PROMOTING CIRCULARITY OF BUILDING MATERIALS THROUGH NOVEL STRUCTURAL SYSTEMS FOR ADAPTIVE, DECONSTRUCTABLE HYBRID STEEL-CLT DESIGNS

Jerome F Hajjar, Northeastern University, Boston, USA
Sanjay Arwade, University of Massachusetts – Amherst, Amherst, USA
Baiyu Chen, Northeastern University, Boston, USA
Matthew J Eckelman, Northeastern University, Boston, USA
Michael Kane, Northeastern University, Boston, USA
Michelle Laboy, Northeastern University, Boston, USA
Jack Lesko, Northeastern University, Boston, USA
Fiona O'Donnell, Swarthmore College, Swarthmore, USA
Kara Peterman, University of Massachusetts – Amherst, Amherst, USA
Nathan Post, Northeastern University, Boston, USA
Mark Webster, Simpson Gumpertz & Hager, Waltham, USA

Abstract

Concrete and its steel reinforcement account for up to 50% of the embodied carbon emissions in typical high-rise commercial buildings. Replacing concrete floors with cross-laminated timber (CLT) can lead to dramatic reductions in embodied carbon, and these reductions can be extended further if steel and CLT elements can be recovered, potentially recertified, and reused in another structural application. Vibrations and noise travel more easily through lightweight timber diaphragm floors compared to concrete slabs. These vibrations are typically reduced by pouring 1-2" of concrete on top of mass-timber floors, which impair the adaptability of the floor-diaphragm systems for deconstruction and reuse. The challenge is to design a system of connections and floor assemblies that provides the requisite structural performance, adherence to Type IV-B building codes for vibration, acoustics, and fire, while still enabling deconstruction and circularity of the structural materials.

This submission will present an innovative design strategy for deconstructable, carbon storing buildings that can enable large-scale uptake of CLT into steel-framed commercial projects. Attendees will learn about the engineering and architectural challenges in designing hybrid steel-CLT buildings without typical concrete toppings, and how the proposed design uses novel connections that allow for rapid deconstruction that reduces costs associated with building material reuse. We will also cover the functional structural performance achieved by utilizing high-strength bolted connectors in steel-CLT hybrid structures, supplemented by experimental tests results, and how these results can be used to support major changes to code requirements that would enable deconstructability of an important class of buildings where it is currently rarely done. Finally, the presentation will guide attendees through the environmental benefits of this approach through application of life cycle assessment, but using a dynamic accounting framework that reveals that CLT must stay in use for more than 60 years in order for the prototype building to achieve net zero embodied carbon, either in the original building or reused in a new structure.

Introduction

The timing of carbon emissions reductions strongly influences the effectiveness of climate change mitigation actions, underscored by the concept of the "time value of carbon" (Parisa et al., 2022). Early stage emissions reductions or sequestration of carbon have a greater effect in keeping global warming well below the target of 2°C above pre-industrial levels than reductions that occur later in time (Fuglestvedt et al., 2018). Delayed action may result in a higher peak in temperature increases, and increased future costs (Matthews et al., 2023), highlighting the recent emphasis in reducing upfront carbon and sequestration. At the same time, early actions must be long-lasting enough that the sequestered carbon stays out of the atmosphere and is not re-emitted. One of the largest opportunities for long-term carbon storage is in buildings and infrastructure (Arehart et al., 2021), where forward-looking design and circularity are key to prolonging the useful life of buildings and building materials. This research examined design strategies that both reduce upfront emissions—accelerating the uptake of biogenic carbon in commonly high-carbon steel structures—while simultaneously extending the timeline of carbon storage and reducing end-of-life emissions through design for adaptability and deconstruction (DfAD).

