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DEVELOPMENT OF SAFE DESIGN PROCEDURES FOR PRODUCTS, ASSEMBLIES, AND SYSTEMS IN WOOD CONSTRUCTION

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ABSTRACT: The Canadian government and its provinces are implementing climate strategies and regulations to decarbonize the building construction sector through nature-based solutions, such as using sustainable and renewable construction materials. Measures include promoting wood education and research, "Wood First" provincial policies, modernizing sustainable forest management, and strengthening the timber supply chain. In line with these efforts, in 2023, the Québec Ministry of Natural Resources and Forests funded the authors of this paper to develop safe design procedures for products and systems in wood construction. The research program will be executed over five years at Université Laval and McGill University in collaboration with twelve industry partners through a series of planned research tasks. The tasks encompass developing 1) novel connection systems for mass timber buildings, 2) new timber-steel braced frames, 3) low-damage rocking timber frame braced systems, and 4) seismic and wind design guidelines for the new systems through numerous experimental campaigns and extensive numerical studies. This paper provides an overview of the project, its status, and upcoming tasks.

KEYWORDS: Hybrid buildings, Mass timber, Steel, Québec, Seismic design

1 – INTRODUCTION

Canada is a world leader in the timber building sector, and forestry is one of Canada's oldest and most important industries, contributing $33.37 billion to the nominal gross domestic product in 2022. More than 500 mass-timber buildings have been constructed in Canada since 2007, and this number is growing exponentially, as is the desire to build taller with timber [1]. For example, the 2020 National Building Code of Canada [2] permitted encapsulated mass timber construction up to 12 storeys. In 2024, the provinces of Ontario and British Columbia allowed 18-storey mass timber construction.

Mass timber buildings exceeding eight storeys are lightweight and flexible, and as a result, lateral drift requirements under frequent wind and earthquakes may govern the design decisions [1]. Additionally, in seismically active regions of the country, under severe earthquake occurrences, mass-timber buildings are expected to respond through an appropriate energy dissipation process via the inelastic response of "ductile" components (e.g., connections), while "non-ductile" components (wood elements) which are crucial for the stability of the building remain elastic. Given these design constraints, employing timber for the complete lateral load resisting system may not be a practical option. Recent studies and real-world projects showed that mass-timber buildings could be designed more economically if hybridized with steel or concrete. Specifically, timber-steel hybridization can extend the application of timber into high seismic regions and high-rise buildings by integrating the excellent ductility of steel with timber to effectively address seismic ductility demands and excessive wind-induced drift [1]. Although ongoing studies on mass timber structures have been conducted in Québec and elsewhere over the past ten years, the potential of combining timber with steel has yet to be fully explored.

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2 – DEVELOPMENT OF CONNECTION SYSTEMS FOR MASS TIMBER BUILDINGS

This task focuses on the experimental evaluation of components, connections, and assemblies to characterize their performance and support the development of design methods capable of resisting gravity, lateral, and accidental loads. The studies aim to address the complex behaviour of wood, considering its anisotropic nature, viscoelasticity, load duration effects, moisture sensitivity, stress concentrations around fasteners, size effects, material variability, and fire resistance. Special emphasis is placed on developing standardized and reliable procedures to assess the resistance, stiffness, energy dissipation, fire performance, and other key parameters of connections and assemblies under various design scenarios. The task involves extensive laboratory testing.

2.1 DEVELOPMENT OF TEST PROTOCOLS

To evaluate new connection systems, it is essential to employ appropriate test methods. However, existing standard procedures are often not well-suited for emerging applications. A notable example is the evaluation of high-capacity concealed joist hangers, which have become increasingly popular in modern mass timber construction due to their aesthetic appeal and potential for enhanced fire resistance.

In North America, joist hangers are typically assessed using the ASTM D7147 [3] standard. This method involves connecting both ends of a short joist segment to headers using joist hangers, with a 3 mm gap introduced at each end to prevent friction between the members during loading (Figure 1). In contrast, European practice follows EAD 130186-00-0603 [4], where a joist with a span of at least eight times its depth is loaded near the end connected to a header with a joist hanger (Figure 2). However, the EAD test setup lacks detailed specifications, leaving boundary conditions open to interpretation.

An experimental campaign was carried out to compare the two test methods and identify appropriate boundary conditions. In this study, a group of self-tapping screws (STS) was installed into the end grain of a glulam beam through a steel plate (the web of a C-channel) and loaded according to both ASTM [3] and EAD [4] procedures. The vertical position of the STS group was varied to assess the influence of effective depth on beam capacity and the potential need for reinforcement. Four different screw configurations were examined. To investigate the role of friction, Teflon strips were inserted between the steel plate and the beam end. In the ASTM [3] setup, the C-channel was rigidly clamped to the base to prevent rotation during loading (Figure 3), while EAD [4] tests were conducted both with and without clamping (Figure 4).

