16TH EUROPEAN CONFERENCE ON
EARTHQUAKE ENGINEERING THESSALONIKI
18 - 21 JUNE 2018

SEISMIC PERFORMANCE OF TIMBER-STEEL HYBRID STRUCTURAL SYSTEM VIA SHAKING TABLE TESTS

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ABSTRACT

The timber-steel hybrid structural system considered in this study is an alternative for the multi-story building. It is composed of steel frames and light-frame wood infill walls. To explore the seismic response of the hybrid structure, a four-story test building was constructed and then subjected to ground motions in Tongji University, Shanghai. Friction dampers were employed in the structure to improve the seismic performance and protect the infill walls under severe earthquake shakings. During the experiment, the hybrid structure was tested when dampers were enabled and disabled. Wenchuan, El-Centro and Kobe earthquake records were selected as seismic inputs in the test. The test results showed that the frequency reduction of the undamped structure was more obvious than the damped structure under major earthquakes, indicating the damped structure suffered less. The dampers decreased the acceleration response of the hybrid structure under major earthquakes. The results also showed that approximately 40% and over of lateral load was resisted by wood shear walls in the test. It means that the wood shear wall subsystem played an important role in the hybrid structure. The hybrid structure showed excellent performance under a series of earthquakes. Throughout the test, the damage to the test specimen was not significant. Only some nail connection failures were observed, and most failures occurred under major and extreme earthquakes.

Keywords: Shaking table test; Timber-steel hybrid; Slotted-bolted friction damper; Multi-story building; Seismic performance

1. INTRODUCTION

Wooden structures are ubiquitous throughout the world. Wood is a kind of common seen sustainable and natural material. Meanwhile, its high strength-to-weight ratio promotes greater use in multi-story buildings. In North America, timber buildings account for a large proportion of the building stock. However, the limitation of the conventional timber structures hinders its application to mid-rise buildings to some extent.

Hybrid system is a feasible approach to address this problem. Hybrid system can combine the benefits of different structural materials and achieve a superior performance. A handful of timber and concrete hybrid structural system concepts were proposed in a research project in Japan (Sakamoto et al. 2004). A shaking table test was carried out on timber frame-reinforced concrete core hybrid structure, and the test results indicated that the torsion effect should not be neglected owing to the plan irregularity (Isoda et al. 2016). Steel and timber hybrid system is another alternative solution. In such system, the timber subsystem can provide considerable lateral resistance, and the use of steel hence can be reduced markedly. Dickof and Tesfamariam et al. (2012, 2013) proposed a steel and wood hybrid system, which is constituted of a steel moment resisting frame and crossed laminated timber (CLT). The seismic vulnerability assessment of the hybrid structure demonstrated that the addition of infill bays could facilitate the lower vulnerability(Schneider et al. 2013). Seismic design methodologies for hybrid

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structures were developed and validated to be effective to control the displacement under earthquakes (Tesfamariam et al. 2015; Bezabeh et al. 2016). Besides CLT panels, light-frame timber shear walls were also employed as the infill system in the hybrid structure. The infill wood walls can cooperated with the steel frame effectively, and the lateral capacity of the hybrid structure increased substantially (He et al. 2013). According to the analytical result on load-sharing mechanism, the wall-to-frame stiffness ratio was suggested to be greater than 1.0 (Li et al. 2015).

The steel frame infilled with light-frame timber shear walls has sufficient lateral resistance. Moreover, such structural system can speed up the construction progress due to the high level of prefabrication. However, the lack of the thorough study on seismic behavior is an impediment to the development of the timber-steel hybrid structure. This paper presents a series of shaking table tests on timber-steel hybrid shear wall system. In order to avoid unrepairable damage under severe seismic excitations, slotted-bolted friction dampers were employed in the hybrid structure. The seismic behavior of the damped and undamped hybrid structure were compared.

2. DESCRIPTION OF TEST SPECIMEN

2.1 Geometry of the specimen and the structural elements

The prototype building was a common four-story office building in China. One bay of the prototype building was separated as a partial sub-structure, and the partial sub-structure was further scaled to 2/3 of the original size to serve as the shaking table test specimen. Figure 1 presents the test specimen and detail of the plan views. The specimen has a rectangular plan, 8.00m by 3.75m in axis. The total height of the structure was 8.80m, and the height for each story was identical.

