Chapter 16
Hybrid Slab Systems in High-rises for More Sustainable Design

Katherine Berger, Samuel Benzoni, Zhaoshuo Jiang, Wenshen Pong, Juan Caicedo, David Shook, and Christopher Horiuchi

Abstract Greenhouse gases trap heat within our atmosphere, leading to an unnatural increase in temperature. Carbon dioxide and its equivalent emissions have been a large focus when considering sustainability in the civil engineering field, with a reduction of global warming potential being a top priority. According to a 2017 report by the World Green Building Council, the construction and usage of buildings account for 39 percent of human carbon emissions in the United States, almost one third of which are from the extraction, manufacturing, and transportation of materials. Substituting wood for high emission materials could greatly reduce carbon if harvested and disposed of in a controlled way. To investigate this important issue, San Francisco State University and University of South Carolina partnered with Skidmore, Owings & Merrill LLP, a world leader in designing high-rise buildings, through a National Science Foundation (NSF) Research Experience for Undergraduates (REU) Site program, to investigate and quantify the embodied carbons of various slab system designs using a high-rise residential complex in San Francisco as a case study. Three concept designs were considered: a concrete building with cementitious replacement, a concrete building without cementitious replacement, and a concrete building with cementitious replacement and nail-laminated timber wood inlays inserted into various areas of the superstructure slabs. The composite structural slab system has the potential to surpass the limitations of wood-framed structures yet incorporate the carbon sequestration that makes wood a more sustainable material. The results show that wood substitution could decrease overall emissions from the aforementioned designs and reduce the environmental footprint of the construction industry.

Keywords Carbon · Emissions · Timber · Concrete · Sustainability

16.1 Introduction

According to the National Oceanic and Atmospheric Administration, six of the past seven years fill several spots in the top seven warmest years on record [1]. The greenhouse effect is widely accepted to be the cause of this trend, and carbon dioxide (CO_2) is the largest contributor to the greenhouse effect. If the temperature continues to climb the way it has been, it is predicted that the rising sea levels will inundate 48 square miles of the San Francisco Bay Area by the year 2100 [2]. Buildings are responsible for 39 percent of human greenhouse gas emissions [3]. These emissions can be categorized into a couple different areas. The main categories are the operational carbon and the embodied carbon. Operational carbon is defined as the emissions of greenhouse gases converted into their carbon dioxide equivalents resulting from building usage. This usage includes heating, cooling, lighting, and all other appliances that consume energy derived from fossil fuels [4]. As operational carbon has been widely studied and its emissions have been greatly reduced in the recent years, this paper will focus on embodied carbon. Embodied carbon refers to the emissions associated with the extraction, creation, processing, and manufacturing of materials used in buildings, as well as the emissions associated with building construction and demolition

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[4]. Embodied carbon represents around 28% of the total carbon emissions associated with the building and construction industry, making it an area of interest for reducing global emissions [3].

Several studies were carried out to investigate and quantify the embodied carbon emissions. For example, Oka et al. [5] studied the energy consumption and resultant kg CO_2eq/m^2 of six office buildings with a range of areas and structural compositions. The resultant energy consumption of the structure, finishing, equipment, and waste disposal was calculated for each building. This energy was then converted to kg CO_2eq through an inter-industry relations table. This study concluded that the structure of a building is one of the greatest contributors to embodied carbon emissions.

