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

AN ENTIRELY WOOD FLOOR SYSTEM DESIGNED FOR BIOGENIC CARBON STORAGE, ADAPTABILITY, AND END-OF-LIFE DE/RE/CONSTRUCTION – ASSEMBLY DESIGN

Sovanroth Ou[1], Amin Nabati[2], Muzan Williams Ijeoma[3], Weichiang Pang[4], Michael Stoner[5], Brandon Ross[6], Dustin Albright[7], Patricia Layton[8], Mik Carbajales-Dale[9]

ABSTRACT: This study investigates a mass timber composite floor system designed for long-span applications with enhanced de-constructability. The system utilizes two connections: adhesive with screws and sharp plates with screws. Experimental testing demonstrated high degrees of composite action (DCA), with the adhesive specimen achieving 95% DCA and the sharp plate specimen reaching 92% DCA. Both configurations exhibited similar stiffness and elasticity at service loads while achieving comparable peak strength. Shear failure around openings in the sharp plate specimen raised concerns when pushing the limit of opening size, which were mitigated through screw reinforcement in the adhesive specimen. The mechanically jointed beam theory from Eurocode 5 effectively predicted the effective bending stiffness, with deviations of 3% and 12% from experimental results. Additionally, post-failure deconstruction confirmed the reusability of components. Future research will focus on evaluating the system's performance under fatigue loading to assess long-term stiffness degradation and de-constructability.

KEYWORDS: mass timber, timber floor, long-span, de-constructability, composite.

1 – INTRODUCTION

Mass timber is a category of engineered wood products that combine solid wood layers to create large, structurally robust components in various shapes and sizes. The advancement of mass timber, particularly Cross-Laminated Timber (CLT), has enabled the construction of larger and more complex buildings, expanding its use beyond traditional light-frame construction. As a result, mass timber is gaining traction in the commercial building sector, supporting the development of taller and larger structures than those feasible with light-frame methods.

However, CLT has limitations, including relatively low bending strength and susceptibility to deflection and vibrations over longer spans. To address these challenges, various timber composite floor systems have been developed, including pure timber composite floors, timber-concrete composite floors, timber-steel composite floors, and timber-aluminum composite floors. While incorporating materials like concrete and steel can mitigate excessive deflection and vibration issues, these materials also have a significant environmental impact.

Construction and materials manufacturing in the global building sector contribute an estimated 10% or more of total global carbon dioxide (CO_2) emissions [1]. Steel and concrete, in particular, sequester little to no carbon while producing significantly higher emissions per unit. Steel manufacturing emits approximately 0.54 tons of carbon (tC) per ton of material [2], while cement production releases around 0.776 tC per ton [3]. In contrast, mass

[1] Sovanroth Ou, Glenn Dept. of Civil Engineering, Clemson University, Clemson, USA, sovanro@clemson.edu

[2] Amin Nabati, Glenn Dept. of Civil Engineering, Clemson University, Clemson, USA, anabati@clemson.edu

[3] Muzan Williams Ijeoma. of Civil Engineering, Clemson University, Clemson, USA, mijeoma@clemson.edu

[4] Weichiang Pang, Glenn Dept. of Civil Engineering, Clemson University, Clemson, USA, wpang@clemson.edu

[5] Michael Stoner, Glenn Dept. of Civil Engineering, Clemson University, Clemson, USA, mwstone@clemson.edu

[6] Brandon Ross, Glenn Dept. of Civil Engineering, Clemson University, Clemson, USA, bross2@clemson.edu

[7] Dustin Albright, School of Architecture, Clemson University, Clemson, USA, dalbrig@clemson.edu

[8] Patricia Layton, Forestry and Environmental Conservation Dept., Clemson University, Clemson, USA, playton@clemson.edu

[9] Mik Carbajales-Dale, Dept. of Environmental Engineering and Earth Sciences, Clemson University, Clemson, USA, madale@clemson.edu

https://doi.org/10.52202/080513-0608

timber sequesters about 0.48 tC per ton of material and emits only 0.12 tC during production, resulting in a net carbon sequestration of approximately 0.36 tC per ton [4]. Consequently, using pure mass timber can significantly offset carbon emissions from building operations and even achieve a negative carbon footprint over a building's lifetime.

