World Conference on
Timber Engineering
Oslo 2023

STRUCTURAL AND LIFE CYCLE ANALYSES FOR A TIMBER-CONCRETE HYBRID BUILDING

Xiaoyue Zhang [1], Wanru Huang [2], Mehdi Khajehpour [3], Mehrdad Asgari[4], Thomas Tannert [5],

ABSTRACT: The concerns related to the impact of construction materials are increasing globally. Timber-based hybrid buildings combine the structural benefits of multiple materials, reduce the carbon footprint, shorten construction times, and potentially improve seismic and building physics performances. In this paper, a ten-story timber-concrete hybrid building, designed for a location in the Guizhou Province, China, is compared to a pure concrete building. The structural analysis showed that the self-weight of the hybrid structure was reduced by 30% compared with the concrete structure, and the base shear forces in X- and Y-directions decreased by 43% and 29%, respectively. The life-cycle analysis showed that hybrid building had lower impacts than the concrete building in six categories: global warming potential, acidification potential, human health particulate, eutrophication potential, ozone depletion potential, and photochemical ozone formation potential. Specifically, in terms of global warming potential, the hybrid building had nearly 65% lower emissions, and the wood components have the additional advantage to store carbon over their lifetime. These results promote the development and application of high-rise timber-based hybrid buildings in China.

KEYWORDS: Tall Timber, Hybrid Building, Structural Design, Life Cycle Analysis

1 INTRODUCTION

1.1 BACKGROUND

Timber-concrete hybrid buildings combine the benefits of both materials, specifically the environmental benefits of timber and the fact that concrete is non-combustible. The most common type of tall wood hybrid structures is combining a cast-in-place concrete core that resists the lateral loads, with the timber structure carrying the gravity load [1]. Many feasibility studies have confirmed the significant potential of timber-concrete and timber-steel hybrid systems in terms of structural performance, sustainability, and construction speed [2-5].

Several timber-hybrid buildings have been successfully constructed. The 8-storey LifeCycle Tower ONE has concrete foundations and a concrete core, with glulam columns and hybrid slabs that span up to 9 meters [6]. The world's tallest hybrid wood-based building, the 18-story "Brock Commons" in Vancouver, Canada, features a cast-in-place concrete ground floor and two elevator cores with CLT floors and Glulam columns [7]. The 17 stories of mass-timber superstructure carry all gravity loads, while two concrete cores act as LLRS.

These successful examples illustrate the potential of timber-concrete hybrid buildings in offering a combination of structural and environmental benefits.

1.2 LIFE CYCLE ASSESSMENT

To evaluate the environmental impact of buildings, Life Cycle Assessment (LCA) has been developed to provide an in-depth assessment of the life cycle performances of entire buildings, construction materials, and components, from the "cradle" to the "grave" [8]. Designers use LCA to assess the impact of a building's energy and materials on the environment, systematically integrating the complete life cycle of products to develop sustainable building solutions [9]. LCA allows estimating the environmental impact over the entire lifespan of residential, commercial, and industrial buildings, from resource extraction to land filling and beyond [10].

Numerous previous studies have compared wood to other building materials such as reinforced concrete. For instance, Robertson et al. [11] demonstrated that the environmental impact from the cradle-to-construction site of traditional cast-in-place concrete is higher than that of wood products (hybrid CLT and glulam).

[1] Xiaoyue Zhang, Chongqing University, Chongqing China, xiaoyuezhang@cqu.edu.cn
[2] Wanru Huang, Chongqing University, Chongqing China, 13364030956@163.com
[3] Mehdi Khajehpour, University of Northern British Columbia, Prince George BC Canada
[4] Mehrdad Asgari <masgari@unbc.ca
[5] Thomas Tannert, University of Northern British Columbia, BC Canada, Thomas.Tannert@unbc.ca

https://doi.org/10.52202/069179-0129

Basaglia et al. [12] compared the LCA of three materials (GLT, CLT, and concrete) and showed that the embodied energy of CLT is almost 2.5 times higher than that of concrete. Lu et al. [13] sowed that emissions of engineered wood in the environmental categories of greenhouse gas, acidification, human toxicity, and fission depletion are all low compared to concrete and steel for multi-storey residential buildings. Jayalath et al. [14] assessed the environmental impact of high-rise residential buildings in CLT and showed that the carbon dioxide emissions were reduced by up to 34% compared with reinforced concrete residential buildings. However, there is limited research on LCA for timber-concrete hybrid systems.

