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Experimental study on performance of multi-scale fiber lightweight concrete

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Abstract

The box section is the most commonly used in the long-span concrete Bridges built at home and abroad. Compared with other section forms, the box section beams have the characteristics of large section torsional stiffness, good stability and excellent spatial bearing capacity. The numerical model of box beam was established in ABAQUS software for analysis, including the establishment of concrete unit, the establishment of reinforcement unit, the analysis step and parameter setting, grid division, etc., to obtain the load displacement diagram and the corresponding shear performance index under the simulation state. Through the finite element simulation analysis of box beam, the load displacement curve of box beam with different fiber content was analyzed.

Keywords

Nonlinear finite element; ABAQUS; Box beam; Shear resistance.

1. Introduction

The box section is often used as the section form of long span prestressed concrete bridge in the concrete Bridges built at home and abroad in recent decades. Because box beam has the advantages of giving full play to the mechanical properties of materials, and can obtain a larger section resistance moment with less materials, it reduces the amount of materials in the construction of bridge, reduces the structural weight, and has the advantages of superior overall spatial mechanical performance, many box beam members are used in long-span bridge structures. However, there are few researches on the shear properties of box beams, and even fewer on fiber concrete box beams.

Because of the characteristic of closed section, box beam has a good advantage in space bearing capacity. So far, domestic and foreign scholars and researchers have done research on the mechanical properties of box beams, but the current research mainly focuses on the bending, torsion, distortion and shear lag effect of box beams, and the corresponding literature on the study of the shear properties of box beams is less. Most of the existing design codes at home and abroad only equivalent the box section form to the I-section form for relevant calculation and analysis, but this method for the calculation of the shear capacity of the box beam and the applicability of the actual situation has a certain gap. In addition, it is quite difficult to carry out real structural tests on Bridges because of their large size. However, the conclusions obtained from the experimental study on the small scale components of the actual bridge in the laboratory are different from the guiding function and practical significance of the real structure.

In addition to experimental research, finite element analysis has been paid more and more attention by relevant researchers, and has become a major method for structural stress correlation analysis. This topic will be the fiber concrete box beam members based on the finite element modeling analysis, analysis of different fiber (steel fiber, polypropylene fiber), fiber content of two parameters on the influence of fiber concrete box beam shear performance, study its shear performance. The shear performance of fiber reinforced concrete box beams is studied by combining theoretical analysis and numerical simulation, which is of certain reference value for future experimental research and practical application.

2. Constitutive relation of fiber reinforced concrete

Fiber concrete is to improve the mechanical properties of concrete materials by adding fiber into the concrete matrix. The fiber can be generally divided into high elastic modulus fiber (such as steel fiber, carbon fiber) and low elastic modulus synthetic fiber (such as polypropylene fiber). High elastic modulus fiber can improve the strength of concrete, low elastic modulus synthetic fiber can enhance the toughness of concrete. According to the study of fiber concrete by relevant researchers, it can be shown that steel fiber coagulation takes into account the excellent characteristics of ordinary concrete and the addition of steel fiber significantly improves the tensile, flexural, impact resistance and durability of concrete. Polypropylene fiber can effectively limit the early cracking of concrete, so as to enhance the cracking resistance and durability of concrete.

2.1. Uniaxial compression constitutive relation

In this paper, Zhang Yuanyuan from Wuhan University is used to study and verify the stress-strain relationship of hybrid fiber concrete under axial compression according to the experimental study, and the dimensionless expression is adopted, that is, $x=\frac{\varepsilon}{\varepsilon_0}$, $y=\frac{\sigma}{\sigma_0}$ (σ is the peak stress of the curve is the compressive strength of the axial center, and ε_0 is the strain corresponding to the peak stress of the curve) :

