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Shaking table tests for a Full-Scale Model of a Steel –Timber Composite Structure

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Abstract: A shaking table test was performed by a full-scale two-storey model a steel-timber for composite house structure to investigate its dynamic characteristics and seismic behaviors. The test model was a light steel framed house whose size is 6.0m and 5.0m in plain and 6.4m in height.Its dynamic characteristics and structural dynamic responses in different input seismic wave excitation were tested and analyzed. The test results indicated that the specimens performed elastically under the circumstances of 0.20g PGA (Peak Ground Acceleration). The tested building model can withstand successive applications of different seismic ground motions and had no visual damages under the circumstances of 0.30g PGA. The symmetrical ultra-light steel framed house specimen can meet the requirements for the seismic intensity of 8 as described in the Code for seismic design of buildings in China.

Keywords: *Shaking Table test; Steel-timber Composite Structure; Frame System; Seismic*

1. Introduction

Light timber structure is the most common style of residential buildings in North American. The kind of structure system is mainly composed of wood shear walls system, wooden floor system and wooden roof system composition. It is applicable to Low-rise buildings civil construction. The kind of structure has the advantages of convenience construction, simple structure, beautiful and energy saving. Under the large action of horizontal force, the traditional wooden houses normally have been great level of deformation caused by structural damage, which is short of enough stiffness. A new type of assembly integral structure was put forward to improve the mechanical capability. The new kind of assembled monolithic structure taking cold-formed thin-walled steel and glulam as the main body was presented, which is assembled from high strength cold-formed steel columns, beams, glulam secondary beams and floor slab. Through a reasonable combination of steel structure and timber structure in the structure system, it can not only significantly reduce the number of components and the size of section but also better meet the requirements of larger space, sound insulation and heat insulation. This kind of structure with less steel, better integrity, shorter construction period has becoming a promising application in emergency or permanent housing construction after the earthquake and other natural disasters.

Though domestic and foreign academic studies generally believed that the light steel structure has a good seismic performance, the experimental evidence is obviously insufficient. What’s more, there is no publicly available information of reliability research results about the steel columns, glulam beams in the mixed material structure system under strong earthquakes. As a result, the structure model of a column steel beam is designed and processed to test dynamic characteristics and seismic performance of the structure system.

2. Experiment Model

Shaking table tests were carried out by a full-scale two-storey light steel structure. The test model(Fig.1) had a rectangular 5.0m*6.0m footprint and two stories(ground floor, first floor and roof) with a total height of 6.4m, separately 2.8m,3.0m. As shown in Fig.2, the columns (KZ) and beams (KL) were made of rectangular thin wall steel tube whose yield strength is 550MPa with the section feature respectively 110mm x 2mm, 90mm * 2mm. The secondary beams (LL) were made of glulam whose tensile strength is 30.9 MPa, the compressive strength is 35.9 MPa and modulus of elasticity is 10760 MPa with the section of 100mm x 200mm. And the thickness of the floor is 60mm. In addition, double oblique Φ8 steel rod was set between the outer columns of each layer, whose yield strength is 270 MPa.

According to China's load code for the design of building structure GB 50009-2012, residential building standard value of floor live load is taken 2.0kN/m^2 and characteristics value of variable load on roof is taken 0.5kN/m^2. When there is an earthquake, the combined coefficient of floor live load is 0.5 and the roof live load according to the adverse factors is considered to be 1.0. At the same time, the dead weights of the actual structure of the partition wall and the external wall are equivalent to the floor uniform load. It is estimated that counter weight of 900kg and 550Kg should be respectively located on the first floor and the roof of the test model. In the practical test, according to the estimated value, the standard lead 20kg / block, and Φ6 iron wire connect structure of the secondary beam, roofing beam connection is reliable. The total weight of the model structure was 3120kg.

