WORLD CONFERENCE ON TIMBER ENGINEERING 2025
BRISBANE, AUSTRALIA
Advancing Timber for the Future Built Environment

IMPLEMENTATION OF ADAPTABLE DESIGN PRINCIPLES FOR HIGH-PERFORMANCE LIGHT TIMBER FRAMED PANELISED BUILDINGS: AN AUSTRALIAN CASE STUDY

Zidi Yan[1], Marcus Strang[2], Lisa-Mareike Ottenhaus[3], Paola Leardini[4], Paul Adams[5], Keith Crews[6]

ABSTRACT: Australia faces a housing crisis marked by high mortgages for oversized, underperforming homes, making home ownership increasingly inaccessible for younger generations. Adaptable housing allows homes to evolve with household needs and incorporates future-proof design principles. This paper present findings of applied research aimed to explore the technical feasibility of adaptable housing in Southeast Queensland using a novel modular, reconfigurable, and relocatable light timber-framed building system that can respond to changing occupant needs. Design considerations, technical challenges and corresponding solutions are presented with a focus on structural and hygrothermal design and performance.

KEYWORDS: *Adaptable housing, reversible connections, light timber framing, hygrothermal performance, circular economy*

1 - INTRODUCTION

Australia is facing a housing quality and affordability crisis, with high mortgage costs for oversized yet underperforming homes. While home ownership remains central to Australia's retirement strategy and social insurance, this economic model is becoming increasingly inaccessible to younger generations. Statistical data indicates that many Australian families relocate due to insufficient living space as their household grows [1]. Adaptable housing, designed to evolve with changing household needs, offers a potential solution by enabling first-home buyers to enter the market without compromising on quality, living space, and long-term building performance [2].

Researchers at the University of Queensland (UQ) initiated a research project in collaboration with Fairweather Homes Pty Ltd (a modular housing architecture, supplier, and building company based in Melbourne and Brisbane, Australia) to develop, prototype, and monitor an adaptable timber construction system to explore the social, economic, and environmental benefits of adaptable housing in Southeast Queensland (SEQ), where low-density suburban dwellings are predominant. By combining adaptable design with high-performance components, the system aims to enable spatial and functional flexibility, component disassembly and reuse, and climate responsiveness, thereby enhancing affordability over the building's lifecycle. By only purchasing high-quality components to shape spaces that occupants need at any given time, long-term household changes can be accommodated without increasing initial dwelling costs and without compromising on building quality.

This paper examines the complex and multifaceted challenges encountered in the development of the system and its implementation into a full-scale prototype, which considered multiple building lifecycle stages, from offsite manufacturing to on-site assembly, disassembly, and reassembly. The study particularly focuses on the integration of reversible connectors and innovative solutions for water- and airtightness, ensuring long-term structural integrity and hygrothermal performance across various spatial configurations. The challenges and advantages of this adaptable timber-framed system are critically analysed to provide insights into its potential to transform Australia's housing sector.

2 - BACKGROUND

The global shift towards prefabricated and modular construction has demonstrated its potential for sustainable housing solutions, particularly in Europe and North America. Offsite timber construction offers significant benefits, including improved precision, waste reduction, and enhanced efficiency. Offsite manufacture also offers significant benefits within the circular economy (CE), a widely recognised approach to reduce reliance on non-renewable construction materials while mitigating climate change impacts [3]. Design for Adaptability, Disassembly,

[1] Zidi Yan, The University of Queensland, St Lucia QLD 4072, Australia, zidi.yan@uq.edu.au
[2] Marcus Strang, The University of Queensland, St Lucia QLD 4072, Australia, m.strang@uq.net.au
[3] Lisa-Mareike Ottenhaus, The University of Queensland, St Lucia QLD 4072, Australia, l.ottenhaus@uq.edu.au
[4] Paola Leardini, The University of Queensland, St Lucia QLD 4072, Australia, p.leardini@uq.edu.au
[5] Paul Adams, Fairweather Homes Pty Ltd, Melbourne VIC 3000, pa@fairweatherhomes.com.au
[6] Keith Crews, The University of Queensland, St Lucia QLD 4072, Australia, k.crews@uq.edu.au

https://doi.org/10.52202/080513-0156

and Reuse (DfADR) provides a practical pathway for integrating CE principles into conventional residential construction by extending the service life of buildings and their components, thereby minimising waste while also improving resource efficiency and long-term sustainability.

This research adopted both approaches: offsite manufacture in an Australian context, addressing its unique climatic and regulatory challenge, as well as DfADR to develop a high-performance housing system capable of adapting to shifting household needs and climatic conditions. Prefabricated timber panels were utilised to enhance construction quality, minimise material waste, and streamline assembly. Furthermore, Passivhaus design principles were applied to optimise hygrothermal performance and indoor environmental quality while reducing heating and cooling loads.

3 - PROJECT DESCRIPTION AND OBJECTIVES

The project discussed in this paper embraces a novel approach to system design in timber construction, conceptualising buildings as customised assemblies of standardised and high-performance components linked by reversible connectors. This design enables multiple spatial reconfigurations over time in response to environmental and social changes.

The research project set two main objectives. The first objective was to develop and build an adaptable building system with reversible connectors and a high-performance envelope, designed to be manufactured off-site and assembled at UQ's Pinjarra Hills research facility (**Error! Reference source not found.**). The second objective was to assess the feasibility of this system by testing the reversible connectors, structural and hygrothermal performance solutions through multiple reconfigurations, involving cycles of disassembly and reassembly.

