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The Seismic Behavior of Cross-Laminated-Timber Composite Slab in High-Rise Building

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Abstract—**This paper discusses the seismic performance of Cross-Laminated-Timber (CLT) floor slab in high-rise buildings. Due to its lower ductility and brittle failure mechanisms, CLT shows many advantages that can offer to construction sectors such as CLT walls or floor slabs. Substituting ultra lightweight slab material (CLT) for reinforced concrete floors or roofs can utilize its advantages to strengthen structural capacities. Moreover, the CLT-to-Steel Connection test illustrates that these connection components are sufficiently strong. Besides it can reduce these negative impacts of gravity forces associated with occupied built spaces. Therefore, applying CLT into these tall buildings superstructures where reinforcement concrete frameworks are the primary feasible. In a case study, SAP2000 models (a 24-storey framework) compare variable parameters between Concrete-Steel composite slab and CLT-Steel composite slab during lateral seismic events.**

Index Terms—**CLT slab, RC slab, seismic behavior, high-rise building, SAP2000.**

I. INTRODUCTION

Cross-Laminated-Timber (CLT) is well-established construction material in Europe since the early 1990s. This engineering wood product not only has lower embodied energy but stronger structural performance [1]. CLT panel are suitable for apply into walls, roofs and floors [2]. Also, it is a plated-like timber product and layers of planks are glued orientated at 90° to each other (Fig. 1). The cross-laminating process enhances stability of this product, which allows for prefabrication of long and wide floor panel and longer one-storey walls [2]. Experience shows that this system not only can be used in low-rise houses, but also can be applied to mid and high-rise buildings [3]. Due to its light self-weight, prefabrication and mechanical properties, it is formed a solid element intended for wall, roof and floor applications of tall building systems [4]. Between 1995 and 2005, CLT buildings had developed from 3-storey to 5-storey buildings in several European countries. In 2008 and the following years, it had been applying in higher rise buildings in Sweden, Germany, Italy and the UK [5]. Currently, the highest CLT building (10 storeys) was completed in Australia in 2013. During the strong development of manufacturing technologies in the last decade, CLT can be bearing heavy structural applications, which is only up to 500 mm thickness. Moreover, compared with reinforced concrete slabs, Cross-Laminated-Timber has strong stiffness and strength with massive and relatively lightweight. Therefore, CLT panels can create an effective lateral load resisting system during seismic motion due to its rigidity and stability. For instance, in Japan, a 7-storey CLT building was still stable during it suffers world’s largest shake table. Thus, CLT has the potential to show its excellent seismic behavior in high-rise buildings during earthquake-like motions. This paper presents these results from the case study that compares these relative parameters (mode shapes, deformed moment and storey drift) of a concrete-steel slab 24-storey building prime with CLT-steel composite slab.

Fig. 1. CLT panel configuration.

II. EMPLOYING CLT INTO HIGH-RISE BUILDING

Normally, the densities of CLT are around 1/4 of the weight of normal concrete (i.e., densities of massive-timber products as floor or slab materials are about 500 to 600 kg/m^3). Owing to the light-weight of Cross-Laminated-Timber, it can reduce specifications in building foundation and superstructure [6]. Also, it provides a two-way action capability due to its high strength and stiffness properties of in-plane and out-of-plane [7]. Besides, CLT reduces the construction times and costs due to its off-site prefabrication. Therefore, it is suitable for high-rise building as non-structural or structural parts. The strength and stiffness properties of concrete and CLT used in analysis are shown in Table I.

TABLE I: MECHANICAL PROPERTIES OF CONCRETE AND CLT

Properties	**Concrete**	**CLT**
Directional property	Isotropic	Orthotropic
Density (kg/m^3)	2,400	400
Elastic modulus	25	$E_1 = 9$ $E_2 = 4.5$
Poisson’s ratio	0.25	$G_{12} = 0.5$
Strength (MPa)	27.5	$f_{t\text{-}1} = 20$, $f_{t\text{-}2} = 15$ $f_{c\text{-}1} = 30$, $f_{c\text{-}2} = 25$ $f_{\text{shear}} = 5$

Note: ***E*** **= modulus of elasticity;** ***G*** **= shear modulus; l = CLT major direction; 2 = CLT minor direction;** ***t*** **= tension; and** ***c*** **= compression**

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These two floor connection systems can be compared visibly in Fig. 2 a conventional reinforced concrete floor and a new cross-laminated-timber floor [8]. The transitional RC slabs consisting of permanent corrugated steel formwork and cast in situ concrete, these 1.6 m width plates consist of CLT slabs that interlock edge-to-edge splice joints secured using self-tapping wood screws. Although both CLT slabs and RC slabs are mechanically fastened into steel joist, the connections of them with RC frameworks are different. Both of RC slabs and CLT slabs are connected to framework elements by elastic link elements, which can make semi-rigid translational attachments at the positions of mechanical fasteners in connections and joints [9]. Generally, RC slabs are monolithically cast with RC frameworks, while CLT slabs are mechanically attached to RC frameworks.

