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Advancing Timber for the Future Built Environment

Cyclic Behaviour of Composite Steel-Cross-Laminated-Timber Structural System

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ABSTRACT: In pursuit of achieving near-net-zero carbon buildings, this project investigates the development of a new structural system for high seismic zones that consists of steel framing with cross-laminated timber (CLT) floor diaphragms acting compositely with the steel floor framing. A Design for Deconstruction (DfD) design strategy is incorporated into the structural system to allow all primary structural components to be reused rather than recycled or scrapped at the end of the useful life of the structure. One of the key objectives is to develop a deconstructable connection strategy that connects the CLT to the steel beams to enable composite action. The system incorporates the use of high strength bolted connectors to achieve composite action and explore construction benefits. A complete set of tests, including material tests, full cyclic connectors tests, composite beam tests, and large-scale composite diaphragm tests, aims to advance the understanding of the structural behaviour of this composite system. Additional work on this project includes the investigation of material aspects (characterization of low-value species) for future uses, architectural considerations (e.g., fire safety, acoustic, vibration, floor framing plans, etc.), and using life cycle assessment (LCA) to inform sustainable design decisions. This paper emphasizes the structural performance achieved by utilizing high-strength bolted connectors in steel-CLT hybrid structures, supplemented by experimental tests results, and highlights future planned work.

KEYWORDS: *CLT-steel composite hybrid structure, Composite action, Cyclic performance, DfD (design for deconstruction)*

1– INTRODUCTION

In the current environmental landscape, characterized by the escalating threat of global warming and the pressing need for action, the construction industry has come under pressure to reduce its significant contribution to greenhouse gas emissions. Forecasts predict a doubling of natural resources in construction by 2060, primarily propelled by the manufacturing of steel, concrete, and cement[1]. In response to these challenges, the strategic use of reusable, renewable, and low embodied carbon materials have emerged as a key approach to achieving net-zero building emissions. This work develops steel-framed buildings with cross-laminated timber floor diaphragms (steel+CLT) as a viable path towards the near-zero carbon construction.

This research established prototype steel + CLT composite structures in high-wind and high-seismic zones, examining both low-rise and high-rise models, to develop a resilient sustainable structural system across applications. Furthermore, the composite connection is designed to allow efficient assembly and disassembly of structural members, promoting a circular economy. The recertification of CLT in both the short-term and long-term is evaluated in the development of reuse strategies. Other key components of this system include integrating bio-based non-structural systems and optimizing CLT floor panel layouts to accelerate progress toward net-zero carbon. Additionally, the project explores the uses of underutilized species such as Eastern White Pine and Eastern Hemlock for CLT manufacturing in U.S east coast. This approach provides an example of how to

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maximize local forest resources, reduces shipping costs, and supports sustainable material sourcing.

Aiming to advance an understanding of the behaviour and design of steel+CLT composite structural systems that incorporate DfD strategies, this paper summarizes key tasks, including developing high-strength DfD connectors for the composite system, conducting full-scale structural tests and parametric simulations of connections.

2 – BACKGROUND

Over the past twenty years, mass timber structures have gained significant popularity. As of December 2024, WOODWORKS construction data reports 2,338 mass timber projects in the U.S., with 58% incorporating CLT [2]. American Institute of Steel Construction (AISC) Design Guide 37 Hybrid Steel Frames with Wood Floors provides guidance for design without composite action and mentions the potential benefits and efficiencies of incorporating composite action between the CLT slab and steel framing [3]. The European Convention for Constructional Steel work (ECCS) has recently published a state-of-the-art guide for Steel-Timber-(Concrete) Structures, which compiles international research on connection, beam, and diaphragm tests incorporating composite action between timber floors and steel framing, and also discusses future goals for development of standards on composite action between timber floors and steel framing [4]. Mass timber floors coupled with steel floor framing have the potential to enable composite action, similar to traditional concrete floor-steel framing composite structures, where two materials work together structurally to enable the reduction in steel beam depth and weight, improving material efficiency. However, despite these potential benefits, there are currently no established guidelines for designing composite action in steel-CLT structures, and current practice typically assumes no composite action.

