BEARING CAPACITY OF T BEAM UNDER DIFFERENT PRESTRESS LEVELS: FULL-SCALE EXPERIMENT AND FEM ANALYSIS

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ABSTRACT

Insufficient prestress will cause cracks in the T beam, which will influence its stiffness and bearing capacity. This paper is devoted to studying the influence of prestress levels on the bearing capacity of the T beam and then judging its working state. A full-scale model experiment is carried out on the 13 meters prestressed concrete T beam. At the same time, a nonlinear finite element model is established and verified. The experimental results show the numerical simulation results are in good agreement with the experimental results. Finally, the finite element model is used to simulate the bearing capacity of T beams under different prestress levels. The mathematical relationship between prestress levels and bearing capacity is obtained based on the results of the finite element model. The relationships between the mid-span deflection and load of the experimental beam are the same under different prestress levels, including three stages: elastic stage, crack development stage, and failure stage. With the increase of the prestress levels, the stiffness of the experimental beam before cracking is improved significantly.

KEYWORDS

FEM, Prestressed concrete, T beams, Prestress levels, Full-scale experiment, Bearing capacity

INTRODUCTION

The prestressed concrete beam has the advantages of small structure height, convenient construction, reasonable force, good durability [1], and the micro-cracks generated after bearing load can be closed [2]. Therefore, it is a widely used structure type. However, a variety of reasons will cause the reduction of prestress, such as concrete shrinkage and creep, anchor end shrinkage, broken wire, etc. The removal of prestress will lead to the decrease of prestress level, which may have a harmful effect on its bearing capacity. Up to now, there has been no quantitative study on the relationship between the level of prestress and the bearing capacity of prestressed concrete beams.

Ardalan et al. [3] found that only when a certain prestress level is exerted on the beam can the micro-cracks be closed, thereby increasing its fatigue life. However, in practical engineering, due to insufficient tensioning of steel bars, delayed grouting, poor filling, and steel bar corrosion fatigue. There exists deviation between actual and designed prestress [4-5]. Liu et al. [6] found the actual prestress was only 40% to 50% of the theoretical design values in prestressed concrete bridges by detection, which had a significant impact on the compressive stress reserves of the lower edge concrete [7], such as the premature appearance of cracks [8]. On the one hand, the aesthetics of the bridge will be influenced because of the formation of cracks, on the other hand, it will cause a reduction of the cross-sectional stiffness of the bridge, and the typical feature is a more significant beam deflection [9-11]. At the same time, cracks caused by insufficient prestress have a significant impact on the working condition and bearing capacity of the bridge [12-13]. The

damage stiffness assessment method was established by Zhao et al. [14] based on the characteristics of flexural cracks. The results showed that after cracking of prestressed concrete, the section stiffness would have rapid attenuation, and the bearing capacity would be reduced obviously.

The prestress level has a significant impact on the bearing capacity of prestressed concrete beams, so it is necessary to study the prestress influence to judge the working state of the bridge accurately. Conducted static load tests were carried out by Jure et al. [15] on partially prestressed concrete beams and fully prestressed concrete beams under different prestress levels. It was found that by increasing the prestress level, the service state and bearing capacity of the beams could be improved. Through experimental comparison, Guo et al. [16] found the bearing capacity and section stiffness were greatly increased, and the crack width was significantly reduced after the prestressed reinforcement of reinforced concrete beams. In addition, the higher the prestress levels were, the better the reinforcement influences would be. An experimental research was carried out on the cracked unbonded prestressed concrete beams by Han et al. [17], the results showed that when prestress levels increased, the stress of the tensile reinforcement and the deflection of the control section reduced significantly, and the flexural rigidity of the cracked section increased obviously.