It has been shown that the embodied carbon emissions associated with the production of wood are significantly lower than that of other common structural materials such as concrete and steel [6]. In addition to the fact that the processing of the material is severely less carbon-intensive, wood acquires and stores carbon during its life until a turning point where harvesting the material is optimal [7]. This carbon sequestration makes wood a very valuable material from an environmental standpoint. Buchanan and Honey [6] looked into different classifications of buildings and proposed various structural designs for each. The residential complex showed a comparison of the most common residential construction materials and sought to maximize and minimize the carbon impact based on these results. From this case study, the wood house was shown to sequester almost as much carbon as was emitted from the other material processes. The industrial complex compared a steel design and a glue-laminated timber design. The results showed that the steel building emitted twice as much CO_2eq as the glulam design. Finally, office building designs were compared for reinforced concrete and steel models, as well as for reinforced concrete and glulam models. These two cases showed that reinforced concrete is slightly lower in emissions than steel, but the glulam frame emits around one-fourth of the CO_2eq of the aforementioned designs. This study was one of the first to emphasize wood's sequestration of carbon and note the impact that this could have on the neutrality of structural systems. In another study, Salazar and Meil [7] compared the emissions of a "wood-intensive" home and a standard wood-framed home based on the harvesting of wood, the embodied carbon of the materials used, and the end of life disposal. Wood that is harvested during its late immature growth phase is shown to be most effective at sequestering carbon because the forest is forced to return to its pre-harvest state and take in carbon for regrowth. Trees that are not harvested can be subject to forest fires, which results in all stored carbon being released, and bacterial decomposition, which releases methane and other GHGs. Taking these into account, the wood-intensive home was shown to reduce more emissions and act as a net carbon sink when compared to the standard wood-framed home. The authors stressed the importance of properly disposing of wood and note the large impact that various disposal methods have on the environment.

Although the quantification of embodied carbon emissions has been investigated by many, the scope of each study varies and can cause a misinterpretation of results. These methodologies include the comparison of structural material emissions, which can range from a narrow view of extraction, manufacturing, and processing to a broader analysis of the entire life cycle energy. It is important to note this scope to ensure an accurate comparison. From there, emissions are quantified through conversion factors for each material and process in the scope. Only structural materials and their emissions will be accounted for in this paper. This study intends to provide a quick and easily implementable approach to designing less carbon-intensive buildings by creating carbon-based design charts for designers. A concept design of a high-rise residential complex in San Francisco was first adopted to validate the methods used to quantify the carbon emissions. The validated method was then applied to a 30-story prototype residential building to study how the insertion of cross-laminated timber panels into slabs could reduce the carbon profile and help achieve carbon neutrality.

16.2 Method Validation

To validate the quantification method of carbon emissions, concept designs of a high-rise residential complex in San Francisco were analyzed. The building was considered to be a sufficient representation of a typical residential structure. The carbon emissions profiles were developed for three case scenarios: (1) a concrete building with no cementitious replacement; (2) a concrete building with cementitious replacement; and (3) a concrete building with cementitious replacement and cross-laminated timber (CLT) inlays inserted into 40% of the superstructure floor area. This percentage acted as a starting point in the original design and was used to test the effect of these inlays on overall neutrality. The results were then compared to those from the Environmental Analysis (EA) Tool developed in-house by Skidmore, Owings & Merrill LLP, which can be used to quantify embodied carbon and give a general overview of emissions in the areas of materials, construction, and probabilistic failure. Note that these analyses will only account for the structural elements of a building.

The case study building consists of an 8″ post-tensioned flat slab system. The whole structure is around 320 ft tall and has approximately 484,341 ft^2 gross floor area.

Fig. 16.1 Typical floor plan of high-rise residential complex – green geometries represent wood inlays within slab

Table 16.1 Carbon emissions result comparison between hand calculation and EA Tool

Case scenario	Hand calculations (lbs CO_2eq/ft^2)	EA tool calculations (lbs CO_2eq/ft^2)	Difference (%)
1. Cement	90	80	12.5
2. Fly Ash/Slag Replacement	74	68	8.8
3. Slab with 40% Wood Inlay	62	–	–

