Experimental Study on Seismic Performance of Eccentrically Braced Steel Frame with Full Bolts Connection

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Abstract. In order to study the seismic performance of fully bolted semi-rigid eccentrically braced steel frame, a pseudo-static loading test was carried out on a single-story single-span eccentrically braced steel frame. The seismic behavior of the specimen has been analyzed according to the failure mode, hysteresis curve, bearing capacity, ductility, energy dissipation performance, and stiffness degeneration etc. The experiment results show that this structural system has fairly good energy dissipation capacity, strong bearing capacity and excellent ductility. Except for the link, other members of the frame are in the elastic stage, indicating that the specimen is easy to repair after earthquake. The hysteresis curve of the specimen shows significant pinch phenomenon owing to the slip of the bolt.

1. Introduction
Although the ductility of the steel frame is good, the lateral rigidity is small; the lateral rigidity of the centrally braced steel frame system is relatively large, but the lateral rigidity drops sharply after the diagonal brace buckling. The eccentrically braced steel frame system takes into account the advantages of the first two steel frames and has better energy consumption capacity. The concept of eccentrically braced frame is put forward for the first time by Popov. Through static analysis and dynamic analysis, it is proved that the structure has sufficient lateral stiffness, good ductility and energy dissipation capacity, and the correctness of the theoretical analysis is verified by experiments [1-3]. Mehmet completed 8 cyclic loading tests on the eccentrically braced steel frame. The study showed that the length and strength of the link, the loading method, the connection type, the bolt pre-tightening force and the gap of the splicing connection were the main factors affecting the test results [4]. Foutch carried out pseudo-dynamic tests on the central braced and eccentric braced steel frames. The test results indicated that the central braced structure members were easy to buckle, which led to a decrease in supporting force, while the eccentric braced frame had a plump hysteretic curve and stronger degeneration ability [5]. Liusheng Duan, Mingzhou Su and some others completed experimental studies on monotonic and cyclic loading of 4 single-span high strength steel K eccentric bracing steel frames. The test results demonstrated that the high-strength steel composite K-shaped eccentrically braced steel frame has high bearing capacity, good ductility, and strong energy dissipation capacity; the energy dissipation capacity of the shear-yield specimen is better than that of the bending-yield specimen; the bearing capacity, ductility and displacement of the frame after restoration were not much different from the original structure, and the specimen after restoration was
sufficiently safe [6-7]. Qiang Shi and others conducted low-cycle reciprocating loading experiments on eccentrically braced steel frames with different link lengths, and analyzed the influence of the link length on the seismic performance of eccentrically braced steel frames [8].

In domestic and foreign codes (GB50011-2010 [9], AISC2016 [10], CSA2009 [11]), the link and the frame main structure are designed as a whole, that is, the components are connected into a whole by welding connection. And the welding connection makes the post-earthquake repair process complex, which is difficult to construct and has high cost. In order to improve the above defects, this paper puts forward the eccentric braced steel frame structure with full bolt connection. The advantages of this system are as follows: the steel components are prefabricated in advance, the field is assembled quickly, the degree of industrialization is high, and it is easy to repair after the earthquake, saving time and cost.

In this paper, in order to explore the seismic performance of fully bolted eccentrically braced steel frame, a 1:2 scale K-shaped eccentrically braced steel frame is subjected to a low-cycle reciprocating load test to analyze its failure mode, bearing capacity, hysteretic performance, and energy consumption ability, stiffness degradation, ductility and so on, which provides experimental basis for engineering application.

2. Experiment Overview

2.1. Specimen Design

A steel frame in the bottom layer of a traditional 8-story K eccentric braced steel frame is taken as the research object. The height of the layer is 3.6 meters and the span is 6.0 meters. The test specimen is designed according to the scale of 1:2 scale, then the height of the layer is 1.8 meters and the span is 3.0 meters. The prototype structure locates at 8 degree seismic fortification area, fundamental earthquake acceleration level 0.3g, site classification I class, earthquake design group first group. The components are designed according to China criteria (GB50011-2010 [9], GB50017-2017 [12]), checking the strength, stiffness and stability of the components. The section of link and frame beam is H250×125×6×9, the length of the link is 400 mm, the thickness of end plate is 20 mm. The brace section is H125×125×6.5×9, and the column section is H200×200×8×12. Each member is connected by 10.9 grade M20 high strength bolts. To ensure that the link yields earlier than the main frame structure, the link adopts Q235B steel with lower yield point, and the other members adopt Q345B steel. The model diagram is shown in figure 1 and the size diagram is shown in figure 2.