Figure 1: *Photo of shaking table test specimen*

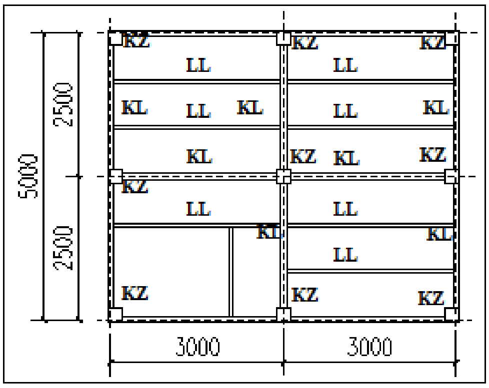

Figure 2: *Main floor plan*

3. Experimental Methods

In order to simulate various site conditions, two actual seismic acceleration records (hereinafter referred to as seismic wave) were selected as the ground motion input. At the same time, the white noise excitation tests were carried out on the structural model. The selected ground motion information were as follows:

(1) El Centro recorded the north south direction component on May 18, 1940 in Imperial Valley, California, USA, of which the PGA was 347.1 cm/s2 and the duration was 53.73s.
(2) Qian An recorded the north south direction component in 1976 in Qian An, when the Tangshan Earthquake occurred. The PGA was 145.8 cm/s2 and the duration was 19.90s.
(3) White Noise used artificial simulation, of which the PGA was 7.0 cm/s2, the duration was 225.28s and the frequency range was 0.5-50Hz.

In the shaking table tests, duration of seismic wave was constant while the PGA was scaled to three levels 0.10g, 0.20g, 0.30g and equivalent to 7 degree and 8 degree provisions of the Chinese Code for Seismic Design of Buildings. The white noise tests were used to test dynamic characteristics of model structure. Keep the amplitude in the testing process of 0.07g invariantly6 acceleration sensors, 4 wide-range linear variable differential transformers(LVDT),2 normal displacement transducers and 16 maximum strain sensors were set up in this experiment.

The acceleration sensors and wide-range LVDT were arranged at the bottom of the foundation, floor elevation of the first floor and ridge, measuring acceleration and absolute displacement. The normal displacement transducers were arranged at the bottom of the middle columns of the ground floor and the first floor, measuring the relative displacement of the columns and frame beams. The strain gauges were arranged at the both ends of the side columns and middle columns of the ground floor and the first floor, as well as the end of the beam which was connected to the column on the first floor. As shown in Fig.3 is the facade of the main instrument arrangement in Y direction.

Table 1: *Test sequence*

Number	Input fields vibration	Maximum peak acceleration(g)
1	WN	0.1
2	El-Centro wave	0.1
3	Qian'an wave	0.1
4	El-Centro wave	0.2
5	Qian'an wave	0.2
6	El-Centro wave	0.3
7	Qian'an wave	0.3

4. Results and Analysis

4. 1. Experimental Phenomena

The steel frame showed good seismic performance during the tests. None of the structural members were broken or damaged. When the value of the input acceleration was large(such as 0.30g),the model structure came a loud and clear extrusion and friction sound, which is the phenomenon of the extrusion and occlusion of the structural members. After the tests the model structure was observed, and multiple gaps of joints of beams and columns became larger. Connecting members of both beams and griders and secondary beams and griders were no significant folded, winkled or damaged. However, parts of bolts of the ground floor and the first floor were slack. Some threaded bolts were cut out. With no obvious damage, the timber beams were partly cracking at the connection members of the end of beams. Node strain test results showed that the Z direction strain value of column end node area was larger than both X direction and Y direction. The maximum strain occurred to the top layer of 1-C axis of the column with the maximum dynamic strain about 1900με, indicating the steel did not yield.

