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Enhancing Mechanical Performance of Dowel Laminated Timber through Dowel Configuration and Bolted System Integration

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ABSTRACT: Dowel Laminated Timber (DLT) is an innovative, adhesive-free engineered wood product that utilizes hardwood dowels to fasten laminated layers through moisture-induced expansion and friction. This study aims to enhance DLT's mechanical performance by optimizing its manufacturing process using domestically sourced Japanese cedar (laminae) and Taiwan acacia (dowels). Two primary strategies were explored: (1) adjusting dowel insertion quantities and angles to increase frictional resistance and prevent laminae loosening, and (2) developing a novel bolt-reinforced laminated timber (BRLT) system with standard /industrial components in a non-adhesive configuration. Mechanical properties were evaluated through static bending tests, assessing variables such as dowel configuration and bolt torque (5 N-m and 20 N-m). Results indicate that angled dowels modestly improve strength (MOR up to 50.2 MPa), while higher bolt torque significantly enhances load-bearing capacity (MOR = 51.62 MPa at 20 N-m) and stability, reducing lateral displacement by up to 64%. These findings demonstrate that optimized dowel configurations and bolted systems can substantially improve DLT's structural reliability, offering a sustainable, high-performance alternative for modern construction applications.

KEYWORDS: Engineered Wood Product, Dowel Laminated Timber, Bolt-Reinforced Laminated Timber, Mechanical Properties, Static Bending Test

1– INTRODUCTION

Dowel Laminated Timber (DLT) represents an innovative engineered wood product (EWP) that eliminates adhesives, relying instead on hardwood dowels to mechanically fasten laminae through moisture-induced expansion and frictional forces. This adhesive-free approach enhances sustainability and recyclability compared to conventional EWPs such as Glued Laminated Timber (GLT) and Cross Laminated Timber (CLT), which depend on synthetic resins (Sotayo et al., 2020). The growing interest in adhesive-free timber products stems from environmental and health concerns associated with adhesives, such as formaldehyde emissions, prompting research into sustainable alternatives like DLT (Guan et al., 2018). However, DLT's structural reliability is challenged by environmental factors, notably humidity and temperature fluctuations, which can cause dowel loosening and compromise integrity (Henderson et al., 2012). Comparative analyses indicate that while DLT offers competitive bending performance, its mechanical properties require optimization to match or exceed those of adhesive-based EWPs (Ogunrinde, 2019).

The significance of improving DLT lies in its potential to address these challenges while offering a high-performance, eco-friendly option for modern construction. Research has explored various strategies, such as the use of compressed wood dowels, which leverage densified structures to enhance shear performance (Jung et al., 2008), and alternative dowel materials like steel, which improve load-bearing capacity in related timber systems (Li et al., 2023). Despite these advancements, systematic studies on optimizing dowel configurations and integrating novel fastening systems remain limited, underscoring the need for further investigation.

This study investigates methods to enhance DLT's mechanical performance by optimizing dowel configurations and introducing a novel bolt-reinforced system. Using domestically sourced Japanese cedar (*Cryptomeria japonica*) for laminae and Taiwan acacia (*Acacia confusa*) for dowels, the research aims to improve structural stability and load-bearing capacity while supporting Taiwan's timber industry. Two primary approaches are explored: (1) adjusting dowel insertion quantities and angles to increase frictional resistance, and (2) developing a Bolt-reinforced Laminated Timber (BRLT) system inspired by prestressing techniques shown

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to enhance timber beam performance (Negrão, 2012; Yeoh et al., 2023). Experimental outcomes are anticipated to inform sustainable construction practices and broaden DLT's applicability, contributing to the global shift toward adhesive-free timber buildings (Guan et al., 2018).

2– BACKGROUND

EWPs enhance the mechanical properties of timber through industrial processes, offering superior strength and dimensional stability compared to solid wood (Ramage et al., 2017). Predominant EWPs like GLT and CLT rely on adhesives such as resorcinol-formaldehyde (RF) resin for bonding. While RF resin provides high strength and cost-effectiveness, its formaldehyde emissions raise concerns regarding indoor air quality and human health (Lee & Lan, 2006; Kim et al., 2010). In contrast, DLT employs hardwood dowels as fasteners, eliminating adhesive-related environmental drawbacks and enabling disassembly for reuse (Sotayo et al., 2020). This adhesive-free approach aligns with efforts to develop sustainable timber products, as evidenced by research into adhesive-free engineered wood systems aimed at reducing environmental impact (Guan et al., 2018).

