Experimental Study on Seismic Behavior of K-type Eccentrically Braced Steel Frame with Semi-rigid Joints

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Abstract. In order to study how different connection types and floor height affect the seismic behavior of eccentrically braced steel frame, there has been processing 4 pseudo-static tests for eccentrically-braced steel frame, including two one-layer specimen and two three-layer specimen. The seismic behavior of the specimen has been analyzed according to hysteresis curve, carrying capacity, stiffness degeneration, ductility, and energy dissipation ability etc. The experiments’ results show that the connection types have greater impact on seismic behavior, adopting specimen destruction model of high-strength bolts connection as beam segment end-plate weld or web fracture. The rest of components do not appear significant yielding deformation and crack, which caters for post-earthquake restoration and replacement of energy dissipation beam segment. The carrying capacity of high-strength bolts connection specimen is slightly lower than welded connection specimen, but the ductility of the former is far beyond the welded specimen. Because of the slippage between components, hysteresis curves of bolts-connected eccentric braced steel frame structure appear to have pinned phenomenon with various degrees.

1. Introduction
Since 1972, Japanese scholar M. Fujimoto first raised to apply anti-wind eccentrically braced frame into construction steel structure, many more scholars have since studied the eccentrically braced frame structure [1]. Ricle.S, Popov, Rossi, Lombardo, Daneshmad and Hosseini and so on [2-4]. By experiments, there has been raise the concept of inelastic property of beam unit model for energy dissipation beam segment, analyzing the super strong parameter of energy dissipation beam segment under earthquake based on the capacity design and evaluating mechanics behavior of shear-flexural structure and bending structure. Through analysis and comparison, two main reasons are found to affect the behaviors of two types of energy dissipation beam segment. Jiaru Qian is the first one in China to introduce the concept of eccentrically braced frame and relevant study [5]. Shujun Hu takes into account of the geometric non-linearity, material non-linearity, residual stress, initial imperfectness, semi-rigid connection and some other elements, deducting the plastic design method of eccentrically braced frame steel structure based on its behaviour [6]. Bin Guo, Yongjiu Shi and some others complete the low cycled reversed loading experiments of several eccentrically braced frame steel structure to analyze the carrying capacity of the structure and its deformation characteristics and to study the destruction form of the structure [7-8]. Mingzhou Su and some others process a serial
intensive combinations of seismic experiments on eccentrically braced frame to analyze the impact of steel’s intensity on eccentrically braced frame [9].

Currently, among eccentrically braced frame structure designs (AISC2005, CSA2009, NZS3404, GB20011-2010), all components adopt welded connection type. On one hand, this connection type does not suit factory fabrication and field assembly prefabricated building; on the other hand, energy dissipation beam segment is designed to dissipate earthquake energy by significant plastic deformation, mostly demanding restoration and replacement of the components after earthquake, and welded connection makes all difficult.

This essay studies the destruction principle of semi-rigid connection and eccentrically braced frame by low cycled reversed loading experiment, emphasizing the seismic behavior and carrying capacity of prefabricated eccentric brace to provide the basis for engineering applications [10].

2. Experiment Overview

2.1. Specimen Design

The specimen’s prototype has 6-layers of steel frame structure, height 3.6 meters, span 6 meters, structure’s total height 21.6 meters. The prototype structure locates at 8 degree seismic fortification area, fundamental earthquake acceleration level 0.3g, site classification II class, earthquake design group second group.

Experiment specimen is design in 1:2 scale, taking the floor’s height 8 meters, span 3 meters. Each component is according to “construction seismic design criterion” (GB50011-2010) [11], “steel structure design standard” (GB50017-2017) [12], taking into the consideration of American steel structure building seismic design regulation AISC341-16 [13], calculating the carrying capacity of specimen’s frame. The design principle of eccentrically braced steel frame structure is intensive column, intensive beam, intensive brace, and weak energy dissipation beam segment. Being the first yielding component, the intensity of energy dissipation beam segment can’t be too high. Based on the principles above, each component’s section and material of specimen is showed in table 1.

| Component name | Size          | Material |
|----------------|---------------|----------|
| beam           | H250×125×6×9  | Q345B    |
| column         | H200×200×8×12 | Q345B    |
| brace          | H125×125×6.5×9| Q345B    |
| Link           | H250×125×6×9  | Q235B    |

Details of specimen is showed in table 2.

| Specimen number | Connection type | Floor | Column Axial compression (kN) |
|-----------------|-----------------|-------|------------------------------|
| KEBF1           | bolt            | 1     | 200                          |
| KEBF2           | weld            | 1     | 200                          |
| KEBF3           | bolt            | 3     | 200                          |
| KEBF4           | weld            | 3     | 200                          |

2.2. Material Parameters
All specimen’s steel of the experiment belongs to same batch, taking the ratio sample of square horizontal section from beam, column’s flange, and web, with rust-removal on the appearance. One group of specimen for one type of web thickness, three samples per group. Uniaxial tension experiment is processed on 600kn monad universal testing machine to receive the yielding intensity of steel, tensile curve, and percentages elongation after fracture. The material results are shown in table 3.

