Finite element Analysis on Shear Performance of Bolt connectors of Assembled Composite beams

Xiuying Jing1*, Dongchuan Zhou2, Senqiang Lu3

1 Civil Engineering and Architecture Institute, Jiangsu University of Science and Technology, Zhenjiang, Jiangsu, 212000, China
2 Yuyao Transportation Bureau, Hangzhou, Zhejiang, 311100, China
3 Collaborative Innovation Center for Highway Water Transportation Steel Structure Bridges, Zhejiang Institute of Communications, Hangzhou, Zhejiang, 311100, China

*182100012@stu.just.edu.cn
*Corresponding author’s e-mail: 2502089903@qq.com

Abstract. In order to realize the rapid assembly of steel-concrete composite beams, high-strength bolts are used as shear connectors instead of studs. In order to study the shear performance of high-strength bolt connector, the finite element model of push out specimen was established by ABAQUS. The validity of the model was verified and the conclusion that the shear bearing capacity of high-strength bolt connector would be reduced by enlarging the bolt diameter. On this basis, the influence of concrete strength, bolt tensile strength, bolt diameter and pretension on shear bearing capacity of high strength bolt connections were analyzed. The results showed that the shear capacity of high-strength bolt connectors mainly depended on concrete strength, bolt tensile strength and bolt diameter, and is less affected by pretension. The research results have reference value for the application of high strength bolt connectors in prefabricated composite beams.

1. Introduction

Steel concrete composite beam has been widely used in bridge construction, but traditional steel-concrete composite beam adopts cast-in-place reinforced concrete or prestressed reinforced concrete, which has a long construction period and great impact on traffic [1-2]. In order to realize the rapid construction of bridge, the United States has established a bridge structure system based on full height precast bridge deck. The prefabricated concrete slab and steel beam were quickly assembled by welding stud connectors on site, marking that the steel cast-in-place concrete composite beam has entered the stage of prefabrication and assembly [3].

In order to further speed up the repair of damaged concrete slab, a fabricated steel-concrete composite beam using high-strength bolts instead of welding studs as shear connectors is proposed in reference [4]. Chen et al. [5] performed static push-out tests on bolt shear connectors. Their research showed that bolt connectors exhibited a low initial slip load, however, achieved similar ductility and bearing capacity as conventional stud. Liu et al. [6] investigated the failure mode, fatigue performance and load slip characteristics of shear connectors with high-strength bolts, and found that the high-strength bolt connectors have the same good working performance as welded stud. Sameera et al. [7] respectively established the finite element models of blind bolt connector and stud connector to
study the shear performance of the two shear connectors. The results showed that the shear strength of blind bolt connector was higher than that of stud. Liu Zhongliang et al.[8] improved push-out specimen with high-strength bolt connector. Corrugated pipe was arranged in the bolt hole and high-strength cement slurry was poured into the bellows. The push-out test results showed that all the specimens had bolt shear failure, and the fracture location was at the interface between steel beam and concrete slab. Zhang et al.[9] established a finite element model for push-out specimens to study the shear performance of high-strength bolts. According to the different failure modes of the specimens, the shear bearing capacity calculation formula of high-strength bolt connectors was proposed. Although domestic and foreign scholars have carried out some tentative studies on high-strength bolt connectors, the research on the factors affecting the shear capacity of bolt connectors is not comprehensive. Therefore, this paper takes the diameter of bolt hole, concrete strength, bolt tensile strength, bolt diameter and pretension as parameters to establish a finite element model to study the mechanical properties of high-strength bolt connectors.

2. Establishment of finite element model

2.1. Specimen design

In order to study the influence of bolt hole diameter on the shear performance of bolt connectors, three kinds of specimens with different bolt hole diameters were made. The specific geometric dimensions of specimens are shown in table 1. In the test, a 500 ton-four column press was used for static loading. During the loading process, the displacement was used as the loading control condition. The test device is shown in figure 1.

| Specimen ID | Specimen number | Steel Beam Section (mm) | Pretension (kN) | Bolt diameter (mm) | Bolt hole diameter (mm) |
|-------------|----------------|-------------------------|----------------|-------------------|-----------------------|
| K24         | 3              | H260×260×16×12           | 155            | 20                | 24                    |
| K28         | 3              | H260×260×16×12           | 155            | 20                | 28                    |
| K32         | 3              | H260×260×16×12           | 155            | 20                | 32                    |

2.2. Element selection

In order to verify the reliability of numerical simulation, ABAQUS software is used to establish the finite element model according to the parameters of test specimen. In order to improve the convergence accuracy of the model, three-dimensional eight node solid element (C3D8R) is used for concrete slab, steel beam, high-strength bolt and pad, and three-dimensional truss linear element (T3D2) is used for rebar. Due to the symmetry of push-out specimen, only a quarter of finite element model can be established, as shown in figure 2.
2.3. Interaction and contact conditions
The face to face contact in ABAQUS is suitable for defining the contact relationship between parts except rebar in the model. The interaction characteristics of contact surface include normal and tangential interaction. The rebar is embedded in the concrete through "embedded", and the bond slip between the two is ignored[10].

