Finite element analysis of mechanics performance for GFRP beam-column joints connected by angle steel with slotted-hole

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Abstract. In this paper, a group of GFRP beam-column joints connected with slotted-hole angle steel were analysed under monotonic loading. Based on ABAQUS software, the nonlinear finite element analysis of slotted-hole on beam for GFRP joint and influence of different slotted-hole lengths on mechanical properties of joints were carried out. Considering influence of friction and pretightening force, a conventional circular hole specimen C1 and three specimens K2, K3 and K4 with slotted-hole lengths of 2mm, 4mm and 6mm were designed. The universal contact element and pretension element were applied on ABAQUS finite element modeling of bolted connections. Finally, differences in failure mode, moment-rotation curve, rotational capacity, displacement ductility coefficient and other aspects between angle steel joints with conventional round holes and those with different slotted-hole sizes were compared. The results show that: 1) the rotational capacity of slotted-hole joints was about 6%-19% higher than that of ordinary round-hole joints. The longer the slotted-hole length is, the larger the plastic rotation angle steel will be. However, too large slotted-hole size will also cause excessive deformation of components and collapse.2) The slotted-hole method will not increase bearing capacity of joints, but displacement ductility coefficient of joint K4 with slotted-hole size of 6mm was 1.17 times that of conventional joint C1 with circular hole.

1. Introduction

With the continuous development of science and technology, new materials are gradually applied to civil engineering area to meet the needs of social development. GFRP composite materials are characterized by light weight, high strength, corrosion resistance and low maintenance cost. With the commercialization of extrusion molding technology, pultruded GFRP components are increasingly applied to building construction and bridge engineering.

Joints are an important part of structural system, and their performance directly affects stiffness, ductility and bearing capacity of structural system [1]. Joints connected by bolts and connectors (such as steel tube connection, angle steel connection, etc.) can withstand a certain bending moment and have a certain rotation. Many scholars have carried out a lot of research work on such joints and achieved good results [2]. Making GFRP into a structure requires reliable connections, most of which are made of angle steel and tube connections [3]. Considering low Young's modulus of GFRP profiles, semi-rigid connections are needed to improve the overall structural stiffness [4]. Smith et al. [5] found in their study on rigidity of I-shaped section and tubular section that, under the same bending stiffness, connection rigidity of tubular section increased by 25% and strength by 280%. This is because the tubular section improves buckling characteristics of web, torsional stiffness and weak axial stiffness and so on.
However, it is very limited to improve mechanical properties of joints only by angle steel connection. In this paper, the slotted-hole method in GFRP beam-column joints is proposed to improve deformation of joints. The energy dissipation of beam-column joints connected by angle steel and slotted-hole bolt can be achieved in terms of plastic deformation of angle steel and sliding of slotted-hole bolts. In addition, this kind of joint has advantages of convenient construction, easy repair and reinforcement [6-7]. Monotonic loading performance of beam-column joints is an important basis for studying seismic performance of joints. In this paper, important mechanical parameters such as rotational capacity, bearing capacity and displacement ductility factor of new joints are analyzed, and other mechanical properties of joint are also comprehensively analyzed.

2. Validation of finite element method

In order to verify adaptation of using finite element method to analyze monotonic performance of GFRP beam-column joints with slotted-hole diameter of 6mm, this paper selected a GFRP beam-column joints with bolted connection to carry out experiments. The applicability of finite element model in this paper was verified by comparison between experimental and finite element simulation results. The test specimen of GFRP beams-columns joint was all box-type cross-sections with a cross-section size of 100*100*5. The bolts were high-strength bolts of 8.8 grades M12 with a preload of 10kN. The beam length of the specimen was 1m, the column length was 1.4m, and connection gap between GFRP beam and GFRP column was 15mm. The detail of experimental model was shown in figure 1. The mechanical property parameters of steel and GFRP referred to literature [8-9]. The experiment was carried out on a 50T servo hydraulic press, and loading device was shown in figure 2.

Comparison between results of finite element simulation and the test was shown in figure 3. It can be indicated by figure 3 that relationship between bending moment and rotation of finite element simulation were in good agreement with those obtained in experiment. To be specific, during elastic stage, the finite element results were essentially coincident with the test curve. For sliding stage, the finite element simulation was very close to the test in terms of sliding load and slip length. However, interestingly, after sliding the finite element simulation was lower than the experimental values gradually; in general, the finite element method can well simulate joint slip, yield and strength degradation, though the simulation results are more conservative.
3. Finite element modeling

3.1 Basic Model Information

In order to analyze influence of different slotted-hole lengths on mechanical properties of joints, specimens of C1, K2, K3 and K4 were designed and details of four specimens were shown in table 1. According to American standard ASTM D1761 [10], one-way loading adopted displacement control, and loading rate was constant. The displacement loading point was shown in figure 4, and slotted-hole size of long circular hole was shown in figure 5.

![Diagram of displacement loading](image)

![Diagram of slotted-hole](image)

Table 1. Details of specimens

| Specimen | Slotted-hole length (mm) | Thickness of sideplate (mm) | Thickness of endplate (mm) | High strength bolt on beam |
|----------|--------------------------|----------------------------|---------------------------|---------------------------|
|          |                          |                             |                           | Amount | Bolt form | Pretension (kN) |
| C1       | 0a                       | 6                           | 4                         | 4     | Unilateralb | 10              |
| K2       | 2                        | 6                           | 4                         | 4     | Unilateral  | 10              |
| K3       | 4                        | 6                           | 4                         | 4     | Unilateral  | 10              |
| K4       | 6                        | 6                           | 4                         | 4     | Unilateral  | 10              |

aThe slotted-hole length "0" represents round hole.
bIn the bolt form, Unilateral means that bolt is connected through only one side flange of beam.
3.2 Model elements and boundary conditions
The model was adopted solid elements, and meshed by 8-node hexahedron one-step reduction integral control unit (C3D8R). The bolts on the beam were connected by contact, and the "finite slip" attribute was used to simulate the relatively large slip of the interface between the contact surface. The bottom of the column was used to simulate fixed end by constraining all degrees of freedom. The meshing of the finite element model was shown in figure 6 (a).

