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Numerical Simulation on Mechanical Properties of Segmental Prefabricated Concrete T-section Beams

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Abstract: At present, there are few application cases of segmental prefabricated concrete T-section beams in bridge structures, and the research on mechanical properties is still insufficient. The division of segments makes the beam body have multiple joints, and the longitudinal reinforcement cannot be arranged continuously, which results in the discontinuous local mechanical behavior of the beam body at the joint position. In this paper, 6 beams are selected, and the number of single key-joint at the joint and the shear-span ratio are used as independent variables for research. The finite element model was established by ABAQUS software to simulate the stress and deflection, and ultimate bearing capacity of the segmental precast concrete T-section joint beams under two load cases. The following conclusions can be obtained by the data processed, which can provide a reference for the optimal design of segmental prefabricated concrete T-section beams in engineering applications. The conclusions include: that the joint sections of B and C conform to the assumption of plane section. Under the two-shear-span ratio, the stress transfer of the integral beam is better than that of the segmental beam, and the single key-joint beam is superior to the double key-joints segmental beam. At the joint section, the stress transfer of the same type of beam is better with a shear-span ratio of 2.3 than with a shear-span ratio of 3.3. When the shear-to-span ratio is the same, the bending stiffness of the integral T-section beams is the largest among the three beams. The second is the single key-joint segment beam, and the last is the double key-joints segment beam. When the shear-to-span ratio is different, the deflection when the shear-span ratio is 3.3 is more significant than when the shear-span ratio is 2.3. In conclusion, the mechanical properties of the integral beam are better than those of the other two segmental beams, and the mechanical properties of the single key-joint segmental beam are relatively better than that of the double key-joints segmental beam.

Keywords: Bridge Structure, Segment Prefabrication, Mechanical Properties, Epoxy-Joint, Key-Joint, Shear-Span Ratio

1. Introduction

In the 1950s, the bridge prefabricated assembly technology was born in France which is a factory concentrated on the production of concrete components and transported them to the site for assembly. The advantages are avoidance of on-site concrete pouring, reduced manual workload, and reduced impact of construction on the environment and existing traffic. While improving the construction speed, the construction period is shortened and the cost is controllable [4]. The division of segments results in the presence of multiple seams across the span of segmental precast girder bridges. At this time, the longitudinal ordinary steel bars cannot be arranged continuously, resulting in the discontinuous local stress behavior of the beam body at the joints. Under stress conditions, if the joints open, the bearing area of the concrete in the shear compression zone will decrease. At this time, the occlusal effect of aggregate, the pinning effect of longitudinal reinforcement, and the shearing effect of stirrups are weakened, which makes the failure mechanism of segmental prefabricated beams more complicated than the spatial stress distribution state of integral beams [12].

Segmental prefabrication has a non-negligible impact on the mechanical properties of bridge structures. The most effective measure to study the mechanical properties of segmental prefabricated beams is to observe the failure process of beams through-beam tests. In 2006, Li Guoping [5, 6] conducted a systematic and comprehensive experimental study on the mechanical properties of segmental precast concrete beams, and based on the experimental results, he performed a fitting regression on the calculation formula of the flexural bearing capacity. In 2011, Liu Zhao et al. [4] conducted an experimental study on the performance of the 48m full-size segment girder of the Fourth Nanjing Yangtze River Bridge. The results show that the mechanical properties are the same as that of the integral beams when the beams are in the elastic stage. In 2013-2015, Li G., Zhang C., and Yuan A. [7-9] conducted a detailed study on the mechanical properties of segmental prefabricated beams through experiments and numerical simulations. R. J. MacGregor, M. E. Kreger, J. E. Brent, and Carin L [12-14] obtained through experiments that cracks in segmental precast beams mainly occurred near the joints. In 2015, Yuan Aimin of Hohai University and Professor Jiang Haibo of Guangdong University of Technology [16-18] discussed the incremental change law of in vitro prestressing under the limit state of segmental beams. In 2016, Jiang Haibo et al. [10, 11] studied the influence of the number of key-joints, and the results showed that the number of key-joints has a certain influence on the flexural bearing capacity of segmental precast beams. In 2018, Gao Mingchang et al. [15] obtained through experiments that the ultimate tensile strength of epoxy resin gel and the concrete surface can reach about 3 Mpa. So far, the structural design clauses of segmental beams formulated by various countries are mainly based on the design and analysis methods of integral beams for empirical reduction and do not fully consider the performance differences between segmental beams and traditional integral beams.

