Seismic numerical evaluation of GFRP beam-column joints connected by angle steel with slotted-hole

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Abstract. This paper is based on the ABAQUS finite element simulation software to study the seismic performance of the glass fiber reinforced polymer (GFRP) beam-column joint connected by the slotted-hole angle steel. Non-linear finite element analysis for the effect of slotted-hole on GFRP beams and different slotted-hole sizes on the seismic performance of joints were conducted. Four specimens D1, D2, D3 and D4 with different slotted-hole lengths were designed. The moment-rotation hysteretic curve, skeleton curve and energy dissipation curve of the specimen are obtained. The finite element analysis results show that: 1) the energy consumption of the slotted-hole joint is about 4%-21% higher than that of the ordinary circular hole joint. 2) The longer the slotted holes length is, the better the seismic energy dissipation performance is. The energy dissipation capacity increases by 3%-12% for each 2 mm increase in the slotted-hole length. 3) Although the larger the slotted-hole length is, the better the energy consumption is, the larger the deformation of the component will be caused. Therefore, according to the requirements of serviceability limit state, it is suggested that the slotted-hole length should be between 2 mm and 4 mm.

1. Introduction
Glass fiber reinforced polymer (GFRP) composite material is a new type of high-performance engineering material that has been successfully applied in civil engineering structures in recent years. It has the advantages of light weight, high strength, corrosion resistance, and convenient in construction and molding [1]. At present, GFRP components with various cross-sectional shapes can be produced through pultrusion technology. GFRP has shown great potential in frame structures. However, to apply GFRP to a structure requires a reliable connection. In most cases, angle steel and tube connection are used [2]. Research on angle steel connection of GFRP I-shaped section showed that the connection is related to its brittle failure mode and generally the separation of the column flange and the web and the delamination of the top corner root were found [3]. Box section has better mechanical properties than the I-shaped section for GFRP material. Smith et al. studied the stiffness of the I-shaped section and the box section and found that under the same bending stiffness, the box-shaped section connection stiffness increased by 25% and the strength increased by 280%, but the failure mode is mostly brittle failure. In order to change the failure mode of the joints, the energy consumption of the joints can be increased by plastic deformation of angle steel and sliding of the slotted-hole bolt to meet seismic demand of joints [4]. Slotted holes bolts are generally high-strength friction bolts. When the external force exceeds the friction of the bolt, the bolt will slip. The mechanism of slotted-holes is to use this high-strength friction bolts' slippage to dissipate energy. In this paper, specimens of GFRP beam-column joints with different slotted-holes lengths are used to
study the influence of slotted holes length on the seismic performance of the joints. Through the seismic performance analysis of the joints with different slotted-holes lengths, it is proposed an optimal slotted-holes length to provide reference for practical engineering applications.

2. Validation of finite element method
In order to verify the applicability of finite element, the test specimens are shown in figure 1. The beam length of the specimen is 1 m, the column length is 1.4 m, and the GFRP beams and columns are all box sections. The cross-section size is 100*100*5, the bolts are 8.8 grade M12 high-strength bolts, and the slotted holes length is 6 mm. The preload is 10 KN. The connection gap between GFRP beam and GFRP column is 15 mm. The test was carried out on a 50 t servo hydraulic press, and the loading device was shown in figure 2. The mechanical properties of steel and GFRP were shown in Table 1 [5-7]. A three-fold line model of stress-strain relationship of steel adopted as shown in figure 3. The loading point located at the end of the beam, and a low-cycle loading was used. The upper and lower ends of the column fixed. The comparison between the simulation result and the experiment was shown in figure 4.

| Materials      | Elastic Modulus (GPa) | Poisson's ratio | Yield Strength (MPa) | Tensile Strength (MPa) | Shear Strength (MPa) |
|----------------|-----------------------|-----------------|----------------------|------------------------|----------------------|
| GFRP           | 32.2                  | 0.32            | /a                   | 307                    | 26.7                 |
| Q235           | 203                   | 0.28            | 235                  | 410                    | 303                  |
| 8.8 grade high strength bolts | 208                   | 0.3             | 800                  | 1043                   | 791                  |

/a Indicates that it does not have this material property.

It can be seen from Figure 4 that the hysteresis curve of the finite element simulation was in good agreement with the test results, and they were all parallelograms. During the experiment, due to wearing of the friction surface, the anti-slip coefficient in the later stage of the experiment was
reduced, which causes the slip load of the joint to decrease. The analysis did not consider wearing of the friction surface, so the simulation results did not show a drop in slip loading. Due to Bauschinger effect of steel during the experiment, the hysteresis curve was not completely symmetrical. In the finite element simulation, because Bauschinger effect is not considered, the simulated hysteresis curve is symmetrical. In general, finite element simulation can better simulate slip and yield of joints.

3. Influence of different slotted holes length on seismic performance for GFRP beam-column joints

3.1. Model design
In order to study effect of slotted-hole length on the seismic performance of GFRP beam-column joints, four GFRP angle steel connecting beam-column joint specimens were designed in this paper. The specimen model is the same as the specimen in Figure 1, except that slotted holes length was different. Four specimens were numbered T1, T2, T3, T4, and slotted holes length corresponds to 0 mm, 2 mm, 4 mm, 6 mm (where 0 mm represented round hole).

