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EXPERIMENTAL STUDY INTO MECHANICAL PROPERTIES OF A NOVEL MASS TIMBER T-BEAM SYSTEM

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ABSTRACT: This study investigates the bending stiffness and strength of a novel mass timber floor system in the form of 6-layer T-beams using North American Spruce-Pine-Fir (SPF). The T-beams were fabricated by the authors and tested in four-point bending. The results showed promising improvement in the efficiency of major axis properties when compared to conventional 3-layer CLTs and indicate structural viability of the new configuration.

KEYWORDS: Mass timber, T-beams, Cross-laminated timber (CLT), SPF (spruce-pine-fir).

1 – INTRODUCTION

Having emerged from Germany and Austria roughly three decades ago, Cross-Laminated Timber (CLT) has witnessed a substantial increase in application, a development formalized by its acceptance as a mid-to-high-rise construction material within the 2021 International Building Code (IBC) [1]. CLT has a unique composition that allows its application in large-scale walls, stairs, roofs and floor elements as well as other large load-bearing structural components in mid-rise and high-rise structures and its renewable nature and carbon storage capability make it a key material for eco-friendly construction.

Composed of perpendicular layers of dimension lumber glued together, CLT's composition and configuration is simple. As it is a relatively new product, there are still many research questions to be answered and potential enhancements to be explored. As mass timber products continue to evolve, structural innovations such as hybrid and reinforced configurations are gaining attention. The need for alternative solutions stems from the growing demand for higher performance while maintaining sustainability.

This study addresses this by introducing a novel mass timber 6-layer T-beam system as shown in Fig. 1. The

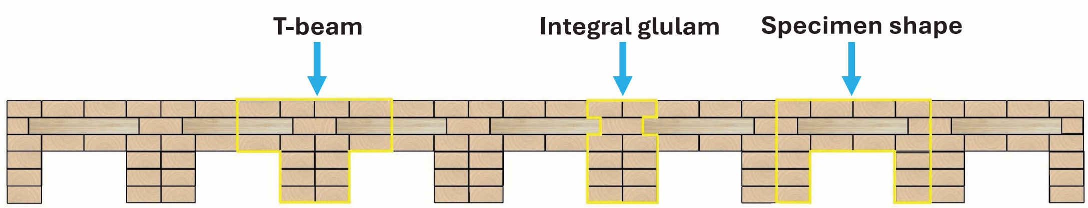

Figure 1 - Proposed T-Beam Floor System with Integral Glulam

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system strategically integrates longitudinal reinforcements within the cross layers. The T-beams comprise CLT panels that are integrally reinforced with narrow glulam-like beams.

This study is an experimental study into the mechanical properties of the 6-layer T-Beams. They are made from the US species group spruce-pine-fir (SPF). The design aims to mitigate any potential rolling shear weakness with the use of longitudinal boards within the flange cross-layer and to improve the major axis stiffness and strength of the panel system. Through an analytical comparison of bending stiffness, this research evaluates the potential of T-beam configurations as a possible alternative to conventional CLT panels, particularly in long-span applications.

2 – BACKGROUND

Researchers have explored various aspects of CLT properties, some focusing on species, others on cross-layer orientation, and many on rolling shear behavior of CLT. Rolling shear stress is the stress that occurs within the cross layers of CLT due to its fiber orientation being orthogonal to the beam axis. The resulting shear deformation can be significant for CLT due to wood's relatively low rolling shear modulus, making it important to consider in structural design, particularly with high stress loading conditions.

Research has identified several alternative species suitable for use in CLT, including Irish Sitka spruce [2], New Zealand Radiata Pine [3], and Eastern Hemlock [4]. Optimizing layer orientations and geometric configurations, such as ±45° angles, has shown significant improvements in mechanical properties [5]. Additionally, efforts to improve rolling shear capacity include incorporating LSL in cross layers [6] and using thinner cross layers [7].

This current study follows from a previous study by the authors on investigating mass timber T-Beams [1]. In the previous study, a comparative analysis was carried out between the bending stiffness and strength of 3- and 5-layer CLT vs. 5- and 6-layer T-Beam configurations as shown in Fig. 2. This previous study found that T-beam systems may offer significant performance efficiencies compared to conventional CLT systems. Specifically, the Shear Analogy Method [8] was employed to predict and compare the bending stiffness and strength of 3- and 5-layer CLT vs. 5- and 6-layer T-Beam configurations and it was found that 6-layer T-Beams had 3.7 times the stiffness to weight ratio and 1.5 times the strength to weight ratio of 3-layer CLT. Their respective Allowable Stress Design properties were obtained from the NDS [9].

