4C2B: Century-scale Carbon-sequestration in Cross-laminated Timber Composite Bolted-steel Buildings

Background

To attain net-zero embodied carbon buildings, substituting carbon-intensive materials with sustainable alternatives is crucial. Timber, a viable carbon-storing material when harvested sustainably, provides new opportunities to integrate carbon sequestration within steel frame construction (Figure 1A). This project investigates the use of steel frame structures with diaphragms constructed using cross-laminated timber (CLT), a robust panel with layered dimensional lumber for bi-directional strength (Figure 1B). While relatively recent in North America, CLT has proven a cost-effective and eco-friendly alternative in Europe since the 2000's, notably replacing prefabricated concrete panels in large-scale construction. The use of cross-laminated timber floor diaphragms presents unaddressed engineering design challenges, including ability to integrate composite action with the steel beams, seismic performance of the diaphragm, and connections that facilitate energy dissipation and Design for Deconstruction.

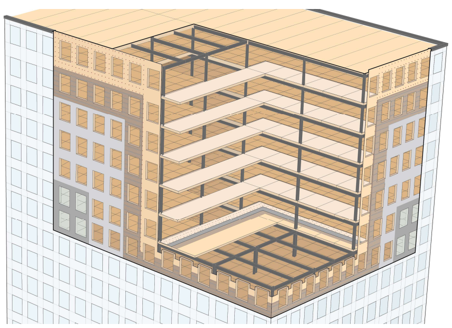

Figure 1A: Model of composite structure of Bolted-steel with Cross-Laminated Timber (CLT) floor & non-structural CLT building envelope layers

Figure 1B: Plank Testing of Novel CLT Lay-ups

Steel+CLT Hybrid Buildings

Concrete and steel reinforcement often contribute approximately 50% of the embodied carbon in typical commercial buildings (Figure 2). Substituting concrete diaphragms with lighter and more sustainable alternatives, such as cross-laminated timber (CLT), holds potential for significantly reducing embodied carbon emissions. This reduction extends beyond mitigating emissions from concrete, steel reinforcement, and corrugated decking, as it also results in a decreased floor load, consequently lightening the steel frame and foundation weight. The utilization of CLT diaphragms not only lessens carbon emissions, but also allows for carbon sequestration. In addition, structural steel is increasingly fabricated from 100% recycled steel using 100% renewable energy, and the steel and CLT planks may be designed to be re-used rather than scrapped or recycled. Opting for steel framing with CLT diaphragms (steel+CLT) is a promising approach to swiftly achieve net-zero buildings on a consequential scale by 2050.

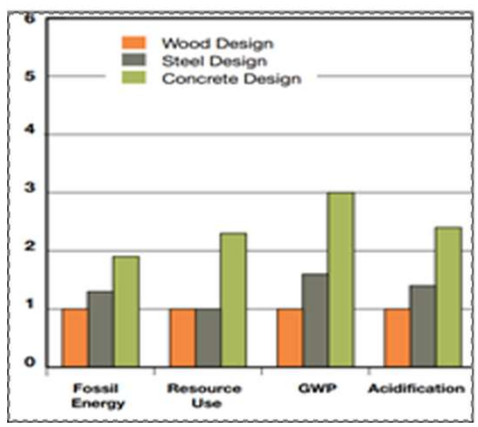

Figure 2: Sustainability of Construction Materials

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Objectives:

Develop new structural system integrating cross-laminated timber floor diaphragms within steel frame structures using Design for Deconstruction, novel wood species and lay-ups, and bio-based non-structural materials to achieve net-zero construction

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Innovations

Design for Deconstruction (DfD)

Commercial buildings typically last 30-60 years and are often taken down not due to lack of structural integrity but rather due to no longer being of use to the owner. Design for Deconstruction coupled with carbon sequestration provide key opportunities for creating carbon-negative designs, which can extend the reduction of carbon emissions through increasing the number of reuses. Design for Deconstruction not only aids sustainability, but also enables more adaptability over the life of the structure. This research investigates efficient approaches for achieving composite action between the steel and CLT diaphragms that incorporate Design for Deconstruction using innovative through-bolted connections.

