Research on performance of prefabricated bridge joint

Wentao Xie¹, Yun Sun², Shan Chang¹, Jianqi Qian¹ and Ming Yang¹*

¹School of Transportation, Southeast University, Nanjing, Jiangsu, 211189, China
²School of Civil and Transportation Engineering, Ningbo University of Technology, Ningbo, Zhejiang, 315211, China
*Corresponding author's e-mail: mingyang@seu.edu.cn

Abstract. In this paper, the influence of different parameters such as joint form, joint stiffness and shear key form on the mechanical properties of the joint was analyzed based on an asymmetric simply supported-continuous box girder. The finite element analysis model of the bridge was established by the finite element software MIDAS CIVIL 2017, and the mechanical properties of the whole bridge were analyzed. Based on the general finite element software ABAQUS 2017, the local solid finite element models of the four types of joints, such as C50 concrete wet joint, C80 concrete wet joint, dense key prefabricated assembly joint and sparse key prefabricated assembly joint, were established to study the mechanical properties and feasibility. The results show that the cracking moments of the four types of joints are more than twice of the negative moment of the middle fulcrum section under the most unfavorable state, which meet the requirement of the service performance. The breaking moments of the four types of joints are more than three times of the negative moment of the middle fulcrum section under the most unfavorable state, which meet the requirement of the carrying capacity.

1. Introduction

With the technological progress of large construction machinery and equipment, bridge prefabrication and assembling technology has been widely used, especially the prefabricated beam technology, which has been a more general type in the design and construction of highway and municipal bridges. Prefabricated bridges often have structural system transformation processes during construction, such as the common simply supported-continuous system. In this process, there are a large number of joints, which are prone to stress concentration in some weak or defective joints, resulting in fatigue failure at the joints. The reliability of joints directly affects the durability and service life of prefabricated bridges. It is of great significance to analyze the force at the joint by finite element software, and study the force characteristics at the joint in depth for creating or improving the structure at the joint.

For segmental prefabricated and assembled bridges, many related studies have been carried out internationally. Based on the scale model of three-span segmental unbonded prestressed concrete continuous beam, the flexural behavior and shear failure mechanism of externally prestressed concrete beam were studied in Austin University of Texas [1]. Antoine et al. carried out full-scale model test of simply supported beam based on Bangkok Phase II expressway system and studied the ultimate bending failure process [2-4]. Zhenggang Yu used ANSYS software to carry out finite element analysis on four model beams, and proposed a finite element analysis method suitable for the mechanical characteristics of prefabricated simply supported-continuous beam bridge [5]. Through the modeling analysis of the finite element software ANSYS and test validation method, Rongda Li carried out the research on the new joint form of simply supported-continuous beam [6]. Kejian Sheng
used external prestressing technology to assemble simply supported beams and prefabricated joints. Through laboratory test and finite element numerical analysis, the structure and mechanical properties of prefabricated joints with external cables were discussed [7]. Wenhai Zheng believes that the small-size joint type of simply supported-continuous bridge affects the rationality of internal force distribution and the aesthetic performance of such bridges. If the joint size is enlarged, it can play a reasonable role in adjusting the internal force of the main girder to a certain extent [8]. Yuanjia Lv put forward a new type of negative moment section structure, which can simplify the construction process and reduce the influence of insufficient effective prestress caused by difficult construction [9]. Xuefei Shi analyzed the structural response of the test beam in the process of ultimate failure, such as deformation, crack development and stress increment of external prestressing tendons, through full-scale test of a complete external prestressed segmental prestressed continuous girder bridge [10].

