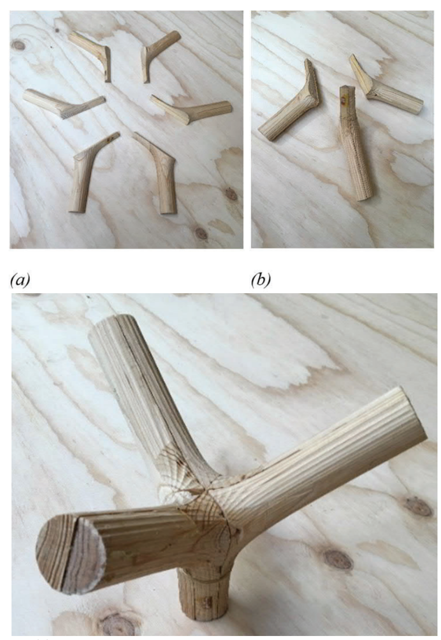
(a) (b)

Figure 4. (a) The branches of the cluster shown in Figure 3, with nodes separated from adjacent roundwood members. (b) Now shown bisected by the planes that are common to both the primary (lowermost) node arms, and each of the departing (uppermost) node arms. Note the relative simplicity of the 2-way co-planer node being bisected just once, resulting in two parts, versus the 3-way node being bisected three times, resulting in six parts.

This ensures a much closer fit to the final branch geometry, thus resulting in less waste, but it also maintains tangential grain direction that aligns the node arm direction to the intersecting member[1]. Prototypes of the geometric bisection of geometries were developed at 1:5 scale as can be shown in Figure 5.

3.2 LVL NODE LAMINATION

To fabricate each of the node arms, the geometry of each node arm was separated into individual elements and rotated so that the plane of bisection was oriented to the x-y plane of the model space. This also corresponds to the flat working plane for machining purposes. By defining the geometry of each node arm by its central plane of bisection, it allows for the node arms to be fabricated on a flatbed CNC router, where the material can be laid flat on a machining bed and milled from above with a 3-axis router. In this method, each node arm would be machined in two back-to-back parts, corresponding to a total of six parts for a three-way node, as is shown in the prototype in Figure 5. However, if the final machining of the node can be performed by a multi-axis robot arm with a router spindle head with the capability for undercutting, the fabrication of the parts is not constrained by the three axes, and the three node arms (for a three-way node) can be machined from a single element requiring a total of three parts. For the final fabrication of the pavilion, this method was used[9].

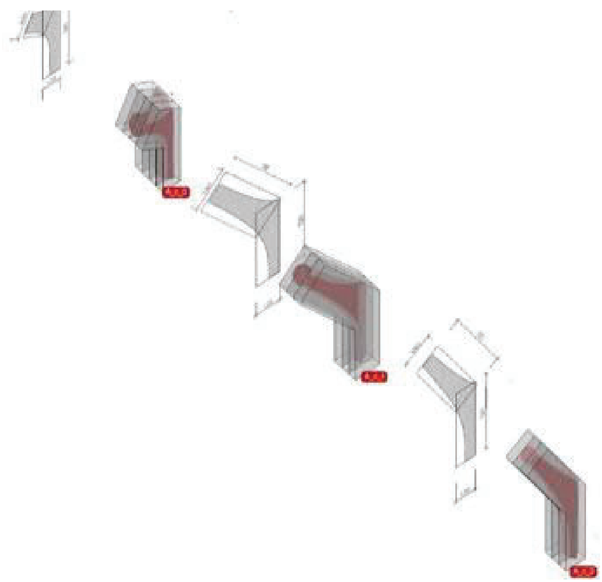


(a) (b) (c)

