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BENCHMARK LIFE-CYCLE AND CONSTRUCTABILITY ASSESSMENT OF COMPOSITE STEEL-TIMBER SYSTEMS

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ABSTRACT: This study presents comparative structural designs and life cycle assessment of the impact of composite steel-timber flooring systems in mid- to high-rise construction. Four architecturally consistent benchmark buildings are analysed, two each with steel-concrete and steel-timber structural systems. Additional comparisons are made between a steel-timber composite and a steel-timber hybrid structural system. The life-cycle assessment focuses primarily on the structural system and its direct impacts, assuming building use and architectural elements remain the same across the structural systems. The Life-Cycle Assessment evaluates global warming impact, total embodied energy, material quantities, combined life-cycle energy, and energy consumption, primarily relying on the commercial LCA software Tally. Contextualization is provided of the steel-timber composite system within recent studies on constructability of mass timber and other modular construction techniques. The study finds significant benefits to the steel-timber composite systems from a life-cycle assessment perspective, with room for further benefits if the systems can be better optimized for vibration.

KEYWORDS: LCA, Composite, Constructability, Mass Timber, Steel.

1 INTRODUCTION

Despite significant advancements in the acceptance and recognition of the benefits of mass timber construction, the building industry in the United States is still dominated by steel and concrete structural systems for non-residential and multi-story residential construction (Figure 1).

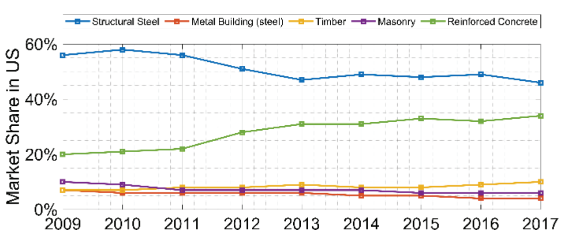

Figure 1. Market share by construction material in the US based on building footprint area. Data from Dodge Analytics [1].

One promising avenue to increasing the use of mass timber in commercial construction is through replacing concrete floors in steel buildings with mass timber floors. This approach has been successfully applied in hybrid steel-mass timber systems, but the structural benefits of the composite behaviour of the mass timber with the steel framing has typically been ignored, despite some recent studies demonstrating feasibility (e.g., [2], [3]). Given the structural benefits, there is a need to quantify the potential global impacts of using composite steel-mass timber systems relative to other common structural systems. In parallel with a separate experimental study being conducted by the authors [4], the objective of this study is to provide benchmark life-cycle assessments (LCA) of composite steel-mass timber systems relative to other traditional structural systems.

2 BENCHMARK BUILDINGS

The focus of this study was on mid- to high-rise commercial and mixed-use buildings. Steel-timber composite (STC) and steel-concrete composite (SCC) structural systems are compared. The steel-timber structural system consisted of steel columns and floor beams with cross-laminated timber (CLT) spanning between floor beams to form the floor system. The benchmark buildings are architecturally consistent, with one seven story building and one eighteen story building for each structural system. All buildings have a story height of 3.66 m and column spacing of 9.14 m (Figure 2) and are assumed to have the same usage (business) and architectural elements. The geometric constraints for the design of the structure were in accordance with IBC 2021, and specifically met the requirements for Occupancy B, Type IV. Total building heights were 25.6 m and 66 m in

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the 7-story (conforming to Type IV-C) and 18-story (conforming to Type IV-A) structures. Similarly, 9.1 m by 9.1 m bay sizes were chosen to maintain dimensional consistency in framing plans. Spans of 3.0 m and 4.6 m were chosen for the concrete and timber slabs respectively.

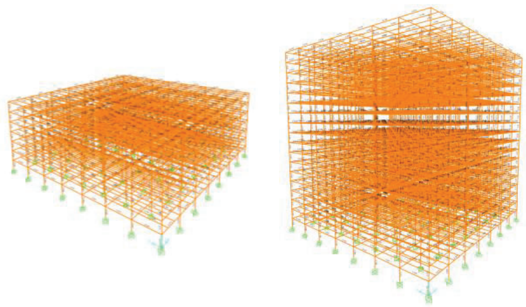

Figure 2. Structural layout of the (left) seven story, and (right) eighteen story benchmark buildings.

