Nonlinear Finite Element Analysis of Corrugated Steel Web Composite Beam Based on ABAQUS

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Abstract. Considering the nonlinearity of the material, this paper uses the finite element analysis software Abaqus to model and analyse the external prestressed concrete composite beam of corrugated steel web. In this paper, the key processing methods in the modeling process are described in detail. The whole process of loading and destroying the prestressed concrete composite beams of corrugated steel webs is simulated. The calculated load-deflection curve and load-stress increment curve are in good agreement with the author's early test results, which verifies the accuracy and reliability of the calculation analysis of external prestressed concrete composite beams of corrugated steel webs. Further analysis shows that in the calculation analysis, the secondary effect of the external prestressing tendon cannot be ignored. In addition, under the limit state, the calculated stress increment of the external prestressed tendons is smaller than the actual measurement, and the preliminary analysis may be related to the calculation of the tensile constitutive model of the concrete material. The in-depth study of the external reinforced stress increment and the transmission mechanism between the concrete and the corrugated steel web will be carried out in the following state.

1. Introduction

The corrugated steel web prestressed composite beam is a force structure composed of corrugated steel webs, concrete upper and lower flange plates, ordinary steel bars and prestressed steel bars. Due to its excellent mechanical properties, it has been widely concerned in bridge engineering. The literature [1] provides a comprehensive introduction to the research status of corrugated steel web prestressed composite beam structures. The current bridge design specifications of China have not covered this special structure. The design and construction of such structures in China are based on foreign standards, and the design calculations for such structures are mostly using the conventional bar systems. However, due to the particularity of this structure, its mechanical properties and working mechanism are more complicated. The concrete materials in the structure have many complicated mechanical behaviors such as cracking and crushing. Therefore, it is necessary to adopt solid nonlinear finite element analysis on the basis of theoretical and experimental research. As a large-scale general finite element analysis software, Abaqus contains a wealth of cell libraries and material libraries, which can simulate the mechanical behavior of various structures and materials, especially suitable for nonlinear analysis of structures. In this paper, a reasonable material constitutive relation is selected, and the damage plasticity model of concrete material is used. The modeling method of external prestressed concrete composite beam of corrugated steel web is introduced, and the material nonlinearity is considered. The Abaqus simulation and analysis of the stress and deformation characteristics of the prestressed composite beam of corrugated steel web from loading to failure are carried out.

2. Material constitutive relation and parameter determination

2.1. stress-strain constitutive relation of concrete

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The uniaxial compressive stress-strain relationship of ordinary concrete materials studied in this paper adopts the Saenz formula of the literature [2], ignoring the influence of the descending segment. That is defined as:

$$\begin{cases} \sigma = \dfrac{E_c \varepsilon}{1+\left(\dfrac{E_c}{E_c^{'}}-2\right)\dfrac{\varepsilon}{\varepsilon_0}+\left(\dfrac{\varepsilon}{\varepsilon_0}\right)^2} & 0<\varepsilon\le\varepsilon_0 \\ \sigma=\sigma_0 & \varepsilon_0<\varepsilon\le\varepsilon_u \end{cases} \tag{1}$$

Where E_c is the Initial modulus of elasticity and $E_c^{'}$ is the secant modulus of elasticity at the peak of stress, $E_c^{'}=\sigma_0/\varepsilon_0$, σ_0 and ε_0 represent the stress and strain when the stress reaches the peak. ε_0=0.002, ε_{cu} is the ultimate compressive strain of concrete, $\varepsilon_{cu}=0.003$.

The stress-strain relationship of the unidirectional tension of ordinary concrete materials studied in this paper is based on the formula [3]. That is defined as:

$$y=\begin{cases} 1.2x-0.2x^6 & x\le 1 \\ \dfrac{x}{\alpha_t(x-1)^{1.7}+x} & x>1 \end{cases} \tag{2}$$

$x=\varepsilon/\varepsilon_t$, $y=\sigma/f_t$. f_t and ε_t represent the concrete tensile strength and its corresponding peak strain.

The concrete damage plasticity model (CDP model) in Abaqus has good convergence for uniaxial loading and cyclic loading. Therefore, the CDP model is used to define the plastic behaviour of prestressed composite beams with corrugated steel webs under bending loads to analyse the nonlinear characteristics of the materials.

2.2. Stress-strain constitutive relation of steel

In the analysis and calculation of this paper, the ideal elastoplastic constitutive model is adopted for corrugated steel webs, upper and lower flange steel plates and ordinary steel bars. The measured yield strength f_y of the test beam corrugated steel web and ordinary steel in this paper are 330MPa and 315 MPa, respectively, Poisson's ratio takes =0.3,ultimate tensile strain takes =0.01（At this time, it is considered that the ordinary tension steel bar is broken and the beam body is broken.）.