Despite these advantages, DLT's performance is sensitive to moisture variations, which affect dowel expansion and frictional bonding (Henderson et al., 2012). Previous studies indicate that dowel loosening under cyclic humidity reduces shear strength, limiting DLT's adoption in load-bearing applications (Bradley et al., 2018). Research on dowel materials has explored compressed wood dowels, which offer enhanced shear performance due to their densified structure (Jung et al., 2008), and steel dowels, which improve the mechanical properties of laminated timber products like cross-laminated bamboo and timber (Li et al., 2023). Numerical analyses further suggest that compressed wood dowels in DLT enhance structural behavior, providing a basis for optimizing dowel configurations (O'Ceallaigh et al., 2023). Comparative studies of lamination techniques show that DLT's bending performance, while promising, lags behind nail-laminated timber in some contexts, highlighting areas for improvement (Ogunrinde, 2019).

To address these limitations, researchers have investigated advanced fastening systems. Prestressing techniques, applied to timber beams, enhance load-bearing capacity and reduce deflection under load (Negrão, 2012; Yeoh et al., 2023), offering a foundation for the BRLT system developed in this study. Preliminary shear tests in this research align with findings that pre-stressed connections improve timber composite performance (Wang et al., 2019). Additionally, innovations such as hollow steel dowels in semi-rigid timber connections demonstrate the potential of alternative dowel designs to enhance joint flexibility and strength (Guan & Rodd, 2001). These studies collectively underscore the need for systematic investigations into dowel configuration and prestressed systems to improve DLT's mechanical reliability.

This research builds on these foundations by optimizing dowel insertion angles and quantities, as well as integrating a pre-stressed BRLT system using steel bolts and tubes. By leveraging locally sourced materials and drawing from global advancements in adhesive-free timber technology, the study aims to enhance DLT's structural performance while addressing environmental sensitivity and supporting sustainable construction practices.

3– PROJECT DESCRIPTION

This research seeks to enhance the mechanical performance and durability of DLT by addressing laminae loosening through two approaches:

(1) **Optimizing dowel insertion angles and quantities to increase frictional resistance (Fig 1.).**

Figure 1*:Angled dowel insertion DLT*

(2) **Developing a pre-stressed Bolt-Reinforced Laminated Timber (BRLT) system using bolts to replace wooden dowels.**

The study utilizes locally sourced Japanese cedar for laminae and Taiwan acacia for dowels, reducing carbon footprint and valorizing Taiwan's forest resources.

The experimental design evaluates the effects of dowel configuration (vertical vs. angled insertion, 5 vs. 6 dowels) on bending properties and stability. Additionally, the BRLT system introduces steel-threaded rods and tubes, with torque settings of 5 N-m and 20 N-m, to assess pre-stress impacts. Mechanical performance is quantified via static bending tests, with outcomes expected to provide insights into sustainable, high-strength timber solutions for construction applications.

4– EXPERIMENTAL SETUP

This study investigates the mechanical performance of DLT and BRLT through controlled specimen fabrication and testing protocols. Experiments were conducted in a laboratory maintained at 23 ± 2°C and 50 ± 5% relative humidity to standardize environmental conditions unless otherwise specified.

4.1 MATERIALS

Laminae were fabricated from Japanese cedar (*Cryptomeria japonica*), a softwood sourced from central Taiwan forests, with a mean density of 380 kg/m³ (12% moisture content, MC) and longitudinal compressive strength of approximately 35 MPa. Dowels were prepared from Taiwan acacia (*Acacia confusa*), a hardwood selected for its shear strength of 12.3 ± 0.5 MPa and volumetric shrinkage rate of 7.8% (radial) and 11.2% (tangential) from green to oven-dry conditions. Both materials were kiln-dried to 12 ± 1% MC prior to use. For BRLT assemblies, M12 steel-threaded rods and seamless steel tubes were procured from a certified industrial supplier.