2.1 STRUCTURAL DESIGN METHODS

Buildings were structurally designed for gravity loads only, assuming an office occupancy to determine appropriate live loads (3.11 kPa) and superimposed dead load (0.5 kPa). Deflection criteria was considered, including superimposed load deflections and live load deflections. Vibration due to walking excitation was also considered based on a limit of $a_p/g \leq 0.005$, using AISC Design Guide 11 [5] for the steel-concrete floor systems and the US Mass Timber Floor Vibration Design Guide [6] for the steel-timber floor systems. CLT floor slabs were additionally sized to meet fire resistance requirements. Both steel-timber and steel-concrete floor systems utilized a normal weight concrete topping slab, as this is common practice to mitigate vibration, meet acoustical requirements, and support flooring products.

Structural designs were performed using a combination of manual calculations and structural design software, specifically CSI ETABS. Roof and floor beams were first sized for gravity loads, including dead and live loads, and deflection and vibration criteria, using the relevant material-specific design standards. The manually sized floor and roof beams were then defined in the structural analysis software along with the gravity loads, and the software was allowed to optimize the column designs accordingly. Foundations and lateral force resisting systems were not considered.

For steel-timber composite designs, for which no design guides yet exist, a method consistent with steel-concrete composite design was utilized [7]. A partial composite action corresponding to 25% was assumed to be achieved by self-tapping screws transferring interfacial shear that connect steel floor beams/girders and CLT panels. The flexural capacity of a STC member was resultant of the internal resisting force couple and the force couple moment arm. The compressive capacity of the CLT was a summation of the compressive strength of each lamination, which is dependent on orientation to the beam span and therefore varied with panel orientation. Because the STC members were designed to 25% composite action, the depth of the compression block corresponded to 25% of the compressive strength of the full CLT section. Tension in the CLT was ignored in this study; therefore, tension capacity was resultant of the tensile capacity of the steel wide-flange sections alone.

2.2 STRUCTURAL DESIGN RESULTS

Typical beam and girder cross-sections for the STC and SCC systems are shown in Figure 3. All STC floor systems were composed of 5-ply Southern Pine CLT with 38 mm normal weight concrete topping. Typical floor framing consisted of W18x40 beams, framing into W24x55 girders. Typical roof framing consisted of W14x22 beams, framing into W18x35 girders. Columns in the 7-story STC varied in size between W12x26 and W14x61, while in the 18-story buildings, columns varied in size between W12x30 and W14x145. All SCC floor systems were composed of a 127 mm slab on a 51 mm deep 20-gauge steel deck. Typical floor framing consisted of W12x26 beams, framing into W21x50 girders. The roof decking systems were 89 mm slabs on a 38.1 mm deep 20-gauge deck. Typical roof framing consisted of W12x19 beams, framing into W18x40 girders. Floor beams and girders for the SCC system were also designed to approximately 25% composite action. Columns varied in size between W12x30 and W12x65, and between W12x30 and W14x159 for the 7-story and 18-story buildings respectively.

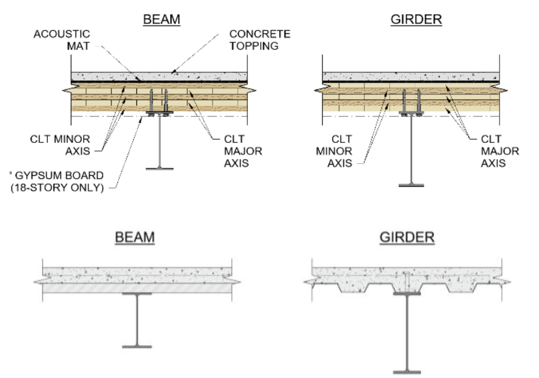

Figure 3. Typical cross-sections for (top) steel-timber composite and (bottom) steel-concrete composite structural floor systems.