![Figure 1. Configuration of specimen.](image1)

![Figure 2. Details of specimen.](image2)

2.2. Material Parameters

All specimens’ steel of the experiment belongs to same batch. Material properties of prepared specimens were tested in accordance with the relevant provisions of (GB /T 228.1-2010) [13]. The material properties test results of the steel used in the test are shown in table 1. The $f_y$ and $f_u$ are the yield strength and tensile strength, $E$ and $\delta$ of the material, respectively, elastic modulus and elongation.
Table 1. Material test results.

| Component     | $E$ (GPa) | $f_y$ (MPa) | $\varepsilon_y$ (%) | $f_u$ (MPa) | $\delta$ (%) |
|---------------|-----------|-------------|---------------------|-------------|--------------|
| Column web    | 224       | 379         | 0.211               | 543         | 29.8         |
| Column flange | 223       | 337         | 0.179               | 526         | 33.8         |
| Beam web      | 201       | 369         | 0.182               | 536         | 32.2         |
| Beam flange   | 227       | 356         | 0.181               | 530         | 29.3         |
| Brace web     | 220       | 335         | 0.165               | 461         | 28.3         |
| Brace flange  | 225       | 290         | 0.167               | 460         | 26.7         |
| Link web      | 236       | 271         | 0.163               | 447         | 37.0         |
| Link flange   | 241       | 260         | 0.157               | 460         | 30.7         |

2.3. Measurement Programme

Two horizontal displacement meters were arranged at the elevation of the steel frame floor to measure and record the lateral displacement of the specimen under horizontal load. The vertical displacement gauges were placed at both ends of the link to monitor its vertical rotation deformation. A large number of strain gauges were applied to the flange and web of the link and the key parts of the frame beam, the column, the brace and the bolts in order to observe the stress distribution.

2.4. Test Procedure

The vertical load of 400 kN was first applied to the top of the two columns through the vertical actuator. After the vertical load and the frame were stabilized, the horizontal load (40 kN) was applied for a cycle to check whether the instruments can run normally and record. Under the requirements of code for Seismic Testing of Buildings (JCJ/T101—2015) [14], a force-displacement hybrid control loading system was adopted for test loading. First, the load was controlled by force, and the load cycle of each stage was once. Switching to displacement control when specimen reached yielding, each displacement load cycle did 3 times. When the bearing capacity dropped to 85% of the maximum value or the specimen is damaged, the test ended.

2.5. Test Configuration

The test device is shown in figure 3. The bottom of the frame column was fixed on the rigid ground by anchor bolts. Two vertical 2000 kN hydraulic servo actuators were used to apply axial pressure to the top of the column. A horizontal 1000 kN hydraulic servo actuator was used to apply horizontal reciprocating load. A lateral limit was set at the frame beam to prevent out-of-plane instability of the steel frame.

![Figure 3. Test configuration.](image_url)
3. Experiment Phenomenon and Failure Mode
The experiment phenomenon of the test specimen is shown in figure 4. Table 2 shows the phenomenon of specimen loading. At the initial loading, the specimen didn’t show significant deformation. At 1\(\Delta_y\) (yielding displacement), the link web plate reached yield strain. At 5\(\Delta_y\), the end plate of the link was warped obviously, and a 2 mm clear dislocation between link endplate and structural beam endplate occurred. At 7\(\Delta_y\), slight buckling occurred in the web of the link. When loading increased to 8\(\Delta_y\) or 9\(\Delta_y\), the upper and lower flanges of the link buckled. When specimen processed 10\(\Delta_y\), whole the entire web of the link was bulged and buckled.