This paper focuses on the first objective, with an elaboration on the challenges encountered during the design phase and the solutions implemented to overcome these challenges.

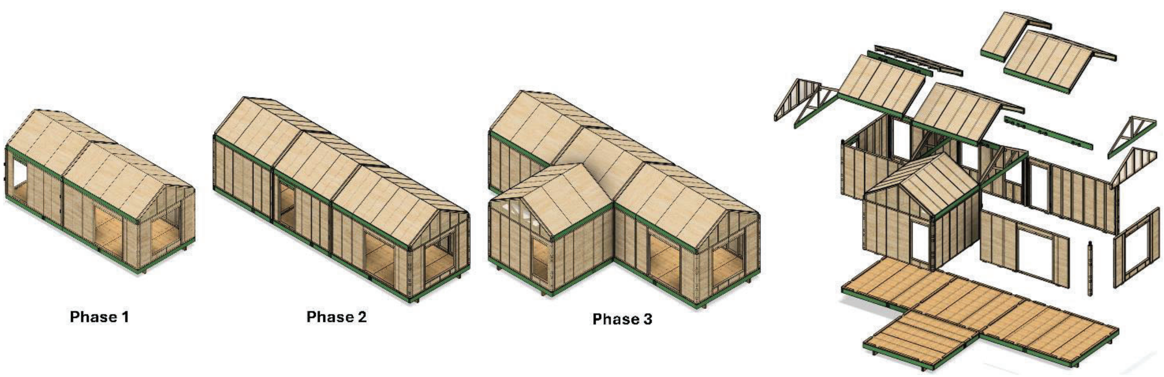

Figure 1. Overview of the adaptable building design and spatial reconfiguration stages.

4 - DESIGN CHALLENGES

4.1 ADAPTABLE STRUCTURAL DESIGN AND REVERSIBLE CONNECTORS

Connections played a crucial role in the system design. In traditional timber structures, connections govern the overall structural performance. Additionally, in adaptable timber buildings, connections are essential to delivering the functionality and reversibility of the system. To implement DfADR principles, highly standardised building components integrated with reversible timber connections were developed. Previous research by Yan et al. [4] identified connector tolerances as a critical challenge as dimensional changes in timber members affect reversibility of tight-fit connectors.

Ease of on-site assembly of building components was identified as another major challenge. The weight of structural modules, such roof cassettes, poses significant difficulties for builders and workers, particularly when working at heights and for positioning the modules correctly. The existing workflow for conventional, irreversible construction is both time-consuming and labour-intensive. Thus, two connection details and one new connector were designed for the most critical junctions to overcome the limitations of existing connectors. Each joint was tested in small-scale experiments to assess the structural capacity in the desired application.

Finally, identifying the installation and disassembly sequences of building components is essential for the reconfiguration of the building. It is important to minimise the amount of work as well as the number of building components that need to be disassembled during the reconfiguration phases. Hence, several standardised modular building components were designed to facilitate spatial reconfiguration, which represent a departure from conventional timber-framed systems.

https://doi.org/10.52202/080513-0156

4.2 RESOLUTION OF THE AIR AND THERMAL CONTROL LAYERS

Consideration of control layers is critical to building performance to minimise energy usage, ensure durability of materials, and to provide a thermally comfortable indoor environment. To achieve an airtight construction there must be a continuous, identified air barrier around the building envelope; likewise, achieving a high-performance thermal layer requires consideration of any penetrations in the insulation materials, avoiding thermal bridging, which is a localised area of the building envelope where the heat flow is different (usually increased) in comparison with adjacent areas (assessed as per standard ISO 10211 [5]). Due to the high-performance targets of the project, thermal bridging required careful evaluation and novel solutions, to ensure that the reversible connections were designed in such a way that they were not detrimental to the energy-efficiency of the envelope.

4.3 MOISTURE SAFETY

Airtight construction needs to be considered in conjunction with a moisture free assembly that has dry-out capacity and a managed ventilation strategy to maintain good indoor air quality and hygiene. The dry-out capacity of the assemblies was modelled in WUFI Pro [6], a dynamic, coupled heat and moisture transport software (as per ASHRAE 160 [7]), to understand the risk of long-term interstitial biodeterioration in a subtropical climate. This allows for the correct development of climate-adapted insulation placement, ventilation systems, vapour controls and construction material properties.

4.4 ENERGY EFFICIECY AND THERMAL COMFORT

The energy performance of the prototype was modelled for all three construction phases (Figure 1) using the **Passive House Planning Package** (PHPP) [8]. The PHPP is a single-zone, quasi-static spreadsheet model with a monthly balance energy calculation tool based on EN 13790 [9], which is intended to assist in the design of Passivhaus certified buildings [10] and has been validated by multiple studies globally [11], [12], [13], [14], yet with a noticeable gap in hot and humid climates. Comparative analysis of results from simulation and the prototype's monitoring campaign are expected to contribute to the PHPP validation in sub-tropical climates.

5 - RESULTS

5.1 STRUCTURAL DESIGN

5.1.1 PANEL-TO-PANEL CONNECTOR

Three types of proprietary reversible beam-column connectors were experimentally tested to assess their structural performance and reversibility when using Australian sawn timber [4]. However, their installation direction and tight tolerance were impractical for spatial system reconfigurations as required in this project. Other reversible connectors were considered, which exhibited similar low tolerances or lacked a thorough evaluation of their reversibility performance [15]. These limitations rendered them unsuitable for the newly developed system.