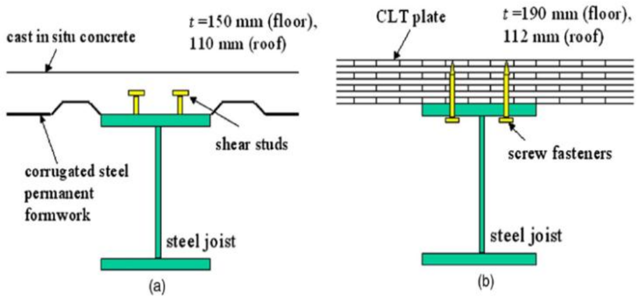


Fig. 1. Floor connection systems: (a) reinforced concrete floor; (b) cross-laminated-timber.

III. SEISMIC BEHAVIOR OF CLT BUILDING

Previous worldwide research work conducted a series of quasistatic experiences on CLT panels as building walls. In 2009, the Trees and Timber Institute of Italy worked small and large scale shake table seismic tests on two CLT buildings in Japan [7]. The result of these tests shows the CLT wall panels illustrated adequate seismic performance. Due to the nonlinear behaviour is happened in the bracket and hold-down connection areas, even after failure of the connections, the CLT panels play the role as the vertical load bearing elements. Additionally, CLT wall panels can give a system sharing effect and a degree of redundancy, owing to that these panels provide gravity and lateral resistance capacities. Thus, the CLT wall-panels can be an effective lateral load resisting system and enhance the seismic performance of CLT building.

Then considering about using the CLT panels as horizontal slabs in buildings is the other method to investigate seismic behaviour of CLT floor applied in buildings. The following parts will compare the seismic performance of CLT composite slab and reinforced concrete composite slab.

IV. CASE STUDY

This structure was modelled as a twenty-four-storey steel framework building with RC shear-wall core (Fig. 3). The 24-storey framework sections are shown in Fig. 4. In this case study, the RC slabs will be substituted by CLT slabs for comparison (*CLTf* versus *RCf*). Additionally, based on an approach of addressing fire performance requirements associated with applying combustible materials in high-rise buildings, the RC floors would be applied in each four-storey-high fire compartments (*Firef*), which means this mode was mixed by RC and CLT floors. For *CLTf*, *RCf* and *Firef* three systems, gravity and earthquake loads are combined in the lateral load situation. *RCf* has the total weight about 116 MN while for the system with CLT slabs and steel framework is about 57 MN. In addition, the total weight of the *Firef* system is 69 MN. Obviously, self-weight of *RCf* slabs are much heavier than the other two systems [10].

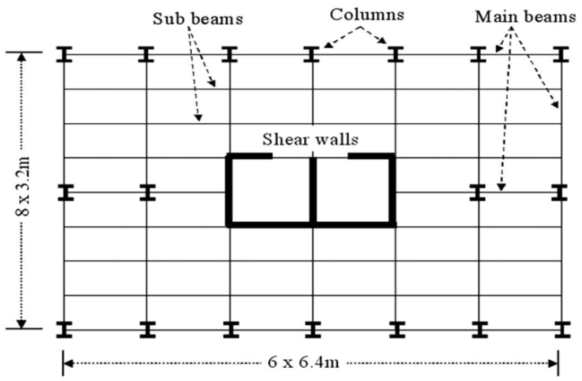
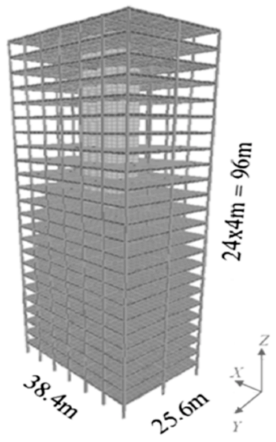


Fig. 3. Layout of the 24-storey building



Framework sections		
Steel framework	Columns	1st- 8th: W14x500
		9th- 16th: W14x342
		17th – 24th: W1x159
	Main beams	W24x94
	Secondary beams	W16x49
RC framework	Columns	1st- 12th: 800x1200
		13th – 24th: 600x800
	Main beams	350x650
	Secondary beams	200x400

Fig. 4. 24-storey building with steel or RC frame and RC shear-wall core.