Reductions Through Long-term Biogenic Storage

Bio-based products, including wood, comprise approximately 50% carbon by dry mass, presenting a means to store carbon in buildings (Churkina et al., 2020). Timber buildings are promoted as effective carbon sinks, with studies showing that cross-laminated timber (CLT) buildings have 70% less embodied carbon than reinforced concrete structures. (Nakano et al., 2020). Although mass timber construction in the United States is increasing, its often higher costs, limited production capacity, relative unfamiliarity among structural engineers, and larger member size may limit its use. Hybrid buildings may offer more competitive ways to introduce wood products and other biogenic materials into more buildings rapidly in the short term. In recent years, the popularity of light wood framing construction on top of a steel or concrete podium has surged, because this type can be built much quicker than all-concrete or all-steel construction and thus may lead to lower costs (WoodWorks, n.d.). Despite this cost advantage, light wood framing is less physically durable and less architecturally adaptable than traditional construction methods, leading to early demolition and limiting its potential for long-term carbon storage. There is an urgent need for design strategies that extend the useful life and value of buildings, and/or their components, and facilitate their deconstruction and reuse. However, direct reuse of timber is challenged by the absence of design considerations for deconstruction, and the need to recertify the quality and structural integrity of salvaged timber for reuse in new projects (Chúláin et al., 2023).

Reductions Through Deconstruction

Conventional building demolition methods typically produce substantial waste volumes that end up in landfills, exacerbating greenhouse gas emissions and discarding potentially reusable material resources (Wu et al., 2019). Recycling and reuse lower emissions by reducing the demand for new materials. Diverting waste from landfills can reduce global methane (CH_4) emissions, a greenhouse gas produced from the anaerobic decomposition of organic waste. Design for Deconstruction (DfD) anticipates and facilitates non-destructive methods of disassembly that allow recovery and reuse of materials in other buildings. “De-construction,” described as “construction in reverse” (Kanters, 2018), requires innovative strategies to extend the life of structural components and reduce future end-of-life carbon emissions. Future deconstruction comes with uncertainties about future markets, yet many of these strategies have low upfront cost. Furthermore, because DfD facilitates the disassembly and recovery of materials by part, avoiding damage at the end of their useful life, it reduces costs by ensuring that valuable materials can be salvaged and repurposed. The concept, which originated in the early 1990s, aligns with circular economy principles resulting in robust body of research and guidance (Eckelman et al., 2018). DfD strategies have considerable potential to lower carbon emissions in buildings.

Accelerating Upfront Reductions with Steel-framed Buildings

Structural steel has been established as the primary framing material for non-residential buildings in the United States, with over half of the annually constructed square footage framed in structural steel (American Iron and Steel Institute, n.d.). Although concrete remains a strong competitor, advances in steel production and skilled labor makes it a preferred choice in large commercial buildings in the United States. This is primarily due to its mechanical properties, construction efficiency, and mature supply chains. Unlike mass timber, steel can achieve desirable long spans with relatively limited floor depth, which allows developers to maximize the number of floors and thus floor

area within a regulated maximum height. Compared to concrete, steel's shorter construction time means faster leasing revenue. Despite steel's high embodied carbon per unit of weight, the industry is progressively promoting and adopting sustainable practices. Structural steel manufactured domestically comprises, on average, 93% recycled content. Over the long life of buildings, steel is not subject to the strength reductions that timber can suffer over time, making it a natural candidate for DfD structural applications. However, steel framed buildings complicate their deconstruction potential due to the common use of composite floors made of steel corrugated decking and cast-in-place concrete slabs. Studies estimate that concrete slabs constitute between 27% and 72% of total embodied carbon, with alternative slab designs like voided slabs reducing emissions by up to 34% (Omar et al., 2014; Paik et al., 2019). Incorporating supplementary cementitious materials and recycling practices can partially reduce these emissions; however, their use is limited by current building codes. Developing cost-effective and carbon-negative strategies to replace the floor system in steel buildings with biogenic materials, while maintaining steel's advantages of structural efficiency, recyclability, and cost in the structural frame, could accelerate the transition to next zero carbon structures.

Prototype Design Strategies

This research explored the use of deconstructable CLT floors to replace typical concrete slabs used in medium- to high-rise buildings in the US. CLT floors are very compatible with steel frame buildings, and their biogenic carbon content has the potentially to offset the carbon emissions of steel frames while simplifying and speeding up construction. However, when replacing concrete decks with CLT it is important to consider the many advantages and non-structural functions of concrete floors in steel structures. The mass and stiffness of concrete provides acoustic isolation, fire resistance, and helps dampen structural vibrations. Concrete and steel complement each other, with steel providing tensile strength and concrete adding compressive strength, leading to improved resilience (Kuang et al., 2014). The composite action of steel and concrete contribute to cost-effectiveness through reductions in beam sizes. However, disadvantages such as differential thermal expansion can lead to debonding, while concrete's susceptibility to moisture can corrode embedded steel, impacting durability (Niu, 2024).