Additionally, several commercial and custom-made concealed joist hanger models were tested using a modified ASTM D7147 setup. Results demonstrated that the current ASTM [3] procedure is inadequate for evaluating hangers in mass timber applications, particularly for examining the influence of variables such as splitting on connection resistance. Subsequent tests were conducted using the modified EAD [4] setup, which proved more suitable.

Based on these findings, recommendations for revising the ASTM D7147 standard will be proposed to the ASTM D07 Committee on Wood.

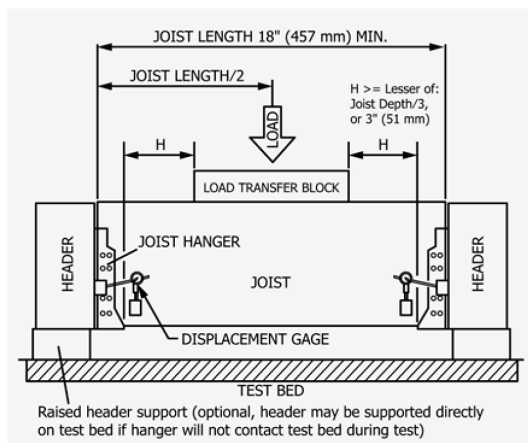

Figure 1. ASTM D7147 test setup for joist hangers [3].

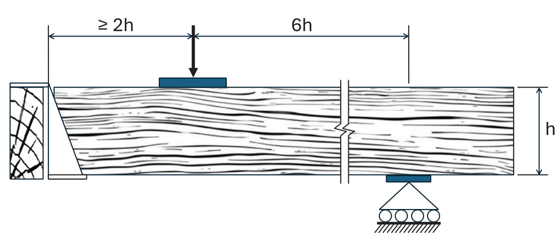

Figure 2. EAD 130186-00-0603 test setup for joist hangers [4].

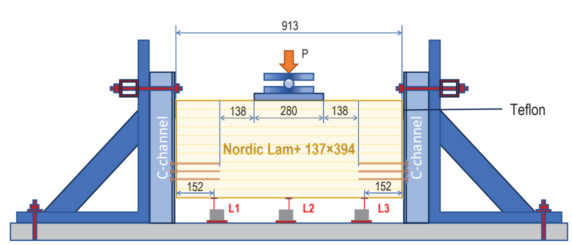

Figure 3. Modified ASTM [3] test setup (mm).

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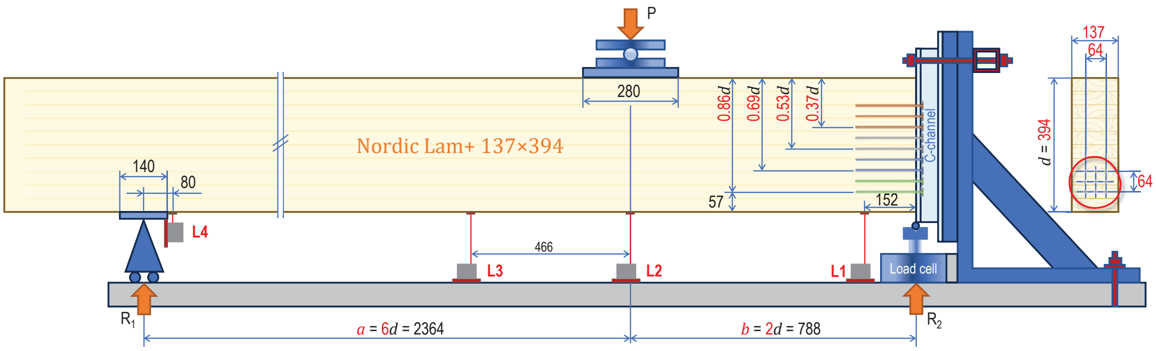

Figure 4. Modified EAD [4] test setup (mm).