In response to these challenges, a new panel-to-panel connector, AusCon, was developed in collaboration with SHERPA Connectors and Fairweather Homes. The design of the connector was guided by three key considerations: construction feasibility, structural performance and commercial viability. This holistic approach is depicted in Figure 2, where the interrelation of these three critical factors is illustrated through overlapping circles, each signifying a fundamental aspect of connector design and implementation. By addressing these three critical factors simultaneously, the newly developed connector has proven capable of providing a robust and adaptable solution for the next generation of prefabricated timber construction.

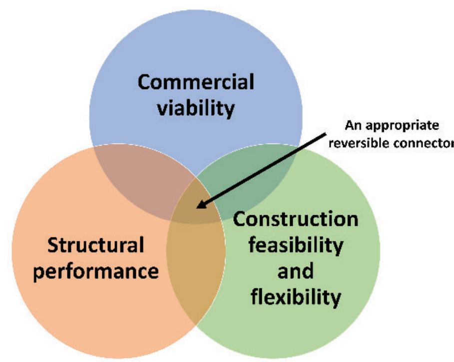

Figure 2. Critical factors for an appropriate connector design [16].

The commercial viability of the connector ensures cost-effective production, making it competitive in the market and commercially sustainable. The AusCon connector draws inspiration from the existing SHERPA XS-XXL connector series, particularly the M20 series [17]. Its design, as shown in Figure 3, involves dividing the dovetail tongue component into two symmetric plates and integrating both orthogonal and inclined countersunk screw holes. The dovetail groove adopts a cap fastened with two M6 lock screws. The dovetail tongue and groove components are identical, simplifying the manufacturing process and improving cost-effectiveness for commercial production.

https://doi.org/10.52202/080513-0156

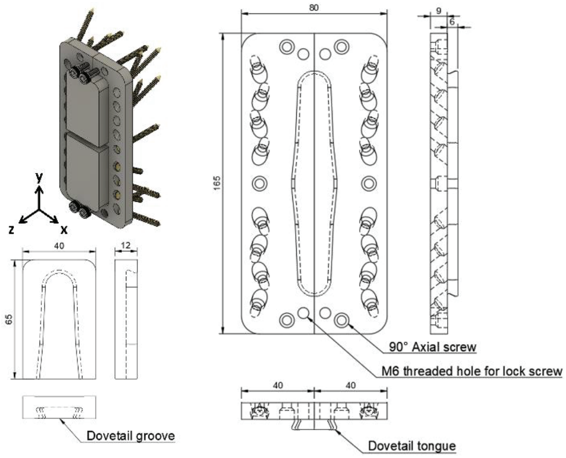

Figure 3. Schematic diagrams of AusCon connector.

Construction feasibility and flexibility are critical for ensuring ease of installation, adaptability to different construction methods, and efficiency in modular construction processes. The connector maximises installation degrees of freedom, allowing for both translations and rotations in X, Y, and Z-axes (Figure 3). The dovetail features two slope angles to enhance installation tolerance and does not require all four lock screws to be installed.

If vertical (Y-axis) tolerance is an issue, the cap can be adjusted to its maximum allowable position, requiring only one lock screw to resist uplift loads without comprising load bearing capacities. Additionally, the connector is designed for installation on the internal face of wall panels, allowing for internal installation without the need to remove adjacent building components during the reconfiguration phases.

Structural performance is a crucial factor in ensuring the durability and longevity of the reversible connector in service. The connector is equipped with eight inclined screws, selected based on outcomes from previous studies [4], [17]. The chosen inclination angle mirrors that of the M20 connector, balancing structural strength, ease of installation, and manufacturing efficiency. Constructed from aluminium alloy Al 6082-T6, the same material used in the SHERPA XS-XXL series, the connector offers excellent mechanical properties and corrosion resistance. Experimental tests conducted at UQ assessed its performance in three loading directions [16]. The experimental results confirmed that the current design of the AusCon connector exhibits sufficient structural capacity, making it suitable for integration within the newly developed building system.

5.1.2 CARPENTRY CASTELLATED CONNECTIONS

Despite the numerous advantages of offsite construction, several tasks in conventional prefabricated construction still require on-site completion. These include lifting, aligning building components, and accurately positioning them while ensuring they remain securely in place under their own weight.

A significant challenge frequently encountered during the assembly of prefabricated roof cassette modules with ridge beams was identified. Roof modules often require machinery to lift them to the desired height, involving at least two workers standing on scaffolding to manually hold the panel in place and make fine adjustments using considerable physical effort. This process is not only labour-intensive but also introduces potential alignment difficulties, increasing construction time and dependency on skilled workers.

Two castellated carpentry joints were developed for panel-to-floor and roof-to-ridge beam junctions incorporating principles of DfADR while overcoming the previously mentioned challenges.

The geometry of the castellated joints was adapted from mass timber exemplar projects and consists of two primary components: an angled castellated shear block and a corresponding dovetail groove. Figure 4 illustrates the working mechanism of the castellated shear blocks, which are designed to be attached to the bottom plate of the wall panels for floor castellated joints, and to the blocking plate of the roof cassettes for roof castellated joints using high-performance self-tapping screws.