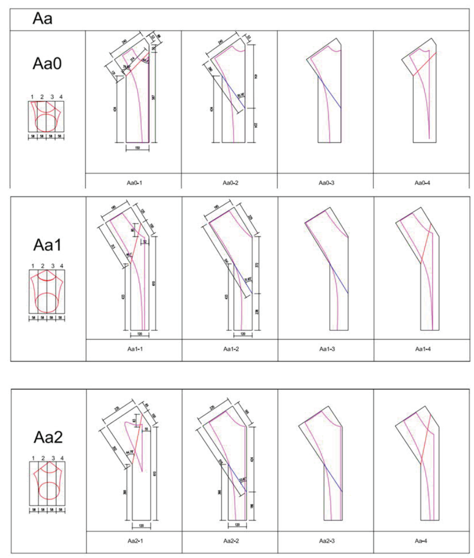
Figure 5. Prototyping of a non-coplanar node at 1:5 scale, showing (a) the 6 individual node parts machined prior to assembly, (b) assembly of the 3 upper branches about their individual common planes, and (c) assembly of the complete node with the all branches assembled about the single common axis of the primary lower branch.

9 FARM Architectural were responsible for the final machining of the nodes, the final fabrication stages and the assembly and installation of the pavilion at the State Library of Queensland. For the machining, they utilised a multi axis robotic arm with a router spindle head.

Each node arm part, once rotated to align with the x-y plane, was then subdivided through contouring parallel to x-y plane to generate a series of lamellas, in this case 60mm thick, corresponding to 60mm thick LVL members, made up of a combination 150mm or 240mm wide members. As can be seen in Figure 6(a), each node arm part, depending on its maximum thickness, required three or four lamellas to build up a node arm 'blank' or 'billet', where the geometry of the billet was fabricated to cater for the maximum thickness. It also included the required angle of rotation from which the final solid geometry could be machined from. As can be seen in Figure 6(b), each LVL lamella was also comprised of two or three end-to-edge glued LVL members that were sawn to a mitred geometry aligning to the axes of the centrelines of the corresponding node arms. When stacking and glueing the lamellas, alternate overlapping mitring patterns were used to ensure sufficient cross bonding of individual LVL members between the lamellas, increasing the overall stiffness of the node arm, and enabling the node to have a degree of moment resistance in its structural performance. Assembled lamellas were then then laminated and press glued to complete the billet for the subsequent stage of machining, as shown in Figure 7.



(a)



(b)

Figure 6. (a) The three node arm geometries making up a node, shown as side profiles and 3-dimensional views with the lamellas required to enable construction of a custom profiled billet. (b) Each node arm billet, shown in top view on the left, and side view on the right, showing the alternate mitring patterns of the LVL lamination.

(a)

(b)

Figure 7. (a) Assembly, glueing and clamping of the mitred LVL lamellas. (b) The completed custom profiled laminated billets.

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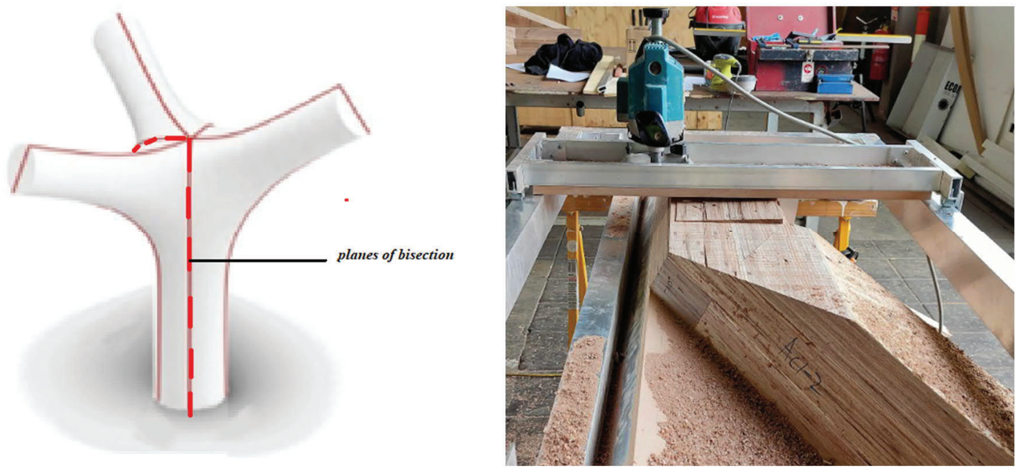
Once each of the custom laminated billets for the node arms were completed, the following step in the fabrication process involved a longitudinal mitring of the billet along the plane of bisection of the primary (lowermost) node arm as shown in Figure 8(a). This was undertaken using a rotating machining bed and a purpose made router gantry overhead, enabling surface planing of the mitred face of the node arm along each of the planes of bisection, shown in Figure 8(b).