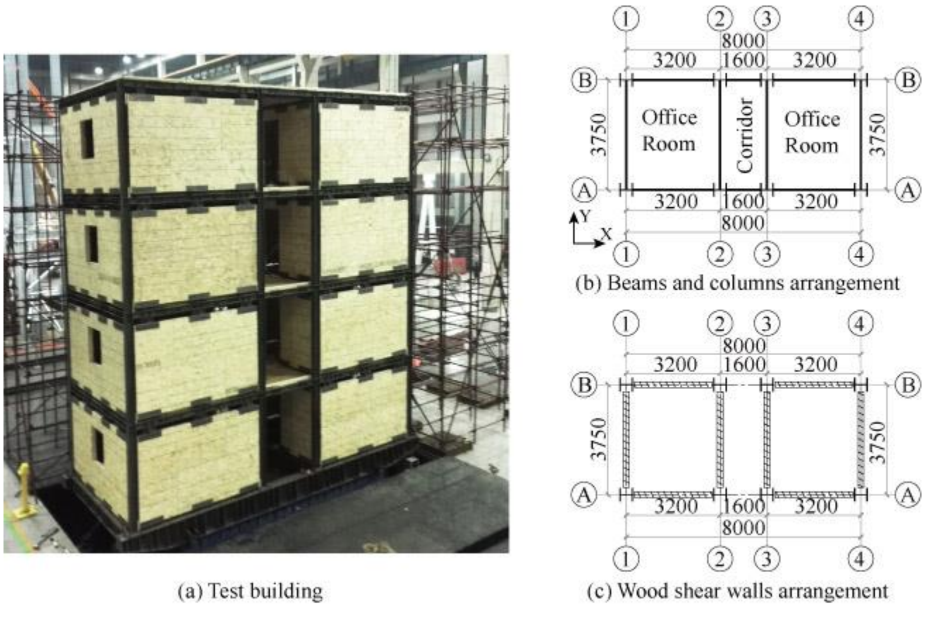
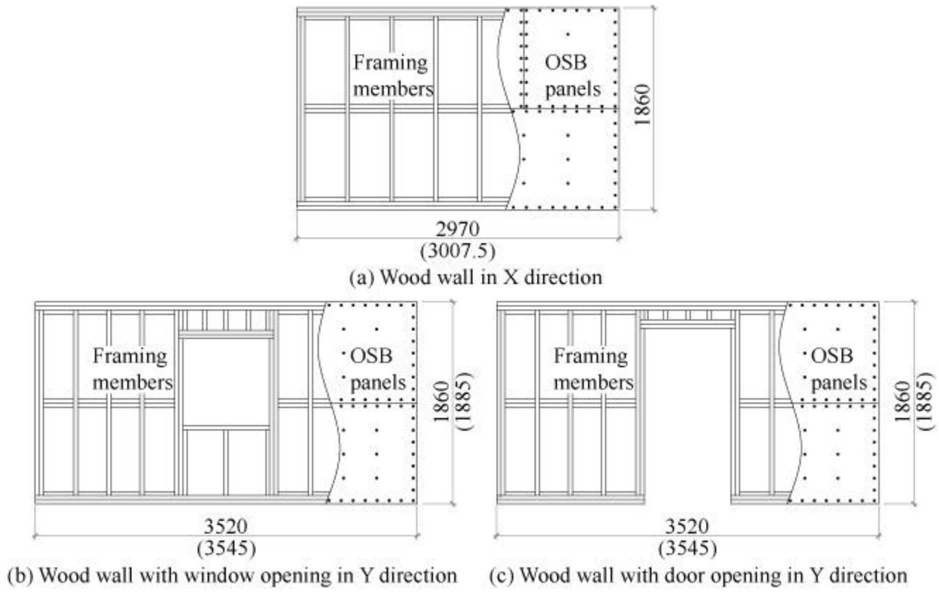


Figure 1. Test building and plan view of the specimen

The hybrid structure involves steel moment-resisting frame and wood infill walls. The steel frame was formed with hot-rolled H-shaped steel, and the steel profiles were manufactured using Q235 low carbon steel. The nominal strength of the steel was 235 MPa in accordance with Chinese Code for Design of Steel Structures (Ministry of Construction of the People's Republic of China 2003). From the story one to the story three, the columns sections were HW150×150×7×10, whereas the columns section for the top story were HW125×125×6.5×9. Nearly all the beams were HW125×125×6.5×9 except that the beams in Y direction for the top story were HW100×100×6×8. For the sake of prefabrication, field bolted splice connections were adopted as the beam-to-column connections, and high-strength grade 8.8 bolts served as the fasteners in the connections. Thus there was no welding work on site.

The frame of the wood infill walls included 38mm by 89mm SPF (Spruce-Pine-Fir) lumber of No. 2

grade. 12 mm-thick OSB (oriented strands boards) panels served as shear wall sheathings, and the wood shear walls were sheathed on outside or double sides due to the structural needs. Figure 2 illustrates the configuration of the wood walls. The window openings were set on the exterior walls in Y direction, while the door openings were set on the interior walls in Y direction. The nail spacing is the key determinant of the capacity and stiffness of the timber shear walls. Table 1 summarizes the nail spacing of the wood infill walls. The floors of the test specimen were light-frame timber diaphragms, which were constituted of SPF lumber joists and OSB sheathings. The cross section of the joists was 38 mm by 184 mm, and the thickness of the sheathing panels was 15 mm.



