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SEISMIC PERFORMANCE OF SIX-STORY FABRICATED STEEL FRAMES UNDER PSEUDO-DYNAMIC TESTING

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In order to study the seismic behaviors of fabricated steel frames with bolted beam-height adjustable steel beam-to-column connections (BHA connections), a six-story steel frame was designed to run pseudo-dynamic experiments. Experiments were first carried out with the steel frames with and without buckling-restrained braces (BRBs) under three different types of seismic records under 35 gal and 70 gal. Then the seismic records of EL_CENTRO amplified from 220 gal to 1,600 gal were loaded on the braced frame. Results showed that there was no detachment, sliding, or yielding detected in BHA connections. After BRBs were installed, the story drift and the top-story maximum displacement could easily meet the codes, and the structure was still working in the elastic stage under 620 gal. It could therefore be concluded that BHA connections have excellent seismic performance and they are suitable for application in fabricated steel frames. The braced frame using BHA connections has good lateral stiffness and energy dissipation capacity.

Keywords: Bolted beam-height adjustable steel beam-to-column connection, Buckling-restrained brace, Fabricated steel system, Pseudo-dynamic test.

1 INTRODUCTION

Fabricated steel frame with bolted beam-height adjustable steel beam-to-column connections (BHA connections) and construction members to resist the lateral load is a kind of aseismic structure systems. They have a wide scope of applications because of their better eco-friendly performance, industrialized production, easy installation and maintenance.

For fabricated steel frame structure system, the reliable connection form of beam and column is essential. Therefore, some studies were conducted on some new types of connections. Cao *et al*. (2015) carried out an experimental study on bolted beam-height adjustable steel beam-to-column connections using quasi-static method. Using the ABAQUS software, they drew a comparison between the results of numerical simulation and experiment. Studies showed that BHA connections have excellent behaviors under low cycle reversed loading.

Li *et al*. (2009) conducted a lot of studies on BRBs and a type of TJ BRBs was introduced. It was demonstrated that the TJ BRB could be well applied to the practical engineering based on his researches. Berman and Bruneau (2009) put forward a new kind of joint with buckling restrained braces (BRBs) connected to beams only, and carried out a quasi-static test with a two-bay three-story reduced scale model. During the experiment, the connection form showed an excellent ductility, and it was proved to be an alternative to traditional connections.

Pseudo dynamic test could effectively simulate the seismic process. Due to the slow loading rate, the whole process of structural damage could be fully observed. Therefore, pseudo-dynamic tests were run with fabricated steel frame models with BHA connections. According to the analysis of the test data under different amplitude and ground motions, the seismic behaviors of the structure system had been achieved. However, more attention should be paid to the performance of connections. This study would be valuable for the promotion of fabricated steel frame with BHA connections.

2 EXPERIMENTAL SECTION

2.1 Prototype Building and Test Frame

This experiment was run with a typical fabricated steel frame located on Site class II. The prototype building was composed of a six-story steel frame and another frame with BRBs. These two frames consisted of BHA connections, BRBs, and H-section steel columns and beams. And they were both two-bay six-story three-dimensional frames, with a total height of 18 m, and 3 m for each story.

The strength model of artificial mass simulation was used for this experiment. The test frames were related to the prototype frame through a scale factor of 0.25. According to the principle of equivalent degree of freedom, the mass of each story was concentrated to the floor, and then the six degrees of freedom were equivalent to two degrees of freedom. As shown in Figure 1, the specimens were 4.5 m high for 6 stories. With an axes spacing of 1m, the columns were connected to the ground using bottom beams of 400 mm high. The specimen was 3.98 m away from the reaction wall and the load was generated using two 100 T hydraulic MTS actuators. The latter structure was obtained by adding several BRBs to the former after the former was tested.

(a) Spatial steel frame.

(b) Frame with BRBs.

Figure 1. Test models.

2.2 Design of BRBs

In order to study the role of BRBs in fabricated steel frame, a comparative study was made with steel frame and frame braced with BRBs. As shown in Figure 6, the BRBs used for the test had a cross ductile steel core placed inside a square steel tube to resist the axial load. And the square steel tube could restrain the buckling of core. The BRBs was connected to the end plate by four angle steels, as shown in Figure 2 and 3.

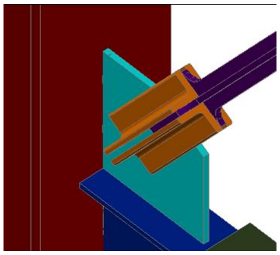


Figure 2. Connection diagram.

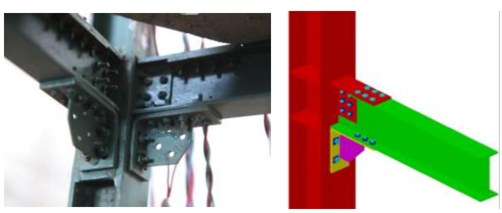
Figure 3. Photograph of BRB connection.