3.3 Failure criterion
Since GFRP material is brittle material and its shear strength is far lower than its tensile strength, the following phenomena occurred in the finite element simulation, which means failure of specimens and loading should be stopped.

1) Maximum principal stress at any point in GFRP beams and columns exceeds tensile strength of GFRP material.
2) Shear stress at any point in GFRP beams and columns exceeds shear strength of GFRP material.
3) Mises stress at any point in the angle steel exceeds tensile strength of steel.

According to above failure criterion, shear stress of GFRP beam reached 26.7MPa, which means exceeding ultimate shear strength of GFRP material [8-9], and the model reached the failure stage.

The bolt slippage in the slotted-hole was shown in figure 6(b) and failure mode of the specimen was also shown in figure 6(c).

As shown in figure 6(c), due to large deformation of angle steel, there was large shear deformation occurred at bolt near the column flange. When external force exceeds internal friction force, the bolt slips and GFRP beam suffers shear failure.

4. Results and discussions

4.1 Moment-Rotation curve
The bending moment-rotation curve of each joint under monotonic loading at the loading point was shown in figure 7. As can be seen from figure 7, all curves showed obvious nonlinear performance and curves of joint C and joints K2-K4 basically coincided before loading to 1.0kN (equivalent to bending moment of 1.1kN·m). Loading from 1.0kN to 1.9kN (equivalent to bending moment of 2.09kN·m), "sliding" section of curves of joint C and joints K2-K4 appeared, in which "sliding" phenomenon was more obvious for joints K2-K4 due to use of slotted holes, and displacement of beam end for joints K2-K4 was greater than that of joint C, while stiffness of joint C was smaller. After loading to 1.9kN, bolt sliding of joints K2-K4 ended, and its stiffness was basically the same as that of joint C. It can be seen from figure 7 that ultimate bending moment of all joints was 3.81kN·m, indicating that joints K2-K4 with slotted-hole will not increase in terms of bearing capacity of joints.
4.2. Plastic rotation of joints

The plastic rotation of joints can be used to evaluate plastic rotation ability of joints under monotonic loading.

The plastic rotation of joints \( \theta_p \) was defined as plastic displacement of beam end divided by the calculated length of beam. For joints in this paper, it was calculated according to Equation (1)

\[
\theta_p = \frac{2CL\delta - \delta_{CL1,CL2}}{L_{CL1,CL2}}
\]

Where \( \delta_{CL1} \) and \( \delta_{CL2} \) are vertical displacements at points CL1 and CL2 of the lower flange of beam and \( L_{CL1,CL2} \) is the beam length between points CL1 and CL2. The results were shown in Table 2. Compared with joint C1, plastic rotational capacity of K2, K3 and K4 joints increased with increasing of slotted-hole size, and plastic rotational capacity reached 1.06, 1.13 and 1.19 times that of joint C1, respectively.

![Figure 7. Moment-rotation curve](image)

Table 2. Plastic rotation of joints

| Specimen | Plastic rotation of joints, \( \theta_p \) (rad) |
|----------|-----------------------------------------------|
| C1       | 0.172                                         |
| K2       | 0.183                                         |
| K3       | 0.195                                         |
| K4       | 0.205                                         |

4.3. Ductility coefficient

Ductility is an important index to evaluate seismic performance of structures or members, which is usually measured by displacement ductility coefficient. Displacement ductility coefficient \( \mu \) is defined as ratio of limit displacement \( \Delta \mu \) and yield displacement \( \Delta y \) [11]. Table 3 showed the ductility coefficient of four different joints, from which displacement ductility coefficient of joint C1 was smallest, while displacement ductility coefficient for joints of K series increased to different degrees due to different slotted holes size, in which displacement ductility coefficient for joint K4 with slotted holes of 6 mm was 1.17 times that of C joint. Therefore, it was concluded that slotted-hole method can improve ductility of angle steel connection joints to a certain extent and the large the slotted-hole size, the greater the ductility of joints.

Table 3. Displacement ductility coefficient

| Specimen | \( \mu \)        |
|----------|------------------|
| C1       | 4.61             |
| K2       | 5.24             |
5. Conclusion
In this paper, finite element analysis of mechanical properties of GFRP beam-column joints with different slotted-hole angle steel was carried out, and applicability of finite element simulation was verified by monotonic loading experiment. Four different specimens of GFRP beam-column joints were designed, and the following conclusions were drawn:

1) Rotational capacity of slotted-hole joints was about 6%-19% higher than that of ordinary round-hole joints. The longer the slotted-hole length is, the larger the plastic rotation will be. However, too large slotted holes will also cause excessive deformation of components, which was dangerous to the structures.

2) The slotted-hole method will not increase bearing capacity of joints, but displacement ductility coefficient of joints K4 with slotted-hole size of 6mm was 1.17 times that of the conventional circular hole joint C1.

3) The failure mode of slotted-hole joint and conventional circular hole joint was shear failure of GFRP beam, and results of finite element simulation were relatively conservative.

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