While the composite action in conventional mass timber floors with span limits up to 9 m (30 ft) has been extensively studied, developing efficient mass timber composite floors with spans exceeding 12 m (39.4 ft) remains an open research challenge.

2 – BACKGROUND

Mass timber has experienced notable advancements over recent decades, gaining widespread adoption in Europe and growing interest in countries such as Canada and Australia. However, its presence in the United States remains relatively modest. As of December 2024, a total of 2,338 mass timber projects had been completed or were underway in the U.S. [5], a small fraction compared to the more than 5.9 million commercial buildings reported nationwide in 2018 [6]. This contrast underscores the early-stage adoption of mass timber in the U.S. market, primarily due to regulatory challenges, fire safety concerns, and a limited body of research.

Historically, U.S. building codes have largely restricted wood construction to light-frame structures of only a few stories or heavy timber systems [2]. It was not until 2019 that the International Code Council (ICC), the primary authority on model building codes in the U.S., approved provisions for tall wood buildings in the 2021 International Building Code (IBC). These updates introduced three new construction types, allowing mass timber buildings between 9 and 18 stories.

A key factor limiting mass timber adoption is the misconception surrounding its fire performance [2]. Much of the concern arises from the association of mass timber with light-frame wood construction, which consists of small wood members that ignite and spread fire quickly. In contrast, mass timber is composed of large, solid wood elements that char on the surface rather than burn outright, creating a protective layer that slows combustion. Extensive research has been conducted on the fire behavior of mass timber, examining protective measures such as encapsulation with fire-resistant materials and structural design approaches that ensure stability even after charring. These studies have informed building codes and industry standards, gradually increasing confidence in mass timber's fire resistance.

The origins of mass timber technology can be linked to early innovations in engineered wood. In 1920, Walse and Watts patented a composite lumber product resembling modern CLT but used cement as a binder rather than conventional adhesives [7]. More recent advancements emerged from research at the Department of Timber Engineering at Graz University of Technology (TUG), which has been investigating solid timber construction since 1990 [8]. This work led to the formal development of CLT, first introduced in a dissertation by Schickhofer in 1994. By 1998, CLT had received approval from the Austrian Technical Approval (OTZ) authorities, facilitating its adoption in both residential and commercial construction in Austria from the late 1990s onward [8],[9]. Over the past few decades, mass timber technology has been extensively researched and successfully implemented in multi-story buildings worldwide. Prominent examples include Ascent MKE in Milwaukee, Brock Commons Tallwood House in Canada, and Treet in Norway.

2.1 LITERATURE REVIEW

The composite action of mass timber floor systems has been widely studied over the past few decades, as it allows mass timber floors to span further and more efficiently. Mass timber composite floors come in various configurations, including the joist floor systems and stressed-skin panels. While the stressed-skin panels offer greater span capacity, they require additional fabrication steps and incur higher costs compared to the joist floor systems, as noted by Brazli, Heitzmann, and Ashrafi [10].

Mass timber composite floor systems are extensively explored for spanning less than 12 m (39.4 ft). Several studies have investigated different connection types to enhance the composite action of mass timber. Jacquier and Girhammar proposed double-sided punched metal plates, which significantly improve composite action and load-carrying capacity [11]. Shahnewaz et al. investigated conventional connections, including adhesive and inclined screws, enabling spans of up to 7.2 m (23.6 ft) [12]. Zabihi proposed stressed-skin timber floor modules using adhesive and screws, achieving spans of up to 8 m (26.2 ft) with Laminated Veneer Lumber (LVL) [13]. Natalini explored self-tapping screws at different angles, achieving a span length of 6 m (20 ft) and suggesting the potential for spans of up to 10 m (32.8 ft) using 5-ply CLT in parametric studies [14].

In addition to pure mass timber systems, hybrid mass timber floors incorporating mineral-based materials, such as timber-concrete, timber-steel, and timber-aluminum composite floors, have also been extensively studied.

https://doi.org/10.52202/080513-0608

Some of these were discussed by Ceccotti et al. [15], Zhang et al. [16], Zeman et al. [17], Hassanieh, Valipour, and Bradford [18], and Chybinski and Polus [19].

