FEM Analysis of Hole-opened Metallic Plate Connections in Prefabricated Energy-dissipation Joint

Mingbei Tuo¹, Di Wang², Guiyun Yan²*, Xiaofei Xiao² and Liwei Xu²
¹CSCEC Strait Construction and Development Co., Ltd, Fuzhou 350115, China
²College of Civil Engineering, Fujian University of Technology, Fuzhou 350118, China

*Corresponding author email: 2190603020@smail.fjut.edu.cn

Abstract. The prefabricated structure is vigorously promoted due to its obvious superiorities of high-efficiency construction rate and environment-friendly construction scheme. However, this fast-growing new structural system is still facing the threat of earthquakes, especially its beam-to-column connecting joints which are the weaker link in the entire structural system all the time. This study investigates the failure behaviour of hole-opened metallic plate connections in prefabricated energy-dissipation joints and its finite element models were provided. Parametric study was performed to obtain the influence of metallic-plate size on the bearing capacity, deformation performance, and ductility. Based on the results of numerical simulation, the failure modes of specimens were focused on weakened sections. Moreover, proposed design sizes were given, comprising that the weakened length $a/L$ of holes is from 0.25 to 0.55 and the weakened width $b/B$ is from 0.3 to 0.5. The suggested value of width to thickness ratio is 0.2 and the value of the gap is within 0.5 to 2 mm.

Keywords: Prefabricated hole-opened metallic plate connection; Failure behaviour; Finite element model; Metallic-plate size; Parametric study.

1. Introduction

Prefabricated beam-to-column connecting joints are vulnerable to earthquake threats causing the failure of structures [1-2]. Researchers are eager to focus on the material and construction of joints to improve the seismic performance of beam-to-column connecting joints. With the proposal of new joints used new materials, such as the fibre-reinforced polymer system, glulam-concrete composite beam-to-column joints, and shape memory alloy [3-4], joints adopted new materials exhibited better performance on seismic behavior. On the other hand, considering the construction of beam-to-column joints, the connection method of unbonded post-tensioned prestressed concrete beams and columns using friction devices were provided and a new ductile flexural prefabricated beam-column joint connection for high seismic zones was developed [5-6]. A kind of prefabricated concrete beam-to-column connection joint with grout sleeves was developed and it indicated that the new precast joint could achieve a similar seismic performance of cast-in-place joints [7]. Simultaneously, installing dampers regarded as energy-dissipation components at beam-to-column joints bring the possibility of fast recoverability-function after the slight earthquake damage. Wang et al. [8] use MR dampers to test the feasibility of nonlinear seismic control of RC frame structures, results show that MR dampers are effective for the damage control of structures under earthquake action, and the performance of semi-active control and passive control is better. Based on the thinking of passive control, a steel joint with a damper [9] was used to replace the cast-in-place concrete beam-to-column joint. Experiments show that the joint has better hysteretic performance and higher energy dissipation,
and its ductility is higher than that of the integral joint. A precast concrete connection with all-steel bamboo-shaped energy dissipaters [10] appears good self-centering ability. Some corresponding finite element models were also performed to analyze the mechanical properties of joints [11-12].

This work presents a finite element model of the hole-opened metallic plate connection as the key role in prefabricated energy-dissipation joints which was shown in figure 1. Proposal of hole-opened metallic plate connections is to transfer damage to the outside of the beam-to-column joints and undertakes the tensile and compressive axial force generated by the decomposition of bending moment. Based on the numerical simulation, the failure modes were observed. Besides, several parametric analyses were performed to study the influence of hole-opened metallic plate connections on bearing capacity, deformation performance, and ductility. The suggested design values of hole-opened metallic plate connections were obtained.

Figure 1. Innovative prefabricated energy-dissipation joint (unit: mm).

2. Numerical Modeling of SPDs

A numerical simulation was established to obtain an innovative numerical model of specimens by the software ABAQUS. ABAQUS was used to establish the numerical model of hole-opened metallic plate connections to simulate its strength performance under axial reciprocating load. The established numerical model considers the influence of factors such as material, geometrical nonlinearity, material damage degradation, and connection contact.