The external prestressing tendons are based on the formula [4].

$$\varepsilon_p=\frac{\sigma_p}{E_p}+0.002\left(\frac{\sigma_p}{f_{0.2}}\right)^{13.5} \tag{3}$$

Where Ep is the external elastic modulus of external prestressing tendons, tensile yield stress takes $f_{0.2}$=0.85f_b=1581MPa, Poisson's ratio takes =0.3.

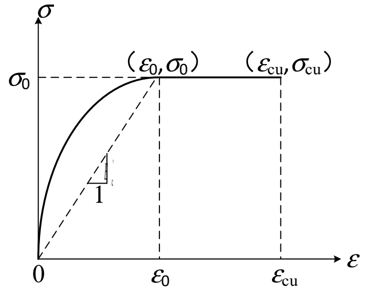

Figure 1. concrete stress-strain curve

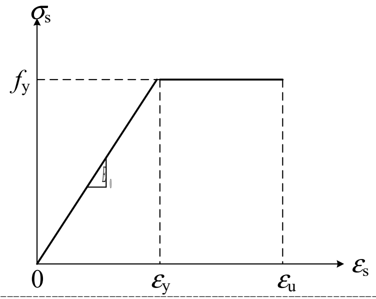

Figure 2. stress-strain curve of corrugated steel webs and ordinary steel bars

3. Modeling method based on Abaqus

The structure studied in this paper is a combined structure consisting of corrugated steel webs and their steel flange plates, concrete top and bottom plates, ordinary steel bars and external prestressing tendons. The key to modeling is the use of suitable material elements and contact connections between various types of units to ensure the common force behavior of the simulated structure. Based on this, this paper intends to adopt a subordinate plan[5-7].

(1) The displacement coordinated separation model is used to divide ordinary steel bars, external prestressing tendons, concrete, corrugated steel webs and steel flange plates into different units. The concrete adopts C3D8R eight-node linear hexahedral solid element, ordinary steel bars and external prestressing tendons. T3D2 two-node linear three-dimensional truss unit, corrugated steel web and steel flange plate adopt S4R four-node shell unit. Then separate combined modeling is performed.

(2) In order to avoid local stress concentration, a rectangular discrete piece is set at the position of the beam end fulcrum, the position of the external prestressing tendon anchor point, and the beam top loading position, respectively. It is bound to the concrete beam by Tie consolidation, and the load is applied to the reference point of the rigid sheet.

(3) For steel-mixed composite beam bridges, the correctness of the contact simulation between components made up of multiple materials is directly related to the stress of the structure. So, in contact with the concrete simulation, it must be ensured that the concrete and corrugated steel webs are flat and rotating. And the stress can be transmitted to resist the longitudinal shear stress between the two contact surfaces, preventing the relative slip between the concrete and the corrugated steel web. The upper and lower parts of corrugated steel webs and their steel flange plates are embedded in concrete, so embed method of embedding element technology in Abaqus will require some corrugated steel webs and shells embedded in concrete entity unit, and the change of concrete entity unit will control the degree of freedom of embedding element. In the same way, ordinary steel bars are also embedded in concrete in the Embed way to achieve deformation coordination.

(4) The external prestressing tendons are in the form of a straight double steering arrangement. In the modeling, the line segments between the two transverse partitions, the anchoring end and the transverse partition are respectively taken as one unit. There is no adhesion between the external prestressed tendons and the concrete, and both of them will have relative slip, there is no deformation coordination relationship between the external prestressing tendons and the surrounding concrete. Therefore, the external prestressing tendons and the anchoring blocks are connected by MPC. This constraint gives the truss unit and the anchor point block the same displacement and curvature, simulating the coordination of the external prestressing tendons and the concrete deformation at the anchor point. In order to ensure that the eccentricity of the external prestressing tendons is at the position of the diaphragm, the position is not changed by the force of the diaphragm. At the same time, in order to avoid stress concentration at the diaphragm, and to produce relative slip along the length of the beam. Establish a reference point near the point of contact between the diaphragm and the external prestressing tendon, and by means of coupling constraints, the degree of freedom along the length of the beam is released, simulating the contact state of the external tendon at the diaphragm.

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(5) The boundary conditions are in the three directions of X, Y and Z, and the other side constrains the X and Y directions to simulate the simple supported beam structure.

