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STRUCTURAL DESIGN AND ANALYSIS OF HIGH-RISE BUILDING USING ULTRA-LIGHTWEIGHT FLOOR SYSTEM

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The main objective of this paper is to study feasibility of using ultra-lightweight (ULW) slab as an alternative design solution for floor component used in high-rise buildings. The main method is numerical case study by comparing the structural performances of 60-storey building in which floor component designed using one type of ULW called cross laminated timber (CLT) relative to floor component designed using conventional reinforced concrete (RC) slab using ETABS. The structural performances were compared between the two types of floor system including: total drift, inter-story drift, and base reaction which results in smaller frame sections and less reactions for the foundation demands by using ultra-lightweight (ULW). Additional survey to assess the awareness level of the public and engineering professionals about general high-rise building demand and new alternative building materials such as timber and its potential application in Saudi Arabia was also conducted.

Keywords: Tall building, Ultra-lightweight slab, Structural performances, Lateral load, Drifts, Survey of building demand and material alternative.

1 INTRODUCTION

Floor is one of the critical load path components in high-rise building, because it will dictate how much lateral load from wind or earthquake can be transmitted to the lateral load resisting system. This is in addition to resisting gravity load from dead and live load acting on it. Economically, floor composes 20% of the total structure weight and it will contribute to the foundation demand of the building. Conventional floor system for high-rise buildings is composed of reinforced concrete (RC) slab connected to steel beam (or RC beam) via shear connector as shown in Figure 1(a). The RC slab can be made cast in-situ with corrugated metal plate or designed with prefabricated system. The alternative floor system is utilizing ultra-lightweight (ULW) slab such as cross-laminated timber (CLT) connected to the beam via the shear connector that is normally made of long-screws pre-drilled through steel flange up to a certain design depth (Figure 1(b)). It should be noted that there are many other type of ULW slabs that are potentially applicable as those of the CLT slab. In this study, the main reason of utilizing CLT is because there have been a few applications in Europe and North America for medium-rise buildings and there has been a strong research and development to apply this non-traditional material as major structural components in high-rise buildings (AWC 2015) and (Gagnon and Pirvu 2011).

There are previous studies about feasibility using CLT slab as floor components of medium and high-rise buildings lower than 30 stories with steel and RC as the main skeleton (Asiz and Smith 2009, 2011). The results have indicated that under heavy lateral load, CLT based floor system outperforms conventional RC floor system in term of structural performances including drifts, steel demand, dynamic performance and base reactions. The following study is intended to investigate CLT based floor performance in high-rise buildings located in Saudi Arabia where lateral load from extreme wind would be the governing design load criteria.

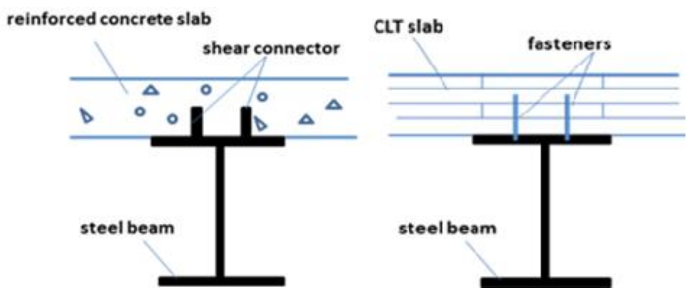

Figure 1. (a) Floor systems of tall building RC slab floor system (left) and (b) floor systems of tall building (right).

Unlike steel and concrete, CLT is considered to be orthotropic material meaning that the properties are dependent on the orientation. There is what so called major and minor directions for CLT materials. As CLT is always manufactured with odd layers (three, five, seven, or nine cross-wise layers), the major direction is normally associated with the most oriented layer. Table 1 shows the physical and mechanical properties of CLT from Asiz and Smith (2009 and 2011).

Table 1. Mechanical properties of CLT slab.