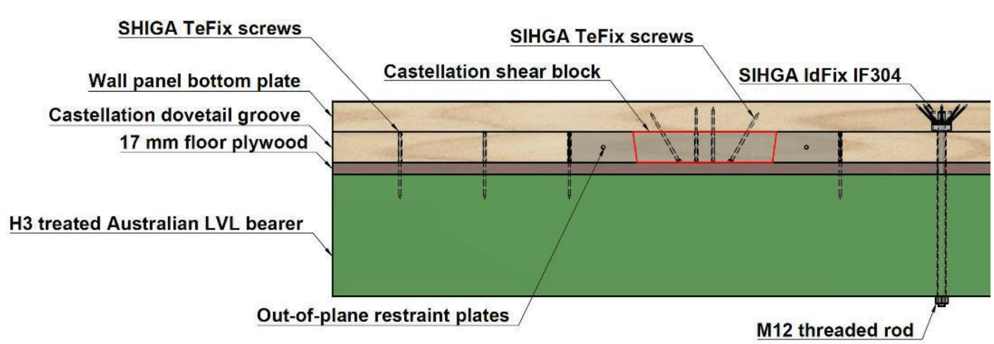

Figure 4. Schematic diagram of floor castellation connection.

https://doi.org/10.52202/080513-0156

The grooves (i.e., recessed notches) are assembled to the corresponding floor bearers and ridge beams using stainless steel high-performance self-tapping screws. The angle of the shear block slope and the screw installation layouts were experimentally tested at UQ, confirming both ease of installation and reliable structural performance. Due to the inclined surface of the shear blocks and the prefabricated grooves on the floor and ridge beams, workers can easily position wall panels and roof cassettes using a crane. Once lifted into the proximity, the modules will then self-align, thereby significantly simplifying the installation process.

It should be noted that to prevent tilting, additional out-of-plane restraints need to be installed to enclose the groove and form a complete cavity. However, due to the geometry limitations of these castellated connections, the uplift bearing capacity can be managed and controlled by separate connections (e.g. a SIHGA IdFix IF304 and threaded rod).

To ensure consistency and minimise potential tolerance issues, the shear blocks and grooves were cut from the same piece of timber. Stainless steel screws were used due to the application of H3-treated LVL bearers and ridges, which require enhanced corrosion resistance. Conventional screw coatings, such as zinc, can react with timber preservatives following moisture ingress during construction stages or accidental water leakage, leading to significant reductions in fastener strength. Furthermore, the integration of acoustic layers between floor and wall panels was structurally tested, and experimental results confirmed that the addition of these layers had no negative impact on structural performance. Instead, airborne and impact sound transmission could be effectively managed, improving the overall acoustic performance of the system.

5.1.4 DESIGN OF STRUCTURAL MEMBERS AND CONNECTION VERIFICATION

In addition to connection design, the building components were engineered using DfADR. The structural system design took a low-variance approach, where most building elements are designed with a uniform nominal size and standardised geometry. The wall studs, roof rafters, and floor joists are precisely aligned, as shown in Figure 5, ensuring seamless integration across all structural components.

This standardisation offers several key benefits. First, it simplifies the manufacturing process by maintaining uniform spacing across structural members, which reduces assembly errors and tolerance, and improves manufacturing efficiency. Second, it enables the precise installation of batten strips onto the structural studs, optimising prefabrication processes and minimising on-site adjustments. Finally, maintaining consistent alignment establishes a continuous load transfer path, ensuring that roof joists, wall studs, and floor joists work in unison to enhance the overall structural integrity of the system. Moreover, the standardised design of building components promotes efficient mass production, maximising the benefits of prefabricated construction and improving overall cost-effectiveness, scalability, and installation efficiency.

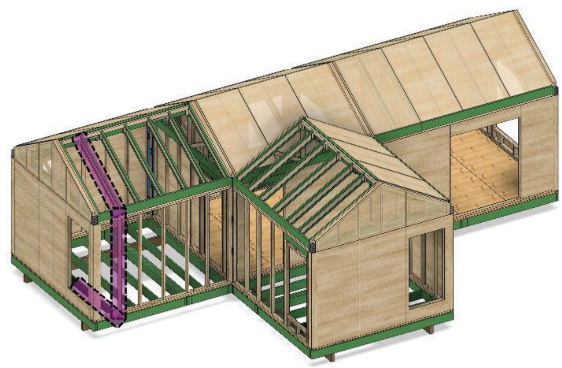

Figure 5. Schematic overall structural design.

By incorporating innovative connections and optimised member designs, the newly developed system significantly enhances structural performance, construction efficiency and reconfigurability. The systematic integration of reversible connectors, precision-engineered load paths, and modular adaptability enable efficient disassembly, reuse, and spatial adaptation over multiple building lifecycles, which reinforces its long-term viability within a circular economy framework.

A computer model was developed to perform a detailed structural analysis based on site-specific location data and member properties as shown in Figure 6. Two wind load directions were considered and modelled as distinct wind load cases. All modular wall panels were designed to comply with AS 1684.2 [18] and AS 1720.1 [19]., ensuring proper stud spacing, lintel placement, jamb studs, and other essential framing elements. Within the computer model, wall panels, roof panels, and roof cassettes were treated as rigid plate elements, with self-weight calculated based on unit mass per cubic meter.

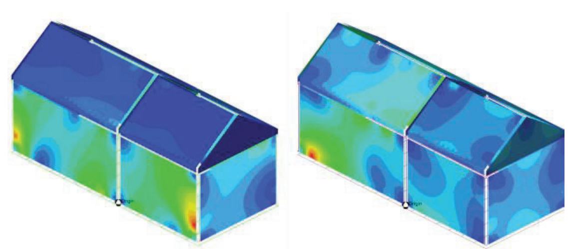

Figure 6. Examples of computer model wind loads from different orientations.

https://doi.org/10.52202/080513-0156

5.2 HYGROTHERMAL PERFORMANCE

5.2.1 RESOLUTION OF THE AIR AND THERMAL CONTROL LAYERS

Ensuring an airtight envelope and sufficient thermal bridging mitigation for the project's climate required novel solutions when integrated into modular, reversible, and reconfigurable detailing. This optimisation process led to an overall reduction in structural timber at the noggins, window jambs, and trusses. Insulation was required between non-continuous column adaptors (shown in Figure 7), improving the thermal performance, while maintaining adequate structural performance.

