



# Structural Design and Analysis for a Timber-Concrete Hybrid Building

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The benefits of using wood in tall and commercial construction are undisputed, namely reducing the carbon footprint, shortening construction times, and enhancing seismic and building physics performance. The international market for wood as a structural material in tall and non-residential construction, however, is still relatively untapped. China is home to the world's largest population and the largest construction sector worldwide, yet wood products are only used in a small fraction of buildings. The main reasons for this situation are the fire regulations and lack of guidelines for novel wood-based structural systems. This paper describes the design of a 10-storey timber-concrete business hotel which will be erected in the Guizhou province of China. The foundation design, gravity system design, lateral load resisting system design, seismic analysis and the fire resistance design were conducted, and the procedure provided appropriate information to the technological feasibility to promote the development of timber-based hybrid high-rise construction systems in China.

**Keywords:** tall timber-concrete hybrid building, glulam column, structural design, ground motion, seismic analysis

## INTRODUCTION

### Background

Wood, as one of the most attractive construction materials due to its renewability and carbon sequestration, has always been an essential part of the built environment (Foliente, 2000). Multiple studies (Buchanan et al., 2012; De Wolf et al., 2017; Andersen et al., 2021; Ryberg et al., 2021) demonstrated when compared to concrete or steel, using wood or its engineered wood product derivatives, e.g. Glued-Laminated Timber (GLT), Cross Laminated Timber (CLT), Laminated Veneer Lumber (LVL) and so on, as building materials present a favourable environmental balance. Wood contains a lot of solar energy, only a small amount of fossil fuel is needed in the production process, that is generally pollution-free in the production process. Modern wood structures produce little construction waste, which can improve the utilization efficiency of materials. Moreover, wood waste can be burned as renewable energy instead of fossil fuel to reduce energy consumption. The carbon dioxide released by wood combustion is the solar energy stored in the wood itself, which is part of the natural cycle and will not lead to the increase of greenhouse gases (Buchanan, 2007). According to Ritter et al., the proper installation and use of wood products in houses often reduce the greenhouse gases produced by products, and the environmental burden is lower than other building materials with the same function (Ritter et al., 2011). According to the case of tall wooden buildings, it is found that the cost of a 20-storey CLT building with the same function is roughly the same as that of a concrete building (Robertson et al., 2012). With the proposal of sustainable development goals and the increasing

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### Specialty section:

This article was submitted to  
Structural Materials,  
a section of the journal  
Frontiers in Materials

**Received:** 28 December 2021

**Accepted:** 24 January 2022

**Published:** 25 February 2022

### Citation:

Zhang X, Xuan L, Huang W, Yuan L  
and Li P (2022) Structural Design and  
Analysis for a Timber-Concrete  
Hybrid Building.  
Front. Mater. 9:844398.  
doi: 10.3389/fmats.2022.844398



FIGURE 1 | Sketch of 10 storey timber-concrete hybrid building.

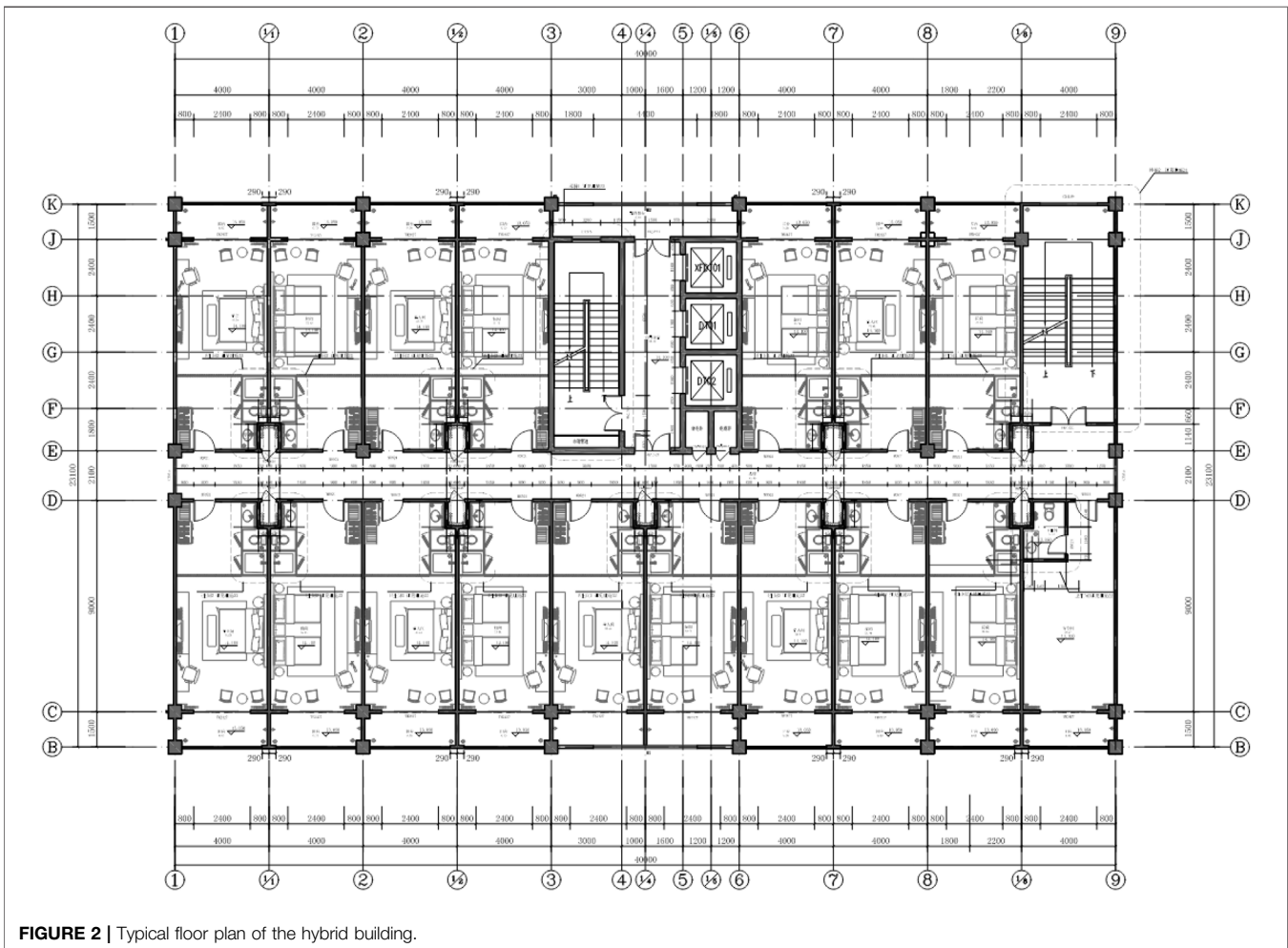


FIGURE 2 | Typical floor plan of the hybrid building.

awareness of environmental protection, the positive attributes of wood are gradually highlighted, making it become the preferred green building material to replace steel and concrete.

Although the application of wood in building systems has a good performance record, the international market for wood as a structural material in tall and commercial construction is still relatively small and the building regulations all over the world

limit the building height and area of wood in high-rise buildings, especially in China, where the relative research on the timber-based structure is backward.

### Tall and Hybrid Timber Construction

With the rapidly increasing human population and the corresponding pressures on land resources, it has been

**TABLE 1** | Structural member specifications and material parameters (GB T 50708, 2012) (GB 50010-2012: Code for design of concrete structures, 2015).