This current study's design analysis follows the same approach as in Ayodele et al., 2025. Specifically, the Shear Analogy Method [5], [8] was employed to predict and compare the bending stiffness (EI_{eff}) of the 6 layer T-beams. Apparent bending stiffness (which considers the effects of shear deformation) was employed for the CLT panels (Eq #1) and effective bending stiffness was employed for the T-Beams (neglecting shear deformation) (Eq #2).

$$EI_{eff,0} = \sum_{i=1}^{n} E_i \times b_i \times \frac{h_i^3}{12} + \sum_{i=1}^{n} E_i \times A_i \times z_i^2 \quad (1)$$

$$\frac{a^2}{\left[\left(\frac{h_1}{2G_1 b}\right)+\left(\frac{h_2}{2G_2 b}\right)+\left(\frac{h_3}{2G_3 b}\right)\right]} \quad (2)$$

where:

$EI_{eff,o}$ = Effective bending stiffness for major axis

E_i = Modulus of Elasticity of layer

b_i = Width of the i-th layer

h_i = Thickness of the i-th layer

A_i = Cross-sectional area of the i-th layer

z_i = Distance from the natural axis to the centroid of the i-th layer

a = Effective shear span

G_i = Rolling shear modulus of the i-th layer

b = Panel width

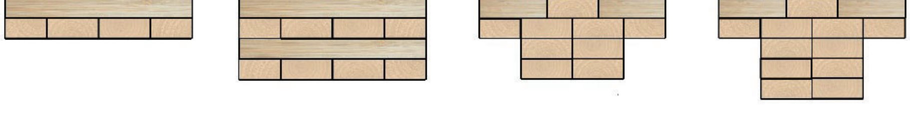

Figure 2 – Mass timber configurations studied in Ayodele et.al. 2025

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In contrast to a CLT beam, the T-beam system incorporates glulam-style longitudinal reinforcements, which greatly lowers shear-induced deformation. Consequently, the actual bending stiffness of the T-beam is not subject to the same decreases applied to CLT panels. This important difference points out how effectively T-beams might offer rigidity and improved stiffness.

This study extends the previous research study by experimentally investigating the major-axis bending stiffness and strength of 6-layer T-beams. We seek to understand failure mechanisms and accuracy of structural predictions for 6-layer T-beams.

3 – PROJECT DESCRIPTION

Specimens were fabricated in house at the University of Massachusetts Amherst. A total of 5 prototype panels were fabricated.

Materials

Kiln-dried 2x4 No.2 or better spruce-pine-fir (SPF) dimension lumber boards, graded #2 or better, were sourced from local lumber suppliers. The boards were planed and joined to dimensions of 33 mm × 84 mm, with lengths over 3 meters. Specimen layup followed the ANSI/APA PRG 320 [10] standard requirements.

For optimal consistency in fabrication, all specimens were conditioned for at least 30 days in a controlled environment chamber at (EnvironAir) 20°C and 65% relative humidity (RH) to maintain a stable moisture content of around 12% before fabrication and testing. This step reduced variability owing to moisture-related expansion and contraction, resulting in a more reliable assessment of mechanical properties. The adhesive selection was also important as polyurethane-based adhesives provide stronger bonding performance and moisture resistance, which are required to ensure bond integrity over the structure's lifespan.

Specimen Fabrication

A total of five prototype 6-layer T-Beams were fabricated using SPF species group. Specimen layup followed the ANSI/APA PRG 320 [10] standard requirements, each measuring 165mm thick × 305mm wide and 3048mm long. The specimen shape was an upside down ‘u-letter’ shape for testing purposes (Fig. 1).

Before applying adhesive, a surfactant solution (5% Loctite PR 3105 Purbond and 95% water) was sprayed on bonding surfaces and air-dried for 20 minutes according to manufacturer's instruction (Henkel Corporation, Düsseldorf, Germany). Then, a moisture-activated polyurethane adhesive (Loctite HB X602 Purbond) was applied with contact rollers at 1,290 m^3/m^2. Adhesive was applied only on the faces, not the edges (Fig.3 left). Panels were assembled in a hydraulic cold press (0.61 m × 3.66 m) at 0.69 MPa for 6 hours, with lateral pressure from screw-driven clamps. The average open assembly time was 26 minutes. After curing, panels were trimmed to 99 mm × 305 mm × 3.048 m and returned to the environmental chamber. The moisture content before testing was averaged at 11.8%.