With the planes of bisection along the primary branch of the node arm machined, each of the node arms could then be laminated to each other about the central axis of the primary node arm. At this step, the node is 'stood up' so that the axis of the primary node arm is aligned with the z-axis in 3-dimensional space. The node arms were laminated together with epoxy glue and clamped. After the glue had cured, clamps were removed and glued node blocks, shown in Figure 9, were then ready for the final robotic CNC machining, .



(a) *(b)*

Figure 8. (a) The planes of bisection on the primary branch of the node arm. (b) Gantry and router showing planing of one of the planes of bisection.

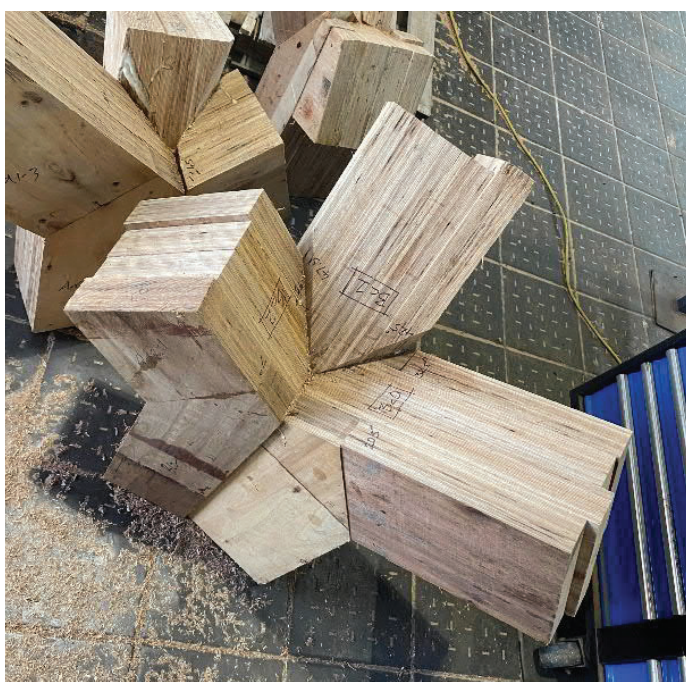


Figure 9. A glued node blank, ready for final machining. Three custom laminated node arm billets are glued together about the central axis of the primary node arm.

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3.3 ROBOTIC MACHINING AND ASSEMBLY

In the final process of node fabrication, the glued node blanks were mounted to a custom-made steel base plate that enabled coach bolts to be fixed through the underside of the node blank, parallel to and at the bottom of the primary node arm axis. This ensured that the node blank could be rigidly connected to the machining table of the robot arm and precisely aligned with the z-axis of the robot arm machining space.

The first pass of robotic machining was a 'rough' milling operation undertaken in vertical contouring using a roughing router bit with a relatively fast travel speed, as shown in Figure 10(a). During this process, considerable vibration was encountered, necessitating temporary propping of the node blank. The final pass of the machining was done with a finishing ball-nose router bit in a cross laced pattern to produce the smooth finish as per Figure 10(b). The node was then subsequently sanding with a handheld orbital sander.

