Finite element analysis of mechanical properties of cut plate flange type connectors and comparison of connection schemes

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Abstract. A connector between corrugated steel webs and concrete is proposed in this paper, named cutting-plate-flange connector. Combined with finite element method, the differences among various shear connectors in the structural characteristics, mechanical performance, economy, and applicability to segmental precast assembly construction are compared and analyzed. The results show that the new connector meets the shear requirements and can be constructed easily. It can be applied to segmental prefabricated composite girder bridges with corrugated steel webs.

Keywords: segmental precast; corrugated steel webs; shear connector; structural optimization.

1 Introduction

The composite girder bridge with corrugated steel webs has a reinforced concrete structure for the top and bottom plates, a corrugated steel plate for the webs. The prestressing tendon is arranged in a combination of internal and external. Compared with the traditional concrete girder bridge, this structural type has the advantages of a lightweight, high prestress efficiency, good durability, and fast construction speed, which has been studied and promoted in many countries[1-4].In recent years, bridge construction began to develop in the direction of industrialization, assembly, and standardization. In the field of concrete girder bridge construction, segmental prefabrication and assembly construction has the characteristics of fast erection speed, easy quality control, good environmental protection, and low cost, which has been more and more widely used[5-8]. Compared with concrete girder bridge, composite girder bridge with corrugated steel webs has more advantages in economy, durability, and energy saving. Therefore, the application prospect of segmental prefabricated composite girder bridges with corrugated steel webs will be broader[9,10].

As an important part of the composite girder bridge with corrugated steel webs, shear connectors ensure that the corrugated steel webs and concrete form a whole to bear the force together. However, based on meeting the structural stress requirements, whether the traditional shear connectors are suitable for assembly line operation and rapid

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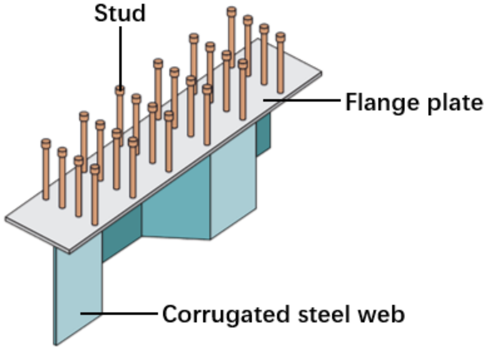
assembly of segment prefabrication and assembly technology is a question worthy of study. Based on the existing research, the shear connectors of segmental prefabricated composite girder bridges with corrugated steel webs are optimized, in order to adapt to the construction method.

2 Structure and finite element analysis of common shear connectors

2.1 Structure of common shear connectors

According to the different configurations, the connectors are mainly divided into embedded and flanged connectors. The flanged connectors include stud connectors, angle steel connectors, perforated plate connectors, etc. Several common shear connectors are shown in Figure 1. The embedded connector relies on the mutual restraint between corrugated steel webs and concrete, as well as transverse reinforcement for shear transfer and transverse moment distribution; the flanged connectors rely on different structures above the flange plates to meet the force requirements of steel-concrete connections. Generally, a flange-type connector should be used for the connection between the corrugated steel web and the top plate.



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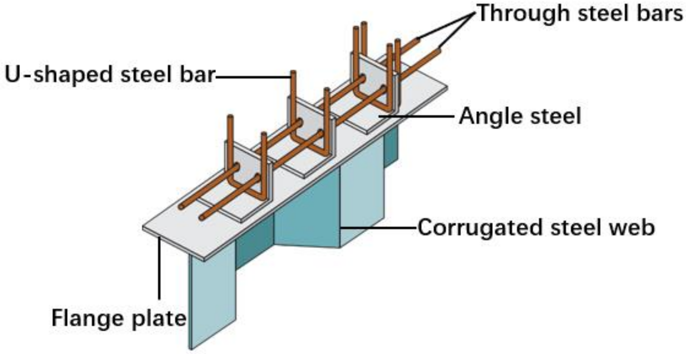

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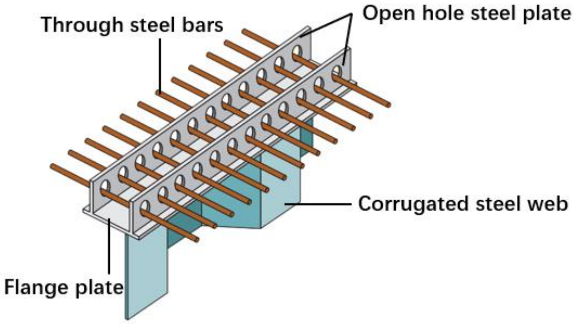

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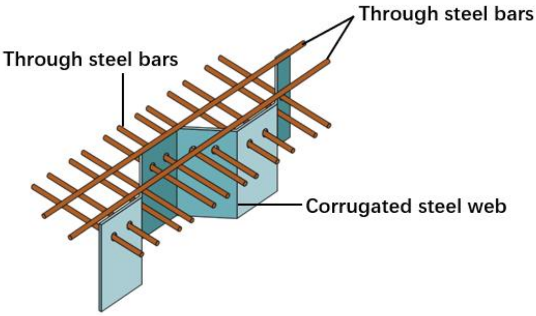


(d)

Fig. 1. Common shear connectors. (a) Stud connector; (b) Angle steel connector; (c) Twin perfobond rib connector; (d) Embedded connector.

2.2 Finite element model

According to the principle of consistent shear capacity, three groups of specimens were designed, including angle steel connector, twin perfobond rib connector and embedded connector. The force transfer mechanism and deformation performance of each connector and demonstrates the stress reliability of the new connector is analyzed by using the finite element method.

