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DESIGN AND PERFORMANCE OF HIGH-RISE STRUCTURE USING ULTRA-LIGHTWEIGHT CROSS LAMINATED TIMBER FLOOR SYSTEM

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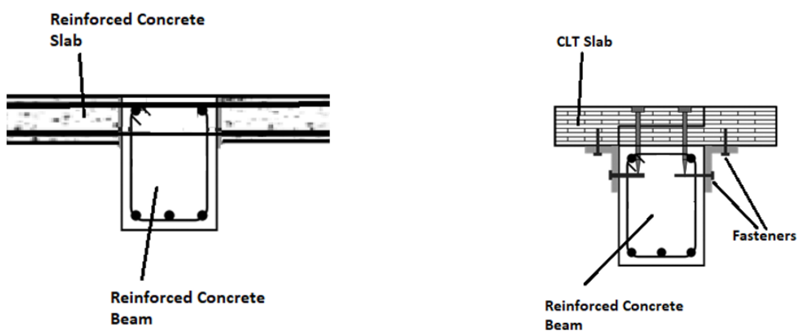
The main objective of this paper is to study the structural performance of a high-rise structure when alternative lightweight material known as cross-laminated timber was used as a slab in floor system in lieu of conventional reinforced concrete slab. A numerical case study was conducted using a highly irregular RC frame building with its two 60-story towers joined at the top. Three major analyses were considered. First, modeling and analyzing the building with an RC slab was conducted to determine the design reference. Second, substituting the RC slab with the CLT slab was performed using the same building skeleton. Third, redesigning and optimizing the building skeleton with that CLT to observe skeleton material saving obtained using the same structural performance criteria. Major lateral loads applicable in the Eastern Province of Saudi Arabia were inputted. Strengths and serviceability requirements for floor diaphragm and lateral load resisting system were checked first before performing a comparative analysis between traditional RC and CLT slabs as floor diaphragm. The structural performance criteria to be used for comparative study between RC and CLT slabs included total drift, inter-story drift due to lateral loads, and base reactions. Structural periods and acceleration responses for each floor were investigated and contrasted with the existing building code. The foundation demand was also investigated based on the structural weight and reactions generated from the RC and CLT floor systems.

Keywords: Floor diaphragm, Tall buildings, Lateral loads, Lateral deflections.

1 INTRODUCTION

Tall building construction is booming in Saudi Arabia and the Middle East. Most of the tall buildings were designed using conventional materials such as steel and concrete, with the latter dominating the current practice in the region. There has been a shortage of the main ingredient of concrete (i.e., cement) demand recently in Saudi Arabia with only four major cement operating companies in Saudi Arabia. Also, production of a massive amount of cement materials has caused concern on the long run to the environment due to excessive carbon dioxide produced during the manufacturing process. Steel materials have a similar trait and even with more negative impact due to the massive amount of energy required to produce and high carbon dioxide produced, which is around ten times bigger than that of concrete production. The issue is compounded with a challenge in the design and construction of tall buildings due to difficult soil conditions in the region requiring an expensive big foundation system. To keep the reasonable growth in the building construction sector, there needs to be thinking about exploring alternative materials with similar performance and, at the same time, having a low impact on the environment. Cross-laminated timber (CLT) is one of the new construction materials that has potential use in tall building construction either as floor or shear wall components, in combination with concrete or steel frames (FPInnovation 2019). Previous numerical studies indicated that CLT could substitute reinforced concrete (RC) slab as floor components of tall buildings. Lateral deflection (lateral deflections) can be reduced significantly for medium-rise buildings loaded under seismic load without compromising strength performance criteria (Asiz and Smith 2014, Ahmed and Asiz 2017). Experimentally, the hybrid floor diaphragm system has shown promising results in resisting lateral loads (e.g., Loss and Frangi 2017). Figure 1 describes a typical floor system of multi-story buildings utilizing RC and CLT slab components (Yeoh *et al.* 2011). Table 1 shows the mechanical properties of steel, concrete, and CLT to illustrate the range or ratio of weight over strength.



(a) RC slab floor system (b) CLT slab floor system

Figure 1. Floor systems of tall building.

Table 1. Basic properties of CLT material (FPInnovation 2019).

