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Feasibility Study of Hybrid Timber-Concrete Tall Buildings

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Abstract- Adverse impacts of global warming are increasing worldwide. The construction industry accounts for more than 40% of CO_2 emissions worldwide. To lower the carbon footprint of the construction industry, sustainable construction methods and materials should be adopted. Timber is an alternative sustainable construction material, as timber construction produces far less CO_2 emissions during production and service life compared to conventional construction materials such as concrete and steel. Using timber alone for constructing high-rise structures has limitations due to its lightweight (higher floor accelerations), fire resistance, flexibility, etc. Also, there are disadvantages related to ductility properties to provide seismic resistance in tall timber buildings and the hesitancy on the part of designers and contractors to build high-rise timber structures. One possible solution is the use of hybrid structures, combining two or more materials by taking advantage of their individual strengths. The current work is focused on exploring the feasibility of high-rise hybrid timber-concrete structures over high-rise concrete structures in terms of their seismic and sustainability performance. The purpose of this study is to help designers and engineers towards understanding the behavior of hybrid timber-concrete tall buildings, instigating the development of more sustainable and practical design using timber.

Keywords- Sustainable construction, Green building material, Hybrid timber-concrete high rise.

1 Introduction

The increasing adverse effects of global warming due to the release of Carbon dioxide (CO_2) in the atmosphere is posing a significant threat to the environment. To contain these drastic effects, 175 countries signed a ‘Paris Agreement’ at the COP21 in Paris, which went into force in November 2016, and it was agreed to limit global temperature rise to well below 2 degrees centigrade in this century [1]. To achieve this ambitious target, a multifaceted approach is needed with a significant reduction of CO_2 emissions from most major industries of the world including the construction industry.

The world population has been increasing rapidly with an average estimated increase in the population of 81 million people per year [2]. This increase in population along with migration towards urban centers is causing an ever-increasing burden on the governments to build urban infrastructure including the housing units. As per UN-Habitats, 3 billion people in the world today will need a new home over the next 20 years. Constructing high-rise structures to cater to this demand is proving to be an effective solution, resulting in massive investment in infrastructure development. The carbon footprint associated with the building construction is referred to as “Embodied carbon footprint” of the building. According to a report published by United Nations Environment Program, global CO_2 emission from the building construction sector reached the highest ever level in 2019 by accounting for approximately 38% [3]. China’s national CO_2 emission from the construction industry was 90% and this percentage was 66%, 82%, 51%, and 42% for USA, India, Japan, and Canada respectively for the period between 2009 and 2020 [4]. Therefore, a concerted effort is required to lower the carbon footprint of construction industry by using sustainable construction methods and materials.

A deeper look reveals that the production of materials used in the construction industry is a major contributor to the embodied carbon footprint. To lower the embodied carbon footprint of buildings, building materials that are less carbon extensive should be promoted. To lower the carbon footprint of buildings, Architecture 2030 issued a 2030 challenge in 2006 asking the global architecture and construction industry to achieve net-zero embodied carbon emission by 2030 [5]. The least carbon extensive material at our disposal is wood or timber. Wood is produced by a process called photosynthesis which makes it a carbon sink. Also, the process to make mass timber products take less energy than steel and concrete. The bar chart in Figure 1 clearly shows that the environmental impact of wood design is significantly lower than concrete and steel [6].

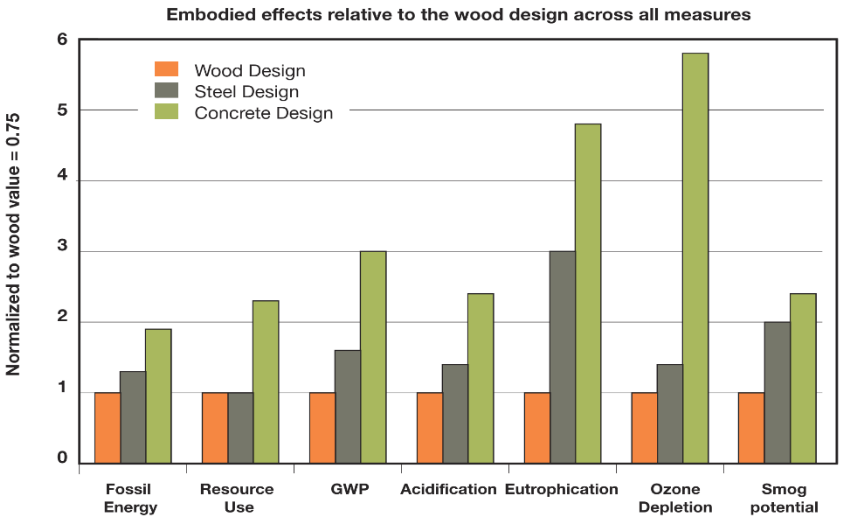

Figure 1: Comparison of environmental impacts of construction materials
Source: Dovetail Partners using the Athena Eco-Calculator (2014)