Figure 10 also shows the dowel pockets routed into the ends of the node arms for the final connection dowels. This connection detail was designed as double ended dowel tenon made from 35mm hardwood dowel of kiln dried Spotted Gum (*Corymbia Maculata*). Dowel pockets with 150mm depth were machined into the ends of the node arms during the robotic machining stage and into the ends of the roundwood members using a hand drill attached to a drilling guide jig. The hardwood dowels were cut to 290mm long to enable some tolerance and ensure a close fitting butt joint between ends the node arms and the roundwood members.

(a) *(b)* *(c)*

Figure 10. The robotic milling of the node blank showing (a) the first rough milling pass of vertical contouring, (b) the final cross lacing pass to achieve a smooth finish, and (c) the completed and sanded node. Also visible are the dowel pockets and the inserted dowel in the bottom of the primary node arm.

Once all the nodes and roundwood members were prefabricated, the assembly of the structure on site was relatively efficient, given that that the complexity of the connection detail was resolved through the precise modelling and prefabrication of the node off-site. The simple double ended dowel tenon was also forgiving, in that it was able to tolerate rotational displacement of the roundwood member relative to the node. The key challenge during construction was following a sequence of assembly that ensured nodes were not subjected to adverse temporary load concentrations. As such, it was important that the roundwood members were temporarily supported via suspended strapping. Once the entire structure was integrally connected to each of the members, and to the overhead canopy, the load distribution was equilibrated, and temporary supports could be removed. At this stage, a single countersunk batten screw was fixed at either side of the connection of the node arm and the roundwood member. This locked the dowel from lateral displacement and the roundwood from rotational displacement. It was also concealed from view from below.

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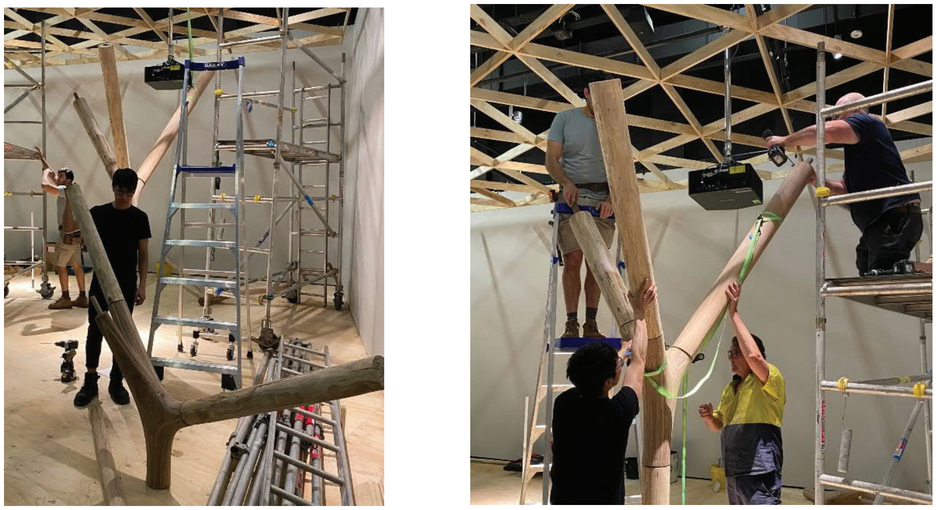
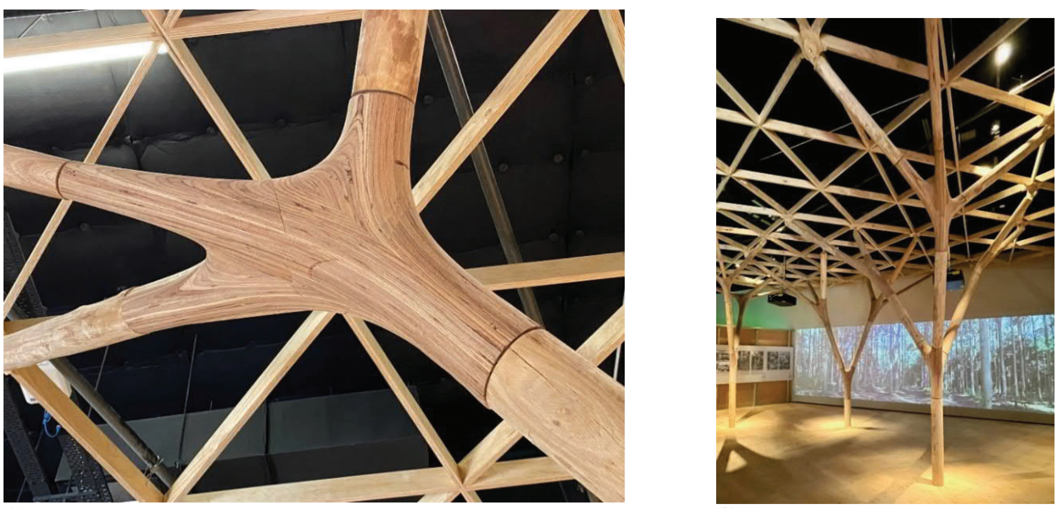