Note: the dimensions in the brackets are the size of walls for top story.(Unit: mm)

Figure 2. Configuration of wood walls

Table 1. Nail parameters for the wood walls.

Story	Nail spacing for walls in X direction		Nail spacing for walls in Y direction	
	Perimeter/mm	**Inner/mm**	**Perimeter/mm**	**Inner/mm**
4	125	250	150	300
3	150	300	100	200
2	100	200	75	150
1	75	150	75	150

Note: the walls in the X direction in top story were one-side sheathed, while others were two-sides sheathed

2.2 Frame-to-wall connection

The frame-to-wall connection of the hybrid structure should be designed carefully to avoid potential problems derived from material incompatibility. The reliability of connections is the essential factor for the collaborative work between steel frame and wood shear walls. In the meantime, it should be feasible for the connection to be switched to be a damper when needed. As can be seen in the Figure 3, two inverted L-shaped connectors and an inverted Y-shaped connector constituted the slotted-bolted damper connection. High-strength bolts facilitated the inverted L-shaped connectors to be connected to the beam flange, whereas self-tapping screws facilitated the inverted Y-shaped connectors to be fixed on the timber shear walls. In each inverted L-shaped connector, there were two milled recesses which constrained the slip of the friction pads during the test. If all the three bolts were inserted into the holes in the connection, the inverted L-shaped connectors could not slide relatively to the inverted Y-shaped connector. If the two bolts in the side holes were withdrawn, the middle bolt could move along the longitudinal direction of the slotted holes in the inverted Y-shaped connector, and then the connection could serve as a damper. In order to control the activation force of the dampers, specific bolts torques were applied to the middle bolts in different stories. If the shear force carried by the damper connection surpasses the activation force, it will start to slide. The damper connection can increase the energy dissipation of the hybrid structure and protect the timber walls. In the test, the connections of the walls along X direction from story one to story three could be switched to be dampers when needed.