In recent decades, the development of mass timber products like glued-laminated timber, cross-laminated timber, etc., created a renewed interest in lightweight and sustainable timber structures. However, using timber alone for building high-rise structures has limitations due to its lightweight which could cause higher floor accelerations and flexibility which may cause higher displacement demand [7]. Also, there are disadvantages related to ductility requirements to provide seismic resistance in tall timber buildings [8]. The use of timber for constructing tall structures has geared up in the recent decade but design codes are still lagging behind for designing timber tall buildings, as *National building code of Canada* (NBCC) 2014 does not allow an all-timber construction above 6 stories. One possible solution is to shift to more sustainable construction materials like timber in a relatively gradual manner by first exploring the use of hybrid timber-concrete structures [9] especially as the code does not have any restriction on the maximum height of these structures. E.C Slooten et. al. [10] studied the technical feasibility of super tall hybrid timber-concrete building, and mainly focused on optimizing the wind-induced dynamic behavior. Kaushik [11] studied the feasibility of 30-story hybrid timber-concrete structure, making the gravity load resisting system as hybrid timber-concrete by introducing concrete slab at every third story, and discussed inter-story drift and base shear results. Wu k. et. al. [12] also studied the behavior of six different hybrid structural systems and compared only drift demands. Schuirmann et. al. [13] also studied the feasibility of hybrid tall timber-concrete structures with different slab types (1-way and 2-way) by performing non-iterative P-Delta analysis. However, still more work is needed including the development of codal requirements, experimental testing, design procedures, etc., to enable the designers and contractors to adopt this sustainable alternative. This research aims to assess the feasibility of high-rise hybrid timber-concrete structures over high-rise concrete structures in terms of seismic and sustainability performance, by comparing story shear, story displacement, Inter-story drift, and concrete core shear results of both structures.

2 Case study structures

To assess the potential of using timber-concrete hybrid structures, a 20-story case study building is selected. Plan and 3-D view of the building are shown in Figure 2. The case study building consists of a core wall and stairwell (referred hereafter as core wall) in the center connected by framing on the sides. The core wall is designed to act as a lateral force-resisting system while the beams and columns are designed primarily to resist only gravity loading. Initially, the whole structure is designed as a concrete building (CB). Few works in the past have used timber as a part of the lateral force-resisting system; however, the values of force reduction and over-strength factors for such systems are still not clear and need further research. Therefore, timber structural components in this study are used for only gravity load resisting system. The second case study building is same as CB except that the beams and columns are composed of glued laminated timber while the slabs are composed of cross-laminated timber with concrete topping referred hereafter as hybrid timber-concrete building (HTCB). Structural members of both the buildings are designed using the factored loads to select the material and cross-section properties according to CSA-A23.3-14 and CSA O86-2014 for concrete and timber design, respectively. Table 1 shows the structural member properties of two buildings. Case study buildings are assumed to be located in the Vancouver area with site class C as per NBCC 2015. Values of force reduction factor (R_d) and overstrength factor (R_o) for CB are chosen as 3.5 and 1.6, respectively from the NBCC 2015. Although the HTCB is composed of both concrete and timber and both have different values of these factors, the same values of R_d and R_o are used for HTCB as the concrete core is assumed to resist all of the lateral actions. This assumption will be validated in the results section. Dead load is composed of self-weight of the structure plus the super-imposed dead load of 4kPa while the live load is 2kPa.

