THE STUDY ON MECHANICAL PERFORMANCE AND CARBON FOOTPRINT OF ADHESIVE FREE ENGINEERED WOOD

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ABSTRACT: Regarding the issue of global change, based on the full life cycle carbon footprint assessment, engineered wood is also facing the development towards net-zero sustainability. Although many advanced modern engineered woods have excellent mechanical properties, they also have relatively high Carbon footprint, therefore, this study conducted a series of mechanical experiments on wood structural elements of beams and plates constructed without gluing. In addition to comparing different construction methods, it also found out the basic performance for future structural engineering design, and based on A full-scale experimental structure is an example of future practical applications. This study also conducted a carbon footprint assessment analysis for this example. The research takes DLT (Dowel Laminated Timber) as Adhesive-Free Engineered Wood (AFEW) systems, collecting relevant international research literatures in the past few years, The research also conducted mechanical experiments on four-point bending moments to obtain different rigidity and Modulus of Elasticity. We also analyzed the failure mode and the damage causes as well from different configurations of specimen. In addition, a full-scale demonstration structure was constructed to explain the possible applications in architectural design.

KEYWORDS: Adhesive-Free Engineered Wood, DLT, Carbon Footprint Assessment

1 – INTRODUCTION

Research Background and Motivation

Global challenges posed by climate change have prompted countries to adopt net-zero and low-carbon development policies. As the construction industry is a major contributor to energy consumption and carbon emissions, there is an urgent need for innovative structural technologies that can reduce the carbon footprint over the entire life cycle. Traditional reinforced concrete (RC) and steel-reinforced concrete (SRC) structures are energy-intensive in both production and construction. Timber structures, with their renewable nature, carbon sequestration capability, and lightweight characteristics, have emerged as attractive alternatives for low-carbon construction. However, while modern adhesive-bonded engineered wood products (e.g., CLT and GLT) demonstrate excellent mechanical performance, their reliance on adhesives and energy-intensive manufacturing processes leads to high embodied carbon emissions. Adhesive-free engineered wood systems, such as DLT and NLT, use wood dowels or nails for mechanical connections, reducing energy consumption and chemical usage, and better aligning with local timber resources and on-site processing conditions.

1.1 RESEARCH OBJECTIVES

Design and fabricate adhesive-free engineered wood (DLT) specimens using locally sourced Cryptomeria (Taiwan cedar) and Zelkova, and determine their bending and shear properties.

Develop a finite element numerical model to simulate the structural response under different dowel spacings and connection configurations, and validate the model with experimental data.

Design and construct a full-scale demonstration building, detailing its structural design, modular prefabrication process, and construction procedures, while quantifying its embodied carbon emissions over the production phase.

Use SimaPro software for life cycle assessment (LCA) to calculate the embodied carbon emissions of the system and compare these results with those of conventional RC and hybrid RC–timber systems.

1.2 METHODOLOGY AND WORKFLOW

Literature Review: Consolidate domestic and international research on adhesive-free engineered wood, DLT, NLT, carbon footprint assessment, and low-carbon construction to establish a theoretical foundation.

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Experimental Specimen Design and Fabrication: Design full-scale specimens in accordance with ASTM-D198 for four-point bending tests and wood dowel shear tests, obtaining key parameters such as the modulus of elasticity (MOE), modulus of rupture (MOR), and flexural stiffness.

Numerical Simulation: Establish three-dimensional FEM models for DLT structures to simulate the structural response under various dowel spacing and connection configurations, and validate the simulation with experimental data.

Life Cycle Assessment: Use SimaPro with the Ecoinvent database, following the IPCC 2013 GWP 100a method, to calculate the embodied carbon emissions during the production phase and compare these with traditional RC systems.

Demonstration Building Design and Carbon Footprint Analysis: Based on experimental and simulation results, design a demonstration building and describe its structural system, modular prefabrication process, construction procedures, and energy-saving technologies. Then, apply LCA to quantify the total embodied carbon emissions of the demonstration building over the production phase.