At present, the research on the mechanical properties of segmental prefabricated beams mainly focuses on the direct shear performance analysis of the joints of the test blocks. Even if there is a T-section beam, it is a 3-segment beam or even a 2-segment beam for a simple structure. Prestressed steel bars are generally arranged outside the body. Given these characteristics, the mechanical properties of segmental prefabricated concrete T-section beams are analyzed with the Sungai Tondano Bridge in Indonesia as the research background. It is proposed to study two key-joint types based on the six 5-segment horseshoe-shaped T-section beams.

2. Design of T-section Beams

2.1. Parameter Selection of T-section Beams

The mechanical performance of the prefabricated and assembled concrete T-section beams with prestressed sections in the body is studied. By the corresponding national construction industry standards and specifications [1-3], the author designed the size parameters of segmental prefabricated concrete T-section beams. The cross-section of the beam is a T-section beam with a horseshoe. The total length of the beam is 5m, and the calculated length is 4.5m. Both are 1m, the beam height is 0.55m, and the roof width is 0.5m.

Among them, the concrete strength adopts C50, the longitudinal reinforcement adopts 10mm HRB400 reinforcement, and the stirrup adopts 8mm HRB335 reinforcement. The prestressed steel bars are steel strands with a tensile strength of 1860Mpa. The interface agent is epoxy resin gel, the key-joint type is single and double key-joints, and the key-joint slope angle is 45°. At the same time, the beam is divided into 5 points along with the beam height, and the stress distribution law of the B and C nodes during the beam loading process is analyzed. By analyzing the numerical simulation results, it can be concluded that the stress and deflection of the B and C segments are not significantly different. All values for segmental C-sections are used to illustrate the authors' study. The three-dimensional model of the single and double key-joint is shown in Figure 2. The specific information of segmental prefabricated concrete T-section beam is shown in Figure 1, in which the front view (a), the arrangement of stirrups at the single and double key-joints (b) (c), the single and double key-joints dimensions (d) (e), Reinforcing diagram of end section and mid-span position (f) (g), the size of the key-joints of the C joint section in the A dotted line frame (h), the stirrup arrangement of the three beams (i) (j) (k).