From the above research, it can be found that there is still a lack of research on the properties of prefabricated assembly joints with shear keys for simply supported-continuous beams. In this paper, relying on a practical engineering of four-span simply supported-continuous box girder, the finite element software MIDAS CIVIL 2017 was used to establish the superstructure model of the whole bridge, so that the negative moment of the middle fulcrum section under the most unfavorable state was obtained. Then, the finite element models of four kinds of joints, namely C50 concrete wet joint, C80 concrete wet joint, dense key prefabricated assembly joint and sparse key prefabricated assembly joint, were established by using finite element software ABAQUS 2017. The cracking load and carrying capacity were studied, and the feasibility of prefabricated assembly joint was evaluated.

2. General situation of the engineering

A viaduct is a bi-directional four-lane partitioned box girder bridge. The design load is grade I of highway of China. Each viaduct is divided into two parts, each of which is prefabricated separately. The construction method is simply supported-continuous. The top width of the prefabricated beam is 12.45 m, and the bottom width is 4.45 m. The top plate is designed as a 2% cross slope and the height of the main girder is 2.25 m-2.5 m. The prefabricated beams adopt asymmetric cross sections with different inner and outer cantilevers. The outer cantilever is 3.8 m long and is divided into 1.8 m and 2 m segments. The inner cantilever is 1.7 m long. The thickness of the roof of box girder is 26 cm, which is increased to 55 cm in the fulcrum section. The thickness of the bottom plate is 25 cm, which is increased to 55 cm in the fulcrum section. The thickness of the mid-span web is 40 cm, and it gradually becomes 60 cm from 10.75 m outside the fulcrum, and the length of the transition section is 6.5 m. The webs of the fulcrum section are thickened to 110 cm for satisfying the need of bearing force transmission. The typical cross sections are shown in figure 1 and figure 2.

![Figure 1. Typical cross section in midspan of partitioned prefabricated box girder.](image1)

![Figure 2. Typical cross section in supporting point of partitioned prefabricated box girder.](image2)
In terms of material, C50 concrete is used, and the compensating shrinkage concrete is used for cast-in-situ end diaphragm beam, middle diaphragm beam and wet joint. HRB400 ribbed bars with diameter of 12 mm and 16 mm are used for common steel bars.

The prefabricated box girder has 35 m, 32.5 m, 30 m and 27.5 m spans. There are many kinds of span combinations. The 4*35 m span combination was selected for analysis in this paper.

3. Analysis of mechanical characteristics of box girder bridge

Midas civil 2017 software was used to build 4*35 m continuous beam model. The full bridge model is shown in figure 3.

For prestressing loads, eight 19-∅15.2 web prestressing tendons and three 14-∅15.2 floor prestressing tendons are used for longitudinal prestressing reinforcement of prefabricated box girders. Longitudinal continuous prestressing tendons are arranged at the upper edge and lower edge of the middle fulcrum, twelve top prestressing tendons of 14-∅15.2 are used at the upper edge and four bottom prestressing tendons of 14-∅15.2 are used at the lower edge. The circular anchorage is used for all anchorages, and the ultimate tension control stress under anchorage is 1395 MPa.

Considering the self-weight, prestressing load, secondary loads, vehicle load, temperature load, bearing settlement, concrete shrinkage and creep, load combination was carried out according to the code of China. Then from the model, the maximum positive moment is 36387.3 kN·m at 16.75 m from the beam end. The maximum negative moment is -17259.7 kN·m at the first middle fulcrum section from the beam end. The envelope diagram of bending moment is shown in figure 4.

Figure 3. Finite element model of full bridge.

Figure 4. Envelope diagram of main girder bending moment.
4. Finite element model for local analysis of four kinds of joints

4.1. Local analysis model of C50 concrete wet joint

The local analysis model of C50 concrete wet joint is shown in figure 5.

![Figure 5. Local analysis model of C50 concrete wet joint.](image)

The finite element software ABAQUS 2017 provides three constitutive models of concrete: brittle cracking model, dispersive cracking model and plastic damage model. Because the plastic damage model can be better used in unidirectional loading, cyclic loading and dynamic loading, and has better convergence. Therefore, the plastic damage model was adopted in the constitutive relationship of concrete in this paper.