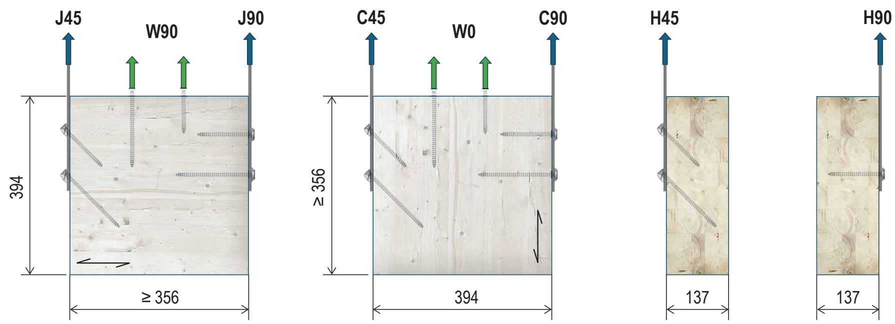

Figure 5. Test configurations for STS tests at various installation and loading angles (mm).

2.2 DEVELOPMENT OF DESIGN RULES

A critical component in the adoption of new connection systems for mass timber structures is the development of robust and reliable design rules. In 2024, the Canadian timber design standard CSA O86 [5] incorporated design provisions for self-tapping screws (STS) for the first time. These provisions are largely based on design guidelines developed in Europe; however, several aspects require refinement and adaptation to better align with Canadian wood products and existing design methodologies—particularly the equations governing the lateral resistance of STS installed and loaded at various angles to the grain.

To support this effort, a comprehensive experimental campaign has been launched to investigate the performance of STS with varying diameters and lengths, installed and loaded at different angles, with the aim of validating and refining the adopted equations for Canadian-manufactured glulam products such as Nordic Lam+ and Douglas-fir 20f-EX. The range of tested variables is illustrated in Figure 5. Fully threaded STS in two diameters (8 mm and 11 mm) and two lengths from two different suppliers were tested on matched specimens, with a minimum of 15 replicates per configuration to ensure statistical robustness.

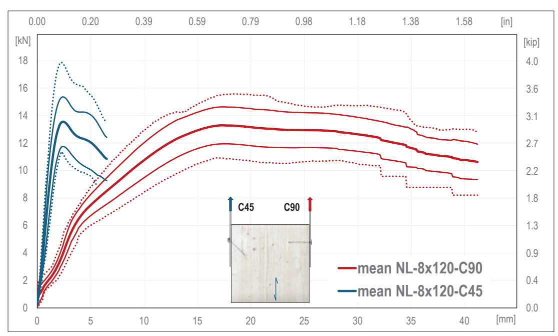

Figure 6. Load-slip graphs for STS loaded at 90° and 45° to the shear plane.

The testing program is ongoing. Preliminary analysis of the results has highlighted the need to clarify the displacement levels at which design resistance should be defined. Examples of load–slip curves obtained from STS loaded parallel to the grain, at both 90° and 45° to the shear plane, are presented in Figure 6. These findings are essential for validating current design equations and for informing the development of improved design rules for STS connections installed at mixed angles, as well as for their use in reinforcement applications.

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2.3 COLD-FORMED STEEL BEARING ON CLT PLATFORM

As hybrid construction systems combining cold-formed steel (CFS) framing with cross-laminated timber (CLT) platforms become increasingly common for buildings of six stories and taller, the issue of wood deformation and resistance perpendicular to the grain under gravity loads warrants greater attention from designers. Current standards do not adequately address compression perpendicular to the grain in such configurations. The ASTM D143 [5] standard requires the evaluation of compression perpendicular to the grain using a 50×50 mm steel plate bearing on a 51×51×150 mm specimen of clear, green wood, fully supported at the base. The test measures the proportional limit and the stress corresponding to a 1 mm displacement (Figure 7). In contrast, the EN 408 [6] standard specifies the application of a full-surface compression load and defines resistance at the intersection of the load–displacement curve and a straight line offset by 1% of the specimen depth, parallel to the linear-elastic portion of the curve (Figure 8).

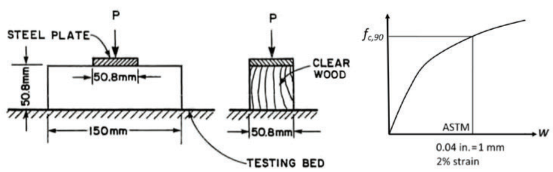

Figure 7. ASTM D143 compression perpendicular to grain test.

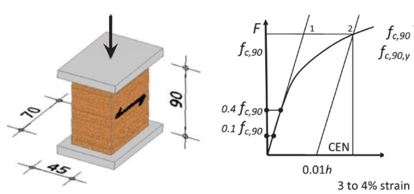

Figure 8. EN 408 compression perpendicular to grain test.

Figure 9. CFS tracks bearing on CLT test.