Previous research [5-16] on shear connections between timber floors and steel framing has been conducted by several international research teams, covering a range of connection types focusing on screws, bolts, and mechanical connectors in cementitious material or adhesive material across different engineered wood products such as CLT, Laminated Veneer Lumber (LVL), and glulam. Studies include experimental testing and numerical analysis, evaluating factors such as strength, stiffness, and long-term performance. Findings from studies has shown that the bolt connections exhibit great ductility and provide sufficient strength and resistance to enable the development of composite action.

Hassenieh et al. [9] investigated grade 8.8 bolts with low pretension levels (8-14% of bolt yield strength of 660 MPa [96 ksi]) in connections between CLT or LVL and steel beams under monotonic loading. This study discussed the potential loosening of bolt pretension due to wood creep behaviour and noted that while pretension has minimal impact on the ultimate strength of the connection, it enhances slip resistance in the early stages, providing a key advantage for composite action. Test results from end connection setups involving high-strength friction grip bolts showed a substantial improvement in slip resistance with higher pretension levels, where a pretension of 60% of the bolt yield was applied.

Romero et al. [13] tested grade 10.9 high-strength M20 bolts within 6.3 mm thick round steel tube and various bottom plates in connections between LVL and steel under monotonic loading, including loading-unloading cycles at specific load levels. The bolts were subjected to pretension levels equivalent to those typically required for slip-critical connections in steel, which is 70% of the ultimate strength of the bolt (172 kN [39 kips]). The connections showed no slip up to the maximum of 43.3 kN (9.7 kips) in testing, approximately meeting the AISC slip-critical strength design strength for steel structures [17]. Failure occurred in a ductile manner, characterized by an ultimate slip of about 140 mm (5.5 inches) and the formation of a plastic hinge in the bolt shank.

Existing studies on cyclic loading tests for Steel- Timber composite connection remain limited. Loss et al.[11] conducted both force-controlled and displacement-controlled cyclic tests on screws and connectors embedded in adhesive materials, following Eurocode 4 Design of composite steel and concrete structures and EN 12512 Timber structures - Test methods - Cyclic testing of joints made with mechanical fasteners. Bompa et al.[7] performed numerical simulations to analyze the inelastic cyclic response of beam-to-column connections in hybrid steel-timber moment frames. Ataei et al.[6] tested bolts and screw shear connector assemblies in steel-timber composite beams under low-cyclic, high amplitude loading, in accordance with EN 12512.

Overall, bolt connections have demonstrated significantly greater strength compared to nails and screws and have shown reliable performance under both serviceability conditions and ultimate loads. However, there has been no direct investigation of slip-critical high-strength bolt-type connections subjected to cyclic loading, as may be seen with diaphragm action during an earthquake. Additionally, there has been limited exploration of through-bolt connections for steel-CLT systems.

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Composite beam tests have confirmed the presence of composite action in timber slab-to-steel beam configurations, investigating various parameters such as connector design, connector spacing, beam length, timber panel grain orientation, mass timber types, beam material, and span width. However, challenges remain in developing design calculations for composite action in the steel+CLT structures, including methods for estimating the shear force limit of the CLT in composite action, understanding the stress distribution within the floor slab, finding ways to calculate effective width for composite action prediction, and predicting the ultimate design strength of the cross section. Diaphragm tests on CLT-steel composite structures with high-slip-resistance connections remain limited and are important to the understanding of the performance of the system subjected to cyclic loading.

In addition, challenges remain in establishing comprehensive design guidelines, particularly regarding composite action and the behaviour of these systems under cyclic loading. This project aims to address these gaps through a systematic experimental plan, including material tests, connection tests, beam tests, and diaphragm tests, using CLT, steel beams, and slip-critical high-strength bolt connectors.

3 – PROJECT DESCRIPTION

Prototype buildings have been designed for local conditions, floor patterns, and building types to inform structural element sizes for testing and analysis. These include low-rise (4-story) and high-rise (12-story) structures design for two distinct geographic zones: Boston, Massachusetts (high wind, cold climate) and Irvine, California (seismic, mild climate). Figure 1 shows a typical layout of the prototype structure. The prototypes also incorporate two structural patterns, examining both regular and longer-span applications of CLT. In addition, biobased and other low carbon products are used to replace the cladding. Concrete toppings are not being used in this system. A life cycle waterfall chart has demonstrated the potential of the steel+CLT composite structure to achieve net-negative carbon emissions, as shown in Figure 2.

