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Numerical Analysis of Bolted Beam-Column Joint with FRP Reinforced at Beam-End

YiLong Ye^{1*} and LianQiong Zheng¹

¹Fujian Provincial Key Laboratory of Advanced Technology and Informatization in Civil Engineering, College of civil engineering, Fujian University of Technology, Fuzhou, 350118, China

*546112401@qq.com

Abstract. In recent years, some scholars suggested that the beam-end of beam-column joint of steel frame can be reinforced by fiber reinforced plastics (FRP) and filled with concrete. In this paper, the reversed cyclic behavior of this new kind of plastic hinge outward joint were studied by finite element analysis. The numerical study shows that, the plastic hinge can be successfully moved outside by reinforced beam-end as reinforced by FRP at the beam end and pouring concrete in the cavity. According to the parameter analysis, it can be found that, as the length of the FRP and the length of the concrete increased, the load carrying capacity and the initial stiffness of the joint increases, but the energy performance of the joint decreases slightly. The thickness of the FRP, paste FRP vertically or horizontally has slightly influence on the cyclic behavior of bolted beam-column joint with FRP reinforced at beam-end.

1.Introduction

Steel has the characteristics of light weight, high strength, beautiful and so on. The steel frame designed according to "strong column and weak beam, strong joint and weak member" did not give full play to the ductility of steel in 1994 Northridge earthquake [1] and 1995 Hyogoken Nanbu earthquake of Japan [2]. Beam-column welding joint of traditional steel structures is subjected to various degrees of serious brittle damage, resulting in a large number of buildings damaged or even collapsed. After the earthquake, it was found by scholars that the lack of ductility and deformability of the joints is the main cause of damage to the buildings. Therefore, a new type of joint study of plastic hinges is proposed. There are two typical methods of plastic hinge outward, weakened of beam section and reinforced beam-end. Hui Cao, Yuanqing Wang [3] and others have experimentally studied that the beam end joint can effectively improve its bearing capacity and energy dissipation capacity, and move the plastic hinge to the height of the section of the cover plate about 1/4 of the beam. Yan Wang, Peng Gao [4] and others studied that the seismic performance of the beam-edge flanged airfoil-type joints is better than that of the beam-end flange side-slab reinforcement. Yousheng Yu, Yan Wang [5] and others studied that the flange weakened joints can avoid the premature plastic failure of the beam-column joint welds due to the stress development at the root of the beam. In recent years, some scholars suggested that the beam-end can be reinforced by fiber reinforced plastics (FRP) and filled with concrete. In this study, the reversed cyclic behavior of this new kind of plastic hinge outward joint in steel frame, as shown in Fig.1, has been investigated through non-linear numerical studies. A finite element analysis (FEA) model is developed using ABAQUS, and the details of modeling is explained.



2. Finite Element Model

2.1 Establishment of Geometric models

The steel beam adopts HW300×300×10×15, the steel column adopts HW400×400×13×21, the bolt length is 540mm, the height of the nut is 30mm, the thickness of the pad is 9mm, and the diameter of the opening is $D=34$ mm. At the end where the steel beam and the steel column are connected, four layers of FRP are wound laterally on the steel beam, and the length is 300 mm, and concrete (C30) is poured in the cavity of the FRP and the flange and the web.

