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# Seismic performance assessment of steel frame infilled with prefabricated wood shear walls

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ABSTRACT

Steel-timber hybrid structural systems offer a modern solution for building multi-story structures with more environmentally-friendly features. This paper presents a comprehensive seismic performance assessment for a kind of multi-story steel-timber hybrid structure. In such a hybrid structure, steel moment resisting frames are infilled with prefabricated light wood frame shear walls to serve as the lateral load resisting system (LLRS). In this paper, drift-based performance objectives under various seismic hazard levels were proposed based on experimental observations. Then, a numerical model of the hybrid structure considering damage accumulation and stiffness degradation was developed and verified by experimental results, and nonlinear time-history analyses were conducted to establish a database of seismic responses. The numerical results further serve as a technical basis for estimating the structure's fundamental period and evaluating post-yielding behavior and failure probabilities of the hybrid structure under various seismic hazard levels. A load sharing parameter was defined to describe the wall-frame lateral force distribution, and a formula was proposed and calibrated by the time-history analytical results to estimate the load sharing parameter. Moreover, earthquake-induced non-structural damage and residual deformation were also evaluated, showing that if designed properly, desirable seismic performance with acceptable repair effort can be obtained for the proposed steel-timber hybrid structural system.


## 1. Introduction

In recent devastating earthquakes around the world, many buildings suffered severe damage, leading to huge social and economic losses. The 2008 Wenchuan earthquake in China, with a magnitude of Mw 8.0, caused approximately $130 billion USD in property losses [1]. The post-earthquake survey revealed that casualties were primarily caused by the collapse of masonry or concrete buildings with large seismic mass and poor construction quality. The 2011 Christchurch earthquake in New Zealand, with a magnitude of Mw 6.3, caused 185 deaths, and the central city of Christchurch was badly affected with severe damage to buildings and infrastructures that were already weakened by the preceding Canterbury earthquake, with a magnitude of Mw 7.1, in 2010 [2]. Experiences from past major earthquakes demonstrated that relatively lightweight timber or timber-based buildings kept more people safe. To provide an alternative for multi-story building systems in seismic-prone zones, a steel-timber hybrid structure was proposed by He et al. [3] and Li et al. [4]. In such structures, the steel moment-resisting frames are infilled with prefabricated light wood frame shear walls to serve as the lateral load resisting system (LLRS), and the diaphragms are composed of C-shaped steel joints and dimension lumber decking. The weight of the proposed structural system is largely reduced with the application of wood assemblies; thus, the seismic action on the entire building is also considerably reduced.

With the urgent need for building industrialization and the use of more environmentally-friendly materials, such as wood, in building construction, multi-story steel-timber hybrid structural systems have attracted much research attention in the past decade. The seismic performance of a steel-timber hybrid system, where cross-laminated timber (CLT) panels are used as infill walls in a steel moment-resisting frame, was analytically investigated by Tesfamariam et al. [5]. Seismic vulnerability assessments were conducted on the hybrid system, and a parametric study was carried out with a 1-story, 1-bay model using pushover analysis to investigate the effects of CLT panel thickness on the behavior of the LLRS. Subsequently, a ductility factor of 2.5 and an over-strength factor of 1.25 were recommended for the steel frame infilled with CLT panels [6]. Zhang et al. [7] investigated the ductility of a 12-story steel-timber hybrid structure, where CLT panels serve as shear walls and are connected to each other through steel beams, and the potential ductility factor for the prototype structure was calibrated based on nonlinear time-history analyses.

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In this study, the proposed structural system utilizes light wood frame shear walls as infills, instead of CLT panels, to provide lateral resistance. CLT is a solid panel product with a crosswise layup of wood boards bonded with adhesives. Although CLT has a considerably higher in-plane stiffness compared to a light frame wood system, high production costs may limit its wide application, especially in a country with limited forestry resources, such as China. Thus, with a relatively low production cost, light wood frame shear walls can provide a more cost-effective solution for multi-story steel-timber hybrid buildings. In the proposed structural system, the LLRS is composed of a steel moment-resisting frame and infill light wood frame shear wall. For a shear wall-frame interactive system, it is noted from ASCE 7–10 [8] that the shear strength of the shear walls shall be at least 75% of the design story shear at each story. Accordingly, the frames of the shear wall-frame interactive system shall be capable of resisting at least 25% of the design story shear in each story. However, previous experimental results from He et al. [3] demonstrated that the light wood frame shear walls are normally insufficient to resist 75% of the design story shear in a steel-timber hybrid structure. Thus, the evaluation of the load sharing mechanism between the steel frame and the infill wood shear wall appears necessary to reach a more comprehensive understanding of the structure's seismic behavior. This paper presents a seismic performance assessment of the multi-story steel-timber hybrid structure. A nonlinear numerical model considering damage accumulation and stiffness degradation was created and verified by test results, and the seismic performance of the proposed hybrid structure was evaluated with performance-based approaches.