Figure 3 - Manufacturing and Testing of 6-layer CLT(Gs): primer sprayed for additional stem (left), flexural test configuration.(right)

4 – EXPERIMENTAL SETUP

Four-point bending tests were conducted to evaluate the bending performance of the T-beam panels (Fig. 3 right) following the ASTM D198 standard [11]. The span-to-depth ratio of 30:1 per standard was used to induce bending failure. Load was applied at third points along the span. Two linear variable displacement transducers (LVDTs) were placed at the neutral axis on either side of the specimen at mid-span to precisely measure beam displacement.

During testing, the key technical data recorded included the maximum load (P_{max}), deflection at peak load (Δat peak), and bending stiffness. The universal testing machine MTS (Material Test System) recorded real-time load and displacement values, allowing the creation of load-displacement curves.

5 – RESULTS

Fig. 4 shows the typical failure mechanisms observed in the experiments. During testing, the T-beams typically failed due to tensile stress at the bottom flange. Defects such as knots and grain deviations caused stress concentrations that contributed to crack initiation and propagation. All the specimens exhibited compression failure in the top layer, especially between the load points. This was observed in several specimens: indicating fiber crushing before the ultimate failure. No rolling shear failures occurred in the cross layers and the longitudinal reinforcements effectively improved shear performance. This finding reinforces the hypothesis that the T-beam design mitigates common weaknesses found in traditional CLT panels. As the additional glulam in the T-Beam resists expected shear forces leading to higher shear properties in the major strength direction. The specimens showed typical failure tensile failure pattern.

Table 1 – 6 Layer T-Beam Test Results

Specimen	P_{max} (kN)	$\Delta_{at\ peak}$ (mm)	EI_{app} (10^9 N·mm²/m)	F_bS_{eff} (10^6 N·mm/m)
6.2.1	85.88	45.64	3862.01	140
6.2.2	78.73	40.54	4038.11	128
6.2.3	101.74	52.71	3916.35	165
6.2.4	72.45	38.51	3806.90	118
6.2.5	93.32	55.60	4179.42	152
Mean	86.42	46.60	3960.56	140.44
COV (%)	13.41	15.97	3.77	13.41

The load-displacement curves, illustrated in Fig. 5, show a primarily linear elastic behavior in the initial phase of the maximum load, after which the curves became nonlinear leading to failure. All the specimens exhibited consistency in stiffness with wide variation in peak load capacity. The extent to which peak load varied among specimens was influenced by the presence of considerably large defects such as knots and pronounced slope-of-grain deviations. Specimens with considerably fewer and smaller knots in many high-stress regions sustained substantially higher peak loads; however, specimens with several prominent defects failed greatly sooner. A rapid change from elastic to plastic behavior considerably lowered load capacity following ultimate failure, which is an indication of brittle failure modes. The uniform stiffness exhibited by