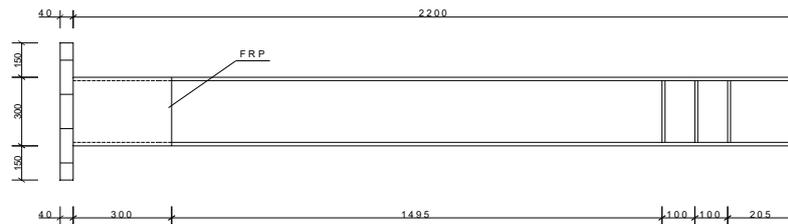


Figure1. Steel beam structure

2.2 Constitutive model of Material

Among the joints studied in this study, the material of the steel is Q235B. Stress-strain relationship using a double-line model. In the elastic phase, the elastic modulus E_s is the stiffness of the steel. After the yield strength f_y is reached, the stiffness of the steel in the strengthening section is $0.01 E_s$. After the strength of the steel reaches the ultimate strength f_u , the stress of the steel does not increase. FRP adopts the bond-slip constitutive model proposed by Xinzheng Lu, Lieping Ye [6], etc. In this paper, the “precise model” is selected, in which the bond slip curve is composed of the ascending and descending segments, and the bond stress tends to zero when the slip is very large. The initial stiffness $f_{ar \max}$ is greater than the secant stiffness when the bond strength is reached. The concrete adopts the compressive stress-strain curve of confined concrete proposed by Mander [7], and the stress-strain constitutive model of Jumin Shen [8] is used in the tensioned part.

2.3 Contact Condition

In this paper, the edge joint is selected as the research object, and the beam takes half a span, and the upper and lower sides of the column take half of the height. Between the bolt rod and the bolt hole, between the concrete end and the connecting plate, between the FRP and the concrete, the connecting plate and the steel column flange are in surface contact, and the tangential friction coefficient is 0.4, normal use hard contact. The main and secondary planes of the contact surface are selected as: the bolt hole is the main plane, the screw is the slave plane, the connecting plate is the main plane, the concrete is the plane, the FRP is the plane, the concrete is the plane, the connecting plate is the main plane, the steel column flange is from the plane. Binding constraints are applied to the upper and lower contact faces of the FRP and the steel beam, and the steel beam flanges are embedded with constraints. The steel beam surface and the connecting plate are connected by coupling.

2.4 Loading Method

When the constraint is applied, the upper and lower ends of the test piece column are fixedly constrained in three directions of X, Y, and Z, and all the joints of the beam end section are coupled in the Z direction. The external force is applied to the coupling surface in a displacement manner, and an X-direction constraint is applied to the flange of the beam. The load is a low-cycle reciprocating load, and the loading system refers to the relevant requirements of FEMA350 [9] and the American Steel Structure Seismic Regulation AISC [10]. In the displacement grading loading control, the inter-layer displacement angle (rad) is selected as the control displacement value. When the interlayer displacement angle is 0.00375 rad, 0.005 rad, and 0.0075 rad, each stage is reciprocally loaded 6 times. Reciprocally

loaded 4 times when the displacement angle of the 4th layer is 0.01 rad. Cyclic and reloading 2 times when the interlayer displacement angle is 0.015 rad, 0.02 rad, 0.03 rad, 0.04 rad. Thereafter, the displacement increment is 0.01 rad, and each stage is loaded twice, until the test piece is broken or the load bearing capacity drops below 80% of the peak value.

2.5 Meshing

For finite element model division, the column and bolt adopt C3D8R unit, and the beam adopts shell unit. The mesh shape of the column and the concrete uses a hexahedral element, the mesh shape of the FRP is mainly a tetrahedron, and the mesh shape of the beam uses a tetrahedron. The grid size of the joint domain is 30 cm, the grid size is 30 cm at the beam end FRP and concrete, and the grid size is 50 cm in other non-encrypted areas. (as shown in Fig.2)

3. Analysis of the Mechanism of Oblique Hysteresis

3.1 Destructive Modal Analysis

As shown in Fig.3, under reciprocating load, there is no fracture of the joint bolt, the flange of the steel beam is buckling and the web of the steel beam is also buckling. At the end of the beam reinforcement, the deformation of the FRP is significant, and there is a gap between the FRP and the concrete contact surface.