Although CLT has been used to replace traditional concrete slabs in some recent innovative steel-CLT buildings, more detailed research and structural testing is needed to provide equivalent or better performance than concrete in all these areas, and to account for their embodied carbon. Nonetheless, CLT has significant advantages. Unlike concrete which must be formed, shored, and allowed to cure before it is structurally active in the building, the CLT floor can be placed relatively quickly, entire floors in a day as opposed to a week or more of partial curing, and once installed, it is immediately able to carry loads and brace the structure, reducing the need for temporary bracing. Furthermore, this research shows that the ability to brace the steel frame combined with the longer spanning capacity of the CLT up to 60 ft. panels could reduce the number of steel beams in the direction that the CLT spans (Figure 1) effectively reducing embodied carbon by increasing the ratio of timber to steel.

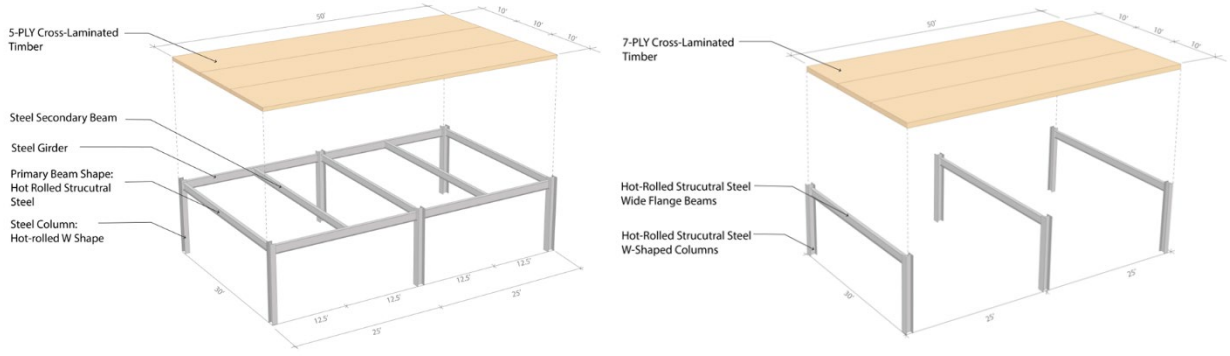

Figure 1. Base (short span) pattern (left), and (b) Stretch (long span) pattern (right).

This research identified opportunities to improve the potential circularity and deconstruction benefits of CLT as a part of a hybrid floor system. Specifically, in recent hybrid structures the CLT is fastened to the top flange of the beam from the underside. This method can be more difficult than fastening from the top and can make deconstruction more difficult and time-consuming, increasing costs and decreasing the economic viability of circular practices. Furthermore, many of these buildings add a cementitious topping to provide code-required fire separation and address acoustics, undoing the carbon benefits of the CLT and potentially damaging its top layer during mechanical methods

of removal. A key innovation toward DfD in this project is the development of novel connector systems that facilitate construction and deconstruction of the CLT, while also achieving composite action to reduce steel sizes. Instead of using numerous long screws that can be physically difficult to remove and potentially damaging to the CLT, inhibiting future reuse, this new design uses bolted connections, fastened from the top through steel sleeves sunk into the CLT, such that the whole floor assembly can be deconstructed rapidly by crews working at each floor level (Figure 2).