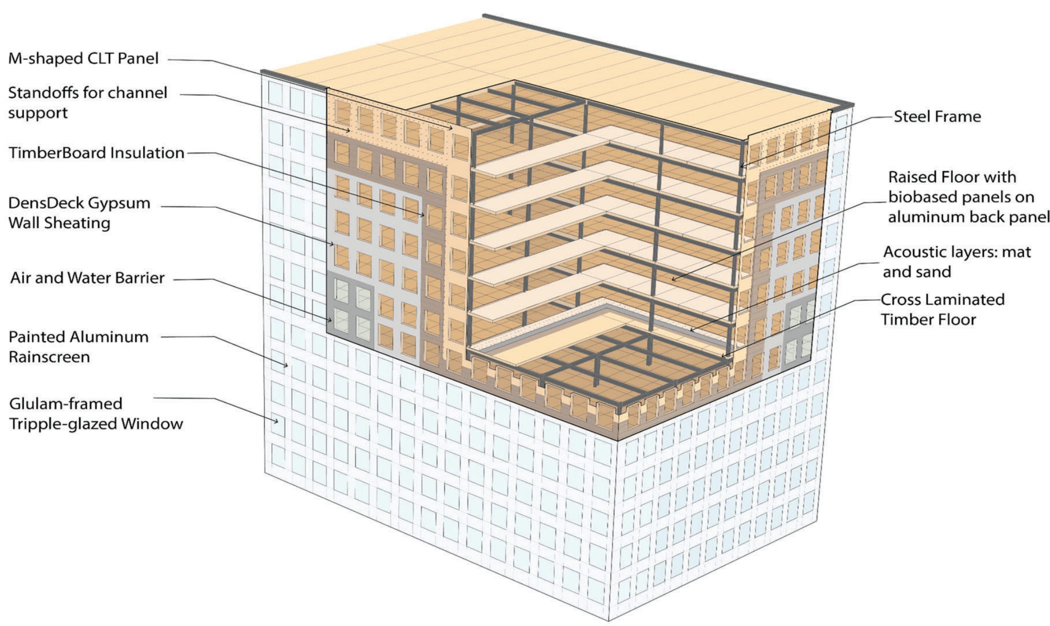

Figure 1. Typical Prototype Building for Steel-CLT Structural Systems

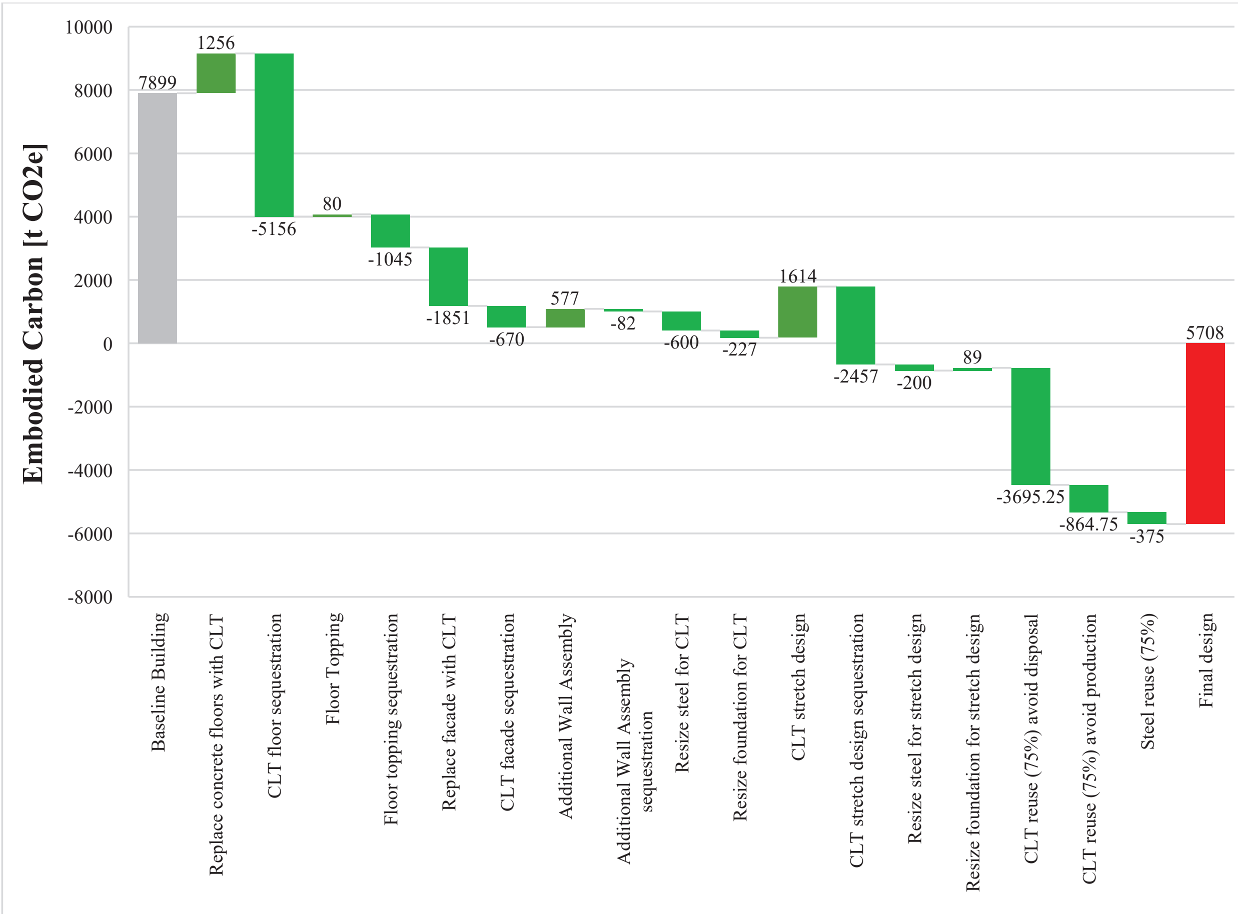

Figure 2. Life Cycle Analysis Waterfall Chart

Beyond traditionally utilized species in CLT manufacturing, experiments have been conducted to characterize the mechanistic properties of novel species, including Eastern Hemlock and Eastern White Pine. These species have previously been considered to be of low value and have not been commonly used in CLT production. The long-distance transportation of CLT often presents challenges of cost and reduces the carbon benefits associated with its use. Therefore, exploring the feasibility of incorporating underutilized local species could enhance sustainable forest resource utilization while minimizing transportation-related carbon emissions. The experimental results and statical analyses show that these two underutilized species do not have higher coefficients of variation than the typical species used in CLT fabrication. In this work, various properties of these species are characterized via parametric studies. Following lumber tests, plank tests are being conducted on CLT with novel layups, including mixed species, underutilized species, and variation in layer angles.