In this paper, considering the cost and accuracy of calculation, the constitutive relationship of common steel bar adopted a trilinear elastic-plastic hardening model with yield strength of 400 MPa. Because the stress level of the prestressing tendons was low and the yield strength could not be reached, the elastic model was used.

Concrete adopted 8-node hexahedral linear reduction integration element (C3D8R). The element has three translational degrees of freedom and is suitable for non-linear finite element analysis including contact, large deformation and failure. The edge length of the element was 0.15 m. The concrete meshing is shown in figure 6. For common steel bars and longitudinal and transverse prestressing tendons, two-node three-dimensional truss element (T3D2) was selected with the element length of 0.15 m. The meshing of common steel bars and prestressing tendons is shown in figure 7.

![Figure 6. Mesh generation of concrete.](image)  ![Figure 7. Mesh generation of common steel bars and prestressing tendons.](image)

The load was applied in three analysis steps. The first step was to apply transverse prestressing load, the second step was to apply longitudinal prestressing load, and the third step was to apply external load. This paper mainly studied the carrying capacity at the fulcrum section, so only the displacement load was applied at the two ends of the local model to produce larger bending moment at the middle fulcrum. Reference points were set at the center of shape at both ends of the model, and the reference points were coupled with the cross sections at both ends. Then vertical downward displacement loads were applied at the reference points, the size of which was 0.005 m.
4.2. Local analysis model of C80 concrete wet joint

The local analysis model of C80 concrete wet joint was almost the same as that of C50 concrete wet joint. The only difference was that the C50 concrete of pier top wet joint was replaced by C80 concrete, and only the material properties and constitutive relationship of concrete need to be changed accordingly.

4.3. Local analysis model of prefabricated assembly joint with dense key

The local analysis model of dense key prefabricated assembly joint was similar to the local analysis model of C50 concrete wet joint, but there were two differences. Firstly, the shear key assembly method was adopted for the dense key prefabricated assembly joint. Before assembling, epoxy resin adhesive should be applied on the joint surface. In this paper, the web shear keys, which played a major role in shear resistance, were considered. The dimensions of the web shear keys were set by reference to the approach bridge of Nanjing Yangtze River Fourth Bridge. The width of the key teeth is 13 cm, the spacing of the key teeth is 6 cm, the height of the key teeth is 3.5 cm, the inclination angle of the shear keys is 45 degrees. The key blocks and keyways are shown in figure 8 and figure 9. Secondly, because the dense key prefabricated assembly joint was connected by shear key and epoxy resin adhesive, the common steel bars were not continuous on the joint surface. The longitudinal common steel bars are shown in figure 10.

![Figure 8. The key blocks of dense shear key.](image1)

![Figure 9. The keyways of dense shear key.](image2)

![Figure 10. Longitudinal common steel bars.](image3)

The simulation of epoxy resin adhesive was realized by setting cohesive contact. Cohesive contact expresses the complex failure process in terms of the relative separation displacement-force relationship between two surfaces. In the existing literatures, the constitutive relations of common rubber layer include Nakaba model, Neubauer-Rostasy model, Monti model, Xinzheng Lu accurate model, Xinzheng Lu simplified model, Xinzheng Lu bilinear model, etc [11]. In this paper, based on the existing research results of bond-slip constitutive model of concrete adhesive surface, Xinzheng Lu bilinear model was choosed.

4.4. Local analysis model of prefabricated assembly joint with sparse key

When the local analysis model of sparse key prefabricated assembly joint was established, only the size of shear key was changed on the local analysis model of dense key prefabricated assembly joint.
In this paper, the width of sparse key teeth is 13 cm, the spacing of key teeth is 25 cm, the height of key teeth is 3.5 cm, the inclination angle of shear keys is 45 degrees. The key blocks and keyways are shown in figure 11 and figure 12.