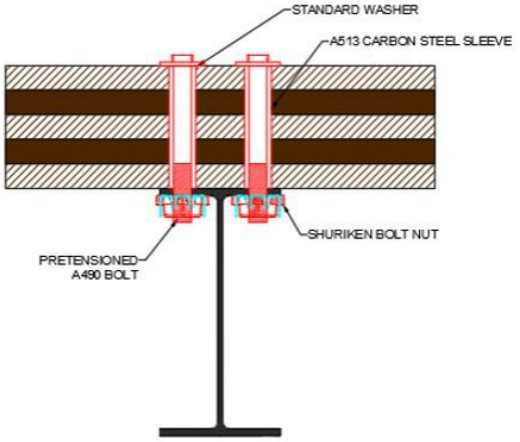

Figure 2. Detail of hybrid CLT-steel bolted connections for DfD

The use of raised floor assemblies has a critical advantage for DfAD for the steel members as well. Steel-framed commercial buildings usually have dropped ceilings hiding ductwork and pipes, some of which penetrate the steel in random locations and compromise its reuse. By prioritizing a floor plenum for delivery of fresh air and other services, the number of penetrations in the steel can be minimized. This has the added advantage of allowing uninterrupted exposure of the CLT in the ceiling, which has aesthetic and biophilic appeal. Although limited exposure to moisture during construction does not affect the structural capacity, CLT that will be used as a finished ceiling requires temporary protection during construction to limit staining. This research found that CLT manufacturers require a vapor retardant layer to be applied on the top of the steel during construction for this purpose. Although DfD strategies prioritize non-bonded layers, this type of membrane on the floor side of the CLT has a protective function during construction and may also protect it during deconstruction to preserve its valuable finish on the exposed ceiling side. Furthermore, unlike removing a concrete topping slab, removal of this membrane is not destructive and enables recovery of CLT for future reuse.

Estimates suggest that well-maintained timber structures can last between 50 to 100 years, depending on factors such as environmental conditions and maintenance practices (Rinne et al., 2022). However, the longevity of timber buildings is often challenged by several factors. including moisture, which can lead to decay and structural failure. The use of CLT as part of a steel-framed building keeps this timber above grade and fully inside the envelope. The raised floor and other layers protects it from small spills. However, having pipes within the raised floor can conceal leaks. Strategies studied in this project included consolidation of plumbing areas, which if carefully planned can have backup gutters and electronic leak detection.

Although CLT has the fire-resistance advantages of mass timber, which chars and burns slowly, the building code in the United States (International Building Code) still requires a 1-inch (25.4) non-combustible layers over a mass timber floor. This requirement is a barrier to reducing embodied carbon with timber floors, as it is one of the reasons that architects commonly add a cementitious layer on top of the CLT in mass timber buildings. This practice makes it impossible to economically recover CLT at the end of life of the building, preventing circularity and leading to landfilling of the resulting demolition debris.

The floor assemblies explored in this research sought to satisfy this requirement with non-cementitious layers that have dual function of fire separation and mass for acoustics, including sand. For the enclosure, the mass timber is the innermost layer, protected by a rain screen, and other protective layers. Studies have shown that mass timber walls control flame spread while exposed on the interior and protected on the exterior with either gypsum board or mineral wool board insulation (Barber & Blomgren, 2023). The research presented in this paper built on these earlier studies by exploring the addition of bio-based insulation on the exterior to increase biogenic carbon. Although physical fire tests are still needed, performance-based fire modeling simulated the physical test conditions. Results showed that

protecting the biobased insulation with two outer layers of gypsum wall board and the CLT on the inside keeps the insulation below ignition temperature. If physical tests confirm this, these findings could move codes towards expand the use of biogenic materials in taller commercial buildings in the United States and accelerating the path to net zero carbon buildings.

Methods

Analysis of Embodied Carbon Considering Circularity

Life cycle assessment (LCA) was used to examine the impacts of each phase of the prototype design: from structure to enclosure to floor assembly, compared to a conventional building design of steel superstructure with cast-in-place concrete floors on steel decking, following standards EN15978 for whole-building LCA and EN15804 for individual building products. The functional unit of comparison was 360,000 gross square feet of commercial floorspace in 12 stories that would meet building codes for energy, seismic resistance, fire, acoustics and vibration. In comparing the floor systems, the criteria for the performance implicit in the functional unit included (a) structural design loads that allow for use adaptability, (b) a minimum 1-inch (2.54 cm) non-cementitious non-combustible layer on the CLT floor to meet the prescriptive code requirement for fire separation, (b) acoustic layers that achieved the required minimum Sound Transmission Class (STC) of 50 or higher and an Impact Insulation Class (IIC) of 50 or higher, (c) a raised floor that allowed distribution of air and power systems to minimize penetrations of ducts and pipes in steel beams for future reuse of components, and (d) separation layers to meet the code prohibition of concealed combustibles within the floor cavity. Seven floor assemblies were designed based on the WoodWorks inventory of tested assemblies and modified to replace cementitious layers with an equivalent mass of non-cementitious, non-combustible materials (e.g. sand), and compared with LCA.