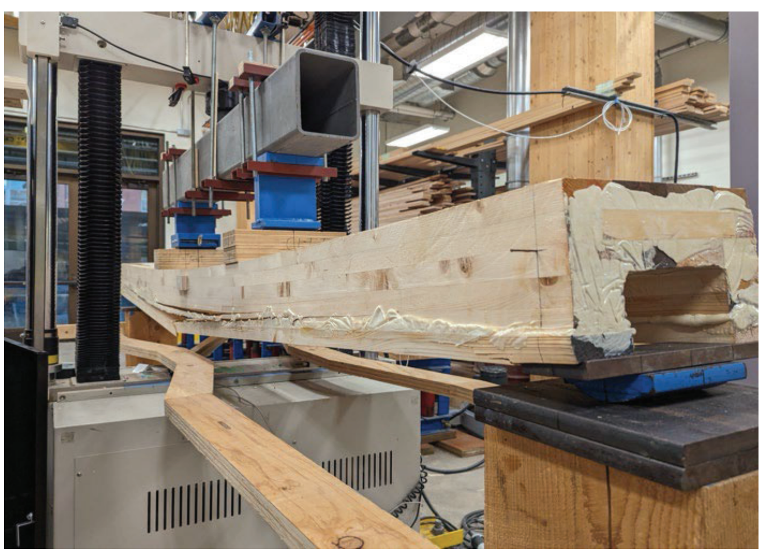

Figure 4 – Typical Failure Mechanism of 6 layer T-Beams

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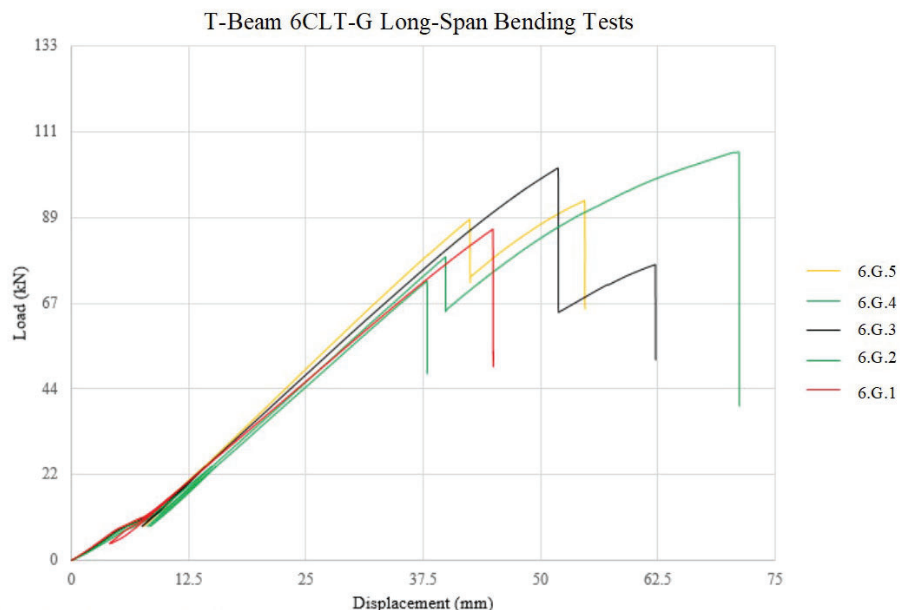

Figure 5– Load- Mid-span Displacement Graphs

the specimens provides evidence of consistent and reliable bonding performance. This curve shows material integrity across the tested samples.

The test results in Table 1 show the performance of the 6-layer T-beam system under bending loads. The mean maximum load (P_{max}) was 86.42kN with a coefficient of variation of 13.41%. With regards to apparent bending stiffness (EI_{app}): The mean experimental bending stiffness of the 6-layer was 3960.5 x 10^9 N·mm^2/m, with a COV of 4%. This value is slightly more than the predicted value of 3842.0 x 10^9 N·mm^2/m indicating that using EI_{eff} (neglecting shear deflection) is an appropriate method to estimate T-beam stiffness.

The relatively low COV for stiffness (3.77%) is promising, showing that the integral reinforcement approach (i.e. layup reconfiguration) provided uniform performance across specimens. Whereas the higher variability in the bending strength values reflects defects attributing to the ultimate failure modes. These findings not only validate the theoretical predictions but also demonstrate that the proposed 6-layer T-beam system enhances bending stiffness. This indicates that it is a viable option for structural applications requiring longer spans while optimizing material usage. Importantly, these findings underscore the potential of T-beam systems as a promising commercial wood product.

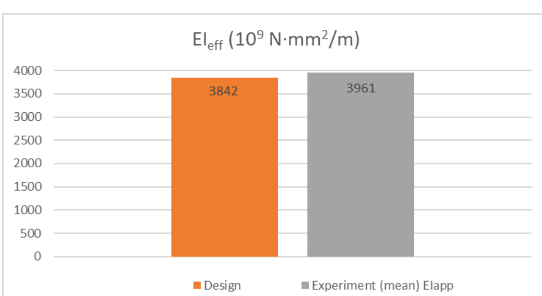

Figure 6 – Design vs Experimental Results for Bending Stiffness

6 – CONCLUSION

This study presents the concept and initial evaluation of 6-layer T-beam systems in mass timber construction. A comparative design analysis utilizing the shear analogy method in a previous paper [1], revealed that the T-beam configuration offers significant major-axis structural efficiencies compared to the conventional CLT configuration. These efficiencies mean using less lumber while maintaining equal or superior mechanical performance. This paper is a follow-up experimental study.

The experimental results demonstrate that the 6-layer T-beams exhibit enhanced mechanical properties in comparison to traditional CLT panels. The improvements position them as a promising alternative for both industrial and commercial structural applications. However, further studies are necessary to focus on the mechanical performance of other species and configurations. Additionally, long-term performance should be evaluated under various conditions, including fire resistance, service environments, and cost-effectiveness. A comprehensive understanding of these factors will be essential for the widespread adoption of T-beam systems in the building industry.

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