To address this gap, an experimental campaign has been initiated to evaluate the deformation behaviour of CLT under bearing loads from CFS tracks of various gauges, loaded through the CFS studs positioned above and below (Figure 9). The tests comprise three-ply and five-ply CLT panels manufactured in Canada, with loading applied near panel edges both parallel and perpendicular to the major strength direction. The testing is ongoing. The results will support the development of analytical models and design procedures for multi-storey hybrid buildings incorporating CFS frames on CLT platforms, and will provide valuable data for structural designers working with these systems.

2.4 CYCLIC PERFORMANCE OF DOWEL CONNECTIONS WITH SLOTTED-IN PLATES

Mass timber braced frame systems often incorporate steel dowel-type fasteners (e.g., bolts and dowels) with slotted-in steel plates. These connections can exhibit ductile, brittle, or mixed failure modes, with premature brittle failures significantly limiting overall system ductility and energy dissipation capacity. A project comprised the investigation of the stiffness, strength, ductility, and energy dissipation of dowel connections in glulam through 68 monotonic and cyclic tests. The tested configurations involved 12.7 mm dowels inserted into one or two slotted-in steel plates, designed in accordance with CSA O86-24 [7] and loaded in tension parallel to the grain. The test setup is illustrated in Figure 10. Key variables included in-row and between-row dowel spacing, end distance, number of slotted-in steel plates, and number of dowels. Test results were compared against CSA O86 design predictions.

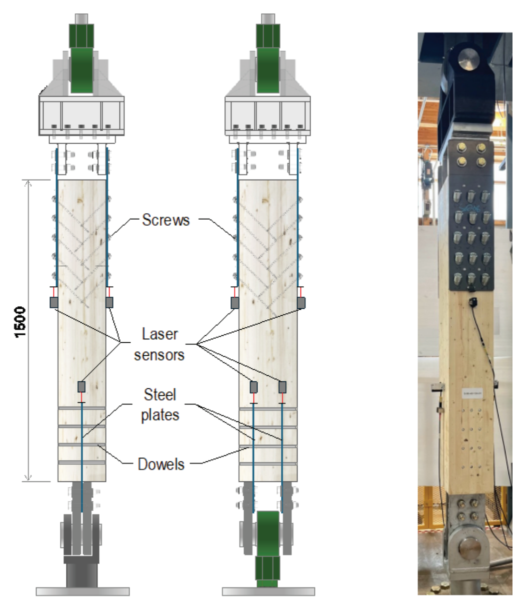

Figure 10. Test setup for dowel connections with slotted-in plates.

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The findings showed that increasing the in-row dowel spacing from 50 mm (4d) to 90 mm (7d) improved strength, stiffness, and ductility. In contrast, increasing the between-row spacing from 40 mm (3d) to 64 mm (5d) primarily enhanced stiffness. The number of dowels and shear planes had a strong influence on connection behaviour: double slotted-in plates increased strength but reduced ductility, while adding more dowels improved both strength and stiffness at the cost of ductility. Failure modes varied with the connection configuration. Single slotted-in plate assemblies generally exhibited ductile behaviour characterized by dowel yielding followed by wood splitting. In contrast, connections with double slotted-in plates often experienced premature splitting and pushing out of the outer wood members, leading to reduced ductility. Comparison with CSA O86 predictions showed good agreement for single slotted-in plate connections with 7d in-row spacing, while configurations with smaller spacing and double slotted-in plates were found to have their resistance overestimated by the design equations. These results offer valuable guidance for improving the ductility and reliability of dowel-type connections in seismic applications. Dowel slenderness and spacing should be explicitly considered during design to prevent brittle failures and ensure robust energy dissipation in timber structures.

3– DEVELOPMENT OF NEW TIMBER-STEEL HYBRID BUILDING SYSTEMS

This task has two major phases. The first phase aims at performing a holistic feasibility study to identify and develop new steel-timber hybrid systems with the greatest potential for performance under lateral loading (wind & seismic) concentrating on framing type, connection type, constructability, cost, life cycle assessment (LCA), carbon emissions, seismic and wind hazard, etc. The second phase comprises the development of a design approach for the initially identified best-performing hybrid systems; one system for wind & low seismic, and another system for moderate/high seismic. This will require some additional laboratory testing of connections and the lateral systems in full-scale, along with supplemental numerical finite element analyses to characterize the load transfer between the wood and steel, quantify the nonlinear inelastic response of the energy dissipating components, and estimate system- and building-level responses to seismic and wind loads. This information will then be used in performance-based assessment of hybrid buildings to verify the adequacy of the proposed design approach.