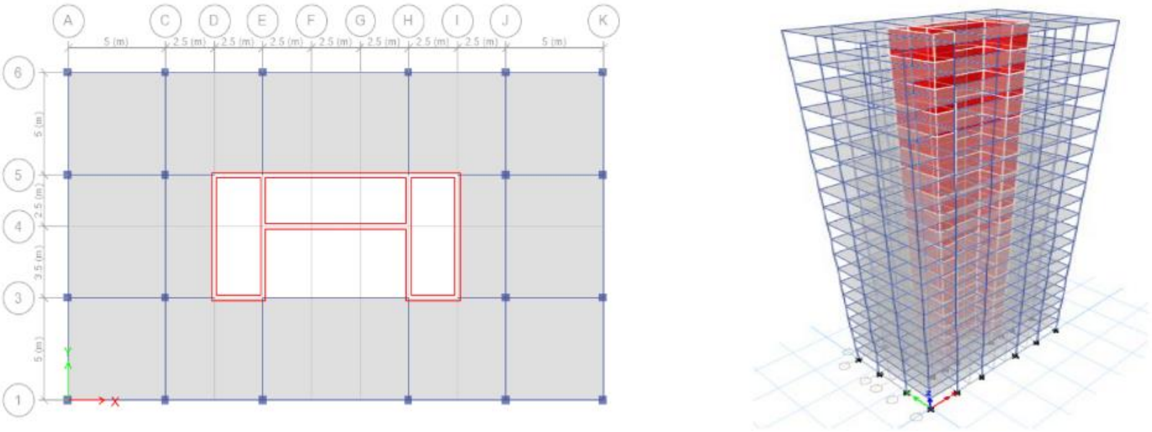

Figure 2: Typical plan and 3-D elevation of case study buildings

Table 1: Material and section properties of case study structures

CB			HTCB		
Section property	**Size/Thickness**	**Grade**	**Section property**	**Size/Thickness**	**Grade**
Slab	150 mm	3000 psi	CLT slab	243 mm, 9 layers	E2
Beams	250 x 500 mm	4000 psi	Perimeter glulam beams	215 x 532 mm	24f-EX
			Interior glulam beams	365 x 874 mm	24f-EX
Columns	400 x 400 mm	4000 psi	Glulam columns	365 x 380 mm	16c-E
Concrete core	250 mm	4000 psi	Concrete core	250 mm	4000 psi

3 Modeling and Analysis

The case study buildings are modeled in commercially available software ETABS. Linear elastic modeling is done in this study. Initially, an equivalent lateral force procedure (ELFP) is performed to calculate total seismic demands and the seismic demands carried by different structural components for both buildings. The case study building has a significant torsional response and therefore, results from response spectrum analysis capable of considering higher mode effects are also discussed. The strength and stiffness properties of glued laminated and CLT timber sections are defined for different directions as timber is an orthotropic material using timber grades defined in Table 1. It is important to note here that only linear static analysis (ELFP and RSP) are performed in this study. Also, this study is focused on only the global behavior of the structures against the design basis earthquake level of seismic intensity.

4 Results and Discussion

The foremost advantage of using a hybrid structural system can be seen by looking at the self-weight of the two case study buildings as shown in Table 2. The HTCB has almost 30% lower self-weight and seismic weight compared to CB. This implies reduced shear and moment demands for beams and reduced axial load ratios for columns. Furthermore, it can also significantly reduce the forces and moments for foundation design, resulting in cost savings. Seismic weight in this study is calculated by using 100% of dead and super dead load and 25% of live load. It is important to mention here that the total lateral seismic forces acting on a structure represent a portion of a total seismic weight acting laterally described in most codes as seismic response coefficient for ELFP. So, a reduced value of seismic weight would result in lower seismic demand for same seismic response coefficient or same spectral acceleration.

Table 2: Seismic characteristics of case study buildings

Building Type	**Self-weight (KN)**	**Seismic Weight (KN)**	**T_X (Sec)**	**T_Y (Sec)**
CB	59,155	92,005	1.22	1.90
HTCB	31,630	64,480	1.04	1.74

The fundamental time periods for CB in X and Y-direction of responses are 1.22 sec and 1.9 sec, respectively which are reduced to 1.04 sec and 1.74 sec for HTCB. Time period of a structure is dependent on the ratio of mass and stiffness. Although the HTCB has reduced stiffness compared to CB, the reduction in mass is even higher, resulting in a reduced mass/stiffness ratio or time period. In a typical design spectrum as in the current study, a decrease in the time period in the concerned range results in a higher spectral acceleration value resulting in higher shear demand. HTCB has a lower time period compared to CB meaning a higher spectral acceleration ordinate however reduced seismic weight means that the shear values in the absolute terms would be lower. Figure 3 shows the shear force results for the case study buildings. Overall, the shear values for both CB and HTCB are higher in Y-direction than in X-direction. The contribution of higher modes seems to be limited as seen in the shear profile along the height. For both X and Y directions of response, HTCB is showing an almost 25% less base shear compared to CB and a similar pattern is observed along the height. This shows a significant drop in shear demand, signifying the effectiveness of hybrid solution as far as force demands are concerned.