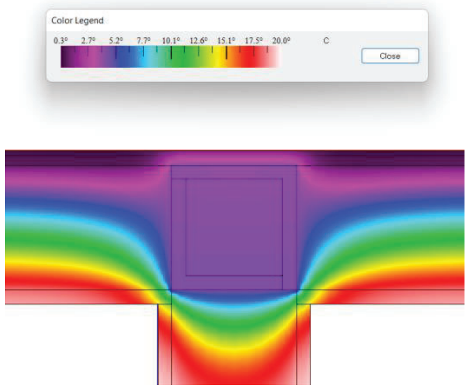

Figure 7. Finite element modelling of the column adaptors C-shape customised fixing.

Critical junctions that required resolution for the airtightness system were the castellation joints, rafter joints, SIHGA IdeFix hold-downs, column adaptors with customised metal fixings, and other challenging 3D joints. Each junction was comprehensively detailed with off-the-shelf airtightness membranes and tapes (as shown in Figure 8) to understand where issues might arise while ambitiously targeting a maximum whole building infiltration rate of 0.6 air changes per hour at an air pressure differential of 50 Pascal, to demonstrate compliance with the Passivhaus Standard.

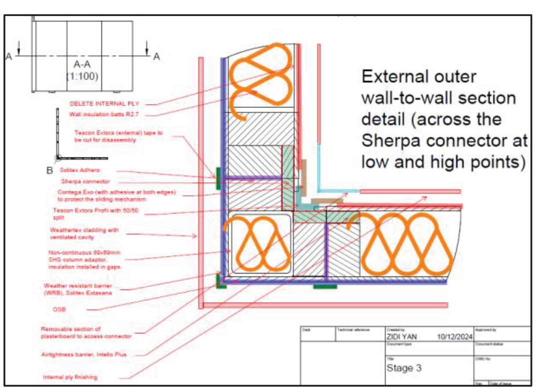

Figure 8. Comprehensive detailing considered for all construction junctions in the project

5.2.2 ENSURING MOISTURE SAFETY

As this project is located in a subtropical climate, a small high-performance Laros Lunomat miniature enthalpy recover ventilation (ERV) unit was specified to ensure the supply of fresh air, while also re-using the heat energy or "coolth" of exhausted ventilated indoor air. The inclusion of an ERV required resolution of the ventilation duct distribution layout, to ensure that the mechanical services design is coherent with the disassembly and reassembly concept (shown in Figure 9). Modelling the dry-out capacity of the assemblies in WUFI Pro [6] demonstrated high moisture risk in Brisbane, without an internal airtightness membrane; however, this can be avoided when an internal airtightness membrane, weather resistant barrier (WRB) and ventilated cavities behind the cladding are specified.

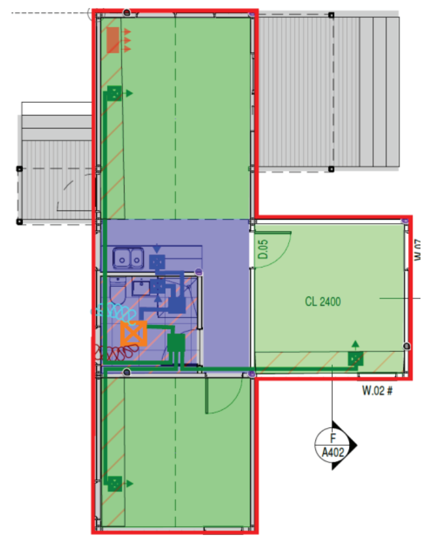

Figure 9. Distribution plan for the mechanical ventilation system located in the bathroom's false ceiling. Blue ducts are extracting air and green ducts are supply air.

5.2.3 ENSURING ENERGY EFFICIENCY AND THERMAL COMFORT

The PHPP modelling found that Phase 2 and Phase 3, depicted in Figure 10, were compliant with the PHI Low Energy Building standard [10], which specifies total envelope thermal performance values are not overly stringent, with a U-value of 0.16, 0.36, 0.19, and 1.5 $W/(m^2K)$ for the roof, walls, floors, and windows respectively. To ensure adequate thermal comfort inside the prototype in line with the PH Standard, the operation of a dehumidifier and external blinds are required. A larger configuration model to resemble conventional residential projects was also assessed against the PH standard. This was done to verify that the proposed system would achieve PH standard.