The finite element software ABAQUS was used to simulate the three kinds of specimens. The concrete, section steel and I-shaped steel of the four specimens are simulated by C3D8R solid elements; the reinforcement is simulated by T3D2 truss elements. The material parameters in the model are: the steel is Q345 steel, the elastic modulus is 2.1×10^5MPa, and the Poisson's ratio is 0.3; the concrete label is C50, and the elastic modulus is 3.45×10^4MPa. The finite element model of each test piece is shown in the figure 2.

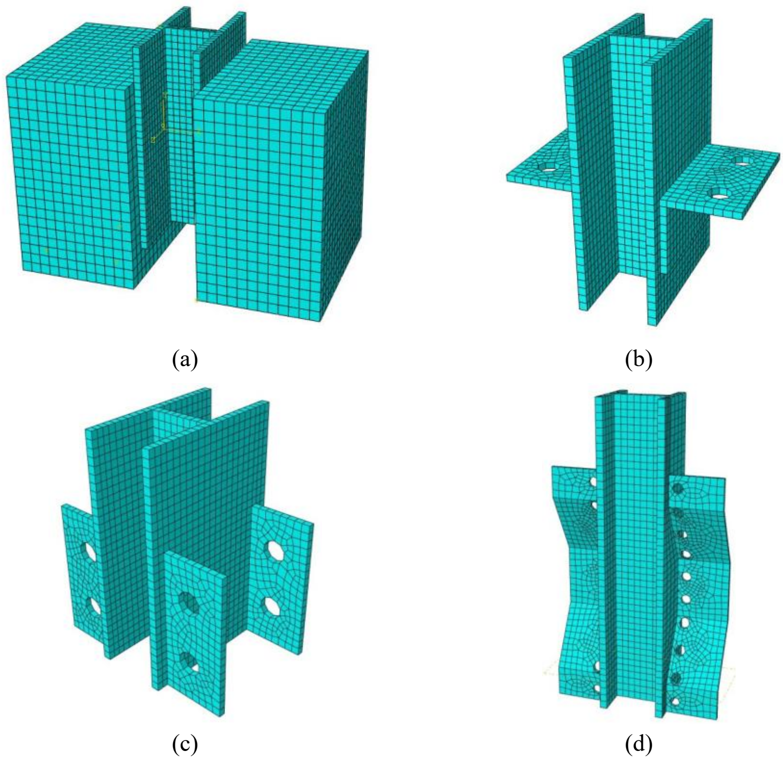


Fig. 2. The finite element model of each shear connector. (a) The overall meshing of the model; (b) Angle steel connector; (c) Twin perfobond rib connector; (d) Embedded connector.

The boundary conditions of the finite element model (as shown in Figure 3): constrain all displacements of the nodes on the bottom surface of the concrete; apply a uniform load in the vertical direction (Y direction) on the top surface of the I-shaped steel.

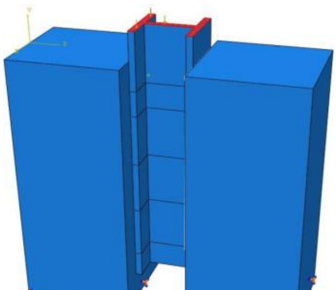


Fig. 3. Model boundary conditions and loading methods

2.3 Finite element analysis results

(1) Angle steel connector

The results of finite element analysis are shown in Figure 4. It can be seen from the figure that in the process of load increase, the extreme value of stress at the joint of angle steel and I-steel gradually shifts from the joint of angle steel and I-steel to the top of I-steel, while still maintaining a higher stress level at the joint. The stress from the angle steel weld to the cantilever end gradually decreases.