However, research on pure mass timber composite floor systems exceeding 12 m (40 ft) remains limited. In 2017, Gu proposed a box module design with self-tapping screws installed at a 30-degree angle, achieving a span of 12.2 m (40 ft) [20]. While this proposed mass timber composite floor demonstrated sufficient load-carrying capacity, it fell short in terms of serviceability. More recently, Zhang, Zheng, and Lam published a study on a composite box timber floor using inclined self-tapping screws, achieving a 12 m (39.4 ft) span with LVL panel and Glued-Laminated Timber (GLT) [21]. Their study showed that the proposed timber composite floor provided adequate composite action to satisfy the standard serviceability requirements.

3 – PROJECT DESCRIPTION

The mass timber composite floor assembly, investigated in this project, has a span length of 12.2 m (40 ft) and was designed for office occupancy, as shown in Fig. 1. The box module design incorporated accesses for installing and inspecting essential building appliances within the concealed space which offset the lost clear floor-to-floor height due to member depth. The assembly includes 3-ply CLT as both the top and bottom flanges. The top CLT has a width of 2.4 m (8 ft) with access openings along the span while the bottom CLT has a width of 1.8 m (6 ft), providing 0.6 m (24 in) strip access openings from the bottom. This floor design features access openings from both the top and bottom, making it adaptable for multi-occupancy scenarios. This flexibility allows different users on separate floors to have independent access, enhancing functionality and versatility in various building applications. A 130 mm (5.125 in) GLT was selected for the webs, positioning 457 mm (18 in) away from the edge of the top CLT which is an optimal location for responding to both concentrated and uniform live loads.

The selection of connections for the CLT and GLT is based on the strength, stiffness, de-constructability, and cost. A series of connection tests were conducted to identify the optimal connection for this application including self-tapping screw at various angles, sharp metal hooked plate, adhesive, epoxied coupler with bolt, and hollow tube, as illustrated in Fig. 2.

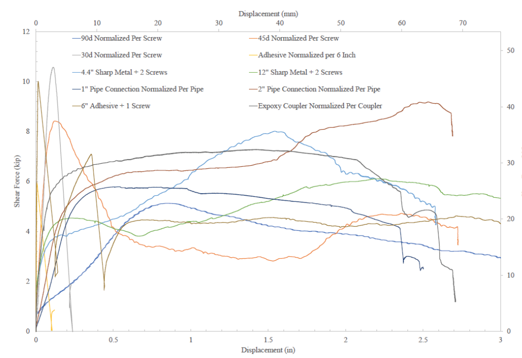

Figure 2. Preliminary connection tests result.

From the preliminary findings, these connections were narrowed down to four based on their structural performance and constructability: inclined screw at a 45-degree angle, sharp metal hooked plate, epoxied coupler with bolt, and adhesive with screw. The Simpson SDCF271958 was selected for the inclined screw while