Member	Material	Grade	Material properties				
			$f_m$ (MPa)	$f_c$ (MPa)	$f_t$ (MPa)	$f_v$ (MPa)	$E$ (MPa)
Glulam beam	Douglas fir	TC <sub>T</sub> 21	21	—	—	2.2	11,700 <sup>a</sup>
Glulam column	Douglas fir	TC <sub>T</sub> 21	21	20	15	—	8,000
Structural core	Concrete	C45	—	21.1	1.8	2.8	33,500

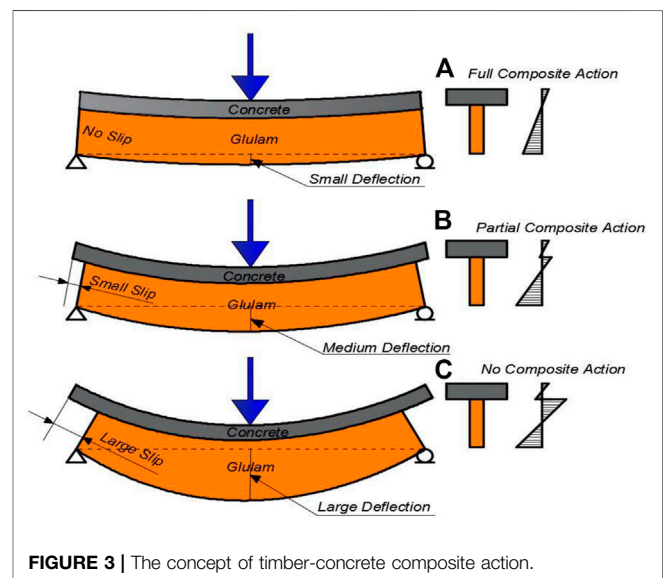
<sup>a</sup>The Glulam Beam is locally manufactured by YF, its elasticity modulus is obtained based on their tested results.

**TABLE 2** | Glulam beam design.

Glulam beam design		
Label	GB1:Glulam Girder	GB2:Glulam Secondary Beam
Beam size	290×2–290 mm	240 × 400 mm
Ratio of resistance vs. demand for the member with maximum force loaded		
Shear	45.8%	28.4%
Moment	46.4%	58.0%
Shear (1-h fire)	42.1%	92.4%
Moment (1-h fire)	61.2%	28.1%
Natural frequency of vibration	8.0 Hz	5.7 Hz

argued that it is a matter of urgency to find a way to expand the possibilities of using wood as an efficient solution for large-scale tall buildings (Green and Karsh, 2012). Therefore, timber high-rise or timber-hybrid buildings are attracting more and more attention worldwide. Many studies have confirmed that timber and timber-hybrid buildings have enormous potential to reach higher heights with desired structural and environmental performance (Foster et al., 2016; Ramage et al., 2017; Wimmers, 2017; Zhang et al., 2021). Over the last decade, North America, Europe and other countries have begun to study the new system of building multi-storey and high-rise timber hybrid structures with other materials, for example, the concrete or the steel (He et al., 2016; Zhang et al., 2017; Zhang et al., 2018). Several feasibility studies for innovative tall timber-based hybrid structural systems were carried out, and many prototype buildings were tested (Kuilen et al., 2011; Hristovski et al., 2013; Zhang et al., 2016; Izzi et al., 2018). Meanwhile, several tall timber and timber-hybrid buildings, e.g., the 18-story Brock Commons in Canada (Tannert and Moudgil, 2017) and the 18-story Mjøstårnet in Norway (Abrahamsen, 2017), have been successfully built and are operating well, which demonstrates great competitiveness in the aspects of structural performance, environmental friendliness, and construction speed.

Timber-concrete hybrid building refers to the structure form dominated by wood structure and concrete structure. The most common type of tall wood hybrid structures is combining a case-in-place concrete core that resists the lateral loads, with the timber structure carrying the remainder of the gravity load and diaphragm loads. According to relevant research, timber concrete hybrid structure gives full play to the best performance of wood and concrete, and has higher bearing capacity, fire resistance and

**FIGURE 3** | The concept of timber-concrete composite action.

seismic performance compared with pure wood structure (Poirier et al., 2016).

## Timber Construction in China

Building tall structures with wood in China is not new - pagodas built hundreds of years ago are still standing despite exposure to seismic events, strong winds, and high-moisture environments (Lam et al., 2008). However, due to the shortage of wood resources and fire safety considerations, the government set strict rules to limit the use of timber and more attention was paid on the study and construction of steel and concrete

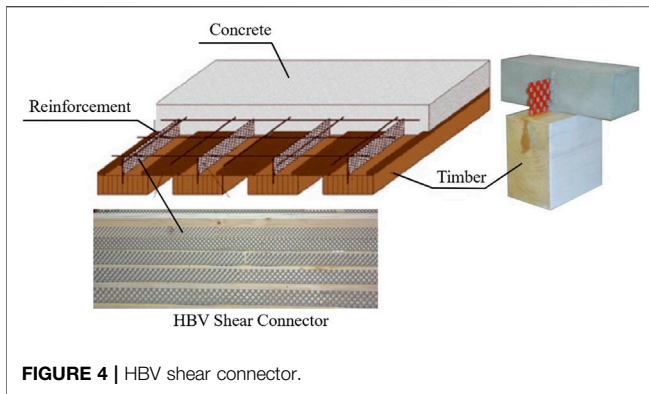


FIGURE 4 | HBV shear connector.

structures (Li et al., 2016; Karol et al., 2018; Li and Wang, 2021). Thus, the timber construction decreased rapidly and there have height and area limitations on it (timber structures were once limited to no more than three storeys in China, and the height was limited to no more than 10 m) (GB50016-2014: Code for Building Design on Fire protection, 2018).

Thanks to the advances in fire separation/fire-stopping system technology and the production of engineered wood products in worldwide, especially the global integration of low-carbon economy, increasing attention has been paid to using and researching structural timber in China in the past 2 decades. Imported dimension timber, glued-laminated timber and cross-laminated timber have recently been used to build homes, schools, shopping malls and stadiums, and substantial research has been undertaken on novel timber-based hybrid structures (Li et al., 2018).

Since the long construction periods for reinforced concrete buildings cause serious on-site noise and dust pollution, the Chinese government recently proposed a reform of the national approach to building systems and an implementation of the industrialization of buildings. Efforts are made to promote and develop prefabricated buildings which also include wood

constructions. With the growing interest in using timber for structures and in expanding the tall wood building sector, there is a desire to develop design guidance for timber high-rises under consideration of the very strict fire resistance requirements in China. One approach, and currently the most feasible for China, to overcome the height and scale limitations in building codes is to use wood in combination with non-combustible materials. The timber-concrete hybrid building is one of the good options to provide a good balance for people’s living quality, environmental conservation, and fire protection.

### Objective

The Objective of this study is to provide appropriate information on developing a timber concrete hybrid high rise building in China. Case studies of a 10-storey glulam timber frame with the concrete core business hotel are provided to present its structural design details and seismic performance.