Ascending stage: $y = x\alpha + (3-2\alpha)x^2 + (\alpha-2)x^3$, $0 \le x \le 1$

Descending stage: $y = \frac{x}{b(x-1)^2+x}$, $x > 1$

Parameters a and b of the ascending and descending sections can be obtained by fitting the curve of the test data. The calculation formula is as follows:

$$\alpha = 28.2283 - 23.2771 f_{fc}^{0.0374} + 0.4772\lambda_{sf} - 0.491\lambda_{pf}$$

$$b = 1 + 0.3688 f_{ft}^{-0.2846} + \lambda_{sf} + \lambda_{pf}$$

In formula:

λ_{fc}——Compressive strength of hybrid fiber concrete axis;

λ_{sf}——Characteristic value of steel fiber, $\lambda_{sf} = \frac{\rho_{sf} l_{sf}}{d_{sf}}$, icluding ρ_{sf} is the volume percentage of steel fiber, $\frac{l_{sf}}{d_{sf}}$ is the length-diameter ratio of steel fiber;

λ_{pf}——Characteristic value of polypropylene fiber, $\lambda_{pf} = \frac{\rho_{pf} l_{pf}}{d_{pf}}$, icluding ρ_{pf} is the volume percentage of polypropylene fiber, $\frac{l_{pf}}{d_{pf}}$ is the length-diameter ratio of polypropylene fiber;

In order to meet the set feature requirement of the slope of stress-strain curve decreasing onotonically without inflection point, $1.5 \le \alpha \le 3$, α=1.5 when $\alpha < 1.5$, α=3 when $\alpha > 3$.

2.2. Uniaxial tension constitutive relation

The tension stress-strain relation of fiber reinforced concrete adopts the constitutive relation proposed by Mei Guodong of Wuhan University:

Ascending stage: $y = \alpha_1 x + (1.5 - 1.25\alpha_1)x^2 + (0.25\alpha_1 - 0.5)x^6$, $x \le 1$

Descending stage: $y = \frac{x}{\alpha_t(x-1)^{1.7}+x}$, $x > 1$

The parameters α_1 and α_t of the ascending and descending sections were obtained by curve fitting of the test data. The calculation formula is as follows:

$$\alpha_1 = 1.2(1 + 0.265\lambda_{sf} + 0.277\lambda_{pf})$$

$$\alpha_t = \frac{0.312 f_{mt}^2}{1 + 3.366\lambda_{sf} + 3.858\lambda_{pf}}$$

In formula:

$x = \frac{\varepsilon}{\varepsilon_t}$, icluding ε_t is the tensile strain corresponding to the axial tensile strength;

$y = \frac{\sigma}{\sigma_t}$, icluding σ_t is the axial tensile strength;

f_{mt}^2——Peak tensile strength of matrix concrete axis.

For ordinary concrete, when α_1=1.2, α_t=0.312f_{mt}^2, the formula is consistent with the code for the design of concrete structures (GB50010-2002).

Table 1 Physical property of fiber

Fibre type	Aspect ratio	Type	Density (g/cm^3)	Tensile strength (Mpa)	Shape
Steel fibre	60	Carbon steel shear type	7.8	≥600	ripple type
Polypropylene Fiber	396	Modified polypropylene fine fiber	0.91	>400	filiform

In addition to the behavior of concrete matrix, fiber content, fiber dispersion and fiber geometry will affect the mechanical properties of fiber concrete. In this study, corrugated shear steel fiber (SFRC) and modified polypropylene fine fiber (PFRC) are selected. The physical properties of the fiber are shown in Table 1.

Table 2 Fiber hybrid way

Type	PF0	PF0.05	PF0.1
SF0	√		
SF0.5	√	√	
SF1.5	√		√

Note: SF stands for steel fiber, PF stands for polypropylene fiber. For example, SF0.5 means that the volume rate of steel fiber content in concrete is 0.5%, and PF0.05 means that the volume rate of polypropylene fiber content in concrete is 0.05%.

The composite concrete material formed by adding two or more kinds of fibers into the concrete matrix is called hybrid fiber concrete. Mixed fiber in concrete matrix can produce complementary and synergistic effects in many aspects, and has excellent ductility characteristics and crack control ability compared with ordinary concrete. This project intends to adopt the hybrid of steel fiber and polypropylene fiber, and the hybrid mode is shown in Table 2.