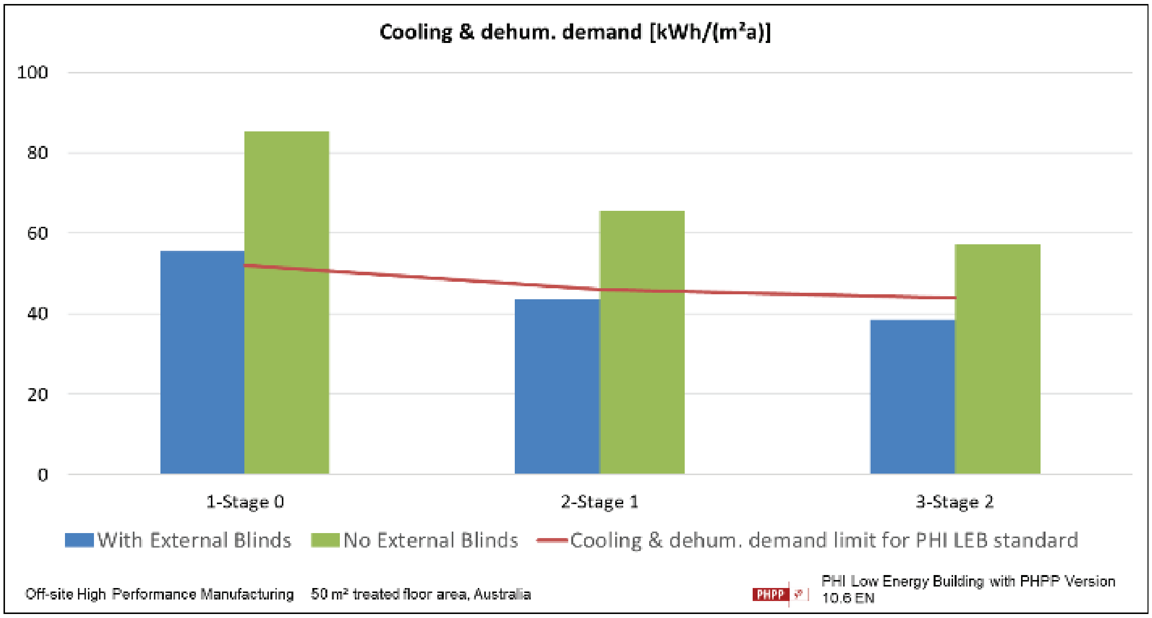

Figure 10. Energy analysis of construction stages.

6 - DISCUSSION

In Australia, compliance with the National Construction Code (NCC) can be achieved through two primary pathways: (1) Deemed-to-Satisfy (DTS) Solution involves following specific, pre-defined materials, components, design factors, and construction methods detailed within the NCC; (2) Performance Solution offers flexibility by allowing for innovative or non-standard designs and methods, provided they can be demonstrated to meet or exceed the relevant performance requirements.

In this project, due to the absence of specific design, existing reversible connectors, and calculation methods for adaptable buildings in the Australian Standards, authors developed the current structural design as a performance solution, as outlined in the relevant Australian Standards and the NCC. The expected loads on critical joints were extracted from the computer model and cross-checked with theoretical calculations and previous experimental investigations conducted at UQ, ensuring the reliability and robustness of the design. To ensure DfADR, the elastic limit of reversible joints was taken as the design capacity, based on either calculations or experimental results.

After conducting a numbers of iterative design processes and checking all critical junctions (shown in Figure 11), one joint approached the elastic limit when considering the combined effects of tension and out-of-plane shear, while remaining within the ultimate load capacity. This highlights the need to monitor the structural loading in adaptable buildings, such as displacements and strains, to gather real-time data on the structural response under varying conditions that may affect future reconfiguration.

https://doi.org/10.52202/080513-0156

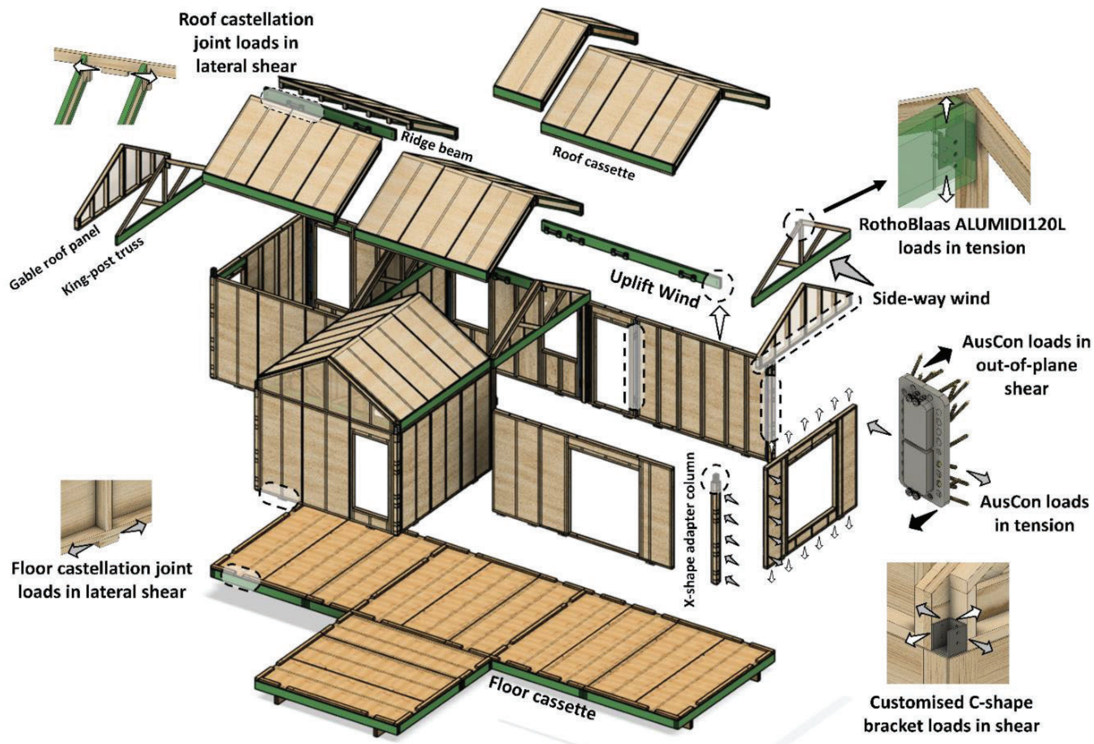

Figure 11. Schematic diagram of the system's joints and loading scenarios.