Considering structural performance, three hybrid systems are chosen for detailed study, i.e., timber-steel hybrid eccentrically braced frames (TS-EBFs), low-damage controlled rocking braced timber frames (CR-BTFs), cross-laminated timber coupled walls (CLT-CWs) with steel link beams, and post-tensioned CLT (PT-CLT) walls. TS-EBF and CR-BTFs were developed for the first time in this project (Section 3.2), while CLT-CWs and PT-CLT walls were tested and numerically studied previously. To facilitate the adoption of these hybrid systems as alternative lateral load systems (LLRS) in Canada, it is essential to quantify their structural performance and assess the embodied carbon emissions through life cycle assessment (LCA) studies. However, comparative assessments of the total embodied carbon emissions of different building types and heights across Canada is scarce. In addition, the effect of hybridization of mass timber with steel on embodied carbon emissions has not been studied. To address these challenges, two-stage LCA studies were performed, the results of which are elaborated briefly in the subsequent subsections.

3.1 LIFE CYCLE ASSESSMENT OF HYBRID BUILDINGS

Initially, LCA of functionally equivalent three- and six-storey reinforced concrete (RC), structural steel (SS), and mass-timber (MT) buildings in Vancouver, Montreal, and Toronto, Canada, was conducted using the Athena Impact Estimator for Buildings (IE4B) tool. The assessments show that, excluding biogenic carbon, MT reduces Global Warming Potential (GWP) by 33–36% and 27–32% for three- and six-storey buildings compared to RC in phases A–C (production to end-of-life), and by 14–19% and 5–14% compared to SS, respectively (Figure 11). Including phase D (beyond end-of-life) and biogenic carbon, MT reduces GWP by 99–102% and 109–118% for the three- and six-storey buildings compared to RC, and by 99–105% and 118–139% compared to SS, respectively (Figure 12).

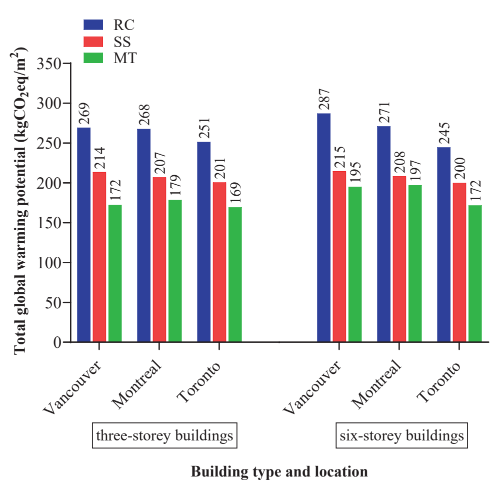

Figure 11. Total GWP (Phases A–C) excluding biogenic carbon.

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In the second stage LCA, the embodied carbon emission potential of the hybrid systems (TS-EBF, CR-BTF, PT-CLT, and CLT-CWs) was compared for MT and SS buildings. The results, presented in Figure 13, show that hybridization significantly reduces GWP compared to fully SS buildings, with CLT-CWs by 131%, PT-CLT walls by 119%, and TS-EBF by 120%. However, when compared to MT, hybrid buildings exhibit higher GWP, with increases of 9% for CLT-CWs, 45% for PT-CLT walls, and 42% for TS-EBF. Despite this increase, hybrid systems offer a necessary balance between sustainability and structural performance, enabling the design of taller buildings while maintaining a lower carbon footprint than SS. This two-stage LCA highlights the importance of timber-steel hybridization in advancing sustainable construction.

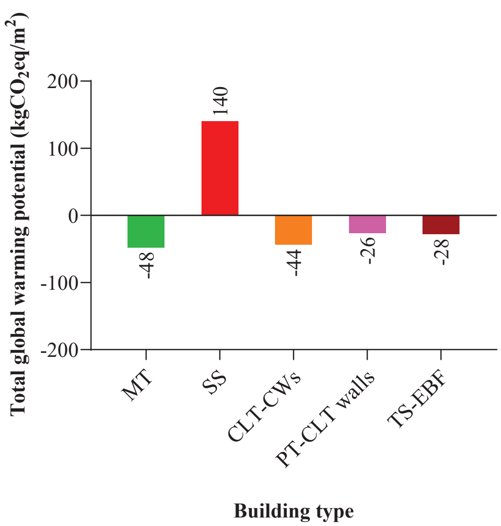

Figure 12. Total GWP (Phases A–D) of hybrid buildings.