Directional property	**orthotropic**
Density (kg/m3)	400
Elastic modulus (GPa)	E1 = 9, E2 = 4.5, G12 = 0.5
Poisson's ratio	ν12 = 0.3
Strength (MPa)	$f_{t\text{-}1}$ = 20, $ft_{\text{-}2}$ = 15, $f_{c\text{-}1}$ = 30, $f_{c\text{-}2}$ = 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 DESCRIPTION AND GEOMETRY

The basic floor layout selected in this study was derived from existing 60-storey building analyzed previously by Shin *et al.* (2009). The main reason taking 60-storey building is because there were previous study about CLT slab feasibility in 24-storey and 40-storey floor components, and it is considered important to explore extreme wind load for higher building that is particularly situated in Saudi Arabia. The structural layout was modified to simplify the design process for major lateral load resisting systems including the steel moment frame and RC frame that is equipped both with RC shear walls as the additional lateral load resisting system.

The building was intended for commercial use and has layout size of 261.72 m x 19.81 m. Since the building is nearly three times slender on one side relative to the other side, shear walls were incorporated on the shorter sides to reduce the drift generated from the lateral load. The typical floor layout can be seen in Figure 2(a) showing major beams (girder) that are mostly spanned between the columns and shear walls and sub-beams between girders that are incorporated to accommodate gravitational (dead and live) loads and CLT slab size. The typical girder span is 7.62 m and sub-beam span is 6.86 m. Figure 2(b) shows the 3-d view of the building displayed using computer model output ETABS (CSI 2015). Of the 60 floors, the first fourth floor heights are 3.96 m and the rest are 3.05 m, and in total building has height 186.54 m.

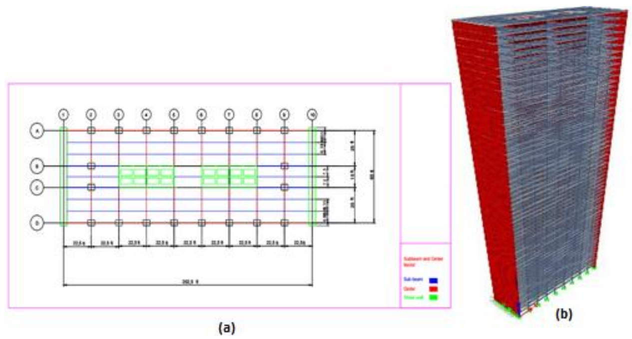

Figure 2. (a) Typical floor layout and (b) 3-D view of the 60-story building studied.

There were four cases in this study in terms of the main vertical and lateral resisting frame systems, two with steel frames and the other two with RC frames. Two types of floor systems were incorporated in the analyses. The first one was using the traditional RC slab, and the second one was using ULW slab with CLT material. The floors that used traditional RC slab were used as a reference. All the analyses were performed in the linear range using the structural analysis and design of building software ETABS (CSI 2015).

The steel sizing used was based on available AISC dimensions (AISC 2011). Preliminary sizing of the floor framing systems were performed to obtain girder and beam dimensions based on the vertical loads including the assumed RC slab of 150 mm thick and 220 mm thick of CLT slab. The major vertical loads applied were the gravity load plus superimposed dead loads and the live load for commercial building intended for office spaces. The major lateral loads applied were medium earthquake with peak ground acceleration 0.1g and extreme wind load with basic speed 200 km/hr intended for a location in the Eastern Province of Saudi Arabia. The load combinations between gravity and lateral loads were based on the Saudi Building Code (SBC 2007). Lateral load analyses were performed to check whether the preliminary sizing was adequate with respect to the allowable drifts according to the SBC code.

In the ETABS software, the floor diaphragm was modeled as shell elements connected rigidly to the floor framing both for RC and CLT slabs. This is a simplification of connection model for the CLT slab since it was found in the previous study that for high-rise building there is insignificant different in term of drifts between connectors that are modeled as rigid and flexible, i.e., with assigned stiffness (Asiz and Ahmed 2013). Also, gaps between CLT slabs were ignored in the floor modeling, i.e., CLT slabs were distributed monolithically as RC slab. All columns were connected as pin to the foundation. Study is ongoing at PMU to study the effect of ignoring gaps between CLT slabs in the floor system of high-rise buildings. However, it is anticipated that the different is insignificant due to building system effects.