To make an appropriate comparison between a typical concrete slab and the alternative CLT floor in a steel-framed building truly equivalent, it is necessary to consider non only the structural functions but also other non-structural functions that the concrete performs, including the performance of providing a code compliant path for buildings of this height. Therefore, the models for the steel-CLT prototype include any additional components that help the CLT achieve required levels of performance in fire and acoustic performance (the raised floor and acoustic layers) and other layers that help meet current codes even if it is considered unnecessary for performance (e.g. the 1-inch or 2.54 cm non-combustible layers on the floor). Another important path to code compliance is to have a non-combustible enclosure that meets fire and thermal performance for buildings of this use and type. Therefore, the models include the all the layers of the enclosure for both the conventional steel-concrete and novel steel-CLT hybrid prototype designs.

Both the steel-concrete and prototype steel-CLT designs were modeled in Revit and the LCA was carried out using the Tally plug-in, with EPDs used to supplement novel materials not included in the Tally material library, including GUTEX wood fiber insulation and the Ligna raised floor system. The CLT was modeled using a bespoke forest products model developed at Lawrence Berkeley National Laboratory for eastern white pine CLT (Scown et al., unpublished). This CLT has an embodied carbon value for A1-A5 (including biogenic carbon storage) of -591 kg CO_2e/m^3, compared to -779 kg CO_2e/m^3 from an established EPD for SmartLam CLT derived from spruce. This less negative value for white pine CLT reflects the less efficient forestry operations for this species compared to the more conventional use of spruce for CLT, thus requiring more energy use and higher emissions during harvesting, processing, and CLT manufacturing. Building lifetime assumptions were 100 years, enabled by the adaptive reuse design considerations noted above. Following building decommissioning, reuse of structural steel and CLT (Module D) was modeled with an assumption of 75% recovery, informed by estimates from deconstruction industry stakeholders and the worst case adaptive-reuse scenario considered in Figure 3, below.

Design Criteria

Compliance was assessed in reference to recent codes in the United States that added the new construction Type IV-B. This is the mid-range of three new types (Type IV-A, B, and C) that emerged in the 2021 version of the International Building Code (ICC, 2020), allowing larger buildings to use mass timber as part of the primary structure. Type IV-B allows mass timber buildings up to 12 stories or 180 feet (54.9 m) in height, comparable to the more restrictive construction types usually including steel-concrete hybrids, and comes with requirements for separation of combustibles in floors and enclosure. The comparison included the design of a prototype baseline building in steel-concrete with the typical systems of structure and enclosure used in commercial buildings in the US (Figure 2a). This design was based on the experience of the team's structural engineers working in hundreds of projects across the country, and on the input from well-known enclosure fabricators working on many comparable projects in the

northeastern United States. The inclusion of the enclosure and floor layers necessary for code compliance means that the research adapts the most relevant principles of WBLCA to study innovations of the structural system but excludes other non-structural materials such as interior partitions and finishes (though these are considered in calculating design loads for the building.

The criteria for the design of the enclosure included (1) prescriptive thermal insulation requirements, i.e. combining the required R-value for continuous insulation and cavity insulation for a cold climate (zone 5) in the IBC, and (2) proving non-combustibility through performance-based modeling of material separation strategies to protect proposed combustibles materials (timber fiber insulation board on the code-permitted mass timber substrate) from reaching ignition temperature, which the team defined as meeting testing performance for tall building enclosures.