2 - LITERATURE REVIEW

1. Development Background of Adhesive-Free Engineered Wood

With the increasing emphasis on sustainability, modern engineered wood products (e.g., CLT, GLT) have been widely applied in long-span and high-rise construction. However, these adhesive-bonded products require significant amounts of adhesive and energy-intensive processing, resulting in high embodied carbon emissions and the release of volatile organic compounds (VOCs) and formaldehyde (Gustavsson & Sathre, 2011). In response, many countries have initiated research into adhesive-free engineered wood to reduce both energy consumption and environmental impact while maintaining structural performance.

2. Main Types of Adhesive-Free Technologies

Currently, adhesive-free engineered wood mainly falls into two categories, both techniques reduce processing energy consumption and toxic emissions, thus offering clear advantages for low-carbon, sustainable construction. DLT (Dowel Laminated Timber): This system employs hardwood dowels (e.g., beech) to mechanically connect softwood panels (e.g., spruce, Cryptomeria) without adhesives. Originating in the 1990s, DLT has been applied in parts of Europe and North America, with connection performance influenced by dowel size, spacing, and the moisture content of the wood (Natterer et al., 1996). NLT (Nail Laminated Timber): This system uses metal nails or screws to fasten the layers together. It is simpler and less costly to produce; however, its connection performance is sensitive to nail spacing and diameter (WoodWorks, 2019).

3. Current Research on DLT and NLT Researches on DLT

DLT was first proposed by German engineers such as Julius Natterer and has since been applied in multi-story timber construction in Switzerland, Austria, and the United Kingdom—for example, at Acharacle Primary School in Scotland and Coed y Brenin Visitor Centre in Wales (Görlacher, 2008). These cases demonstrate the feasibility and economic benefits of DLT in public building applications.

Mechanical Performance and Failure Modes:

Research shows that the performance of DLT systems is significantly influenced by dowel diameter, dowel spacing, and the T/D ratio (the ratio of panel thickness to dowel diameter). An optimal T/D ratio of approximately 2 to 3 provides high connection stiffness and ductility (Bell, 2018). Failure typically initiates at wood knots within the laminated panels and progresses in a staggered manner, offering an early warning mechanism for structural safety (O'Loinsigh et al., 2012).

Environmental and Carbon Footprint Studies

Several international studies using LCA have demonstrated that the embodied carbon emissions during the production phase of DLT systems are significantly lower than those of conventional adhesive-bonded engineered wood products (Brettstapel.org, 2016), making DLT a promising low-carbon construction technology.

Comparative Mechanical Performance:

Comparative four-point bending tests have shown that while NLT systems offer advantages in terms of cost and construction speed, their overall connection stiffness and durability may be lower than those of DLT systems, suggesting that further optimization of nail layouts and connection details is necessary.

4. Studies on Mechanical Performance and Failure Modes

Four-Point Bending Test

The four-point bending test is a standard method for determining the modulus of elasticity (MOE) and modulus of rupture (MOR) of timber elements, as specified in ASTM D198 or EN 408. The load–displacement curve obtained during bending tests is used to calculate flexural stiffness. Studies have found that adhesive-free systems typically exhibit failure starting at the connections or wood knot locations in a staggered fashion, which aids in early detection of structural damage (Bohnhoff & Moody, 2009).

Classification of Failure Modes

Joint Shear Failure: Localized splitting occurs at dowel or nail connection points due to concentrated stresses.

Knot-Induced Tensile Failure: Larger knots within the laminated panels initiate crack propagation under tensile stress.

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Interlaminar Slippage: Excessively spaced dowels or nails result in slippage between layers, ultimately leading to failure. These findings provide a basis for optimizing connection design.

Carbon footprint assessment and life cycle analysis

Life Cycle Assessment (LCA) systematically evaluates the environmental impacts of a product throughout its entire life cycle—from raw material extraction, manufacturing, transportation, construction, usage to disposal. In this study, the focus is on the production phase (A1–A3). Using SimaPro software and the Ecoinvent database, the embodied carbon emissions are calculated according to the IPCC 2013 GWP 100a method (ISO 14040 & 14044, 2006).

