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Seismic performance evaluation of timber-steel hybrid structure through large-scale shaking table tests

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ABSTRACT

The experimental results and numerical simulation of shaking table tests on a two-thirds scale four-story timber-steel hybrid structure are reported in this paper. The hybrid structural system, developed recently, consists of prefabricated infill wood shear walls and moment-resisting steel frames serving as structural subassemblies to resist seismic loads together. The hybrid structure was subjected to earthquake ground motions at three different hazard levels with peak ground accelerations scaled to 0.14 g, 0.40 g, and 0.80 g, respectively. The responses of the structure, in terms of acceleration, inter-story drift, roof displacement, load sharing between the steel frames and infill walls, etc., were measured by different types of sensors. Peak shear force ratio (R) was defined to assess the proportion of the shear force resisted by the infill wood shear walls, and the results showed that the infill walls significantly contributed to the lateral resistance of the hybrid structure. The structure performed very well with little damage observed after severe earthquake excitations corresponding to the maximum credible earthquake. In addition, a non-linear numerical model of the hybrid structure was established in Abaqus with the Abaqus User Element to model the seismic behavior of the infill wood shear walls, and the numerical model was further validated by shaking table test results.

1. Introduction

As a building material, wood is gaining more popularities due to its renewability and sustainability. Numerous publications have highlighted the smaller environmental footprint of wood over other construction materials [1]. Wood buildings are able to store carbon during the life cycles and reduce greenhouse gas emissions significantly. As a building material, wood has a much lower density compared with other conventional building materials, meaning lower seismic load demand and reduced foundation cost. In the previous two decades, a series of significant breakthroughs have been made in the field of multi-story timber and timber hybrid buildings. Timber Frame 2000 project (TF2000 project), initiated by the Building Research Establishment (BRE) in the U.K., was carried out to examine the performance and economic benefits of multi-story timber frame structures. The TF2000 project offered a safe and uncomplicated method to ensure good performance of mid-rise timber structures, which helped to open up a new market for timber buildings up to 7 stories [2,3]. In 1999, researchers in Japan launched a project focusing on hybrid timber solutions [4]. Three timber-reinforced concrete structures were subjected to a series of earthquakes [5], and performance evaluation methods and design guidelines for such timber-based hybrid structures were proposed [6]. In Europe, the performance of prefabricated cross-laminated timber (CLT) structures was investigated under the SOFIE project [7–9]. A full-scale CLT building with a height of 23.5 m was tested under a series of earthquakes, and the test results showed superior seismic performance of the building [10–12]. In order to model the building, an advanced numerical model was further developed and validated against the shaking table test results [13]. Upon the trend of building taller wood buildings, two multi-institutional research projects were launched in North America. The NEESWood project in the U.S. focused on multi-story light timber frame buildings and developed performance-based design procedures. Shaking table tests were performed on a full-scale multi-story timber light-frame structure in 2009 [14]. No significant structural damage to the building was observed even under the maximum considered earthquake (MCE) shaking. The developed performance-based design procedure was shown to be quite effective in ensuring life safety [15–17]. The Newbuilds project in Canada seeks to explore new opportunities for multi-story and high-rise timber buildings. Tesfamariam et al. developed a hybrid solution with infill CLT walls and steel frames [18,19]. To study the performance of connections between the infill CLT panel and the steel frame, experimental

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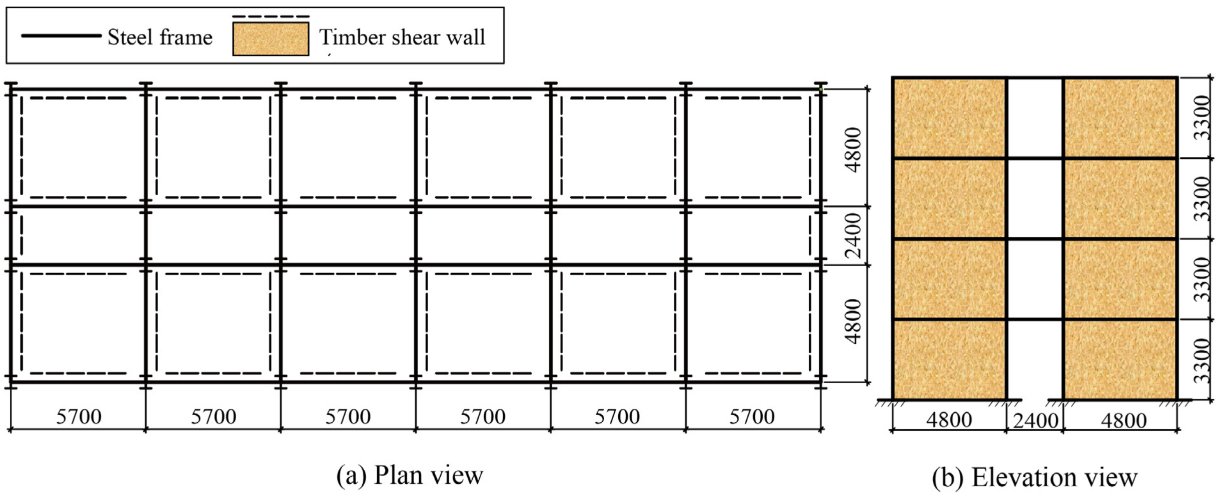

Fig. 1. Plan view and elevation of the prototype building (all dimension are in millimeter).