6.2 VERIFICATION OF HYGROTHEROMAL PERFORMANCE

The design of this system has undergone several types of simulations. Hygrothermal modelling confirmed that the dry-out capacity of the assemblies can be maintained when an internal airtightness membrane, WRB, and ventilated cavities behind the cladding are specified. Energy modelling confirmed that the PHI LEB standard can be achieved when a MVHR, dehumidifier and external blinds are proposed. Thermal bridge modelling provided verification that while the insulation layer was compromised at the adaptor columns, the detail was moisture safe given the subtropical climate. While detailing for an airtight assembly that could still be disassembled was achieved with off-the-shelf products.

Regarding real-world hygrothermal testing of the novel assemblies, while prefabricated methods can mitigate moisture risks of wetting from precipitation during construction, this assumption has not been tested for this system, especially in subtropical climates with monsoon seasons. If moisture penetration occurs, panels may not dry out within a reasonable period, and decay and damages can occur. To identify possible risks, prefabricated panels will be instrumented with moisture content sensors during the fabrication stage, and continuously monitored during transport, construction, use, and reconfiguration. The sensor locations in the finished prototype are shown in Figure 12. Additionally, the interior conditions and mechanical ventilation system airstreams are monitored.

The monitoring campaign is distributed over an estimated total time of 26 months, across three construction phases. This is done so that the hygrothermal performance can be tested while the reversible, and reconfigurable detailing of the assemblies are tested.

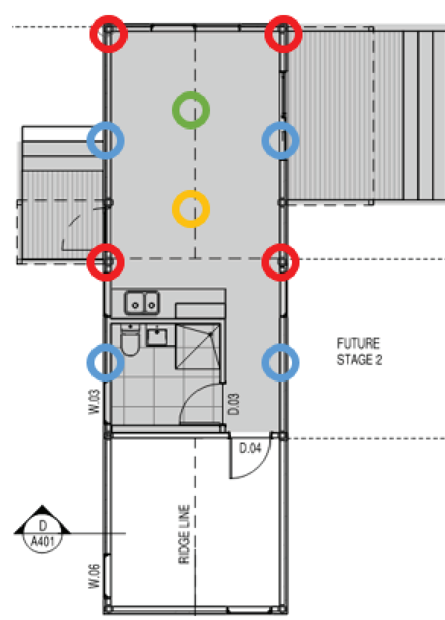

Figure 12. Location of moisture content sensors (assessing temperature, RH, and electrical resistance) in the wall assemblies (blue), wall junctions (red), roof cassette (green), and floor cassette (orange).

https://doi.org/10.52202/080513-0156

6.3 SMALL SCALE MOCK-UP PROTOTYPE

Prior to the production of full-scale building components, two small-scale mock-up prototypes were constructed by the authors at Fairweather Homes' factory, as shown in Figure 13. These prototypes enabled the practical evaluation of the new panelised system, incorporating the AUSCON connector alongside other novel connection solutions, and also assessed the feasibility of insulation strategies aimed at achieving high hydro-thermal performance. Following the successful validation of feasibility and assembly processes, detailed shop drawings for full-scale production were prepared in close collaboration with a structural engineer and architect, ensuring clarity, constructability, and ease of interpretation for both manufacturing and on-site installation. This preliminary prototype phase represented a critical milestone for the research team and Fairweather Homes, facilitating a smooth and efficient transition from experimental validation to real-world construction application.

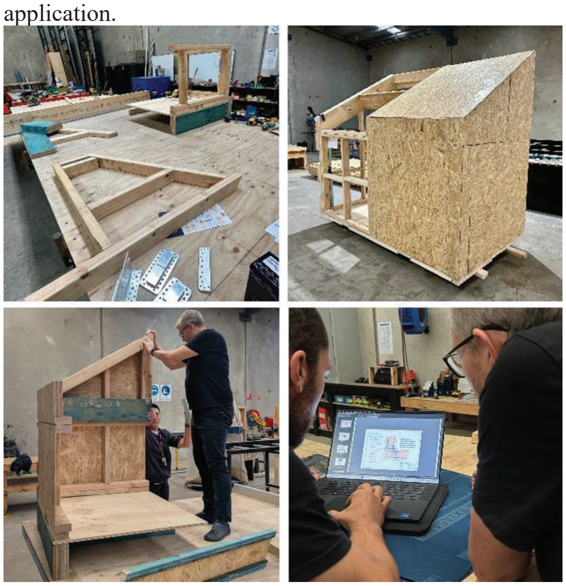

Figure 13. Small-scale mock-up prototypes constructed at Fairweather Homes' factory

The small-scale prototype allowed the manufacturer to achieve several key objectives. First, it provided a comprehensive understanding of how the novel reversible connectors should be installed onto their respective structural members, including an assessment of the required tools and the maximum tolerances the connectors could accommodate. Second, it served as a training platform for workers, bridging the gap between lessons learned from previous experimental tests and their application in mass production, ensuring that practical knowledge was effectively transferred. Third, it enabled a feasibility assessment of the novel structural system and connectors, evaluating their transition from 3D models to real-world applications and identifying any necessary refinements before full-scale production. Finally, the mock-up prototype played a crucial role in establishing optimal installation and disassembly sequences, ensuring efficiency and consistency in both assembly and future reconfigurations. This also included evaluating how insulation, membranes and cladding systems could be added and removed efficiently, maintaining the system's adaptability, modularity and performance.