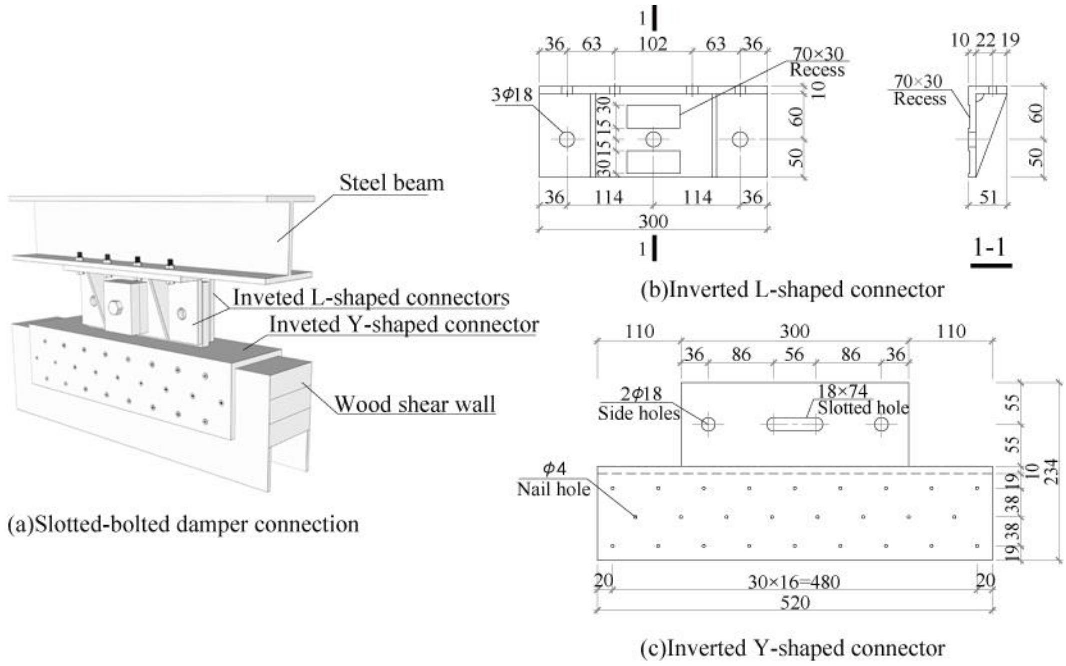


Figure 3. Configuration of slotted-bolted damper connection

2.3 Additional mass

In consideration of the seismic mass except for the as-built load, mass blocks were added to the floor for each story. To be more realistic, the weights of plumbing, floor finishes, insulation and the exterior finish were taken into consideration. Conforming to the Chinese Code for seismic design of buildings (Ministry of Housing and Urban-Rural Development of the People's Republic of China 2010), the equivalent seismic mass of the prototype included all the dead load and half of the live load. Due to the limitations of the shaking table, the similitude factors for the acceleration and elastic modulus were determined as 2.0 and 1.0, respectively. According to the similitude law, the similitude factor for the mass was 2/9. As a consequence, the additional masses were 7955 kg, 7955 kg,7955 kg and 5115 kg for story one to story four, respectively.

2.4 Construction

The construction of the test specimen lasted for approximately half a month. Besides, it took over one week to be ready for the test, including the preparations of the measuring system and other related works. The steel members and wood shear walls were manufactured in different factories and then were transported to the laboratory. Steel columns were erected first, and then steel beams were spliced to the stub beams which were welded to the columns in the factory (see Figure 4 (a) and (b)). As can be seen in Figure 4 (c), the prefabricated wood infill walls and timber diaphragms were installed. After that, the test specimen was conveyed on the shaking table (see Figure 4 (d)).

3. TEST SET UP AND INPUT GROUND MOTION

3.1 Instrumentation

Different types of sensors were installed in order to obtain the response of the test specimen. Displacement, acceleration and strain were involved in the measuring system in the test. The displacement transducers monitored the horizontal displacement of each story of the specimen. The accelerometers were capable of measuring the acceleration response of the structure and acquiring the change of the fundamental frequencies during the test. The strain gages made it possible to obtain the shear force in the steel columns. As shown in Figure 5, one steel segment near the point of inflection of steel column was selected. The bending moments at upper and lower section of the steel segment (M_u and M_l) were respectively measured by strain gages. The shear force V was calculated based on the bending moments and the length of the steel segment. The total shear force resisted by each story was derived from the known acceleration and mass. Accordingly, the proportion of the lateral load carried by timber shear walls could be determined. During the test, the measurement sampling of the seismic excitations was performed with a frequency of 256 Hz.

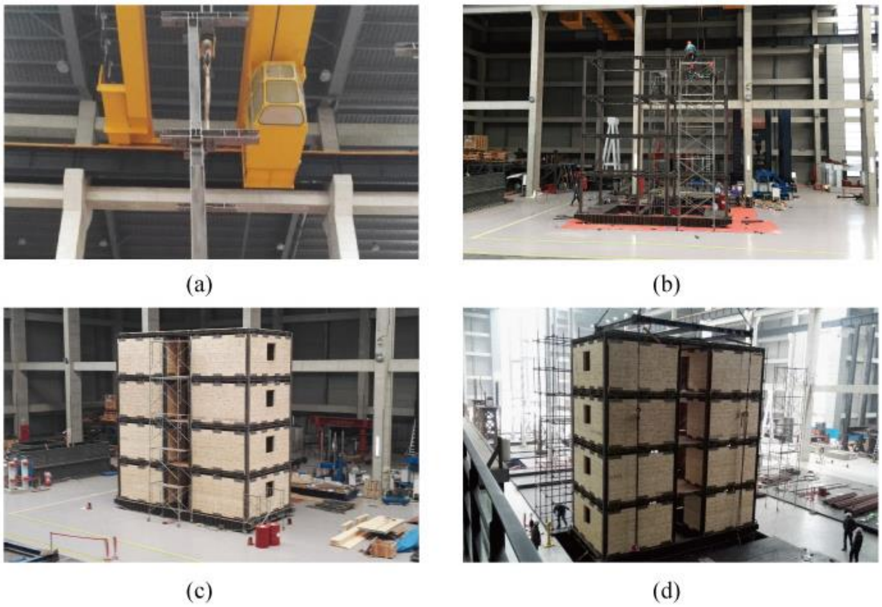


Figure 4. Construction of the test specimen

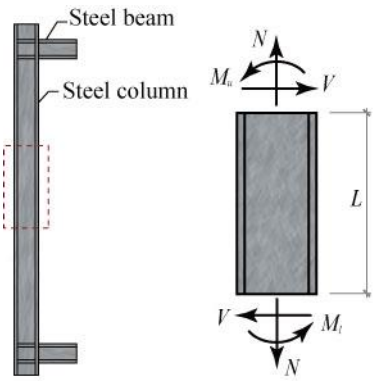


Figure 5. Calculation approach for the shear force in columns

3.2 Input Ground Motion

Sichuan Province is an earthquake-prone region in the southwestern part of China. The prototype was assumed to be in Sichuan, with a seismic precautionary intensity of Degree 8. In accordance with the Chinese code, the design basic acceleration of the ground motion is 0.20g. In order to explore the seismic