1.3 OBJECTIVE

The objective of this research was to promote the development of timber-based hybrid high-rise construction systems in China. To meet this objective, the structural and environmental performance a 10-storey case-study glulam timber frame with concrete core structure is compared to that of a pure concrete building.

1.4 BUILDING DESCRIPTION

A hybrid system composed of wood frames and concrete shear walls for a 10-storey hotel, located in Jianhe County, Guizhou province of China, was designed. The storey height was 3.9 m, for a total building height of 46.4 m to the top of the roof, with a typical story floor area of 924 m^2 (23.1 × 40 m) for a total 10,000 m^2 building area.

The hybrid building, shown in Figure 1a, consisted of a concrete core, concrete base, and a glulam frame system. The first concrete floor is the parking lot, and the upper nine stories consist of mass-timber superstructure, carrying all gravity loads. The concrete core acts as the wind and seismic lateral load-resisting system [15]. The structure was designed in accordance with the structural design codes and technical standards of China. For some connection and component design, i.e., the timber-concrete composite (TCC) beams, Eurocode 5 [16] was used as a reference.

The pure concrete building, illustrated in Figure 1b, also consisted of a concrete core and a concrete base used as the parking lot, but instead of using wood frames for the gravity system, it had a reinforced concrete gravity framing. The design was based on Chinese building code GB50010-2010[17].

2 METHODS

2.1 STRUCTURAL DESIGN

The gravity loads included dead load, live load, and snow load. The total dead load for typical floor (including 100 mm concrete topping, partition load and miscellaneous) was 380 kg/m^2. For the roof, the total dead load was 280 kg/m^2. The live load was 250 kg/m^2, and the roof snow load was 500 kg/m^2, based on the location. All values are typical for Chinese hotels and were obtained from GB 50009-2012 [18]. According to GB50011-2010 [19], the lateral systems were designed for seismic intensity 7 with a basic ground acceleration of 0.1 g for a site class II.

The hybrid model adopted Glulam frames to transfer the gravity loads to the foundation. Grade TC_T21 was used for both girders and columns [15,18]. Based on the vertical loads, the typical column size was 580 × 580 mm. The Glulam girders as the main framing beams span between 9 and 11 m in north-south direction with secondary glulam beams placed on top in east-west direction, see Figure 2. The depth of girders was 580 mm to satisfy the structural clearance requirements. The 290 × 290 mm cross section was selected for the glulam beam girders and 240 × 400 mm cross section was selected for secondary glulam beams, all based on the Chinese timber building design codes GB 50009-2012 [18], GB5005-2017 [20], GB 50206-2012 [21], and GB T 50329 2002 [22].