Generally, the SAP2000 finite element analysis shows the design loads needed to combine three different loads impacts: static gravity loads (self-weight and imposed floor and roof loads, wind pressure and dynamic earthquake loads. In this experiment, based on the National Building Code of Canada for office building, Asiz & Smith (2014) assumed a dead load (1.25 kN/m^2) on roof plates and floor, which represented the impact of another permanent load (SDL). Gravity live loads (LL) of floors and roofs were 5.0 and 2.5 kN/m^2 respectively. Besides, dynamic earthquake loads (EQ) was applied using a peak ground acceleration of 0.5 g [10]. In these earthquake seismic analyses, these parameters were corresponding to high seismic risk locations in North America. In addition, X and Y horizontal axis directions of response spectrum were assumed as combinations of two types excitations (100%X and 30%Y or 30%X and 100%Y). For steel frame members, due to individual factored loads to each factored member resistances, the ratios of stresses should not exceed 1.0. The design load combinations of RC members should be considered as follow:

$$1.2DL + 1.2SDL + 0.5LL + 1.0EQ. \qquad (1)$$

The outputs of SAP2000 finite element analysis included story drifts, mode shapes and modal periods.

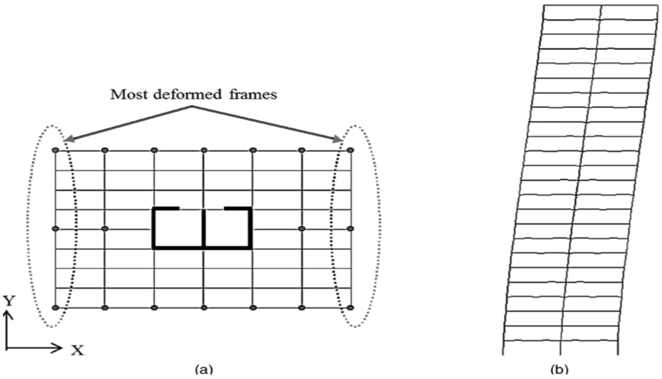


Fig. 5. Most deformed moment resisting frame in systems in system during seismic events [EQ (30%x + 100%Y)]; (a) floor plan; (b) deformed shape of frames.

V. RESULTS AND DISCUSSION

The results show the behaviors of both framework material and horizontal slab material in slender superstructures. In this case, there is enough stiffness capacity to carry wind load for lateral load resisting system (steel framework and RC shear wall). Thus, earthquake load is used to be the only critical design criteria. Nevertheless, during the actual design, it is necessary to consider the impact of wind load. Fig. 5 shows the most deformed moment resisting frame in systems during earthquake loads case (30%-X and 100%-Y). As Fig. 6 shown, the peak drift of the roof level for *RCf* system is 2.5 times than that of the *CLTf* system and 1.3 times than the *Firef* system.

Predictably, during the earthquake and wind loads, maximum lateral drifts for this frame structure with CLT floors are in the order of 1/2 to 2/3 of these other two frames. The maximum inter-story drift is happened in the 17th storey, which is about 12 mm in *RCf*, however for *CLTf* the value is only 7.9 mm. The connections (steel screws or bolts) between slab and framework elements can provide lateral force resistance to horizontal shear force. The deformed shape of mid-span lateral drift (d_{mid}), the average lateral drift (d_{avg}) and ends $(d_1+d_2)/2$ are defined in Fig. 7. However, the results show that the flexibility of *CLTf* is approximate 10% higher than *RCf* in same places. As a result, to control the capacity of resistance in flexural action, designing adequate frames or chords at the building perimeter is an efficient way to transfer the lateral forces to vertical resisting system [10].

In the dynamic analysis, it is also important to consider about these factors that impact on the deformed shape behavior. The experiment only shows the three lowest-order mode shapes of *CLTf* system due to it is similar to these three systems. Fig. 8 illustrates that these three different mode shapes. The first one is similar to a simple cantilever deflection and the other two modes have strong torsion components. Also Table II shows the modal periods values of each system in these three different modes. Obviously, these modal periods are different owing to that modal stiffness is decided by the cooperation between steel framework and RC shear walls. Therefore, *RCf* system has the greatest mode period compared with *CLTf* system and *Firef* system.

