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Advancing Timber for the Future Built Environment

NEW PERFORMING ARTS VENUE CROSS-LAMINATED TIMBER AUDITORIUM

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ABSTRACT: The New Performing Arts Venue (NPAV) in Brisbane incorporates innovative design solutions, notably the use of Cross-Laminated Timber (CLT) for its 1500 auditorium seats. This paper discusses the constructability and structural performance considerations that led to the adoption of CLT and highlights the benefits of this material choice. Timber offered unique benefits to the project, allowing improved control of sightlines, reduced weight of cantilever balconies, and a construction sequence that took placement of tiered seating off the critical path. The project demonstrates that there are many unique applications for timber on projects, including large scale public buildings and is not confined to multi-storey mass timber structures. The adoption of the material on this major project brought many lessons and experiences presented here.

KEYWORDS: cross-laminated timber, auditorium, theatre, dynamics

1 – INTRODUCTION

The New Performing Arts Venue (NPAV) is an extension to the existing heritage-listed Queensland Performing Arts Centre (QPAC), located at Brisbane's Queensland Cultural Centre, South Bank, and funded by the Queensland Government and QPAC. The new state-of-the-art venue comprises a 1500-capacity theatre to host diverse performances that showcase local, national, and international productions. Arup supported Blight Rayner Snøhetta in their design competition-winning entry for the venue and is working with Managing Contractor Lendlease to deliver the project, which is scheduled for completion in the next year.

The project site is heavily constrained, being bound to the west and south by Grey Street and Russell Street, respectively, while to the north and east, the building adjoins and interfaces with the existing QPAC buildings. The project relied on partial demolition of the existing QPAC building, and cantilevering structure over Grey and Russell Streets to achieve the necessary spatial requirements of the design brief.

During schematic design, it was proposed that the design would adopt CLT auditorium seating plats in lieu of precast concrete, due to a multitude of design, construction and sustainability factors. This paper will cover the general structural system, specific design considerations, factors that lead to the adoption of CLT over conventional precast concrete seating plats, and lessons learnt.

Figure 1. NPAV external competition render (Courtesy: Blight Rayner Snøhetta)

2 – STRUCTURAL SYSTEM

The NPAV structure is composed of reinforced concrete, post-tensioned concrete, steel and composite slabs due to its complex nature and varying requirements, selected with an overarching aim of minimising construction program. The structure adopts in-situ concrete for the flood resilient basement and ground floor, as well as a transfer slab on Level 2. The upper levels are constructed primarily of steel, unpropped composite metal deck slabs, and precast concrete. These were chosen as appropriate and cost-effective materials that offered the potential to maximise safety and speed of construction.

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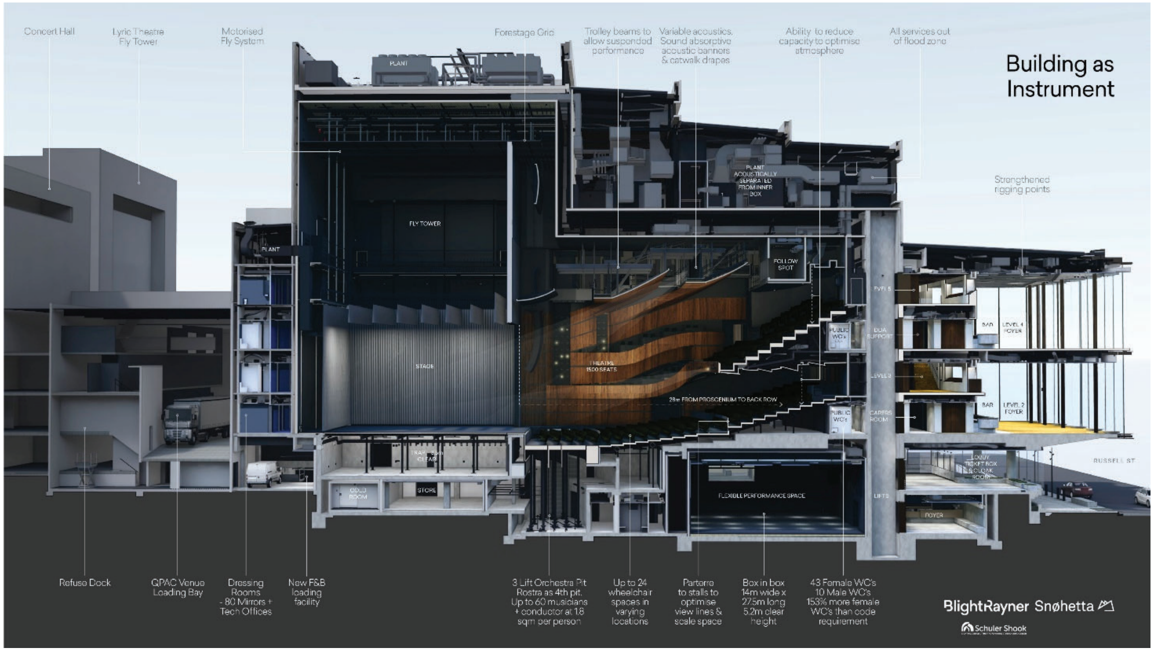