3.2 PROGRESS IN THE DEVELOPMENT OF NEW TIMBER-STEEL HYBRID SYSTEMS

3.2.1 Timber-Steel Hybrid EBF (TS-EBF)

EBFs are seismic force-resisting systems (SFRS) in which the line of action of two braces, or a brace and a column, is intentionally offset to create a beam segment known as a link beam. This link beam dissipates energy through controlled and stable plastic deformation during severe seismic events. EBFs are recognized for their excellent energy dissipation capabilities due to the plastic deformation of the links and high lateral stiffness due to braces [8]. The use of replaceable links in EBFs accelerates repairability after major earthquakes, as the ductile part of the beam is isolated from the elastic part and connected through bolts. This approach paves the way for the hybridization of EBFs with timber. Such a hybridization results in a robust and sustainable SFRS, TS-EBF. Figure 13 shows two configurations of TS-EBFs. In a TS-EBF system, steel is utilized as a shear link due to its high ductility and energy dissipation capabilities, and timber elements are employed as the elastic (force-controlled) components. Various engineered wood products (EWPs) such as glulam, laminated veneer lumber (LVL), or parallel strand lumber (PSL) can be used in the elastic regions (beams, columns and braces). Figure 13a depicts a symmetric chevron bracing TS-EBF configuration with a horizontal link. The link in this configuration experiences minimal or no axial forces (dependent on the location of the braced frame with respect to the mass of the building), and the frame exhibits high lateral stiffness. Figure 13b shows a TS-EBF with vertical links, where the links are not an integral part of the beam.

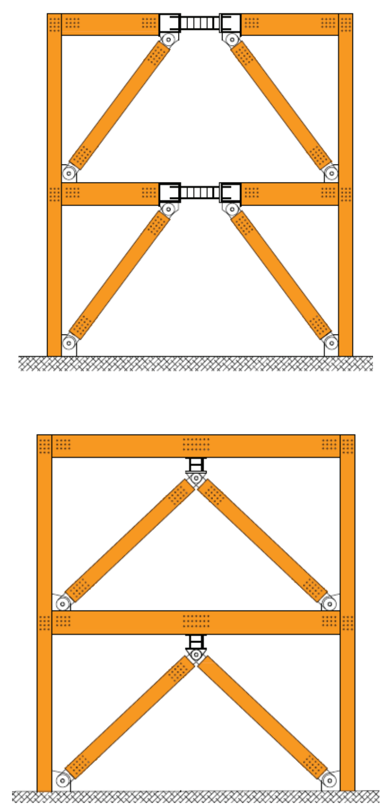

Figure 13. Timber-steel eccentrically braced frames (TS-EBFs): a) with a horizontal link, and b) with a vertical link.

In the TS-EBF system, links are classified as shear, flexural, or intermediate, depending on the dominant force causing the yielding. Among these, shear links are

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preferred due to their uniform energy dissipation and higher plastic rotation capacity (0.08 rad vs. 0.02 rad for flexural links), as recognized by CSA S16-24 [9] and AISC 341-22 [10]. To ensure stable inelastic behaviour and prevent premature failure modes such as plastic local buckling, strict detailing requirements for web stiffeners and section compactness must be followed.

The elastic members of the TS-EBFs must be designed to resist the maximum forces generated by a fully yielded and strain-hardened link. Traditionally, an overstrength factor of 1.5 has been used for this estimation. The CSA S16-24 [9] recommends an overstrength factor of $1.3R_y$ for wide-flange links, where R_y represents the ratio of nominal to minimum yield stress. A key challenge in TS-EBFs is the strength disparity between steel and timber, which can lead to oversized timber members if designed using standard steel sections available in the Canadian market. To control the link capacity, approaches such as perforated replaceable links, low-yield steels, or custom-made links can be used.

Unlike traditional timber structures, where seismic energy dissipation occurs through ductile connections, hybrid SFRSs, including TS-EBFs, use capacity-protected connections to ensure that yielding is confined to the link. High-capacity connections, such as dowels, self-tapping screws, and glued-in rods, are essential to keep both the connections and the connected timber members elastic. Numerous experimental studies have confirmed that these connections are suitable for hybrid systems under seismic loading.

OpenSeesPy and *Abaqus* numerical models for TS-EBFs have been developed and validated with component level tests reported in the literature [6]. In addition, a force- and displacement-based seismic design methodologies have been developed and used to design six-storey mass timber building with TS-EBF SFRS. The preliminary analysis results for the seismicity of Vancouver, BC, Canada indicate that the TS-EBF SFRS effectively dissipated seismic energy through the controlled plastic yielding of shear links and met the drift requirements of the NBCC 2020 [11].