performance of the timber-steel hybrid structure, minor, moderate, major and extreme earthquakes were involved in the test, corresponding to peak ground accelerations (PGA) of 0.07g, 0.20g, 0.40g and 0.51g, respectively. According to the laws of similitude, the PGA of the input excitations should be further scaled by S_a=2.0. It means that the PGA of these four levels of seismic inputs should be scaled to 0.14g, 0.40g, 0.80g and 1.00g, respectively. In the meantime, a time similitude factor of 0.5774 was applied to the time of the input excitations. The hybrid structure was subjected to three earthquake records, i.e. Wenchuan earthquake ground motion (China, 2008), El-Centro earthquake ground motion (America, 1940) and Kobe earthquake ground motion (Japan, 1995). All the seismic excitations were applied along the X direction. Figure 6 presents the scaled earthquake waves and the spectral accelerations.
The investigation concerns the implication of the dampers on the seismic behavior of the hybrid structures. As mentioned previously, the status of the dampers (enabled or disabled) could be easily changed by inserting or withdrawing the bolts in the side holes of the damper connections. For the same seismic intensity, the specimen with enabled dampers was subjected to the seismic excitations first, and then the dampers were disabled. The test was carried out in seven stages, which is presented in Figure 7.

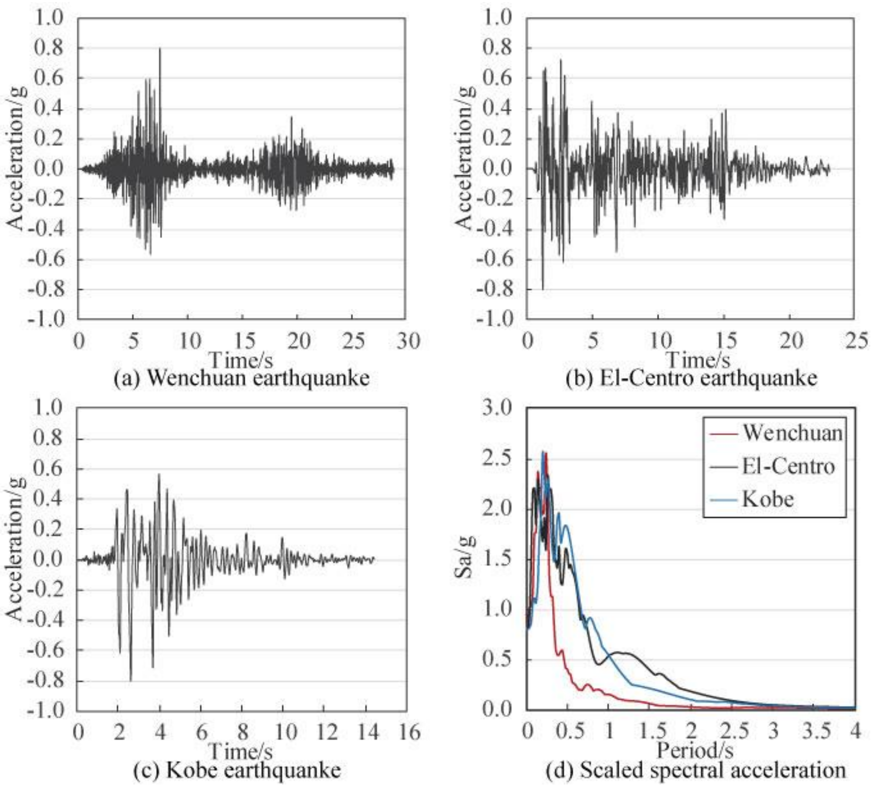


Figure 6. Scaled earthquake ground motions and spectral acceleration

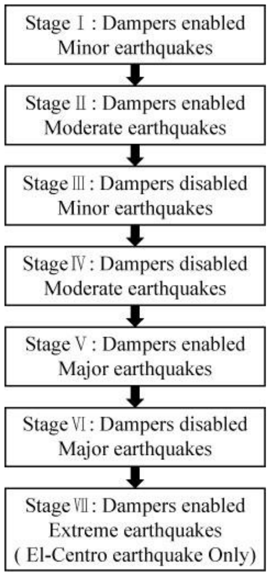


Figure 7. Flow chart of the test stage

4. TEST RESULTS

4.1 Fundamental frequency and mode shape

White noise scanning was performed to acquire the change of the fundamental frequencies and determine the mode shapes of the specimen. It can help to evaluate the damage experienced by the hybrid structure during the test. The time history of the acceleration recorded by accelerometers was utilized to generate the transfer function. The results indicated that the frequency reductions were mainly induced by El-Centro and Kobe earthquakes during the test. Figure 8 shows the transfer function (TF) amplitude of test specimen before and after El-Centro earthquake with a PGA of 0.80g. The TF amplitude of both damped and undamped hybrid structure changed after El-Centro earthquake. This gives an indication of the damage experienced by the building. As can be seen in Figure 8, the change of the TF amplitude of the undamped structure was more apparent.