This iterative mock-up phase not only validated the feasibility of the developed system but also enhanced the manufacturing process, enabling adjustments that would facilitate large-scale production while maintaining design intent, adaptability, and ease of assembly.

7 - CONCLUSIONS AND FUTURE WORK

This paper presents the preliminary outcomes of a novel modular and adaptable timber construction system that developed to meet the evolving housing needs in Australia. Through the building design, connector development and testing, and mock-up prototype assembly, the technical feasibility, constructability, and practical potential of this building system have been demonstrated.

The introduction and successful use of innovative reversible connectors in the small-scale prototype effectively addressed key challenges in installation tolerances, structural reliability, and assembly efficiency. The inherent structural redundancy of the P-LTF system ensures robustness and supports future spatial reconfiguration and relocation, aligning with principles of DfADR and CE in building construction.

Improvements in assembly sequencing and component detailing simplified the construction, disassembly, and reassembly procedures, and delivered benefits such as enhanced site efficiency, reduced labour requirements, and improved worker safety. The research also identified current limitations in airtightness in modular timber systems, prompting future innovation towards achieving high-performance building envelopes. Furthermore, thermal bridging at reversible joints was effectively mitigated through detailed design development and performance modelling.

The success of this work was enabled by a strong collaborative partnership between academia and industry, which facilitated the translation of research outcomes into practical and buildable solutions. The iterative feedback between design, testing, and production significantly improved project efficiency and system refinement.

Full-scale construction is planned for 2025, which accompanied by comprehensive monitoring campaigns to evaluate long-term performance and adaptability. The progress to date highlights the promising potential of this modular, adaptable timber-framed system to deliver affordable, high-quality, and sustainable housing within a CE framework tailored to the Australian context.

ACKNOWLEDGEMENTS

https://doi.org/10.52202/080513-0156

This research was funded by the Australian Research Council Linkage Project "Offsite manufacture reimagined for high-performance adaptable housing". Fairweather Homes Pty Ltd, Pro Clima Australia, SHERPA Connectors GmbH, SIHGA GmbH, and Wesbeam are gratefully acknowledged.

REFERENCES

[1] D. Phillips, M. Guaralda, and S. Sawang, "Innovative housing adoption: Modular housing for the Australian growing family," Journal of Green Building.

[2] P. Palma and G. Fink, "Design for fobustness, adaptability, disassembly and reuse, and repairability of taller timber buildings: a state of art report," 2022.

[3] C. Mair and T. Stern, "Cascading Utilization of Wood: a Matter of Circular Economy?," *For. Policy, Econ. Soc. Res. (A Toppinen, Sect. Ed.*, 2017, doi: 10.1007/s40725-017-0067-y.

[4] Z. Yan, L.-M. Ottenhaus, P. Leardini, and R. Jockwer, "Performance of reversible timber connections in Australian light timber framed panelised construction," *J. Build. Eng.*, vol. 61, p. 105244, Dec. 2022, doi: 10.1016/J.JOBE.2022.105244.

[5] British Standards Institution, "BS EN ISO 10211-2017- Thermal bridges in building construction," 2017.

[6] Fraunhofer IBP, "WUFI Ver 6.1." 2017.

[7] ASHRAE, "Standard 160-2021:Criteria for Moisture-Control Design Analysis in Buildings," 2021.

[8] PHI, "Passive House Planning Package (PHPP) Version 10.6.xlsx." 2023.

[9] International Standards Organisation, "ISO 13790 - Energy performance of buildings — Calculation of energy use for space heating and cooling." 2008.

[10] PHI, "Criteria for the Passive House, EnerPHit and PHI Low Energy Building Standard. Version 10b." 2022.

[11] D. Johnston, M. Siddall, O. Ottinger, S. Peper, and W. Feist, "Are the energy savings of the passive house standard reliable?," *Springer Nat.*, 2020.

[12] D. Johnston and M. Siddall, "The Building Fabric Thermal Performance of Passivhaus Dwellings—Does It Do What It Says on the Tin?," *Sustain.*, vol. 8, no. 97, 2016, [Online]. Available: https://doi.org/10.3390/su8010097

[13] S. Peper and W. Feist, "Energy efficiency of the Passive House Standard: Expectations confirmed by measurements in practice," 2015.

[14] M. Strang, "Moisture safety for energy-efficient CLT envelopes: pathways to net-zero operational energy for engineered wood multi-storey buildings in Australian tropical and subtropical climates," The University of Queensland, A thesis submitted for the degree of Doctor of Philosophy, 2023. doi: 10.14264/80ca907.

[15] Z. Li and K. D. Tsavdaridis, "Limited-damage 3D-printed interlocking connection for timber volumetric structures: Experimental validation and computational modelling," *J. Build. Eng.*, vol. 63, p. 105373, Jan. 2023, doi: 10.1016/J.JOBE.2022.105373.

[16] Z. Yan, "Design and Performance Evaluation of Reversible Connections for Modular Adaptable Timber Buildings," The University of Queensland, A thesis submitted for the degree of Doctor of Philosophy, 2024. doi: 10.14264/f836ca9.

[17] J. Kowal and M. Augustin, "Sherpa - Standardized timber connection system based on aluminium plates and inclined fully threaded screws," in *WCTE 2016 - World Conference on Timber Engineering*, 2016.

[18] Standards Australia, "AS 1684.2-2010 Residential timber-framed construction Part 2 : Non-cyclonic areas," 2010.

[19] Standards Australia, *Australian Standard 1720.1-2010 Timber structures Part 1: Design methods*, vol. 2010. Sydney, NSW 2001, Australia: SAI Global & Standards Australia, 2010.