According to the selected constitutive relations and relevant data processing, then origin mapping software is used to draw the corresponding stress-strain curves of the five fiber reinforced concrete data processing results, as shown in Figure 1 and Figure 2.

Figure 1 is the compression constitutive model of fiber reinforced concrete. It can be seen from the figure that the rising section of the stress-strain curve of fiber reinforced concrete has the same trend (because the y value of the selected constitutive relation formula represents the ratio of the actual stress to the axial compressive strength, and its maximum value is 1, so the five curve vertices coincide). The compressive capacity of concrete matrix increases with the increase of fiber content in descending section.

Figure 2 is the tension constitutive model of fiber reinforced concrete. It can be seen from the figure that the rising section of the stress-strain curve of fiber reinforced concrete has the same trend (because the y value of the selected constitutive relation formula represents the ratio of the actual stress to the axial tensile strength, and its maximum value is 1, so the five curve vertices coincide). With the increase of fiber content in descending section, the tensile capacity of concrete matrix is increased, and the improvement effect is obvious.

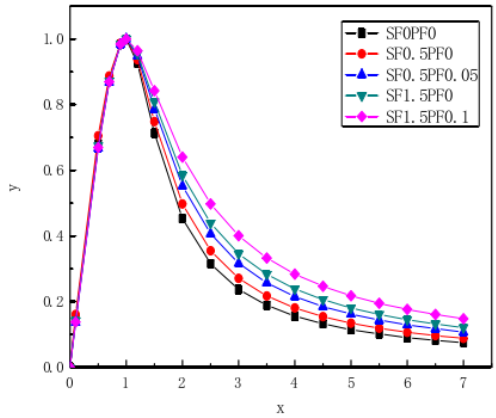


Fig.1 Compression constitutive model of fiber reinforced concrete

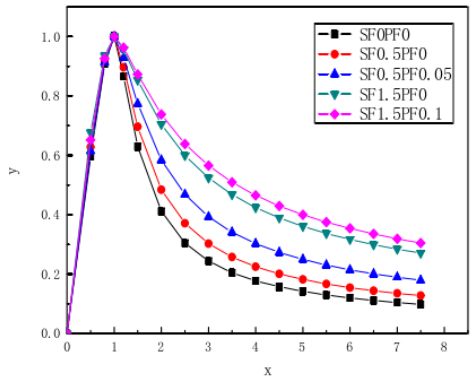


Fig.2 Tension constitutive model of fiber reinforced concrete

3. Comparison of experiment and finite element analysis

3.1. Test component design

In order to study the rationality of the finite element analysis of ABAQUS, the modeling analysis was carried out with reference to the experiment done by Zhang Taofang of Hunan University.

The length of the test beam is 4.3m, the calculated span is 4.4m, the section height is 0.5m, and the effective height is 0.46m. The section form is box type, the width of the box beam roof is 2200mm, the width of the bottom plate is 1200mm, the thickness of each side web is 80mm, the thickness of the top plate is 70mm, and the thickness of the bottom plate is 80mm. 16 HRB335 ribbed steel bars with a diameter of 16mm were selected for the longitudinal bars of the bottom plate, and HPB235 steel bars with a diameter of 6mm were selected for the longitudinal bars of the top plate and web plate.

The concrete strength grade of the test beam was C40, and the shear span ratio was 1.5. The reinforcement ratio of the test beam is shown in Table 3.

Table 3 The reinforcement of test beam

	Roof reinforcement ratio	Reinforcement ratio of bottom plate	Web longitudinal reinforcement ratio
Test beam	1.33	4.17	0.59

3.2. Model beam parameter

The concrete strength grade is C40, the density is 2500 kg/m^3, the elastic modulus is 3.25× 10^4MPa, the Poisson's ratio is 0.3, the concrete expansion Angle is 38*, the eccentricity is 0.1, and the viscosity parameter is 0.00001. The mass density of the bar is 7800kg/m^3 and Poisson's ratio is 0.3. The mechanical properties of reinforcement selected for the test beam are shown in Table 4.