5. Analysis of results of local finite element model of different joints

5.1. Damage analysis under prestressing and external load
Under the combined action of prestressing force and external load, the tensile damage nephograms of four kinds of local analysis models of joints are shown in figure 13-16.

Figure 13. Nephograms of tensile damage of C50 concrete wet joint.
Figure 14. Nephograms of tensile damage of C80 concrete wet joint.
Figure 15. Nephograms of tensile damage of precast assembly joint with dense keys.

(c) Adhesive surface

Figure 16. Nephograms of tensile damage of precast assembly joint with sparse keys.

From figure 13-16, it can be seen that under the action of prestressing force and external load, the concrete of the four kinds of local analysis models of joints all suffer great damage. Cracks appear in places with large damage. Under the action of external load, the longitudinal bending moment of the middle fulcrum section is larger, so the longitudinal tensile stress at the roof is larger, which causes transverse cracks in concrete. In addition, due to the wider and asymmetric roof, a larger lateral tension is generated under external load, which results in the roof cracking along with longitudinal cracks. Therefore, the reinforcement ratio of the roof transverse prestressing tendons should be increased in actual construction. Because the loading mode is chosen at both ends of the local model, large diagonal shear cracks will occur in the later stage of loading, but they have little effect on the cracking load of roof and the carrying capacity of local model of joints. There are few such cracks in practical engineering. For prefabricated assembly joints, there is also great damage on the adhesive surface, which indicates that the epoxy resin adhesive has reached the tensile strength and the adhesive surface cracks. In addition, from the damage nephogram, it can be seen that the concrete damage of the roof and web on the side of the long flange plate is larger, so the common steel bars’ reinforcement ratio of the roof and web on the side of the long flange plate should be increased appropriately in actual construction.
5.2. Analysis of cracking load
The first place where concrete damages occurred is the first place where the cracks appear. The time-history diagram of stress-analysis step of common steel bar on the top floor is extracted. The sudden change of the stress of the steel bar indicates that the crack develops to the position of the steel bar, and the external load is taken as the cracking load. The time-history diagram of stress-analysis step of common steel bar is shown in figure 17.

![Time-history diagram of stress-analysis step](image)

Figure 17. Time-history diagram of stress-analysis step of common steel bar.

From figure 17, it can be seen that the stress of steel bars in the four models changes abruptly, and the roof concrete cracks at this time. The reaction forces at the corresponding loading points are 9239.6 kN, 9729.35 kN, 9490.45 kN and 9662.54 kN, respectively. The corresponding cracking moment is as follows:

- C50 concrete wet joint:
  \[ M_{cr} = 9239.6 \times 4.25 = 39268.3 \text{kN} \cdot \text{m} \]

- C80 concrete wet joint:
  \[ M_{cr} = 9729.35 \times 4.25 = 41349.7 \text{kN} \cdot \text{m} \]

- Dense key prefabricated assembly joint:
  \[ M_{cr} = 9490.45 \times 4.25 = 40334.4 \text{kN} \cdot \text{m} \]

- Sparse key prefabricated assembly joint:
  \[ M_{cr} = 9662.54 \times 4.25 = 41065.8 \text{kN} \cdot \text{m} \]

According to the calculation results, the relationship between cracking loads of four kinds of joint models is as follows: C80 concrete wet joint > sparse key prefabricated assembly joint > dense key prefabricated assembly joint > C50 concrete wet joint. Compared with C50 concrete wet joint, the cracking moment of roof of middle fulcrum section is larger when C80 concrete wet joint is used, which can improve the mechanical properties of the wet joint. The cracking moment of prefabricated assembly joint is between the two, which shows that the prefabricated assembly joint can also obtain larger cracking moment on the premise of guaranteeing the construction quality of adhesive surface. In addition, according to the results of chapter 2, the maximum negative moment of middle fulcrum section is 17259.7 kN·m under load combination. It can be seen that the cracking moment of four
types of joints is more than twice the negative moment of the middle fulcrum section under the most disadvantageous condition. Therefore, no matter whether the wet joint or prefabricated assembly joint is used, the cross-section roof of the middle fulcrum will not produce cracks, which meets the requirement of service performance.