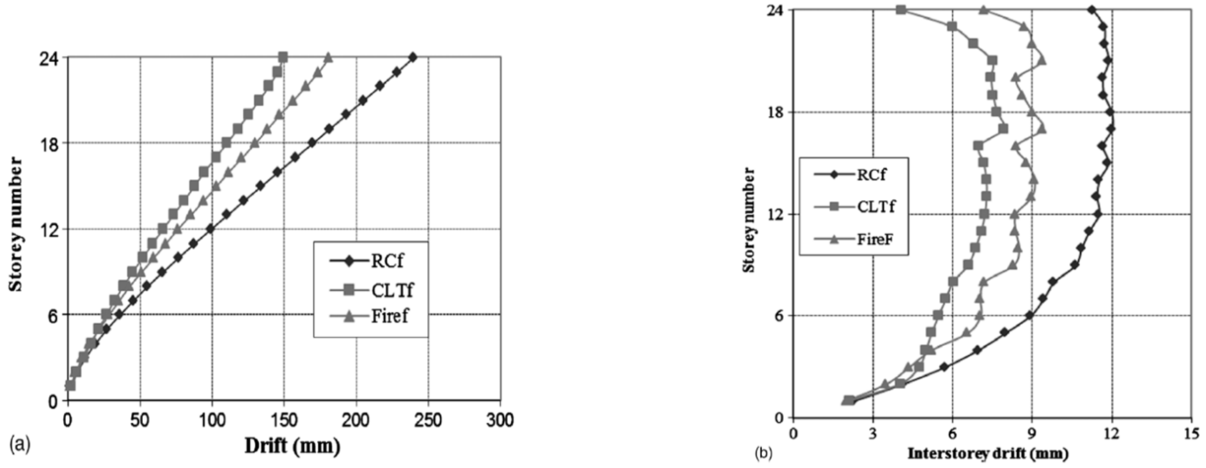


Fig. 6. Peak drift and inter-storey drift in steel framework systems during seismic events.

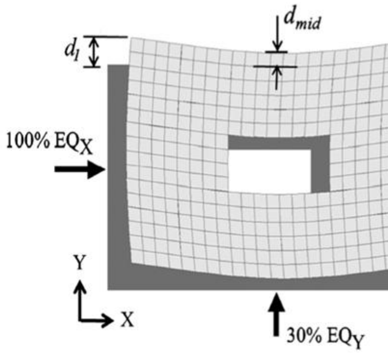


Fig. 7. Typical deformed shape of a horizontal diaphragm.

TABLE II: PERIODS FOR STEEL FRAMEWORKS

System	1st mode	2nd mode	3rd mode
CLTf $_{\textit{Steel-frame}}$	1.96 sec	1.69 sec	1.20 sec
Firef $_{\textit{Steel-frame}}$	2.29 sec	2.03 sec	1.42 sec
RCf $_{\textit{Steel-frame}}$	2.90 sec	2.41 sec	1.74 sec

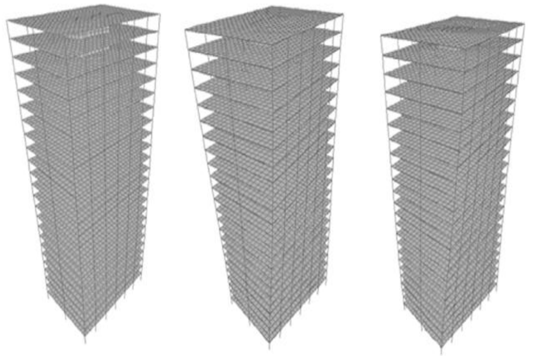


Fig. 8. Mode shapes for steel frameworks in the *CLTf* system.

VI. CONCLUSION

In this primary study, it demonstrates the structures and the relative mechanical capacities of *RCf* system, *CLTf* system and *Firef* system. Meanwhile, by comparing the outputs of SAP2000 analysis software, it explains the difference of seismic behavior between these three systems. In terms of deformed moment resistance, peak drift and interstory drift, *CLTf* system has better performance than *RCf* system. Additionally, because of lightweight of *CLTf* system, it can reduce the requirement of foundation specification. Although *CLTf* system has weaker flexural ability compare with *RCf* system, providing chords at the building surrounding can enhance flexibility resistance capacity. Besides, consider with the environmental impact, laminated timber is more suitable for sustainable development than concrete. Hence, by comprehensive consideration of Cross-Laminated-Timber slab with concrete slab, *CLTf* system has higher efficiency and sustainable development in earthquake action resistance. However, there are still future works need to consider. For instance, this experience did not do the comparison for the type of slab connection system based on different fastener or joint type. Also, the following step is to investigate the construction fee and maintenance costs of three systems, which is based on the similar seismic behaviors.

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