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STRUCTURAL AND ENVIRONMENTAL ANALYSES OF TALL WOOD-CONCRETE HYBRID SYSTEM

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Abstract: Sustainable construction methods are becoming a priority topic in the 21st century to reduce the environmental footprint of the building industry. Hybrid systems, which combine wood with other materials, can enable application of engineered wood products beyond mid-rise construction. This paper presents structural and environmental analyses on a novel tall wood-concrete hybrid system, where a concrete frame consisting of slabs at every third storey provides fire separation as well as the necessary stiffness and strength to resist gravity and lateral loads. The intermediate storeys including their floors are constructed using wood modules to create the usable space. This approach reduces the environmental footprint of the building, reduces the building weight and therefore the seismic demand on connections and foundation, and speeds up the construction process. To study this hybrid concept, a 30-storey case-study building with regular floor plan was designed and compared to a regular all-concrete building. The gravity and lateral loads were analyzed for a building location of Vancouver, BC according to the 2015 National Building Code of Canada. The results showed that the lighter hybrid option allows the use of a smaller concrete core to resist the lateral loads. While inter-storey drift code requirements were met, wind became the governing lateral load case over seismic load demands due to the reduction of building mass. In addition to the structural design, a life cycle assessment was performed using the Athena Impact Estimator for Buildings. The hybrid building was significantly superior by reducing the amount of concrete by almost 60% which leads to lower environmental impacts in multiple categories. The research demonstrated the feasibility of the proposed hybrid system for tall buildings in high seismic zones.

1 INTRODUCTION

1.1 Background

Sustainable construction methods are becoming a priority topic in the 21st century to address the looming climate crisis. Particularly in China, air pollution has become a serious health threat to the population and small particulate matter from cement production for large-scale construction projects is estimated to cause the death of 1.6 million Chinese people each year from respiratory illnesses (Wikipedia 2018). Due to the amounts of smog, the construction period in parts of China is limited to 6 months a year; this is primarily due to fossil fuel heating demands during the winter months that increase the amount of air pollution.

The mass timber components of the hybrid buildings consist of glulam beam and cross-laminated timber (CLT) floor systems (Gagnon S and Pirvu C 2012). These mass timber elements and panels are fabricated off site in a controlled shop environment and therefore eliminate onsite fabrication and decrease erection time. An increasing number of mid-rise buildings that use mass timber / concrete hybrid systems tare erected faster than concrete buildings. One such example is the Brock Commons Tallwood House building in Vancouver, BC (Tannert and Moudgil 2017).

The recent building code in China limits wood construction to a maximum of three storeys (GB 50005-2017). Therefore, the proposed 30 story hybrid building would contain two stories of mass timber floors consisting of glulam beams and CLT panels that are supported by the concrete gravity columns and the concrete lateral-load resisting system (LLRS). These mass timber sections are separated by a flat concrete slab at every third story of the building to comply with the China building code for wood construction. A similar approach can be taken in countries that have building codes that limit the building height for wood construction, providing that firefighting requirements are not breached.

1.2 Objective

The motivation for this project was to provide a timber-based hybrid alternative for tall buildings to reduce their global warming potential and to reduce construction time by reducing the number of concrete pours replacing every two out of three stories with mass timber construction. In the research project presented herein, three variations of a 30-story building were investigated for structural load demands and environmental impact based on the superstructure material use for a building location in Vancouver BC.

2 STRUCTURAL DESIGN OF CASE STUDY BUILDING

2.1 Overview

A concrete (Figure 1 a) and a hybrid building (Figure 1 b and c) were investigated to compare their LLRS and the material amount required to meet structural demands of Part 4 of NBCC (2015). The buildings were designed for Vancouver BC, using the data from NBCC 2015. Both the concrete and hybrid buildings had plan dimensions of 27m x 27m with 30 3m tall stories for a total building height of 90m. The structural system for the concrete building consists of perimeter gravity columns that support a flat plate slab system and a center elevator / stair well core that supports the slab and resists the lateral wind and seismic loads. The hybrid buildings eliminated two out of every three flat plate slab systems and implemented the glulam beam and CLT floor system. This system carried the gravity loads and transferred them to the perimeter concrete columns and the center concrete core similar to the flat plate slab. The façade and foundation design were not part of this projects' scope. Two different glulam beam and CLT floor systems are compared for the hybrid building. One system with a 4.5m on center beam layout with 1-way spanning CLT panel system and one with a 3m on center beam layout with 2-way spanning CLT panels.