TS-EBFs have never been experimentally tested, and their behaviour has only been predicted through numerical models that rely on component tests. To address this gap, full-scale TS-EBF tests are required to understand their structural behaviour under monotonic pushover and cyclic loading. In addition, the results will validate numerical models, providing a reliable foundation for further research and design guide development. Using the experimental setup shown in Figure 14, it is planned to test full-scale single-bay single-storey TS-EBFs at the Jamieson Structures Laboratory, McGill University.

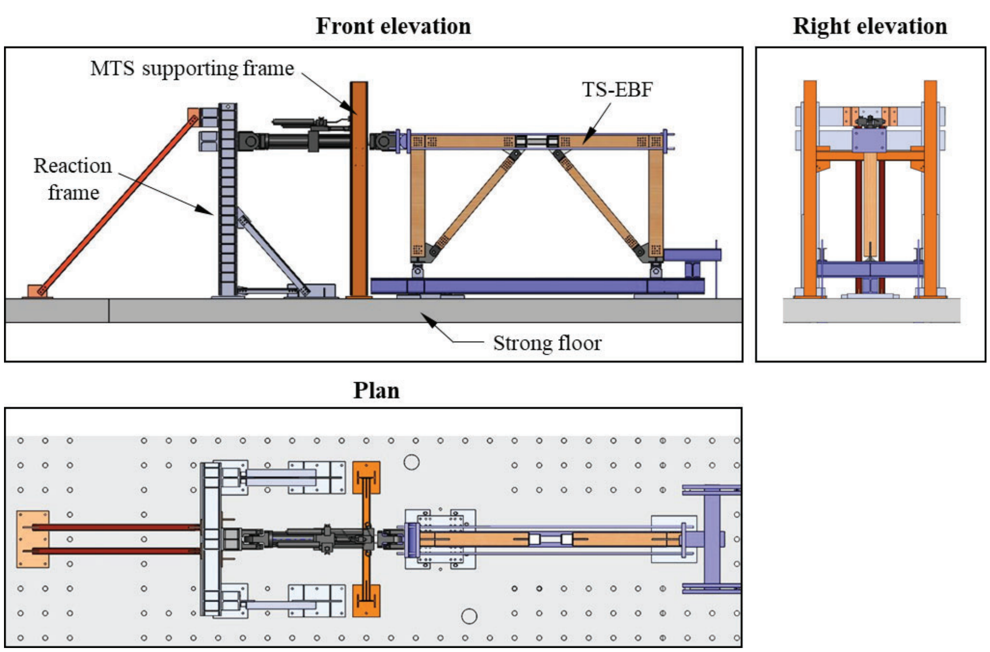

Figure 14. Experiment set up for TS-EBFs.

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3.2.2 Controlled Rocking Braced Timber Frames (CR-BTFs)

PT-CLT rocking shear walls coupled with energy dissipation devices have been demonstrated to be a low-damage, resilient seismic force-resisting system due to their self-centring capability and stable energy dissipation [12]. With over two decades of research on the seismic design and performance assessment of PT-CLT walls, efforts are ongoing to incorporate the system into the building codes and design standards of various countries. The success of PT-CLT walls indicates that other rocking timber systems could have a comparable or better structural performance. In this regarding, rocking timber braced frames may be a viable option. Although rocking steel braced frames have been extensively studied, the rocking response of timber braced frames remains largely unexplored. As such, in this project, a controlled rocking BTF (CR-BTF) was developed, which contains EWPs as force-controlled elements, unbonded post-tension cables to provide overturning resistance and self-centring, and butterfly fuses to dissipate energy. Figure 15 shows single and coupled configurations of CR-BTFs, respectively.