(a) *(b)*

Figure 11. A node with pre-fitted upper roundwood members and dowels inserted. (b) Roundwood members during assembly being temporarily supported.



(a) *(b)*

Figure 12. (a) A completed and installed node. Note the direction of the grain in the custom laminated LVL aligns with the grain direction of the intersecting roundwood members. (b) The completed structure as installed in the State Library of Queensland as part of the 'Purpose Built' Exhibition.

5 – OUTCOMES AND REFLECTIONS

The design of this node demonstrates a novel fabrication strategy, involving the bespoke lamination of alternately mitred LVL lamellas, which are laminated about a common primary node arm axis. This can be shown to be novel and desirable for three key reasons. Firstly, this method ensures the grain direction of each node arm is aligned to the compressive load path through the node. Secondly, it allows for a more efficient consumption of material, as the constituent members used to build up the billet are very close in dimension to the final machined part. Thirdly; the visual effect of aligning the grain of the LVL in each node arm, to the grain of the connected roundwood member, provides a seamless and elegant aesthetic result in the connection detail.

6 – CONCLUSION

The result of this research is the demonstration of a parametric modelling and fabrication technique that uses custom lamination techniques to produce a novel node made solely from timber, that is well suited to complex 3-dimensional geometries and architectural forms. The design was parametrically modelled with toolpaths defined for digital fabrication, and the workflow developed, can be repeated for structures of similar topologies. The complexity of the 3-dimensional mitring and milling involved development of novel fabrication techniques that employed a combination of traditional sawing, hand routing, CNC routing and robotic arm milling. The novel node design offers an exemplar that minimises material waste, exhibits a semi-rigid moment resisting connection without the use of steel, and has a unique aesthetic appearance, where the direction of the grain expresses the latent geometry of the structure.

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8 – REFERENCES

[1] K. R. Baber *et al.*, "Inventory-constrained design of a variable small diameter round timber structure," in *Proceedings of IASS Annual Symposia*, 2023, vol. 2023, no. 2: International Association for Shell and Spatial Structures (IASS), pp. 1-12.

[2] J. Brütting, P. O. Ohlbrock, J. Hofer, and P. D'Acunto, "Stock-constrained truss design exploration through combinatorial equilibrium modeling," *International Journal of Space Structures,* vol. 36, no. 4, pp. 253-269, 2021.

[3] A. Bukauskas *et al.*, "Whole timber construction: A state of the art review," *Construction and Building Materials,* vol. 213, pp. 748-769, 2019.

[4] R. Burton, M. Dickson, and R. Harris, "The use of roundwood thinnings in buildings–a case study," *Building Research & Information,* vol. 26, no. 2, pp. 76-93, 1998.

https://doi.org/10.52202/080513-0109