Property	Steel	Concrete	CLT
Directional property	isotropic	isotropic	orthotropic
Density (kg/m^3)	7200	2400	400
Elastic modulus (GPa)	200	25	E_1=9, E_2=4.5, G_{12}=0.5
Poisson's ratio	0.30	0.25	ν_{12}=0.3
Strength (MPa)	250	27.5	ft-1=20, f_{t-2}=15, f_{c-1}=30, f_{c-2}=25, f_{shear}=5
Notation: E = modulus of elasticity; G = modulus of rigidity; 1 = CLT major direction; 2 = CLT minor direction; t = tension; c = compression			

2 BUILDING DESIGN AND MODELING

Figure 2 shows the typical floor layout and 3D isometric view of the building to be designed and analyzed. Two 60-story towers were connected at the top via four long-span stories. The 'twin' towers were 40 m apart (clear distance), one was purposed for a residential tower and the other one was for a commercial hub. The total projected area of the whole building was 120m×60m, and each tower was 40m×60m. The floor-to-floor height was designed the same as 4m. The building was selected in this study due to highly irregular in term of connecting the two towers at the top stories, optimizing the chance to explore the complex response of the floor diaphragms between the towers and around the 'portal corners' when a combination of gravity and lateral loads applied to the building. The building was originally inspired by a proposed corporate office building to be located in Makati Central Business District in the Philippines. The floor layout was slightly modified from the original proposed design to adjust to applying uniform columns spacing. The building was modeled and analyzed using ETABS (CSI 2016) with column dimensions shown in Table 2. There were three modeling cases. The first case was modeling the building using RC slab for all floors; the second case was replacing the RC slab with CLT slab for all floors while retaining the same columns and beams frames as was in the first case, and the third case was using the CLT slab for all floors with reduced dimensions of all columns and beams frames including the shear wall. The reduced dimensions for the ultra-lightweight CLT slab were expected under the same structural performance criteria. The RC slab (18 cm) and CLT slab (36 cm) were both modeled as shell elements connected rigidly to the floor framing system. The main intention of having a shell element rather than assuming a rigid diaphragm was to capture stress distribution for strength check and observation. The CLT slab corresponded to 7 layers of wood ply normally used for heavy CLT plate construction, and its mechanical property can be seen in Table 1. The shear wall components were also modeled as shell elements having a uniform thickness of 60 cm (first and second cases) and 50 cm (third case). Two types of beam dimensions were used for the floor framing system, 1m x 1.25m and 1.2m x 1.4m (first and second cases), and 91mx1.25m and 1.1m x 1.35m (third case). All beams were modeled as frame elements having rigid connections with the columns and floors. For all three cases, the 'bridge' between the two towers was composed of long-span floors designed using built-up steel girders that combined W36x652 (W 920x970) with four L8x8x1/2 (L 203x203x12.7) on each web-flange corners.

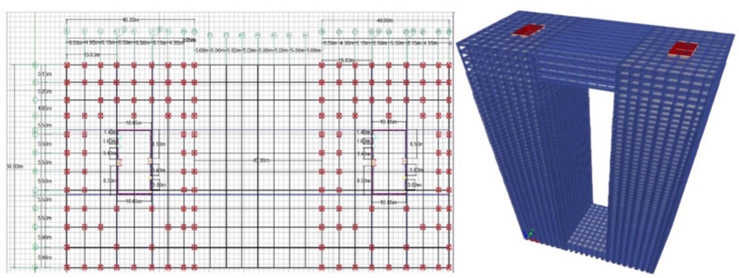


Figure 2. 60-story twin building layout and 3D (modeling) view.

Table 2. Columns dimensions with master stories for 60-story twin building.

RC slab		**CLT slab**	
Stories	**Columns**	**Stories**	**Columns**
1-4	3.2 m X 3.2 m	**1-4**	2.9 m X 2.9 m
5-12	3.1 m X 3.1 m	**5-12**	2.7 m X 2.7 m
13-20	2.8 m X 2.8 m	**13-20**	2.5 m X 2.5 m
21-28	2.6 m X 2.6 m	**21-28**	2.3 m X 2.3 m
29-36	2.4 m X 2.4 m	**29-36**	2.1 m X 2.1 m
37-44	2.1 m X 2.1 m	**37-44**	1.8 m X 1.8 m
45-52	1.8 m X 1.8 m	**45-52**	1.5 m X 1.5 m
53-56	1.3 m X 1.3 m	**53-56**	1.2 m X 1.2 m
57-60	0.7 m X 0.7 m	**57-60**	0.7 m X 0.7 m