## STRUCTURAL DESIGN OF THE TIMBER-STEEL HYBRID BUILDING

### Overview

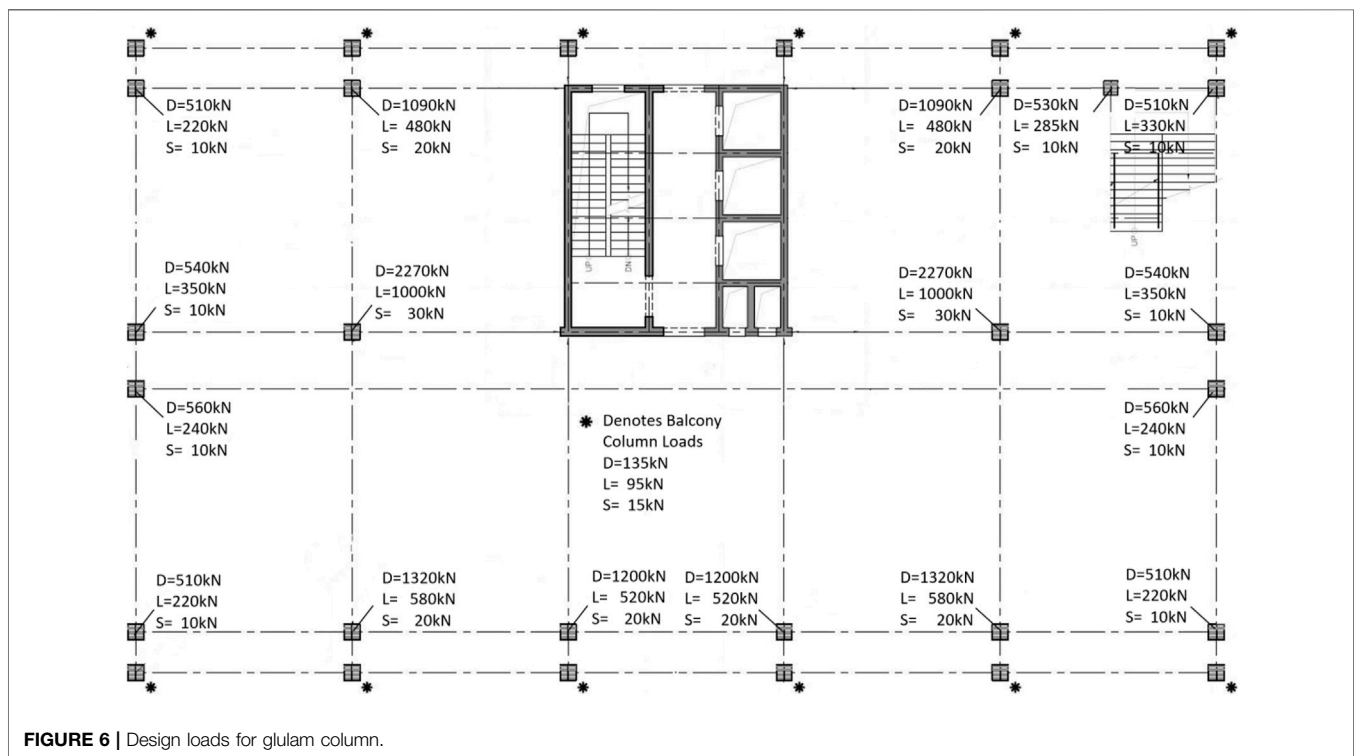
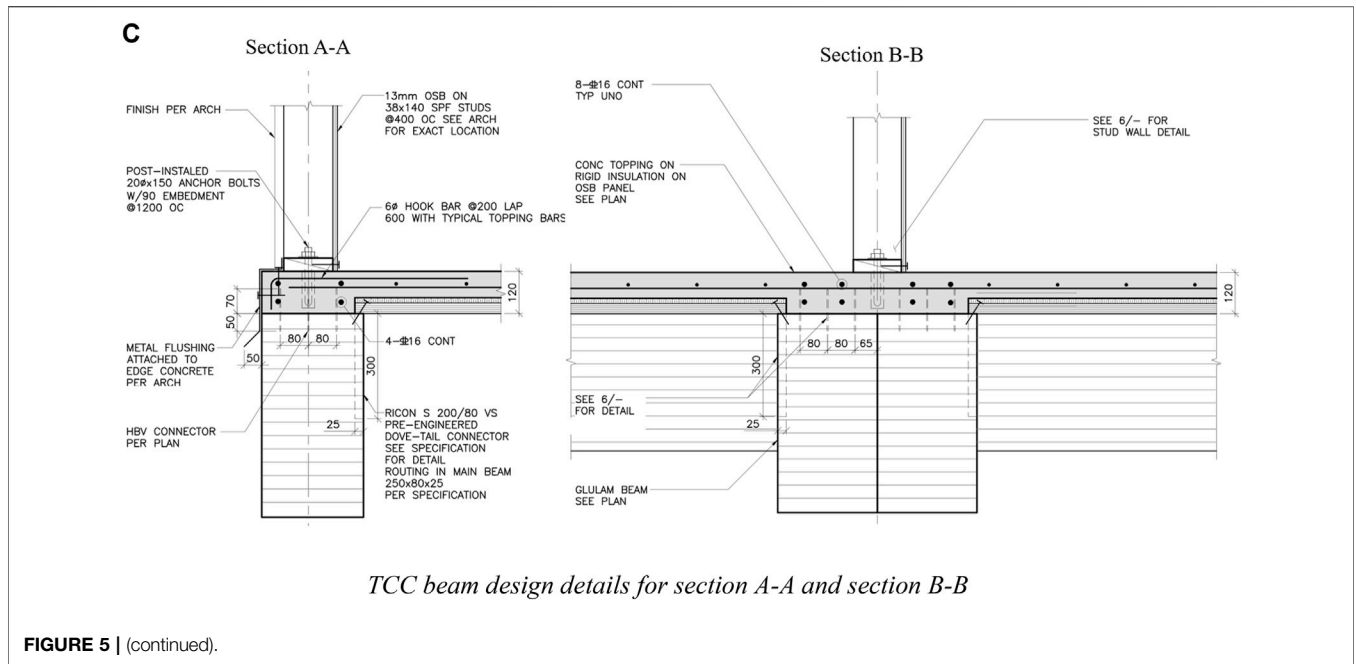
A 10-storey timber-concrete hybrid building, proposed by the Guizhou Jianhe Yuanfang Forestry Investment & Explore Co., Ltd. (YF for short). was designed by Equilibrium Consulting Inc. The building was proposed for the location Jianhe County, Guizhou province of China and is designed for occupation as a luxury business hotel.

The building consists of a concrete core, concrete base and a Glulam frame system, shown in **Figure 1**, the first concrete floor is the parking lot, top nine stories of mass-timber superstructure, carrying all gravity loads, rest on the concrete core that act as both the wind and seismic lateral load-resisting systems. As shown in **Figure 2**, The 10-storey building has a typical inter-storey height of 3.9 m, a total building height of 46.43 m to the top of the timber roof, a typical storey floor area of 924 m<sup>2</sup> (23.1 × 40 m), a total

TABLE 3 | Timber concrete composite (TCC) beam design.