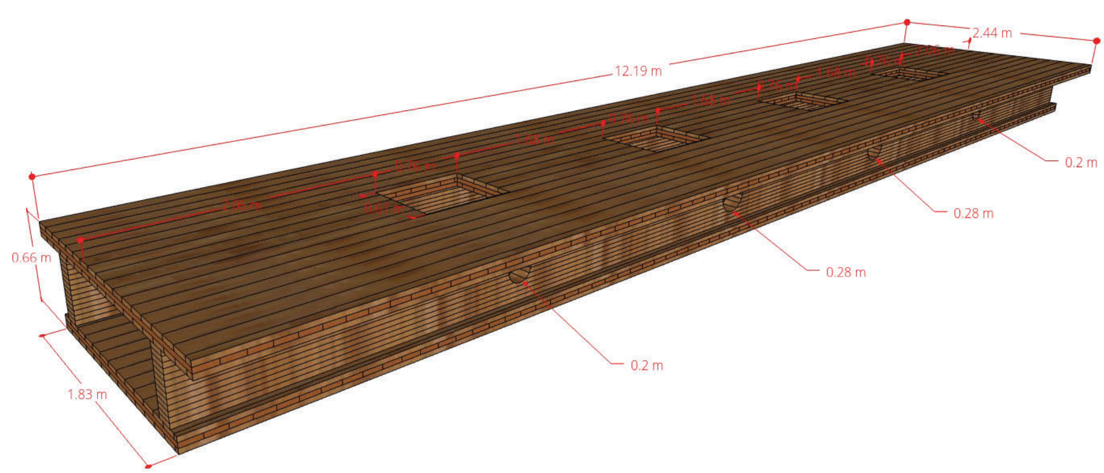

Figure 1. Mass timber composite floor assembly specimen.

the Rothoblaas TBS822 screw and ULS13373 washer were used to achieve sufficient clamping pressure for the sharp metal hooked plate. The epoxied coupler with bolt connection consisted of two couplers, each 19 mm (0.75 in) in diameter and 76 mm (3 in) in length. Each coupler was epoxied to both the CLT and GLT, creating a continuous thread for a bolt to connect the member. The Simpson SDCF27912 was used with both adhesive and hollow tube connections. Table 1 presents the estimated cost (based on retail prices as of 2024) of these connections for the proposed composite floor assembly, along with the other relevant criteria.

Table 1. Summarized criteria for selecting connections.

Connection	Inclined Screw	Sharp Metal	Epoxied Coupler	Screw + Adhesive
Cost Per Square Foot	\$9.28	\$5.71	\$35.64	\$4.25
Installation	Moderate	Easy	Very Hard	Easy
De-Constructability	Moderate	Easy	Easy	Easy
Ultimate Strength kN (kip)	38.6 (8.68)	37.1 (8.34)	32.4 (7.28)	46.7 (10.51)
Stiffness kN/mm (kip/in)	33.7 (192.2)	26.9 (153.8)	19.8 (112.8)	> 87.6 (> 500)
Normalization	Per screw	2 screw + 12” sharp plate	2 couplers + 1 bolt	1 screw + 6” adhesive

Two assembly specimens were investigated, one featuring the sharp metal with screws and the other using adhesive with screws, as illustrated in Fig. 3. These connections were selected based on cost and other criteria, summarized in Table 1. A minimal number of screws are typically used with adhesive to generate sufficient clamping pressure for the adhesive to set. However, the design for the adhesive specimen utilized a thin strip of adhesive to provide adequate serviceability, which allows for de-constructability, while sufficient strength is provided with screws.

4 – EXPERIMENTAL SETUP

The mass timber composite floor assembly was tested with a four-point bending test following ASTM D4761 [22], with adjustments to accommodate the assembly configuration, as shown in Fig. 4. The specimens were loaded to service and design load using the load-controlled procedure before being loaded to failure with the displacement-controlled procedure. The specimens were then deconstructed into components to demonstrate their de-constructability.