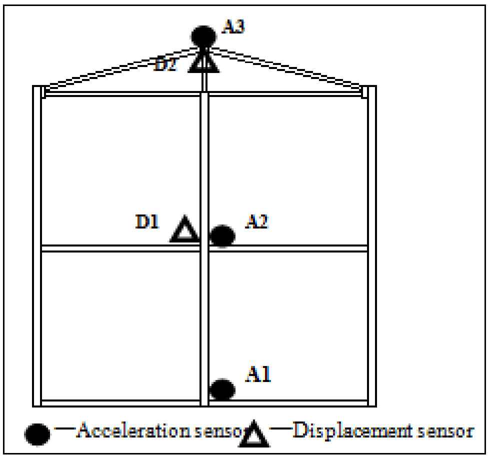

Figure 3: *Instrumentation on model structure*

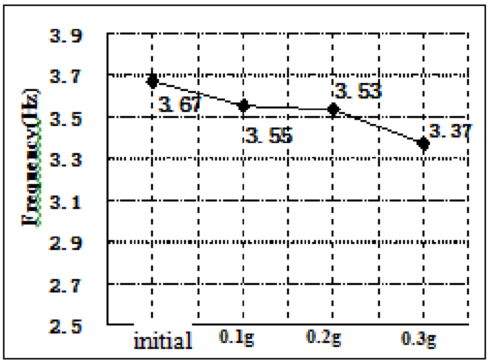

Figure 4: *Basic frequency of Y*

4. 2. Dynamic Characteristics

Free vibration method and white noise sweep excitation method were used to measure the dynamic characteristics of the model structure, such as the natural frequency, damping ratio and so on. Model structure damping ratio determined by the transfer function curve based on half-power point method, since the structure model wore no vulnerable maintenances and partition walls. As a result, damping ratio of the model structure changed little before and after the shaking table tests. Before the test, the damping ratio was 0.014. After 0.10g and 0.20g test conditions damping ratio was 0.015 and after 0.30g test conditions test value of damping ratio was 0.017.

Table2: *Maximum response of structure under different peak acceleration seismic wave incentive*

Number	**Maximum displacement (mm)**		**Maximum acceleration (m·s^{-2})**	
	The first floor	**roof**	**The first floor**	**roof**
El-Centro (0.1g)	1.38	2.20	0.41	0.59
El-Centro (0.2g)	8.82	11.56	1.42	1.93
El-Centro (0.3g)	29.90	43.65	2.53	3.35
Qian An (0.1g)	2.36	4.21	0.31	0.64
Qian An (0.2g)	15.60	28.14	1.83	1.21
Qian An (0.3g)	34.40	55.31	3.41	2.83

As shown in Fig.4 is frequency comparison of various experimental conditions. The results showed that the first natural frequency was 3.67Hz before the simulated earthquake tests. In the PGA of 0.10g after each test condition, vibration frequency of the structure decreased to 3.55Hz. Technically, at this time the model structure was in elastic stage. Thus, the reduce of free vibration frequency was attributed to cooperative para position of each members in the action of small vibration. In the PGA of 0.20g after each test condition, vibration frequency of the structure was 3.55Hz, indicating that model structure under the excitation of the ground motion maintained a flexible working state. In the PGA of 0.30g after each test condition, vibration frequency of the structure decreased to 3.37Hz. Compared with the fundamental frequency of models of each stage in initial state and before each phase, it can be seen that the natural vibration frequency of models before the earthquake tests is less than that of models after the tests. As mentioned earlier, at this time structure did not appear obvious plastic deformation. The model structure self-vibration frequency reduced from oblique to the pole of the relaxation and partial beam column connection bolts loosening.

Because the structural stiffness is roughly proportional to the square of the natural vibration frequency, the change of the structural stiffness is reflected by the change of natural vibration frequency. As can be seen from fig. 5, the fundamental frequency of the model structure has not changed after 0.1 g and 0.2 g seismic tests, which means the stiffness of the model structure is basically no change, still in the elastic state.

4.3. Shear-Weight Ratio

The mass of layer roof and roof of the model is simplified to a particle. According to the maximum acceleration response of the corresponding position, the shear distribution of the model can be obtained. As the total mass of the structure is proportional to the shear, for comparison, the ratio of the shear and the total mass of the structure can be used to analyze the variation of the shear. It can be seen from the figure that the seismic wave and the seismic acceleration are different. In each condition, the ratio of interlayer shear to the base shear of each layer is various. In the earthquake action of 0.1g, the shear force of the first layer is 1.4 to1.5 times the second layer. In the earthquake action of 0.2g, the sheer force of the first layer is the maximum 1.0 to 1.5 times the second layer. In the earthquake action of 0.3g, the shear force of the first layer is 2.4 to 3.0 times the second layer.

The data analysis shows that the ratio of the interlayer shear of each floor is close to the ratio of mass of each floor, so it can be considered that the distribution of the interlayer shear is mainly determined by the mass ratio. The floor live load is 4 times of the roof live load; as a result, the interlayer shear of the first layer is larger than that of the second layer. Fig.9 shows comparison of the shear-weight ratio of the floor/roof under different peak acceleration seismic wave incentive.