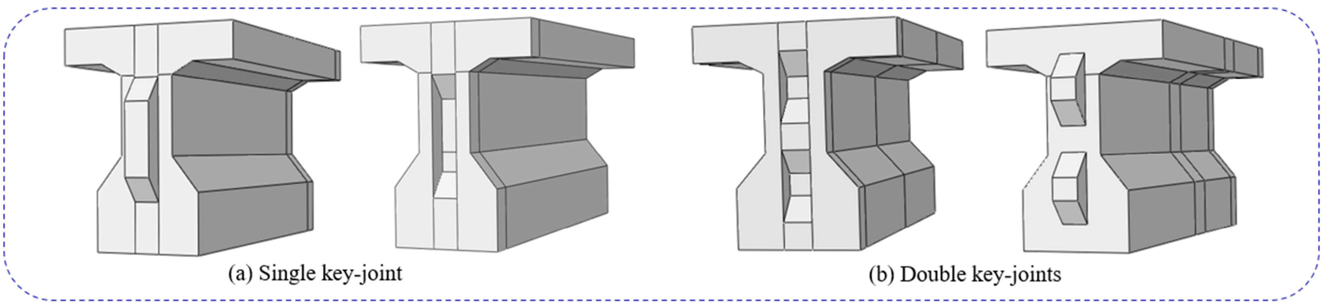

Figure 1. *3D perspective view of single key-joint and double key-joints.*

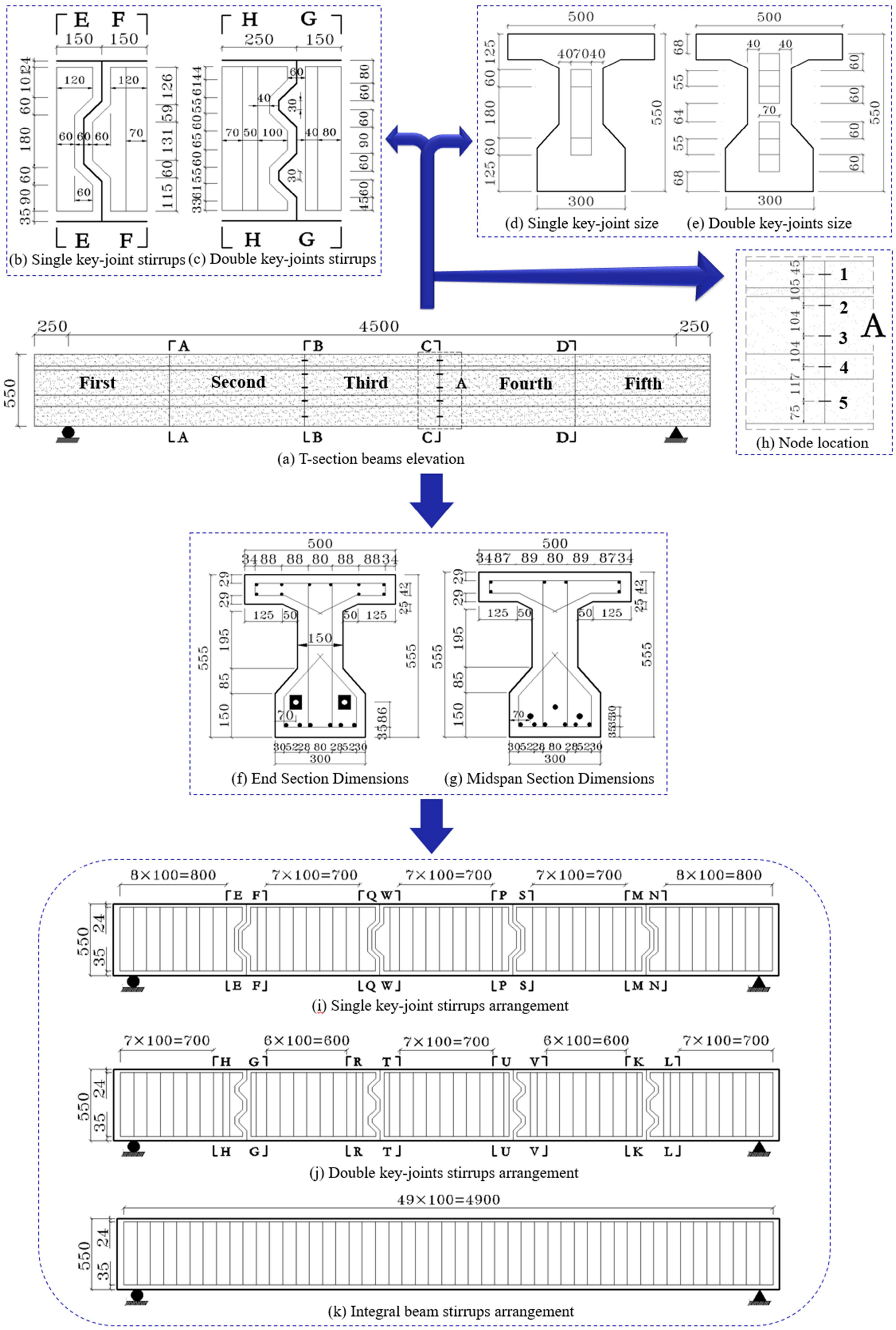

Figure 2. *Segmental prefabricated concrete T-section beams (mm).*

2.2. Loading Conditions

The sheer span ratio (λ) is an important parameter that affects the shear failure form and shear bearing capacity. With the increase of λ, the shear bearing capacity decreases. When λ is less than 2, the shear bearing capacity decreases the most. At this time, the steel skeleton plays a leading role. After the shear-span ratio exceeds 3, the shear bearing capacity does not change much, and the shear bearing capacity is mainly controlled by the concrete tensile strength. The two-point symmetrical concentrated load was used to explore the mechanical properties of segmental precast concrete T-section beams, and the loading position should avoid the key-joints. According to the above statement, when the load is applied to the first and the fifth segments, the shear span ratio λ is less than 1, so it is not meant to set the loading position at the first and fifth segments. when the loading position is at the third segment, then the shear-span ratio is 3.3~4.2. Avoid the position of the key-joints and leave the largest construction space for the two small distribution beams. At the same time, the loading position with the shear-span ratio closest to 3 is selected, as shown in (a) in Figure 3, and the parameter λ is 3.3. The shear-span ratio is between 1.8 and 2.9 when the loading position is at the 2nd and 4th segments. The author took an intermediate value of 2.3, which can be better compared with λ of 3.3, as shown in (b) in Figure 3.

Select 6 beams, including 2 single key-joint segment T-section beams, 2 double key-joints segment T-section beams, and 2 integral T-section beams. The specific information is shown in Table 1.