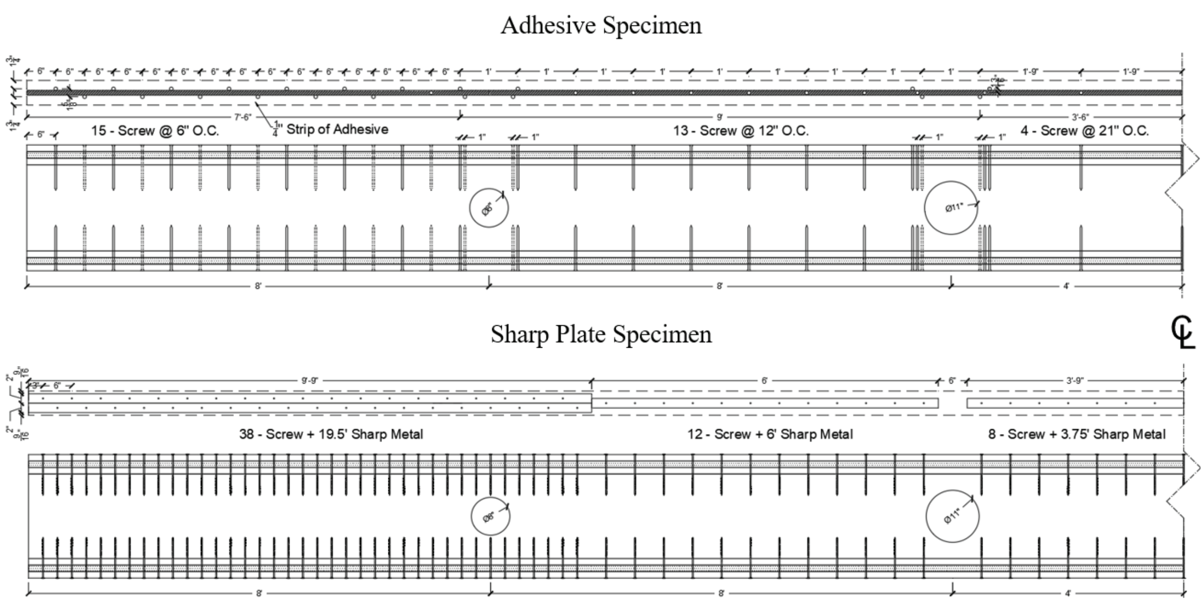

Figure 3. Design for assembly specimens.

https://doi.org/10.52202/080513-0608

Figure 4. Assembly test setup.

The experimental results were quantified in comparison to the theoretical analysis using the mechanically jointed beam theory, discussed in Eurocode 5 [23], and the structural effect of openings, discussed in APA report No. V700E [24]. The composite action is quantified with the Degree of Composite Action (DCA), shown in Eq. 1.

$$DCA = (EI_{ef} - EI_0) / (EI_\infty - EI_0) \times 100\% \quad (1)$$

Where EI_{ef} is the measured effective bending stiffness, EI_0 *and* EI_∞ are the effective bending stiffness of timber composite floors under no and full composite action, respectively.

5 – RESULTS

At service load, the two specimens exhibited similar stiffness and elasticity even up to design level load. They achieve comparable peak strength; however, the sharp plate specimen was significantly more ductile than the adhesive specimen, as demonstrated in Fig. 5.

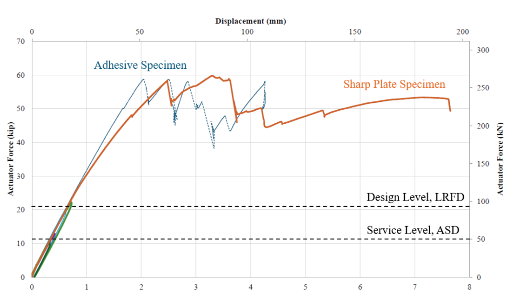

Figure 5. Actuator force-displacement graph of assembly test.

Table 2 demonstrates that both assembly specimen designs provided sufficient load-carrying capacity and serviceability. The adhesive specimen failed at the fastener as intended; however, the sharp plate specimen failed due to shear around the opening, attributed to insufficient screw reinforcement around the opening. The adhesive and sharp plate specimens had a deflection of L/1364 and L/1225 at service level load respectively, showcasing their adequate serviceability.

Table 2. A summary result of assembly tests.

Criterion		Adhesive	Sharp Plate
Fastener Force kN (kip)	Tested	54.3 (12.2)	39.2 (8.81)
	Design Capacity	17.9 (4.03)	13.8 (3.11)
Shear kN (kip)	Tested	130.8 (29.4)	129.9 (29.2)
	Design Capacity	116.5 (26.2)	116.5 (26.2)
Moment kN.m (kip.ft)	Tested	727 (536)	723 (533)
	Design Capacity	355 (262)	355 (262)
Service Level Deflection		L/1364	L/1225

The effective bending stiffness of the specimens was predicted using the mechanically jointed beam theory, as illustrated in Fig. 6. This model accurately predicted the specimens' effective bending stiffness within a reasonable range. The measured bending stiffness of the adhesive and sharp plate specimens deviated from the predicted values by 3% and 12%, respectively, yielding DCA values of 95% and 92%.