4.2 SPECIMEN FABRICATION

DLT specimen panels, with maximum dimensions of 3000 mm (length) × 450 mm (width) × 138 mm (thickness), were manufactured using a custom-built apparatus. The fabrication system comprised three modules (Fig 2.):

(1) **Clamping Module**: Ten screw-type clamps, driven by a hydraulic torque wrench, applied a uniform pressure to align and secure laminae.
(2) **Drilling Module**: An electric drill (50–2000 RPM, frequency-modulated) equipped with a 8-mm carbide-tipped bit drilled dowel holes to a depth of 450 mm, with positional accuracy of ±2 mm.
(3) **Insertion Module**: A hydraulic cylinder (maximum thrust 15 kN) inserted dowels into pre-drilled holes, monitored by a load cell to prevent laminae splitting.

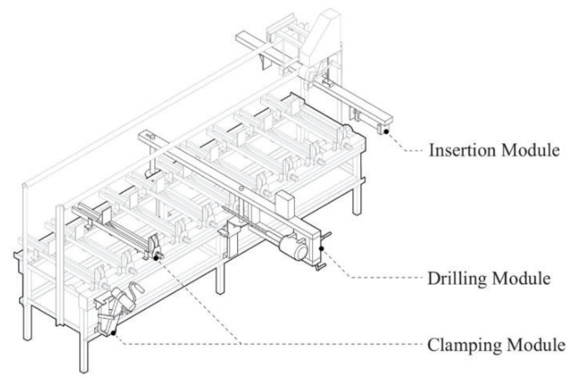

Figure 2*:Custom-built apparatus prototype modules*

Laminae were arranged with parallel grain orientation, and dowels were oven-dried before insertion. Post-fabrication, panels were conditioned at 20°C and 65% relative humidity for 96 hours to facilitate dowel expansion and frictional locking. Dimensional accuracy was verified using a digital caliper, and specimens with visible cracks or deviations exceeding ±5 mm were discarded. All specimens were processed following standard procedures and strict quality control to ensure reliable experimental data.

4.3 DEVELOPMENT OF BRLT

Our research team proposed a pre-stressed bolt-reinforced laminated timber (BRLT) system, which integrates traditional wood dowels with modern materials **(Fig 3.)**, offering structural advantages through the combination of wood, steel pipes, and bolts. Bolts are used to connect laminae, replacing traditional adhesives or dowels while also providing pre-stress to enhance stability and enable disassembly for maintenance. Steel pipes improve compressive strength, rigidity, and the lifespan of the structure by better withstanding dynamic loads and environmental factors.

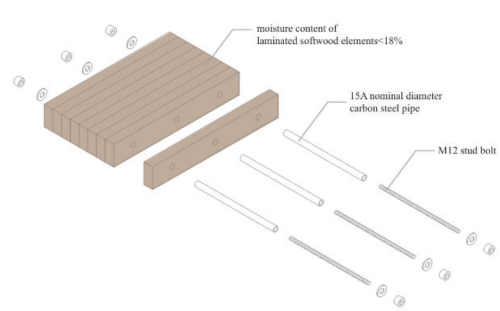

Figure 3*:BRLT configuration*

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To ensure optimal performance, this study designed holes with a slightly smaller diameter than the dowels and used oven-drying to shrink the dowels for easier insertion. A hydraulic press is required for dowel insertion, though it presents a risk of dowel breaking. In the bolted system, steel tubes house threaded rods, with nuts applying lateral pressure to create pre-tension, preventing laminae from loosening. Since the material of the laminae is relatively soft, excessive fastening torque may cause material compression. Therefore, this study determined the optimal fastening torque to be 20 N-m to prevent surface indentation. A comparative torque setting of 5 N-m will be used for the specimens.

BRLT's performance advantages include high strength, lightweight structure, excellent bending and shear resistance, durability, maintainability, and modularity. Steel pipes provide a strong core, while wood reduces weight for efficient performance and easy construction. Additionally, the screw and steel pipe combination ensures good shear performance, and the modular design facilitates disassembly and reusability, catering to modern construction needs.

Preliminary shear tests show that the bolted system prevents laminae from deforming and loosening, with increased torque improving shear strength. This study will further explore enhancing DLT properties by adjusting torque settings. Design considerations such as stress concentration at joints, material compatibility, construction precision, and the increased cost and carbon emissions from using steel pipes will also be addressed to optimize BRLT's overall performance and sustainability.