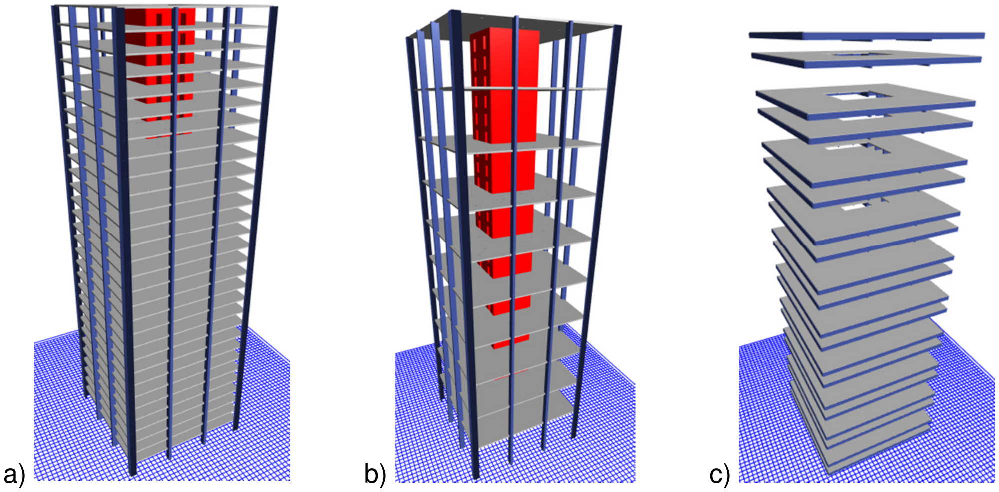


Figure 1: a) Concrete building; b) concrete elements of hybrid building; c) timber floors of hybrid building

2.2 Gravity design

The buildings were modelled using ETABS (Computers and Structures (2018) and analyzed for CSA A23.1 (2014). NBCC 2015 was used for this project and Vancouver was used for its moderately high force demands to compare the LLRS for both wind and seismic loads. The three buildings are broken into three separate height sections that utilize three different concrete strength classes, see Table 1. The loading was applied to the rigid diaphragm 2-way slabs on each story of the concrete building and similarly to the CLT floor systems of the hybrid buildings. The dead load includes 0.3 kPa equivalent floor area load to account for the façade dead load of 0.6 kPa x 3m tall walls per story.

Table 1: Concrete elements for gravity design

Storey	Concrete Strength: (MPa)	Total # of Pieces Concrete Building:	Total # of Pieces: Hybrid Buildings
1-10	40	120x 3m col. + slab + core	36x 9m col. + slab + core
11-20	35	120x 3m col. + slab + core	36x 9m col. + slab + core
21-30	30	120x 3m col. + slab + core	48x 9m col. + slab + core

The columns and flat slab are modelled as continuous members having no end releases, see Figure 2a. All cross sections excluding the wall sections were sized using gravity design with load combinations including self-weight, dead load, live load and snow load. The floor plan layout for all 30 stories is shown in Figure 2b. The columns exclusively support the vertical loads that are transferred from the 2-way slab to the center concrete core and the outer perimeter gravity columns. The floor layouts for both hybrid buildings are shown in Figure 2 c and d, indicating the 1-way and 2-way floor systems that are separated by the concrete slab floor on every third story.