From the floor plan as shown in Fig. 16.1, the mass of concrete and steel of the superstructure was found for the first two designs (cases 1 & 2). These values were then converted to kg CO_2eq using conversion factors from the EA Tool user guide. For the wood inlay design (case 3), the emissions and sequestration of wood were taken into account. From previous studies, it is shown that the emissions of cross-laminated timber are around 0.39 kg CO_2eq/kg wood and its sequestration is around 1.8 kg CO_2eq/kg wood [8, 9]. The resultant CO_2eq was recorded for each concept design to analyze the impact of wood inlay slabs on reducing carbon emissions. The comparison results are shown in Table 16.1. As can been seen from the results, the comparisons in the first two designs showed reasonable consistence given the uncertainty involved in carbon emission quantification. This provides confidence to use hand calculation results for the quantification of the wood inlay slab system as there is no current way to check the carbon emission output with the EA Tool. Looking at the resultant outputs, it is shown that the insertion of wood inlays is promising to reduce carbon emissions with a 31% reduction comparing to the cement option.

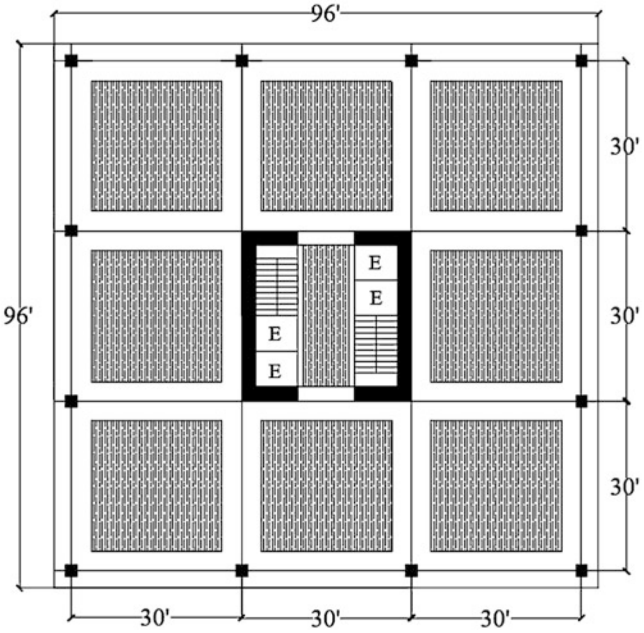

Fig. 16.2 Typical floor plan of the prototype building – the hatched regions represent the wood inlays in the slab

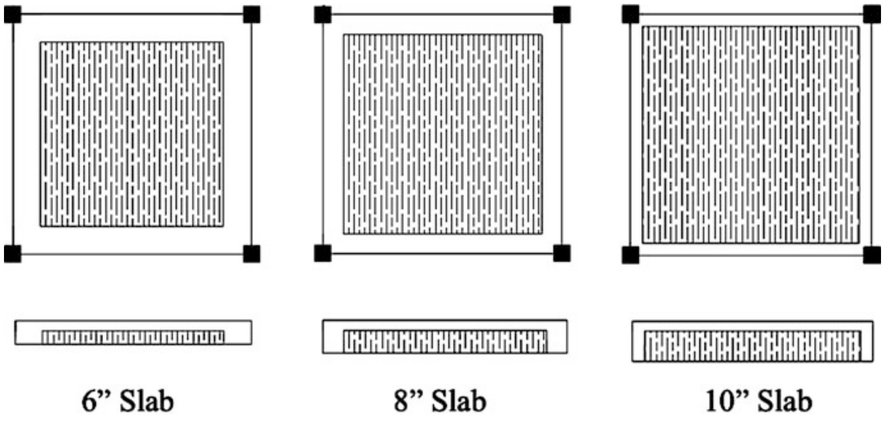

Fig. 16.3 Plans and sections through one bay of a wood inlay slab for various slab thicknesses

16.3 Case Study

Given the promising results from the concept design study, a prototype of a 30-story residential building with 30′ column spans and a 96′ × 96′ floor area was created to further investigate the effects of cross-laminated timber panels inserted into the slabs. In this study, the slab thickness of one level in the superstructure was varied from 6″ to 18″ with the wood inlays inserted to analyze the effects on the total embodied carbon footprint. A typical floor plan of the prototype building is shown in Fig. 16.2.