3 RESULTS AND DISCUSSION

The critical load was resulted from the combination of vertical and wind loads. In this study, key structural performances such as drifts and base reactions were discussed. Vertical deflections of the floor elements were also determined analytically and numerically, and they were found all less than the allowable deflection stated in the SBC. Another design check that was performed under this study was vertical shortening of the columns and it was found that they are insignificant compared to the vertical deflection of the floor elements (girders, sub beams, and slab elements). Detailed design checks can be seen in the senior design project report by Hajjaj *et al*. (2016). Figure 3(a) shows the drift due to wind for different cases in y-direction and Figure 3(b) show the drift due to earthquake in y-direction. It should be noted that y-direction corresponds to the smaller dimension in the building layout. It can be seen that the wind load produced drifts, which is around ten times higher than that of the earthquake. This is consistent with the practical design situation where earthquake is rarely the determining factor in tall building design in Saudi Arabia. The critical drifts produced from the wind load for all cases are within the allowable drift according to the SBC code, which is 2.5% of the total building height. This also implies that the inter-story drifts produced are less than allowable (2.5% of the story height). Since high-rise building drift is a critical design criterion, the stress ratios for the steel frame cases are less than the critical value of 1.0. The steel stress ratio of steel members is defined as the ratio between acting stresses generated from external load over strength of that steel member.

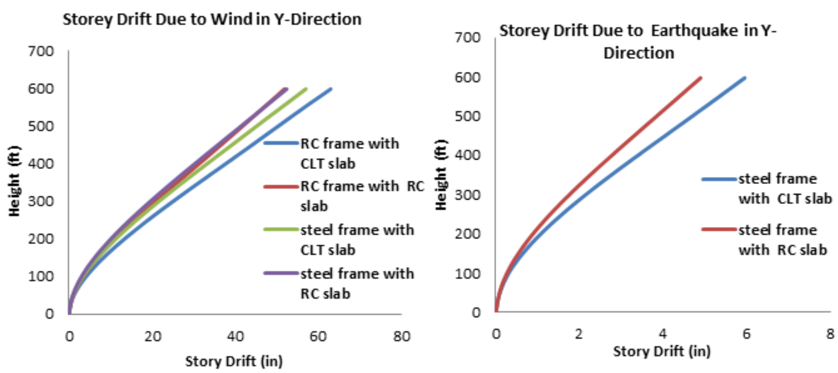

Figure 3. (a) Storey drift due to wind in y-direction and (b) storey drift due to earthquake in y-direction.

Further analysis indicated that the drifts in the vertical steel frame with RC slab were less than in the CLT slab, and the steel stress ratios was higher in the RC slab than in the CLT slab structure. This could lead to an opportunity to save more material if the main vertical and lateral load-resisting frame was designed according to the CLT weight. The drifts in the vertical RC frame with RC slab were less than the concrete frame with CLT by 18%. The difference between the RC slab and CLT slab is that the building with CLT slab has 15% more deflection than that of RC slab. This is due to higher in-plane flexibility of the CLT slab relative to the RC slab.

Although it is not the focus of the study, the RC frame cases produce higher drifts compared to the steel frame cases. Under the wind load, it is anticipated that the drifts produced are close between RC and CLT slabs because of the nature of the load that acts on the same building enclosure area, and this is the case for the vertical frame cases. Whereas for the RC vertical frame, the different is relatively big (around 10%) between these two floor systems.

Table 2 and 3 shows base reactions and the foundation demand which includes the raft plus pile foundation for all case studies. The foundation is made from two parts, the mat foundation and underneath the piles to increase the fixture of the building. The foundation demand here was expressed as the raft foundation depth required. The pile was designed according to the critical load combination in the column structural supports. Typical sandy soil layer commonly encountered in the Eastern Province of Saudi Arabia was used as input for the foundation design. As was in the drift analysis, the wind load acting in the y-direction is the determining factor in the foundation load design. In general, it can be seen that there is significant difference in the foundation demand due to difference in the structural weight. The reaction forces for the CLT slab structure was less than the RC slab by around 20%. This resulted in the mat foundation demand for CLT slab structure were less than the reinforced concrete slab structure by 20% indicated by reduction in the required length of the pile foundation from 2 m to 2.5 m. For the RC vertical frame, mat foundation demand for the CLT slab is from 2.6 m to 3 m, which is 17% less than that of the RC slab. It can be observed that the base reaction forces are proportional with the foundation demand. It also can be seen that the pile foundation settlements are less for the CLT slab specifically for the vertical steel frame cases.