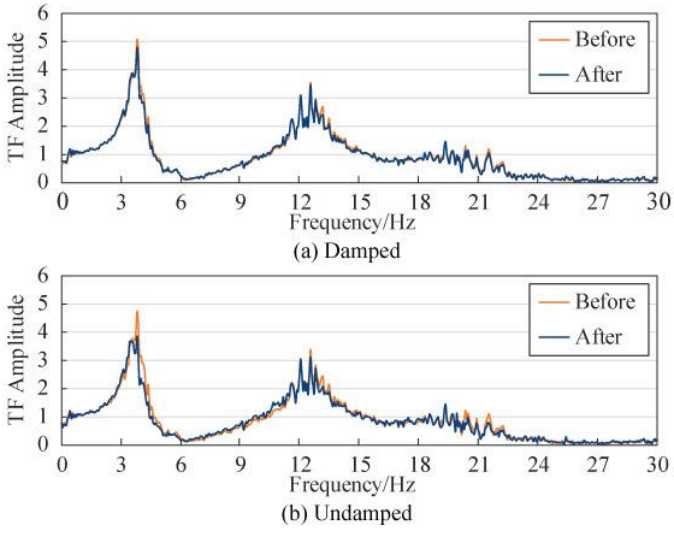


Figure 8. Transfer functions before and after El-Centro earthquake (PGA=0.80g)

After three major earthquakes were carried out on the damped structure, bolts were inserted into the side

holes of each damper and then the test specimen was switched to the undamped structure. This process led to a slight increase in the stiffness of the specimen. Coincidently, the fundamental frequencies for the damped and undamped structure before the El-Centro earthquake (PGA=0.80g) were identical, namely 3.813Hz. However, after the earthquake, the frequency decreased to 3.750Hz and 3.719Hz for the damped and undamped structure, respectively. It indicates that the dampers indeed reduced the damage to the hybrid structure.
Figure 9 shows the mode shapes of the test specimen before and after three major earthquakes. It is manifest that the change of the mode shape was not significant.

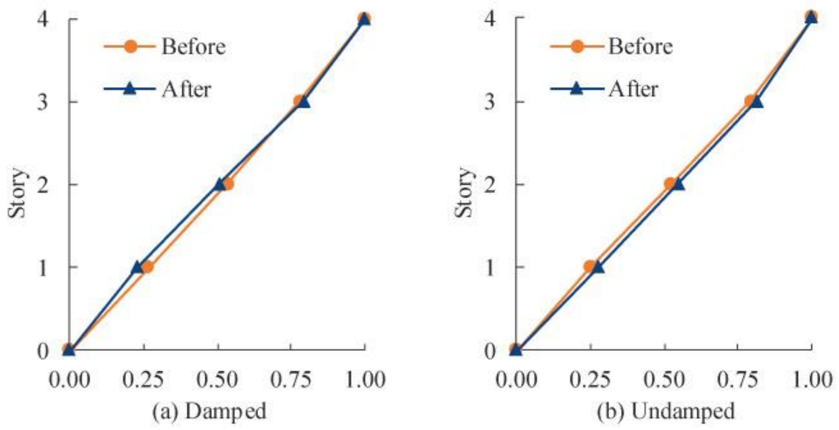


Figure 9. Mode shapes of the specimen before and after three major earthquakes

4.2 Acceleration

Excessively high accelerations under earthquakes may lead to severe consequence, especially for upper stories of buildings. Owing to high acceleration responses, habitants may feel uncomfortable or even suffer from the falling objects. Figure 10 shows the acceleration responses of the hybrid structure under El-Centro earthquakes. The acceleration responses in upper stories were relatively high. The accelerations for the damped and the undamped structure reached 1.51g and 1.68g under major earthquake, respectively. The acceleration responses were reasonable under this seismic intensity. The accelerations for damped and undamped structure under minor earthquake were almost the same, while the difference under major earthquake was obvious. It means the dampers can reduce the lateral load and overturning moment under severe earthquakes. The acceleration amplification factor decreased as the seismic intensity increased. Throughout the whole test, the amplification factor varied from 0.65 to 3.08.