Testing Plausible CLT Reuse Scenarios

This project focused on both upfront reductions to embodied carbon (biogenic storage) and long-term reductions (through deconstruction). Both require defining scenarios for proper accounting of end-of-life scenarios. The innovations in deconstruction innovations are emerging from the structural side of the research team, which is designing connections between the CLT and the steel for both composite action (to reduce the size of the steel by considering the contribution of the CLT) and novel connectors for deconstruction (from the top of the floor). Part of the goal of the LCA was to understand the amount of CLT with potential for reuse, i.e. how much of the CLT would be intact after first use and deconstruction. To capture the impacts of long-term use adaptability to the reuse of components, the prototype design included programmatic fit out tests to define potential location of plumbing and mechanical penetrations in different use scenarios, including office space and residential conversion. (Figure 3) Each scenario tested the percent of CLT that is cut from the panel, and the portion of panels that becomes unusable for future reuse of components after deconstruction, finding a range of 5-25% of the panels would be unsuitable for reuse in another building; the LCA used the worst-case assumption of 25%. The unusable panels were assigned end-of-life scenarios in the LCA representative of US average waste management for wood demolition debris: 64% landfilling, 22% incineration, and 14% downcycling.

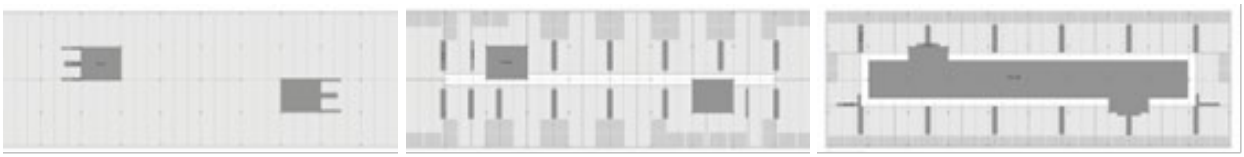

Figure 3. Floorplans of three scenarios of building use with potential areas of penetrations or cuts in CLT (shown in dark gray), for Office use (left), Residential, with deep units (center), (c) Residential with atrium (right).

Carbon Reductions

Figure 4 shows the embodied carbon of the conventional steel-concrete building on the left (gray bar) and the increases and reductions of emissions from each set of design strategies, showing the relative and cumulative reductions approaching net zero carbon. The first strategy on the left is the replacement of concrete floors with CLT, which initially increases embodied carbon when only considering A1-A3 emissions but then decreases markedly in the next step accounting for biogenic carbon sequestration in the CLT in the floor. The following steps include addition of bio-based acoustic mats, CLT replacing the façade, and the new wall assembly needed to meet energy and fire code, all with both the change in A1-A3 emissions followed by the sequestration considered in the long-lived bio-based materials. Because the base prototype building is lighter than the steel-concrete building it is replacing, the structural columns and foundation can be downsized, leading to further embodied carbon reductions. The next big changes come from the optimization of the structural pattern to have a longer span and thicker CLT. Again, the A1-A3 emissions from this substitution lead to an increase while the added sequestration because of the change from 5-ply to 7-ply CLT for the longer spans results in a decrease. The Stretch prototype building is heavier than the base version, so the structural columns and foundation again need to be resized, this time resulting in higher emissions. Finally, deconstruction and reuse of the CLT avoids both the substantial re-emission of biogenic CO_2 at end-of-life from incineration or decomposition in landfills as well as the emissions associated with producing new CLT panels, with a smaller reduction from recovery and direct reuse of the structural steel.