Timber concrete composite beam design					
Label	TCC <sub>1</sub>	TCC <sub>2</sub>	TCC <sub>3</sub>	TCC <sub>4</sub>	
Beam Size			290mm×2–290 mm		
Shear Connection	3-HBV 1000 × 120 at 1350	2-HBV 1000 × 120 at 1350	1-HBV 1000 × 120 at 1350	3-HBV 1000 × 120 at 1100	
Ratio of resistance vs. demand for the member with maximum force loaded					
Shear	Concrete	84.9%	51.6%	15.9%	89.7%
	Timber	41.3%	24.1%	7.8%	43.2%
	HBV	92.1%	66.4%	50.1%	96.7%
Moment	Concrete	32.3%	20.8%	37.5%	28.4%
	Timber	48.6%	39.1%	46.8%	17.9%
	HBV	80.0%	56.2%	46.9%	83.2%
Shear (1-h fire)	Concrete	74.6%	44.5%	14.3%	77.8%
	Timber	52.3%	33.2%	10.5%	44.1%
	HBV	80.0%	56.2%	46.9%	83.2%
Moment (1-h fire)	Concrete	37.3%	22.9%	43.5%	36.4%
	Timber	70.5%	55.2%	68.1%	63.7%
	HBV	80.0%	56.2%	46.9%	83.2%
Vibration Frequency of Vibration		9.6hz	9.6hz	20.6hz	7.0hz



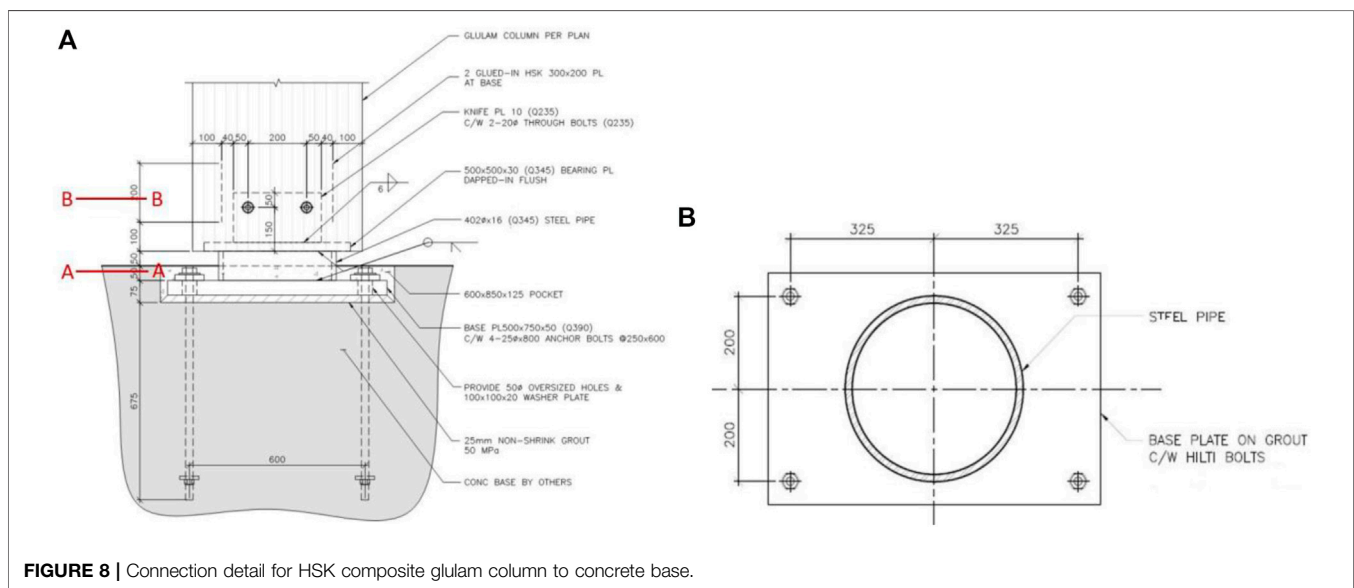
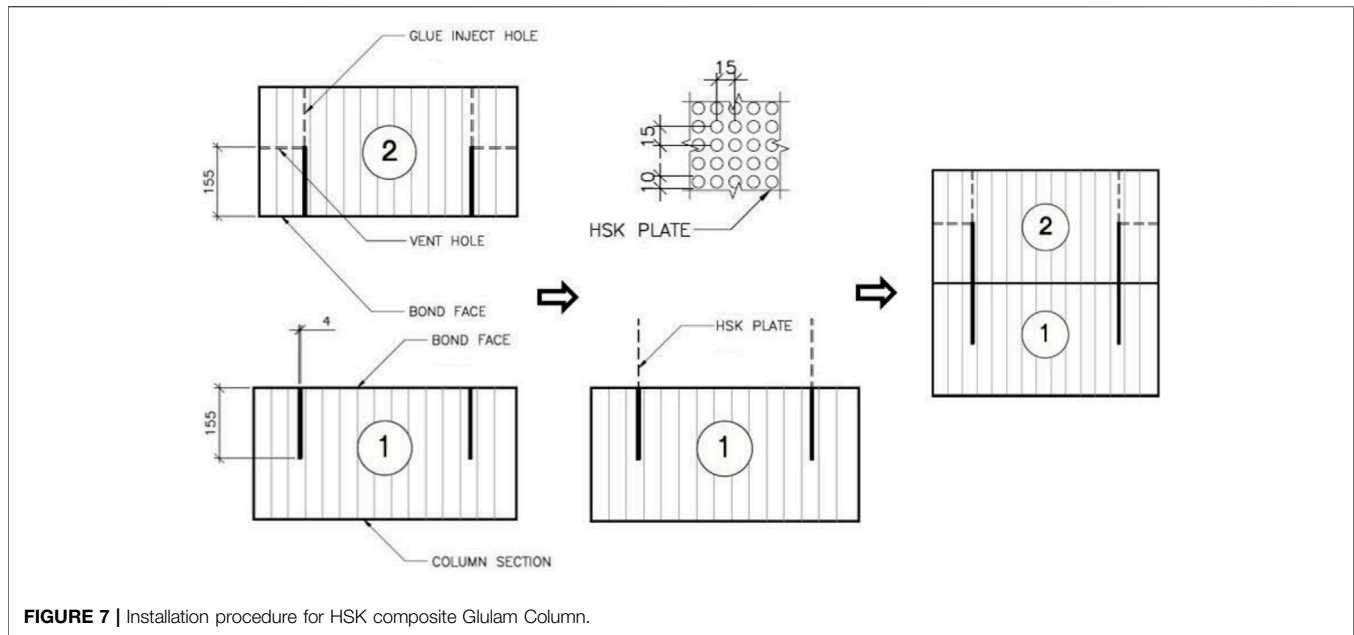


## Foundation

Foundation design depends on the several factors like site location and soil conditions. Guizhou is a mountainous province with higher altitudes at the eastern end of the Yungui Plateau. According to Geotechnical Engineering Investigation Code of China (GB50021-2001 Code for Geotechnical engineering Investigation, 2002), the subsurface soil conditions at the

proposed development site consisted of miscellaneous filling soil ( $Q_4^{ml}$ ) and moderately weathered argillaceous-siliceous rock, which are selected as the foundation bearing layer based on the geological investigation report.

Shallow foundations are recommended for most concrete columns as they located on rocks. The columns in the southwest corner adopt traditional manual hole digging pile



because of the soft fill dirt. Raft footing are utilized for foundation of cores on the base and rock bolts are applied at critical locations to provide adequate anti-overturning moment. The reinforced cast-in-place concrete sheets are placed on top of layered compacted soil, and sufficient soft fill dirt is substituted in the southwest corner in order to reduce the uneven settlement.

## Gravity Load Resisting System

### Glulam Beam and Timber-Concrete Composite Beam

The timber-concrete hybrid building was designed for seismic precautionary intensity 7 with a basic acceleration of ground motion 0.1 g according to the GB50011-2010 (GB50011-2010 Code for Seismic Design of Buildings, 2016) for a site class II in

Guizhou, China. The dead load for typical timber floor was 2.5 kPa, for concrete floor was 5.0 kPa and for timber roof was 1.5 kPa respectively. On the roof, the live load was considered as 0.5 kPa. In the typical floors, the live load for the guest rooms was 2.0 kPa, for public space (including balcony, corridors, lobby, tea room and private room) was 2.5 kPa, for stairs was 3.5 kPa, for mechanical/electrical space was 7 kPa, and for partition was 1.0 kPa respectively. The reference snow pressure and reference wind pressure with a 50-year return period was 0.2 and 0.3 kPa respectively. All the load values were obtained based on GB 50009-2012 (GB 50009-2012 Load code for the design of building structures, 2012) and they are typical for Chinese hotels.