In recent years, various commercial finite element analysis software has provided better analytical methods for evaluating the bearing capacity of prestressed concrete complex structures [18]. The nonlinear finite element model was established by Hu et al. [19] using the finite element analysis software ABAQUS, the accuracy and reliability of the model were verified through the experimental results, and the model was also used to study the mechanical properties of prestressed concrete (PC) beams reinforced with CFRP. Simulation and analyses were made to the whole process of three externally prestressed supported beams from loading to failure by Qin et al. [20] with ABAQUS. The results showed the nonlinear finite element analysis software could simulate the beam better. Meng et al. [21] conducted experiments on the flexural performance of 14 prestressed steel-ultra-high-strength concrete composite beams, and made numerical simulation calculations with ANSYS software. The results showed the calculated values were in good agreement with the experimental values among the three elements of cracking load, yield load, and ultimate load of the experimental beams, which verified the correctness of the finite element model. Anil et al. [22] used ABAQUS to model the culvert with a three-dimensional shell element and solid element. They made a comparison between the load-deflection curve obtained by the finite element model and the experimental results. The two curves showed a high consistency, and the finite element model could predict the location of cracks accurately. Wu et al. [23] studied the impact of the prestress levels on the bearing capacity of bridges by using the theory of three-dimensional entity degradation virtual laminated unit. They found that different prestress levels had a significant impact on the bearing capacity of bridges. Mohammadali et al. [24] made a proposition of three-dimensional nonlinear finite element method by conducting four-point loading experiments on five beams with different prestress levels to make simulations of the nonlinear behaviors of the experimental beams, and the bearing capacity of the beams increased obviously with the increase of the prestress levels. Gao R. et al. [25] carried out loading experiments, and ANSYS software simulations on RC beams strengthened by external prestressing and concluded that the higher the prestress levels are, the greater the bearing capacity of the reinforced beams will be.

The relationship between the prestress levels, and the bearing capacity of T beams is seldom discussed in existing literature, and most of them are qualitative analyses; quantitative research is blank. Therefore, to study the relationship between different prestress levels and the bearing capacity of T beams, a full-scale T beam model with a length of 13 meters is made. At the same time, nonlinear finite element analysis software MIDAS/FEA [26] is used for numerical simulation. The accuracy of finite element analysis results is verified by comparing with experimental results. The load-deflection curve of T beams under different prestress levels is figured out by the finite element model. Then the mathematical expression of the relationship between prestress levels and bearing capacity is obtained by fitting.

Experiment description

Specimen Preparation

The experimental beam is a full-scale model of a prestressed concrete T-beam made under the guidance of China's "Code for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts" (JTG 3362-2018) [27]. The geometric dimensions and reinforcement layout of the experimental beam are shown in Figure 1, and the characteristics of steel bars and concrete materials used in the experimental beam are shown in Table 1 and 2.

The experimental beam is prestressed by the post-tensioning method, the design tensile stress is 500MPa, and the prestress level is [6].

The prestress level is defined as Equation (1).

$$\alpha = \frac{\sigma_1^{'}}{\sigma_1} \times 100\% \tag{1}$$

In Equation (1), the theoretical tensile control stress ($\sigma_1^{'}$) is 1395MPa, and the actual tensile stress is 500MPa.
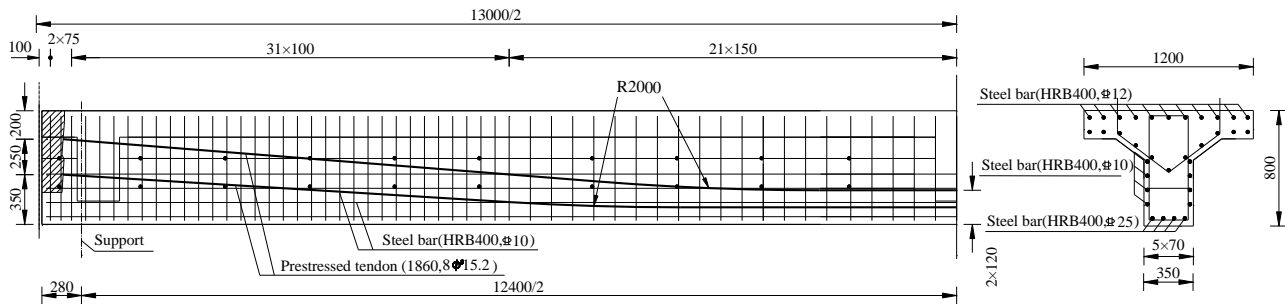