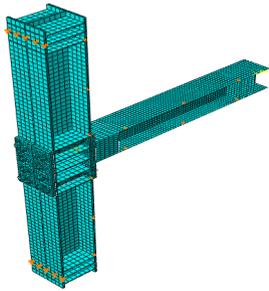


Figure2. A schematic view of the FEA model

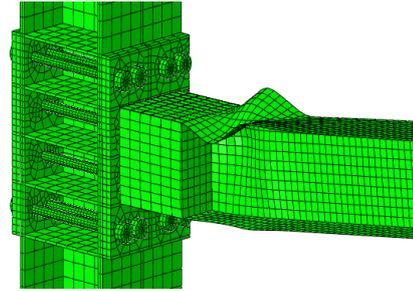


Figure3. Failure mode of the new joint

3.2 Load-displacement Hysteresis Curve

The hysteresis curve of the structure refers to the relationship between the force acting on the structure and the displacement under the action of low-cycle repeated loading. It can be seen from Fig.4 that the loading and unloading process of the hysteresis curve is basically linear, and the hysteresis curve of the joint is full. As the displacement increases, the fullness of the hysteresis loop increases, indicating that the energy dissipation performance of the joint is higher. it is good.

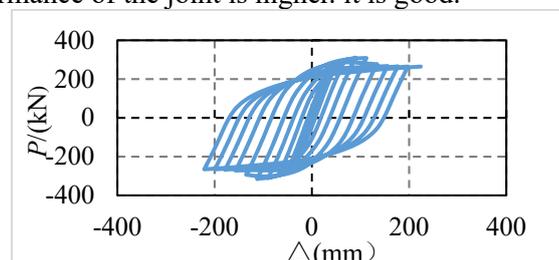


Figure4. Type hysteresis curve of the new type of joint

3.3 Stress and strain development

In the initial stage, the stress of the steel is mainly concentrated at the boundary between the flange and the web at the end of the beam, and is gradually transmitted to the ribs and bolts of the steel column, and the upper and lower flanges of the steel beam reinforcement area are slightly expanded. In the middle stage, the steel beam on the right side of the beam end reinforcement area of the steel beam increases and bends, but no plastic hinge is formed. In the final stage, the upper and lower flanges of the right steel

beam of the steel beam reinforcement zone are buckling, and the web begins to gradually deform, and finally a plastic hinge is formed.

4. Parameter Analysis

In this paper, a series of joint models of A, B and C are established by using finite element software ABAQUS. Study on different FRP lengths, different FRP thicknesses and vertical and horizontal FRP as the variation parameters. The specific change parameters are shown in Table 1(Where X is the horizontal direction, Y is the vertical direction, and 4 is the number of layers.).

Table 1. Joint change parameter.

| No | Series | joint | FRP layer | Lateral FRP length (mm) | Longitudinal FRP length (mm) |
|----|--------|-------|-----------|-------------------------|------------------------------|
| 1 | A | A-1 | 4 | 150 | 0 |
| 2 | | A-2 | 4 | 300 | 0 |
| 3 | | A-3 | 4 | 450 | 0 |
| 4 | B | B-1 | 4 | 300 | 0 |
| 5 | | B-2 | 6 | 300 | 0 |
| 6 | | B-3 | 4 | 450 | 0 |
| 7 | | B-4 | 6 | 450 | 0 |
| 8 | C | C-1 | X:4,Y:4 | 300 | 0 |
| 9 | | C-2 | X:4,Y:4 | 300 | 300 |
| 10 | | C-3 | X:4,Y:4 | 300 | 450 |

4.1 Different FRP Lengths

The length of the A series of joints is based on the length of the FRP and the flange and the web to be poured into the concrete. The length of the FRP of all the test pieces is 4 layers. From the hysteresis curves of the three models, it can be seen that the hysteresis curves of the three models are full and have good energy dissipation. It can be seen from the skeleton line of each joint in Fig. 5(a) that as the winding length of the FRP and the casting length of the concrete are lengthened, the bearing capacity of the joint is improved, and the rigidity in the elastic phase is not significantly increased. In the elastic stage, the stress and strain of the three specimens in the A series are almost the same, that is, the joints do not have a large ductility decrease with the lengthening of the FRP and the concrete. The displacement value is about 50mm, the stiffness of the joint begins to decrease significantly, and the skeleton curves of each joint are more consistent.