### Table 3. Steel material parameters.

| Component                        | E (GPa) | $f_y$ (MPa) | $\epsilon_y$ (%) | $f_u$ (MPa) | Elongation (%) |
|----------------------------------|---------|-------------|------------------|-------------|----------------|
| Beam web                         | 196     | 369         | 0.18             | 536         | 32             |
| Beam flange                      | 221     | 356         | 0.18             | 530         | 29             |
| Column web                       | 210     | 379         | 0.21             | 543         | 30             |
| Column flange                    | 218     | 337         | 0.179            | 526         | 34             |
| Brace web                        | 210     | 334         | 0.165            | 461         | 28             |
| Brace flange                     | 212     | 289         | 0.167            | 460         | 27             |
| Energy dissipation beam segment web | 227   | 271         | 0.163            | 447         | 35             |
| Energy dissipation beam segment flange | 230  | 261         | 0.157            | 427         | 30             |
| 16mm thick endplate              | 218     | 253         | 0.155            | 458         | 34             |
| 24mm thick endplate              | 217     | 241         | 0.153            | 445         | 32             |
| Stiffener                         | 211     | 258         | 0.162            | 462         | 35             |

2.3. Test Procedure

Experiment is of planar structure, based on “construction seismic experiment regulation (JCJ/T101-2015)” [14], with one-direction loading under force-displacement hybrid control loading system, controlling the loading by force first, switching to displacement control when specimen reaches yielding, and finishing until the specimen is destroyed. The experiment loading system is shown in figure 1.

![Figure 1. Loading protocol.](image)

2.4. Test Configuration

The experiment imposes axial compression on two columns by two vertical 2000 kn hydraulic servo apparatus, and imposes horizontal load by one horizontal 1000 kn hydraulic servo actuator. In order to prevent the deformation of the frame outside plan, there is a lateral restraint device. The experiment’s model is shown in figure 2 and figure 3. The construction site is shown in figure4 and figure5.
3. Experiment Phenomenon, Fracture Mode, Test Result

3.1. Experiment Phenomenon
The experiment phenomenon of each component is shown in figure 6. At the initial loading, the endplate does not show significant deformation. The clear dislocation between energy dissipation beam segment endplate and structural beam endplate occurs when loading increases to 3 or 4 times yielding displacement, with huge sound from the connection area, energy dissipation beam segment endplate starting deforming. When it increases to 5 or 7 times yielding displacement, spray of the column base slightly fall off, energy dissipation beam flange starts to deform, and energy dissipation beam segment endplate deforms intensively. When specimen KEBF1 processes 8 times yielding displacement, the energy dissipation beam segment web shows crack, resulting in declination of structure carrying capacity. When specimen KEBF2 processes 8 times yielding displacement, whole energy dissipation beam segment yields, web cut broken. When specimen KEBF3 processes 8 times yielding displacement, the welding joint of structural beam endplate breaks, with the web tearing subsequently, and the experiment ends. When specimen PDKB-4 processes 8 time yielding displacement, the welding joint’s neighborhood of energy dissipation beam endplate cracks.

3.2. Failure Mode
Destroying mechanism of each specimen is shown in table 4.

3.3. Experiment Result
Table5 shows the result of displacement and actuator loading. As the length of the energy dissipation beam segment increases, both the yield loading and limit carrying capacity of eccentrically braced semi-rigid steel frame decreases. The one layer weld specimen KEBF2 possesses the maximum yield loading and limit carrying capacity, with 24KN and 788KN respectively; the one layer bolt specimen
KEBF2 decrease in 16.4% and 14.5% in yield loading and limit carrying capacity; three layer bolt specimen KEBF3 is lower in 4% and 5.2% than KEBF4 in yield loading and limit carrying capacity. The eccentrically braced frame with weld connection bears stronger carrying capacity, as floors increase, the carrying capacity of high-strength bolt connection specimen approaches that of weld connection specimen. The limit displacement of three layer bolt connection specimen KEBF3 is 49.7% higher than three layer weld connection specimen, one layer bolt connection specimen KEBF1 is 44% higher than one layer weld connection specimen KEBF2. Bolt connection specimen possess the better ductility.