Several assumptions were made throughout this study. In each scenario, the slab reinforcement was kept at 5.85 lbs rebar/ft^3 concrete. This number was identified through experience and was considered sufficient for residential construction. A 2.5″ layer of concrete at the top of the slab was kept consistent in each scenario for acoustic purposes, meaning that wood occupies the remaining thickness of the slab that is not occupied by this layer. Plans and sections through one bay of a wood inlay slab for various slab thicknesses are shown in Fig. 16.3 to demonstrate the configuration.

The reduction of carbon is the goal of this study, with carbon neutrality being the higher goal that all designers must strive for to reduce environmental impact. In order to calculate the carbon footprint of this wood inlay slab system, it is necessary to clarify what carbon neutrality means. In this cradle-to-gate study, it is defined as the ratio of sequestered carbon from the wood inlays to the sum of all embodied carbon emissions from the concrete, steel, and wood used in the slab system. Given the construction constraints, a parameter named structural feasibility is defined for each slab thickness and is dependent on the minimum beam width that is necessary to transfer loads back to the core of the building. These beams act as areas where the wood inlays are not inserted, which limits the percent wood floor area allowed for each slab thickness. These structural feasibility values were based on practical experience and were linearly interpolated assuming that an 8″ slab needs a 5′ beam width, a 10″ slab needs a 3′ beam width, and the minimum allowable beam with is 1.5′. The structural feasibility can be seen in Fig. 16.3; as the slab thickness increases, there is less concrete allotted on either side of the wood inlay in order to maximize the floor area that contains CLT inlays. Keeping these assumptions and definitions in mind, the percent floor area of wood inlays necessary for 100% neutrality, 75% neutrality, and 50% neutrality was recorded.

Once the percent wood floor area was found for each slab thickness, the carbon neutralization of other components of the superstructure from the wood inlay slab system was considered. The scope of this study included the core walls, link beams, and columns, and well as the original slab material quantities.

To reduce carbon emissions as much as possible in the prototypical design, analyses were conducted to determine the minimum core wall thickness allowable for each slab thickness. ETABS, a structural analysis software by Computers and Structures Incorporated, was used to perform these analyses. The insertion of wood inlays into the concrete slabs led to a loss of seismic weight and lateral forces. In order to maintain a code-specified requirement for design-level earthquakes, the stiffness of the building, and therefore the core wall thickness, could reduce. This reduction of material could lead to a lower carbon footprint of the overall building and a greater likelihood that the wood inlays could completely neutralize the superstructure emissions. The parameters for this study were maximum interstory drift and maximum story shear and were based on requirements for design-level earthquakes. To achieve a building with reduced core wall thicknesses that performs at code level, the maximum interstory drift was 2% and the maximum story shear was considered to be

$$V_n = 0.6 * A_{cv} * 6\sqrt{f'_c} \tag{16.1}$$

where A_{cv} is the gross area acted upon in a seismic event and f'_c is 8000 psi for high strength concrete. Note that the story shear based on an ACI 318-R14 is given by

$$V_n = 0.75 * A_{cv} * 8\sqrt{f'_c} \tag{16.2}$$

For this study, 0.75 was used instead of 0.6 and the factor of 8 was changed to 6 to provide conservative estimates for this prototype building in a seismic event.

The definition of structural feasibility remained consistent from the study previously conducted. All additional structural elements in this study were considered as solid reinforced concrete members and were calculated accordingly. Similarly, these elements were all defined as high strength concrete with the core walls and columns having 15% cement replacement and the link beams having 50% cement replacement. With the ETABS results in mind, the emissions from the core walls, columns, link beams, and slabs were recorded and the percent floor area of wood inlays necessary for 100%, 75%, and 50% neutrality were found.

16.4 Results

In an attempt to make these results more tangible and easily adoptable by designers, a chart was created for each scenario to show carbon neutrality possibilities. Figure 16.4 shows possibilities for carbon neutrality in the floor plan of a 96′ × 96′ slab with a 30′ column span. The chart included four-point series overlaid to show overlap for what could be possible. Plotted are the structural feasibility line, the 100% carbon neutral line, the 75% carbon neutral line, and the 50% carbon neutral line. Each area in this plot has a different implication and is intended to give an idea for sustainable practices when designing a floor slab.