The gravity system for this 10-storey timber-concrete hybrid structure adopts Glulam frame system as shown in **Figure 1**. The

Load Combination For Each Storey																	
Floor Level	Floor Height [m]	(Short-D) [kN]	(Long-D+0.5L) [kN]	(Short-D) [kN]	(Long-D+0.5L) [kN]	(Short-D) [kN]	(Long-D+0.5L) [kN]	(Short-D) [kN]	(Long-D+0.5L) [kN]	(Short-D) [kN]	(Long-D+0.5L) [kN]	(Short-D) [kN]	(Long-D+0.5L) [kN]	(Short-D) [kN]	(Long-D+0.5L) [kN]	(Short-D) [kN]	(Long-D+0.5L) [kN]
9	3.9	278.2	366.5	278.2	366.5	278.2	366.5	278.2	366.5	278.2	366.5	278.2	366.5	278.2	366.5	278.2	366.5
8	3.9	351.0	469.4	351.0	469.4	351.0	469.4	351.0	469.4	351.0	469.4	351.0	469.4	351.0	469.4	351.0	469.4
7	3.9	310.8	403.8	310.8	403.8	310.8	403.8	310.8	403.8	310.8	403.8	310.8	403.8	310.8	403.8	310.8	403.8
6	3.9	310.8	403.8	310.8	403.8	310.8	403.8	310.8	403.8	310.8	403.8	310.8	403.8	310.8	403.8	310.8	403.8
5	3.9	310.8	403.8	310.8	403.8	310.8	403.8	310.8	403.8	310.8	403.8	310.8	403.8	310.8	403.8	310.8	403.8
4	3.9	310.8	403.8	310.8	403.8	310.8	403.8	310.8	403.8	310.8	403.8	310.8	403.8	310.8	403.8	310.8	403.8
3	3.9	310.8	403.8	310.8	403.8	310.8	403.8	310.8	403.8	310.8	403.8	310.8	403.8	310.8	403.8	310.8	403.8
2	5.1	201.0	301.5	201.0	301.5	201.0	301.5	201.0	301.5	201.0	301.5	201.0	301.5	201.0	301.5	201.0	301.5
Floor Built		2-9		3-9		4-9		5-9		6-9		7-9		8-9		9	

Glulam Column Shortening for Individual Storey																	
Floor Level	Floor Height [m]	(Short-D) [mm]	(Long-D+0.5L) [mm]	(Short-D) [mm]	(Long-D+0.5L) [mm]	(Short-D) [mm]	(Long-D+0.5L) [mm]	(Short-D) [mm]	(Long-D+0.5L) [mm]	(Short-D) [mm]	(Long-D+0.5L) [mm]	(Short-D) [mm]	(Long-D+0.5L) [mm]	(Short-D) [mm]	(Long-D+0.5L) [mm]	(Short-D) [mm]	(Long-D+0.5L) [mm]
9	3.9	0.276	0.531	0.276	0.531	0.276	0.531	0.276	0.531	0.276	0.531	0.276	0.531	0.276	0.531	0.276	0.531
8	3.9	0.348	0.680	0.348	0.680	0.348	0.680	0.348	0.680	0.348	0.680	0.348	0.680	0.348	0.680	0.348	0.680
7	3.9	0.308	0.585	0.308	0.585	0.308	0.585	0.308	0.585	0.308	0.585	0.308	0.585	0.308	0.585	0.308	0.585
6	3.9	0.308	0.585	0.308	0.585	0.308	0.585	0.308	0.585	0.308	0.585	0.308	0.585	0.308	0.585	0.308	0.585
5	3.9	0.308	0.585	0.308	0.585	0.308	0.585	0.308	0.585	0.308	0.585	0.308	0.585	0.308	0.585	0.308	0.585
4	3.9	0.308	0.585	0.308	0.585	0.308	0.585	0.308	0.585	0.308	0.585	0.308	0.585	0.308	0.585	0.308	0.585
3	3.9	0.308	0.585	0.308	0.585	0.308	0.585	0.308	0.585	0.308	0.585	0.308	0.585	0.308	0.585	0.308	0.585
2	5.1	0.260	0.571	0.260	0.571	0.260	0.571	0.260	0.571	0.260	0.571	0.260	0.571	0.260	0.571	0.260	0.571
Floor Built		2-9		3-9		4-9		5-9		6-9		7-9		8-9		9	

Total Shortening for Each Storey		
Floor Level	(Short-D) [mm]	(Long-D+0.5L) [mm]
9	0.276	0.531
8	0.623	1.211
7	0.921	1.796
6	1.239	2.382
5	1.547	2.967
4	1.855	3.552
3	2.163	4.137
2	2.424	4.708

(Short Term-Dead)	
E <sub>c</sub>	11700 [Mpa]

Column Size	
b	580 [mm]
h	580 [mm]

(Long Term-Dead+0.5Live)	
E <sub>c</sub>	8000 [Mpa]

FIGURE 9 | Shortening of the glulam column.

TABLE 4 | Comparison of base shear under equivalent static method (ESM) and mode-superposition method in ETABS.

Direction	Fundamental period (s)	ESM (kN)	ETABS (kN)	ESM/ETABS
East-West (X-X)	0.59	2,474	3,158	0.78
South-North (Y-Y)	0.49	2,954	3,759	0.79

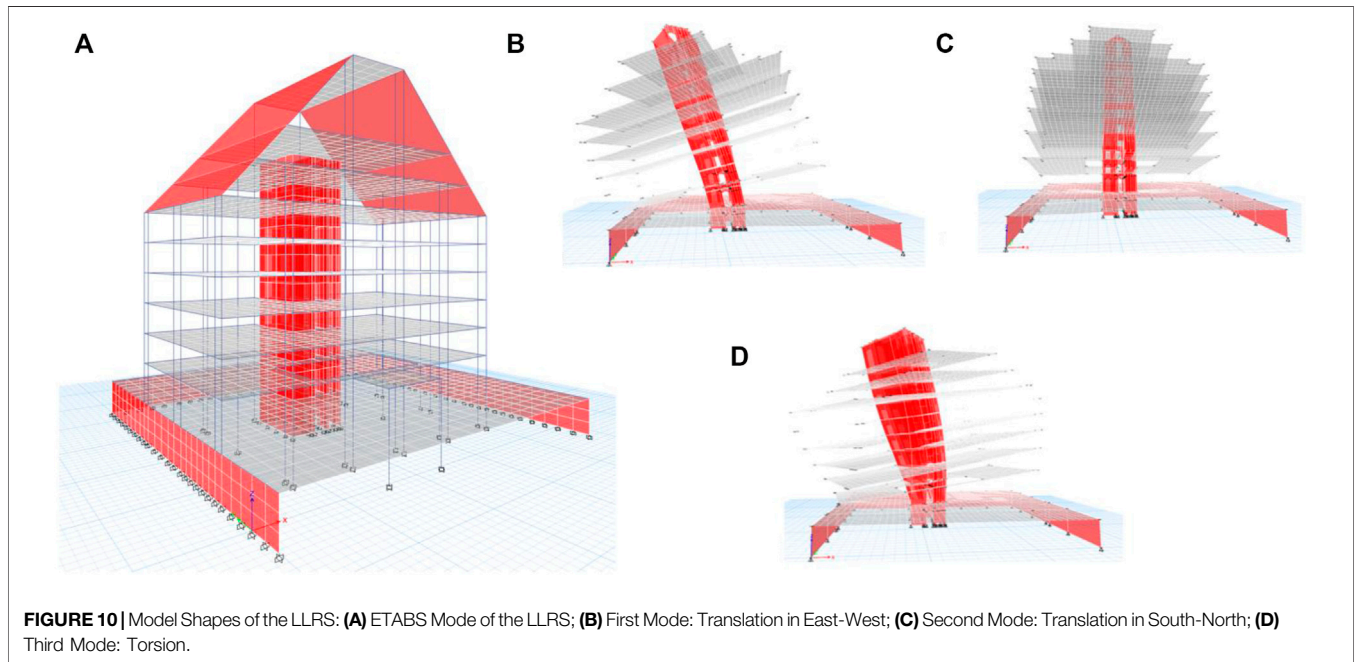


FIGURE 10 | Model Shapes of the LLRS: (A) ETABS Mode of the LLRS; (B) First Mode: Translation in East-West; (C) Second Mode: Translation in South-North; (D) Third Mode: Torsion.