2.1. Constitutive Relationships

The ideal constitutive relationship can be described as the bilinear hardening model. Where $E_s$ represents the initial stiffness of the steel at the elastic stage; $f_y$ is the yielding strength of the steel; After the steel yielded, the stiffness at the strengthening stage was taken as 1/100 of the initial stiffness ($0.01 E_s$) for strengthening. $f_u$ is the ultimate strength of the steel, the stress no longer increases when the steel reaches the ultimate strength $f_u$.

Considering damage degradation of constitutive relationship, ductile damage and damage evolution were added to properties of the metallic plate. When the cumulative plastic damage reaches 0.95, models stop working.

2.2. Elements and Interaction

The finite element model of the hole-opened metallic plate connection is composed of two parts: the constrained steel sleeve and the metallic plate. Unit of the metallic plate and the constrained steel sleeve are both C3D8R elements. The contact relationship is set to set and face-to-face with hard contact. The tangential friction coefficient is taken as 0.1. The loading end releases axial displacement and restricts other displacements, and the fixed end is fixedly connected which is limited displacement and rotation in all directions. It’s necessary to apply the initial imperfection according to the first five buckling modes. The amplitude is 1/1000, 3/5000, 1/5000 of the effective length of the metallic plate. FEM was shown in figure 2.
2.3. Failure Modes
The failure modes of hole-opened metallic plate connections were shown in figure 3. Specimen E-10-200 was took as an example. “E” represents the elliptical open hole. “10” refers to the thickness of steel plates and “200” refers to the weakening length of the open hole. The unit of numerical value is both millimeters. In the final failure mode, the middle hole-opened weakening part of metallic plates all exhibited cracks and fractures. After the stress released, the maximum stress of three specimens was all concentrated on two sides of the weakening open hole. The distribution of the maximum stress presents a certain relationship with the weakening length of the open hole. Only specimen E-10-200 appeared the out-plane buckling phenomenon. The maximum stress was concentrated at two sides of hole-opened weakened metallic plates. The resistance to deformation of specimen E-10-200 was weaker than specimen E-6-100 and E-10-100. It indicated that the increase of the hole-opened weakening length could improve the ductility performance of hole-opened metallic plate connections, but it was also easy to cause the phenomenon of out-plane lateral buckling under compression.

3. Parametric Analysis of Hole-opened Metallic Plate Connections
3.1. Hole-opened Weakening Size
Hole-opened weakening dimension is defined as the ratio of hole-opened length to steel-plate length in specimens’ longitudinal direction and the ratio of hole-opened width to steel-plate width in specimens’ transverse direction. Considering the influence of different hole-opened weakening dimensions on the hysteretic performance of dampers, parametric analysis from twenty-five different weakening-dimension metallic plate was carried out. “B” is the width of metallic plates and “L” is the length of metallic plates. “a” represents the weakening length of holes and “b” represents the weakening width of holes. The effective length of metallic plates is 370mm. Observing the number, the first letter “X” represents the weakening size; the second letter “E” represents the elliptical open hole; the first number represents the serial number that changes with b/B; the second number represents the serial number that changes with a/L. Specific dimensions and examples are listed in table 1 and it listed all examples. Figure 4 exhibited the related sizes of hole-opened metallic plate connections.
Figure 4. Dimension diagram of the metallic plate connection.