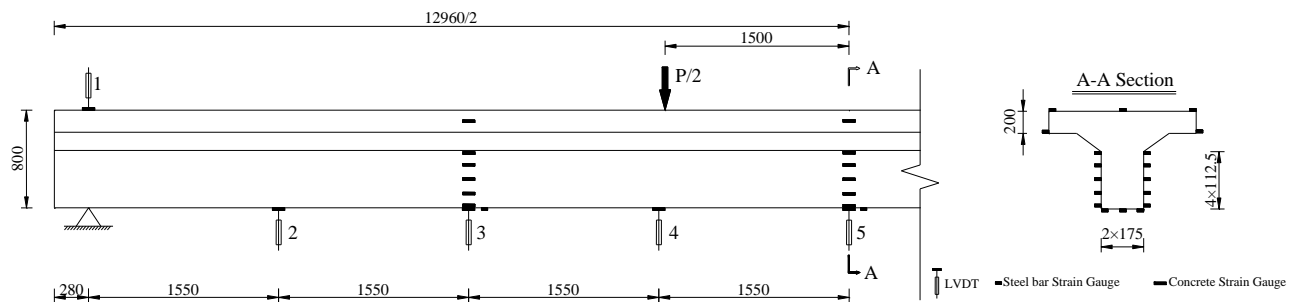*Fig. 1 - Geometric dimension and steel bar layout of the experimental beam (mm)*

Fig. 2 - Layout of loading position and measuring point of the experimental beam (mm)

Tab. 1: Material Properties of Steel Bar

Type	Steel bar			Prestressed Tendon
	Ø10	Ø12	Ø25	$\varnothing^s$15.2
f_y(MPa)	403.5	412.4	422.1	-
f_u(MPa)	572.2	570.3	568.6	1879.4
E_s(MPa)	2.0×10^5	2.0×10^5	2.0×10^5	1.95×10^5

Tab. 2: Material Properties of Concrete

Item	f_{cu}(MPa)	f_t(MPa)	E_c(MPa)	v
Value	52.3	3.21	3.47×10^4	0.2

Experimental procedure and measuring points

Two loading points are arranged 1.5 meters away from the middle span of the experimental beam, and the load is exerted step by step through jacks. During the loading processes, the deflection and strain of the experimental beam are paid close attention. The loading position and measurement point layout are shown in Figure 2.

Nonlinear finite element analysis

MIDAS/FEA nonlinear finite element software is used to build the experimental beam, and the bearing capacity of the experimental beam under different prestress levels is studied. The model details are consistent with the experimental beam described in the following section. The concrete is simulated by adopting hexahedral units. Different prestress levels are simulated by modifying the tensile stress at both ends of the prestressed tendon.
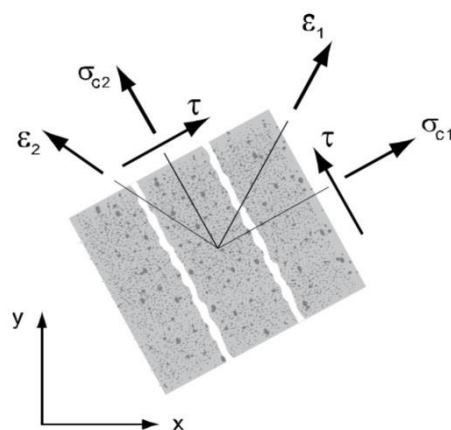
Concrete constitutive model

In the numerical analysis of prestressed concrete structures, the constitutive model of concrete has an important impact on the calculation results [28]. The total strain crack model in MIDAS/FEA is adopted in this paper [29]: After the concrete cracks, cracks develop along the cracking direction and will not change with the main tensile strain direction. Figure 3(a) is the schematic diagram of the model. The constitutive relationship of concrete under compression and tension are shown in Figure 3(b) and (c). The shear stress of concrete is constant. That is, the shear stress and shear strain have a multiple linear relationship with the concrete stiffness. According to the research results of Zuo et al. [30] on shearing failure components, this paper selects =0.5, which is shown in Equation (2):

$$\tau = (\beta G) \cdot \gamma = (0.5G) \cdot \gamma \tag{2}$$

Steel bar constitutive model

The implantable rod units simulate steel bars and prestressed tendons [28]. The steel bars have no degree of freedom and are completely bonded to the concrete elements without relative slippage. After the definition of the steel bar information, the program automatically calculates the intersection point between the concrete units and the steel bars, thus adding the stiffness of the steel bars to the stiffness of the concrete units, and calculating the strain of the steel bars from the deflection of the concrete units. The Von Mises model [31] is adopted for the constitutive model of the steel bars, and the constitutive relation is shown in Figure 4.