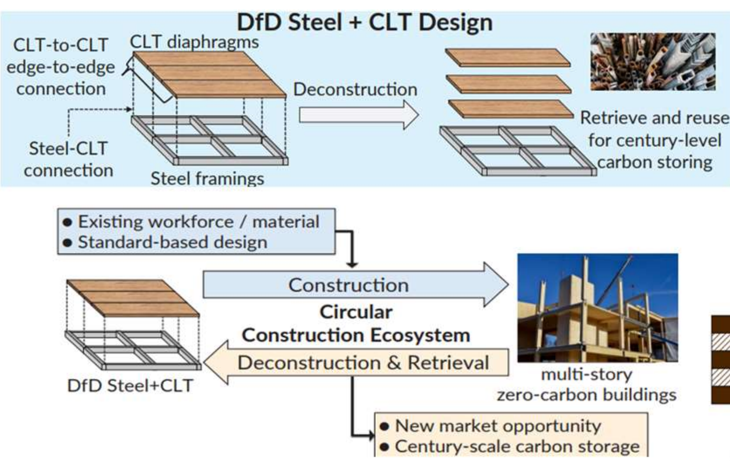

Figure 3A: Model of Deconstruction for CLT diaphragms

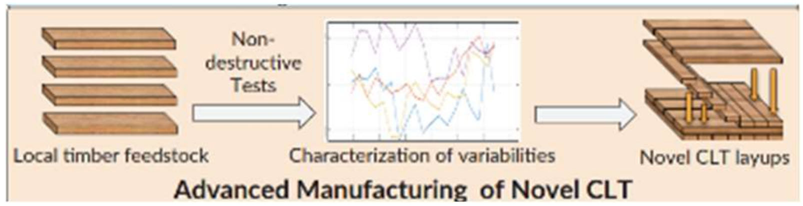

Figure 3B: Model for the Advanced Manufacturing of CLT Layups

Advanced Manufacturing of Novel CLT Layups

Advanced manufacturing techniques enable use of local materials and help satisfy fire, weather, vibration, acoustic, and DfD requirements. This research characterizes the variations in CLT performance based on the variations in local timber feedstocks. A reinforcement learning (RL) framework is being developed such that artificial intelligence (AI) agents can autonomously learn how to optimize CLT layups (e.g., the number of layers, the organization of layers with different grades) to minimize the variations in the mechanical performance of CLT diaphragms (Figure 3B). The proposed work will draw out the full potential of CLT diaphragms, such that the proposed steel+CLT system yields optimal performance. In addition, the optimization technique allows the use of local timber feedstocks, leading to the reduction in embodied carbon emissions during transportation to the construction site.

Structural Integrity

CLT-Steel Connectors

The CLT-Steel connector uses a through-bolt connector inside a steel sleeve to help protect the CLT from localized bearing stresses (Figure 4A). The single-bolt test investigates the slip critical and bearing strength of the connector to facilitate composite action between the CLT and steel beam for gravity loading and in-plane cyclic diaphragm loading, creating an innovative connection solution that promotes DfD (Figure 4B). These tests include different bolt sizes, number of CLT layers, and sleeve dimensions. Additional tests include Composite Beam Tests and Diaphragm Tests (Figure 4C), which are being conducted to observe connection, beam and diaphragm stiffness, strength, and ductility to enable development of associated design equations.

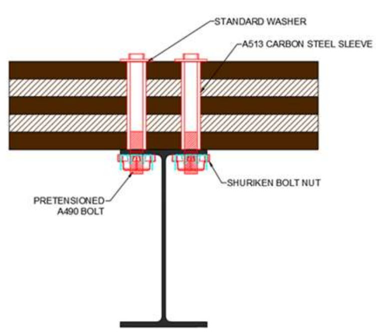

Figure 4A: Proposed Bolted Connections

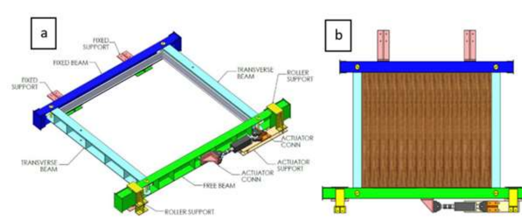

Figure 4C: Diaphragm Test Setup

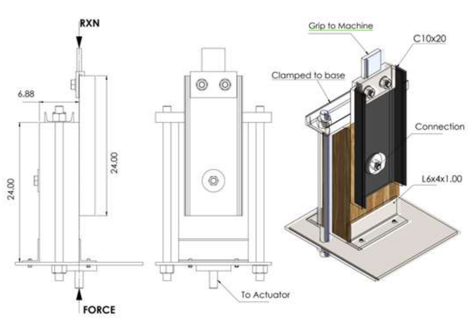

Figure 4B: Single Connector Pushout Test Setup

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