Table 1. Parametric analysis examples based on the change of hole-opened weakening size.

| B=125mm  |  L=370mm | a/L  | 0.135 | 0.270 | 0.405 | 0.541 | 0.676 |
|----------|----------|------|-------|-------|-------|-------|-------|
| t=10mm   | g=1mm    |      |       |       |       |       |       |
| b/B      |          | 0.24 | X-E-1-1 | X-E-1-2 | X-E-1-3 | X-E-1-4 | X-E-1-5 |
|          | 0.32     |      | X-E-2-1 | X-E-2-2 | X-E-2-3 | X-E-2-4 | X-E-2-5 |
|          | 0.4      |      | X-E-3-1 | X-E-3-2 | X-E-3-3 | X-E-3-4 | X-E-3-5 |
|          | 0.48     |      | X-E-4-1 | X-E-4-2 | X-E-4-3 | X-E-4-4 | X-E-4-5 |
|          | 0.56     |      | X-E-5-1 | X-E-5-2 | X-E-5-3 | X-E-5-4 | X-E-5-5 |

Table 2 displays the influence of hole-opened weakening size on ductility. As shown in figure 5(a), it can be seen that when \( b/B \) is constant, the value of \( a/L \) is between 0.270 and 0.541, compared to the value of \( a/L \) which is 0.135 and 0.676, the ductility of the example is relatively good, and the bearing capacity is not much different from that of the calculation example XE-3-1. In figure 5 (b), it can be seen from the figure that when \( a/L \) is constant, the value of \( b/B \) is 0.24–0.56 the hole-opened weakening dimensions of specimens exhibits a certain effect on bearing capacity, deformation capacity, stiffness, energy dissipation, and ductility. When the hole-opened length and the hole-opened width are larger, bearing capacity of SPDs is lower but its ductility and energy-dissipation presents better. Based on the analysis results of different size parameters, recommended hole-opened sizes are given, including that the weakening length \( a/L \) of the hole is from 0.25 to 0.55, the weakened width \( b/B \) is from 0.3 to 0.5.

Table 2. Influence of hole-opened weakening size on ductility.

| Mean value of ductility | a/L  | 0.135 | 0.270 | 0.405 | 0.541 | 0.676 |
|------------------------|------|-------|-------|-------|-------|-------|
|                        |      | 0.24  |       | 6.896 | 6.928 | 7.531 | 11.091 | 10.312 |
|                        |      | 0.32  |       | 6.378 | 7.784 | 8.651 | 9.104  | 9.556  |
| b/B                    |      | 0.4   |       | 6.244 | 8.462 | 8.577 | 10.158 | 10.238 |
|                        |      | 0.48  |       | 7.044 | 7.720 | 8.961 | 10.124 | 9.846  |
|                        |      | 0.56  |       | 7.435 | 9.262 | 9.152 | 9.335  | 11.283 |
3.2. Width-to-thickness Ratio
Observing the number, the first letter “K” represents the width-to-thickness ratio; “E” represents the elliptical open hole; the first number indicates the serial number; the second number indicates the specimens’ number. The first series maintains the section thickness of $t=10\text{mm}$ and changes the section width $B$; the second series keeps the section width $B=125\text{mm}$ unchanged and changes the section thickness of metallic plates.

| First Series | $B/t$ | Initial Section Thickness $t$ (mm) | Section width $B$ (mm) | $a\times b$ (mm$^2$) | Second Series | $B/t$ | Initial Section Thickness $s/t$ (mm) | Section width $B$ (mm) | $a\times b$ (mm$^2$) |
|--------------|-------|------------------------------------|------------------------|----------------------|--------------|-------|------------------------------------|------------------------|----------------------|
| K-E-1-1      | 7.5   | 10                                 | 75                     |          | K-E-2-1      | 20.83 | 6                                  | 125                     |          |
| K-E-1-2      | 10    | 10                                 | 100                    |          | K-E-2-2      | 15.63 | 8                                  | 125                     |          |
| K-E-1-3      | 12.5  | 10                                 | 125                    | 100×25   | K-E-2-3      | 12.50 | 10                                 | 125                     | 100×25   |
| K-E-1-4      | 15    | 10                                 | 150                    |          | K-E-2-4      | 10.42 | 12                                 | 125                     |          |
| K-E-1-5      | 17.5  | 10                                 | 175                    |          | K-E-2-5      | 8.93  | 14                                 | 125                     |          |