3.2. Model elements and boundary conditions
The model adopted solid elements and all elements were C38DR. The bolts were connected by contact. The bottom of column was used to simulate the fixed end by constraining all degrees of freedom.

3.3. Loading method
In this paper, displacement control is adopted during cyclic loading, and loading point located at the end of the beam, as shown in figure 5. Vertical displacement loading refers to the loading system recommended in the American Seismic Code for Steel Structures (ANSI/AISC 341-16), as shown in figure 6 [8].

3.4. Criterion of failure
In this paper, if the following phenomena appeared in the finite element simulation, the component was considered failure and loading stopped.

(1) The maximum principal stress or shear stress at any point of the GFRP beam column exceeds the tensile strength or shear strength of the GFRP material

(2) Mises stress at any point in angle steel exceeded tensile strength of steel.

According to this failure criterion, Shear stress of GFRP beam reaches for all specimens under cyclic loading, reached or exceeded ultimate shear strength of GFRP 26.7 MPa, which meant that all specimens entered failure stage and terminated the model calculation. As expected, the specimen slipped before failure (figure 7), and stress diagram when specimen failed was shown in figure 8.
3.5. Analysis of results

3.5.1. Load-displacement hysteretic curves. Figure 9 was the hysteretic curves of each specimen. When hysteretic curves of each joint was observed, it can be found that when bending moment of each specimen reached 1.1 kNꞏm, horizontal slip stage appeared in the hysteretic curve. This is because preloading force and friction coefficient of each specimen were the same, so the sliding load of each specimen was the same.

Also it can be found that with increase of the slotted holes length, hysteresis curve was more and more close to the parallel quadrilateral, because the longer slotted holes length was, the longer the slip stage was. In addition, with difference of slotted holes length, rotation angle of joints at hardening stage was different, in which D1, D2, D3 and D4 were 0.03 rad, 0.04 rad, 0.06 rad and 0.07 rad respectively. The corresponding stiffness were 43.33 kNꞏm/rad, 32.5 kNꞏm/rad, 21.66 kNꞏm/rad and 18.57 kNꞏm/rad, respectively.

3.5.2. Skeleton curves. The skeleton curves of all joints were shown in figure 10. It can be seen from the skeleton graph that before rotation reached 0.03 rad, skeleton curves of the four joints were almost the same, showed an inverse S-shape. This was because the applied preload was 10kN, the slip load of four joints was the same as 1.1 kN, and bolt slip of the four joints did not end before rotation reached 0.03 rad, so skeleton curves of the four joints before this were almost the same. When the rotation reached 0.03 rad, bolt slip at D1 ended and stiffness began to increase. This was due to high friction type bolt sliding to the end; bolt contacted with the GFRP holes wall. Similarly, for joints D2, D3 and D4, stiffness began to increase when their rotation reached 0.04 rad, 0.06 rad and 0.07 rad respectively. This was because the longer slotted holes length was, the more space slip bolts sliding, so the loading displacement required by contact between high-strength bolts and GFRP holes wall became larger.
3.5.3. Energy dissipation analysis. Figure 11 showed accumulated dissipated energy of joints D1-D4. Energy consumption of the first 3 loading groups was almost close to 0, which was because the specimens were still in the elastic stage. In the third to sixth loading groups, the cumulative energy consumption of the four specimens was almost close. This was because the same preloading force was applied and sliding load was the same. Moreover, the bolts sliding of the four specimens had not yet reached the end, so areas of the hysteretic curves were almost close. At the 6th to 10th loading groups, accumulated energy consumption of specimens D3 and D4 was significantly higher than that of D1 and D2. This was because the bolts of specimens D1 and D2 had slipped to the end and their hysteretic curves entered ascending stage. For specimen D4, the final cumulative energy consumption was about 12% higher than that of D3 and 27% higher than that of D1. For specimen D3, its final cumulative energy consumption was about 11% higher than that of D2. Cumulative energy consumption of D2 was about 5% higher than that of D1.

4. Conclusion
In this paper, finite element analysis was carried out on analysis of seismic performance of GFRP beam-column joints with different slotted-holes length, and four GFRP beam-column joints were designed, and following conclusions were drawn:

(1) Energy consumption of slotted-holes joints were about 5%-27% higher than that of ordinary round-holes joints.

(2) The longer slotted holes length was, the better seismic energy dissipation performance was. An increase of 2 mm in the slotted holes length could increase energy dissipation capacity by about 5%-12%.

(3) Although the larger the slotted holes length was, the better the energy consumption would be, the larger slotted holes length would also cause the excessive deformation of components. According to Steel Structure Design Standard (GB50017-2017), maximum deflection limit in serviceability limit state for beam was $L/400$ ($L$ was span of beams). Therefore, it was suggested that slotted-holes length
should be between 2 mm-4 mm, which not only met seismic requirements, but also ensured that deformation will not affect the normal use.

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