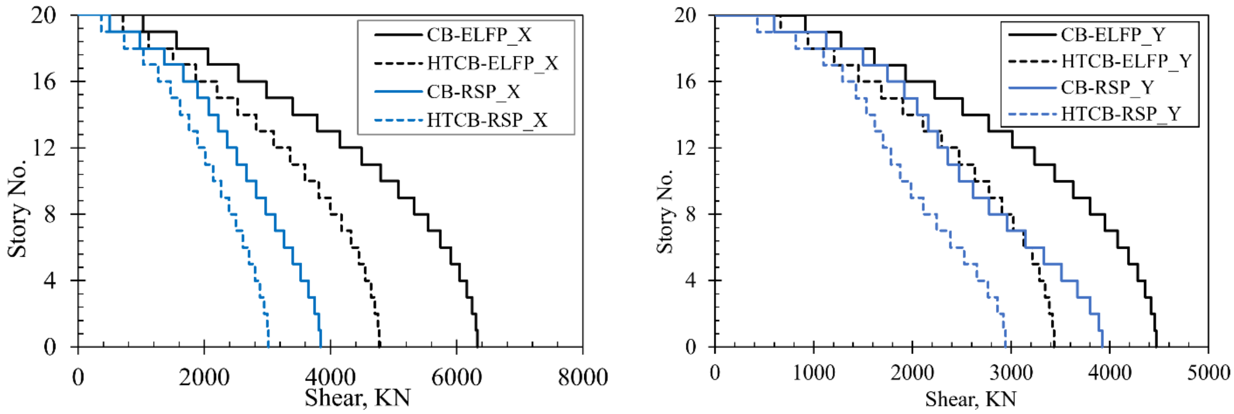

Figure 3: Shear force comparison

The relatively reduced time period for HTCB, on the other hand, has an opposite effect on the displacement and inter-story drift demands with lower spectral displacement ordinate. Figure 4 shows the displacement and inter-story drift results for both CB and HTCB, showing a reduced displacement demand for HTCB in both directions of response. This would eventually lead to better performance for HTCB with reduced residual drifts and damages. The comparison also showed that the displacements in Y-direction are nearly double than in X-direction.

Response spectrum analysis is also performed to calculate the force and displacement demands. Both force and displacement demand for CB and HTCB using RSP are less than demands from ELFP. The difference is particularly high in X direction of response due to torsional behavior. This is because in ELFP, all of the seismic weight is used to calculate the seismic forces by using fundamental time period while in RSP the seismic mass is divided into different modes and is multiplied with individual spectral acceleration for different modes against their time periods and the total response is obtained by using SRSS.