| Initial Stiffness $K_0$ (kN·mm$^{-1}$) | Bearing Capacity $F_u$ (kN) | Ductility Factor $\mu$ | Damping Coefficient $\zeta$ | Initial Stiffness $K_0$ (kN·mm$^{-1}$) | Bearing Capacity $F_u$ (kN) | Ductility Factor $\mu$ | Damping Coefficient $\zeta$ |
|----------------------------------------|-----------------------------|-----------------------|-----------------------------|----------------------------------------|-----------------------------|-----------------------|-----------------------------|
| K-E-1-1                                 | 242.82                      | 93.97                 | 10.829                      | K-E-2-1                                 | 258.76                      | 178.88                | 8.69                        | 0.456                    |
| K-E-1-2                                 | 326.54                      | 195.38                | 8.184                       | K-E-2-2                                 | 342.59                      | 232.03                | 8.89                        | 0.484                    |
| K-E-1-3                                 | 426.22                      | 298.71                | 9.211                       | K-E-2-3                                 | 426.22                      | 298.71                | 9.21                        | 0.466                    |
| K-E-1-4                                 | 540.34                      | 386.18                | 8.414                       | K-E-2-4                                 | 488.35                      | 353.42                | 8.40                        | 0.493                    |
| K-E-1-5                                 | 624.32                      | 476.47                | 8.332                       | K-E-2-5                                 | 593.24                      | 415.26                | 8.68                        | 0.494                    |
Figure 6. Effect of width to thickness ratio on skeleton curves.
As shown in figure 6 and table 4, when the thickness of metallic plates is 10 mm, bearing capacity becomes higher with the increase of width to thickness ratio of sections. When the width of metallic plates is constant, the initial stiffness, bearing capacity, and the equivalent viscous damping coefficient all decrease with the increase of the width-to-thickness ratio, the ductility coefficient $\mu$ is greater than 8.40 and the varietal range is not large. The ductility of specimens is good. The recommended value of the width-to-thickness ratio is from 10 to 15.

3.3. Gap between Constrained Sleeve and Metallic Plate
The gap between the metallic plate and the constraining sleeve in the plate-thickness direction cause relative sliding. Once the gap becomes too large, it may affect the hysteretic performance of hole-opened metallic plate connections. Examples of the gap are listed in Table 5.
As shown in figure 7, skeleton curves are coincident and the growing trend of bearing capacity is the same. With the increase of the gap, the restraining effect of the sleeve is weakened, and the pressure bearing capacity gradually decreases in the process of compression. When the gap is 0.5 mm, the tensile and compressive bearing capacity of hole-opened metallic plate connections is symmetrical, and the working performance is the best. In summary, the gap between the metallic plate and the constraining sleeve should be controlled within 0.5 to 2 mm.

Table 5. Parametric analysis examples of the gap.

| Example | Section dimension/ B×t (mm×mm) | Hole-opened dimension/ a×b (mm×mm) | Gap/g (mm) |
|---------|-------------------------------|-------------------------------|----------|
| V1-G-1  | 125×10                       | 100×50                        | 0.5      |
| V1-G-2  |                               |                               | 1        |
| V1-G-3  |                               |                               | 2        |
| V1-G-4  |                               |                               | 3        |
| V1-G-5  |                               |                               | 4        |
| V1-G-6  |                               |                               | 5        |
Figure 7. Parametric analysis examples of the gap.

4. Summary
Some conclusions have been obtained.
- Based on the simulation of finite element models of hole-opened metallic plate connections, they exhibited reasonable failure modes. The failure of specimens were focused on weakening sections which exhibited fractures and cracks. It successfully achieves the plastic controllability.
- Weakening hole-opened size, width-to-thickness ratio, and the gap between constrained sleeve and metallic plate are important parameters that affect the bearing capacity, ductility and energy-dissipation performance of hole-opened metallic plate connections. The weakening length $a/L$ of the hole is from 0.25 to 0.55. The weakened width $b/B$ is from 0.3 to 0.5. The width-to-thickness ratio is from 10 to 15 and the gap is within 0.5 to 2 mm.

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