Table 1. *Beam Information Sheet.*

Serial number	Numbering	Type of beam	Interface agent	key-joint form	Shear-to-span ratio
1	ES2	segmental beam	Epoxy gel	single key-joint	2.3
2	ES3	segmental beam	Epoxy gel	single key-joint	3.3
3	ED2	segmental beam	Epoxy gel	double key-joints	2.3
4	ED3	segmental beam	Epoxy gel	double key-joints	3.3
5	I2	Integral beam	\	\	2.3
6	I3	Integral beam	\	\	3.3

Note: Beam numbering method description: E-epoxy-joint, S-single key-joint, D-double key-joints. I-integral beam, 2-shear-span ratio 2.3, 3-shear-span ratio 3.3. The loading conditions of the two working conditions are shown in Figure 3.

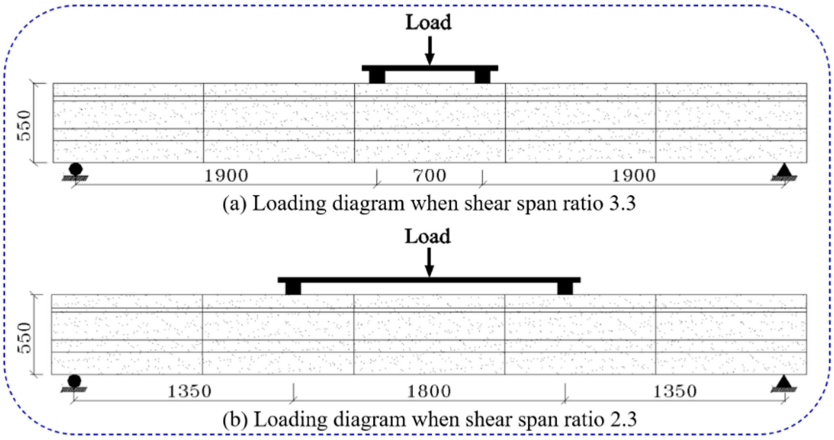

Figure 3. *Two loading conditions of shear span ratio (mm).*

2.3. Material Constitutive Selection

According to the materials and stress conditions of each component in the model, different elements are selected for simulation. Concrete is a solid and homogeneous material, and bears three-dimensional stress under load. The software selects a concrete plastic damage model with relatively comprehensive and suitable functions. Complex contact problems are easy to cause non-convergence of finite element calculation, so in Abaqus, concrete adopts convergence of the eight-node hexahedral reduced-integration solid element (C3D8R) with better performance. Because ordinary steel bars do not consider shear force and only bear unidirectional tensile and compressive stress, a two-node three-dimensional truss element (T3D2) is used for simulation. And the constraint relationship between the steel bar and the concrete is defined by embedded (embedded). The prestressed steel strand adopts the cooling method to simulate the tension process. The specific formula is $\Delta T = F / \alpha EA = \sigma_{con} / \alpha E$, where linear expansion coefficient α is 1.5×10^{-5}, σ_{con} is the tension control stress of the prestressed tendon.

In the actual construction process of glued joints, the coating thickness of epoxy resin gel between the joints should not exceed 3mm, and considering that the damage occurs first in the concrete, in the experiment done by Yang Xiong et al. [12], epoxy resin the bonding strength of the resin-concrete bonding interface is 22 MPa, which is much higher than the tensile strength of concrete, so the failure does not occur at the bonding interface, so the paper simplifies the epoxy resin material into a linear elastic material, the so to simplify the operation and save the calculation cost, the interface between the adhesive layer and the concrete can be regarded as a complete bond. Bundle each of them together. The contact surface of the epoxy resin layer is used as the slave surface, and the corresponding concrete contact surface is used as the main surface. The advantage of binding constraints is that the degree of freedom of the slave surface nodes is no longer considered in the analysis process, the contact state of the slave surface nodes does not need to be judged, and the calculation time is greatly shortened. At this time, the epoxy resin gel and concrete use the same solid unit (C3D8R), the elastic modulus E is 4800 MPa, the Poisson's ratio μ choose 0.2, the expansion angle is 38°, the eccentricity is 0.1, Viscosity parameter = 5×10^{-5}.

2.4. Element Type Selection and Meshing

The paper adopts a structured meshing method with better meshing quality, but for the model simulated in the paper, because of its irregular shape, this method cannot be directly used for meshing, and the Partition tool is required. The model is divided into several parts with relatively regular and simple shapes. After the division, structured meshing can be performed to obtain a more optimized mesh.