4- EXPERIMENTAL PROGRAM

To ensure efficient shear load transfer between CLT floors and steel framing, shear connectors must exhibit high slip resistance and bearing strength. The proposed connection design as shown in Figure 3 incorporates two A490 high strength bolts on each side of the wide flange steel beam. Each bolt is enclosed within a steel sleeve that is flush with the CLT panel’s surface at both the top and the bottom. The steel sleeve, made from a minimum grade 65 material, enables the application of the pretension levels required for slip-critical connections. Another key feature of this design is the pre-mounted Shuriken nut tack welded on the bottom side of the steel beam flange, which allows for installation from the top of the CLT floor, eliminating the need for overhead construction. This connection also facilitates deconstruction at the end of the useful life of the building structure.

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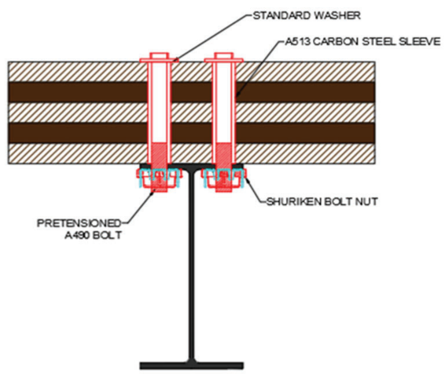
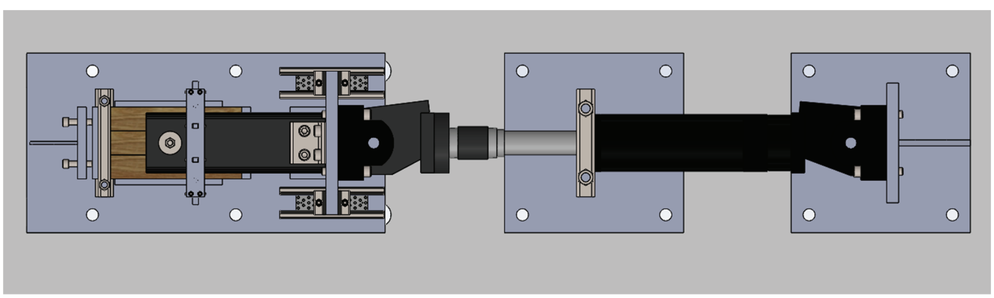