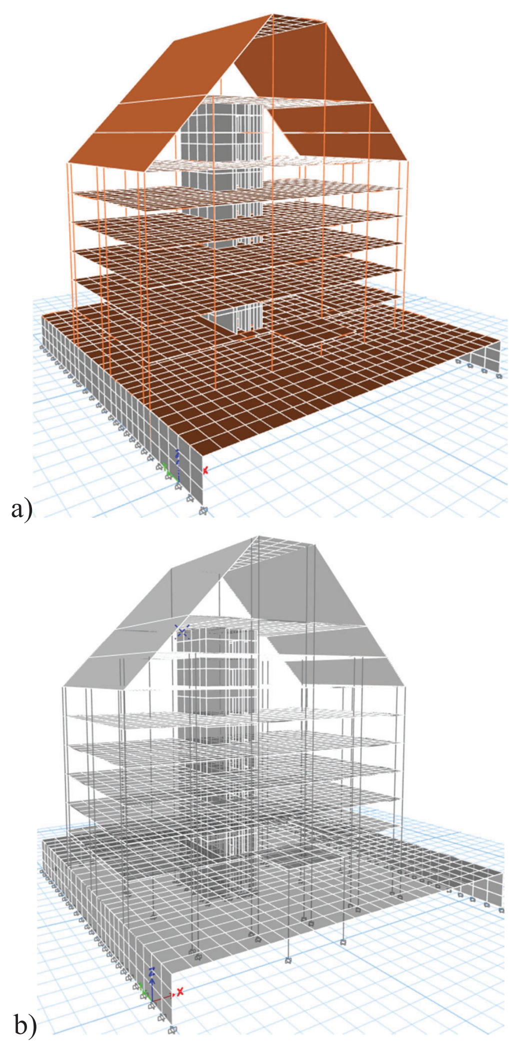

Figure 1: *3D ETABS models: a) hybrid building; b) concrete building*

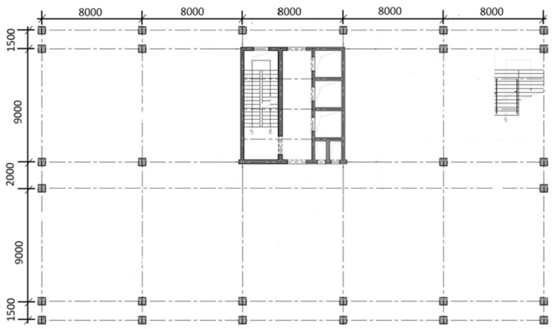

Figure 2: *Typical floor plan for both buildings*

2.2 STRUCTURAL ANALYSIS

Both buildings were modelled in ETABS [23]. In the hybrid model, the wood frames were used to transfer the gravity loads. The columns were pinned to avoid imposing any lateral stiffness on the lateral load-resisting system. P-Delta effects, which are created from the lateral deflections, were also considered.

The concrete building design was based on GB 50010-2010 [17]. There, concrete slabs and columns transfer the gravity loads, and the slab/beams and columns were connected through a fixed connection. Normal density concrete with a strength grade of C30 was used.

For both models, the main structure (top 9 stories) stands on the underground floor with perimeter retaining walls. The loads coming from the soil pressure were also taken into account and imposed on the retaining walls. The column bases were modelled as pinned to the ground to neglect the stiffness of the base column connections, which is negligible compared to the stiffness of the shear walls. The foundations were composed of strip footing under the columns and perimeter retaining walls, with a slab (pad) footing under the core shear wall.

Regarding the lateral load resisting system, ductile-reinforced concrete shear walls were assigned to both models. In the hybrid model, the walls were put in the middle of the plan as a "core" system to accommodate architectural elements. Concrete slabs on the metal deck, which seats on the wood frames, were modelled to carry the gravity loads, and to act as the diaphragm to transfer the seismic shear to the core shear walls. For the concrete model, the shear walls were optimized along with the reinforced concrete moment frames to transfer the seismic loads.

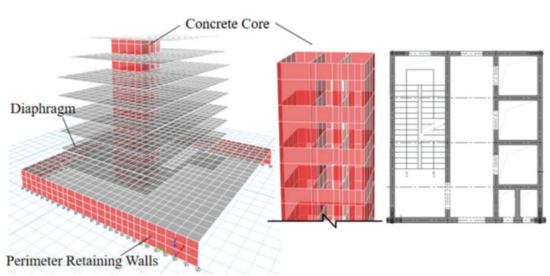

Figure 3: *Lateral Load Resisting System for both models*

2.3 LIFE CYCLE ASSESSMENT

The Athena Impact Estimator for Building (IE4B) [24], an open-source software, was used to assess the environmental impact of both buildings. It can be applied to any type of new construction, renovations, and additions projects in North America.

Athena IE4B contains life cycle inventory (LCI) called the Athena database, or TRACI [25]. LCI is the data collection portion of the LCA [26]. These methods focus on the following impact categories: ozone depletion climate change, acidification, eutrophication, smog formation, and non-renewable energy consumption [27]. The material inputs for LCA came from the building's design blueprints and were included in the Data collection report. 60 years was selected as the service life for a commercial structure. The cradle-to-grave LCA data found within the various LCI databases conform to ISO 14040 standards [28].