material properties of the glulam timber in this research are based on the products supplied by YF, the structural member specifications and material parameters are shown in Table 1.

The glulam girders are the main framing beams which play a role in overall stability of the structure frame. They span between 9 and 11.1 m in north-south direction with secondary glulam



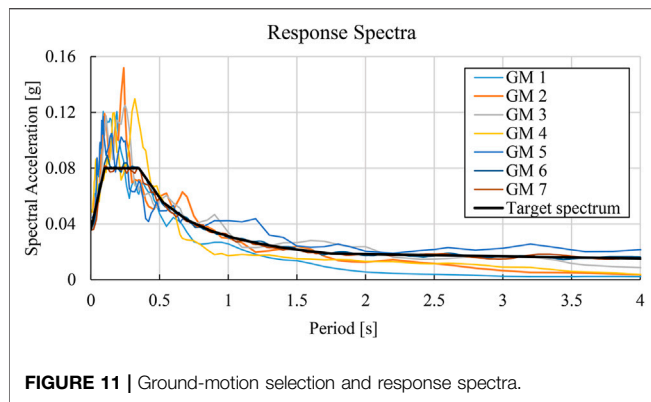


FIGURE 11 | Ground-motion selection and response spectra.

beams placed on top in east-west direction to support the OSB floor slabs and the depth of girders is considered as 580 mm in order to satisfy the structural clearance requirements.

According to the design loads and the tributary-area design methods, the 290×2-290 mm cross section was selected for the glulam beam girders and 240 × 400 mm cross section was selected for secondary glulam beams. **Table 2** summarizes the glulam beam sizes with corresponding utilizations as ratio of resistance vs. demand.

For some main girders which support high design loads with the span-depth ratio of 19 exceeds the common usage of glulam beams (normally round 12~14), the timber (glulam)—concrete composite (TCC) beams are used to meet the structural strength, stiffness, and vibration performance requirements.

The applied TCC beams focus on optimizing performance and material requirements by engineering a structural connection between glulam and concrete components. Structural efficiency is gained by creating composite action between these two materials. The efficiency of TCC beams depends strongly on the shear connection employed and can be expressed as a coefficient between 0 and 1. If the two materials work together perfectly as one beam and no slip between the contacting surfaces, the coefficient can be assumed to be 1, in this case, composite sections can be evaluated based on Euler-Bernoulli beam theory that plane sections remain plane, as shown in **Figure 3A**; if the two materials work separately and there is no composite action, the coefficient is assumed to be 0, as shown in **Figure 3C**. For most engineered TCC beams, partial composite action can be achieved, as shown in **Figure 3B**, with more rigid shear connections, leading to higher coefficients closer to 1. To guarantee sufficient stiffness

and strength of the glulam-concrete composite beam, the glued-in Holz-Beton-Verbund (HBV) shear connector (TiComTec Technical dossier HBV-systems, 2011), as shown in **Figure 4**, is used.

The HBV system consists of an expanded steel mesh with 2.5 mm thickness that is glued into a saw cut in the timber member and then concrete is cast on top. The adhesive and the concrete fill the voids in the mesh creating a mechanical “adhesive dowel” connection, which, if designed properly, will lead to the steel mesh yielding before adhesive failure (Gerber and Tannert, 2015). Glued in rebar, both angled and straight, can help push the failure into the timber beam after full plasticization of the connectors (Ceccotti et al., 2007). The HBV has been successfully tested and approved and maintains a high degree of stiffness and load bearing capacity even through an unsupported separation layer (Lehringer and Gabriel, 2014). The composite coefficient for HBV system is as high as 0.85 and the stiffness of the TCC beams using this type of connector can reach more than three times of traditional glulam beam. The design of the timber-concrete composite beam is based on Eurocode 5 (Steer, 2001), the capacity of the concrete, timber and the HBV connector components that constitute the TCC beam all need to be checked. As shown in **Table 3**, there are four different types of the TCC beam that are marked as TCC<sub>1</sub> to TCC<sub>4</sub>, the location of the TCC beams in the floor framing and their design details are presented in **Figure 5**.