Steel material used in the frames was Q235B, while for the floor and roof, the reinforced concrete slab was made of material C30. The uniaxial tensile material tests were carried out with the sampled standard steel specimens. And the compressive strength of concrete was tested using rebound method. The steel used had a yield strength of 225 N/mm^2, an ultimate strength of 314 N/mm^2, an elastic modulus of 2.1×10^5 N/mm^2, and a Poisson's ratio of 0.3. The concrete used had a compressive strength of 19 N/mm^2.

According to the similarity principle, the material density should be 4 times of the prototype. Due to the same material density, the test model needs to be designed with counterweight. However, the size of the test model and the prototype did not fully conform to 1:4. After a lot of trials, the period ratio of test model with 250kg counterweight in each floor and the prototype was close to 2:1, then T = 0.480. Finally, the equivalent mass of the loading story was 1540 kg for 6-story, and 900 kg for 3-story.

2.3 Design of Connections

The BHA connection was used to ensure the connection of beam with column (Cao *et al.* 2015). This kind of connections (as shown in Figure 4) was composed of T-shaped connector. The connection location could be adjusted when the beam height was changed in a small range, due to the ellipse-shaped holes in the L-shaped connector and the flange of columns.



(a) Photograph. (b) Schematic diagram.

Figure 4. BHA connection.

The construction of BHA connections is particularly convenient and quick. At the first step, the upper flange plate of the beam should be connected to the T-shaped connector. After that, the L-shaped connector would be installed next. This installation method, to a certain extent, could be used to avoid the installation inconvenience caused by machining errors. Therefore, we could greatly speed up the construction and raise our working efficiency. This advantage had been demonstrated in the process of specimen installation.

2.4 Loading Scheme

Because the prototype was located on Site class II, EL_CENTRO and TAFT ground motion records were selected as the inputs. In order to study the influences of different seismic wave types, an artificial ground motion record was also added to the test. According to the motion characteristics, the duration of each ground motion was 15 s. Then the duration was shorten to 7.5 s based on the time similarity ratio of 1:2.

Table 1. Loading scheme.

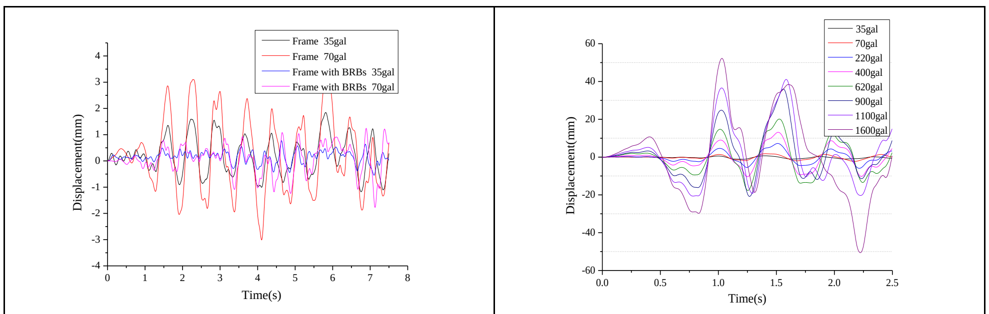
Specimen	Lateral force-resisting members	Loading scheme
SY-1	No	EL、TAFT、Artificial records amplified to 35gal and 70gal
SY-2	BRBs	1: EL、TAFT、Artificial records amplified to 35gal and 70gal 2: Gradual loading under EL records amplified from 220gal to 1600gal

Based on the characteristics of selected ground motions and loading purposes, the loading scheme of the test was determined as shown in Table 1.

3 RESULTS AND DISCUSSIONS

3.1 Displacement Response

It could be seen from Figure 5，that the waveform of each displacement curve was basically the similar when the PGA was less than 620 gal.



(a) Artificial seismic wave. (b) Frame with BRBs (EL_CENTRO).

Figure 5. Displacement-time curves of 3rd story.

The displacement magnitude of the 3rd story increased linearly as the PGA increased, and this indicated the whole structure kept elastic. When PGA was 900 gal, some waveform differences of the displacement curve emerged, indicating that some components yielded. Failure was detected in individual BRBs, and some columns and beams were working in the plastic stage. When PGA was 1,100 gal, more BRBs were damaged, and the structural stiffness decreased rapidly, but the deformation of the two systems satisfied the requirement of the code. When PGA reached 1,600 gal, the shape of the displacement-time curve had a significant change, which illustrated that more parts of the specimen entered the plastic stage. And at the same time the maximum displacement of top story reached 104 mm, more than 2% of the frame height. Throughout the test process, there was no slippage or damage found in the joints, which ensured a reliable beam-to-column connection.