5.3. Analysis of carrying capacity
In the post-processing, the load-displacement curves of four kinds of local analysis models are obtained by extracting the vertical displacement and reaction of loading points, as shown in figure 18. In the figure, the abscissa unit is m and the ordinate unit is N. For ease of observation, figure 19 shows a local enlarged drawing near the highest point of the load-displacement curve.

![Figure 18. Load-displacement curve of local model of joint.](image1)

![Figure 19. Local enlarged drawing near the highest point of the load-displacement curve.](image2)

From figure 18 and figure 19, it can be seen that the load-displacement curves of the four types of local analysis models have obvious descending sections in the later stage of loading, which proves that the ultimate carrying capacity of the structure is reached and the carrying capacity decreases.

For C50 concrete wet joint, the maximum carrying capacity is 13754.4 kN when the loading displacement is 3.60 mm, and the corresponding bending moment at the fulcrum section is:

\[ M_u = 13754.4 \times 4.25 = 58456.2 \text{kN}\cdot\text{m} \]

For C80 concrete wet joint, the maximum carrying capacity is 13766.8 kN when the loading displacement is 3.66 mm, and the corresponding bending moment at the fulcrum section is:

\[ M_u = 13766.8 \times 4.25 = 58508.9 \text{kN}\cdot\text{m} \]

For dense key prefabricated assembly joint, the maximum carrying capacity is 14129.8 kN when the loading displacement is 3.67 mm, and the corresponding bending moment at the fulcrum section is:

\[ M_u = 14129.8 \times 4.25 = 60051.7 \text{kN}\cdot\text{m} \]
For sparse key prefabricated assembly joint, the maximum carrying capacity is 14040.1 kN when the loading displacement is 3.64 mm, and the corresponding bending moment at the fulcrum section is:

$$M_{\text{cr}} = 14040.1 \times 4.25 = 59670.4 \text{kN} \cdot \text{m}$$

According to the calculation results, the relationship between failure loads of four kinds of joint models is as follows: dense key prefabricated assembly joint > sparse key prefabricated assembly joint > C80 concrete wet joint > C50 concrete wet joint. Compared with C50 concrete wet joint, the carrying capacity of C80 concrete wet joint is slightly improving. When prefabricated assembly joint is used, the tensile strength of epoxy resin adhesive is larger than that of concrete, so its carrying capacity is larger than C50 concrete wet joint and C80 concrete wet joint on the premise of guaranteeing the construction quality of adhesive surface. In addition, according to the above analysis results, the maximum negative moment of middle fulcrum section is 17259.7 kN·m under load combination. It can be seen that the breaking bending moment of the four types of joints is more than three times of the negative moment of the middle fulcrum section under the most disadvantageous condition. Therefore, no matter whether the wet joint or prefabricated assembly joint is used, the requirement of carrying capacity is met.

6. Conclusions

The following conclusions are drawn from the results of this study.

1. The relationship between cracking loads of four kinds of joint models is as follows: C80 concrete wet joint > sparse key prefabricated assembly joint > dense key prefabricated assembly joint > C50 concrete wet joint. The cracking moment of four types of joints is more than twice of the negative moment of the middle fulcrum section under the most disadvantageous condition. Whether using wet joint or prefabricated assembly joint, the cross-section roof of the middle fulcrum will not produce cracks, which meets the requirement of service performance. The relationship between failure loads of four kinds of joint models is as follows: dense key prefabricated assembly joint > sparse key prefabricated assembly joint > C80 concrete wet joint > C50 concrete wet joint. The breaking bending moment of the four types of joints is more than three times of the negative moment of the middle fulcrum section under the most disadvantageous condition. Whether using wet joint or prefabricated assembly joint, the requirement of carrying capacity is met.