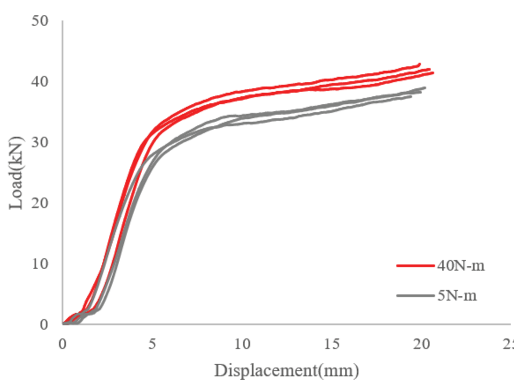

Figure 4:*Load-displacement curves of bolted system shear tests*

4.4 Mechanical Testing

Mechanical properties of DLT and BRLT specimens were evaluated through static four-point bending tests, conducted in accordance with the principles outlined in Chinese National Standards (CNS 11031 - Structural glued-laminated timber) for timber-based materials.

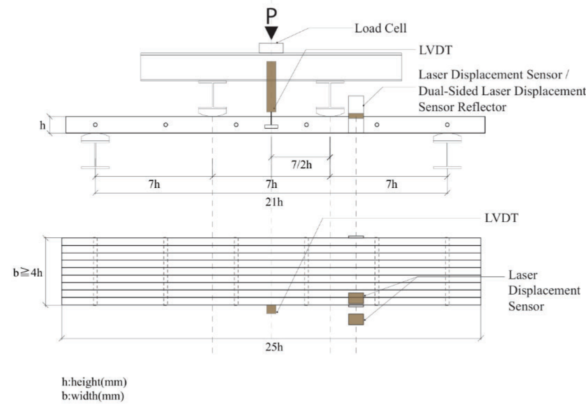

Figure 5:*Four-point bending tests*

Table 1:*Planning Conditions for DLT Bending Test*

specimen dimensions	2250mm x 360mm x 90mm
loading method	four-point loading
experimental standards	This study refers to the domestic standard CNS 16114 (2019) and conducts a bending resistance test with a span of 21 times the DLT height (189 cm).
span length	1890mm
loading rate	Apply the load to the material at a loading rate of 0.2 mm/s or less.
LVDT	Displacement variation in the vertical direction.
Laser Displacement Sensor	Displacement variation in the lateral direction.

Figure 6:*Laser displacement sensor*

Figure 7:*Four-point bending tests*

5 – RESULTS

The bending test comprised 15 DLT specimens subjected to five configurations:

- **B6N9D**: 6 dowels, vertical insertion.
- **B5N9D**: 5 dowels, vertical insertion.
- **B12A9D**: 6 dowels with angled insertion (15°).
- **B5T9B**: Bolted system with 5 N-m torque.
- **B20T9B**: Bolted system with 20 N-m torque