![Failure modes of specimens.](image)

**Figure 4.** Failure modes of specimens.

**Table 2.** Phenomena observed in the test.

| Load level \(\Delta_y\) | Experiment phenomenon                                                                                                                                 |
|----------------------|------------------------------------------------------------------------------------------------------------------------------------------------------|
| \(2\Delta_y\)        | End plate of the link slightly deformed, with a 2-4 mm gap                                                                                               |
| \(3\Delta_y\)        | Paint bumped in the link web                                                                                                                             |
| \(4\Delta_y\)        | Spray of the column base slightly fell off, with a 5 mm gap of end plates                                                                             |
| \(5\Delta_y\)        | Clear dislocation between link endplate and structural beam endplate occurred, with obvious warpage of the end plates                                  |
| \(6\Delta_y\)        | Paint shedding of the link web                                                                                                                          |
| \(7\Delta_y\)        | Web buckling of the link                                                                                                                                |
| \(8\Delta_y\)        | Local buckling of lower flange of the link                                                                                                               |
| \(9\Delta_y\)        | The upper flange of the link were slightly buckled and the end plates were warped seriously                                                            |
| \(10\Delta_y\)       | Severe bulging and buckling failure of the link web                                                                                                     |

4. Test Result

4.1. Hysteresis Curve
Figure 5 shows the load-displacement hysteresis curve of the model, which can effectively reflect the seismic performance and energy dissipation characteristics of the specimen. In the force control stage, the hysteresis loop encircles a small area, showing a long and narrow straight line, with little dissipation of energy. In the initial stage of displacement control, the specimen enters the elastoplastic stage, and the hysteresis curve is of a plump shuttle shape. With the increase of displacement load, the shape of hysteresis curve changes from fusiform to bow, showing significant pinch phenomenon. The specimen reveals good energy dissipation and seismic performance. The reason for the pinch phenomenon of the specimen is that the components are connected by high strength bolts and the bolt pretightening force at the end plates of the link is relaxed in the later stage of loading, which leads to a slippage between components.
4.2. Bearing Capacity and Ductility Coefficient

The skeleton curve is the outer envelope of the hysteresis curve, which reflects the strength and ductility of the structure. Figure 6 is the skeleton curve of the specimen. Through analysis, the skeleton curve shows obvious elastic stage and elastic-plastic development stage; the skeleton curve does not appear obvious descending section, so after the specimen is destroyed, it still has certain bearing capacity and great reliability. The horizontal section of frame curve is longer, reflecting good ductility and strong collapse resistance. The bearing capacity of the frame in the pull direction is slightly higher than in the push direction.

![Figure 5. Hysteretic curves.](image1)

![Figure 6. Skeleton curves.](image2)

### Table 3. Analysis of experimental results.

| Direction of loading | Yield point | Peak point | Limit point | μ   | θ   |
|----------------------|-------------|------------|-------------|-----|-----|
|                      | δy/mm       | Py/kN      | δm/mm       | Pm/kN | δu/mm | Pu/kN |       |     |
| Push                 | 12.12       | 458.46     | 24.00       | 638.00 | 34.68  | 634.65 | 2.86  | 1/52 |
| Pull                 | -11.58      | -500.58    | -34.63      | -670.71 | -34.63 | -670.71 | 2.99  | 1/52 |

Ductility coefficient \( \mu \) is an important index to evaluate the deformation ability of structures. The ductility coefficient of this paper adopts displacement ductility coefficient, that is, the ratio of ultimate displacement \( \delta_u \) to yield displacement \( \delta_y \) of frame structure. According to the analysis in Table 3, the ductility coefficient of the specimen is roughly equal to 3.0, showing good ductility. The story drift ratio \( \theta \) of the specimen is much close to the allowable value 1/50 of elastic plastic story drift angle of the steel frame, indicating that it has an outstanding deformability.

### Table 4. Energy dissipation of specimen.

| Δy | E(kJ) |
|----|-------|
| 1Δy | 0.71  |
| 2Δy | 3.41  |
| 3Δy | 5.50  |
| 4Δy | 8.49  |
| 5Δy | 13.80 |
| 6Δy | 17.51 |
| 7Δy | 20.84 |
| 8Δy | 24.32 |
| 9Δy | 27.61 |
| 10Δy | 33.60 |
4.4. Stiffness Analysis

The law of lateral stiffness degradation reflects the degradation process of the structural performance of the specimen. The secant stiffness $K$ of the specimen is used to reflect the stiffness degradation of the structure. Figure 7 is the stiffness degradation curve of the specimen. According to the analysis shown in figure 7, as the loading level increases, the stiffness degradation rate of the specimen tends to be slow; the lateral stiffness of the structure in the damaged state is 21.4% of the initial lateral stiffness, which demonstrates the degree of stiffness degradation is serious.