(6) The methods of prestressing in Abaqus generally include initial stress method, initial strain method, and cooling method. The cooling method is relatively simple and can simulate the prestress loss. Setting an initial temperature for the external prestressing tendon, and applying a pre-stress, a cooling value can be given to cause shrinkage deformation. Pre-energizing the concrete due to the coordinated displacement between the reinforcement unit and the end concrete unit nodes. The basic calculation principle of the cooling method is: The prestressing tendon elongation is $\Delta L = \Delta T \alpha L = PL / EA$, Thus the cooling value is $\Delta T = P / EA\alpha$, where α is the coefficient of linear expansion of steel, the value is 1.2×10-5/℃.

(7) Due to the prestressing effect, the beam has a certain initial deflection before the external load, so the model sets three analysis steps: ① the initial analysis step is to establish the boundary condition and contact relationship of the simply supported beam. And the constraint relationship between external tendons and concrete beams is the key point of modeling. ② Self-weight of beam and pre-stressing, the analysis step is used to calculate the initial effect under effective pre-stress and self-weight;③ The application of the external load, the analysis step is used to calculate the beam from the beginning of loading until the beam reaches the failure state

4. Nonlinear simulation of test beam based on Abaqus

4.1. Introduction of the test beam

The above finite element modeling method is used to analyse the test beam A in the literature [8] published by the author. The test beam is an I-shaped section with a calculated span of 3.0 m and a beam height of 0.4 m. There are 4 grade I steel bar with the diameter of 8, $A_s^{'} = 201\text{mm}^2$. The bottom plate is equipped with 3 grade I bars, A_s=566mm^2, the external reinforcement consists of 2 prestressing strands with the diameter of 15.2, A_p=138.61mm^2. Straight double steering arrangement, effective prestress is 645.9MPa. Three-point loading mode was adopted for loading. A3 steel was used for corrugated steel web and its upper and lower flange plates with a thickness of 4 mm. The test beams are made of C40 concrete, and the measured compressive strength is 34.7MPa. The general structure and dimensions of the test beam are shown in Figure 3 below. The Abaqus finite element model is shown in Figure 4.

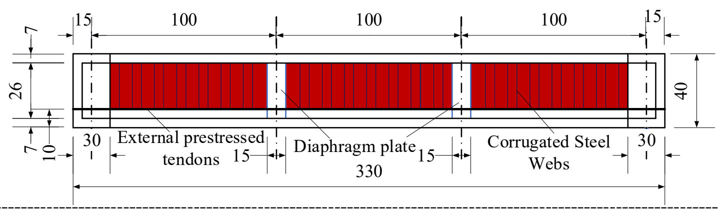

Figure 3. Test beam construction diagram

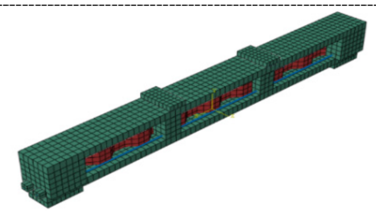

Figure 4. Test beam finite element model

4.2. Test contrast

As can be seen from figures 5 and 6, The calculation results of Abaqus are in good agreement with the experimental results and the results of the whole process analysis program in reference [8].The calculated and measured load-span deflection curves and load-stress increment curves show obvious trigonometric characteristics, which represent three stages respectively: elastic stage before cracking, elastic-plastic stage and plastic stage, and the curve has no obvious descending section.

(1) Elastic stage before cracking: At this stage, the load is linearly related to the deformation and the stress increment of external tendons, and the members are in elastic state, ①point in the figure 10 is the stress state corresponding to the cracking of the test beam.

(2) Elastic-plastic stage: At this stage, when the concrete floor is cracked, the tensile stress of the bottom plate increases rapidly and reaches the yield strength.

(3) Plastic stage: At this stage, when the tensile steel bar is yielded, the stress remains unchanged and the strain increases rapidly. The deflection of the structure and the stress increment of the external reinforcement increase rapidly with the increase of the load, and the cracks increase obviously compared with the second stage. When the tensile strain of the tensile steel reaches the failure state, the component reaches the maximum bearing capacity. ③point in the figure 10 means that he test beam reaches the ultimate load corresponding to the stress state (the calculated value is 183.1kN, and the measured value is 185kN).

(4) As shown in the following figure, The calculated values of the ultimate stress increment and mid-span deflection of the external prestressing tendons are larger than the measured values.