4.4 Earthquake Response

As shown in table 2 is the results of the tests of maximum displacement response and acceleration response under different PGA of El-Centro(Fig.5) and Qian An. Fig.6-Fig.6 show comparison of the acceleration time history curves and power spectrum of the roof under the action of El-Centro with different PGA. The structure acceleration response was relevant to the spectral characteristics of seismic wave, period of free vibration and damping ratio. Comparing table 2 and figure 8 can come to a conclusion that in the same condition each measuring acceleration coefficient gradually increases along the height direction of the floor. In terms of the same measuring point of acceleration response, Qian An wave response was stronger than that of El-Centro wave under the condition of two same level earthquake wave input. Under the action of PGA of 0.30g Qian An, was on the second floor of the structure to produce the largest earthquake acceleration, valuing 3.41m.s^{-2}. The displacement of the structure caused by Qian An was significantly stronger than that of El-Centro.

4.5. Seismic Behaviors

The model structure test research showed that the model structure was in elastic state when suffered from less than 0.10g PGA earthquake. The maximum story drift angle was about 1/1400, which was less than the limit of 1/250 on the steel structure of the elastic angular displacement of Chinese Code for Seismic Design of Buildings specification. The results showed that the building could meet the security requirement of the “no damage in low-level earthquake”. When the PGA was 0.20g and 0.30g, the model structure was composed of linear state transition to nonlinear state. The model structure mainly nonstructural damage could meet the requirements of "repairable under moderate earthquake“. At this time, the maximum story drift angle was 1/90, which was much less than the limit of 1/50 of the elastic angular displacement of Chinese Code for Seismic Design of Buildings specification. It should be noted that the test above did not consider the beneficial effects of model structure and nonstructural components such as wallboard on the structural seismic performance and vibration damping properties. The results showed that structures similar to the model structure can meet the requirements of the 8 degree seismic fortification of the Chinese Code for Seismic Design of Buildings (GB50011-2010).