Figure 5 shows the finite element model of the experimental beam.

(a) Total Strain Crack Model
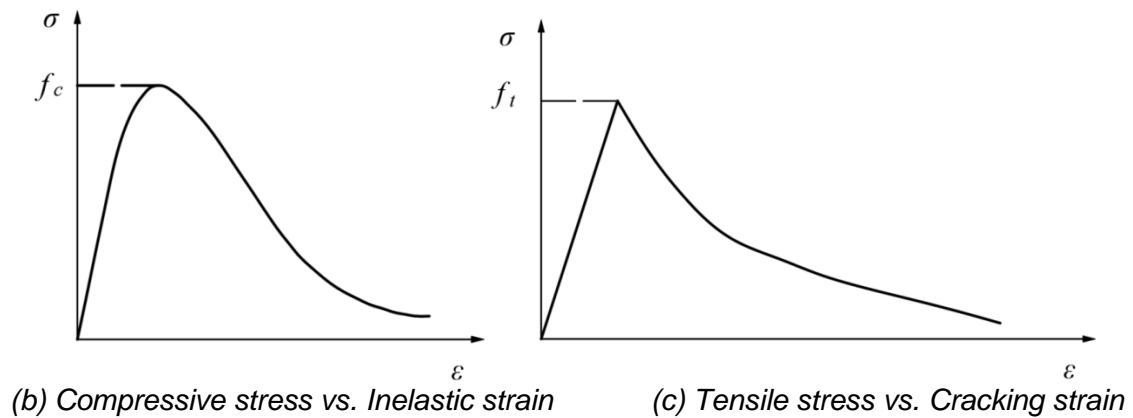
(b) Fig. 3 - Concrete constitutive model

(b) Compressive stress vs. Inelastic strain   *(c) Tensile stress vs. Cracking strain*

Fig. 3 - Concrete constitutive model

(a) Stress-strain curves for steel bars.   *(b) Von Mises yield surface in principal stress space*
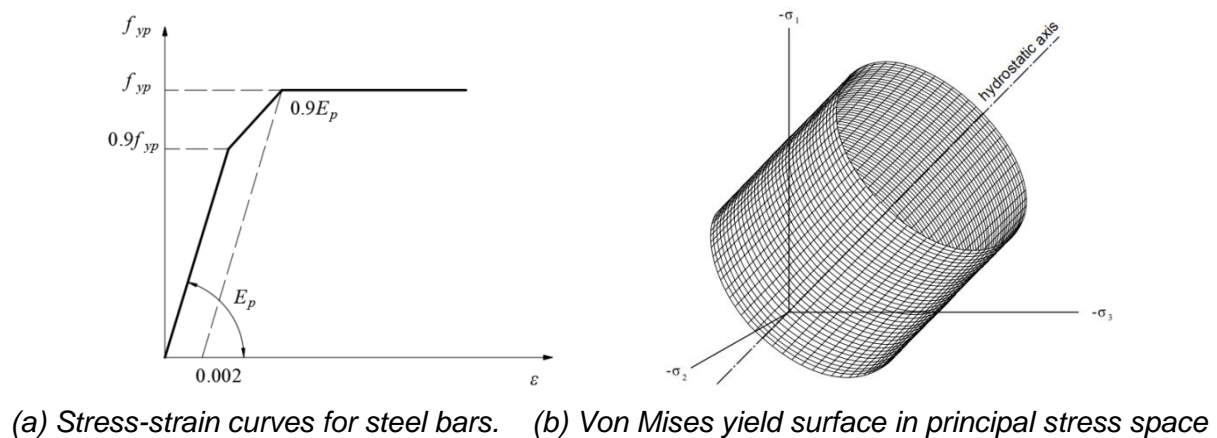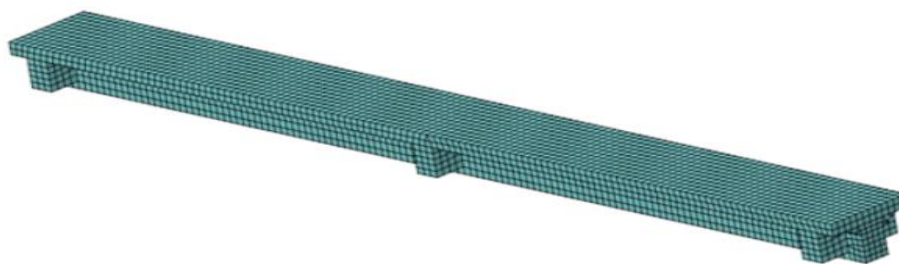
Fig. 4 - Steel bar constitutive model