To conduct LCA and compare the environmental impact of the hybrid and pure concrete buildings, six impact categories of the TRACI protocol were used. The calculation process is divided into three main parts: (i) estimate of quantities of materials and processes in the building; (ii) estimate of environmental impacts for each material and process; (iii) estimate of the total environmental impact of the building. The scope of this LCA was a cradle-to-grave assessment of the material effect of structure, envelope, and operating energy and water use during 60 years modelled by IE4B [24].

3 RESULTS

3.1 BASE SHEAR COMPARISON

The base shear forces were obtained from the ETABS models based on the seismic provisions of the Chinese code. As shown in Figure 4, the seismic base shear forces for hybrid model (timber-concrete hybrid structure) and concrete model (pure concrete structure) in the X direction are 3,449 kN and 4,716 kN respectively, which is 43% different. The values in the Y direction are 3,084 kN and 3,983 kN, almost 29% different. The lower base shear of the hybrid model shows the efficiency of replacing the concrete framing.

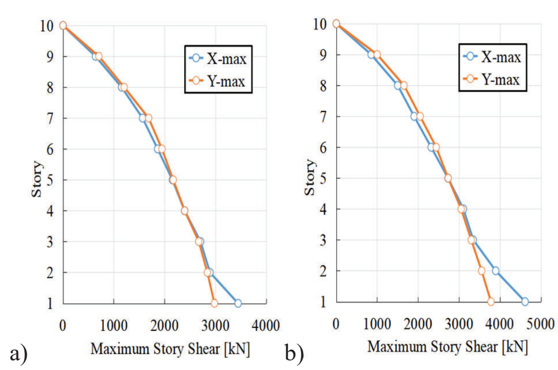

Figure 4: *Storey shear: a) hybrid building; b) concrete building*

https://doi.org/10.52202/069179-0129

3.2 INTER-STORY DRIFT

The current Chinese Code for Seismic Design of Building (GB50011-2010) [19] limits the elastic and elastic-plastic inter-story drift to 1/800 and 1/100, respectively, to limit the damages to the lateral load resisting systems and the non-structural components and sensitive elements of a structure. Figure 5 shows the "elastic" story drifts of hybrid and pure concrete structures, respectively, under the response spectrum in the X direction.

For the real "inelastic" story drifts, these values must be multiplied by the corresponding ductility coefficient of the structure. Since the intention of this article is simply to compare these two systems, we will only consider the elastic story drift ratios. The drift of storey 2 in the hybrid structure is nearly half of that in the pure concrete structure (0.030% versus 0.056%), which were below the drift limit of 1/800. The reason for this large difference is that the weight of the super-structure is much higher in the pure concrete structure.

On the other side, the stiffness of the storey 2 lateral load-resisting system in both buildings is almost the same, since both buildings' shear wall thicknesses are the same. The reason is that, in Chinese concrete code, the shear wall thickness is usually governed by the "minimum" wall thickness based on the level of "ductility" and the height and width of the walls, in other words the geometry. Therefore, both buildings required the same wall thickness. The second main observation is that, for the higher stories, the drift ratios for the pure concrete structure are higher than the hybrid structure, however, this difference is lower, around 25% to 50%.

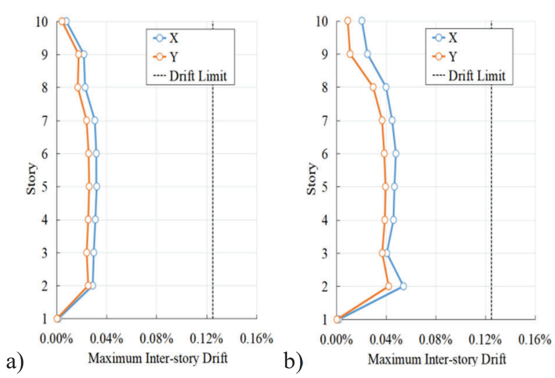

Figure 5: *Maximum story drift in X direction: a) hybrid building; b) concrete building*

3.3 BUILDING MATERIAL INVENTORY

The 10-storey concrete building set the baseline for the Bill of Material (BOM). The BOM of the buildings exported from ETABS includes foundations, columns, beams, floors, and walls. The pure concrete structure consists of a shear wall, concrete slabs, concrete columns and beams, and all the rebars related. On the other hand, the hybrid structure includes a foundation, concrete shear walls, concrete topping of the slab, and glulam beams and columns.