## 2. Basic design considerations

The basic unit of the proposed steel-timber hybrid structure is shown in Fig. 1. The steel frame was assembled with hot rolled H-section steel members with a rigid beam to column connection, and prefabricated light wood frame shear walls were installed as infill walls. As a modularized structural system, light frame wood shear walls consist of a wood frame, made of dimension lumber, and sheathing panels made of oriented strand board (OSB) or plywood board, and the sheathing panels are connected to the wood frame by nails. The wood frame is normally fabricated with lumber with the dimensions 2 × 4 (i.e., 38 mm × 89 mm cross section) or 2 × 6 (i.e., 38 mm × 140 mm in cross section), and the distance between adjacent lumber is normally assigned as 305 mm, 406 mm, or 610 mm. The thickness of sheathing panels can be 9.5 mm, 12 mm, or 14.7 mm. The stiffness and strength of a light frame wood shear wall is primarily determined by the layouts of the sheathing-to-framing nailed connections (i.e., nail spacing, nail size). Bolted connections were used to connect the boundary elements of the infill wall to the steel frame. The bolted connections transfer shear force between the steel fame and the infill wall, ensuring that the infill wall and the steel frame can simultaneously deform and resist lateral loads. The steel moment-resisting frame, combined with the infill wall, act as dual LLRS. When subjected to shear force, the lateral resistance of a light wood frame shear wall comes from the combination of shear resistance from the numerous nailed sheathing-to-framing connections, and it is quite difficult to accurately predict the lateral resistance of a light wood frame shear wall with theoretical calculations. Previous studies [9–10] demonstrated that inter-story drift could be correlated with the lateral load resisting performance of light wood frame shear walls in a straightforward calculation. Therefore, hybrid LLRS can be designed with performance-based approaches. This section provides a preliminary design procedure for the proposed steel-timber hybrid LLRS, which mainly follows the performance-based design procedure recommended by Goel and Chao [11] for steel plate shear walls. The design considered a pre-selected preferred yield mechanism, as shown in Fig. 2. This yield mechanism consists of the formation of plastic hinges at both beam ends and column bases, and the "yielding" of the infill wall. Since the pushover response of the wood shear wall exhibits a high nonlinear property, the "yielding" of a wood shear wall can be considered as the point on the pushover curve corresponding to 40% of ultimate capacity (i.e., 0.4 $P_{peak}$). In accordance with the energy balance concept, the inelastic energy demand is equal to the inelastic work performed internally in a structural system. The total strain energy demand of inelastic single-degree-of-freedom (SDOF) system can be predicted by.

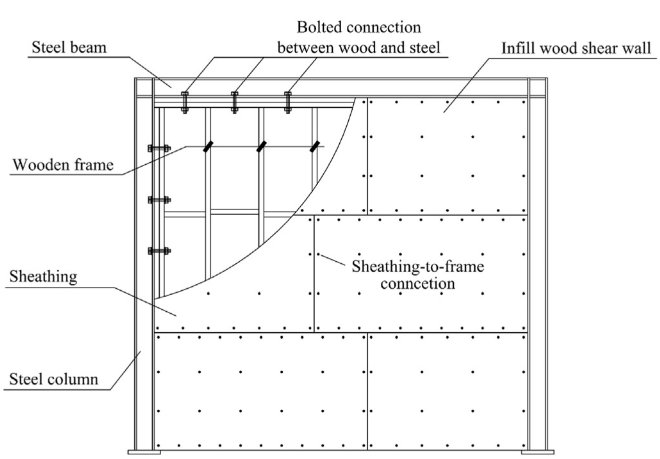


**Fig. 1.** Basic unit of steel-timber hybrid structure.

$$E_e + E_p = \gamma \cdot \frac{1}{2} M S_v^2 = \frac{1}{2} \gamma M \left( \frac{T_1}{2\pi} \cdot S_a g \right)^2 \quad (1)$$

where $E_e$ is the elastic strain energy demand; $E_p$ is the plastic strain energy demand; $\gamma$ is the energy modification factor; $M$ is the seismic mass; $S_v$ is the spectral velocity corresponding to the fundamental period of the structure $T_1$; $S_a$ is the spectral acceleration; and $g$ is the acceleration of gravity. Assuming that the entire structure is a SDOF system, the elastic energy $E_e$ can be estimated by Eq. (2) according to Akiyama [12]:

$$E_e = \frac{1}{2} M \left( \frac{T_1}{2\pi} \cdot \frac{V_b}{G} \cdot g \right)^2 \quad (2)$$

where $V_b$ is the base shear, and $G$ is the seismic weight of the structure. The energy modification factor can be determined by.

$$\gamma = \frac{2\mu_t - 1}{R_u^2} \quad (3)$$

where $\mu_t$ is the target displacement ductility ratio and is equal to $\Delta_t/\Delta_y$. Then, $\Delta_t$ is the target lateral displacement, and $\Delta_y$ is the yield lateral displacement. $R_u$ is the ductility-based reduction factor, equal to $\Delta_{eu}/\Delta_y$, and $\Delta_{eu}$ is the elastic target lateral displacement. Considering the selected yield mechanism, the structure can be idealized as an elastic perfectly plastic equivalent SDOF system, and the plastic energy $E_p$ is calculated by as.

$$E_p = \frac{G T_1^2 g}{8\pi^2} \cdot \left[ \gamma S_a^2 - \left( \frac{V_{by}}{G} \right)^2 \right] \quad (4)$$

where $V_{by}$ is the yield base shear of the structure. The plastic energy demand is equal to the work performed by the lateral force under inelastic deformation as.

$$E_p = \sum F_i H_i \cdot \theta_p = V_{by} \cdot \sum \eta_i H_i \cdot \theta_p \quad (5)$$

where $F_i$ and $H_i$ are the lateral force and height of the ith story; $\theta_p$ is plastic inter-story drift and equal to $\theta_t$-$\theta_y$; $\theta_t$ is the target inter-story drift, and $\theta_y$ is the yield inter-story drift; and $\eta_i$ is the lateral force distribution