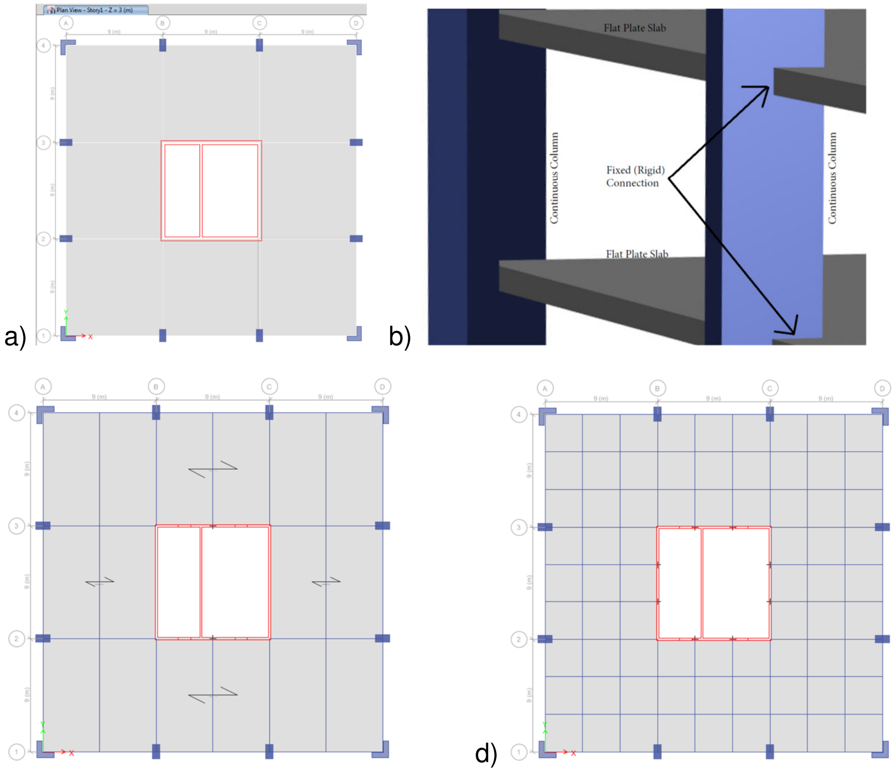
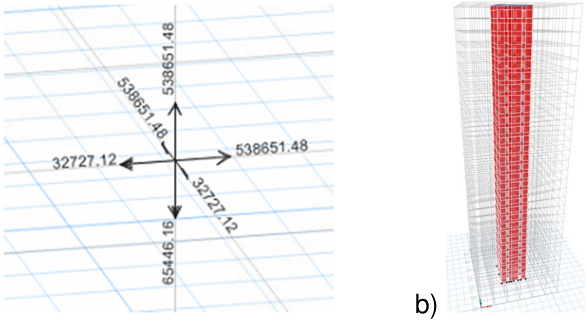


Figure 2: a) Concrete building: typical Floor layout level 1-30; b) Column – Slab rigid connection; c) CLT floor layout Hybrid buildings 1-way and d) 2-way

2.3 Lateral design

The lateral building design includes the wind load and seismic load cases based on NBCC 2015. A separate model was created from the gravity design models for each of the three buildings that has every member except the center core removed, see Figure 3a This was necessary for the concrete building due to the columns and flat plate slab being continuous members and having no end releases, that allow these members to contribute to the LLRS which is not intended for this project. The same method was used for the hybrid building LLRS design.

The self-weight from the gravity system was added to the core weight by converting the story load into mass and applying it in each global direction in addition to a mass moment of inertia in global directions applied to each story elevation at the center of the concrete core as shown in Figure 3b. The self-weight SW load case uses a self-weight multiplier in the Z-axis to include the weight of the elements of the model into the analysis. In addition to the self-weight the flat plate slab end reactions for dead and live load were also added to the concrete core walls in the lateral design model.



a) b)

Figure 3: a) Additional mass & MOI to core at each floor level; b) Concrete core LLRS)

Both the concrete and hybrid buildings use the center concrete core as the sole LLRS. The concrete core walls are modelled as ductile shear walls with Rd & Ro values of 3.5 and 1.6. A dynamic analysis procedure was performed following the requirements from NBCC. Seismic lateral drifts and building base shear values are calculated based on the Modal Response Spectrum Method (MRSM).