![Figure 7. Curves of stiffness degradation.](image1)

![Figure 8. Strain analysis.](image2)

4.5. Strain Analysis

During the entire loading process of the specimen, the local web of the link yielded first, then the strain developed relatively quickly. Subsequently most of the web of the link immediately yielded. The column base of the test piece is connected with the brace through bolts and welded with the stiffener, resulting in stress concentration. Under the action of horizontal load, the outer side of the column foot bears the greatest force, so it is easy to form a plastic hinge here. Figure 8 shows the variation trend of strain at key parts such as the column base, brace and frame beam of the specimen with the load level. When the displacement is loaded to $2\Delta$, the strain at the outer flange of the column base (EZ3) reaches the yield strain, and as the load continues to increase, the strain at the column foot continues to rapidly increase. Effective measures should be taken to reduce the stress at the column base, so that the frame column is in an elastic state to facilitate the post-earthquake repair of the structure. During the entire loading process, the supporting parts have been kept in an elastic state, and mainly bear axial force; the frame beams and beam-column node domains are also always in an elastic state.

5. Conclusion

Through the cyclic loading test of single-layer full bolt connection eccentrically braced steel frame, the following conclusions are obtained:

1. The failure mode of the fully bolted eccentrically braced steel frame is severe bulging deformation of the web of the link beam, which is a typical shear failure. After the structure is destroyed, it still has a certain bearing capacity and meets the seismic requirements of "not to fall in a big earthquake".

2. The eccentrically braced steel frame with full bolt connection has fairly good energy dissipation capacity, great stiffness, strong bearing capacity and excellent ductility.

3. The link of the frame is the first to yield and enter a plastic state, consuming most of the energy, while other parts of the frame are basically in an elastic state, which is convenient for repair after an earthquake. The frame column base is subject to greater force and plastic hinges are easily formed. Effective measures should be taken to prevent premature yielding at the column base.

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References

[1] Roeder C W and Popov E P 1978 Eccentrically braced steel frames for earthquakes Journal of the Structural Division 104(3) 391-412.
[2] Popov E P and Engelhardt M D 1998 Seismic eccentrically braced frames Journal of Constructional Steel Research (10) 321-354.
[3] Popov E P 1983 Recent Research on Eccentrically Braced Frames Engineering Structures 5(1) 3-9
[4] Bozkurt M B and Topkaya C 2017 Replaceable links with direct brace attachments for eccentrically braced frames Earthquake Engineering & Structural Dynamics 13 (46) 2121-2139.
[5] Bosco M and Rossi P P 2009 Seismic Behavior of Eccentrically Braced Frames Engineering Structures 3(31) 664-674.
[6] Duan L S, Su M Z and Hao Q L 2014 Experimental study on seismic retrofit of high strength steel composite K-type eccentrically braced frames Journal of Building Structures 35(7) 18-25
[7] Duan L S and Su M Z 2015 Experimental study on seismic retrofit of high strength steel composite K-type eccentrically braced frames Earthquake Engineering and Engineering Dynamics 35(04) 198-205
[8] Shi Q, Wang X W and Yan S L 2020 Experimental study on seismic behavior of eccentrically braced steel frame with flush end plant connection Journal of Huazhong University of Science and Technology (Natural Science Edition) 48(06) 107-112
[9] GB50011 2010 Code for Seismic Design of Buildings (Beijing: China Architecture Industry Press).
[10] ANSI/AISC341 2016 Seismic Provisions for Structural Steel Buildings (Chicago: American Institute of Steel Construction)
[11] CAN/CSA-S16 2014 Design of Steel Structures (Mississauga: Canadian Standards Association)
[12] GB50017 2017 Code for Design of Steel Structures (Beijing: China Architecture Industry Press)
[13] GB/T228.1 2010 Metallic Materials-Tensile Testing Part1: Method of Test at Room Temperature (Beijing: Standards Press of China)
[14] JGJ/T101 2015 Specification for Seismic Test of Buildings (Beijing: China Architecture Industry Press)