After inputting the BOM of the two buildings, the total mass value of materials used in each building component was computed. As shown in Table 1, replacing concrete frames with wood frames has reduced material consumption. The amount of concrete used in timber-concrete hybrid structure is 5632000 kg, versus 9189000 kg used in the pure concrete structure, which is 40% less. Additionally, the foundation in the hybrid building is only 700 mm thick under the core wall, versus 900 mm thick core wall slab footing under the concrete footing. This will require less excavation and a faster construction procedure. Lower concrete consumption along with the lower base shear has also resulted in less steel reinforcement needed for the composite structure. The hybrid structure only used 39% steel reinforcement of the amount used in the pure concrete structure. This reduction in concrete and steel consumption will have a great impact not only financially, but also in terms of CO_2 emission and environmental effects.

Table 1: *Bill of Material for hybrid and pure concrete building*

Hybrid model			
Materials	Concrete (m^3)	Glulam (m^3)	Steel (kg)
Columns, beams	0	304	0
Floors	1041	1251	26000
Foundation	599	0	16000
Roof	0	0	0
Wall	791	0	35000
Total Volume (m^3)	2431	1555	-
Total Mass (kg)	5632000	727000	77000
Pure concrete model			
Materials	Concrete (m^3)	Glulam (m^3)	Steel (kg)
Columns, beams	210	0	42000
Floors	1933	0	100000
Foundation	889	0	19000
Roof	0	0	0
Wall	791	0	39000
Total Volume (m^3)	3823	0	-
Total Mass (kg)	9189000	0	200000

3.4 LIFE CYCLE ANALYSES

Table 2 shows the comparison of the overall impacts of the two buildings. The hybrid building performs better in all analyzed impact categories. The critical part of these results is the difference in Global Warming Potential (GWP) where the hybrid building has 65% lower value. The tropospheric ozone formation potential (Smog or POCP) value of forest operations is affected by the emissions of a chainsaw, but the wooden material still performs better than concrete with 18.4 kg O_3 eq /m^2 less. Stratospheric Ozone Depletion (ODP) and Acidification Potential of the hybrid building are 9% and 15%, respectively.

Table 2: *Cradle to Grave LCA comparison for two functionally equivalent buildings*

Summary measure	Hybrid building	Concrete building
Global warming potential (kg CO_2 eq)	1.79E+06	6.26E+05
Stratospheric ozone depletion (kg CFC-11 eq)	1.58E-02	1.44E-02
Acidification potential (kg SO_2 eq)	8.76E+03	7.42E+03
Eutrophication (kg N eq)	8.02E+02	7.01E+02
Tropospheri ozone formation (kg O_3 eq)	1.84E+05	1.48E+05
Depletion of non-renewable energy resources (MJ)	1.66E+07	1.25E+07

Figure 6 displays the percentage contributions of the building components to six environmental impact categories using LCA results. For the concrete building, the foundation which was the second most concrete and the floor and roof which was primarily concrete by volume contributed approximately 50% of the building material. Similarly, the timber-concrete hybrid building was separated into the same components, except that the mass-timber superstructure, responsible for carrying all gravity loads, rested on a concrete core that acted as both the wind and seismic lateral load-resisting systems.

The environmental impact indicators for both buildings were primarily attributed to the floors and roof, with roughly 50% impact in all categories, except for Global Warming Potential (GWP), which had a lower emission rate of 15% in the hybrid building due to the use of mass timber. As a result, the GWP was reduced by 35% in the timber-concrete building. In the pure concrete structure, the foundation was responsible for the second-highest emission portion, with 23% in Ozone Depletion Potential (ODP), 22% in Acidification Potential (AP), Human Health (HH) potential, Eutrophication Potential, and 21% in Smog Potential. However, the foundation's contribution decreased to approximately 17% in the timber-concrete hybrid building, while it remained the second-highest emitter in GWP with 42%. Shear walls had similar emissions in both buildings, with approximately 21% in the concrete structure and around 22%, except for GWP with 57%, in the hybrid building. The columns and beams had the lowest contribution to environmental impact, with approximately 7% in the pure concrete building and around 6% in the hybrid building. However, this decreased to -14% in GWP due to the glulam material used.