Carbon Footprint Advantages of DLT and NLT Systems

1. **Adhesive-Free Manufacturing**

The absence of adhesives significantly reduces energy consumption and carbon emissions during production (Adams et al., 2019).

2. **Carbon Sequestration by Wood**

Wood absorbs CO_2 during growth and retains it within its fibers, providing long-term carbon storage benefits that lower the overall life cycle carbon footprint (Churkina et al., 2020). Bell (2018) conducted a carbon footprint analysis on a British DLT system and found that its production-phase carbon emissions were approximately 50–60% lower than those of equivalent RC structures. WoodWorks (2019) reported that NLT systems manufactured in a prefabricated environment also exhibit significantly lower embodied carbon compared to conventional RC systems, making them suitable for mid-span and mid-rise applications.

3 - RESEARCH METHODS AND DEMONSTRATION BUILDING DESIGN

This section details the experimental design, numerical simulation methods, and the design and technical description of the demonstration building. The chapter provides an in-depth explanation of the mechanical testing, FEM modeling, structural system configuration, modular prefabrication process, construction procedures, and quantification of the embodied carbon footprint.

Mechanical Experimental Design and Specimen Fabrication

Four-Point Bending Test:

Specimen Design: In accordance with ASTM-D198, full-scale specimens of DLT vertical laminated components were designed. The dimensions and number of layers were determined based on the mechanical properties of local Cryptomeria and Zelkova. Two dowel spacing configurations (600 mm and 900 mm) were implemented to study the influence of dowel spacing on flexural stiffness and failure mode.

The DLT specimens are bult with 8 layers of planks of 30/140 (mm), doweled vertically, with different dowel interval distances. See Figure 1.

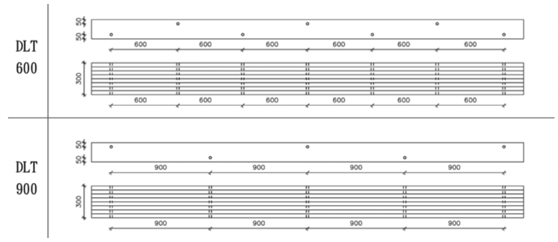
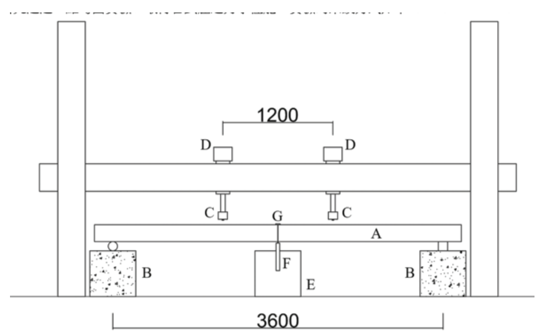


Figure 1 Configuration of DLT

Test Parameters including: High-precision displacement transducers and load cells were used to record bending displacement, yield load, and ultimate load during four-point bending tests. These measurements allowed the calculation of the modulus of elasticity (MOE), modulus of rupture (MOR), and flexural stiffness. See Figure 2 and Figure 3.



Fugure 2 Four Point Bending Cofiguration

Fugure 3 Four Point Bending Test

Failure Mode Observation: High-definition video and visual inspection documented the failure process—particularly the deformation and cracking at wood knot locations and connection zones—providing insights for connection optimization.

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Wood Dowel Shear Test:

Specimen Configuration: Specimens of various types (full-scale, base-type, single-shear, and double-shear) were designed to investigate the shear performance of wood dowel connections. Parameters such as dowel diameter, number, and the T/D ratio (panel thickness to dowel diameter) were clearly defined, with an optimal T/D ratio of approximately 2 to 3 based on previous studies.

Test Method: Universal testing machines applied uniformly distributed shear loads to simulate the in-situ connection performance. Yield and ultimate loads, as well as shear stiffness, were recorded. Digital imaging was used to capture the initiation and progression of failure at the connections.

Numerical Simulation Methods

Finite Element Method (FEM) models were developed for the DLT and GLT systems to simulate their behavior under bending loads. FEM software (ANSYS) was used to solve the model. Load–displacement curves and stress distribution maps were generated and compared with experimental results for model validation and optimization of dowel spacing and connection parameters. The different Shear test specimens are define as in Figure 4.