Fig. 5 - Nonlinear finite element model

Results and discussion

Model validation

During the experiment, data such as the deflection of the experimental beam, and the strain of concrete and steel bars are collected. The accuracy of the finite element model is verified by comparing the deflection and strain data of the experimental beam and the finite element model under the same loading conditions [32]. Figure 6 shows the comparison between the measured deflection and strain data with the finite element calculation results during the loading process. The

measured strain data gradually become invalid due to exceeding the strain gauge range during the loading process.
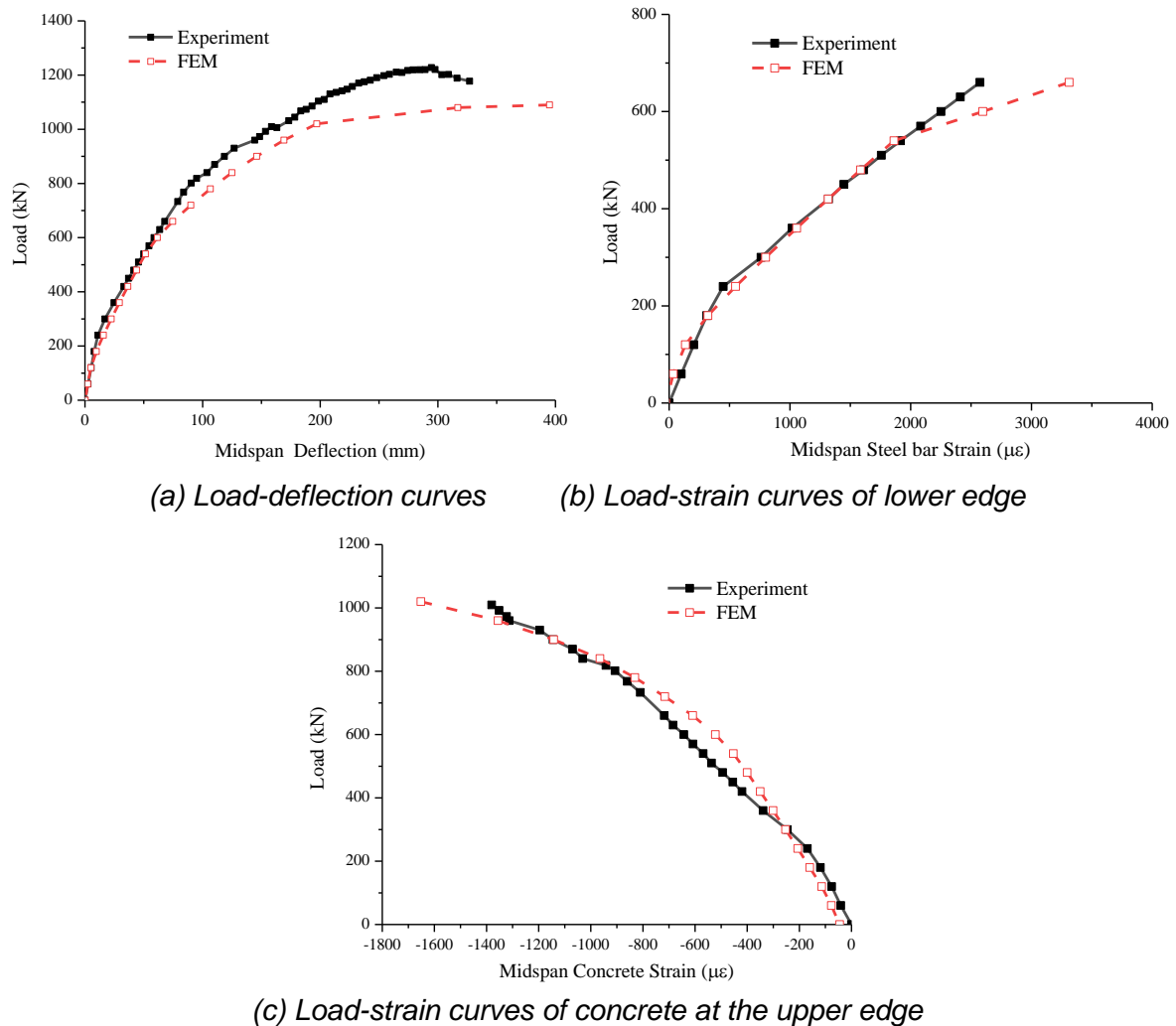