Table 4 Mechanical property of steel

Diameter(mm)	Yield strength(MPa)	Ultimate strength(MPa)	Modulus of elasticity(MPa)
10	365	530	200000
16	350	515	200000
6	260	305	210000

Fig.3 Mesh size of box beam

Figure 4 shows the grid division and boundary conditions of ABAQUS model beams.

3.3. Comparison between test results and finite element simulation results

3.3.1. Failure form of test beam

The loading mode of the test beam is monotone loading, and the failure mode is as follows: when the load is loaded to 270k N, the first oblique crack is generated in the span reduction zone on the web side of one end of the test beam. When the load is applied to 310 kN, oblique cracks are generated on the other side of the web and the web span reduction zone at the other end of the test beam. With the continuous application of load, the inclined cracks and vertical cracks on the test beam gradually increase and become longer, and the cracks are generally parallel. When the load was applied to 1280 kN, the maximum width of the inclined crack on the beam body reached 1mm. Then, with the continuous loading of the load, the crack width increased rapidly. When the load was loaded to 1340 kN, the crack width of the fastest development reached 7mm, and the concrete at the upper part of the inclined crack was crushed.

3.3.2. Fem plastic strain nephogram and result analysis

The finite element software ABAQUS was used for calculation and convergence, and the finite element shape strain nephogram was obtained, as shown in Figure 4. It is used to analyze the accumulation of plastic strain in the whole deformation process.

It can be seen from the plastic strain nephogram that the main plastic deformation of the model beam is concentrated in the span reduction area of the beam, which is similar to the crack development state of the test beam. Therefore, it is of reference value to use ABAQUS software to simulate the box beam.

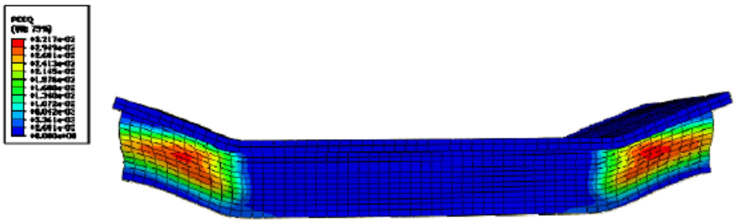


Fig.4 Shaping strain cloud chart

3.3.3. Load-deflection curve

The load-mid-span deflection curve of the model beam was obtained through the simulation calculation of ABAQUS finite element software, and was compared with the load-mid-span deflection curve of the test beam drawn by the test data, as shown in Figure 5. The comparison of the data of the ultimate bearing points of the model beam and the test beam is shown in Table 5.

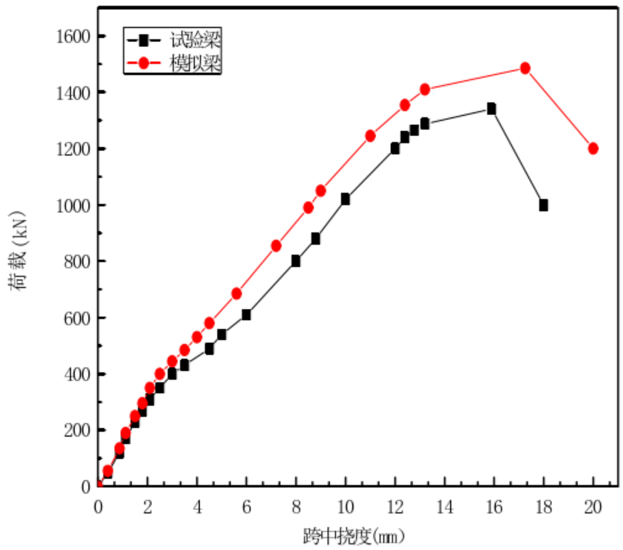


Fig.5 Deflection curve of test beam and model beam

Table 5 Data comparison between model beam and test beam

	Simulated load value $P_{u,cal}$(kN)	Simulated deflection value(mm)	Experimental load value $P_{u,exp}$(kN)	Experimental deflection value(mm)	$\frac{P_{u,exp}}{P_{u,cal}}$
Ultimate bearing point	1485.24	17.25	1340	15.9	0.902