Table 2. Base reactions.

Model Type	**Base Reaction Due To Wind Loads (kips)**		**Base Reaction Due To Earthquake Loads (kips)**	
	X-Direction	Y-Direction	X-Direction	Y-Direction
Steel Frame with CLT Slab	6774.5	16733.5	1259.7	1260.7
Steel Frame with RC Slab	6774.5	16733.5	1656.8	1152.5
RC Frame with CLT Slab	11924.7	23742.0	6921.3	6921.3
RC Frame with RC Slab	11924.7	23742.0	9139.3	9139.3

Table 3. Foundation demand.

Building type	**Steel building with RC slab**	**Steel building with CLT slab**	**RC building with RC slab**	**RC building with RC slab**
Raft foundation depth (m)	2.5	2	3	2.6
Raft foundation As (ft^2/ft)	0.12 for (-) moment	0.1 for (-) moment	0.13 for (-) moment	0.11 for (-) moment
	0.022 for (+) moment	0.018 for (+) moment	0.027 for (+) moment	0.018 for (+) moment
Pile foundation settlement (mm)	0.3	0.2	0.6	0.5

4 SURVEY

The main purpose of the survey was to assess the level of awareness in public and engineering professionals for the demand of high-rise buildings and use of alternative materials such as ULW and timber-based product CLT in high-rise buildings. It is anticipated that the survey outcomes will be used as the basis for exploring further opportunities in utilizing alternative design solution with ULW slabs for high-rise building applications. This survey was conducted in the Eastern Region of Saudi Arabia that included 9 questions ranging from general demand of high-rise buildings to specific questions about CLT and its potential use in high-rise buildings. The questionnaires were designed to represent the general expectations, suggestions and experience of public and engineering professionals about building design and construction. The survey method was mostly interview type by explaining first the research study initiated at PMU and few technical terms about building components and alternative design solutions such that the interviewees only responded with short answer such as yes-or-no, agree-or-disagree, and good-orbad ideas answers. There were more than 20 participants in the survey. In general, it can be seen that most of the people in this region of Saudi Arabia do not familiar with ULW slabs and CLT materials, despite of their awareness that they can benefit in term of construction speed. Not getting familiarity with CLT is natural for the people and professional in Saudi Arabia and Middle East, because timber is rarely used as major and permanent structural components in building due to very limited availability in the construction market. Important suggestion obtained from the survey included regulation (e.g., building code) needs to be developed if this new material is to be used as major structural components in high-rise buildings.

5 CONCLUSION

From the structural performance perspective, the vertical steel frame with CLT slab as the floor components was the lightest and has more potential to save materials and reduce the foundation demand compared with that of RC slabs used in either steel or RC vertical frames. However, the high-rise building with CLT slab produced slightly higher drifts. To obtain better result, the demand of the vertical steel frame with the CLT slab can be optimized considering the lightness of the CLT slab itself. This will result in smaller section of sub beam therefore less weight on the girder and on the columns resulting in reduction of the reaction and the foundation demand. The outcome of this study can be extrapolated to other type of ULW slabs that are currently being marketed and constructed for low-rise building applications in Saudi Arabia and Middle East. Ongoing study at PMU has been focused on the investigation of structural performance of multi-story and medium rise building under lateral load, constructed using CLT slabs with various layout and diaphragm as rigid and flexible floor system to provide input for the design code.

Acknowledgments

Participation in the survey by the selected public and engineering professionals in the Eastern Province of Saudi Arabia was appreciated. Thanks also are extended to Prince Mohammad Bin Fahd University that has facilitated the research study.

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