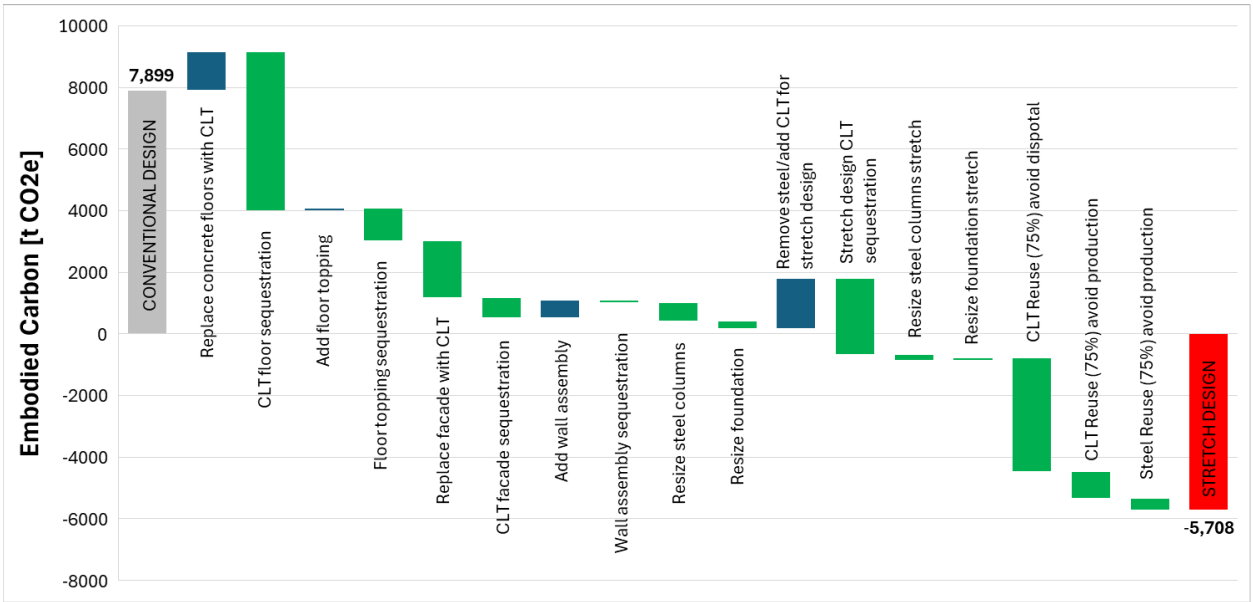

Figure 4. Waterfall chart showing the reductions from the conventional steel-concrete building (left) for each design strategy, culminating in the prototype steel-CLT Stretch design (right).

Conclusions

The results of this research showed how much each of these design iterations improved the embodied carbon relative to the conventional steel-concrete building until nearly reaching net zero carbon. When accounting for biogenic carbon, long-lived building elements, and structural member reuse enabled by deconstructable connections, results show that the structure is significantly carbon negative. The calculation of reductions of each design strategy showed that most of the carbon advantages of the system come from avoiding the use of concrete floors and keeping the biogenic carbon sequestered in the CLT through design for deconstruction and reuse. The feedback received from industry advisors suggests that due to the construction schedule advantages this system has the potential to be more feasible and financially attractive for a wider range of projects than a full mass timber project, although not yet competitive with steel-concrete in terms of cost. The results of the design research and modeling show potential to change regulations related to combustible protection and enclosures, which currently would not allow additional biobased materials, or would negate the carbon benefits with cementitious toppings.

References

American Iron and Steel Institute. (n.d.). Structural Steel Framing. *Build Using Steel*. Retrieved October 15, 2024, from https://www.buildusingsteel.org/build-using-steel/structural-steel-framing/

Arehart, J. H., Hart, J., Pomponi, F., & D'Amico, B. (2021). Carbon sequestration and storage in the built environment. *Sustainable Production and Consumption*, 27, 1047-1063.

Barber, D., & Blomgren, H.-E. (2023). Fire Testing Exterior Cross-Laminated Timber Walls to NFPA 285. *World Conference on Timber Engineering (WCTE 2023)*, 1627–1636. https://doi.org/10.52202/069179-0219

Chúláin, C. U., Llana, D. F., Hogan, P., McGetrick, P., & Harte, A. M. (2023). BENDING CHARACTERISTICS OF CLT FROM RECOVERED SPRUCE. *World Conference on Timber Engineering (WCTE 2023)*, 888–894. https://doi.org/10.52202/069179-0121

Churkina, G., Organschi, A., Reyer, C. P. O., Ruff, A., Vinke, K., Liu, Z., Reck, B. K., Graedel, T. E., & Schellnhuber, H. J. (2020). Buildings as a global carbon sink. *Nature Sustainability*, *3*(4), 269–276. https://doi.org/10.1038/s41893-019-0462-4