**Table 4.** Failure mode for each specimen.

| Specimens | Observed mechanism of failure               |
|-----------|--------------------------------------------|
| KEBF1     | Energy dissipation beam segment web breaks, flange yields |
| KEBF2     | Energy dissipation beam yields, web is cut broke |
| KEBF3     | Structural beam endplate’s weld crack      |
| KEBF4     | Whole energy dissipation shear to deform, web breaks |

![Images of specimens](a) KEBF1  (b) KEBF2  (c) KEBF3  (d) KEBF4

**Figure 6.** Experiment phenomenon.

**Table 5.** Displacement test and actuator loading result.

| Specimen | Yield displacement (mm) | Yield loading (kN) | Final displacement (mm) | Final loading (kN) |
|----------|-------------------------|-------------------|-------------------------|-------------------|
| KEBF1    | 2.89                    | 207               | 35.46                   | 659               |
| KEBF2    | 2.67                    | 242               | 24.63                   | 788               |
| KEBF3    | 8.02                    | 218               | 71.77                   | 580               |
| KEBF4    | 9.58                    | 230               | 47.95                   | 604               |
4. Result’s Analysis and Discussion
Evaluating the seismic behavior and seismic capability of eccentrically braced semi-rigid steel frame, the hysteresis behavior, carrying capacity, ductility, accumulating energy consumption and bolt response etc. of the frame structure should be analyzed.

4.1. Hysteresis Curve
Hysteresis curve is loading–displacement relationship curve with response to repetitive loading, which reflect the deformation characteristics, stiffness degeneration, and energy dissipation ability under repetitive loading. The experiments collect the displacements from restraint reaction force at loading end and displacement meter, building up the hysteresis curve of force-displacement relationship. The specimen’s loading-displacement relationship curve is shown in figure 7. After analysis: eccentrically braced steel frame structure of bolt connection specimen KEBF1 and KEBE3 appear to show significant “pinned” phenomenon, influenced by the slippage between beam endplate and energy dissipation beam segment endplate. Hysteresis curve of weld connection specimen KEBF 2 and KEBF 4 is plump and without “pinned” phenomenon.

![Figure 7. Hysteresis curve.](image)

4.2. Framework Curve
Framework curve is the envelope curve of hysteresis curve, indicating the intensity, stiffness, ductility and anti-collapse ability. Graph 8 is the framework curve of one layer specimen KEBF1 and KEBF2, both showing clear elastic period. Negative limit carrying capacity of KEBF2 is higher than that of KEBF1, indicating the carrying capacity of weld connection specimen is better, but both positive and negative limit displacement is lower than that of bolt connection specimen with poorer ductility.
Figure 8. One layer specimen’s framework curve. Figure 9. Three layer specimen framework curve.

Figure 9 is the framework curve of three layer specimen KEBF3 and KEBF3, both showing clear elastic period. Negative limit carrying capacity of KEBF4 is significantly higher than that of KEBF2, with positive carrying capacity tending to be close. The carrying capacity of weld connection specimen is better. Both the positive and negative limit displacement of KEBF4 are lower than that of bolt connection specimen KEBF4, indicating poorer ductility itself.

4.3. Energy Dissipation Analysis
Energy dissipation ability of the structure is evaluated by variation of accumulating dissipation. Table 6 shows accumulating dissipation for each specimen.

| Specimen | KEBF1 | KEBF 2 | KEBF 3 | KEBF4 |
|----------|-------|--------|--------|-------|
| Accumulating dissipation energy | 31.38  | 27.98  | 72.61  | 65.79 |

As the floors increase, the accumulating dissipation of eccentrically braced steel frame tends to enlarge, KEBF3 is with the highest amount of accumulating dissipation of 72.61 KJ during destruction; one layer weld connection specimen is with the lowest accumulating dissipation of 27.94 KJ. Analysis: floors’ height affects comparatively larger on structural accumulating dissipation. The type of connection affect comparatively less. Accumulating dissipation of weld connection specimen is weaker than that of bolt connection specimen, mainly because the bolt connection specimen possess the greater ductility, with the interact movement between components, bearing higher energy dissipation ability.

5. Conclusion
This essay studies the hysteresis behavior, carrying capacity, accumulating dissipation energy of 4 eccentrically braced steel frames by the pseudo-static method. At the same time , by observing the cooperative working principle and destroying principle of semi-rigid steel frame and eccentrically braced frame, we reach for the following conclusions:

1. Bolt-connected eccentrically braced steel frame, the newly lateral-force, is structurally easy made, with slightly lower carrying capacity than weld connection specimen. It bears the merits including switching the energy dissipation beam segment directly after earthquake, less cost, shorter construction time, saving the welding procedure on site, and higher efficiency.

2. Affected by the slippage of connection endplate, the hysteresis curve of bolt-connected eccentrically braced steel frame all appear to have “pinned” phenomenon, but the hysteresis curve of weld connection specimen is plump.
3. Ductility and energy dissipation ability of bolt connection specimen are both better than that of weld connection specimen, with fairly good seismic behavior.

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