Figure 2. NPAV cross section (Courtesy: Blight Rayner Snøhetta)

The auditorium seating is split in three zones, namely: stalls, balcony and sides boxes as seen in Fig. 2, Fig. 3 and Fig. 4. The steelwork below the stalls is typically supported on the Level 2 transfer slab. The balcony comprises a series of cantilevering steelwork trusses fixed to the main building core walls and the side boxes cantilever off columns within the auditorium side walls. In similar performing arts or stadia venues, precast concrete seating plats are typically used. CLT plats were adopted for this project after detailed evaluation by the design team and contractor, with the main benefits to the project being the contribution to quality and program, which are further discussed in section 3. Consideration of the acoustic requirements and dynamic performance of the auditorium proved critical to the design team.

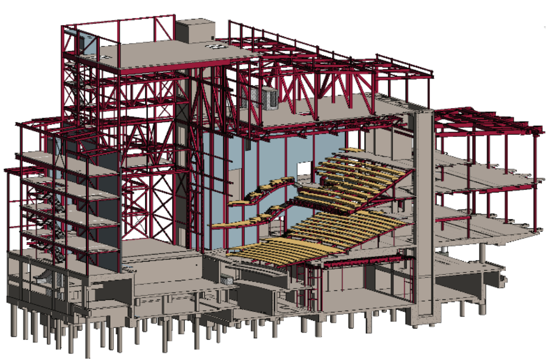

Figure 3. Structural framing cross section (Courtesy: Arup)

2.1 ACOUSTIC STRATEGY

The theatre building includes many spaces with differing uses and stringent acoustic requirements, which require separation to avoid a transfer of both noise and vibration. The acoustic design solution adopted a 'box-in-box' solution in the auditorium to avoid duplication of structure. In the fly tower, acoustic requirements could be met by other means. Separation between the two independent structures were at the proscenium arch.

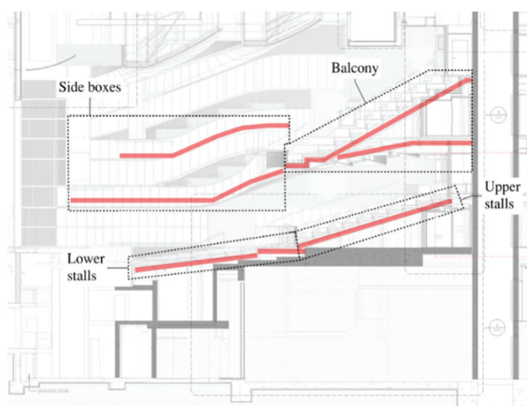

Figure 4. Auditorium section (Background courtesy: Blight Rayner)

The structure of the auditorium has an inner and outer layer to create a 'box-in-a-box'. An acoustic isolation joint is located around the entire auditorium structure, and columns are base-isolated from the Level 2 structure. The implications on the auditorium seating plats were that the stalls required acoustic isolation from the supporting steelwork, while the balcony and balcony boxes did not.

2.2 CLT FRAMING

The CLT seating plats are supported on raking steelwork beams, inclined balcony trusses and horizontal side box

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steelwork beams. Vibration isolation was required between all stall CLT panels and supporting steelwork rakers to achieve the acoustic design strategy. The acoustic design required three layers of Mason Mercer natural rubber Super W waffle pads (total 60mm thick). Recessed bolted connections were adopted with Mason Mercer HG isolation bushings to steelwork, rather than conventional screw fixings, to ensure isolation (Fig. 5).