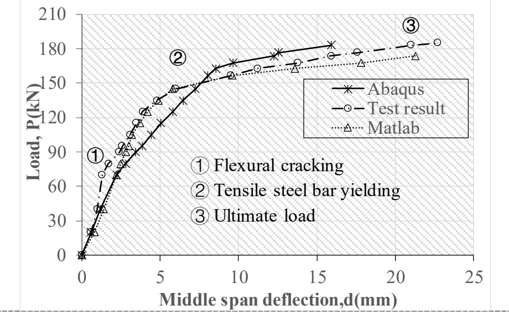

Figure 5. Load- deflection comparison curve of middle span

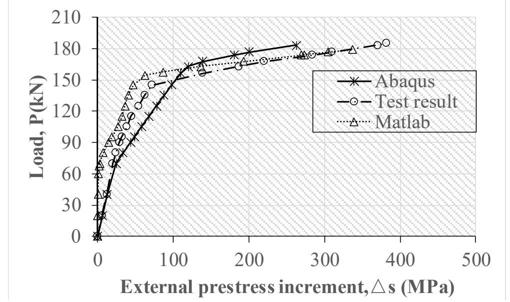

Figure 6. Load stress increment comparison curve

4.3. Further analysis

In order to simulate the secondary effect of external tendons and analyse of the effects of secondary effects of prestress, the full-length prestressing tendons are simplified into several line segments, and the end points of each line segment are coupled with the beam body (figure 7), Realizing the limitation of the displacement of the prestressed tendons relative to the beam in the finite element model. The simulated external cable can only slip along the length of the beam, and the position of the relative beam does not change during the stress process (figure 8 dotted line), and the external prestressing tendon is simulated to have no secondary effect. The strain of the ordinary tensile steel bar is 0.01 as the structural failure control point, and the secondary effect and the structural ultimate load without considering the secondary effect are compared and analyzed, and the prestress increment and deflection under the limit state are changed.

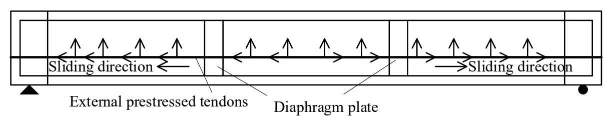

Figure 7. External prestressing tendons and beam position limitation diagram

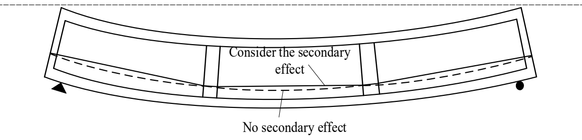

Figure 8. Comparison of the position of external prestressed tendons after deformation

The results show: The ultimate load of the test beam with simulated secondary effect is 183.1kN, the ultimate stress increment of external prestressed tendon is 262.5MPa, and the deflection change is 15.7mm; the ultimate load of the test beam without simulating the secondary effect is 189.3kN, the external prestress limit stress increment is 304MPa, and the deformation is 18.24mm. Regardless of the secondary effect, the calculated value of the ultimate load is increased by 3.4%, the ultimate stress increment of the external tendon is increased by 15.8%, and the deflection of the test beam is increased by 16.2%. The results are similar to those in the literature [9]. In the calculation and analysis, it is unreasonable to consider the secondary effect of the external prestressing tendons, and further verify the reliability of the calculation and analysis of the prestressed concrete composite beams of the corrugated steel webs by Abaqus.

5. Conclusion

In this paper, the process of establishing the finite element model of the external prestressed composite beam of corrugated steel web by Abaqus is introduced: The material constitutive relations of composite beams are used in software, and the selection of various types of material elements, The slip between external prestressing tendons and beams and the combined connection between various material components are simulated. The analysis conclusion is as follows:

(1) By comparing the results of Abaqus calculation with the results of the literature [8] and the results of the whole process analysis, we can see that: the calculated load-deflection curve and load-stress increment curve are in good agreement with the author's early test results, which verifies the accuracy and reliability of the calculation analysis of external prestressed concrete composite beams of corrugated steel webs.

(2) By comparing the results of Abaqus calculation with the results of the literature [9], it can be seen that it is unreasonable to consider the secondary effect of external prestressing tendons in the calculation analysis.

(3) In this paper, under the limit load, the calculated values of the ultimate stress increment and mid-span deflection of the external prestressed tendons are larger than the measured values. The preliminary analysis may be based on the damage plasticity model of the concrete in Abaqus. The concrete in the whole process is involved in the stress analysis, and the structural failure state is not accurately simulated. In the test, the crack develops rapidly due to the near-damage of the beam body, and the concrete of the bottom plate is effective. The external rib stress increases rapidly, and the mid-span deflection also increases rapidly, which leads to a large increment of the measured external rib stress.

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