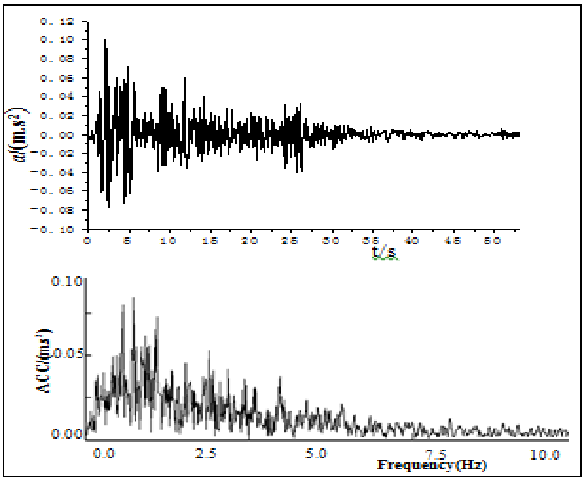

Fig 5: *Time history and Fourier spectrum of the El-Centro wave*

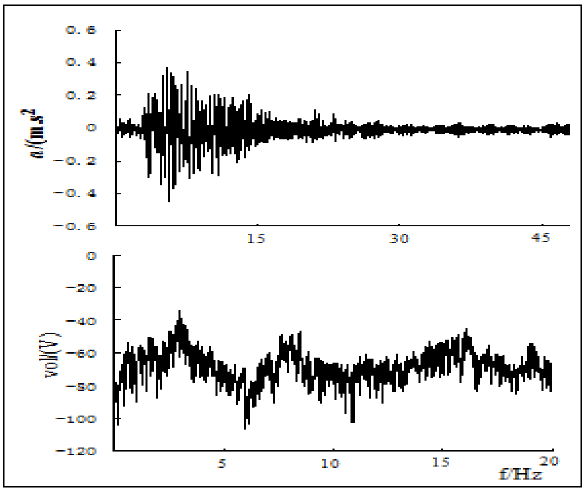

Figure 6: *Vibration response of second floor under El-Centro wave (0.1 g)*

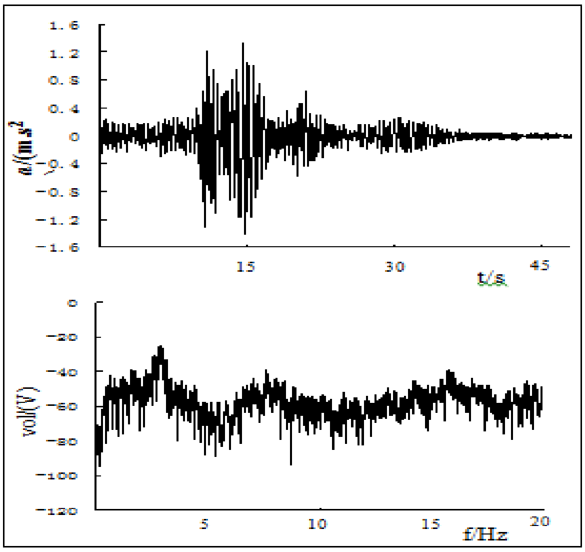

Figure 7: *Vibration response of second floor under El-Centro wave (0.2 g)*

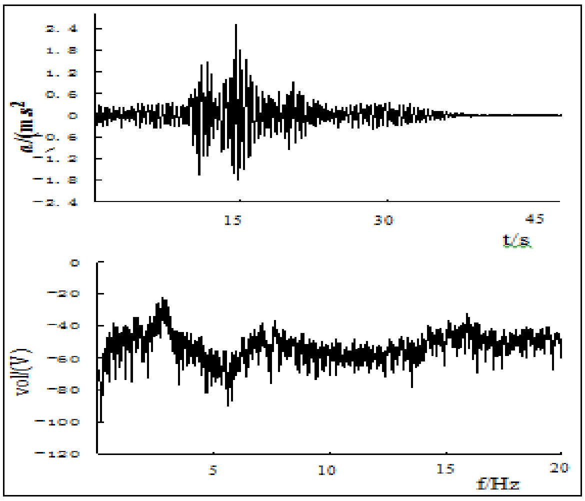

Figure 8: *Vibration response of second floor under El-Centro wave (0.3 g)*

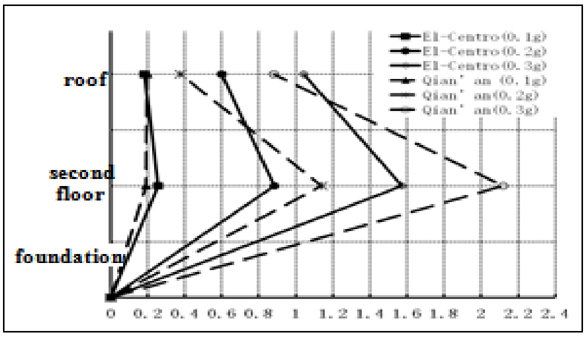

Figure 9: *The maximum displacement value of the point*

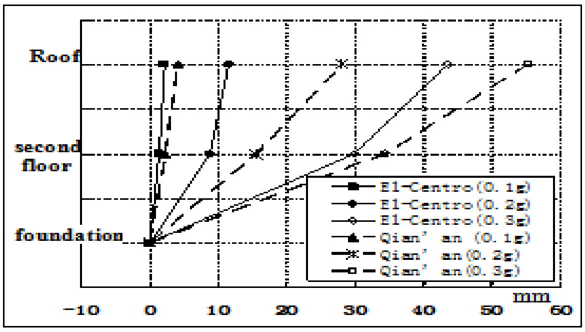

Figure 10: *The maximum displacement value of the point*

5. Conclusion

(1) Under the same seismic intensity, the structural displacement response of Qian An wave is significantly stronger than that of the El-Centro seismic wave. The basic cycle of the structure is 3.67s and the seismic performance of the structure on the soft ground is relatively poor.

(2) When suffered from less than 0.20g PGA earthquake, the model structure basically had no visible damage in elastic state; when the PGA is 0.30g, beams and columns and other main components are not damaged while part of the bolt rod connecting components become loose and the overall stiffness of the structure is reduced. But the joints of the column and beam are still reliable, and the structure can carry on the load without repair.

(3) The storey displacement of the ground floor of the model structure is much larger than that of both the first floor and the roof. When the PGA is 0.10g, 0.20g and 0.30g respectively, the maximum story drift angle of the ground floor is less than 1/250, 1/150 and 1/50.

(4) Those which are similar to the model structure can meet the requirements of the 8 degree seismic fortification of the Chinese Code for Seismic Design of Buildings GB50011-2010).

6. Acknowledgements

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