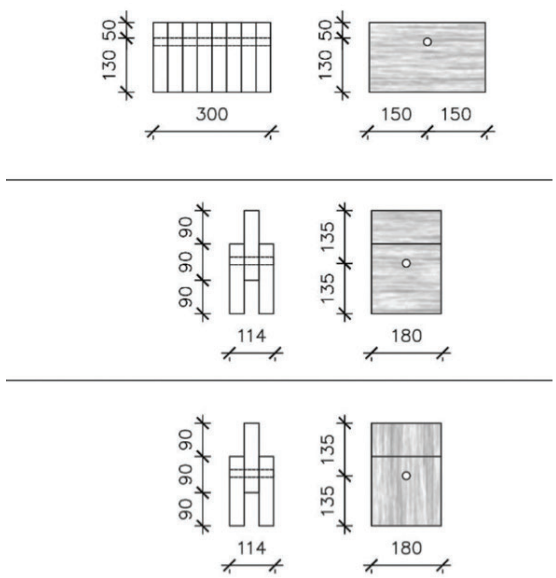

Figure 4 Wood Doweled Specimens for Shear Test

Demonstration Building Design and Technical Description

The demonstration building serves as a practical application case for the adhesive-free engineered wood system. Its design integrates low-carbon sustainability with advanced modular prefabrication techniques. See Figure 5, Figure 6 and Figure 7.

Design Concept

(1) Low-Carbon Sustainability:

The building is primarily constructed using locally sourced Cryptomeria and Zelkova, leveraging wood's natural carbon sequestration to reduce embodied carbon. The adhesive-free connection method eliminates the need for adhesives, reducing energy consumption and environmental impact.

(2) Modular Prefabrication:

All major structural components are prefabricated in a factory setting, ensuring high dimensional accuracy and consistent quality while shortening on-site construction time and reducing energy use.

(3) Structural Safety and Comfort:

The design is based on experimental and simulation results to optimize dowel connection details, ensuring the structure meets bending and shear performance requirements. Additionally, large expanses of glazing and natural ventilation are incorporated to enhance energy efficiency and indoor comfort.

Structural System Configuration

The building's primary structural systems include:

Foundation System:

A reinforced concrete foundation with steel anchorage is used to securely fix the DLT columns, ensuring seismic stability. The foundation design is based on local geotechnical conditions and seismic codes.

DLT Vertical Laminated Components:

These serve as the primary load-bearing walls and floor systems. Multiple DLT panels, pre-drilled and connected with hardwood dowels, are arranged with dowel spacings of 600 mm and 900 mm. This design is optimized based on experimental data to achieve high stiffness and ductility under bending loads.

Wood Dowel Connection Technology:

Connections are designed with an optimal T/D ratio (approximately 2 to 3) to ensure effective force transfer and minimize stress concentrations that could lead to premature failure.

Carbon Footprint Quantification of the Demonstration Building

Using SimaPro software in conjunction with the Ecoinvent database and following the IPCC 2013 GWP 100a methodology, the embodied carbon footprint of the demonstration building during the production phase was quantified

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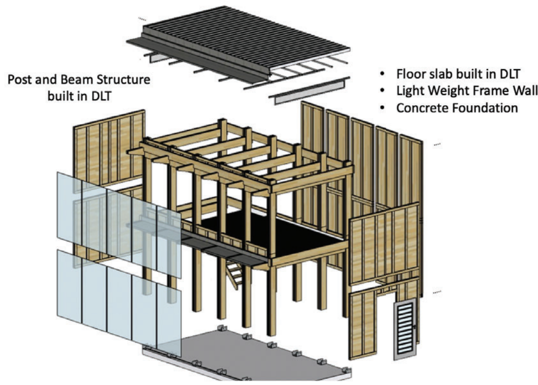