(a) Load-deflection curves

(b) Load-strain curves of lower edge

(c) Load-strain curves of concrete at the upper edge

Fig. 6 - Comparison of measured data and finite element results

It can be seen from Figure 6 the finite element calculation values of the deflection of the experimental beam, the tensile strain of the steel bar, and the compressive strain of the concrete at the upper edge are in good agreement with the experimental values. The measured ultimate loading of the experimental beam is 1227.8kN, and the ultimate loading is predicted to be 1088.8kN by the finite element model. The difference between the expected failure loading and the measured value is 11.32%. The error may be caused by simplifying the finite element model, the deviation between the actual deformation of concrete and steel bar materials, and the finite element constitutive model. Considering the unevenness of the concrete materials, the corresponding error is within the acceptable range. According to Li et al. [32], when the calculated finite element values are in good agreement with the measured values, the results of the finite element model can be extrapolated to make reasonable predictions.

Bearing capacity prediction

To study the relationship between the prestress levels and the bearing capacity of the experimental beam, the bearing capacity is calculated when the tensile stress of the prestressed tendon varies from 100 MPa to 1400 MPa. The corresponding prestresses levels changes from 7.2% to 100.4%. The details are shown in Table 3.

Tab. 3: Different prestress levels

Tensile stress(MPa)	100	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400
Prestress levels (%)	7.2	14.3	21.5	28.7	35.8	43.0	50.2	57.4	64.5	71.7	78.9	86.1	93.2	100.4

Load-deflection curves

The load-deflection curves of the experimental beam under various loadings can be obtained by solving the finite element model under different prestress levels, as shown in Figure 7.
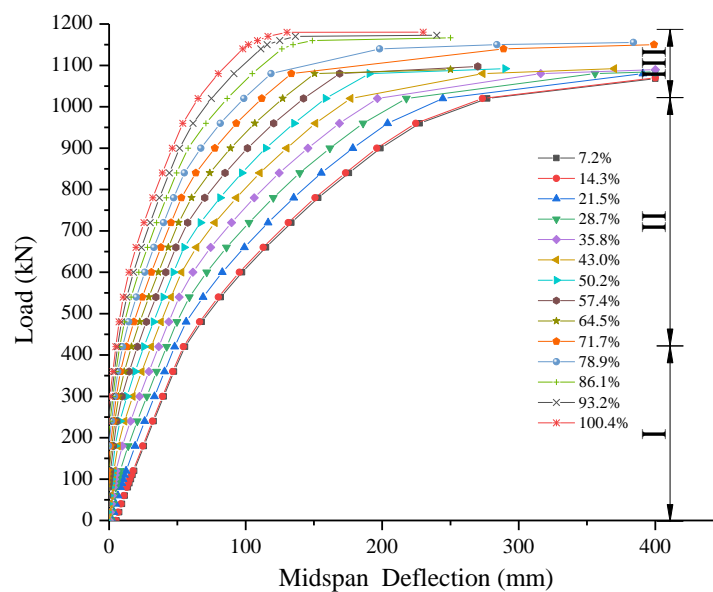