A non-iterative P- Delta analysis based on mass was performed and plotted against the lateral inter-story drift values that do not include a P-Delta effect. P-delta effects are also known as second order effects and account for additional overturning moments due to lateral deflection and the mass of the building. ETABS can perform two types of non-iterative P-Delta analyses which are either based on mass or based on load cases. The based on mass method does not require an iterative solution making it quicker to solve and an approximation. This method is effective when considering a rigid diaphragm at each story level like the models in this report and it does not capture local buckling. The effects of an analysis without considering P-Delta effects and with considering the mass-based P-Delta effects can be seen in the results section.

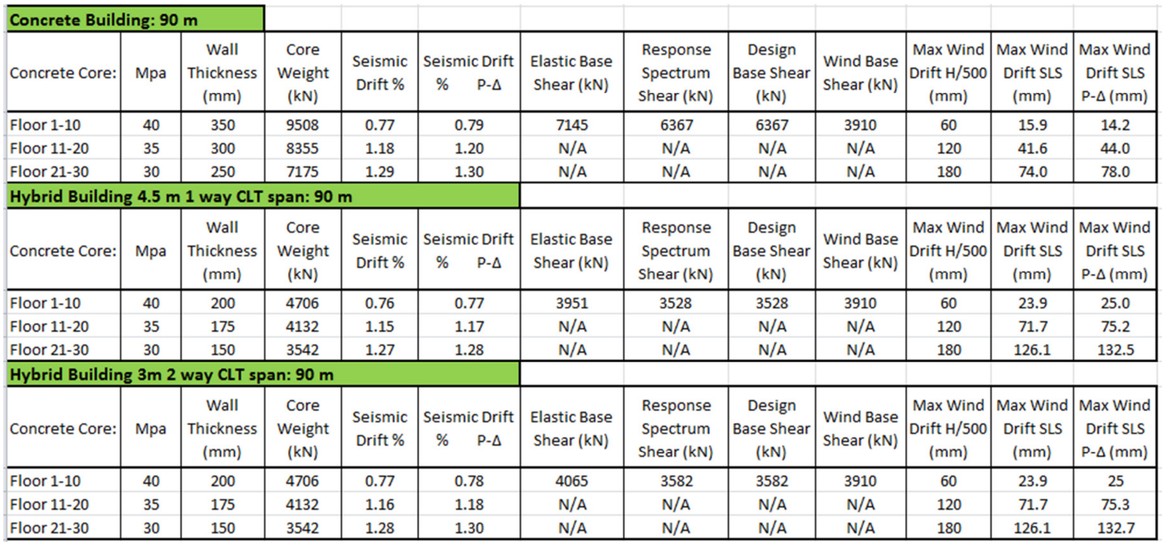
2.4 Results

The response modes of each building (Table 2) follow normal behavior of tall buildings with the first and second modes being lateral movements in both directions and the third being torsion. The periods are above the building code limits for shear wall. However, Part 4.1.8.11 states when using a structural model, for calculating deflections, the period shall not exceed 4sec for wall, coupled wall and wall-frame systems. The results are solely for the concrete core structures and do not account for any additional stiffness provided from the gravity system. Mode 1 and 2 periods reflect the (Ta_{max}) value in co-ordinance with NBCC. The second row in the table shows the building periods using the same core thickness as the concrete building with the building mass for the hybrid buildings. If the core thickness from the concrete building is maintained with the hybrid buildings gravity system mass then the mode 1 and 2 periods are within the NBCC section 4.1.8.11 3) d) iii) (Ta_{max}) limit of 2.92sec.