Figure 5. Configuration of Demo House

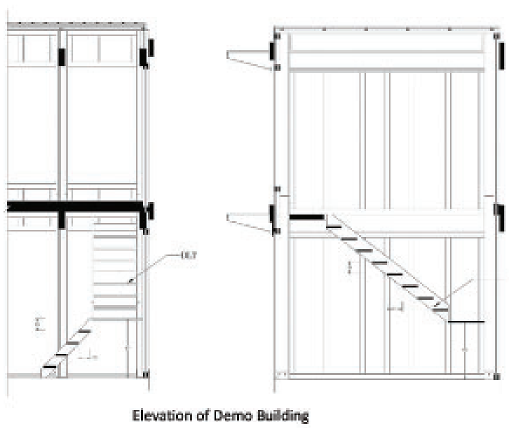


Figure 6 Elevations of Demo House

Figure 7 Demo House built in DLT

4- EXPERIMENTAL RESULTS AND DISCUSSION

Four-Point Bending Test Results and Failure Modes

Full-scale tests on DLT vertical laminated specimens revealed: (DLT-600 and DLT-900 mean the intervals of dowels are 600 mm and 900 m respectively)

DLT-60 specimens exhibited a modulus of elasticity (MOE) of approximately 11.7 GPa, yield loads between 25 – 31 kN, ultimate loads between 80 – 98 kN, and a flexural stiffness of about 1.4 – 1.9 kN/mm. DLT-900 specimens showed slightly lower performance, with flexural stiffness comparable to that of the DLT-600 group. See Figure 8 and Figure 9

Compared to GLT systems, GLT specimens sometimes achieved higher ultimate loads but demonstrated a more brittle failure mode, with lower safety margins.

Failure typically initiated at wood knots within the laminated panels and propagated in a staggered (intermittent) manner, providing an early warning of localized damage. See Figure 10.

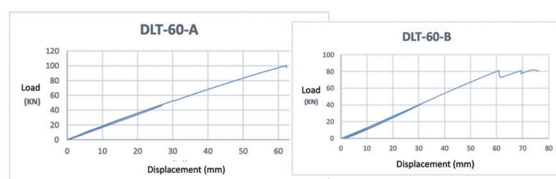


Figure 8 The load-displacement curves of DLT-600

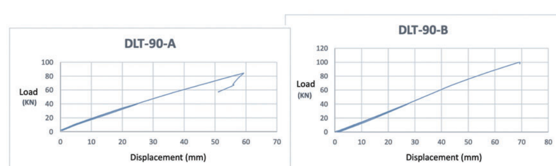


Figure 9 The load-displacement curves of DLT-900

Figure 10 The failure modes of DLT-60 and DLT-90

The same test are carried out on GLT specimen, the test results show in Figure 11.

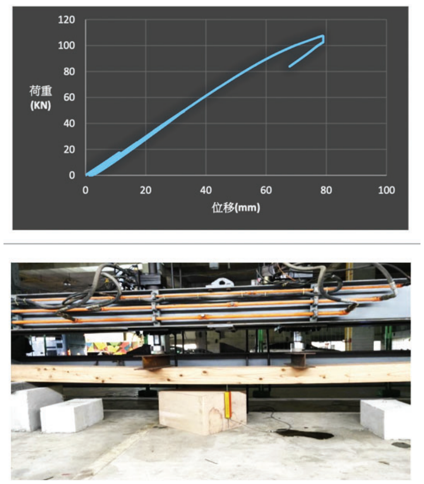
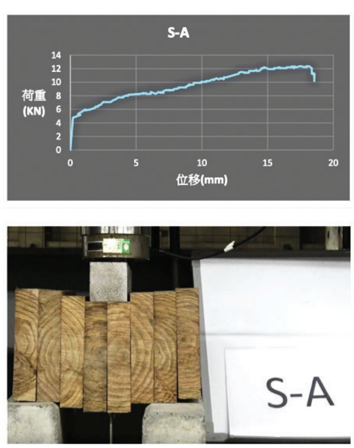


Figure 11 Four Point Bending Test of GLT

Wood Dowel Shear Test Results

The wood dowel shear tests indicated: An optimal T/D ratio of approximately 2 to 3 yields the best connection performance. Yield loads ranged from 5 to 9 kN, and ultimate loads ranged from 12 to 15 kN. Failure predominantly initiated at the wood knot regions within the lamina, following an intermittent failure pattern that supports early structural damage detection. See Figure 12.