As shown in Figure 5 and Table 5, the ultimate bearing point load of the test beam and the finite element simulation results of the simulated beam are 1340k N and 1485.24k N, respectively, with a ratio of 0.902. The mid-span deflection of the test beam and that of the simulated beam are 15.9 and 17.25, respectively, with a ratio of 0.927. It can be seen from the above results that the bearing capacity of the beam in finite element simulation is higher than the test value, and the mid-span deflection corresponding to its ultimate bearing capacity is also higher than the simulated value. It can be seen from the load-deflection curve that both the test results and the simulation results present a two-stage curve, with three rising sections and one falling section. In the ascending stage, the slope of the load -- deflection curve of the finite element simulation is higher than that of the load -- deflection curve based on the test data. In the descending section, the slope of the deflection curve of the load simulated by the finite element method should be close to that of the deflection curve of the load derived from the test data, but the absolute value of the slope of the simulated beam is small. The ultimate bearing capacity and mid-span deflection of the simulated beam are greater than those of the test beam.

By analyzing the appeal phenomenon, the finite element simulation result of beam deflection is smaller than the test result when the same bearing capacity, but the finite element simulation result of beam bearing capacity is higher than the test result when the same deflection value. This is because in the finite element simulation, the stiffness value of the structure is too large, and the stiffness degradation of concrete in practice is not taken into account when the model is established. Moreover, the finite element simulation process cannot simulate the sliding bond effect of steel reinforcement in concrete, as well as the cracking and development of fine cracks inside concrete in practice. Therefore, the stiffness and bearing capacity of the simulated beam are better than that of the actual test, so that the mid-span deflection value of the member when it reaches the ultimate bearing capacity is greater than the experimental value.

However, the simulation results are in good agreement with the experimental results.

4. ABAQUS finite element model design

Based on the simulation verification of the shear test of box beam members in the above section, it can be proved that the application of ABAQUS finite element software is suitable for the research and analysis of this topic, in order to further study the influence of fiber and fiber content on the shear performance of box beam members. The variable parameters of the model beam are analyzed and studied by using ABAQUS software. In this paper, five model beams are designed to study the effect of fiber incorporation on the shear performance of box beams without stirrup.

For the reinforcement of the model beam, adequate longitudinal reinforcement is provided to ensure the expected shear failure of the beam body. The longitudinal reinforcement of the bottom plate is HRB335 ribbed reinforcement with a diameter of 16mm, and the longitudinal reinforcement of the top plate and web adopts HRB235 reinforcement with a diameter of 8mm. The transverse bar of the roof adopts HPB235 bar with diameter of 8mm. The mass density of the bar is 7800 kg/m^3 and Poisson's ratio is 0.3. The mechanical properties of the reinforcement are shown in Table 6.

Table 6 Mechanical property of steel

Diameter(mm)	Yield strength(MPa)	Ultimate strength(MPa)	Modulus of elasticity(MPa)
16	350	515	200000
8	300	305	210000

The structural diagram of the model beam is shown in Figure 7. The cross section shape of the model beam is box type, the length of the model beam is 2.3m, the calculated span is 2.0m, the section height is 0.25m, and the effective height is 0.23m. In the figure, a is the length of the span reduction area, and the corresponding shear span ratio of the length of the span reduction area is 1.63. The thickness of each side web of the box beam is 40mm, the thickness of the top plate is 35mm and the thickness of the bottom plate is 40mm. The section reinforcement diagram of the model beam is shown in Figure 6.