Eckelman, M. J., Brown, C., Troup, L. N., Wang, L., Webster, M. D., & Hajjar, J. F. (2018). Life cycle energy and environmental benefits of novel design-for-deconstruction structural systems in steel buildings. *Building and Environment*, *143*, 421–430. https://doi.org/10.1016/j.buildenv.2018.07.017

Fuglestvedt, J., Rogelj, J., Millar, R. J., Allen, M., Boucher, O., Cain, M., Forster, P. M., Kriegler, E., & Shindell, D. (2018). Implications of possible interpretations of 'greenhouse gas balance' in the Paris Agreement. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *376*(2119), 20160445. https://doi.org/10.1098/rsta.2016.0445

ICC. (2020). Chapter 5 General Building Heights and Areas. In *2021 International Building Code (IBC)*. International Code Council. https://codes.iccsafe.org/content/IBC2021P2/chapter-5-general-building-heights-and-areas

Kanters, J. (2018). Design for Deconstruction in the Design Process: State of the Art. *Buildings*, *8*(11), Article 11. https://doi.org/10.3390/buildings8110150

Kuang, Y. C., Feng, J. R., Yu, Z. W., & Liu, X. J. (2014). Experimental Study and Analysis of the Structural Behavior of Steel-Concrete Composite Beam after Shear Connector Corrosion. *Applied Mechanics and Materials*, *578–579*, 1522–1530. https://doi.org/10.4028/www.scientific.net/AMM.578-579.1522

Laboy, M. M. (2022). Reimagining low-carbon futures: Architectural and ecological tradeoffs of mass timber for durable buildings. *Architecture, Structures and Construction*. https://doi.org/10.1007/s44150-022-00048-7

Matthews, H. D., Zickfeld, K., Koch, A., & Luers, A. (2023). Accounting for the climate benefit of temporary carbon storage in nature. *Nature Communications*, *14*(1), 5485. https://doi.org/10.1038/s41467-023-41242-5

Nakano, K., Koike, W., Yamagishi, K., & Hattori, N. (2020). Environmental impacts of cross-laminated timber production in Japan. *Clean Technologies and Environmental Policy*, *22*(10), 2193–2205. https://doi.org/10.1007/s10098-020-01948-2

Niu, X. (2024). Mechanism of interface debonding in steel-concrete components caused by thermal expansion and contraction. *International Journal of Materials Science and Technology Studies*, *1*(1), Article 1. https://doi.org/10.62051//ijmsts.v1n1.09

Omar, W. M. S. W., Doh, J.-H., Panuwatwanich, K., & Miller, D. (2014). Assessment of the embodied carbon in precast concrete wall panels using a hybrid life cycle assessment approach in Malaysia. *Sustainable Cities and Society*, *10*, 101–111. https://doi.org/10.1016/j.scs.2013.06.002

Paik, I., Na, S., & Yoon, S. (2019). Assessment of CO2 Emissions by Replacing an Ordinary Reinforced Concrete Slab with the Void Slab System in a High-Rise Commercial Residential Complex Building in South Korea. *Sustainability*, *11*(1), Article 1. https://doi.org/10.3390/su11010082

Rinne, R., Ilgın, H. E., & Karjalainen, M. (2022). Comparative Study on Life-Cycle Assessment and Carbon Footprint of Hybrid, Concrete and Timber Apartment Buildings in Finland. *International Journal of Environmental Research and Public Health*, *19*(2), Article 2. https://doi.org/10.3390/ijerph19020774

Venkatesh, A., Jaramillo, P., Griffin, W. M., & Matthews, H. S. (2012). Uncertainty in Life Cycle Greenhouse Gas Emissions from United States Coal. *Energy & Fuels*, *26*(8), 4917–4923. https://doi.org/10.1021/ef300693x

WoodWorks. (n.d.). *Mid-Rise 2.0 Innovative Approaches to Mid-Rise Wood Frame Construction*.

Wu, H., Zuo, J., Yuan, H., Zillante, G., & Wang, J. (2019). A review of performance assessment methods for construction and demolition waste management. *Resources, Conservation and Recycling*, *150*, 104407. https://doi.org/10.1016/j.resconrec.2019.104407