Study on the Seismic Behavior of Eccentrically Braced Steel Frames of Replaceable Shear Links With Web Opening

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Abstract. The replaceable energy-dissipating beam is convenient for post-earthquake repair and reinforcement or direct replacement. A quasi-static test study of an eccentrically supported steel frame with replaceable energy dissipating beam sections was performed, and the hysteretic performance and failure mode of the eccentrically supported steel frame with replaceable energy dissipative beam sections were obtained. Based on the test results, the structure of the energy dissipating beam segment was improved, and a number of K-shaped eccentric support frame finite element models for the web opening ratios of different energy dissipating beam segments were established. Nonlinear numerical analysis was performed on its hysteretic performance. The research shows that the finite element analysis is in good alignment with the test results. The opening of the web in the energy-consuming beam segment can effectively reduce the stress level of the frame beam and ensure that large plastic deformation occurs within the energy-consuming beam segment. With the increase of the opening ratio, the ultimate bearing capacity, initial stiffness and energy consumption of the frame have all shown a downward trend. The research provides a basis for the seismic design of similar structures and can guide the design of related projects.

1. Introduction

Eccentrically braced steel frame (EBF) combines the advantages of moment resisting frame and concentrically braced frame that produces high elastic stiffness and energy dissipation during severe earthquakes [1]. In strong earthquakes, the energy dissipation by the inelastic deformation of the link beam, while other structural members remained in the elastic or experienced only a slight plastification [2]-[5]. Ensuring EBF to be an excellent system on seismic behavior.

Currently, many theoretical and experimental studies have been performed to determine the mechanical behavior and seismic performance of EBFs. For instance, Guobing Shan, Zhuangxiao Yong et al [6] researched by nonlinear finite element of hysteretic performance and failure mode of EBFs with different spacing and thickness of stiffeners. Su mingzhou et al [7] through nonlinear finite element analysis of eccentrically braced steel frame with five different thickness of energy beam webs, they found that with the increase of energy beam segments of web thickness, carrying capacity and energy dissipation capacity are gradually increased, however when the thickness is increased to a certain extent, energy dissipation will experience a sharp decline. Zhang Guangwei et al [8] through non-linear finite element analysis of EBFs with six different lengths of energy beam segment, found that when the energy beam specimen length increased, the energy dissipation capacity is decreased.
Sun shanchuan et al [9] conducted experimental studies on eccentrically supported steel frames with three different lengths of energy beam segments, discovering that with the increased length of energy beam segments, the energy dissipation capacity decreased. Duan Liusheng et al [10] carried out numerical analysis on eccentrically supported steel frames with different steel combinations in terms of steel strength. The results show that when the strength of the energy-consuming beam section is the same, increasing the strength grade of a steel frame can resist its incremental impact on internal force due to the strain hardening of the beam, thereafter slowing down the rate of stiffness degradation, and being beneficial to earthquake resistance.

Therefore, the configuration of the energy dissipating beam section has a direct correlation with the seismic performance of the eccentrically supported frame. Based on the test, this paper conducts the hysteretic performances of the eccentrically supported steel frame with multiple different web openings under the same design conditions through Non-linear finite element analysis. The load capacity, hysteresis curve, skeleton curve and ductility coefficient of each model are compared. Suggestions are made on the structure of replaceable energy-consuming beams, which have certain guidance and reference significance to actual engineering.

2. Experiment Overview

2.1. Experiment Phenomenon
At the initial loading, the frame did not show significant deformation. A loud sound occurred in the connection area when the load increased to 3 or 4 times yielding displacement. When the load increased to 6 times yielding displacement, the spray of the column base started to slightly fall off and the energy dissipation beam flange started to deform. When specimen proceed 8 times yielding displacement, the heat affected zone of the welding between number 1 grid of beam and endplate showed crack and gradually extended to the middle of the web, fracture of the weld which between number 2 grid of energy dissipation beam segment and endplate and flange of number 2 grid experienced severe buckling. The experiment completed as a result of a sharp decline in the carrying capacity. Refer to Figure 1 for specimen failure.