3. Finite Element Analysis

3.1. Stress and Deflection

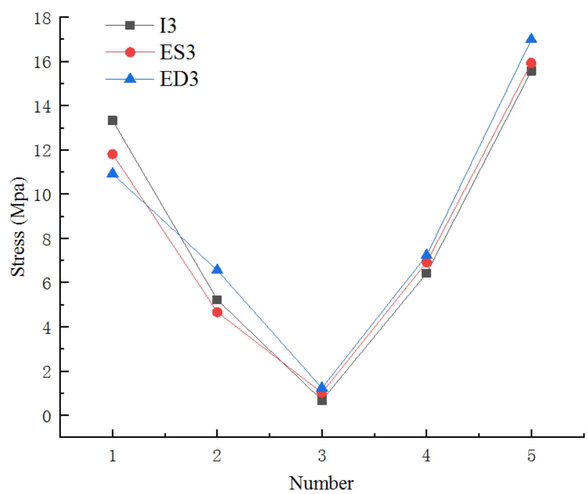

Figure 4. *Top-down stress distribution of joints C of the third segment when λ is 3.3.*

When the shear-span ratio is 3.3, the part of the segmental prefabricated T-section beams with greater stress is distributed on both sides of the joints C, as shown in Figure 1(a), the author pre-studied segmental prefabricated assembly of the mechanical properties of the concrete T-section beams and the integral T-section beams are mainly studied at the positions of the joints C. For more accurate and convenient research, 5 nodes are selected along the beam heights of the simulated beams B and C joints for measurement. The stress distribution of the T-beam along the selected points in Figure 1h is shown in Figure 4.

It can be analyzed from Figure 4 that when λ is 3.3, the stress of the three beams in the B and C joints first decreases and then increases along with the beam height from top to bottom, which is in line with common sense and theoretical knowledge of double key-joints The stress change of the key-joints segmental beam is relatively large among the three-beam bodies, followed by the single key-joint, and the integral beam is the smallest. It can be seen that when the shear-span ratio is 3.3, the stress transfer of the integral beam at the joint is better than that of the single and double key-joints segmental beams, single key-joints segmental beams have better stress transfer at the joints than double key-joints segmental beams.

When the shear-span ratio is 3.3, the paper summarizes the deflection change law of the three beams at the C joint sections, and the specific information is shown in Figure 5.

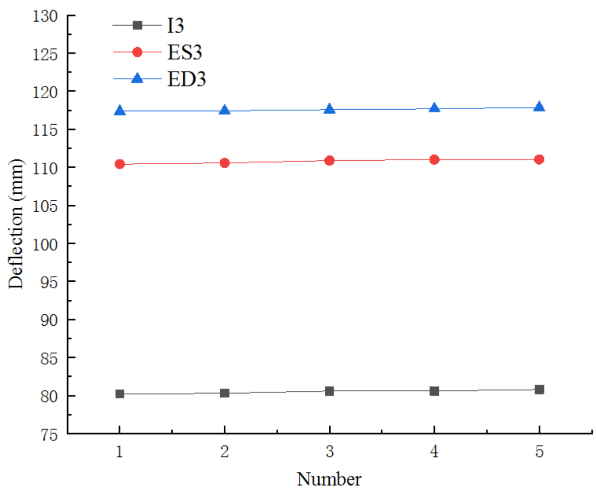

Figure 5. *Top-down deflection curves of joints C of the third segment when λ=3.3.*

From Figure 5, it can be analyzed that when λ is 3.3, the deflection changes of the C joint sections along the beam height are the same, which once again verifies the plane section assumption. From Figure 5, it can be seen that the deflections at the corresponding positions of the joint section C are approximately equal, which is in line with reality. Among the three beams, the integral beam has the smallest deflection and the largest flexural rigidity at the same loading position. The ultimate goal is to make its mechanical properties close to or even equal to the integral beam. The deflection of the single and double key-joints segmental beams at the C joints is not much different, about 112~117mm. Relatively speaking, the single key-joint segmental beam is under the same load. Less deflection and greater bending stiffness at the location.

To sum up, when the shear-span ratio is 3.3, the top-down stress and deflection changes of the joints C of the segmental prefabricated concrete T-section beams are summarized. The stress and deflection laws of three types of beams, including key-joints segment prefabricated beams and integral beams, are summarized.

When the shear-span ratio is 2.3, the distribution of the segmental prefabricated concrete T-section beams with greater stress is also on the third segment and both sides of the C joints. To compare with the result analysis when λ is 3.3 above according to the analysis, the paper will still conduct a comparative study on the stress and deflection of the C joints of beams. The top-to-bottom stress distribution of the C joints of beams is shown in Figure 6.