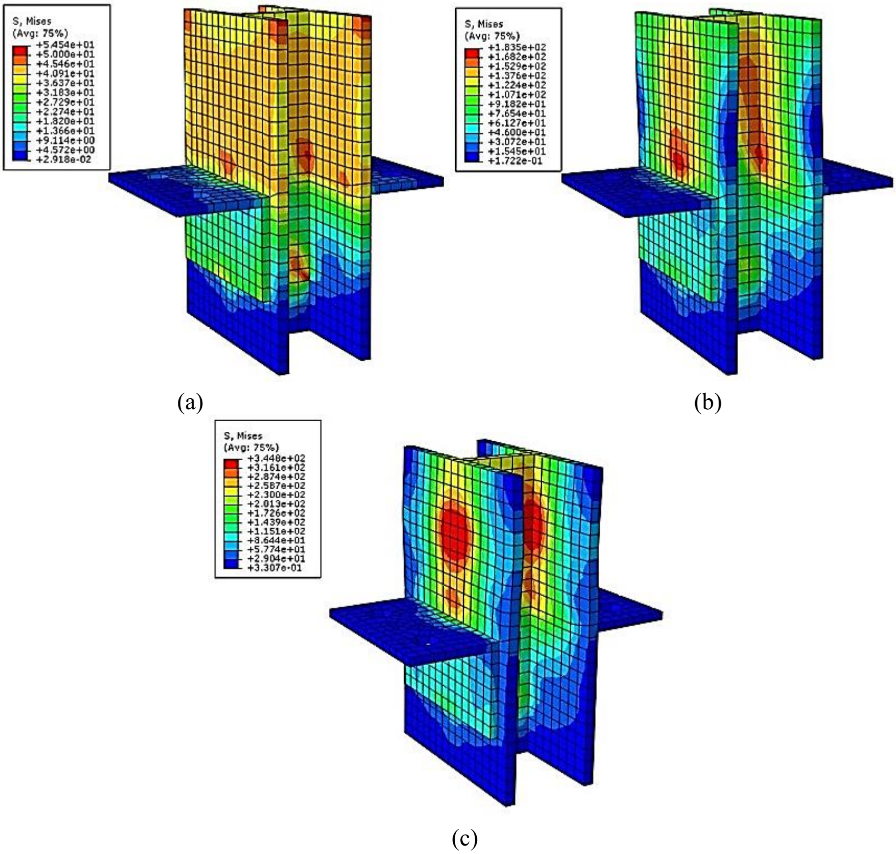


Fig. 4. Mises stress cloud of steel members under various working conditions (unit: MPa). (a)800kN; (b)2000kN; (c)3200kN.

The main tensile stress of concrete under various working conditions is shown in Figure 5, and it can be seen that the stress concentration area of concrete is the concrete block below the angle steel. As the load increases, the concrete above the angle steel also has higher stress, and the development area gradually expands. The stress transfer path is the transfer of the angle steel area to the concrete below.

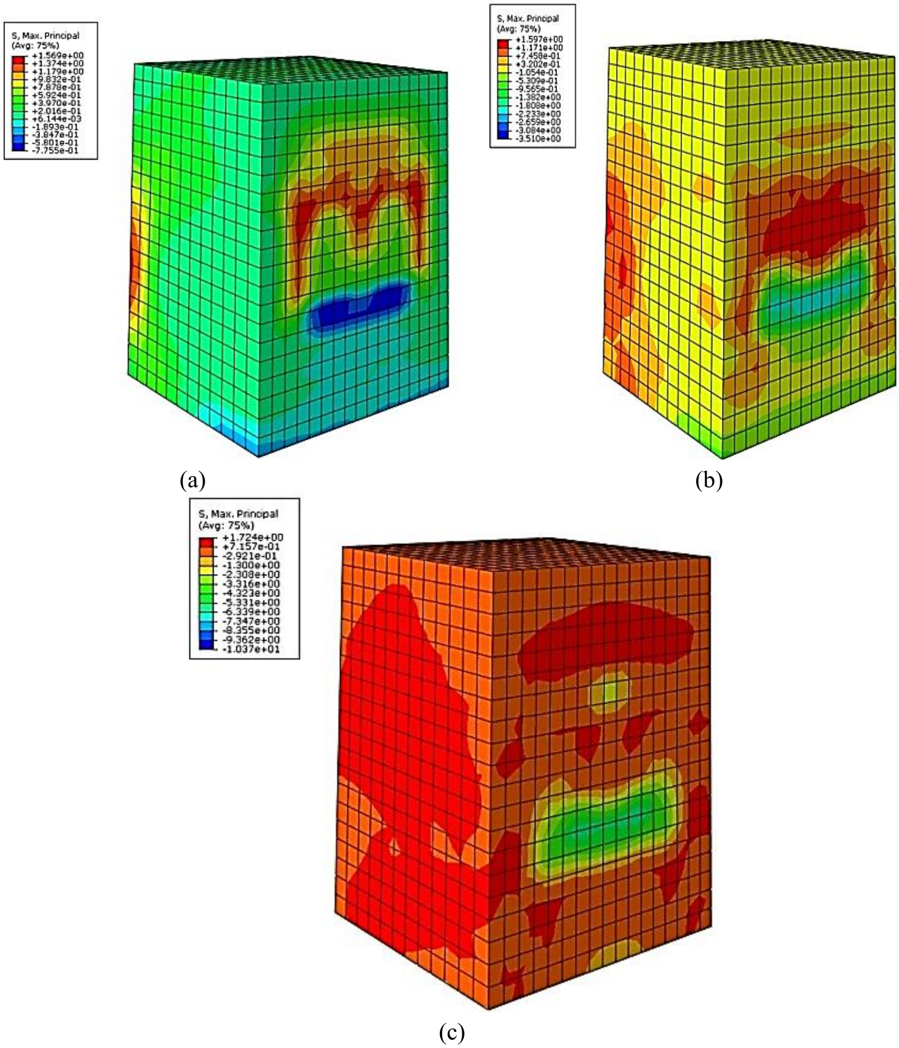


Fig. 5. Nephogram of principal tensile stress of concrete under various working conditions (unit: MPa). (a)800kN; (b)2000kN; (c)3200kN.

(2) Twin perfobond rib connector

The results of finite element analysis are shown in Figure 6. It can be seen from the figure that in the process of load increase, the stress gradually develops to both ends along with the connection between the perforated steel plate and I-shaped steel, while the stress extreme value remains at the upper joint of the perforated steel plate and the I-shaped steel. The stress from the weld of the perforated steel plate to the cantilever decreases gradually.