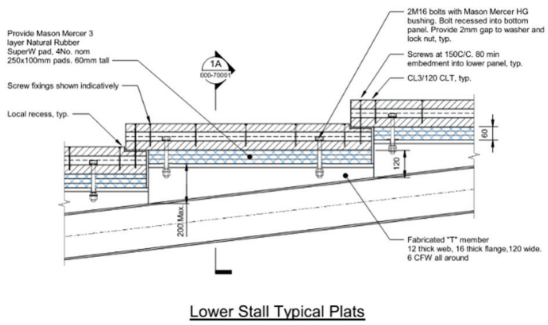

Figure 5. Typical detail of stalls CLT (Courtesy: Arup)

For the balcony, bolted connections were also adopted for consistency, while the horizontal side box beams allowed for simple screw connections between steel flanges and CLT panels. Conventional screwed half-lap joints were used at CLT panel junctions. Noting the varying inclination of steelwork, a level bearing surface was necessary for the CLT panels which was achieved using fabricated steel T-sections, standard T-sections and rectangular hollow sections, refer Fig. 5 and Fig. 6.

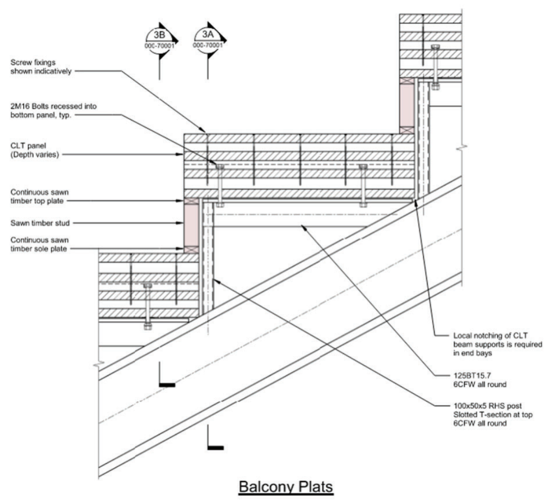

Figure 6. Typical detail of balcony CLT (Courtesy: Arup)

The stalls and balcony steelwork was set out on a radial grid, meaning CLT spans varied. CLT spans in the stalls range from 2.6m to 4.0m with 120mm thick 3-layer CLT panels. Spans on the balcony varied more significantly, from 3.5m to 6m, requiring 5-layer 140-290mm thick panels, with deeper CLT panel sizes driven by dynamic requirements discussed further in sections 2.3 and 4.6.

Steps within the auditorium space were achieved with stacked standard 190mm thick CLT panel blocks. Recesses were created in the lower CLT plats to achieve the necessary step rises. For example, 190mm thick CLT blocks were used with 10mm recess in the underlying CLT panel to achieve 180mm step rises. For more significant stairs within the auditorium, Xlam's proprietary AirStair system was adopted to span top to bottom between CLT panels and avoid the need for intermediate steel supports [1].

2.3 DYNAMICS

The Institution of Structural Engineers (IStructE) guide "Dynamic performance requirements for permanent grandstands subject to crowd action" [2] is generally regarded as the international best practice reference for dynamic performance of grandstands and auditoria. The IStructE guide provides recommendations for levels of dynamic performance for four different types of use/events (referred to as "Scenarios") which will be perceived as comfortable by the majority of patrons and guidance on design approaches.

It is anticipated that the majority of events held in the auditorium are likely to be low energy events best described by Scenario 2: "Classical concert…" with "audience predominantly seated" and "minor excitation" [2]. During detailed design the client outlined their wish to proceed with a design that satisfies IStructE 'Scenario 3' to not restrict its practical use. 'Scenario 3' includes "concerts with medium tempo music and revival pop-concerts with cross generational appeal", involving "Potentially excitable crowd with crowd participation", with the expected crowd "All standing and participating during some part of the programme" [2].

A simple Route 1 analysis can be used for compliance, provided that the frequency of the structure satisfies certain limits. These frequency limits were not achieved with the base structure, and therefore the more involved Route 2 analysis was required to assess the acceleration of the structure under a crowd dynamics event. Oasys GSA design software and was used to assess the structure's crowd dynamics performance. CLT plats were modelled as 1D elements, with steelwork beam stick elements and 2D shell concrete substructure. For the stalls, the Mason Mercer bearing pads deflection curves and effective stiffness were considered and modelled to simulate their effects.