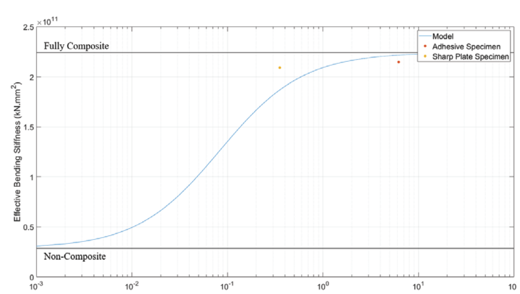

Figure 6. Assemblies' effective bending stiffness.

After being loaded to failure, the two specimens were deconstructed without difficulty as demonstrated in Fig. 7. This confirms the re-constructability of the components used for the mass timber composite floor.

Figure 7. Mass timber components after deconstruction.

6 – CONCLUSION

The proposed mass timber composite floor demonstrates both long-span capacity and de-constructability using adhesive and sharp plate connections. The adhesive specimen, with a thin strip of adhesive, achieved a 95% Degree of Composite Action (DCA) while remaining de-constructible. The sharp plate specimen followed closely with a 92% DCA. Both specimens exhibited similar stiffness and elasticity at service load and comparable peak strength. However, shear failure around the openings in the sharp plate specimen highlighted concerns for stresses around openings when pushing the opening size limit in the GLT. This issue can be mitigated with screw reinforcement, as demonstrated in the adhesive specimen. The mechanically jointed beam theory, as outlined in Eurocode 5 [23], proved to be a reliable predictor of the effective bending stiffness for the proposed assemblies with deviations of 3% and 12%, respectively.

Future work will focus on evaluating the floor's performance under fatigue loading to quantify stiffness degradation over time and assess its de-constructability after repeated service load cycles.

7 – REFERENCES

[1] United Nations Environment Programme (UNEP), *2020 Global Status Report for Building and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector*, 2020. [Online]. Available: https://globalabc.org/sites/default/files/2021-01/Buildings-GSR-2020_ES_ENGLISH.pdf.

[2] A. A. Riddle, *Mass timber: Overview and issues for Congress (CRS Report R47752)*, Congressional Research Service (CRS), Oct. 2023. [Online]. Available: https://crsreports.congress.gov/product/pdf/R/R47752/2.

[3] U.S. Environmental Protection Agency (EPA), *U.S. Cement Industry Carbon Intensities (2019) (EPA 430-F-21-004)*, Oct. 2021. [Online]. Available: https://www.epa.gov/system/files/documents/2021-10/cement-carbon-intensities-fact-sheet.pdf.

[4] K. Hoover and A. A. Riddle, *Forest Carbon Primer (CRS Report R46312)*, Congressional Research Service (CRS), Apr. 2020. [Online] Available: https://crsreports.congress.gov/product/pdf/R/R46312/2.

[5] Woodworks, *Mapping Mass Timber (December 2024)*, 2024. [Online]. Available: https://www.woodworks.org/resources/mapping-mass-timber/.

[6] U.S. Energy Information Administration (EIA), *2018 Commercial Buildings Energy Consumption Survey*, 2020. [Online]. Available: https://www.eia.gov/consumption/commercial/.

[7] F. J. Walse and R. L. Watts, *Composite Lumber*, U.S. Patent No. 1,465,383, 1920. [Online]. Available: https://patentimages.storage.googleapis.com/18/e1/69/852461675334db/US1465383.pdf.

[8] G. Schickhofer and B. Hasewend, *Solid Timber Construction: A Construction System for Residential Houses, Office and Industrial Buildings*, Department of Timber Engineering at Graz University of Technology (TUG), 2000. [Online]. Available: https://www.holzbauforschung.at/fileadmin/user_upload_hbf/News/2011/2000_Venedig_COST_E5.pdf.

[9] G. Schickhofer, *Rigid and flexible composites in area-covering laminated wood structures*, Doctoral dissertation, Graz University of Technology, 1994.

[10] M. Bazli, M. Heitzmann, and H. Ashrafi, "Long-span Timber Flooring Systems: A Systematic Review

https://doi.org/10.52202/080513-0608

from Structural Performance and Design Considerations to Constructability and Sustainability Aspects," *J. Building Engineering,* vol. 48, 2022. [Online]. Available: https://doi.org/10.1016/j.jobe.2021.103981.