The inclusion of the vibration design criteria tended to dominate the beam member for the STC designs relative to the strength and deflection criteria, despite the use of service level live loads (0.6 kPa) and assumption of 100% composite action for vibration design. With the chosen beam span of 9.1 m, the STC beams with 38 mm NWC had a utilization rate (ratio of usage to capacity) of 0.98 for vibration, but only 0.57 and 0.62 for strength and deflection criteria respectively. A parametric study was conducted to evaluate the role of vibration in controlling

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member design for a range of beam spans (Figure 4). The parametric study showed that longer beam spans, and increased topping thickness, both helped balance the utilization ratio across all three criteria. More rigorous studies are needed, but the preliminary results highlight the importance of the architectural layout of the building in optimizing the utilization of steel-timber composite systems.

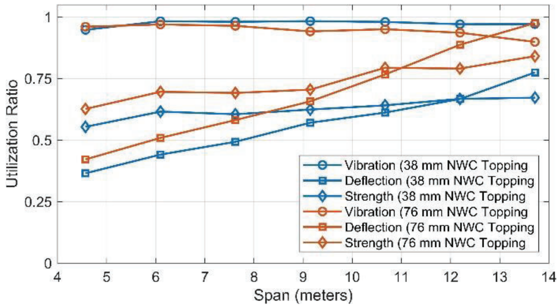

Figure 4. Utilization ratios considering vibration, deflection, and strength criteria for STC beams with 38 mm and 76 mm topping slabs and variable CLT floor spans.

2.3 STEEL-TIMBER COMPOSITE VS HYBRID

While steel-timber composite floor systems are a relatively new structural system, steel-timber hybrid (STH) floor systems have become relatively popular in mass timber construction. In the STH system, CLT floor slabs are still mechanically fastened to the steel beams and girders, but the composite behaviour is ignored in the design. The current study provided an opportunity to evaluate the benefits of composite design by taking the beam sections required to meet the vibration criteria and comparing their utilization rate for strength and deflection criteria both with and without consideration of composite action (i.e., 25% composition action compared to 0% composite action) for two different concrete topping slab thicknesses. The results showed that if the composite action were ignored in the design, the deflection and strength utilization ratios began to govern the design over the vibration criteria. For spans greater than 6.1 m, utilization ratios for deflection criteria were greater than 1.0 (Figure 5), indicating the steel beams would need increased cross-sections if designs assumed hybrid performance. In summary, explicitly accounting for composite action in the steel-timber floor systems likely provides marginal benefits if vibration criteria is part of the design, but stands to provide much greater benefits if vibration criteria is not necessary in the design.

3 LIFE-CYCLE ASSESSMENT

3.1 METHODS

The environmental impacts of the STC and SCC systems were quantified using LCA. The LCA was constrained to include cradle-to-gate (which measures the environmental footprint up to the point where it leaves the manufacturing facility), construction transportation, and end-of-life impacts [8]. The LCA did not include operational use of the buildings, nor the environmental impacts of on-site construction, as these are assumed to be nominally independent of the structural system relative to the impacts in the other stages. The building life expectancy was taken to be 60 years for all structures. Biogenic carbon was accounted for in the cradle-to-gate phase. The study includes raw materials supply, transport, manufacturing, construction process, and end of life stage.

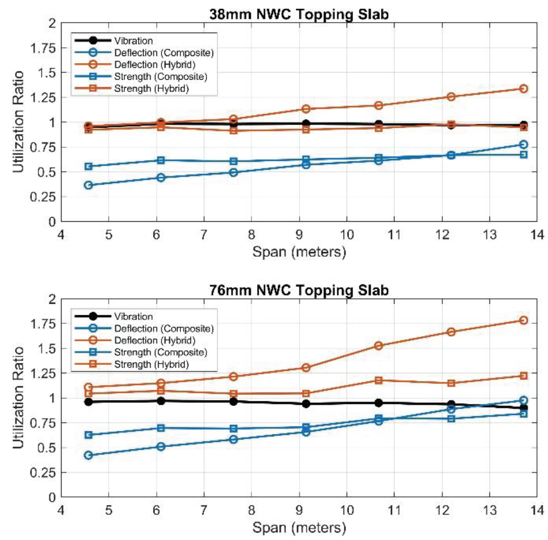

Figure 5. Utilization ratios for composite and hybrid STC designs considering vibration, strength, and deflection with 38 mm and 76 mm topping slabs for variable CLT spans.