2. The carrying capacity of prefabricated assembly joint with shear keys is greater than that of C50 concrete wet joint and C80 concrete wet joint, and its cracking load is also larger than that of C50 concrete wet joint. Therefore, on the premise of guaranteeing the construction quality of adhesive surface, the prefabricated assembly joint can fully meet the requirement of serviceability limit state and ultimate limit state. This type of joint has a very broad development prospects, such as making continuous beams prefabricated, factory and field construction assembly, reducing wet joint cast-in-place operation and environmental pollution, shorting the construction period, improving labor efficiency and product quality.

3. When prefabricated assembly joints are used, it is important to pay attention to the construction quality of the adhesive surface, which is the key to ensure the service performance and carrying capacity of the joints. The analysis shows that the sparse key prefabricated assembly joint has a large carrying capacity, and its cracking load is greater than that of the dense key prefabricated assembly joint. It should be noted that it is difficult to achieve perfection when gluing the joint surface in practical engineering. In addition, considering the need of shear transfer, the prefabricated assembly joint should mainly adopt the dense shear keys. If prefabricated assembly joint with sparse shear keys is adopted, besides ensuring the construction quality of adhesive surface, the amount of common steel bars should be increased around the key teeth and keyways of shear keys.

4. In this paper, the research object is asymmetrical prefabricated box girder. The width of flange plates on both sides of the box girder is different and the roof has a transverse slope. According to the results of finite element analysis, compared with the side of short flange slab, the concrete damage of the roof and web on the side of long flange slab occurs earlier and the damage factor is bigger, which indicates that when the external load is bigger, the concrete of the roof and web on the
side of long flange slab first appears cracks and the cracks are wider, so the common steel bars’ reinforcement ratio of the roof and web on the side of the long flange plate should be increased appropriately in actual construction.

References
[1] Macgregor, R., Kreger, M.E., Breen, J.E. (1990) Strength and ductility of a three-span externally post-tensioned segmental box girder bridge model. Earth & Planetary Science Letters, 305(1-2): 83-91.
[2] Naaman, A.E., Alkhairi, F.M. (1991) Stress at ultimate in unbonded post-tensioning tendons. Aci Structural Journal, 88(5): 641-651.
[3] Naaman, A.E., Alkhairi, F.M. (1991) Stress at ultimate in unbonded post-tensioning tendons. Aci Structural Journal, 88(6): 683-692.
[4] Tassin, D., Dodson, B., Takebayashi, T. (1996) Analyzing the ultimate capacity of a precast segmental box girder bridge. Structural Engineering International, 6(4): 255-258.
[5] Yu, Z.G. (2008) Study on the precast joint style of simple-continuous girder bridges. (Master Thesis). Harbin Institute of Technology, China.
[6] Li, R.D. (2008) Study on new joint style of simply-supported-continuous girder bridges. (Master Thesis). Harbin Institute of Technology, China.
[7] Sheng, K.J., Wang, Z.L., Yu, Z.G. (2009) Externally prestressed prefabricated joint technology in simply-supported continuous bridge. Journal of Harbin Institute of Technology, 41(11): 90-94.
[8] Zheng, W.H. (2010) Research on new structure type of simply-supported-continuous girder bridges. (Master Thesis). Harbin Institute of Technology, China.
[9] Lv, Y.J. (2017) Research on structural improvement test in negative moment section with the change from simple supporting to continuous of the prestressed concrete T-beam. (Master Thesis). Chongqing Jiaotong University, China.
[10] Shi, X.F., Liu, Z.Q., Hu, K., Zhou, Z.J. (2018) Full-scale test of bearing capacity of a complete external prestressed segmental precast continuous girder bridge. China Journal of Highway and Transport, 31(12): 163-173.
[11] Gao, D.W. (2017) Experimental research on GFRP-concrete-steel composite bridge decks and shear connections. (Master Thesis). Southeast University, China.