3.2 Acceleration Response

It can be seen from Figure 6 that under the same kind of seismic waves, the acceleration amplitude of each story increased as PGA increased. But the acceleration waveform began to change from 900 gal, because of the decreasing structure stiffness caused by the destruction of BRBs.

It can be seen from Figure 7 that the acceleration waveform of the braced frame began to change at 1.2 s compared with the unbraced one. After BRBs were installed, the acceleration-time curve of the top story was more similar to the EL_CENTRO curve due to the increased structural rigidity.

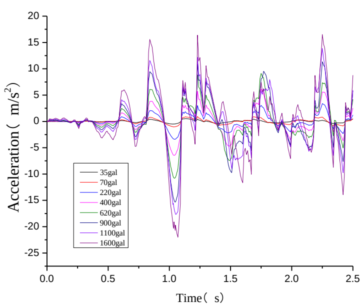


Figure 6. Acceleration-time curves of top story in SY-2 under ranged PGA.

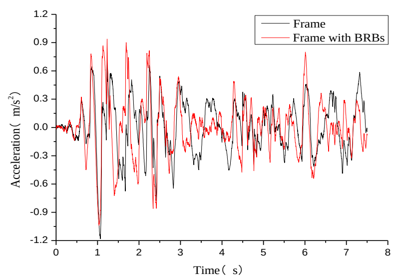
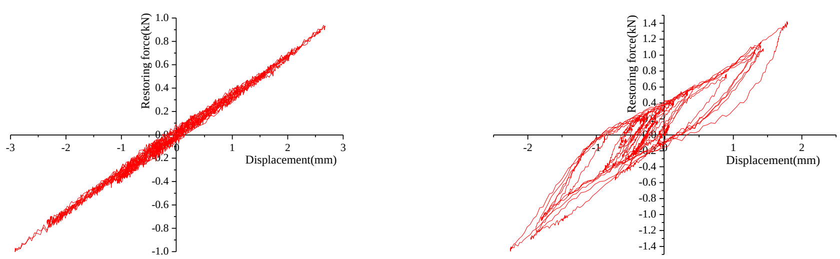


Figure 7. Acceleration-time curves of top story under 70 gal (EL_CENTRO).

3.3 Hysteretic Curve

The test data showed that, when PGA was less than 70 gal, the two specimens were all working in the elastic stage.



(a) SY-1.

(b) SY-2.

Figure 8. Hysteresis loops of 3rd story under 70 gal.

It can be seen from Figure 8 that the hysteretic curve was becoming much plumper after BRBs were installed. Although both main structures worked in elastic stage under 70 gal, the frame with BRBs had already a certain energy capacity due to the presence of BRBs.

When PGA was 70 gal, the hysteresis curve showed the fusiform shape. And then it changed to the Z-shaped with PGA increasing. Because the force of actuators increased, the occurrence of ground beams slippage relative to the ground was resulted in. When PGA increased to 900 gal, the maximum restoring force was about 12 kN. When the PGA reached 1,100 gal and 1,600 gal, the maximum restoring force was still maintained at this level, which means the structure had been in the plastic stage when the PGA reached 900 gal. In addition, all the connections were stable, and no abnormal phenomenon appeared in the joints.

4 CONCLUSIONS

Fabricated steel frames with lateral force resisting components adopt a new type of BHA connections, which make the construction much easier. Tests demonstrated this structural system exhibited perfect seismic performance. After BRBs were installed, the story drift and the top-story maximum displacement was small enough to meet the code requirements for seismic deformation. The braced frame was still working in the elastic stage under seismic input of 620 gal. When PGA was 900 gal, the BRBs began to break up in the ends, and the beams and columns of the first story which were close to the joints positions also began to yield. However, these damages were partial, and the main structure could be repaired due to prefabrication of structural elements.

BHA connections had excellent performance in the tests. This kind of joints could overcome the installation error considerably, which lead to their great applicability for steel frame systems. Under the ground motion of 1,600 gal, the structure just made some sound because of the bolt dislocation. And there was no detachment, sliding, or yielding detected in the joints in the whole test process, which was in accordance with the strong joint design principle. However, if the web plates and the ribbed slabs were weak, the joints were prone to eccentric compression torsion deformation under the action of positive and negative bending moments. This type of joints could be well applied to the steel frames.

The BRBs could effectively increase the stiffness of steel frame structures, and significantly improve their energy-dissipating capacity. As the first line of defense for security of steel frame, the BRBs could protect the main structure from damage under strong seismic action. BRBs damage occurred mainly at the ends of the cross steel core. In the context of the reliable connection with the frame, the variable cross-section at the end of BRBs need more attention to prevent the out-of-plane damage, so that its energy capacity can be brought into full play as a lateral force resisting member.

In summary, the current study of fabricated steel frames with BHA connections would be of significant value to the design of civil engineering applications such as residential constructions and office buildings. And it was believed that this kind of frames would have great development potential in the process of housing industrialization.

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