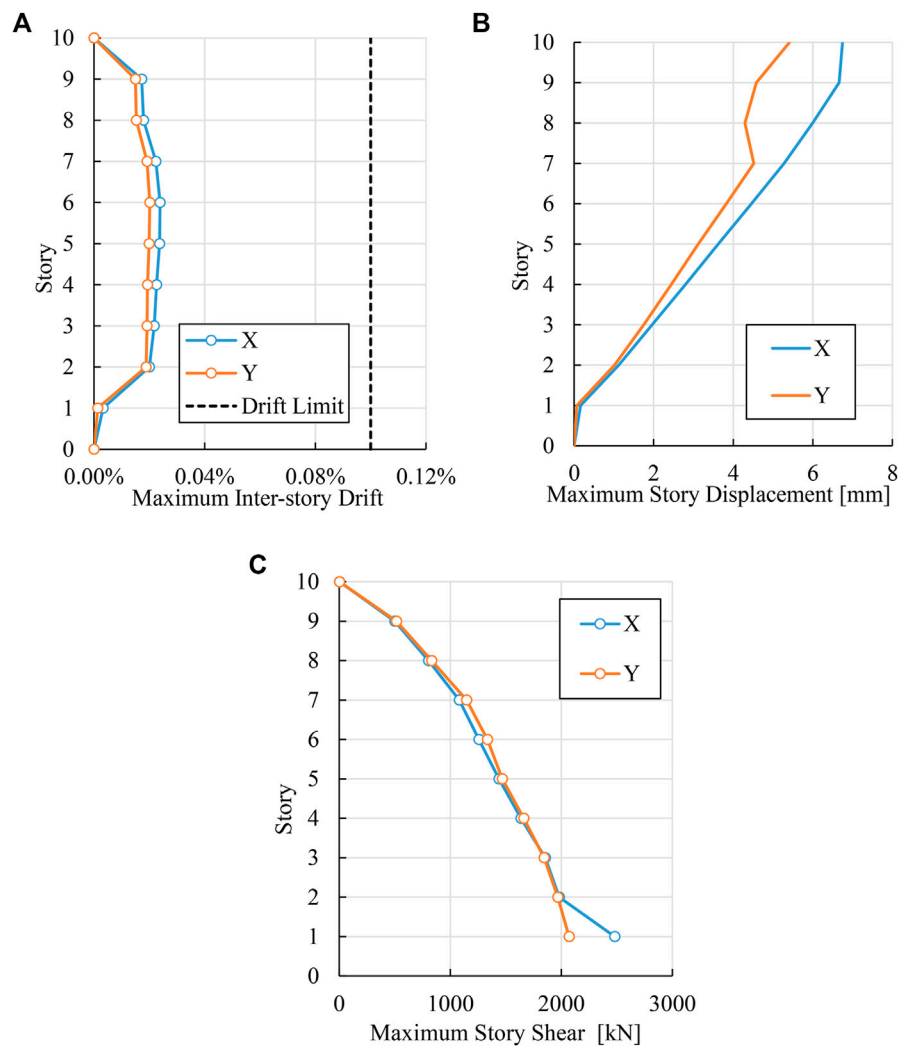
### HSK Composite Glulam Columns

Similar to the glulam beams, the size selection for glulam columns are also based on the Chinese timber building designing codes (GB 50009-2012 Loadcodeforthedesignofbuildingstructures, 2012) (GB5005-2017: Standard for design of timber structures, 2017; GB 50206-2012 Code for construction quality acceptance of timber structures, 2012; GB T 50329 2002, 2002). Based on the vertical load take-off, the design loads for the glulam column on the bottom floor are shown in **Figure 6**, typical column size is designed accordingly as 580 × 580 mm, the ratio of compression resistance versus Demand in the ultimate limit state is 63.3%, 71.6% in 1-hour fire resistance and 99.5% in 2-hour fire resistance respectively.

Considering the limitation of manufacturing technology, two 290 × 580 mm glulam columns are designed and combined using Holz-Stahl-Komposit (HSK) connector as one single column. The HSK connector is based on adhesively bonded perforated steel plates. The holes in the plate are filled by the adhesive after

TABLE 5 | Selected ground motions.

Type	Result ID	RSN	Scaling factor	Earthquake name	Year	Station name	Magnitude	Rrup (km)
Historical	GM 1	72	0.275	San Fernando	1971	Lake Hughes #4	6.6	25.07
	GM 2	1006	0.132	Northridge-01	1994	LA - UCLA Grounds	6.7	22.49
	GM 3	4205	0.674	Niigata_ Japan	2004	NIG015	6.6	40.14
	GM 4	4870	0.265	Chuetsu-oki_ Japan	2007	Horinouchi Uonuma City	6.8	34.51
	GM 5	5750	1.001	Iwate_ Japan	2008	YMT007	6.9	58.12
Artificial	GM 6	AR221_932_1	1.000	n/a	n/a	n/a	n/a	n/a
	GM 7	AR221_932_2	1.000	n/a	n/a	n/a	n/a	n/a



**FIGURE 12 |** Seismic Response, (A) maximum inter-story drift; (B) maximum story displacement; (C) maximum story shear.

inserting it into the wood, forming so-called “Adhesive Dowels”. The “bond capacity” is based on the sum of the individual adhesive dowel capacities which has been proved to equal 0.8kN (Bathon et al., 2014). As long as enough adhesive dowels are provided, the connection can be very stiff and the two glulam columns can perfectly work together as a whole.

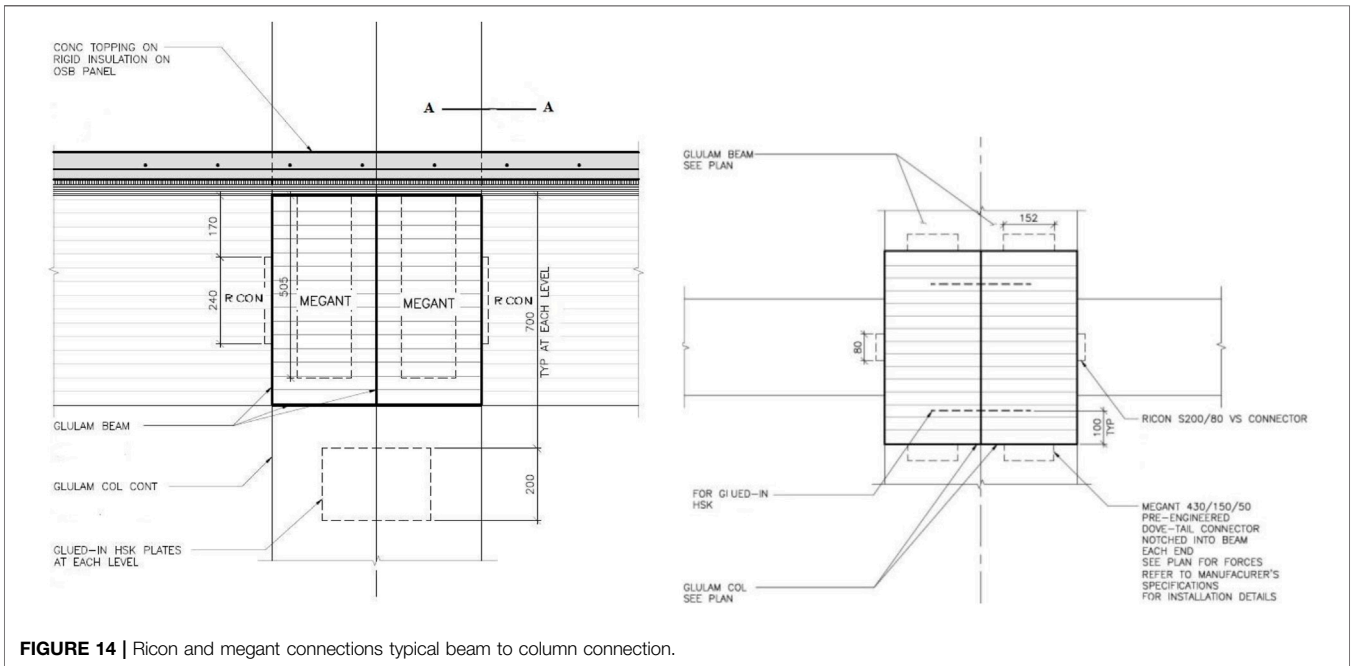
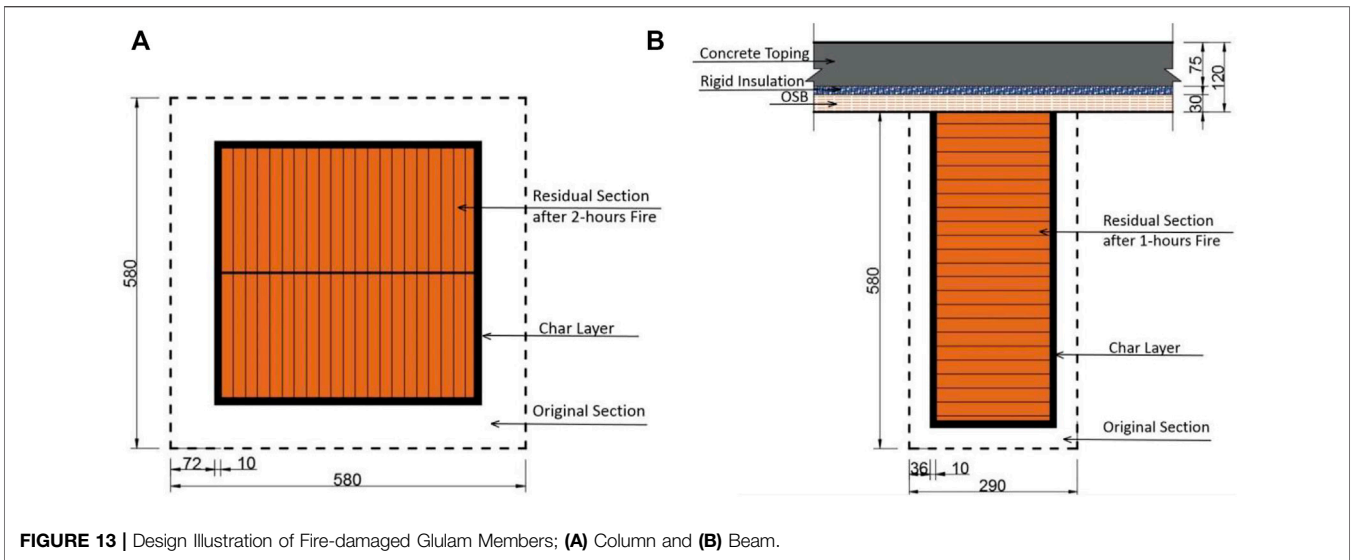
As shown in **Figure 7**, the manufacturing process includes three steps. Firstly, providing slot at the composite face of each segment column; secondly, injecting glue in segment 1 slots and inserting HSK plats; thirdly, combing segment 1 and 2 to form a composite column, injecting glue via holes in segment 2 until glue comes out from vent holes. **Figure 7** shows the connection detail for the HSK composite glulam column to the concrete base.