To conduct the LCA study, the structural analysis models for the benchmark buildings that were generated using the structural design software ETABS were then imported into Revit, where the Tally Revit application was used to perform the LC assessments, which is widely used for comparative building LCA ([9], [10]). The outputs considered are mass, embodied carbon, and embodied energy, both as raw values and normalized by the net floor area (28,679 m^2 and 73,746 m^2 for the 7- and 18-story buildings respectively) or material mass.

The life cycle inventory (LCI) was compiled using Revit's built-in capabilities to calculate total material quantities based on the defined structural sections and geometries. Tally leverages the commercial GaBi 8.5 database along with the EC3 Environmental Product Declaration (EPD) database to perform LCA. Review of the environmental impacts assigned to the various materials used from the GaBi database found that a few manual adjustments were needed. Specifically, the generic CLT in the GaBi database reported environmental impacts were not representative of the EPDs from US CLT manufacturers (primarily with respect to the embodied energy), and further, the database lacked a suitable rubber material analogous to an acoustic mat. The CLT environmental impacts reported by Tally were therefore scaled to match the unit environmental impacts reported in the EPD from a CLT manufacturer in the Southeast US. A similar

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procedure was used for the acoustic mat, adjusting the environmental impacts of a rubber high-traffic commercial flooring product to match the EPD from a US-based acoustic underlayment mat.

Several assumptions were required to complete the LCA analysis, most of which followed the assumptions standard to the Tally software. It was assumed that all individual elements have life spans greater than or equal to the building service life; essentially ignoring repair and replacement activities. Hot-rolled steel and steel decks were assumed to have been fabricated with 100% and 28% recycled material, respectively. Average transportation distances for each product for the US as estimated by Tally were used rather than tying transportation distance to a specific site. This resulted in transportation distances of 332 km for CLT, 431 km for the steel, and 24 km for concrete materials. End-of-life scope varied by material. For CLT, 14.5% was assumed recovered, 22% incinerated with energy recovery, and 63.5% landfilled. Steel was assumed to be 98% recovered. Concrete was assumed to be 55% recycled and 45% landfilled.

3.2 LCA RESULTS

LCA results are presented for the 7-story steel-timber composite (STC), steel-timber hybrid (STH), and steel-concrete composite (SCC), and 18-story steel-timber composite (STC) and steel-concrete composite (SCC).

The total mass varied only slightly across the various structural systems as presented in Figure 6. The STC system had the lowest mass for both stories considered, but the total mass in the 7-story STH and SCC were only 2% and 11% higher than the 7-story STC. Only a 4% increase in total mass was observed in the 18-story SCC relative to the 18-story STC. Floor systems, including the CLT, acoustic mat, metal deck, concrete slab and topping, and gypsum, accounted for between 84% and 87% of the total mass of the structure for all systems considered. Ignoring the composite action in the STC resulted in a 12.7% increase in steel framing mass, but this difference would be significantly higher if vibration criteria were ignored and utilizations were optimized for strength and deflection criteria only.

Differences in environmental impacts, specifically embodied carbon (Figure 7) and embodied energy (Figure 8) were more pronounced between the structural systems for the scope considered (cradle-to-gate, construction transportation, and end-of-life). Total embodied carbon was lowest in the STC, with the SCC system containing almost 200% of the total embodied carbon for the 7-story building, and 171% for the 18-story. Conversely, embodied carbon and embodied energy were 40% and 22% lower in the 18-story STC compared to the 18-story SCC respectively. Most of these differences are driven by the choice to include biogenic carbon in the CLT embodied energy, which results in a net negative effect from the CLT. The differences between the 7-story STC and STH are less pronounced, with only 10% higher embodied carbon in the STH compared to the STC. The high embodied carbon density of steel is clearly evident, with the steel framing accounting for between 41% and 82% of the total embodied energy in each structural systems despite only accounting for less than 15% of the total mass.