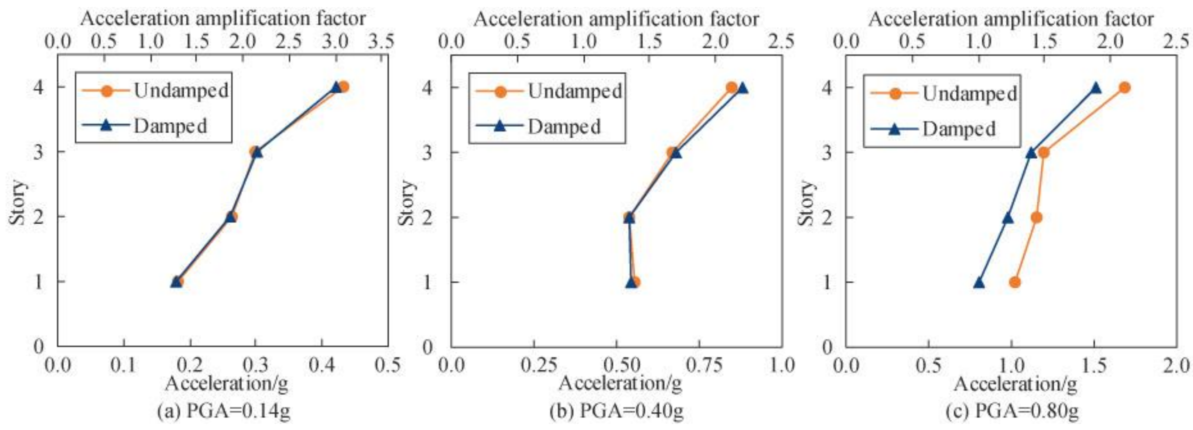


Figure 10. Acceleration response under El-Centro earthquakes

4.3 Displacement

The displacement profiles under El-Centro earthquakes with different intensities are presented in Figure 11. It can be seen that the difference of the displacement for the damped and the undamped structure under minor and moderate earthquakes was not considerable, while the difference under the major earthquakes was more apparent. Maximum roof displacement of 67mm was recorded under extreme earthquake when the dampers enabled. The inter-story drift for the story two was larger than that for other stories, and the maximum inter-story drift ratio was approximately 0.9% under extreme earthquake, which indicated the sufficient stiffness and capacity of the structure.

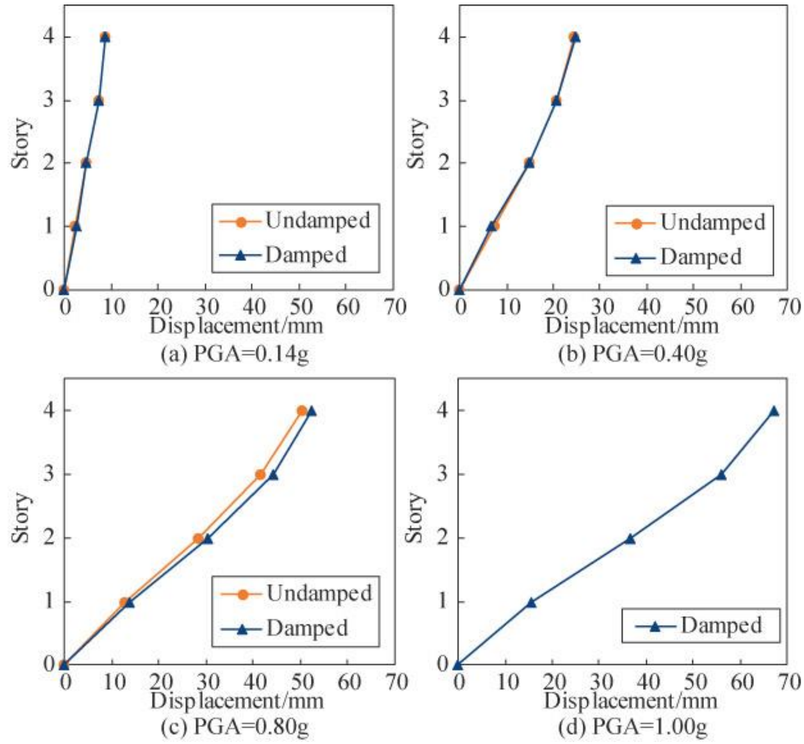


Figure 11. Displacement response under El-Centro earthquakes

4.4 Load sharing

An important concern about the timber-steel hybrid structure is the collaborative work of the two subsystems. The peak force ratio *R* was defined to assess the percentage of the lateral load resisted by wood walls. The ratio *R* can be calculated as follow. When the inter-story shear force for a certain story reached positive and negative peak value, calculate the corresponding ratios of the shear force in wood infill walls against the inter-story shear force, respectively. Then the ratio *R* can be determined as the mean value of these two ratios. Figure 12 illustrates the peak shear force ratio under El-Centro earthquake with a PGA of 0.80g. The dampers indeed caused some difference in peak shear force ratio. In general, the magnitude of *R* decreased story by story. For the story one, the ratio *R* was approximately 40%, which gave an indication that the wood infill system carried a considerable percentage of lateral load. Throughout the whole test, the peak shear force ratio descended as the intensity increased.