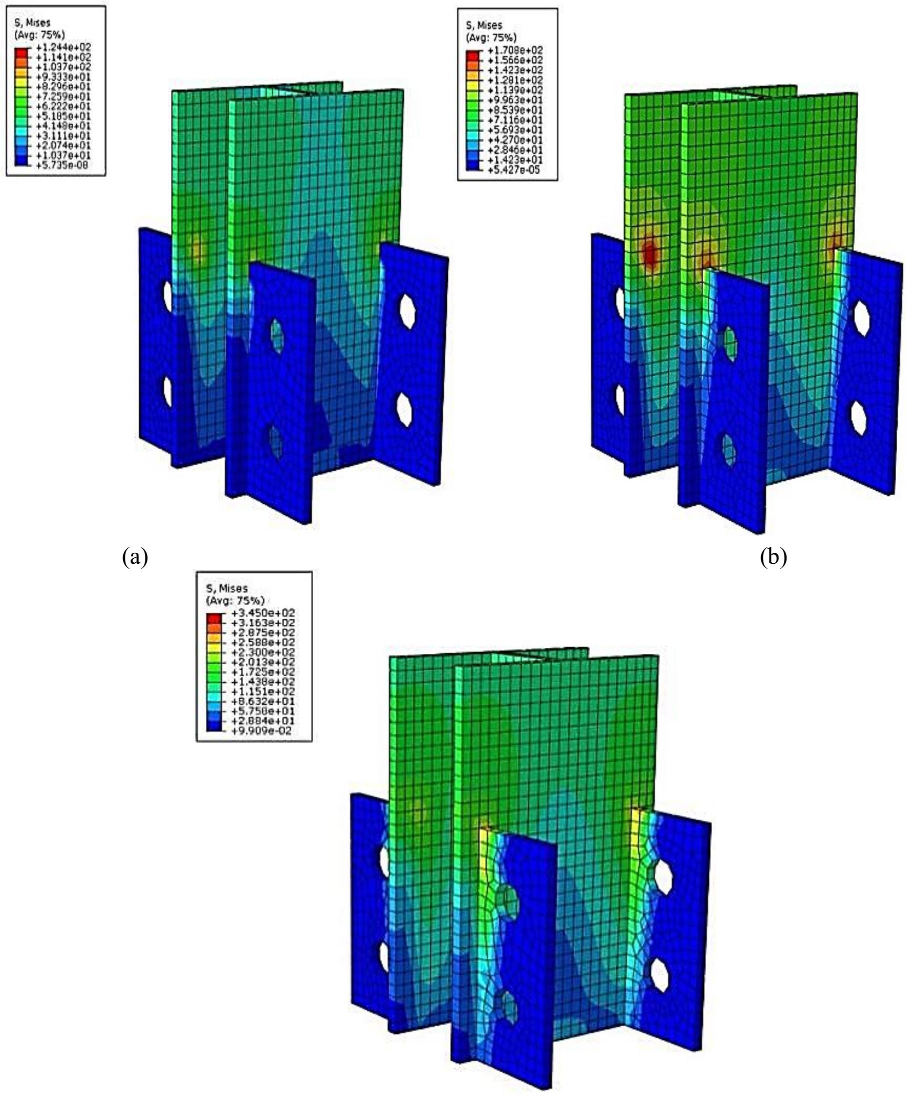


Fig. 6. Mises stress cloud of steel members under various working conditions (unit: MPa). (a)800kN; (b)1600kN; (c)2600kN.

The main tensile stress cloud map of concrete under various working conditions is shown in Figure 7. It can be seen that the concentrated area of main tensile stress in concrete is the concrete area corresponding to the perforated steel plate. As the load increases, the stress extreme point gradually shifts downward, and the development area gradually expands. The stress transfer path is the concrete transmission from the upper area of the perforated steel plate to the lower part.