4.2 Different FRP thickness

The B series joints take the different thicknesses of FRP as the research object, and take 4 joints for comparison. The two groups were compared under the same conditions of FRP length and concrete pouring length (B-1 joint and B-2 joint were compared, B-3 joint was compared with B-4 joint). It can be seen from Fig. 5(b) that the ultimate bearing capacity of the joint is not significantly improved when the length of the FRP and the length of the concrete are the same. The skeleton curves of joint B-2 and joint B-4 show the elastic phase, the post-yield strengthening phase, and the post-peak strengthening degradation phase. After the displacement value of the four joints is greater than 50 mm, the stiffness begins to decrease significantly, and the bearing capacity reaches a peak when the joint displacement is about 100 mm. After the peak bearing capacity is over, as the displacement increases, the bearing capacity of joint B-2 and joint B-4 gradually decreases.

4.3 Paste FRP vertically and horizontally

The C series joints are longitudinally pasted with different lengths of FRP at the upper and lower flanges of the beam as variable parameters. According to the hysteresis curve of each joint, it can be known that the hysteresis curves of each joint are relatively full, so the ductility of the joints is better. It can be seen from Fig. 5(c) that each joint has a displacement value of about 100 mm and reaches the maximum carrying capacity. As the length of the FRP longitudinal paste is lengthened, the ultimate bearing

capacity of the joint is slightly improved. After the displacement value reaches 50 mm, the stiffness of the joint begins to decrease.

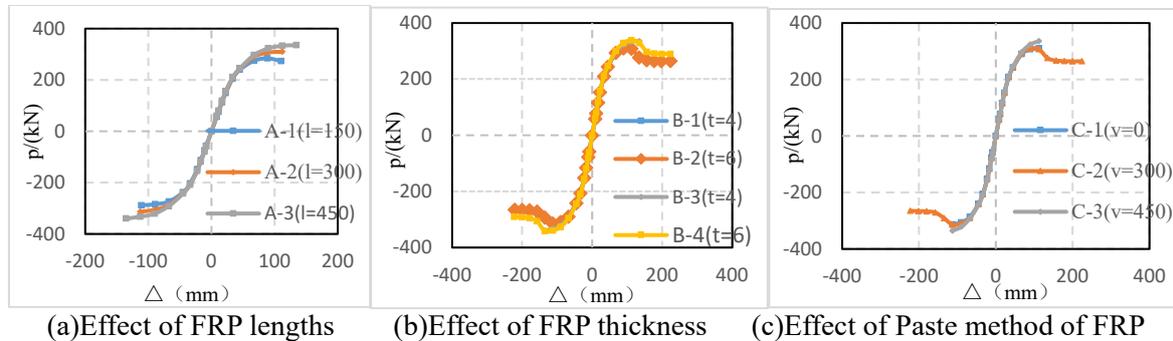


Figure 5. Skeleton curves of plastic hinge outward joint with different parameters

5. Conclusion

(1) The hysteresis curve of 10 joints is full, and both can realize the plastic hinge external displacement of the steel beam, so 10 joints have good energy consumption.

(2) As the thickness and length of the FRP increase, the ductility of the steel frame joints does not decrease very much while the length of the concrete is lengthened. It shows that while this kind of joint improves the stiffness and carrying capacity of the joint, it will not be a large drop in the ductility of the joint, which is in line with the actual engineering requirements.

(3) The beam end flange buckling occurs on the steel beam on the right side of the FRP, and there is a gap between the FRP and the concrete, indicating that the joint structure can effectively improve the ductility of the joint and fully form the plastic hinge of the beam end.

(4) Pouring concrete in the reinforced zone of the H-shaped steel beam can suppress the local buckling of the beam end and improve the rigidity of the joint.

Acknowledgments

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