Figure 3. Proposed Steel- CLT Shear Connection

This study developed a single-bolt test setup as shown in Figure 4 to facilitate a large quantity of connection tests, allowing for the investigation of various parameters and statistical analysis. This setup is designed to accommodate a maximum up to +/- 6-inch movement while capturing the behaviour of a single connection. Steel channels are used to replicate the wide flange beams in the actual application. These channels have the same material grade as the wide flange beams, and their web thickness closely matches the flange thickness of the wide flange profile. All steel profile sizes are informed by the prototype structures. A series of pretension tests will be conducted to establish the bolt-tightening scheme for ensuring a reliable pre-tension in the connector through the bolt acting directly on the steel sleeve.

The connection test matrix was formulated to encompass a wide range of typical design configurations of steel + CLT composite structures, including parameters such as bolt size, the presence of a sleeve, CLT thickness, CLT major and minor strength direction, and one novel CLT layup configuration. Table 1 presents the push-out specimen test matrix for a total of 180 specimens to be tested in this research, with 38 subjected to full cyclic loading to simulate seismic action, 38 subjected to half cyclic loading (loading-unloading cycles primarily under serviceability load level to simulate fluctuating gravity loading), and the remaining subjected to monotonic loading. The test matrix is divided into two parts: the core test plan, which investigates the fundamental behaviour of the connections, and the expanded test matrix, which is designed for data statistical analysis aimed at establishing design equations within a load-and-resistance-factor design framework. Also 16 bolts will be used in a longer-term study to document the percentage pretension level as time passes to evaluate the serviceability performance of the proposed connection. These tests use commercially available CLT material to establish strengths based on currently available materials.



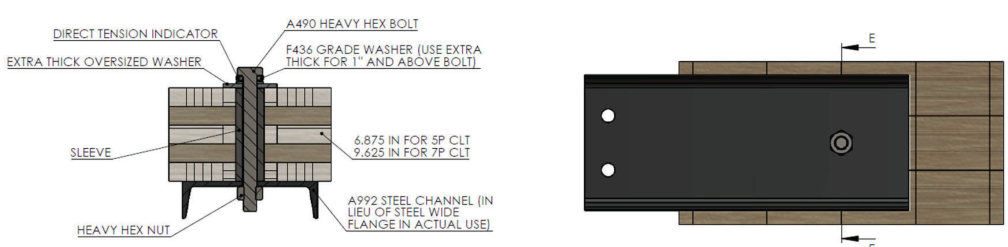
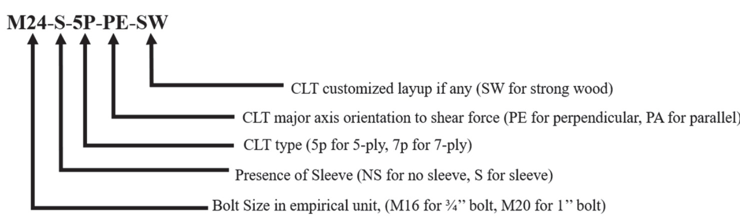


Figure 4a. Steel- CLT Shear Connection Test Setup Details.

Figure 4b. Steel- CLT Shear Connection Test Specimen Details.