![Figure 1. Cyclic loading experiment phenomenon](image)

2.2. Experiment Conclusion
Through the experiment, we found that the cut break of the structure occurred at the end of the frame beam. It is obvious to distinguish this result from our formal expectations that the break may occur in the link beam. In order to actualize the advantages of replaceable energy dissipating beams and avoid the fracture at the ends of frame beams. Opening in the webs of energy dissipating beams are proposed.

3. Finite Element Model of EBF

3.1. Model Design and Mesh Selection
In order to study the influence of the number of openings and the diameter of the openings in the web
of the EBFs on the seismic performance of the eccentrically supported frame, according to "construction seismic design criterion" (GB50011-2010) [11], a set of 5 finite element models was designed for nonlinear finite element analysis which is shown in Table 1. In order to facilitate comparison, all models have the same conditions except the number of openings and the diameter of the openings.

The size of the finite element model is the same as that of the experiment specimen. The model was made using ABAQUS software. High-strength bolts, energy-consuming beam sections, frame beams, brace and frame columns are all modeled by the 8-node solid element (C3D8R).

| Number | Active link | Column | Brace | Beam | Bolt | Number of opening | Diameter of opening |
|--------|-------------|--------|-------|------|------|-------------------|---------------------|
| BASE   | Q235        | Q345   | Q345  | Q345 | M20  | 0                 | 0                   |
| EBF-40-1 | -          | -      | -     | -    | -    | 3                 | 40mm                |
| EBF-40-2 | -          | -      | -     | -    | -    | 6                 | 40mm                |
| EBF-60-1 | -          | -      | -     | -    | -    | 3                 | 60mm                |
| EBF-80-1 | -          | -      | -     | -    | -    | 3                 | 80mm                |

3.2. Material Models and Boundary Condition
The steel material was modeled as a multilinear, A combined hardening was used for the cyclic quasi-static analyses. The elastic modulus E and Poisson’s ratio are assumed to be 2.06×10^5 MPa and 0.3, respectively. The Mises yield criterion is adopted, simplifying the assumption that the weld and the base steel are equally strength, using TIE constraints to bind the contact part of the beam and the end plate, and ignoring the effects of the residual stress of the weld and the initial defects of the component.

Considering the actual boundary conditions of the test specimen, all degrees of freedom of the column base bottom were constrained to consider the rigid connection between the column base and ground. Boundary condition of model is summarized in Figure 2.

3.3. Loading History and Failure Criterion
Coupling column side to RP1, and the load point is placed on RP1. In order to ignore the effect of different loading systems on the energy dissipation capacity of specimens, displacement loading method is adopted. The finite element models (FEMs) were analyzed under a displacement control for one cycle with a magnitude of ±Δ_y, ±2Δ_y, ±3Δ_y, ±4Δ_y (Δ_y is yield displacement of model) as shown in Figure 3. The yield load of FEMs is obtained by the equivalent elastic-plastic yield method. When the hysteresis curve has no falling section, the displacement at the interlayer displacement angle of 2% is taken as the ultimate displacement and the corresponding load is the ultimate load.

![Figure 2. Boundary condition](image1)

![Figure 3. Loading system](image2)
3.4. Finite Element Reliability Verification
In order to ensure the reliability of finite element analysis, the yield load, yield displacement, Ultimate load and ultimate displacement of the numerical simulation are compared with experiment. The result is shown in Table 2.

| Result | Yield load /KN | Yield displacement /mm | Ultimate load /KN | Ultimate displacement/mm |
|--------|----------------|------------------------|-------------------|-------------------------|
| FEM    | 296.84         | 6.1                    | 688.5             | 35.81                   |
| Exp    | 246.44         | 5.89                   | 671.25            | 36                      |

The comparison map consisting of the hysteresis curve and the skeleton curve of the FEM and experiment is shown in Figure 4 and Figure 5. From the Figure 4, FEM has regular hysteresic curve which is spindle shaped and has very good plumpness, embodies preferable energy dissipation capacity, while the hysteretic curve of the experiment is slightly pinched, and fullness is slightly worse than the hysteretic curve of FEM. The reason is that bolt slippage was not considered in FEM. From Table 2, Figure 4 and Figure 5, the result of FEM are basically consistent with experiment, proving the finite element analysis results are reliable.