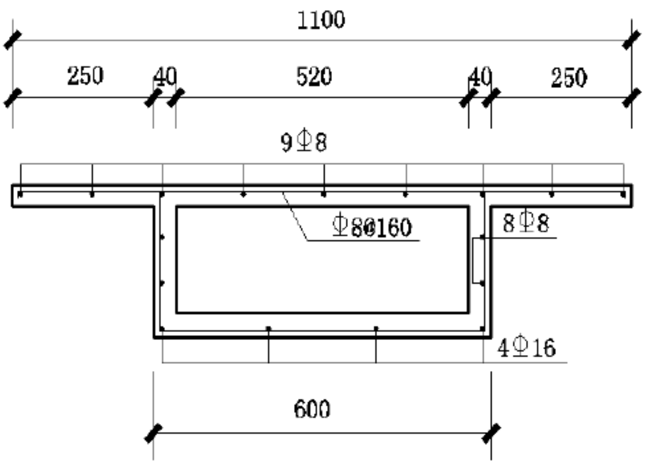


Fig.6 Reinforcement of 1-1 section

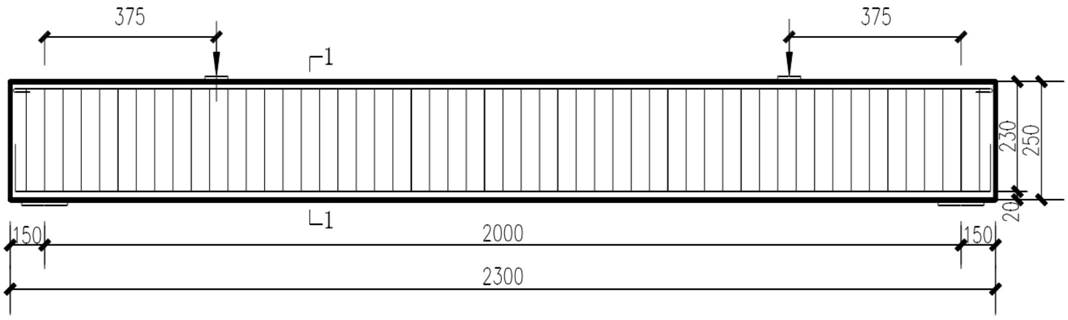


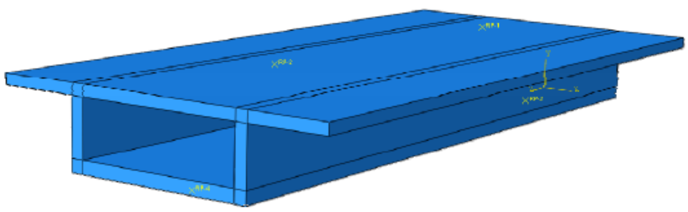
Fig.7 Geometry of beam

In this paper, the influence of fiber type and fiber content on the mechanical mechanism, failure form and shear capacity of box beam members is studied. The main parameters of components are shown in Table 7.

Table 7 Parameter of construction member

Build number	Shear span ratio λ	Stirrup ratio ρ_{sv}/%	Steel fiber content /%	Polypropylene fiber content /%
				0
B1	1.63	0	0	0
B2	1.63	0	0.5	0.05
B3	1.63	0	0.5	0
B4	1.63	0	1.5	0.1
B5	1.63	0	1.5	

Model beams were modeled, and the finite element models of concrete and reinforced skeleton were shown in Figure 8.



Concrete model

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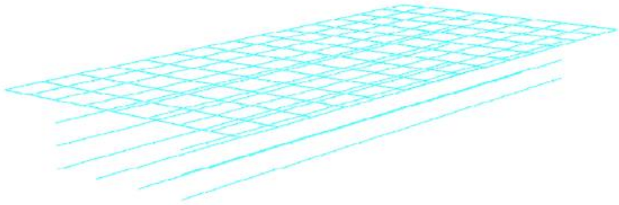

reinforced skeleton model

Fig.8 The finite element mode

5. ABAQUS finite element model design

The research shows that the incorporation of fiber has a significant impact on the compressive strength and tensile strength of concrete. In this paper, two kinds of fiber (steel fiber and polypropylene fiber) are selected to study the influence of fiber on the shear performance of box beam under the shear span ratio (1.63). Table 8 shows the ultimate bearing capacity of model beams B1 to B5 without stirrup and the mid-span deflection corresponding to the ultimate bearing capacity (ultimate displacement).