Table 2: Building Periods

Building	Mode 1 Period; Direction	Mode 2 Period; Direction	Mode 3 Period; Direction
Concrete Building	3.6 sec; Y-axis	3.6; X-axis	1.3 sec; Torsion
Concrete Core w/ Hybrid Wt.	2.9 sec; Y-axis	2.9 sec; X-axis	1.0 sec; Torsion
1-way CLT Hybrid	3.7 sec; Y-axis	3.6 sec; X-axis	1.2 sec; Torsion
2-way CLT Hybrid	3.7 sec; Y-axis	3.7 sec; X-axis	1.3 sec; Torsion

The structural analysis results for the concrete, 1-way and 2-way CLT floor layout buildings that are required for the core wall thickness and lateral drifts are shown in Figure 4. The concrete building requires a much thicker and stiffer concrete core to resist the seismic loading to achieve the same drift limit as the hybrid buildings. This is because with the higher building weight there is a much higher base shear. It is also shown that for each building the resultant wind base shear is constant. This is due to the three buildings having the same overall dimensions. Seismic design governs the concrete building design for the Vancouver area. The ULS design of concrete governs the wall thickness over the SLS design. The concrete core walls for the concrete building could not be further reduced due to the demand for rebar reinforcing even though the lateral inter-story drifts are not close to the 2.5% drift limit. The lateral inter-story drifts for seismic loading are based on the Response Spectrum load case for the dynamic analysis method. Figure 4 also shows the results for lateral inter-story drift for the SLS load combinations: 1.0 Dead Load + 0.75 Wind X and 1.0 Dead Load + 0.75 Wind Y. The hybrid buildings core walls were able to be reduced in thickness significantly while maintaining similar seismic lateral drifts to the concrete building and not failing the sections in the ETABS analysis for rebar requirements for ULS design. Figure 4 further demonstrates how the hybrid buildings lighter weight affects the buildings lateral drift when exposed to the same magnitude of wind loading. Unlike the concrete building which is limited to the seismic load demands, the hybrid buildings are governed by wind serviceability loading due to the large building weight difference. The drifts in directions X and Y are very similar for the three buildings because the building is square and symmetrical. The graphs reflect how accounting for P-Delta effects increases the lateral inter-story drift and deflection for the Response Spectrum load case and the serviceability wind load combinations. P-delta should always be considered in the analysis and becomes more critical the taller a building or structure is.



Concrete Building: 90 m

Concrete Core:	Mpa	Wall Thickness (mm)	Core Weight (kN)	Seismic Drift %	Seismic Drift % P-Δ	Elastic Base Shear (kN)	Response Spectrum Shear (kN)	Design Base Shear (kN)	Wind Base Shear (kN)	Max Wind Drift H/500 (mm)	Max Wind Drift SLS (mm)	Max Wind Drift SLS P-Δ (mm)
Floor 1-10	40	350	9508	0.77	0.79	7145	6367	6367	3910	60	15.9	14.2
Floor 11-20	35	300	8355	1.18	1.20	N/A	N/A	N/A	N/A	120	41.6	44.0
Floor 21-30	30	250	7175	1.29	1.30	N/A	N/A	N/A	N/A	180	74.0	78.0

Hybrid Building 4.5 m 1 way CLT span: 90 m

Concrete Core:	Mpa	Wall Thickness (mm)	Core Weight (kN)	Seismic Drift %	Seismic Drift % P-Δ	Elastic Base Shear (kN)	Response Spectrum Shear (kN)	Design Base Shear (kN)	Wind Base Shear (kN)	Max Wind Drift H/500 (mm)	Max Wind Drift SLS (mm)	Max Wind Drift SLS P-Δ (mm)
Floor 1-10	40	200	4706	0.76	0.77	3951	3528	3528	3910	60	23.9	25.0
Floor 11-20	35	175	4132	1.15	1.17	N/A	N/A	N/A	N/A	120	71.7	75.2
Floor 21-30	30	150	3542	1.27	1.28	N/A	N/A	N/A	N/A	180	126.1	132.5