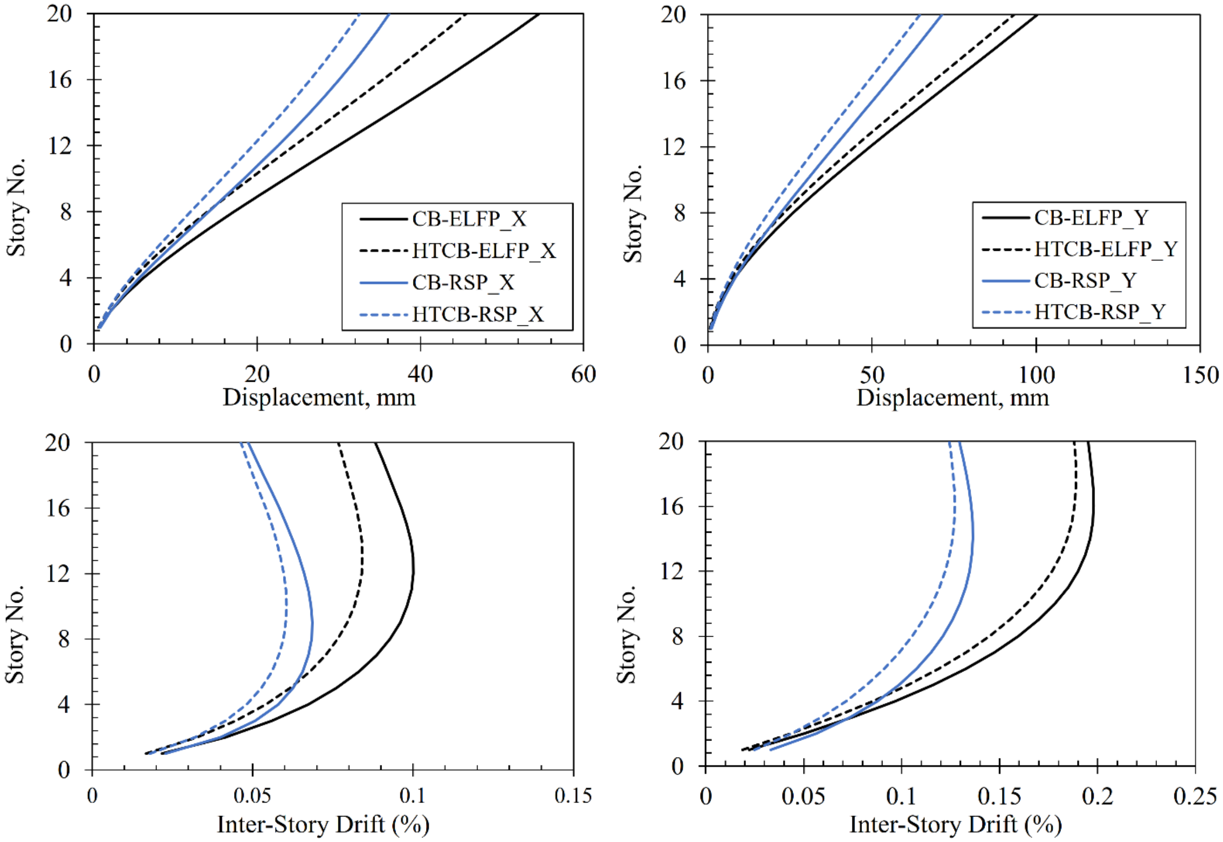

Figure 4: Displacement and Inter-story drift comparison

To evaluate the assumption that the concrete core wall is designed to resist most of the lateral load, seismic response for ELFP for individual walls is shown in Figure 5 for both directions of response it can be seen that for both HTCB and CB, the base shear carried by all the walls combined is more than 95% of the total base shear of the building in both directions, validation the assumption made in the earlier section. It also validates the use of the same values for R_d and R_0 factors for both buildings. Figure 5 also shows the seismic demands of individual walls with walls 9 and 11 taking a maximum lateral load in the X direction of response, almost all walls are contributing equally to resist the lateral load.

Designers and engineers are still hesitant to construct hybrid timber-concrete high rise as much extensive research isn't carried out in this field yet, and also the behavior of hybrid timber-concrete tall buildings is not explored in depth yet. Furthermore, values for seismic factors (R_d and R_0) are not defined in design codes for hybrid timber-concrete tall building design. Results obtained from this study would help engineers and designers to understand the behavior of hybrid timber-concrete tall structures and would provide a way to fulfill the codal requirements related to height and use of seismic factors (R_d and R_0).