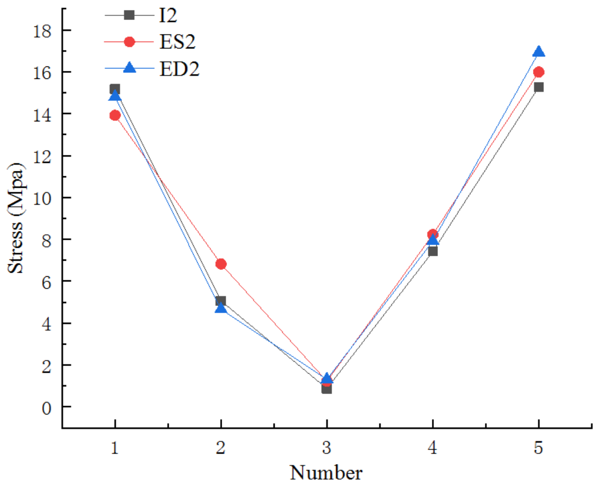

Figure 6. *Top-down stress curves of joints C of the third segment when λ=2.3.*

It can be analyzed from Figure 6 that when the shear-span ratio is 2.3, the curve of the single-double-key-joints beam of the C joints is basically the same as that of the integral beam, and the variation range is large, and the curve along with the beam height also varies from top to bottom. It conforms to the theoretical strain change trend. the integral beam along the beam height stress change is relatively stable compared to the other two beams, and the stress changes of the single key-joint segmental beams in the two types of key-joints segmental beams are compared with those of the double key-joint segmental beams. It is concluded that the single key-joint segmental beam is more stable.

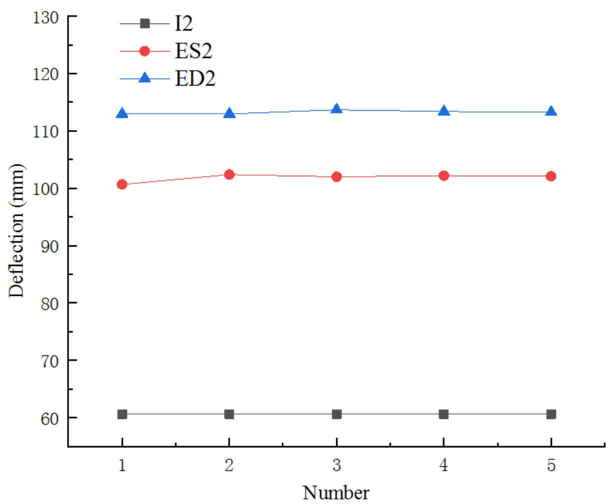

Figure 7. *The top-down deflection curve of joints C of the third segment when λ=2.3.*

When the shear-span ratio is λ=2.3, the paper still summarizes the deflection change law of the segmental prefabricated concrete T-section beams at the C joint sections. The specific information is shown in Figure 7.

It can be analyzed from Figure 7 that when the shear-span ratio is 2.3, the value of the deflection of the joints C is unchanged along with the beam height from top to bottom, that is, the deflection of the section is roughly equal to each other, which verifies the assumption of the plane section. Among the three beams, the deflection of the integral beam at the same loading position is the smallest, about 6cm, it can be seen that the bending stiffness of the integral beam is the largest. The flexural stiffness of the segmental T-section beams is the smallest.

In summary, when 6 beams are integrated, when different shear-span ratios are used, the stress distribution of the three C joint sections of the same beam segment from high to low is shown in Figure 8.

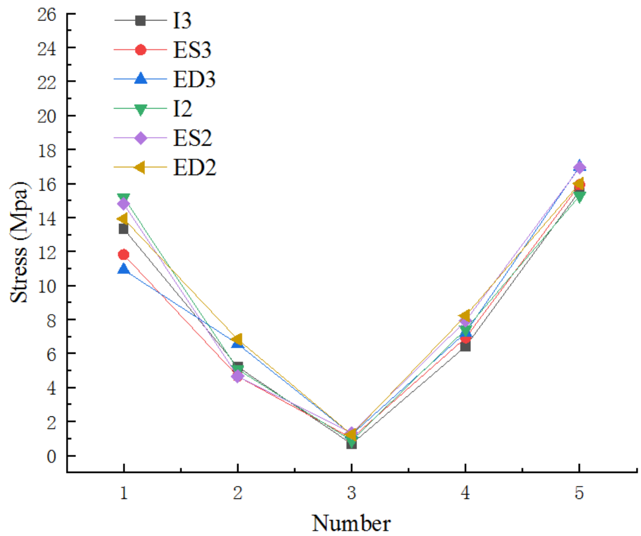

Figure 8. *Stress distribution of joints C of segment III under two working conditions.*