3 – MATERIAL SELECTION

3.1 KEY DRIVERS

The use of cross-laminated timber (CLT) in lieu of precast auditorium seatings plats was proposed by the structural design team during the concept design phase. The benefits outlined to broader project team included:

- Use of small mobile cranes for installation rather than the tower crane - reducing program by taking activities off the critical path
- Ability to manufacture non-standard curved CNC panels to high tolerance with pre-drilled

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seat post ventilation holes thus ensuring sightlines were achieved

- Removed need for on-site drilling of seat posts into precast and associated on-site concrete repair and finishing
- Reduced self-weight on structure and on foundations compared to traditional precast concrete solution, resulting in material savings that partially offset cost increases
- Ability to easily achieve acoustic detailing
- Reduction in upfront embodied carbon.

3.2 SUPPLIER

Lendlease was selected as the contractor using a two-stage managing contractor procurement model. This facilitated input from Lendlease during design. In the initial design phases, the CLT supplier had not been selected, so the design was checked for a range of local and overseas products and corresponding material properties. The final design was based on products supplied by XLam Australia, based in Wodonga, Victoria. XLam manufactures CLT panels in Australia from locally grown plantation pine [1], with the feedstock being sourced entirely from the Hyne timber saw mill at Tumbarumba. The external lamellas are a structural grade dressed timber, while the internal lamellas are rough sawn and of a lower structural grade. The Xlam CLT panels were supplied to site, with installation completed by the steelwork fabricator / installer, idec Solutions.

4 – LESSONS LEARNT

4.1 GENERAL DISCUSSION

A general foreword has been prepared by Bob Shallcross, Construction Manager at Lendlease:

"As a whole, the CLT at NPAV has been a success, in particular comparing it to a traditional precast concrete plat. Moving from concrete to timber allowed the project to use smaller sized cranes which made the install significantly easier both in duration and planning. This also had the outcome of taking the plat install off the project critical path for the most part."

Key areas of learning and improvement identified by the managing contractor are listed below and are discussed in further detail in the following sections:

- Consideration for off-site treatment,
- Storage conditions off-site and inspection prior to loading,
- Lifting arrangements, and
- Accessibility issues with bolts installation.

4.2 PROGRAM BENEFITS AND INSTALLATION

Being a highly constrained site, offsite manufacture was a preferred method of fabrication by removing labour from site. With CLT being a lightweight solution in comparison with traditional precast options, it enabled the use of small mobile cranes for erection instead of the tower crane and thereby reduced overall program by taking the CLT installation off the critical path. Approximately 75% of the CLT was installed using a mobile crane positioned at the main stage after the auditorium was fully enclosed, similar to Fig. 7. During detailed design, some localised panels at the rear of the balcony were identified as being too heavy for the mobile crane and required installation ahead of program using tower cranes.

Figure 7. View from balcony towards stage - stalls auditorium plats with mobile crane (Courtesy: Arup)

The CLT on this project was treated under the same lifting conditions as precast concrete. As such, consideration for a safety lifter, along with the two primary lifting points is needed. Given the unusual geometry of some of these plats, early engagement between design team and rigging team is encouraged to ensure the centre of gravity under given lifting conditions is correctly considered.

Installation of the CLT to steelwork bolts, as shown in Fig. 5 and Fig. 6, caused challenges for the rigging sub-contractor. Safety was maintained at all times, however, consideration in design and early engagement with the selected contractor regarding on-site fixings may have led to adjustments to manage the safe access considerations differently.

4.3 PROCUREMENT

The CLT seating panels were required to have a radial curved geometry to achieve the architectural intent, with limited repetition and varying spans of the panels. The balcony boxes, in particular, required a variety of distinct curved geometries. Furthermore, the building services mechanical strategy of the auditorium relied on seat post diffusers from a plenum below, which required a circular penetration aligned with each seat. The complexity and lack of repetition in the geometry lent itself to CLT and CNC fabrication. This allowed the team to achieve the desired aesthetic outcome at little impact to manufacturing cost or program.

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While the tender process included multiple European suppliers, locally XLam Australia was the primary Australian CLT producer at the time and was ultimately chosen due to a variety of considerations. XLam pressed the CLT panels and used Hundegger CNC machinery for processing and cutting the desired final panel geometries. The CNC machinery is highly flexible and was able to create the required plan curvature of the seating panels, as well as the lap joints and seat post penetrations. The router allowed for simple processing of the various plan curved panel geometries, which would be challenging to fabricate using traditional material choices.