Hybrid Building 3m 2 way CLT span: 90 m

Concrete Core:	Mpa	Wall Thickness (mm)	Core Weight (kN)	Seismic Drift %	Seismic Drift % P-Δ	Elastic Base Shear (kN)	Response Spectrum Shear (kN)	Design Base Shear (kN)	Wind Base Shear (kN)	Max Wind Drift H/500 (mm)	Max Wind Drift SLS (mm)	Max Wind Drift SLS P-Δ (mm)
Floor 1-10	40	200	4706	0.77	0.78	4065	3582	3582	3910	60	23.9	25
Floor 11-20	35	175	4132	1.16	1.18	N/A	N/A	N/A	N/A	120	71.7	75.3
Floor 21-30	30	150	3542	1.28	1.30	N/A	N/A	N/A	N/A	180	126.1	132.7

Figure 4: LLRS Results

3 ENVIRONMENTAL IMPACT ASSESSMENT

3.1 Overview and methods

A partial Environmental Impact Assessment (EIA) was performed using Athena Impact Estimator for Buildings (Athena 2018). Material properties, weights and volumes were exported from ETABS into Athena to calculate values to compare the three buildings. The control location for this comparison was set to Vancouver, BC the same as the climatic data for the structural analysis. In this EIA comparison, only the superstructure of the three buildings are assessed, the foundation, architectural components, building envelope materials and operational energy are not in the scope of this project therefore this is not a Life Cycle Assessment (LCA). The concrete building has a Bill of Materials (BOM) exclusively as volumes of concrete for the columns, flat plate slab and core walls. The two hybrid buildings have additional Douglas-Fir glulam beams and S-P-F CLT panels.

The production of cement for concrete creates large amounts of CO2 that are emitted into the atmosphere and contributes to global warming or climate change and large amounts of air pollution. The use of a renewable building material such as wood can reduce the amount of concrete required to construct mid to high rise buildings and reduce these environmental impacts. Wood also stores carbon, making it an environmentally friendly building material. The stored carbon is released back into the atmosphere at the end of the materials life cycle when the material is burned as fuel or deteriorates.

The reporting format based on the area of the buildings life cycle that is used by Athena Impact Estimator for Buildings software to analyze the results, based on the EN 15804 (212). Only modules A, C and D which include material extraction, processing, construction process, end of life deconstruction, and beyond building life recycling or reuse are analyzed by Athena. The structural materials for the buildings are converted into equivalent environmental impact masses of kilograms of CO2 for global warming potential and kilograms of O_3 for smog potential.

3.2 Results

Setting the concrete building as the baseline for the BOM comparison it is shown that the hybrid buildings use significantly less concrete for the structural system. The columns used as the gravity system are the same cross section for all three buildings. Incorporating mass timber elements eliminates two thirds of the flat plate slabs and allows the concrete core wall thicknesses to be reduced. The 2-way CLT floor system building is used as the baseline for timber material mass comparison because it has a higher quantity of materials than the 1-way CLT floor system. Using the CLT as a 1-way spanning floor system allows for a thinner panel section and less supporting beams which makes it the more material efficient choice for this building layout.

Figure 5 compares global warming and smog potential of the three different types of buildings with the concrete building set as a baseline. The two hybrid building systems produce nearly half the amount Global Warming Potential (GWP) and approximately three quarters of the Smog Potential (SP) as the concrete building during the material extraction, production and construction phases. This confirms that the production of cement for concrete has a significantly higher environmental impact than using wood materials. At the end of the life cycle mass timber elements are easier and require less energy to disassemble than reinforced concrete as presented in the end of life bar chart in the tables. Producing a hybrid building while utilizing both materials for their strengths is shown to have a positive effect on the environmental impact a building can have by using less than half of the concrete and integrating the much lighter carbon storing mass timber elements.