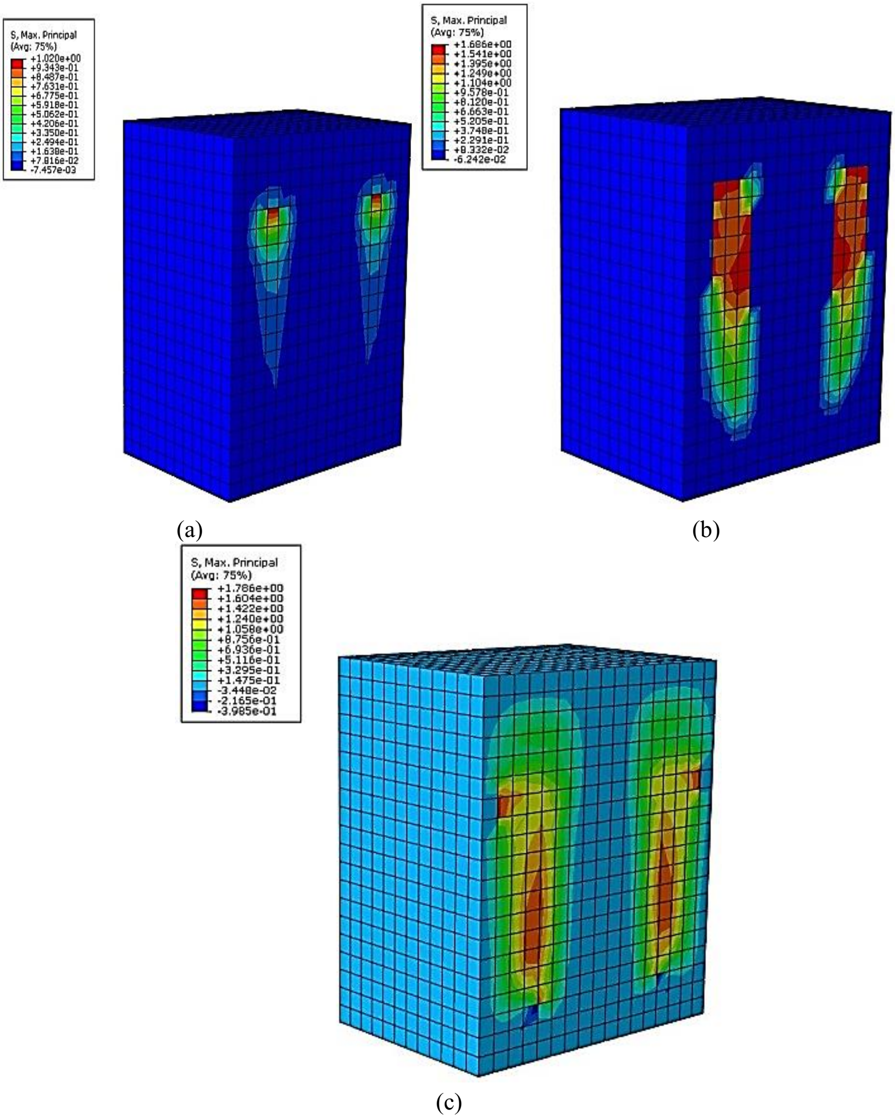


Fig. 7. Nephogram of principal tensile stress of concrete under various working conditions (unit: MPa). (a)800kN; (b)1600kN; (c)2600kN.

(3) Embedded connector

The results of finite element analysis are shown in Figure 8 It can be seen from the figure that the embedded connector has a stress downward transmission process in the process of bearing load. At the initial stage of loading, the stress extreme point appears uppermost part of the corrugated steel plate, and then gradually transfers down to the inclined steel plate of the corrugated steel plate. At this time, the load is mainly borne by the inclined steel plate. With the increase of load, the stress gradually diffuses downward along with the opening position of the corrugated steel plate. It is obvious from the figure that the extreme stress is mainly distributed around the opening. This shows that the destruction of embedded connectors starts from the concrete tenon in the opening, and gradually transfers to the steel bar and corrugated steel plate.

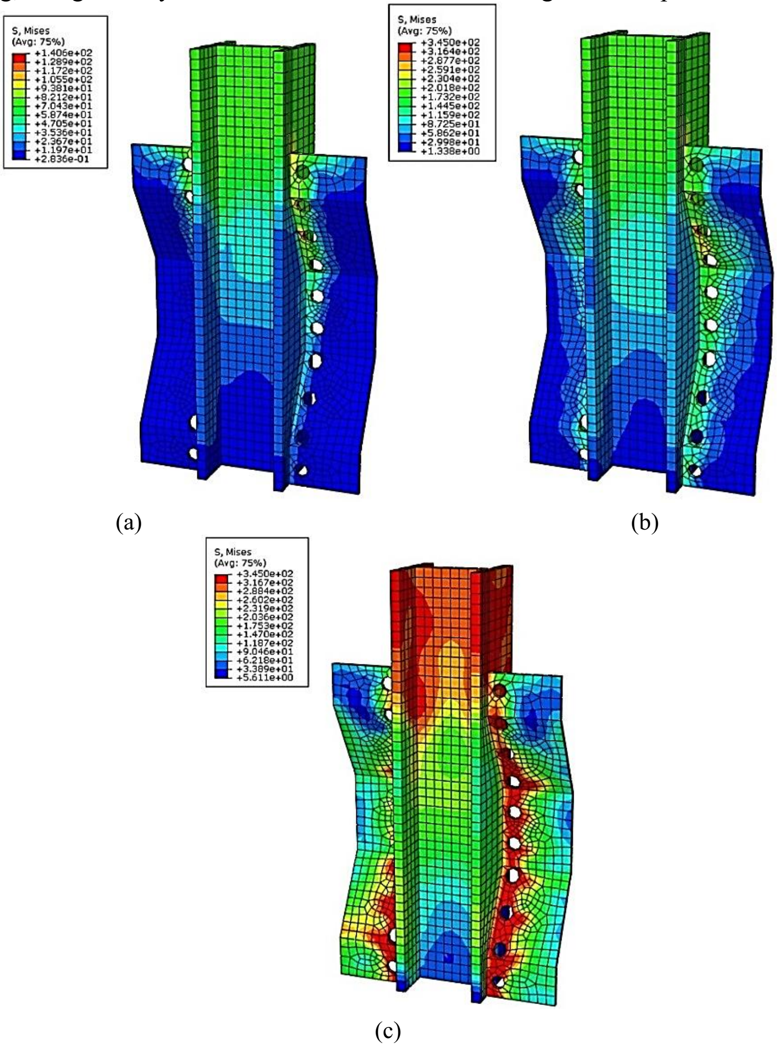


Fig. 8. Mises stress cloud of steel members under various working conditions (unit: MPa). (a)800kN; (b)2000kN; (c)3600kN.

The main tensile stress cloud map of concrete under various working conditions is shown in Figure 9. It can be seen that in the initial loading stage, the concrete is in a compressed state as a whole, and the stress concentration area of the concrete is around the corrugated steel plate. As the load increases, the tensile range gradually expands until the specimen is broken.