The final design of the balcony boxes featured complex curved geometry with little repetition, refer Fig. 8. The tiered floors were joined by bespoke XLam AirStairs which were curved on plan. To achieve this, the AirStair CLT billet is processed on the horizontal plane, with the treads and stair profile cut from a solid panel. However, due to limitations of the equipment at the time, the curved shape on plan was achieved using a series of rationalised straight cut rather than routing.

Since the tender process in early 2021, additional CLT suppliers have emerged in the Australian and global markets, which would likely aid the competitive tender process and improve cost competitiveness. Early supplier engagement during the schematic design can result in fabrication and cost efficiencies.

Figure 8. Render of auditorium with tiered balcony boxes (Courtesy: Blight Rayner Snøhetta)

4.4 COORDINATION AND FABRICATION

The steelwork shop detailing and fabrication program preceded the CLT for program reasons, with fabrication of steelwork overlapping the coordination and shop drawings approval processes for the CLT package. To facilitate this approach, the steelwork fabrication models included CLT panel massing, based on the structural design intent to aid steelwork coordination. This CLT massing was later used and then superseded by the CLT manufacturer's models.

This program meant that adjustments to CLT geometry and resolution of non-typical interfaces often relied on modification of the CLT panels and bespoke timber detailing, rather than adjustment of steelwork. CLT in conjunction with sawn timber was used with screw detailing, to resolve these design issues. The relative simplicity of installing screwed connections aided the installation process, however alternative approaches to programming of these activities could have simplified design details further.

CLT primarily interfaced with steelwork on the project, and the similar dimensional tolerances of the materials meant that both could be modelled and coordinated in 3D fabricator models, and accurately installed. Importantly, the tight dimensional tolerances of the two materials ensured that there was tight control over sightlines and set-out of the seat post diffuser penetrations, which would be challenging with other material selections.

Figure 9. Lower stalls with covers over seat post diffuser penetrations (Courtesy: Arup)

While the majority of the CLT on the project could be installed via mobile cranes when the auditorium was enclosed, some large panels were installed ahead of time and consequently exposed to weather. The plats were treated and remediated in-situ, however, off-site treatment at the time of fabrication would have been preferred.

4.5 OFF-SITE STORAGE

The fabricated CLT was manufactured ahead time and stored off-site until required for installation. Unfortunately, spider infestations were identified in some penetration holes when the CLT arrived on site, which required fumigation and caused delays. Protection of the panels in the off-site storage location and inspection prior to delivery could have limited delays on site and would be recommended in future.

4.6 DYNAMICS

Deflection and dynamic performance of the CLT governed panel depths. Where possible, span lengths were selected to avoid panels being sized to control dynamics. In doing so, dynamics was not a governing factor in design of the stalls, where the 120mm thick CLT panels were suitable to achieve the 'Scenario 3' acceleration requirements.

The CLT plats in this area were supported on steelwork, with short stub columns on the 400-1200mm deep post-tensioned transfer slab. CLT spans in the stalls were typically in the range of 2.6m to 4.0m. The radial setout of the steelwork lead to increased spans near the rear of the lower and upper stalls. Dynamic analysis during the final stages of detailed design identified two localised areas of higher excitation where spans were around 4.2m at the rear of the lower stalls. Additional steel beams were introduced to reduce spans and achieve 'Scenario 3' compliance.

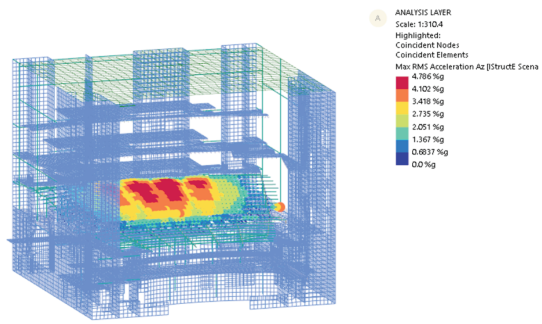

Figure 10. Stalls dynamic 'Scenario 3' accelerations in Oasys GSA (Courtesy: Arup)

The balcony structure, however, was dynamically sensitive, being a lightweight cantilever structure off the building core, with longer CLT spans. During schematic design, frequency checks were completed on the balcony CLT scheme using simplified calculation methods, which indicated that the structure achieved Route 1 compliance for 'Scenario 3'.