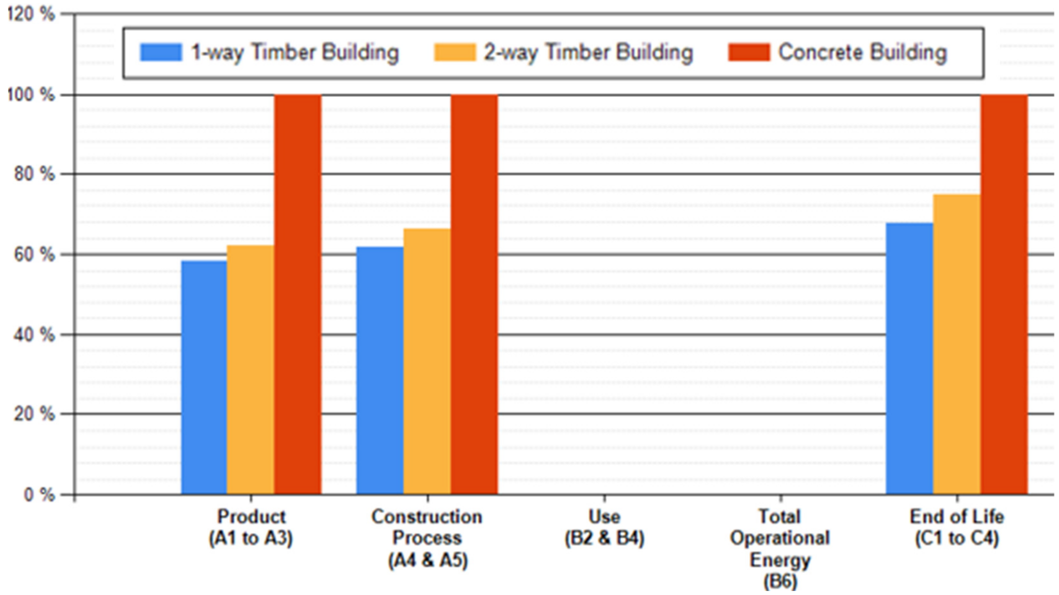


Figure *5*: Global warming potential by life cycle stage, normalized to concrete building

4 DISCUSSION AND CONCLUSIONS

This substitution of two of every three concrete floors with mass timber is based on the target location of China where the current building code limits wood construction to three stories. Substituting two out of every three concrete floors reduces the number of concrete pours, amount of formwork and curing time, hence speeding up onsite building erection time. This paper demonstrates that a 30-storey building can be designed by substituting a significant amount of concrete with mass timber. Wood materials are renewable making them more environmentally friendly and have a much higher strength to weight ratio that concrete. The hybrid building mass was greatly reduced by integrating lighter timber elements resulting in much lower gravity and seismic load demands on the structural system. Reducing the building mass allows the use of thinner concrete core walls for the LLRS while maintaining the lateral drift limits as per NBCC 2015. Unlike the concrete building, where the core thickness was governed by the ULS design for shear rebar reinforcement, the hybrid buildings were governed by SLS for inter-story drift based on the wind loading.

The 1-way CLT panel floor system and 2-way CLT panel floor system layouts were compared because CLT can and is used in both applications. CLT is produced with the intent to be used as a 2-way panel however production in BC is limited to a maximum of 3m width which limits floor layouts. Using a 1-way system uses less supporting beams and a thinner CLT panel resulting in less material. However a 1-way floor system could have a poorer vibration performance when compared to the 2-way system. Using Dowel Laminated Timber for a 1-way spanning floor system would result in a more material efficient system over using CLT as a 1-way spanning floor. These analyses were not within this project's scope.

Integrating mass timber into the structural system resulting in the hybrid buildings reduces the quantity of concrete by 44% compared to the all-concrete building. The hybrid buildings cut down over half of the overall concrete required while only adding between 1,300 to 1,700 tonnes of mass timber. This shows a large reduction in the GWP by cutting down from 18,672 tonnes of total material to 9,482 tonnes and 9,858 tonnes for - hybrid buildings. This EIA only scratches the surface of a LCA and further investigation into building use and operational energy which is widely reflected on the building envelope and building location needs to be performed to have more accurate results. Expanding on this project, further investigations should be done on the connections between the structural elements, and the constructability issues.

Acknowledgements

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