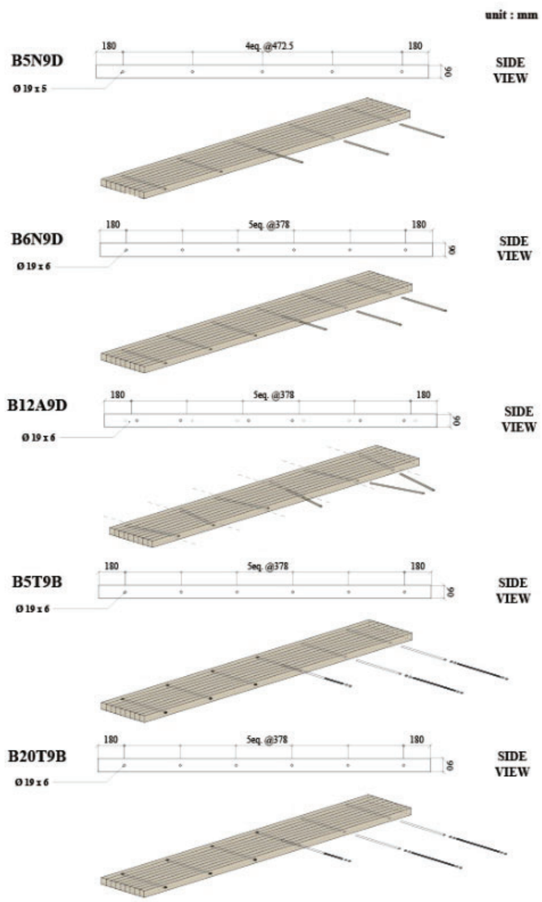

***Figure 8**:15 DLT specimens subjected to five configurations*

Statistical analysis was performed using two-tailed independent t-tests to compare mechanical properties (MOE, MOR) between configurations, with significance set at $p < 0.05$. Data were assumed to follow a normal distribution, and variances were tested for equality using Levene's test ($p > 0.05$ for all comparisons).

5.1 ELASTIC AND BENDING PROPERTIES OF DLT

Bending test results for DLT specimens showed modulus of elasticity (MOE) ranging from 9 GPa to 10 GPa (Table 1). Comparing B5N9D and B6N9D, the MOE difference was not significant ($t(4) = -1.225$, $p = 0.29$), nor was the MOR difference ($t(4) = 1.837$, $p = 0.14$), indicating that dowel quantity (5 vs. 6) has minimal impact on bending properties. However, B12A9D (angled dowels) exhibited a slightly higher MOR than B6N9D ($t(4) = -2.739$, $p = 0.052$), approaching significance, suggesting a modest increase in strength, though MOE was lower ($t(4) = 2.121$, $p = 0.10$). This trade-off implies that angled dowels enhance load-bearing capacity but reduce elasticity.

***Table 2**:Bending Properties of DLT Configurations*

Configuration	MOE (GPa)	MOR (MPa)	Stiffness (N/mm)
B5N9D	9.4 ± 0.1	51.8 ± 0.3	1735.3 ± 15
B6N9D	9.8 ± 0.1	51.8 ± 0.3	1797.4 ± 12
B12A9D	9.1 ± 0.2	54.9 ± 0.4	1665.0 ± 16

5.1.1 LATERAL DISPLACEMENT IN DLT DURING BENDING

Lateral displacement, measured via laser sensors, ranged from 0.04 mm to 3.13 mm (variation: 0.01%–0.87%):

- **B6N9D**: 0.04 ± 0.01 mm, the smallest displacement, reflecting higher dowel density's stabilizing effect.
- **B5N9D**: 1.5 ± 0.2 mm.
- **B12A9D**: 3.13 ± 0.3 mm, the largest, likely due to insertion inaccuracies ($t(4) = -9.849$, $p < 0.001$ vs. B6N9D).

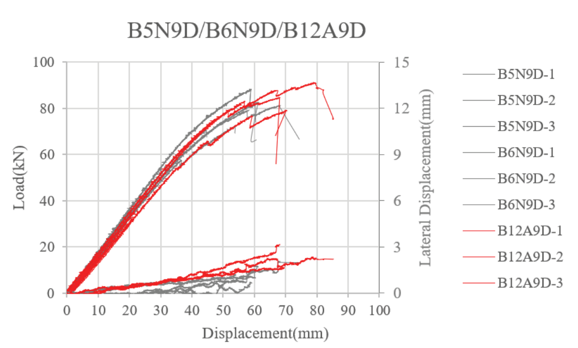

***Figure 9**:Load-displacement-lateral displacement curves of DLT with angled dowels*

Load-displacement curves indicated distinct deformation patterns. B6N9D and B5N9D exhibited elastic behavior

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followed by plastic deformation beyond yield points, with no significant difference in maximum load ($p > 0.05$). B12A9D (angled dowels) showed a gradual post-yield decline, suggesting increased ductility and reduced brittle failure risk, though insertion challenges may limit consistency.

5.2 ELASTIC AND BENDING PROPERTIES OF BRLT

BRLT specimens demonstrated enhanced performance under varying torque settings. Statistical analysis revealed significant differences between B5T9B and B20T9B. The MOR increased with higher torque ($t(4) = -15.897$, $p < 0.001$), confirming that 20 N-m torque markedly enhances strength. Conversely, MOE decreased ($t(4) = 6.532$, $p = 0.003$), and stiffness was slightly lower ($t(4) = 3.873$, $p = 0.018$), indicating that higher torque trades elasticity and stiffness for greater load-bearing capacity.