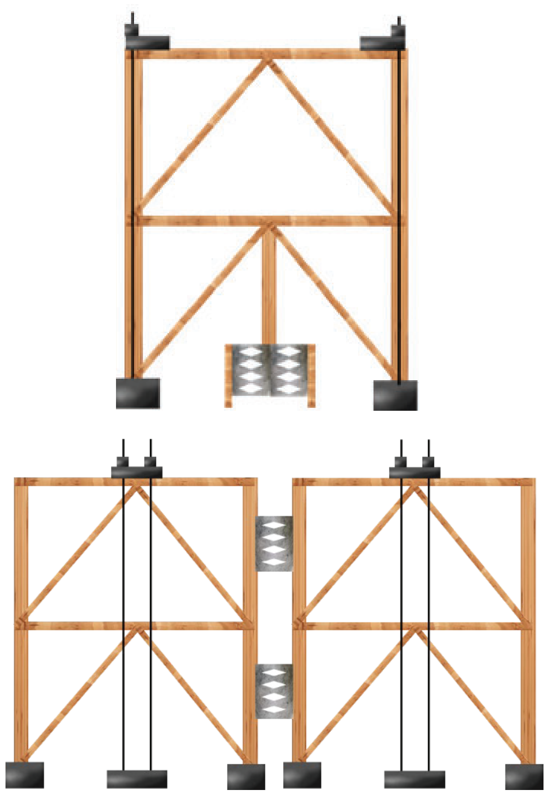

Figure 15.Configuration of controlled rocking braced timber frames (CR-BTFs)

A numerical modelling strategy in *OpenSeesPy* has been developed to study the structural behaviour of CR-BTFs and to conduct a seismic performance assessment. The modelling strategy has been validated with 3 storey full-scale shaking table test of a rocking steel braced frame conducted at the Hyogo Earthquake Engineering Research Centre (E-Defense) in Japan [13]. With this validated *OpenSeesPy* framework, the next stage of the research will involve the development of a modified displacement-based design approach for CR-BTFs, and a detailed seismic performance assessment. Both single and coupled CR-BTF configurations will be investigated, followed by an optimization study to determine the number and locations of the butterfly fuses. This aims to maximize system performance under wind and seismic loads, and to fully exploit the potential of the system.

After thoroughly evaluating the system's behaviour using numerical studies, both component- and system-level experiments will be carried out at the Jamieson Structures Laboratory, McGill University. In addition, it is planned to develop seismic force modification factors and seismic design guidelines for CR-BTFs for possible inclusion in future editions of the NBCC.

4 – SHORT- AND LONG-TERM PLANS

The following projects are ongoing or have been planned to address key challenges associated with the use of modern connection systems and hybrid construction methods in mass timber buildings:

- **Performance of STS installed and used in variable moisture conditions.** This is particularly relevant for cold northern climates with long, severe winters, such as Québec. An experimental campaign has been launched to investigate the behaviour of large-diameter self-tapping screws installed in sawn timber at different stages of drying, including the frozen, green, partially seasoned and air-dry conditions. The goal is to assess the impact of moisture conditions on the screw performance and connection integrity.

- **Prolonged fire resistance of concealed mass-timber connections.** To improve both the aesthetic and fire performance of mass timber construction, connection hardware is often concealed within the cross-section of mass timber elements. This strategy leverages the low thermal gradient across the charred wood to protect metal components from thermo-mechanical degradation. The project focuses on the role of service-induced gaps between wood elements that may allow flame or heat penetration, compromising fire performance. The key outcome will be the development of the design methods and guidelines for modern connections in mass timber constructions, targeting a minimum 2-hour fire resistance rating.

- **Evaluation of mechanical properties of sandwich beams and walls.** The Thermolog® construction product is a composite sandwich beam composed of an expanded polystyrene (EPS) insulating core and facing layers made of ungraded laminated white pine boards of varying thicknesses. This study aims to determine the mechanical properties of the individual components, the composite beam, and wall assemblies made of this product. These values are critical for the development of constitutive or finite element models to enable advanced analysis. The results will form the basis for the performance evaluation and certification of the product to ensure safe and reliable application in future construction projects.

- **Full-scale experimental tests of novel steel-timber hybrid systems.** It is planned to conduct experimental tests at both the component and system levels for TS-EBFs and CR-BTFs in 2025 and 2026. Subsequent to the tests, seismic and wind design suggestions will be developed to supplement Canadian standards and codes.

- **Reliability-based design of connections.** This project aims to calibrate resistance factors for bolted and STS connections designed according to CSA O86-24. Tasks include defining performance objectives, modelling random variables, and calibrating load and resistance factors. The results from this task will enable the design of connections as per the CSA O86 standard to meet the minimum target reliability required by NBCC.

5 – SUMMARY AND CONCLUSION

The main expected results of this project are; 1) effective mass-timber, steel-timber hybrid and composite systems that meet common structural design goals, 2) performance characteristics and design information for the building components, connections and assemblies used in the new generation of wood, hybrid and composite systems, 3) novel timber-steel hybrid structural systems (TS-EBFs and CR-BTFs), and 4) new wind and seismic design guidelines for the innovative timber-steel hybrid buildings. Overall, it is expected that the findings from the research will aid structural engineers in designing timber, timber-steel hybrid, and composite building systems, and included in the future editions of Canadian standards and codes.

6 – ACKNOWLEDGEMENT

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