2.4. Boundary conditions and loading mode
The movement of all joints at the bottom of concrete slab in XYZ direction is limited. According to the symmetry, the translational motion in X direction and the rotation in Y and Z direction of all joints in the thickness direction of steel beam web are limited. The translational motion in Y direction and rotation in X and Z direction are limited for all joints on the flange of steel beam, web side and concrete slab on the other symmetry plane of the specimen. As the loading surface of model, the top of steel beam is coupled to a point, and the displacement load is applied on it along the negative direction of Z axis.

2.5. Material constitutive relation
The constitutive model of steel, rebar, and high-strength bolt adopts the two broken line model. It is considered that the stress increases linearly with the strain before reaching the yield strength. When the stress reaches the yield strength, the stress remains unchanged, while the strain continues to increase.

The plastic damage model of concrete is adopted, and the constitutive relation of concrete under uniaxial tension and compression is referred to in the appendix of code for design of concrete structures [11](GB 50010-2010).

3. Model validation
The finite element calculation results of shear capacity of high strength bolt connectors are compared with test results. The comparison results are listed in table 2.

| specimen | shear bearing capacity (kN) |
|----------|----------------------------|
|          | test value | calculation value |
| K24      | 1746       | 1837            |
| K28      | 1680       | 1765            |
| K32      | 1570       | 1640            |

The results show that the shear bearing capacity calculated by finite element method is close to test results, and the deviation is within 5%. When the bolt hole diameter increases from 24mm to 32mm, the calculated value decreases by 10.7%, indicating that the expansion of bolt hole will reduce the shear bearing capacity of high-strength bolt connectors. The finite element model established by this
method can well simulate the shear bearing capacity of the specimen and provide data support for the subsequent analysis of influencing factors.

### 4. Analysis of influencing factors

According to the above test and finite element results, it is concluded that the increase of bolt hole diameter will reduce the shear bearing capacity of high strength bolt connectors. In order to study the mechanical properties of high-strength bolt connectors in composite beams more systematically, the finite element models of 9 push-out specimens of 4 series are established on the basis of model validation. The effects of bolt tensile strength, concrete strength, pretension and bolt diameter on shear bearing capacity of bolt connectors were studied respectively for specimen groups S1, S2, S3 and S4. The design parameters and finite element calculation results of push-out specimen are shown in table 3, and the load-slip curve are shown in figure 3-6.

#### Table 3. Design parameters and finite element results of push-out test specimens

| Specimen group | Specimen ID | bolt tensile strength (MPa) | bolt diameter (mm) | bolt hole diameter (mm) | pretension (kN) | concrete strength (MPa) | shear bearing capacity (kN) |
|----------------|-------------|-----------------------------|--------------------|-------------------------|----------------|-------------------------|-----------------------------|
| S1             | S1-1        | 800                         | 22                 | 26                      | 160            | 40                      | 1749                        |
|                | S1-2        | 900                         | 22                 | 26                      | 160            | 40                      | 1919                        |
|                | S1-3        | 1000                        | 22                 | 26                      | 160            | 40                      | 2082                        |
| S2             | S2-1        | 1000                        | 22                 | 26                      | 160            | 30                      | 1833                        |
|                | S2-2        | 1000                        | 22                 | 26                      | 160            | 50                      | 2165                        |
| S3             | S3-1        | 1000                        | 22                 | 26                      | 95             | 40                      | 2049                        |
|                | S3-2        | 1000                        | 22                 | 26                      | 125            | 40                      | 2054                        |
| S4             | S4-1        | 1000                        | 20                 | 24                      | 160            | 40                      | 1846                        |
|                | S4-2        | 1000                        | 24                 | 28                      | 160            | 40                      | 2250                        |

![Figure 3. Influence of bolt tensile strength on load-slip curve.](image1)

![Figure 4. Influence of concrete strength on load-slip curve.](image2)
4.1. Bolt tensile strength
According to the load-slip curve shown in figure 3, shear capacity of bolt connector increases with the increase of tensile strength. When tensile strength of bolts increases from 800 MPa to 1000 MPa, the shear capacity increases by 9.7%, 19.0% respectively.

4.2. Concrete strength
It can be seen from figure 4 that the shear capacity of bolts increases with the increase of concrete strength while other parameters remain unchanged. When the concrete strength is low, concrete strength increasing can significantly improve the shear bearing capacity, but when concrete strength is more than 40MPa, the influence of concrete strength increasing on the shear bearing capacity is small.

4.3. Pretension
Figure 5 compares the load-slip curves of specimens with different pretensions of 95kN, 125kN and 160kN. It is found that the increase of pretension can greatly improve the slip load, but the change of pretension has little effect on the shear capacity of high-strength bolt connections.

4.4. Bolt diameter
It can be seen from the figure 6 that the shear bearing capacity of bolt connectors increases with the increase of bolt diameter. When the bolt diameter increases from 20 mm to 24 mm, the shear bearing capacity increases by 12.8% and 21.8% respectively, indicating that the increase of bolt diameter can significantly improve the shear bearing capacity.

5. Conclusion
Through the reasonable finite element modeling method, the influence of bolt hole diameter, concrete strength, bolt tensile strength, bolt diameter and pretension on the shear performance of high strength bolt connectors is analyzed. The main conclusions are as follows:
(1) The increase of bolt hole diameter will reduce the shear capacity of high strength bolt connectors.
(2) The shear bearing capacity of high-strength bolt connectors mainly depends on the concrete strength, bolt tensile strength and bolt diameter, which increases significantly with the increase of the three parameters.
(3) The pretension has little effect on the shear capacity of high strength bolt connectors.

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