Table 3: *Bending Properties of BRLT Configurations*

Configuration	MOE (GPa)	MOR (MPa)	Stiffness (N/mm)
B5T9B	9.8 ± 0.06	49.0 ± 0.12	1787.0 ± 15
B20T9B	9.4 ± 0.05	51.6 ± 0.13	1711.4 ± 12

5.2.1 LATERAL DISPLACEMENT IN BRLT DURING BENDING

BRLT displacement ranged from 0.9 mm to 2.5 mm:

- **B5T9B**: 2.5 ± 0.2 mm.
- **B20T9B**: 0.9 ± 0.1 mm, significantly lower ($t(4) = 7.483$, $p = 0.002$), confirming that higher torque enhances stability by reducing lateral expansion.

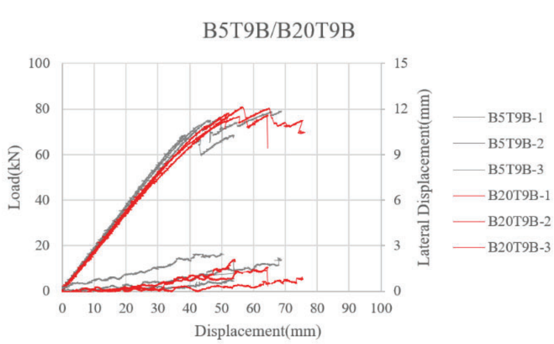

Figure 10*: Load-displacement-lateral displacement curves of BRLT under torque application*

Notably, specimens with higher torque (B20T9B) exhibited the smallest lateral displacement, suggesting that increased bolt torque can effectively reduce lateral expansion in BRLT during bending. This suggests that the torque applied to the bolts has a positive impact on reducing lateral displacement, thus contributing to the stability and structural integrity of the system.

6 – CONCLUSION

Preliminary tests and process optimizations indicate that proper dowel drying is essential for efficient insertion into the DLT structure, ensuring effective assembly. The bolted system is critical in preventing laminae loosening, enhancing DLT performance, and adjusting nut tightness significantly affects the pre-stressed structure and mechanical properties of the DLT.

The DLT manufacturing prototype was developed, and process optimization, standardization, dowel shrinkage, expansion, and shear tests were completed. A series of bending tests, including four-point bending tests for both DLT and BRLT, as well as shear tests on bolts and steel tubes, were also conducted.

Based on the analysis of the results, the following conclusions were drawn:

(1) **Dowel configuration and mechanical performance**
The mechanical performance of DLT is mainly determined by the integrated elements, with minimal impact from dowels. Dowel spacing and diameter have limited effects on DLT's mechanical properties. Higher MOR values observed in this study are likely due to superior integrated elements and a more rigorous manufacturing process, highlighting the importance of both element design and process optimization in enhancing DLT performance.

(2) **Dowel angle and industrial material substitution**
Inserting angled dowels slightly increased MOR compared to vertical insertion, indicating a modest boost in load-bearing capacity. However, this configuration also reduced MOE and led to greater lateral displacement during bending tests, possibly due to difficulties in achieving accurate dowel alignment. This suggests a trade-off between strength and elasticity, highlighting the need for improved insertion methods to reduce manufacturing tolerances and internal stresses. Additionally, replacing wooden dowels with industrial materials like steel bolts and tubes in the BRLT system yielded mechanical

properties similar to traditional DLT. This substitution offers practical benefits, such as easier material sourcing and simplified processing, making it a promising alternative.

(3) **Industrial material substitution and torque impact**

The BRLT system, which incorporates industrial bolts and tubes, alleviated some of the manufacturing challenges associated with wooden dowels while maintaining comparable performance. Increasing bolt torque from 5 N-m to 20 N-m significantly improved load-bearing capacity (MOR) and reduced lateral displacement by up to 64%. This enhancement is likely due to the pre-stressing effect of higher torque, which increases friction between laminae and prevents loosening under load. However, higher torque slightly decreased MOE and overall stiffness, revealing a trade-off between strength and elasticity that designers must account for in practical applications.