Table 1
Loads used for structural design.

Load Type	Location	Unit	Value
Dead load	Floor	kN/m^2	1.9
	Roof	kN/m^2	1.8
	Outer wood wall	kN/m	1.9
	Inner wood wall	kN/m	1.8
Live load	Office room	kN/m^2	2.0
	Corridor	kN/m^2	2.5
	Roof	kN/m^2	0.5
Snow	Roof	kN/m^2	0.5

Table 2
Similitude scale factors.

Parameter	Relation	Scaling factor
Length	S_l	0.6667
Linear displacement	$S_\delta = S_l$	0.6667
Angular displacement	$S_\varphi = S_\sigma/S_E$	1.0000
Strain	$S_\varepsilon = S_\sigma/S_E$	1.0000
MOE	$S_E = S_\sigma$	1.0000
Stress	S_σ	1.0000
Poisson's ratio	S_υ	1.0000
Mass density	$S_\rho = S_\sigma/(S_a \cdot S_l)$	0.7500
Mass	$S_m = S_\sigma \cdot S_l^2/S_a$	0.2222
Force	$S_F = S_\sigma \cdot S_l^2$	0.4444
Stiffness	$S_k = S_\sigma \cdot S_l$	0.6667
Linear load	$S_q = S_\sigma \cdot S_l$	0.6667
Area load	$S_p = S_\sigma$	1.0000
Moment	$S_M = S_\sigma \cdot S_l^3$	0.2963
Damping	$S_c = S_\sigma \cdot S_l^{1.5} \cdot S_a^{-0.5}$	0.3849
Period	$S_T = S_l^{0.5} \cdot S_a^{-0.5}$	0.5774
Frequency	$S_f = S_l^{-0.5} \cdot S_a^{0.5}$	1.7321
Velocity	$S_v = (S_l \cdot S_a)^{0.5}$	1.1547
Acceleration	S_a	2.0000

tests at component levels were conducted [20]. The proposed displacement-based design methodology was validated to be quite effective for this type of structure [21–23].

With the aim to predict the non-linear response of timber shear walls, numerous finite element models were proposed to facilitate computer modeling. A mechanics-based nail model was presented by Foschi [24] to calculate the hysteretic response of nailed connections in wood walls. In this model, nail was considered as an elasto-plastic beam in compression-only wood medium. The model was modified, and then implemented in LightFrame3D, a three-dimensional analysis computer program on wood light-frame structures [25]. Folz and Filiatrault [26] developed a widely-used model, using ten parameters to represent hysteretic behavior of nailed connections. The wall model, embedded into the CASHEW program, was demonstrated to be effective to predict the response of timber walls. Judd and Fonseca [27] developed a non-linear oriented spring pair model, using the initial displacement trajectory of nailed connection to determine the direction of the two non-linear springs. The new analytical model was implemented into both Abaqus and CASHEW. On the basis of BWBN model, Xu and Dolan [28] proposed a modified model to simulate the response of nailed connections in wood walls. The model took account of the coupling characteristics of sheathing-to-framing connection, and it was incorporated into Abaqus software package in the form of User Element.

Timber-based hybrid structures, such as the steel-CLT hybrid structures mentioned above, represent one of the most effective solutions of using more sustainable construction materials. However, the steel-CLT hybrid structural system may cost too much wood, which hinders its application in countries whose forestry resource is quite limited, such as China. Compared to CLT infill walls, light frame timber shear walls cost less wood while still provide good strength and stiffness. It is preferable to adopt light wood frame shear walls rather than CLT walls as the infill systems in China. He et al. [29] and Li et al. [30] proposed an innovative timber-steel hybrid structure. Such a structure consists of moment-resisting steel frames, wood diaphragms and infill light timber frame shear walls. The infill wood shear walls along with the steel frames serve as the lateral load resisting system for the structure. The hybridization can increase the structural efficiency, lead to a higher prefabrication level and reduce overall construction costs. To investigate the lateral performance, monotonic and reversed cyclic tests on single-story timber-steel hybrid structures were performed. The result indicated that the initial lateral stiffness of the steel frame could be significantly increased by the infill wood walls [29,30]. Parametric analyses were also conducted to investigate the loading resisting mechanism, mainly the effect on load-sharing between the steel frame and the timber shear walls [31–33]. With the pursue for improvements in seismic performance of building structures nowadays, a few novel technologies have been developed for improving the seismic resilience of building structures [34–36]. Thus, a damping device was also