Environmental impacts for the studied structural systems were also quantified for each considered LCA stage in terms of embodied carbon (Table 1) and embodied energy (Table 2). According to Table 1, carbon sequestration of lumber products causes the largest portions of the STC structures' carbon footprints to appear at the end-of-life stages. This is because extraction of lumber avoids net carbon emissions due to the large amount of carbon sequestered in lumber. Conversely, the SCC structures' carbon footprints are heavily front-loaded. This is due to the production stages accounting for the bulk of SCC structures' embodied carbon. Conversely, the end-of-life and post-life stages of concrete are associated with the material's environmental credits, due to recycling and re-use. Similarly, the energy required to produce CLT is relatively low compared to the energy required to produce concrete and metal decking. However, the STC structures have no avoided energy burdens throughout their life cycles; whereas, the SCC structures have a net negative embodied energy value in the reuse and recycling phase.

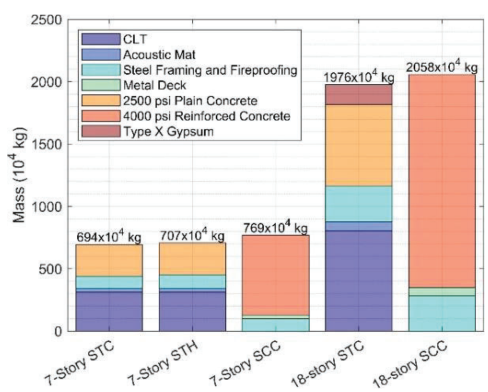

Figure 6. Total mass by structural system and material type.

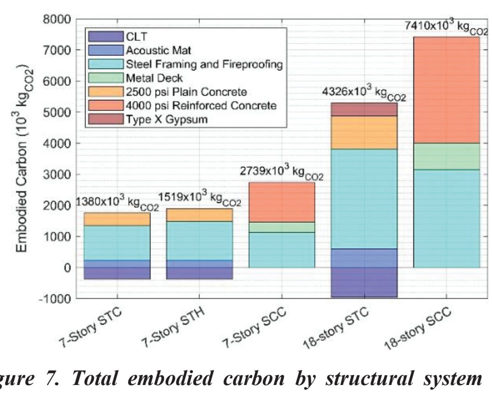

Figure 7. Total embodied carbon by structural system and material type.

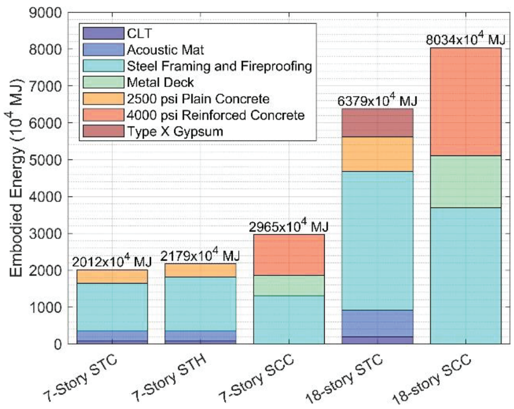

Figure 8. Total embodied energy by structural system and material type.

The net effect is that embodied energy is also heavily concentrated in the Production stage for all systems (Table 2), with the lower energy requirements for CLT production reflected in the slightly lower concentration of embodied energy for the STC and STH systems in the Production stage relative to the SCC systems.

Table 1. Distribution of embodied carbon in each structural system by LCA stage.

Structural System	LCA Stage			
	Production	Transportation	End-of-Life	Post-Life
7S STC	-120%	5%	195%	20%
7S STH	-101%	5%	177%	19%
7S SCC	96%	1%	10%	-8%
18S STC	-83%	4%	161%	17%
18S SCC	96%	1%	10%	-7%

Table 2. Distribution of embodied energy in each structural system by LCA stage.

Structural System	LCA Stage			
	Production	Transportation	End-of-Life	Post-Life
7S STC	90%	2%	6%	2%
7S STH	90%	2%	5%	2%
7S SCC	96%	2%	8%	-6%
18S STC	89%	2%	7%	2%
18S SCC	96%	2%	8%	-5%

4 CONSTRUCTABILITY

Beyond biophilic aesthetics and a decreased environmental impact, the use of mass timber panels in composite timber-steel floor systems has become increasingly attractive to owners, installers, and designers because of its benefits for on-site safety and scheduling efficiencies [10]. These benefits are largely attributed to the modular installation process, which decreases the number of required employees and can reduce construction schedules by 30 to 50 percent [11]. Given the potential constructability benefits, there is a need to quantify the potential labour hours and schedule duration of composite steel-mass timber structural systems relative to other common structural systems.