The dead and live loads specification for office and residential tower, including their load combinations, follow Saudi Building Code (SBC 2018). The wind load used was applicable in Al Khobar (Eastern Province of Saudi Arabia) with the following specifications: wind speed 190 km/h, exposure type B, topographical factor 1, and gust and directional factors 0.85. The 'medium' seismic load was applied using dynamic analysis with spectral accelerations of 0.3g and 0.1g at periods of 0.2 sec and 1 sec, respectively. The soil condition was assumed to have site D (medium to dense soil) with coefficients of Fa=1.5 (short period) and Fv=2.4 (long period). The occupancy important factor was assumed 1.25, response modification factor 6.5, and system overs strength factor 3. It was anticipated that based on a regular 60-story building, the dominant lateral load would be generated from the wind load. However, when the top levels were connected via several 'long-span' stories, interesting results would be observed, as will be described below in the result section.

3 RESULTS

Under the combination of dead and live loads, all three cases were found to satisfy the building code requirement for the allowable deflection. The critical one, which was the cases for CLT slab loaded under two-way slab condition (5mx6m), had mid-span deflection less than 1 inch (25.4 mm), and this is less than allowable one (L/250). The steel reinforcements for the concrete beams, columns, and shear walls were designed to satisfy the strength and serviceability (deflection) requirements. Strength checks were also performed on the slabs based on the in-plane stress distribution generated in the floor diaphragms when the critical in-plane lateral loads were imposed. In practice, a rigid assumption of floor diaphragm was used for distributing the story's lateral loads from wind and earthquake. In this study, since the actual mechanical properties of the RC and CLT slab were incorporated in the modeling, there needs to be checking on the strength requirement. The critical floor diaphragm was found in the first story when the torsion generated response was observed under the combination of dead and wind loads. It was found that using simple strength criteria for timber materials, all in-plane stresses were below the strength of the CLT slabs mentioned in Table 1. For the RC slab, all in-plane stresses that were bigger than the concrete tensile strength were assumed to be carried by the steel reinforcements.

The fundamental structural periods were 3.22, 4.57, and 4.54 seconds for Cases 1, 2, and 3, respectively. For the CLT slabs (Cases 2 and 3), the periods were found to be larger than that of the RC slab due to more flexible CLT based diaphragm. However, this is not a general case for a regular tall building when the CLT slab is used as one of the floor diaphragm components [3 and 5]. The connected two towers via four long-span stories ('giant portal-like' frame) created a complex response that could generate out-of-plane diaphragm response even under lateral load, and this could lead to complex interaction with the in-plane response, and thereby reducing stiffness and increasing the structural period. Table 3 shows the maximum lateral deflection under the critical load combinations. As can be observed, all maximum lateral deflections obtained were less than the allowable total lateral deflection value (H/500=480mm). Also, all the inter-story lateral deflections were less than the allowable value (0.05 of the story height). An interesting observation was found about the lateral force dominance among the RC and CLT slabs. For the RC slab (Case 1), the seismic load was the governing factor, while for the CLT slab, the wind is the governing factor. The lateral deflections generated from the seismic load of the CLT slab (Cases 2 & 3) were always below those of the RC slab. This is due to the light-weight of the CLT relative to RC material. With respect to the wind load, the lateral deflections obtained in the RC were less than those of the CLT slab.

Table 3. Lateral deflection.

Maximum Lateral deflection (mm)			
Load Case/Combination	**(Case 1, RC)**	**(Case 2, CLT)**	**(Case 3, CLT)**
Dead Load + Earthquake X	380	98	350
Dead Load + Earthquake Y	331	84	291
Dead Load + Wind X	376	397	411
Dead Load + Wind Y	338	384	354

Figure 3 shows the base reactions for all three cases. Other than performing comparative analysis, the reactions would be used for designing the foundation system. There was about 10% and 15% less weight in the CLT slabs (Cases 2 and 3) relative to the RC slab (Case 1) if only dead and live loads were considered. If the critical lateral load is considered, 20% less lateral reaction force was obtained in the CLT slabs. This indicated that the foundation system could be designed with fewer dimensions and material needs for the CLT cases.