In conclusion, this research demonstrates that optimizing dowel configurations and integrating a pre-stressed bolted system can significantly enhance the mechanical performance and reliability of DLT. These improvements pave the way for greater use of adhesive-free timber products in sustainable construction, particularly in regions like Taiwan, where local materials can be utilized to achieve both environmental and economic benefits.

7 – REFERENCES

[1] Bradley, D., et al. (2018). Shear performance of dowel-laminated timber under environmental cycling. *Wood Material Science & Engineering, 13*(4), 245–253. https://doi.org/10.1080/17480272.2018.1437406

[2] Guan, Z. W., & Rodd, P. D. (2001). Hollow steel dowels - a new application in semi-rigid timber connections. *Engineering Structures, 23*(1), 110-119. https://doi.org/10.1016/S0141-0296(00)00027-3

[3] Guan, Z. W., Sotayo, A., Oudjene, M., El Houjeyri, I., Harte, A., Mehra, S., Haller, P., Namari, S., Makradi, A., Belouettar, S., & Deneufbourg, F. (2018). Development of adhesive free engineered wood products – towards adhesive free timber buildings. *World Conference on Timber Engineering Seoul 2018*. https://wcte2018.kr/

[4] Henderson, J., et al. (2012). Environmental impacts on dowel laminated timber performance. *Wood Science and Technology, 46*(3), 321–335. https://doi.org/10.1007/s00226-011-0403-4

[5] Jung, K., Kitamori, A., & Komatsu, K. (2008). Evaluation on structural performance of compressed wood as shear dowel. *Holzforschung, 62*(4), 461-467. https://doi.org/10.1515/HF.2008.073

[6] Kim, S., et al. (2010). Formaldehyde emissions from wood products: A review. *Indoor and Built Environment, 19*(1), 5–15. https://doi.org/10.1177/1420326X09351953

[7] Lee, T.-Y., & Lan, C.-W. (2006). Formaldehyde emissions from resorcinol-formaldehyde resins. *Journal of Environmental Engineering, 132*(5), 645–652. https://doi.org/10.1061/(ASCE)0733-9372(2006)132:5(645)

[8] Li, H., Wei, Y., Yan, L., Semple, K. E., & Dai, C. (2023). Structural behavior of steel dowel-reinforced cross-laminated bamboo and timber beams. *Composite Structures, 318*, 1-13. https://doi.org/10.1016/j.compstruct.2023.117123

[9] Negrão, J. H. (2012). Prestressing systems for timber beams. *World Conference on Timber Engineering Auckland 2012*. https://wcte2012.nz/

[10] O'Ceallaigh, C., Harte, A. M., & McGetrick, P. J. (2023). Numerical examination of the behaviour of dowel laminated timber elements utilising compressed wood dowels. *World Conference on Timber Engineering Oslo 2023*, 278-286. https://wcte2023.org/

[11] Ogunrinde, O. (2019). *Evaluation of bending performance of nail laminated and dowel laminated timber* (Master's thesis). The University of New Brunswick, Department of Faculty of Forestry and Environmental Management. https://unbscholar.lib.unb.ca/islandora/object/unbscholar%3A10013

[12] Ramage, M. H., et al. (2017). The wood from the trees: The use of timber in construction. *Renewable and Sustainable Energy Reviews, 68*, 333–359. https://doi.org/10.1016/j.rser.2016.09.107

[13] Sotayo, A., et al. (2020). Review of dowel laminated timber as a sustainable engineered wood product. *Developments in the Built Environment, 1*, 100004. https://doi.org/10.1016/j.dibe.2020.100004

[14] Wang, J., et al. (2019). Pre-stressed timber connections: A review of mechanical performance. *Construction and Building Materials, 211*, 456–467. https://doi.org/10.1016/j.conbuildmat.2019.03.275

[15] Yeoh, D., Leng, V., Jamaluddin, N., Boon, K. H., Jamalaldin, S., Tighnavard, A., & Ghafar, N. H. A. (2023). Bending performance of timber beam strengthened with passive prestressing. *International Journal of Sustainable Construction Engineering and Technology, 14*(3), 419-428. https://doi.org/10.30880/ijscet.2023.14.03.038

https://doi.org/10.52202/080513-0472