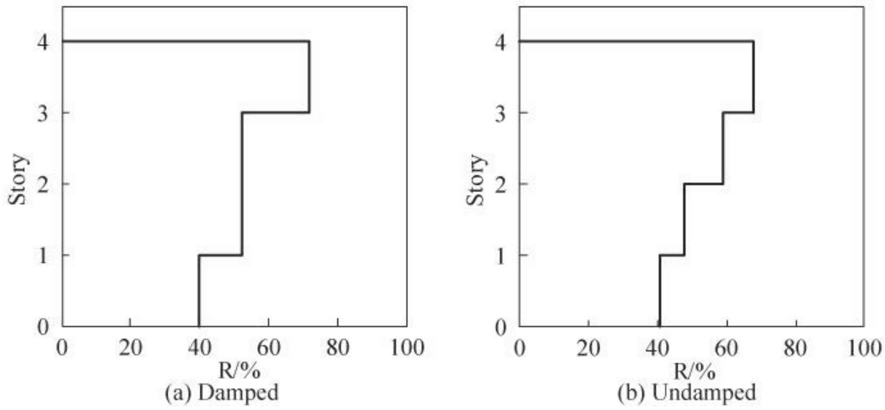


Figure 12.Peak shear force ratio under El-Centro earthquake (PGA=0.80g)

4.5 Damage Observations

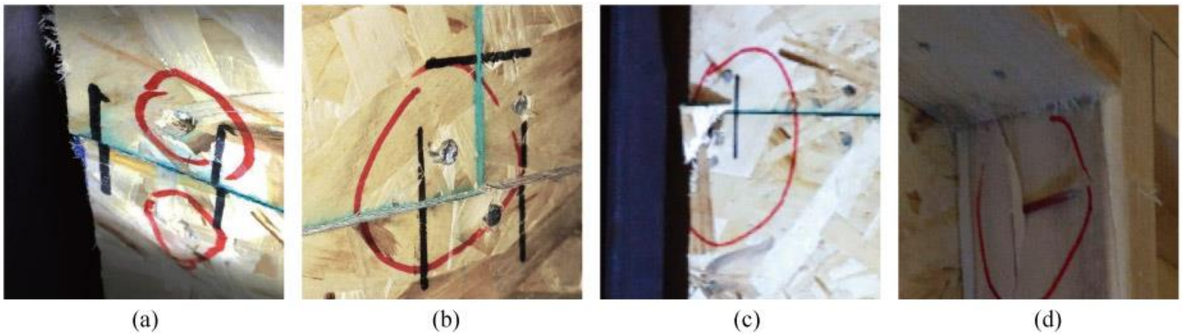


Figure 13.Damage Observations

The damage observations of the test specimen were given in Figure 13. The failure mode was the failure of nail connections in the wood infill walls. Figure 13 (a) and (b) showed nail embedment and nail pulling-out, which were mainly located at the edge and corner of the sheathing panels. As can be seen in Figure 13(c), the corner of an OSB panel was broken. Figure 13 (d) presents the nail pierced through the stud. Damaged nail connections were observed primarily after major and extreme earthquake shakings. The damage to the structure was not serious, which demonstrates a great overall seismic performance of the hybrid structure.

5. CONCLUSIONS

The seismic behavior of the timber-steel hybrid structures and friction dampers (aiming for improving the performance of structures under severe earthquakes) were investigated by shaking table tests. The acceleration and displacement responses indicated that dampers were not activated obviously under minor and moderate earthquakes. During the major earthquakes, dampers indeed worked effectively. In comparison with the undamped structure, dampers reduced the damage to the structure and decreased the acceleration response, leading to lower lateral load and overturning moment.

During the tests, the acceleration and displacement responses were reasonable. The structure had sufficient stiffness and capacity. The result of the peak shear force ratio indicated the shear force carried by the wood shear walls accounted for a significant proportion of the total lateral load. The main failure mode observed was nail connection failure. The hybrid structure showed a good seismic performance, and no significant damage was observed throughout the test.

6. ACKNOWLEDGMENTS

The author acknowledges the financial support provided by National Key R&D Program of China (Grant No. 2017YFC0703507) and New Zealand Earthquake Commission Biennial Contestable Grants Programme "Seismic Design of Timber-steel Hybrid Shear Wall Systems for Mid-rise Light Timber Framed Buildings".

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