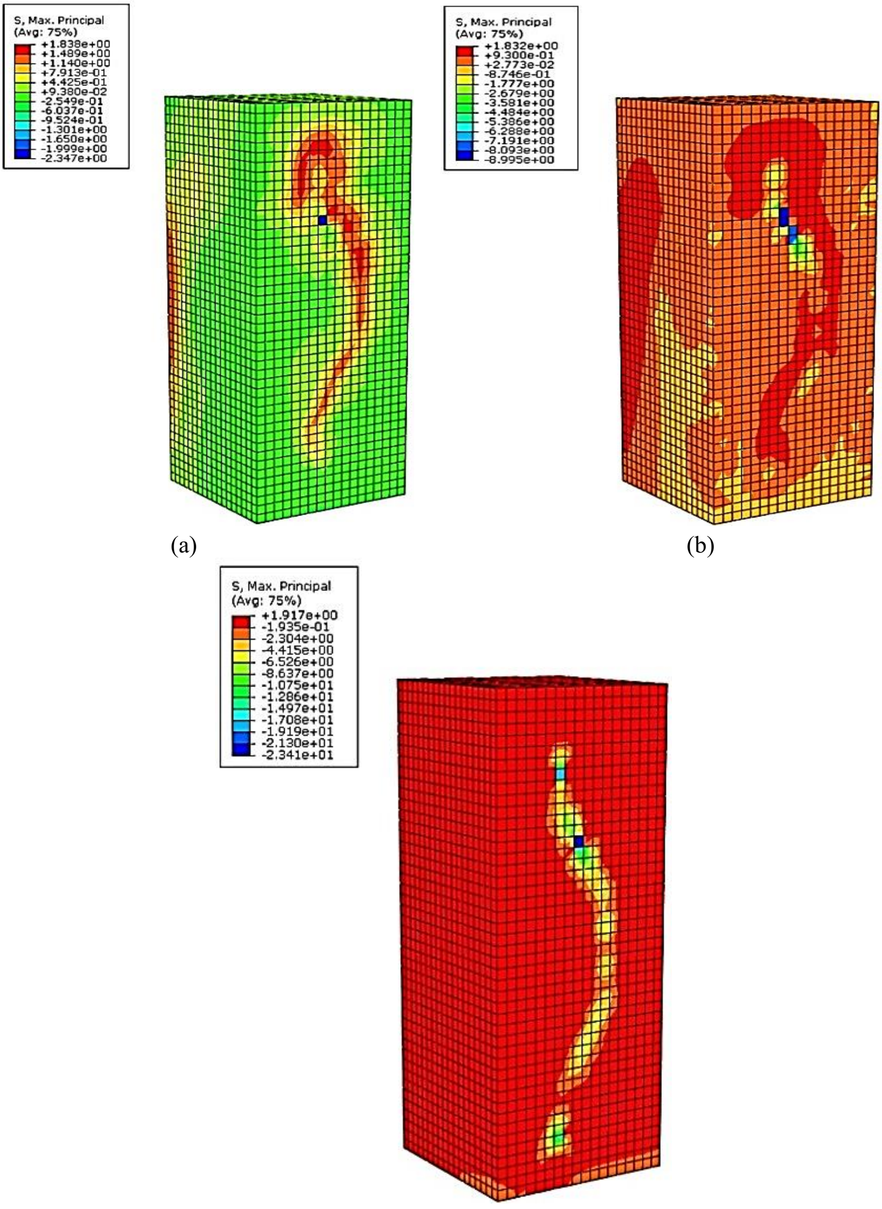


Fig. 9. Nephogram of principal tensile stress of concrete under various working conditions (unit: MPa). (a)800kN; (b)2000kN; (c)3600kN.

3 Structure and finite element analysis of cutting plate flange connector

3.1 Cut plate flange type connector structure

Due to the complex structure of the traditional connectors, they are composed of many plates and short steel bars. During the construction of the short section of the composite box girder with corrugated steel webs, the connector components are likely to conflict with the steel reinforcement in the steel reinforcement cage, which may cause the deviation of reinforcement and corrugated steel web, or even incompatibility. To solve the above technical deficiencies, a new type of connection between the corrugated steel web and the concrete structure is proposed, as shown in Figure 10.

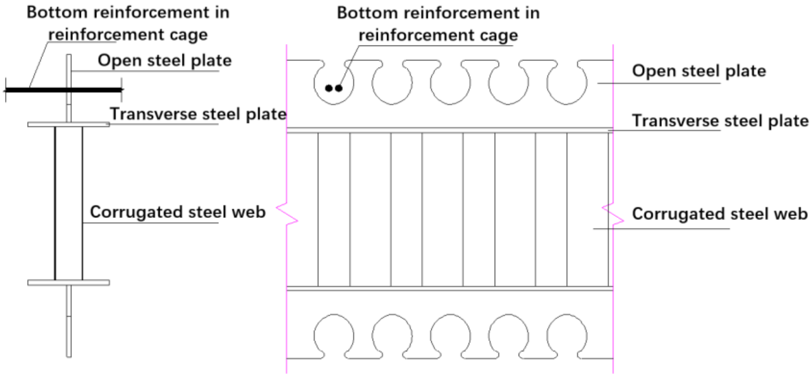


Fig. 10. Structural drawing of new shear connector.

The new type of shear connector is mainly composed of two parts. The first part is an open steel plate (it can be the form in this article or other reasonable forms, but it should meet the requirements of strength and the space requirements of the steel cage), which needs to be inserted into the reinforced concrete during prefabrication; the second part is transverse steel plate, which is mainly used to connect the corrugated steel web and the open steel plate by welding.

Compared with the traditional connector, the new cutting-plate-flange connector has the following characteristics:

(1) The utility model has the advantages of embedded and flange type connectors, and the structure of the perforated steel plate is simple, and the combination of the concrete inner steel bar can meet the requirements of longitudinal shear resistance; the transverse flange steel plate provides sufficient bending resistance while avoiding embedding Corrosion problems often occur in type connectors.

(2) Since the open steel plate is suitable for the factory prefabrication of girder cross-section, it does not need the process of ordinary rebar penetration, and can minimize the position conflict between complex connectors and reinforcement cage; the transverse flange steel plate can also be used as the bottom formwork of the roof concrete in the process of concrete pouring.