Fig. 7 - Load-deflection curves under different prestress levels

It can be seen from Figure 7 that the load-deflection curves change gently under different prestress levels. With the increase in loading, the deflection of the experimental beam can be divided into three distinct stages: Ⅰ is the elastic stage, in which the deflection of the experimental beam increases linearly with the increase of the loading, and the rigidity remains the same. With the increase of the prestress levels, the length of the elastic stage gradually increases; Ⅱ is the crack development stage, during which the deflection of the experimental beam increases nonlinearly with the loading increase. Since the concrete at the bottom of the experimental beam cannot continue to bear the tensile stress due to cracking, the slope of the curve gradually decreases at this time, which means, the stiffness of the experimental beam decays faster after cracking; Ⅲ is the destruction stage, in which the loading increases slowly, but the deflection increases rapidly. With the rise of prestress levels, the mid-span deflection of the beam decreases during the destruction.

The slope of the load-deflection curve represents the stiffness of the beam. Before the experimental beam cracks, the stiffness is linearly related to the prestress levels. After the appearance of the cracks, the curve slope changes at different prestress levels are the same. It can be seen the stiffness of the experimental beam before cracking is improved with the increase of prestress levels.

The relationship between prestress levels and bearing capacity

The curve displays:

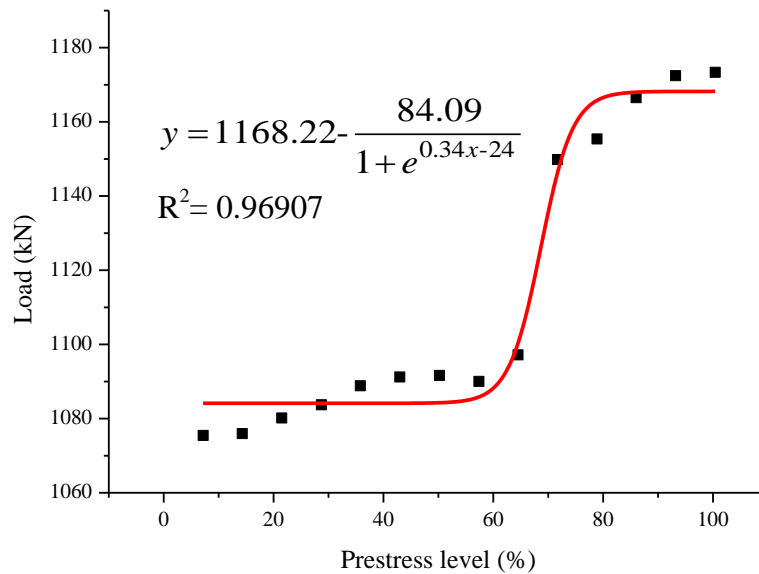$$y = 1168.22 - \frac{84.09}{1+e^{0.34x-24}}$$

$$R^2 = 0.96907$$

Fig. 8 - The curve of the relationship between prestress levels and bearing capacity

As seen in Figure 8, when the prestress level increases from 7.2% to 14.3%, the bearing capacity has barely increased. When the prestress level increases from 21.5% to 64.5%, the bearing capacity increases from 1069.4kN to 1097.18kN. When the prestress level increases to 71.7%, the bearing capacity increases to 1149.86kN significantly, with an 8% increase. After that, the bearing capacity increases linearly with the increase of prestress levels. This rule is consistent with the conclusion of Gao et al. [25], that is, when the prestress level is low, changing the tension control stress has little effect on the bearing capacity. Through data fitting, the mathematical relationship between prestress level and bearing capacity obtained is shown in Equation 3:

$$y = 1168.22 - \frac{84.09}{1+e^{0.34x-24}} \tag{3}$$

CONCLUSION

Based on the full-scale model experiment, the accuracy of the finite element model is verified, and the relationship between prestress levels and bearing capacity is discussed. The conclusions are as follows:

(1) The finite element model is in good agreement with the experimental beam. Based on the results of the finite element model, the mathematical relationship between prestress levels and bearing capacity is obtained.
(2) Under different prestress levels, the mid-span deflection curves of the experimental beams are alike, which can be divided into three stages: elastic stage, crack development stage, and destruction stage.
 (3) With the increase of the prestress levels, the stiffness of the experimental beam before cracking is significantly improved. After the cracking, the trend of the slope of the curves under different prestress levels is the same.

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