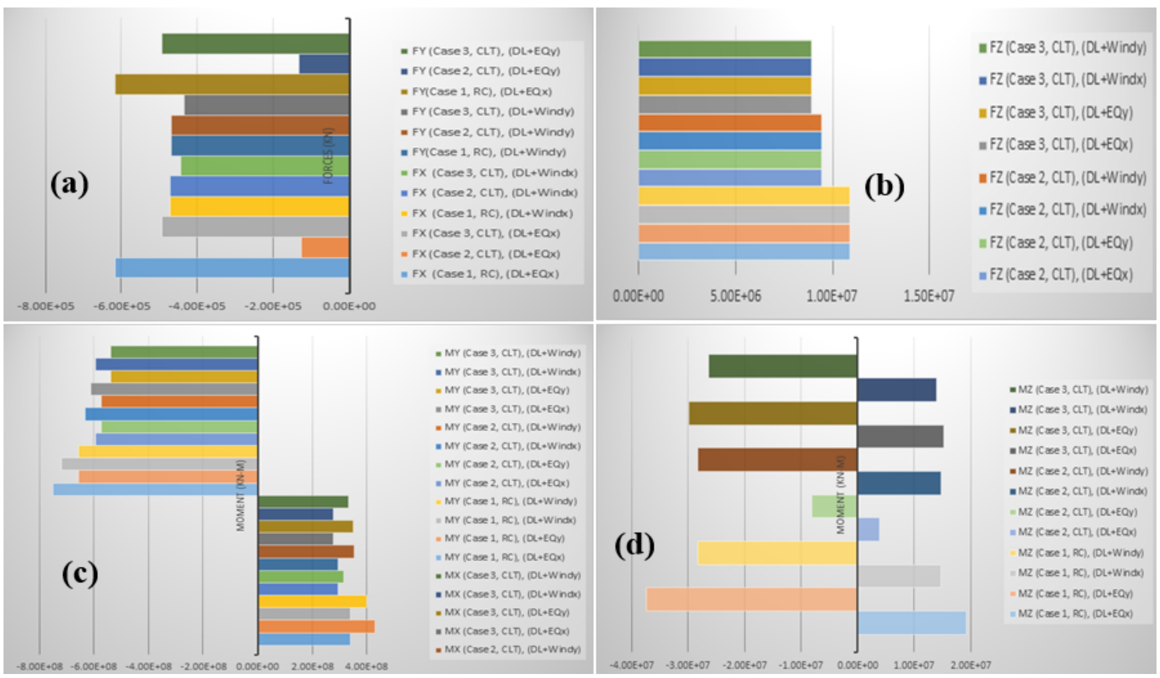


Figure 3. Base reactions (a) FX & FY (kN), (b) FZ (kN), (c) MX & MY (kN.m), & (d) MZ (kN.m).

4 FOUNDATION DEMAND

The design exercise was extended to study the foundation demand. Only two cases were compared (Cases 1 and 3) based on the critical base reactions produced under different load combinations. The foundations for these buildings were designed as a combination of pile and raft, commonly known as piled raft foundation in which loads from the superstructure are shared between the raft and pile system. This foundation system was selected because of its versatility reducing the excessive total settlement, including the differential settlement. The soil property used was in accordance with the typical sandy soil layers found in the Eastern region of Saudi Arabia. Table 4 summarizes design outcomes for the piled raft foundation system for Cases 1 and 3. It can be seen that due to lightness, the CLT slab system produced less demand on the foundation system.

Table 4. Foundation demand.

Model Type	**Case 1**	**Case 3**
Raft foundation depth (m)	3.4	3.2
Raft foundation area of steel (mm^2/m)	15080 (+) moment	10179 (+) moment
	9651 (-) moment	4909 (-) moment
Pile requirement	200 pile, d = 0.6m	200 pile, d = 0.6m

5 CONCLUSION

A numerical case study was performed to investigate the feasibility of using CLT slab in the floor system of complex tall buildings situated in difficult soil conditions of Saudi Arabia. Based on the design and modeling result, the CLT slab is feasible for the floor diaphragm of complex tall building construction as a substitute for the reinforced concrete (RC) slab. Foundation demand for the CLT slab system can be reduced relative to the conventional RC slab system without sacrificing the structural performance criteria such as strength and lateral deflections requirements.

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