Figure 16.5 shows another chart that incorporates the emissions of all structural elements of a single story, including those in Fig. 16.4 and elements such as columns, core walls, and link beams. Similarly, this chart serves to provide a sort of guideline for the design process. It indicates that there is a large amount of work to be done before carbon neutrality can be achieved on a larger scale, as it is much more difficult to achieve a 100% neutral superstructure than a 100% neutral slab.

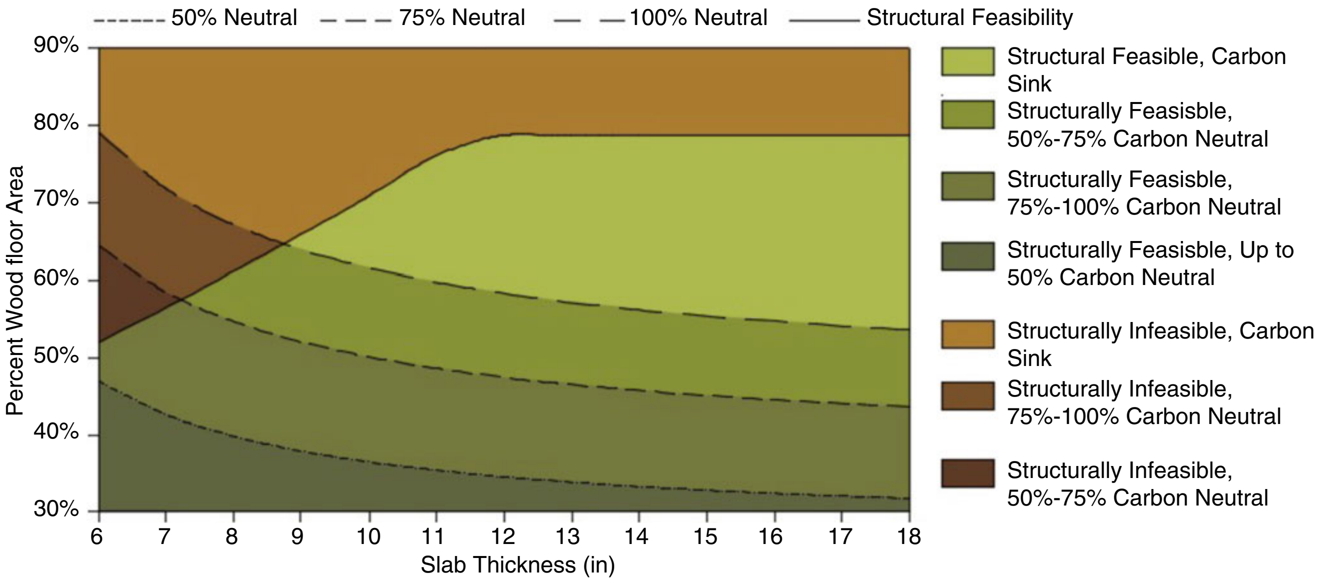

Fig. 16.4 Carbon-based design chart for the floor slab of the prototype building

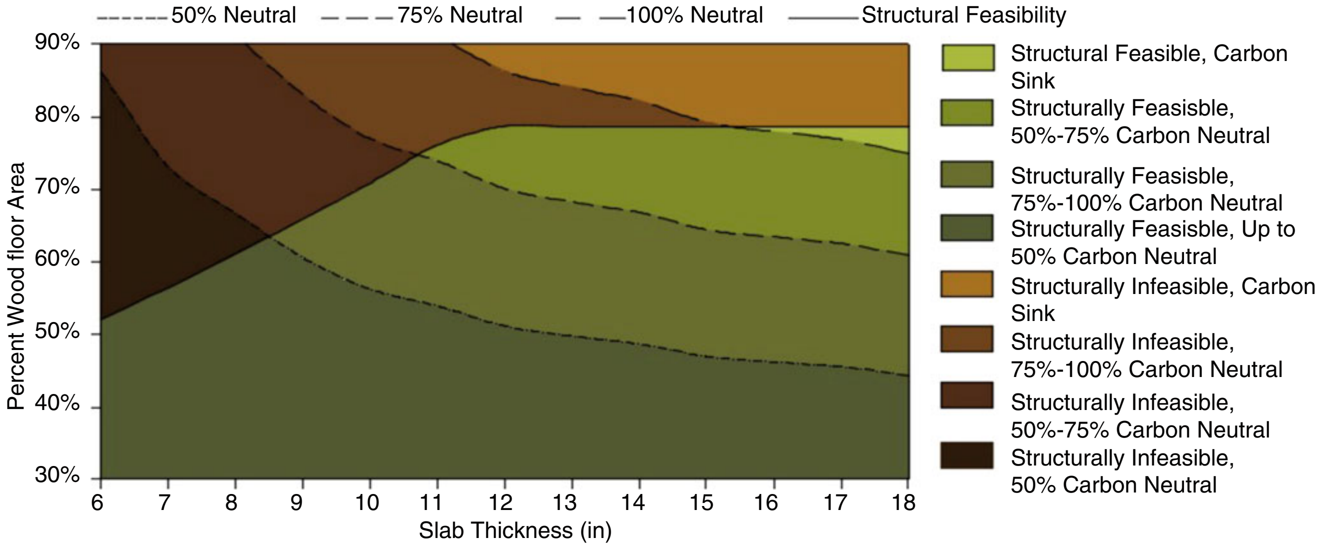

Fig. 16.5 Carbon-based design for an entire story of the prototypical building

In the design phases of a building, one might have a certain carbon reduction or neutrality that is desired. In this case, a user might use these charts and determine how much wood should be incorporated within the slab in order to achieve a certain neutrality, and how feasible this design may be.

To provide an example on how to use these charts, a designer may produce a scheme that calls for an 8″ floor slab. From Fig. 16.4, the designer could achieve over 75% carbon neutrality of the slab system by inserting wood inlays into 60% of the floor area. Since the carbon sequestered by the wood inlays is not enough to 100% neutralize the slabs, they may choose to increase the slab thickness or increase wood usage in other architectural areas for higher carbon sequestration potential. Using the same 8″ floor slab with Fig. 16.5, the designer would note that the 60% wood inlay floor area prescribed by the structural feasibility line would provide less than 50% neutralization when considering all superstructure elements. In this scenario, it would be impossible to achieve 100% carbon neutrality of the superstructure at the given slab thickness.

16.5 Conclusion

With the amount of greenhouse gases currently in the atmosphere, it is crucial that everyone takes steps to reduce their emissions so that our environment may start to return to its natural state. The atmosphere has shown unprecedented heating trends due to carbon dioxide and equivalent greenhouse gases. In the building sector, the manufacturing and processing of structural materials are some of the largest contributions to these emissions. Since wood requires less manufacturing than other materials and trees intake carbon dioxide during their growth, it can act as a carbon sink when considering its overall footprint. The insertion of wood into a concrete slab could cause for reduction, or possible cancellation, of carbon emissions due to these properties. This paper studied the wood inlay slab system through several case studies and created two charts that can serve as guidelines for carbon-based design. The first chart can be used to estimate the percent floor area of wood inlays to achieve certain emission reductions or carbon neutrality within a single slab. The second chart shows how the carbon sequestration of the wood inlay slab system can reduce emissions beyond the slab, such as those associated with core walls, columns, and link beams. Inserting wood within concrete members has the potential to neutralize or offset the carbon footprint of structural systems while surpassing the building limitations of wood. Furthermore, it is a promising way for engineers to actively pursue the reduction of greenhouse gases, leading to restoration of the natural global climate.

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