(3) It is easy to process. Open the steel plate according to the design drawing. The transverse flange steel plate can be welded automatically; the traditional connector processing needs more operation steps than the new connector.

(4) Good economic benefits, between the embedded connection and flange type connector.

3.2 Finite element model

The finite element model of the cutting plate flange type connector is shown in Figure 11, and the material parameters and structural dimensions are consistent with the above model.

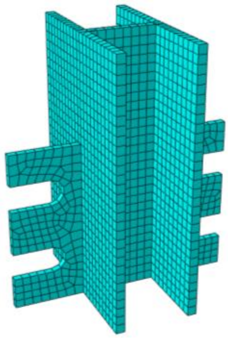
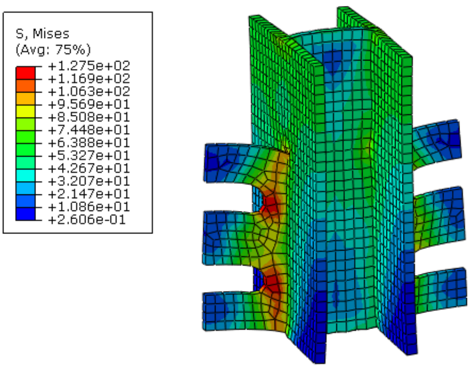


Fig. 11. Finite element model of cutting plate flange connector

3.3 Finite element analysis

The results of finite element analysis are shown in Figure 12. It can be seen from the figure that in the process of load increase, the stress gradually spreads to both ends along the arc of the cutting plate, while the stress extreme value remains at the arc of the cutting plate. The stress decreases gradually from the weld seam of the cut steel plate to the cantilever.



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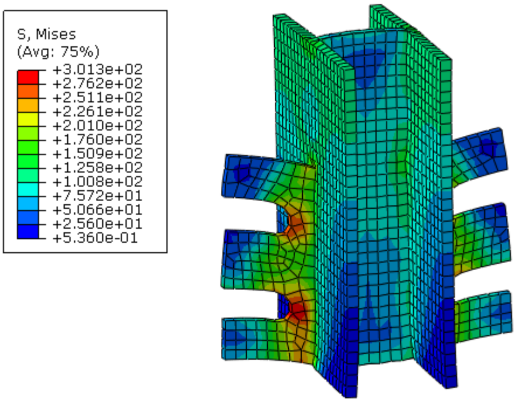

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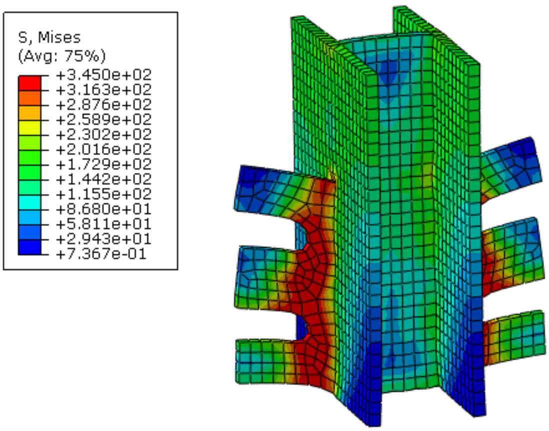
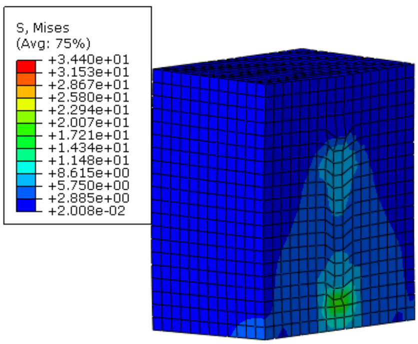


(c)

Fig. 12. Mises stress cloud diagram of steel components under various working conditions (unit: MPa). (a)1000kN; (b)2000kN; (c)3000kN.



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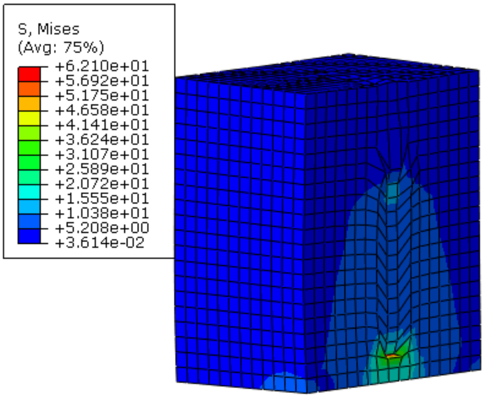

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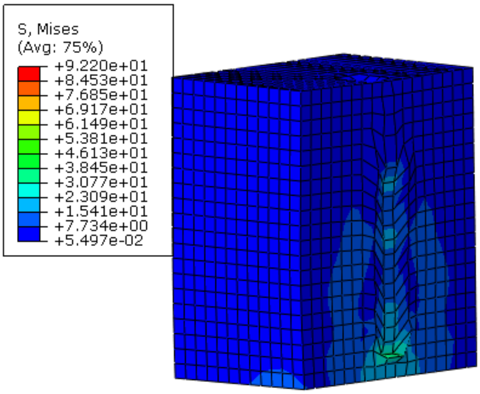

(c)

Fig. 13. Nephogram of principal tensile stress of concrete under various working conditions (unit: MPa). (a)1000kN; (b)2000kN; (c)3000kN.

The main tensile stress cloud map of concrete under various working conditions is shown in Figure 13. It can be seen that the concentrated area of main tensile stress in concrete is the concrete area corresponding to cutting steel plates. As the load increases, the stress extreme point gradually shifts downward, and the development area gradually expands. The stress transfer path is from the upper part of the cutting steel plate to the concrete below.