Unfortunately, such studies are difficult due to lack of building-specific construction data and lack of established modelling methods, although a few limited studies do exist. Bhandari et al. [12] evaluated construction duration per 1000 m^2 of actual buildings that used CLT and reported 10 hybrid CLT with concrete mid-rise buildings were constructed in under 4 weeks. However, no steel-CLT hybrid buildings were included in the dataset. Brisland et al. [13] found daily productivity rates between 67 m^2 and 111 m^2 for multi-story mass-timber buildings. Mirando and Onsarigo [14] tracked construction progress in a multi-story mass timber building and measured a productivity rate of 33 m^2 per person-day, a rate nearly three times that estimated by the authors for cast-in-place concrete based on literature reviews. Real-time data was collected through daily reports generated by the onsite foreman, digital photographs taken by two time-lapse cameras placed on the jobsite, and a 360-degree construction photo documentation system. Tavares et al. [15] evaluated life-cycle effects of prefabrication across a range of building materials and reported that pre-fabrication reduces construction time by between 33-50%. The study did not explicitly consider steel-timber hybrid or composite structures though, and primarily focused on low-rise buildings. Reduced waste, material use, and environmental impacts were also noted in prefabricated structural systems. Mofolasayo [16] noted the benefits of modular construction were closely tied to transportation distances, with long transportation distances limiting the benefits of modularity. In this regard, the constructability of steel-timber composite may be negatively affected relative to steel-concrete composite, given the longer transportation distances typically associated with mass timber relative to concrete (see Section 3.1).

In summary, a literature review of constructability reveals clear benefits to modular construction, which steel-timber systems would benefit from, in terms of costs, erection time, and environmental impacts. These benefits are limited if transportation distances are long. Constructability data is still relatively scarce however, particularly for steel-timber hybrid or composite systems.

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Future efforts are needed to collect research-suitable data during actual construction projects.

5 CONCLUSIONS

Structural designs for gravity loads were completed for functionally-equivalent 7-story and 18-story buildings with steel-timber and steel-concrete structural systems. Lateral force resisting systems and foundation designs were ignored at this time. Life-cycle assessment was then performed on the structures using the material inventories from the structural designs and environmental product declarations primarily obtained through the GaBi database integrated into the Tally LCA software. The following conclusions can be formed from the analysis:

1. Vibration dominated the sizing of steel beam elements in the floor for the considered spans and spacings, with steel members underutilized for strength and deflection criteria as a result. Better understanding of vibration behavior of steel-timber composite systems is needed to develop more optimized design guidelines and enable more efficient overall designs.
2. CLT panel depth was controlled by fire-resistance requirements, resulting in 5-ply panels for all systems. The fire requirements led to an optimal floor panel span of 4.5 meters, demonstrating how secondary design considerations such as vibration, fire, and even acoustics can oftentimes control the overall framing layout in steel-timber composite systems.
3. Significant advantages were found to be associated with STC design relative to non-composite (hybrid) design, with larger beam sizes being needed for the hybrid design relative to the composite design.
4. Embodied carbon and embodied energy were both lower in the steel-timber composite systems relative to the steel-concrete composite systems, with differences in the 18-story buildings as much as 40% for embodied carbon and 22% for embodied energy.
5. The environmental impacts of all structural systems were disproportionately driven by the steel framing, despite its low mass relative to the other building materials.
6. Steel-timber composite structural systems are expected to be advantageous from a constructability standpoint due to the potential for modular construction, but relative to other modular construction techniques, may still be limited by the longer transportation distances associated with steel framing and mass timber procurement.

While this study provides an initial life-cycle assessment of steel-timber structural systems, many knowledge gaps remain. Better guidelines for vibration design of steel-timber composite systems are needed. The relative impacts for lateral force-resisting systems and foundations are also needed. And finally, attempts to evaluate constructability would greatly benefit from focused studies tracking scheduling and manpower for real construction projects.

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