[11] N. Jacquier and U. A. Girhammar, "Evaluation of Bending Tests on Composite Glulam-CLT Beams Connected with Double-sided Punched Metal Plates and Inclined Screws," *J. Construction and Building Materials*, vol. 95, pp. 762-773, 2015. [Online]. Available: https://doi.org/10.1016/j.conbuildmat.2015.07.137.

[12] M. Shahnewaz, C. Dickof, J. Zhou, and T. Tannert, "Vibration and Flexural Performance of Cross-Laminated Timber – Glulam Composite Floors," *J. Composite Structures*, vol. 292, 2022. [Online]. Available: https://doi.org/10.1016/j.compstruct.2022.115682.

[13] Z. Zabihi. "Investigation of a Proposed Long Span Timber Floor for Non-Residential Applications." PhD thesis. University of Technology – School of Civil and Environmental Engineering, 2014.

[14] G. Natalini. "Composite Action in Mass Timber Floor and Beam Systems Connected with Self-Tapping Wood Screws." Master thesis. University of British Columbia – School of Forestry, 2017.

[15] A. Ceccotti, R. Fellow, M. Fragiacomo, and S. Giordano, "Long-term and Collapse Tests on a Timber-Concrete Composite Beam with Glued-in Connection," *Materials and Structures*, vol. 40, pp. 15-25, 2006. [Online]. Available: https://doi.org/10.1617/s11527-006-9094-z.

[16] L. Zhang, J. Zhou, Y. H. Chui, and D. Tomlinson, "Experimental Investigation on the Structural Performance of Mass Timber Panel-Concrete Composite Floors with Notched Connections," *J. Structural Engineering*, vol. 148, 2021. [Online]. Available: https://doi.org/10.1061/(ASCE)ST.1943-541X.0003229.

[17] M. Zeman, P. Sejkot, K. Mikes, M. Fragiacomo, and A. Aloisio, " Glued-in Steel Plate and Screwed Connections in Timber-Concrete Composites Systems: Mechanical Performance and Design Implications," *J. Building Engineering*, vol. 96, 2024. [Online]. Available: https://doi.org/10.1016/j.jobe.2024.110477.

[18] A. Hassanieh, H. R. Valipour, M. A. Bradford, "Experimental and Numerical Investigation of Short-term Behaviour of CLT-steel Composite Beams," *Engineering Structures*, vol. 144, pp. 43-57, 2017. [Online]. Available: https://doi.org/10.1016/j.engstruct.2017.04.052.

[19] M. Chybinski and L. Polus, "Experimental and Numerical Investigations of Aluminum-timber Composite Beams with Bolted Connections," *Structures*, vol. 34, pp. 1942-1960, 2021. [Online]. Available: https://doi.org/10.1016/j.istruc.2021.08.111.

[20] M. Gu. "Strength and Serviceability Performances of Southern Yellow Pine Cross-Laminated Timber (CLT) and CLT-Glulam Composite Beam." PhD thesis. Clemson University – Department of Civil Engineering, 2017.

[21] C. Zhang, X. Zheng, and F. Lam, "Development of Composite Action in a New Long-span Timber Composite Floor: Full-Scale Experiment and Analytical Approach," *Engineering Structures*, vol.279, 2023. [Online]. Available: https://doi.org/10.1016/j.engstruct.2022.115550.

[22] ASTM International, *ASTM D4761-19: Standard Test Methods for Mechanical Properties of Lumber and Wood-base Structural Material,* 2020. [Online]. Available: https://doi.org/10.1520/D4761-19.

[23] European Committee for Standardization (CEN), *Eurocode 5: Design of Timber Structures – Part 1-1: General – Common Rules and Rules for Buildings (EN 1995-1-1:2004)*, 2004.

[24] The Engineered Wood Association, *Effect of Large Diameter Horizontal Holes on the Bending and Shear Properties of Structural Glued Laminated Timber (APA Report No. V700E), 2022*. [Online]. Available: https://www.apawood.org/publication-search?q=v700.