It can be seen from Figure 8 that the stress distribution rules of joints C along the beam height from top to bottom are as follows when the shear-span ratio is different: the stress changes at the two shear-span ratios first decrease and then increase, which conforms to the assumption of plane section. For both shear-span ratios, the integral T-section force transmission is better than that of the two segmental prefabricated concrete T-section beams. Relatively speaking, the single key-joi segmental prefabricated concrete T-section beams at the C joints have better performance. The stress transfer is better than that of the prefabricated concrete T-section beams with double key-joints. when the shear-span ratio is 2.3, the stress transfer at the joint C of segmental precast concrete T-section beams is better than when the shear-span ratio is smaller than 3.3. That is, the shear-span ratio of this model has a great influence on the double key-joints segmental beam. Figure 9 shows the top-to-bottom deflection of C joints.

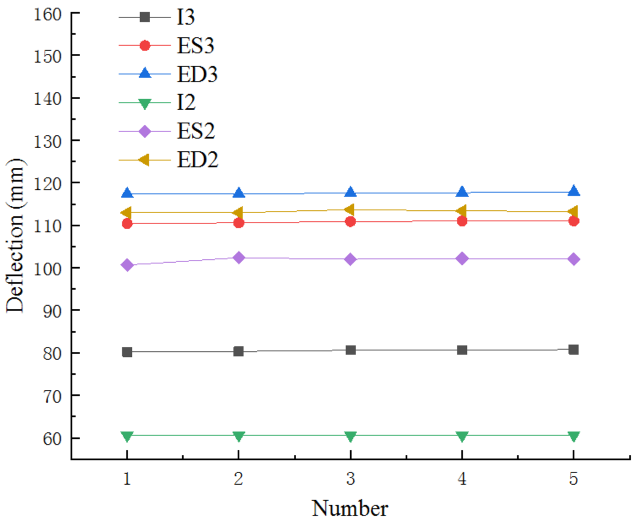

Figure 9. *Section deflection curves of joints C of the third segment under two working conditions.*

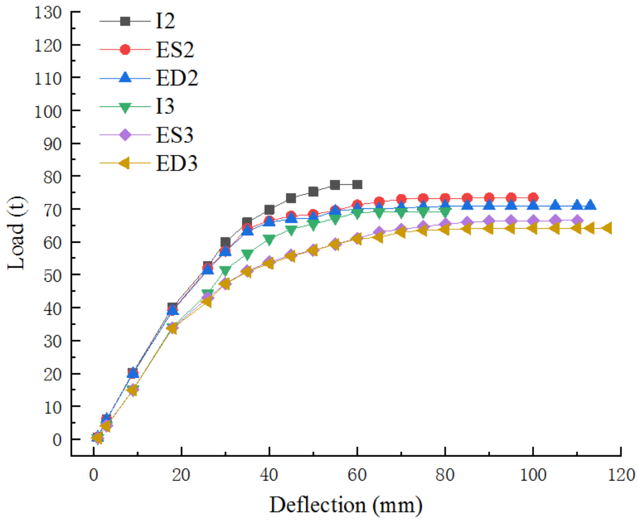

Figure 10. *Load-deflection curves of three beams at two shear-span ratios.*

From Figure 9, it can be concluded that the deflections of the six beams C joint sections along the beam height are the same when loaded under the two working conditions, which indicates that the loading process of the six beams conforms to the theory of plane section assumptions. For the same kind of beams, when the shear-span ratio is 3.3, the deflection value from top to bottom along the beam height is more significant than that when the shear-span ratio is 2.3. From reality and combined with the knowledge learned, this is in line with reality. When different kinds of beams have the same shear-to-span ratio, among the three beams, the deflection value of T-section beams is the smallest, which are 60mm (when the shear-span ratio is 2.3) and 80mm (when the shear-span ratio is 3.3) respectively. The deflection change value is next, about 102mm (when the shear-span ratio is 2.3) and 111mm (when the shear-span ratio is 3.3). the deflection change value of the prefabricated concrete T-section beams with the double key-joints segment is the largest, which are 113mm (when the shear-span ratio is 2.3) and 117mm (when the shear-span ratio is 3.3) or so. It can be seen that among the three types of beams, the integral T-section beams have the highest flexural stiffness, the single key-joint segment prefabricated concrete T-section beams have the second-highest flexural rigidity, and the double key-joints segment prefabricated concrete T-section beams have the smallest flexural rigidity.