![Figure 4. Hysteresis curve](image1)

![Figure 5. Skeleton curve](image2)

4. Analysis Of FEM

4.1. Hysteresis Curve and Skeleton Curve
The hysteretic curves and skeleton curve of all FEMs from the numerical analysis are illustrated in Figure 6. Hysteresis curves of FEMs were very plump which inferred that the energy dissipation capacities of all FEMs were very significant, but the opening rate of the energy-consuming beam section has a certain effect on the hysteretic performance of the model. Ultimate displacement of the model decreases with the increase of the opening ratio. The EBF-40-2 model reach the ultimate stress near the opening when displacement is loaded at -32.8mm, the EBF-60-1 and EBF-80-1 model reach the ultimate stress near the opening at -32.8 mm and -34.4 mm respectively under displacement loading.
4.2. Ductility

Ductility coefficient refers to the deformation capacity of a structure or component after yielding, it is an important indicator of the deformation capacity of a structure. The yield displacement of each model is obtained by equivalent elastic-plastic yield method. It is shown in Table 3.

| Number     | Yield displacement /mm | Yield load /KN | Ultimate displacement /mm | Ultimate load/KN | Ductility coefficient |
|------------|------------------------|----------------|---------------------------|------------------|-----------------------|
| BASE       | 6.1                    | 297.843        | 36                        | 671.955          | 5.90                  |
| EBF-40-1   | 5.63                   | 274.338        | 36                        | 651.341          | 6.39                  |
| EBF-40-2   | 5.65                   | 263.557        | 32.8                      | 614.986          | 5.80                  |
| EBF-60-1   | 5.62                   | 260.017        | 34                        | 616.187          | 6.05                  |
| EBF-80-1   | 5.85                   | 245.765        | 34.4                      | 588.084          | 5.88                  |

As shown in Table 3, the ductility coefficients are around 6 for all five models. Among them the ductility coefficients of EBF-40-1 and EBF-60-1 were 8.3% and 2.54% higher than BASE model respectively and indicate that opening of the active link contributes to the overall plastic deformation of EBF. The ductility coefficients of the EBF-40-2 and EBF-80-1 models are almost the same as those of the BASE, which are lower than those of the EBF-40-1 and EBF-60-1. Such observation indicates that an excessively large opening ratio will cause the model to reach the ultimate state ahead of time, thereby reducing its plastic deformation capacity. It can be seen that the deformation capacity of EBF can be improved by adopting an appropriate opening ratio.

4.3. S23 Stress Analysis of Active Link

Figure 7 shows the S23 stress cloud (shear force in the length and height directions) of the active link in ultimate stage. The as seen in Figure 7, the stress at the weld between the active link and endplate can be significantly reduced, and brittle fracture of the weld can be prevented. As shown in Figure (a), the stress is unevenly distributed in active link. Through web openings, the shear stress can also be
distributed relatively evenly to the web position of the entire active link.

(a) S23 stress cloud of BASE
(b) S23 stress cloud of EBF-40-1
(c) S23 stress cloud of EBF-40-2
(d) S23 stress cloud of EBF-60-1
(e) S23 stress cloud of EBF-80-1

Figure 7. S23 stress cloud of each model

5. Conclusion
In this paper, a cyclic test of EBFs is performed, and an improvement scheme is proposed based on the analysis of its failure mode. Several full-scale FEMs were established to study the effects of web opening in the link to their cyclic behaviors. From the above simulation results, we have obtained the following conclusions:

1. The opening of the web in the energy dissipating beam segment can effectively reduce the stress concentration at the end of the frame beam. Yielding is concentrated only at link and it can be considered as a structural fuse that will dissipate seismic input energy through stable and controlled plastic deformation which is easy to repair after the earthquake.
2. In comparison with the models without opening under the same experimental conditions, the ductility coefficient of the model increases with the increase of the opening rate.
3. Under the same experimental conditions, as the opening ratio increases, the ultimate bearing capacity of the EBFs all showed a downward trend.

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