Overall, the use of timber in the hybrid building results in a lower environmental impact across all indicators, especially in terms of GWP. The environmental emissions of the hybrid building are improved by incorporating TCC floors, replacing the traditional cast-in-place concrete floors. As a result, the GWP of a 10-story timber-concrete hybrid building is estimated to be reduced by approximately 35%.

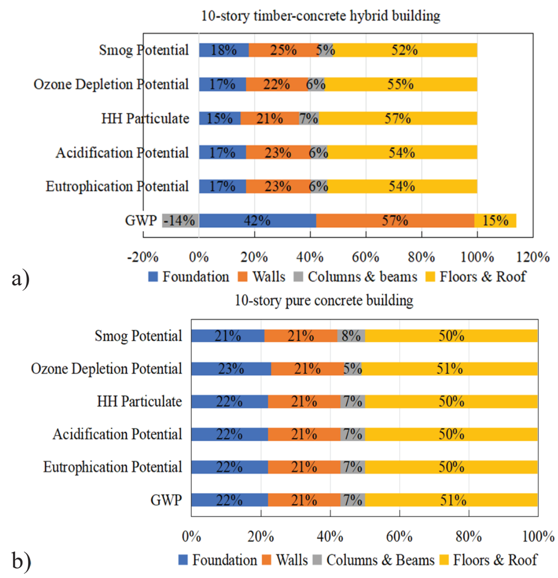

Figure 6: *Percentage of contribution to environmental impact category: a) hybrid building; b) concrete building*

Figure 7 presents the emissions of concrete and mass timber buildings separated by life-cycle stage for the categories of GWP, acidification potential, human health particulate, eutrophication potential, ozone depletion potential, smog potential, and total primary energy. The A1-A3 stage contributed 88% and 87% of the total GWP emissions for concrete and mass timber buildings, respectively. The construction (A4 and A5) and end-of-life (C) stages contributed more to the total emissions of the hybrid buildings than the concrete building. In addition to GWP, ozone depletion potential, and human health particulate, eutrophication potential has a significant environmental impact on both buildings, with total eutrophication potential emissions of 829 and 712 kgN eq for pure concrete and timber-concrete hybrid buildings, respectively, of which 80% and 84% are attributed to the production stage (A1-A3).

The beyond-life considerations are difficult to predict decades into the future. For mass timber buildings, the GWP impact category can be highly influenced by the beyond-building life stage (D) and how carbon emissions are accounted for. Figure 8 studies the beyond-building life emissions (stage D), including the biogenic carbon of the mass timber buildings. The results show that the amount of sequestered carbon for the hybrid building, stage A-D, is significantly lower than the total amount of embodied carbon for stages A-C. It should be noted that this study does not include the contributions of non-structural interior building components, such as partition walls, carpeting, windows, etc. Therefore, the timber-concrete hybrid building has a significantly lower environmental impact than the concrete structure, mainly due to the much smaller amount of sequestered carbon related to the timber-concrete hybrid building.