3.2. Ultimate Load

Draw the deflection-load curve to understand the one-to-one correspondence between the load and deflection of the segmental precast concrete T-section beams during the stress process, as well as the change process of the inflection point, such as the position and load of the inflection point. These are all indispensable parts for studying the mechanical properties of concrete T-section beams. The figure below shows the midspan load-deflection curves of three types of T-section beams at two shear-span ratios of 2.3 and 3.3.

The data can be read from Figure 10: when λ is 2.3, the maximum deflection of the integral T-section beams is 60.9mm, and the corresponding maximum load at this time is 77.39t. The maximum deflection of the prefabricated concrete T-section beams of the single key-joint segment is 102.1 mm, and the corresponding maximum load at this time is 73.33t. The maximum deflection of the prefabricated and assembled concrete T-section beams of the double key-joints segment is 113.25mm, and the corresponding maximum load at this time is 70.96t. When λ is 3.3, the maximum deflection of the integral T-section beams is 80.8mm, and the corresponding maximum load is 69.19t. The maximum deflection of the single key-joint segment prefabricated concrete T-section beams is 111.03mm, and the corresponding maximum load at this time is 66.47t. The maximum deflection of the prefabricated and assembled concrete T-section beams of the double key-joints segment is 117.86mm, and the corresponding maximum load at this time is 64.17t.

In addition, the following rules can be summarized: when the shear-to-span ratio is the same, the slopes of the three beams are roughly straight in the early stage (the deflection is about 30mm), and the deflection-load correspondences of the three beams are basically the same at this time, and then differences begin to appear. In reality, the boundary line of characterization is that the concrete T-section beams have cracks. Before the cracking, the deflection-load curves of the three types of beams overlap, and only after the cracking do the beams show significantly different characteristics from other types of beams. When the shear-span ratio is the same, the integral T-section beams have the largest slope among the three beams, that is, the maximum flexural rigidity. The second is the prefabricated concrete T-section beams with single key-joint segments, and the last is the prefabricated concrete T-section beams with double key-joints segments. The maximum deflection of the three beams is in the mid-span. When the shear-span ratio is different, it can be seen from the loading results of the same type of beams that the deflection of the T-section beams when the shear-span ratio is 3.3 is relatively greater than that when the shear-span ratio is 2.3.

From the stress and deflection analysis of the three beams, it can be seen that the mechanical properties of the integral T-section beams are better than the other two segmental prefabricated concrete T-section beams under the two working conditions. The mechanical properties of the beams are relatively better than those of the prefabricated concrete T-section beams with double key-joints segments.

4. Conclusions

(1) The deflection of the joint sections B and C is unchanged along with the beam height from the top to the bottom, which is consistent with the assumption of a flat section.

(2) At the joint sections of B and C, the stress first decreases and then increases along the beam, indicating that the stress transfer of the integral T-section beams is better than that of the two types of segmental prefabricated beams. The stress transfer of precast concrete T-section beams with single key-joint segments is better than that of double key-joints prefabricated concrete T-section beams. When the shear-span ratio is 2.3, the stress transfer of the same type of segmental prefabricated concrete T-section beams is better than that when the shear-span ratio is 3.3.

(3) When the shear-span ratio is the same, the deflection of the integral T-section beams is the smallest among the three types of beams, that is, the bending stiffness of the integral T-section beams is the largest at this time. The second is prefabricated concrete T-section beams with single key-joint segments, and the last is prefabricated concrete T-section beams with double key-joints segments. The maximum deflection of all three types of beams is at midspan. When the shear-span ratio is different, the deflection of the T-section beams when the shear-span ratio is 3.3 is relatively greater than that when the shear-span ratio is 2.3.

5. Future Research

T-section beams are widely used in small and medium-span highway bridges, so the research on the mechanical properties of T-section beams is very important for the wider application of T-section beams, which also reflects the use of segmental prefabricated concrete T-section beams in the field of transportation.

Based on the current research results on segmental prefabricated T-shaped beams, there are still the following problems: (1) There are few studies on the spatial deformation and internal force distribution of segmental prefabricated beams under the combined action of bending, shearing, and torsion. It is necessary to explore the coupling mechanism of components under the combined action of bending, shearing, and torsion through experiments and finite element software analysis; (2) The numerical simulation efficiency of segmental prefabricated concrete T-section beams is low, and it is necessary to establish a method considering T-section beams efficient rod system analysis model for spatial effects, prestressed tendon slip, and joint discontinuity mechanical behavior in profiled beam structures. A simplified calculation method for the bearing capacity of segmental prefabricated beam structures is proposed.

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