Aside from the calculation of axial compression capacity and stability, the shortening of the glulam column under the compression force should also be taken into account, because the differential shortening between columns and concrete core walls will cause additional stresses on the members.

**Figure 9** presents the detailed shortening calculation of the glulam column which carries the largest compression force. The results shows that the maximum axial shortening of the column under long term loading is only around 5 mm. As the concrete core walls are very stiff, the long-term deformation can be ignored. The distance between them is around 8 m, that results in the slop changes of the floor is only around 0.6% and the stress influence on the floor slab can be ignored.

## Lateral Load Resisting System Design and Seismic Analysis

The concrete core walls for this 10-storey business hotel act as the Lateral Load Resisting System (LLRS) to resist the seismic and wind loads. In seismic design, the core together with the fundamental concrete walls are modelled in ETABS and verified with the hand calculation based on the Equivalent Static Method (ESM).



The calculation of ESM for seismic design is simple, while it is only suitable for building less than 40 m based on seismic design code (GB50011-2010 Code for Seismic Design of Buildings, 2016). As the height of this 10-storey business hotel (47 m) exceeds the limitation, and the mode analysis in ETABS is needed. The mode-superposition method is a linear dynamic-response procedure which evaluates and superimposes free-vibration mode shapes to characterize displacement patterns. Mode shapes describe the configurations into which a structure will naturally displace. The obtained base shears for these two methods were compared in Table 4.

The linear dynamic analysis in ETABS considered twelve vibration modes, the model mass participation ratio reaches 95% which meets the code requirements. The dynamic analysis shows that the fundamental vibration mode contributes the majority of the base shear and the higher-mode effect on the seismic responses can be ignored for this timber-based hybrid tall building.

The first three vibration modes are shown in Figure 10. The fundamental and second vibration modes are translational motion and the third one is torsion. As the torsional stiffness of the concrete core is large, the torsional deformation is controllable. Also, the calculated torsional sensitivity ratio

equals 1.1 which is smaller than 1.7 limitation in the seismic design code, that means torsional effects can be ignored for this structure.

A total of seven ground motion records, including five historical strong earthquake records and two artificial records, were selected for the analyses. According to the GB50011-2010 (GB50011-2010 Code for Seismic Design of Buildings, 2016), for the Jianhe County in Guizhou with 7 seismic fortification and peak ground acceleration of 0.1g, the maximum seismic influence coefficient  $\alpha_{\max}$  is set as 0.08 and the corresponding target spectrum is plotted in **Figure 11**. Those five earthquake records were selected from the Pacific Earthquake Engineering Research (PEER) database (PEER, 2013), as summarized in **Table 5**. All the selected records were linearly scaled so that their response spectra matched to the target design spectrum of the building site, as shown in **Figure 11**.

**Figure 12** shows the mean seismic response results where the blue line represents the translation response in East-West (E-W) direction (X) and red line represents the North-South (N-S) direction (Y). Overall the building exhibited adequate seismic resistance that the maximum inter-story drifts were 0.024 and 0.020% for both directions, which were below the drift limit of 1/1000. The building had a maximum roof displacement of 6.8 and 5.4 mm in the E-W and NS directions, respectively, with a base shear of 2,480 and 2070 kN.

With regard to wind resisting analysis, the calculated maximum wind design force is in the south-west direction and equals 1758kN, which is only 71% of seismic design load in that direction. Therefore, the seismic load governs the design of the LLRS. Besides, as the fundamental period is less than 1s, the structural lateral response (displacement and acceleration) resulting from the wind almost has no effect to the comfort of living.

## Fire Design

The fire design is of great importance for this project as the fire resistance requirements for timber buildings in China are very strict. To meet these requirements, the following strategy was chosen. First, the concrete topping on the floor slabs is an effective fire and smoke barrier. The 30 mm thick OSB floor slab belongs to category of heavy timber which also has some extent of fire protection. Even it burns, the 75 mm thick reinforced concrete topping can provide additional protection during a fire. Besides, as the main components of the gravity system, the glulam columns are designed for 2-hour fire-resistance, and the glulam girders and secondary glulam beams are designed for 1-hour fire resistance. The charring rate is considered 0.6 mm/min and 10 mm addition char layer is reduced to obtain the residual cross section for load capacity calculation (Karacabeyli and Desjardins, 2011). The design illustration of fire-damaged glulam members is shown in **Figure 13**.

Another fire protection consideration is using concealed connections, RICON and MEGANT connections. The RICON connector is a pre-engineered post-to-beam connector, a system manufactured from mild steel with a welded collar bolt. It consists

of two identical parts, one installed in the primary timber member and the other in the secondary member. The MEGANT connector is also a pre-engineered post-to-beam connector, a system manufactured from aluminum with connector plates and threaded rod to secure the connection. These two types of connections have been tested for the North American mass timber market and are applied in the girder to secondary beam joints and girder to column joints in this project, as shown in **Figure 14**.

**Figure 14** gives the connection application detail in glulam beam to column joints. The RICON and MEGANT, as the pre-engineered connections, can be installed fully concealed or visible and provide large shear capacity, not only suitable for timber to timber, but also can be used for connecting the timber element to the concrete core walls.

## CONCLUSION

This paper presented the design detail of a 10-storey timber-concrete hybrid building in China. The procedure includes foundation design, gravity system design, lateral load resisting system design, seismic analysis and the fire resistance design. It meets the requirements of Chinese building code with the advanced timber design technology and the structural analysis results proved the accuracy of the design, it can serve as guidance for subsequent timber-based hybrid high-rise structures and will promote the development of novel construction systems in China.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

## AUTHOR CONTRIBUTIONS

XZ: conceptualization, methodology, validation, analysis, writing-original draft, LX: validation, analysis, WH: validation, investigation, YL: conceptualization, validation, PL: conceptualization, investigation, writing-review and editing.

## FUNDING

The authors would like to thank the National Key R&D Program of China (Grant Nos. 2021YFF0500804), the National Natural Science Foundation of China (Grant Nos. 52108192); the OEICDI fund (Grant Nos. B13041); the Entrepreneurship and Innovation Support Program for Overseas-educated student in Chongqing China (Grant Nos. CX2021085); This study also received funding from MITCAS Canada through an Elevate grant with Equilibrium Consulting Inc.

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**Conflict of Interest:** This study received funding from Equilibrium Consulting Inc. The funder had the following involvement with the study: the gravity system design, lateral load resisting system design and the fire design.

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