During detailed design, with the development of a more sophisticated 3D analysis model, as well as changes to geometry and architectural planning, the frequency of the system was less than 6Hz and 'Route 2' analysis was required. The assessment highlighted the importance of early dynamic assessment, with shortcomings in simplified models for these complex geometries. The analysis highlighted zones in the central rear of the auditorium with particular excitation, which required a localised increase in structural depth to the CLT panels.

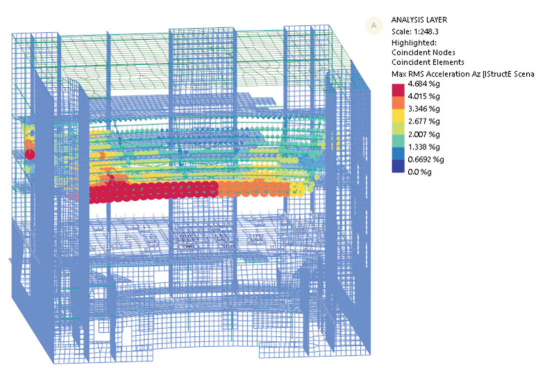

Figure 11. Balcony dynamic 'Scenario 3' accelerations in Oasys GSA (Courtesy: Arup)

4.7 EMBODIED CARBON

The 'For Construction' CLT design was completed in late 2020. Preliminary Xlam CLT embodied carbon factors were used in the initial upfront embodied carbon calculations on the project, with the Xlam CLT EPD formally published in early 2021 [3]. The A1-A3 carbon factor (Global Warming Potential (fossil)) for Xlam CLT was given as 447 kgCO2e/m3 or 0.93 kgCO2e/kg [3]. This value was considerably higher than European CLT suppliers, primarily due to the carbon intensive energy mix in the region where electricity grid mix emissions factors ranged from 1,020 – 1,321 gCO2e/kWh [3]. Even with the high carbon factor for the CLT manufacture, it showed an approximately 20% reduction against a baseline precast concrete solution for an upfront stage A1-A5 embodied carbon assessment.

Fabrication of the first CLT panels for the project commenced in 2022. In January 2022, Xlam changed its electricity supply to 100% renewable energy for their manufacturing facility in Wodonga, with renewable energy provided by GreenPower Australia. This change in supply electricity carbon intensity, reduced the stage A1-A3 production carbon emissions by 45%, down to 248 kgCO2e/m3 or 0.52 kgCO2e/kg [4]. The actual upfront embodied carbon in the project CLT, has consequently been substantially reduced. Ignoring the flow-on effects of reduced CLT weight on reduced substructure tonnage, the adoption of CLT panels in lieu of reinforced precast panels for the auditorium is estimated to have had >40% reduction in stage A1-A5 embodied carbon emissions, and a saving of approximately 50 tonnes of CO2e.

With a maturing CLT market in Australia, an influx in manufacturers, and transition to greener electricity supply alternatives, the lower carbon factors will assist in achieving upfront carbon savings compared to traditional material choices through the appropriate use of timber within new building structures.

5 – CONCLUSIONS

Timber is generally adopted for a variety of drivers, including client aspirations, sustainability, biophilic benefits, low weight and offsite manufacture. The adoption of CLT panels for the 1500 auditorium seats at NPAV illustrates the potential of timber in the construction industry. CLT provided unique benefits compared to conventional building materials in this project application, which were realised during construction.

The lightweight nature of CLT facilitated more efficient construction logistics, namely the use of small mobile cranes rather than tower cranes, which enabled it to be moved off the critical path and alleviated program constraints. The ability to fabricate CLT with CNC technology, not only ensured tight dimensional tolerances, but also enabled irregular curved panels to meet architectural intent. Dynamic performance of the

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lightweight material was critical and needs careful design consideration throughout to ensure compliance with the design brief. With the maturing of the Australian mass timber market, and adoption of low emissions energy sources, the use of CLT can provide significant savings in upfront embodied carbon emissions and be a driver towards more sustainable buildings. Timber is shown to be a reliable and adaptable material choice in a major building projects, when used in suitable applications, which can achieve architectural aspirations and provide benefits to the overall construction process.

6 – ACKNOWLEDGEMENTS

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