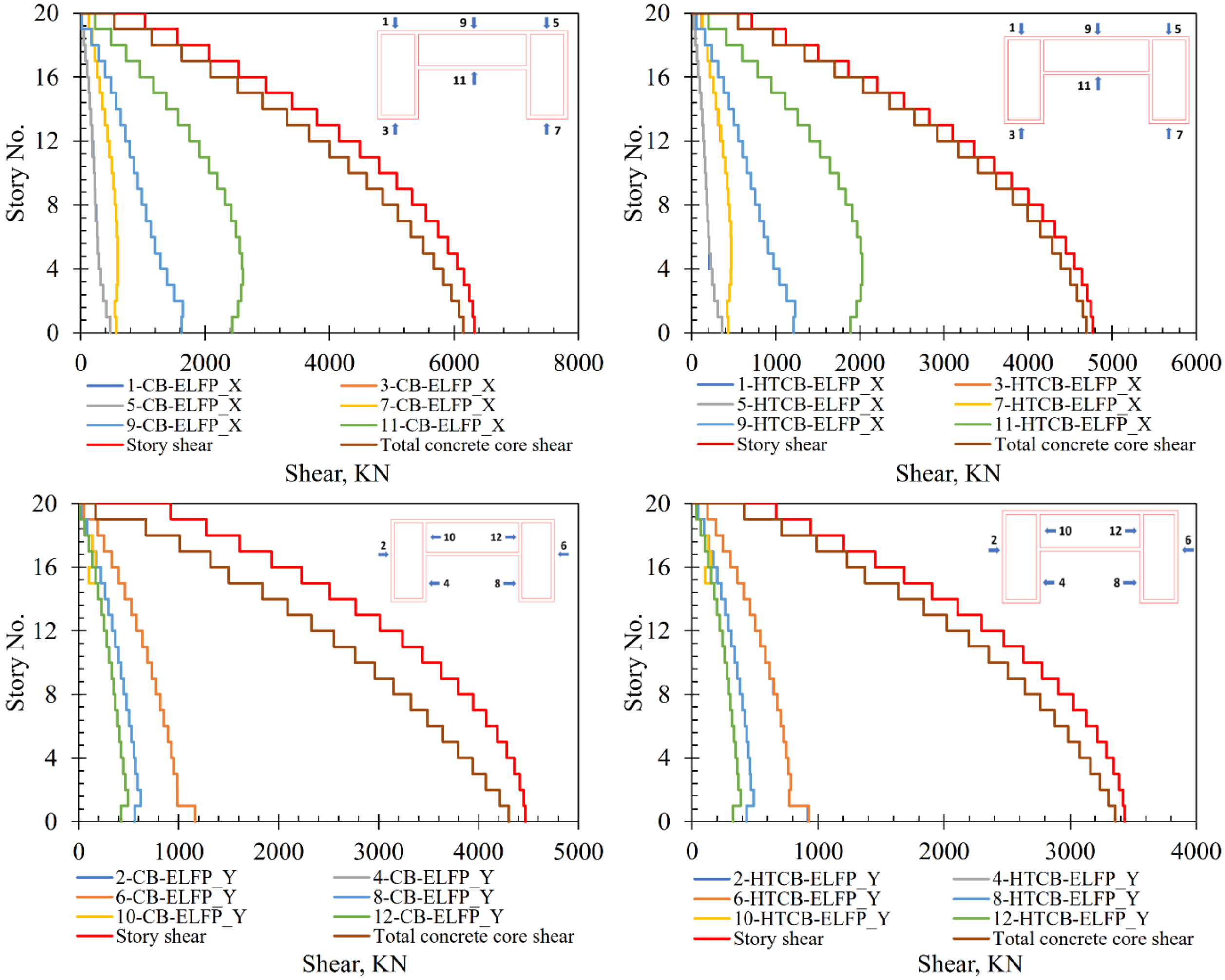

Figure 5: Concrete core shear results

A comparison of the embodied footprint of one building with another can clearly show how using different construction materials can be potentially environment friendly in terms of greenhouse gas emissions. Similar comparison of the case study structures is made in terms of CO_2 production from the usage of concrete, discussed as follows. In this comparison, only carbon footprint from the production of concrete material (Cradle-to-gate) is considered, and Life Cycle Assessment (LCA) is not made in this comparison, as only the superstructure of the two buildings is assessed excluding foundation, architectural components, and operational energy. CB would use 2541 m^3 of concrete and HTCB would use 797 m^3 of concrete, which shows that using timber in HTCB reduces the quantity of concrete by 69% compared to CB. Hong et. al. [14] found that approximately 106 kg of CO_2 is produced per ton of concrete [14]. Based on which it is found that CB would produce approximately 646 Ton CO_2 and HTCB would produce nearly 202 Ton CO_2, which is significantly less than that of CB.

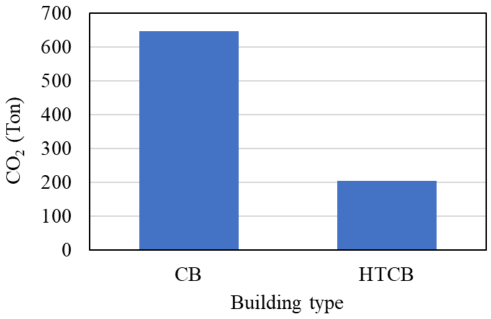

Figure 6: CO_2 production comparison

5 Conclusions

In this study, a 20-story commercial concrete building (CB) and hybrid timber-concrete building (HTCB) located in Vancouver are designed and analyzed against design level seismic hazard. ELFP and RSP are performed as per *National building code of Canada (*NBCC) 2015. The case study buildings (CB and HTCB) are designed with separate lateral and gravity load resisting systems. Following conclusions are drawn from this study.

1. The results show a significant decrease of 30% in self-weight and seismic weight of HTCB compared to CB along with a 25% decrease in base shear values for HTCB.
2. In addition to this, the displacement demands are found to have a marginal decrease for HTCB, signifying a possible reduction in damages also which are closely related to displacement demand.
3. In addition, the HTCB is found to decrease the CO_2 emissions related to the construction materials and activity by a massive 68% compared to CB.

Therefore, it is concluded that the HTCB building has superior seismic and sustainability performance over CB while satisfying the different codal requirements.

Acknowledgement

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