4 Performance Comparative Analysis of Various Connectors

The load displacement curves of the above four different specimens under direct shear are listed in Figure 14. It can be seen from the load-displacement curve that in the initial stage, the relative slip between the connector and the concrete is little, the load-displacement curve is close to a straight line, and the specimens all show great stiffness. After the yield-bearing capacity, the specimen enters the stage of plastic development. At this time, the load increases slowly, but the amount of slip increases greatly, and the shear stiffness of the connector continues to degrade. When the ultimate load is reached, the load-displacement curve changes slowly. At this time, the load decreases slowly and the slip increases continuously until the specimen is completely destroyed.

It can be seen from Figure 14 that the initial stiffness of the cutting-plate-flange type connector is smaller than other connectors, but its ultimate bearing capacity is larger than that of the twin perfobond rib connector, which is like the angle steel connector. Therefore, the bearing capacity of the cutting-plate-flange type connector proposed in this paper meets the shear requirements.

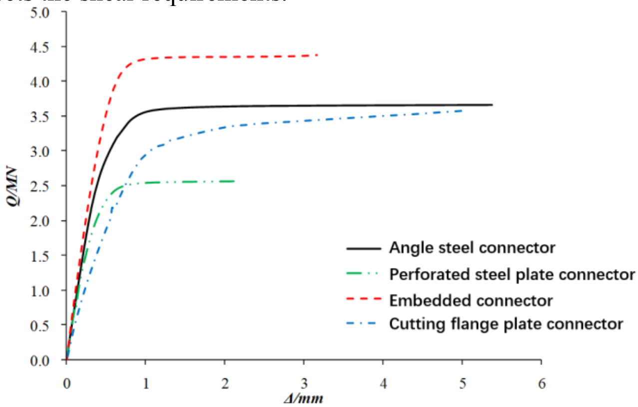

Fig. 14. Load-displacement curves of different connectors

Four kinds of typical shear connectors are compared from four aspects of structural characteristics, stress characteristics, economy and applicability to segmental precast assembly construction, and recommends their combination with the characteristics of the short line matching prefabrication process.

(1) Mechanical characteristics

The stud connector relies on the stud to bear the horizontal shear force in the direction of the bridge axis and the corner bending moment in the direction of the right angle to the bridge axis. The angle steel connector relies on the angle steel and U-shaped reinforcement to bear the longitudinal shear force and relies on the angle steel, U-shaped reinforcement and the through reinforcement passing through the angle steel to bear the bending moment at right angles to the bridge axis. The twin perfobond rib connector bears the longitudinal horizontal shear force and resists the uplift force between the concrete plate and the steel plate relying on the concrete in the hole and the through reinforcement. The embedded connector relies on the inclined section of the corrugated steel plate and the through reinforcement in the opening to bear the longitudinal horizontal shear force, and relies on the through reinforcement in the opening to resist the uplift force. The cutting-plate-flange connector relies on the concrete in the

U-shaped opening and the through reinforcement to bear the longitudinal horizontal shear force and resist the uplift force between the concrete plate and the steel plate.

(2) Economy

The economy of embedded connector is the best, followed by the embedded connector, twin perfobond rib connector, cutting-plate-flange connector, and angle steel connector.

(3) Advantage

The corrugated steel webs with embedded connectors are easy to process. The flange plates of other shear connectors can be used as the concrete bottom formwork at the haunch of the roof during the prefabrication period. There is no need to break the ordinary rebar when using stud connectors. The use of cutting-plate-flange connector does not affect the formation of the roof and floor reinforcement cage.

(4) Disadvantage

During the construction of stud connectors, the layout accuracy of ordinary rebar should be strictly controlled to avoid collision with welding studs. The welding of angle steel connector is tedious. When selecting the twin perfobond rib connector and embedded connector, the ordinary rebar in the joint area needed to be broken, and form the overall stress through the reinforcement, and the prefabricated formwork of embedded connector should consider the waveform. The influence of unclosed opening on the bearing capacity of the flange connector needs to be studied.

(5) Adaptability evaluation of short line method

The flange plates of the above five kinds of connectors can be used as templates in the prefabrication period, which has very good economic benefits. When using the twin perfobond rib connector and embedded connector, the reinforcement shall be penetrated and bound on the prefabricated pedestal or assembly pedestal. The arrangement of the angle steel above the flange plate of the angle steel connector may affect the lowering of the whole reinforcement cage. By cutting the steel plate to stagger the arrangement of the steel bars, the prefabrication can be realized quickly.

In summary, the cutting-plate-flange connector is the most recommended.

5 Summary

Shear connectors of composite girder bridge with corrugated steel webs are optimized to adapt to the segmental precast assembly construction. A connector between corrugated steel webs and concrete is proposed, named cutting-plate-flange connector.

Through finite element modeling calculation, the ultimate bearing capacity of the proposed cutting plate flange connector is close to that of the Angle steel connector, which meets the shear resistance requirements. Through finite element modeling calculation, the ultimate bearing capacity of the proposed cutting plate flange connector is close to that of the Angle steel connector, meeting the shear resistance requirements. Meanwhile, compared with the differences of various connectors in structural characteristics, mechanical performance, economy and applicability of segment prefabrication, the construction of cutting plate flange connector is simple and more suitable for short-line matching prefabrication process. It can be widely used in segment prefabricated composite girder Bridges with corrugated steel webs.

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