Comparison of Finite Element Method (FEM) Simulation Results with Experimental Data

The FEM simulation results closely matched the experimental data, with discrepancies within about 10%. This confirms that:

The numerical model accurately simulates the flexural behavior of the DLT system under various dowel spacing and connection configurations. Simulation data further support the observed differences in ultimate load and failure mode between DLT and GLT systems, providing a scientific basis for optimizing structural design. See Figure 13.

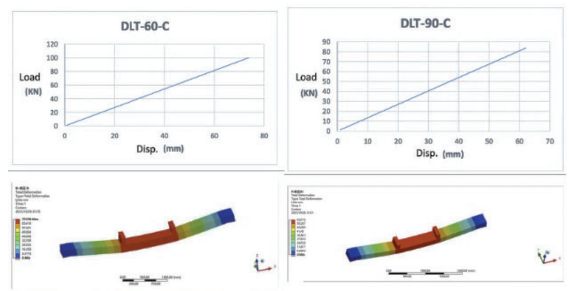


Figure 13 FEM Simulation Results

LCA Carbon Footprint Assessment Results

The embodied carbon emissions for the demonstration building are approximately 72 kg CO_2 eq/m².

For a 300 m² floor area, the total embodied carbon emissions during the production phase amount to about 21,600 kg CO_2 eq. In comparison, conventional RC systems typically emit around 185.53 kg CO_2 eq/m², meaning that the demonstration building achieves a reduction of roughly 61.2%.

Additionally, hybrid RC–timber systems may even achieve net negative carbon emissions (approximately –68.85 kg CO_2 eq/m²) due to the carbon sequestration effect of wood. These findings clearly illustrate the significant environmental advantages of adhesive-free engineered wood systems.

Figure 10 Simulation of RC–timber house and RC house

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5 - CONCLUSIONS

Structural Mechanical Performance:

Four-point bending and wood dowel shear tests demonstrated that the DLT system meets modern structural design requirements in terms of MOE, MOR, and flexural stiffness. The optimal connection parameters (T/D ratio of approximately 2 to 3) significantly enhance connection performance, and the intermittent failure mode provides a useful early warning mechanism for structural damage.

5.2 Reliability of Numerical Simulation:

FEM simulation results show a high degree of concordance with experimental data (within 10% error), confirming that the numerical models can accurately predict the structural behavior of the DLT system under varying dowel spacing and connection configurations. This offers a robust scientific basis for structural design optimization.

5.3 Low-Carbon Environmental Benefits:

LCA analysis revealed that the demonstration building has an embodied carbon emission of approximately 72 kg CO_2 eq/m², compared to about 185.53 kg CO_2 eq/m² for conventional RC systems—a reduction of roughly 61.2%. For a building with a 300 m² floor area, the total production-phase embodied carbon is about 21,600 kg CO_2 eq. Additionally, hybrid RC–timber systems may achieve net negative emissions due to wood's carbon sequestration capability.

Effectiveness of the Demonstration Building Application:

The demonstration building, which integrates modular prefabrication, adhesive-free connections, and advanced construction techniques, not only enhances construction efficiency and structural safety but also substantially reduces embodied carbon emissions. This provides empirical evidence to support the promotion of indigenous timber structural technologies and low-carbon sustainable development.

This study has comprehensively demonstrated the significant advantages of adhesive-free engineered wood systems (DLT and NLT) in terms of structural performance and environmental benefits through experimental testing, numerical simulation, and life cycle assessment. Experimental data confirm that DLT systems provide stable bending and shear performance that meet current design requirements, while FEM models have proven highly accurate (with errors around 10%). LCA results indicate that the demonstration building emits approximately 72 kg CO_2 eq/m², with a total production-phase embodied carbon of about 21,600 kg CO_2 eq—representing a reduction of roughly 61.2% compared to traditional RC systems. Moreover, hybrid RC–timber systems may even achieve net negative carbon emissions due to wood's carbon sequestration capability.

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