Table 1: Connection Test Matrices

#	Test Type	Specimen	Total Test Quantity	Total Core Test Quantity	Monotonic Test	Half Cyclic Test	Full Cyclic Test	Total Expand Test Quantity	Monotonic Test	Half Cyclic Test	Full Cyclic Test
1	M16-5p-NS-PA	5-ply CLT major strength	6	6	2	2	2				
2	**M16-S-5p-PA**	5-ply CLT major strength	26	7	**3**	2	2	**19**	**13**	**3**	**3**
3	**M16-S-5p-PE**	5-ply CLT minor strength	26	7	**3**	2	2	**19**	**13**	**3**	**3**
4	**M24-S-5p-PA**	5-ply CLT major strength	26	7	**3**	2	2	**19**	**13**	**3**	**3**
5	**M24-S-5p-PE**	5-ply CLT minor strength	26	7	**3**	2	2	**19**	**13**	**3**	**3**
6	**M16-S-7p-PA**	7-ply CLT major strength	26	7	**3**	2	2	**19**	**13**	**3**	**3**
7	**M16-S-7p-PE**	7-ply CLT minor strength	26	7	**3**	2	2	**19**	**13**	**3**	**3**
8	M24-S-7p-PA	7-ply CLT major strength	6	6	2	2	2				
9	M24-S-7p-PE	7-ply CLT minor strength	6	6	2	2	2				
10	M24-S-5P-PE-SW	5-ply CLT minor strength SW	6	2	2	2	2				
Total			180	66				114			



5 – SIMULATION

Finite element modeling of the connection shear tests was conducted in Abaqus explicit dynamic analysis. Material models for the A490 bolt and steel channel components were developed using an isotropic hardening model that tracks the average constitutive response from tensile coupon test results. The CLT was modelled using a layer-by-layer approach, with interlayer interactions defined through tie constraints. Each CLT layer utilized a material model based on the Hill yield criterion.

Finite element modelling results provide valuable insights into peak strength, maximum displacement, failure modes, and damage progression. The results presented correspond to a case (test #5) using 1-inch diameter A490 bolts in a 5-ply CLT assembly, where the bottom layers have a grain orientation perpendicular to the shear plane—typical for beam applications in prototype models. Simulations indicate that the connection exhibits significant slip resistance followed by a ductile failure, with a plastic hinge forming at the shear interface. Figure 5 presents the load-slip response for Test #5. Slip between the CLT and steel initiates at about 19.5 kips, aligning closely with the slip critical strength required by AISC. The bearing strength at a slip of 0.6 inch is approximately 30 kips, which exceeds the National Design Specification for Wood Construction dowel connections shear strength prediction [18]. The connection strength continues to increase until reaching its peak at approximately 5.8 inches of slip between the steel and CLT, where the bolt shear controls.

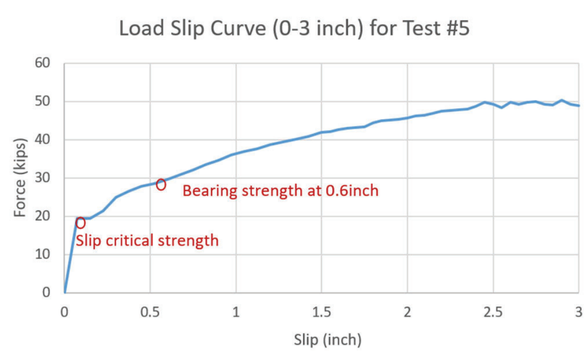


Figure 5. Finite Element Simulation Load-Slip Response

6 – CONCLUSION

The steel-CLT composite structure considered in this study has shown its potential in accelerating the path to net-zero carbon buildings, while also being suitable for

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use in seismic zones. By incorporating more bio-based products in non-structural systems, validating low-value species to provide local wood sources, and optimizing floor layouts to enhance panel reuse and reduce structural components, the system could offer even greater carbon benefits as indicated by life cycle analysis.

Early simulation analyses and past experimental research [13] on a similar connection configuration suggest that the proposed connection exhibits high strength and ductile behaviour. The team will conduct connection tests, beam tests, and diaphragm tests to further evaluate the structural system. Additionally, parametric finite element studies will be performed to explore scenarios not tested. The project aims to refine and develop design guidelines to support connection design and composite action calculations in steel+CLT structures. In the long term, efforts will focus on code adoption and technology-to-market strategies including considering processes for recertifying and reclaiming structural elements at the end of building's useful life to enable Design for Deconstruction.

7 – ACKNOWLEDGEMENT

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