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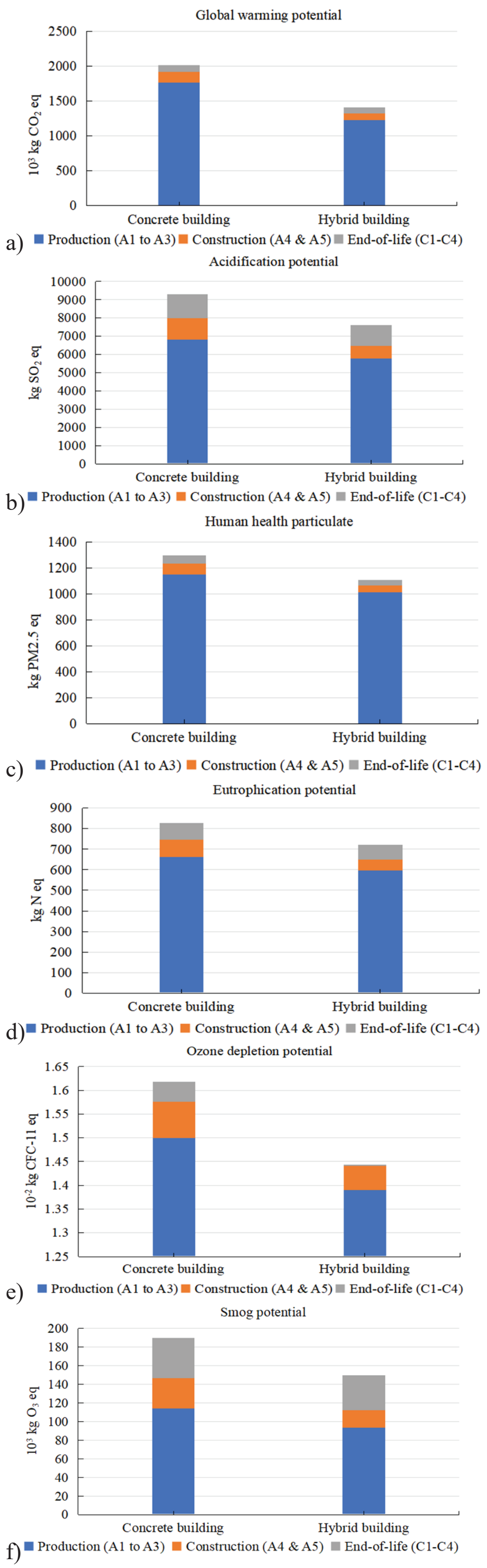

Figure 7: *LCA environmental impact data: a) GWP; b) AP; c) HH; d) EP; e) ODP; f) Smog*

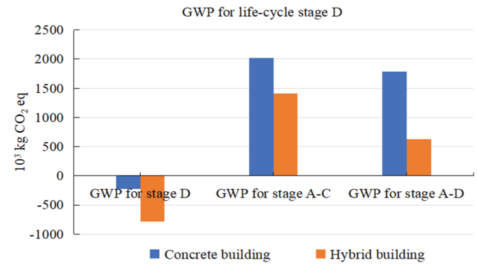

Figure 8: *LCA global warming potential for life-cycle stage D*

4 CONCLUSIONS

The structural and environmental performance of two ten-storey buildings with different frames was compared: one with a wood frame and the other with a concrete frame. The following main conclusions were drawn:

1) Using wood in the hybrid building led to a significant reduction in weight of about 30%. Additionally, the hybrid building had superior seismic performance, which reduced foundation requirements, resulting in time and cost savings. The maximum inter-storey drift in the hybrid structure was almost half that of the all-concrete structure, which was below the drift limit of 1/800.

The LCA results indicated that the hybrid building had favourable values for all categories considered, such as global warming potential, stratospheric ozone depletion, acidification potential, eutrophication, smog potential, human health particulate, non-renewable energy consumption, fossil fuel consumption, and total primary energy consumption. The hybrid building emitted nearly 65% less CO_2, and the wooden components acted as carbon storage for its entire lifetime.

Based on the structural and environmental performance of the hybrid building, this study can serve as a useful guide for the design of timber-based hybrid high-rises in China. The results demonstrate the benefits of using wood in construction, including reduced weight and improved seismic performance, which can save on foundation requirements, time, and cost. Moreover, the significant reduction in CO2 emissions and the carbon storage potential of wooden components in hybrid structures can contribute to mitigating the effects of climate change.

ACKNOWLEDGEMENT

The authors also would like to thank the National Natural Science Foundation of China (Grant Nos. 52108192); China Postdoctoral Science Foundation (Grant Nos. 2022M710528); The Chongqing Technology Innovation and Application Development Project (CSTB2022TIAD-KPX0138); the OEICDI fund (Grant Nos. B13041); the Entrepreneurship and Innovation Support Program for Overseas-educated student in Chongqing China (Grant Nos. CX2021085).

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