Table 8 Ultimate shear load,ultimate displacement and failure mode

Box beam type	Ultimate bearing capacity /KN	Ultimate displacement /mm	Failure mode
B1	56.64	2.25	Shear
B2	75.65	3.56	Shear
B3	85.13	4.65	Shear
B4	88.13	4.05	Shear
B5	95.2	5.03	Shear

Table 8 shows the ultimate bearing capacity of model beams B1 to B5 without stirrup and the mid-span deflection corresponding to the ultimate bearing capacity. The shear span ratio of this series of model beams is 1.63. Figure 9 shows the load-mid-span deflection curve of concrete box beams without stirrup under five different fiber contents.

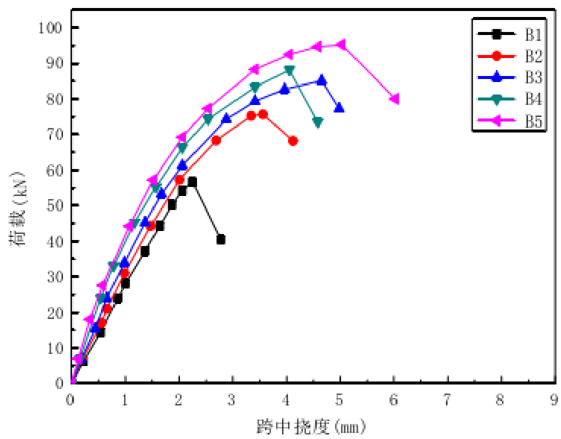

Fig.9 Loading-deflection curve

As can be seen from Figure 9 and Table 8, the ultimate bearing capacity (56.64k N) of model beam B1 is relatively low, and the failure mode is shear failure. The ultimate bearing capacity of model beams B2 and B4 is 33.6% and 55.6% higher than that of model beams B1, respectively. This indicates that adding steel fiber into the concrete matrix can enhance the ductility of the model beam and increase the ultimate bearing capacity of the model beam, and the improvement effect of the ultimate bearing capacity of the model beam is better with the increase of the steel fiber content. Compared with model beam B1, the ultimate bearing capacity of model beam B3 and B5 increases by 50.3% and 68.1%, respectively, and the ultimate displacement increases by 106.7% and 123.6%, respectively. Compared with model beam B2, the ultimate bearing capacity of model beam B3 increases by 12.5%, while the ultimate displacement increases by 30.6%. Compared with model beam B4, the ultimate bearing capacity of model beam B5 increases by 8.0%, while the ultimate displacement increases by 24.2%. This indicates that the concrete matrix mixed with steel fiber and polypropylene fiber can increase the ductility of model beam more obviously, which improves the ultimate displacement and ultimate bearing capacity of model beam, and the effect is better than that of single doped steel fiber.

6. Conclusion

In this paper, the finite element simulation of the test box beam is carried out based on the domestic test of the shear property of the box beam, and the simulation results are in good agreement with the actual experimental values. Five model beams were simulated based on ABAQUS finite element software, and the failure forms, stress distribution and crack development of the components were simulated, and the variable parameters of the fiber concrete box beams were analyzed. By changing the total fiber class and fiber content, the shear properties of fiber concrete box beam members are analyzed, and the following conclusions are drawn:

The ultimate bearing capacity and ultimate displacement of box beams without stirrup can be obviously improved by adding fiber. When the fiber content is 1.5% steel fiber and 0.1% polypropylene fiber, the shear bearing capacity of the beam is greatly improved.

In this paper, the study on the shear behavior of fiber reinforced concrete box beams is limited to finite element simulation. The parameters analyzed are only fiber type and fiber content. Some conclusions obtained in the simulation are limited to ABAQUS finite element simulation. Therefore, relevant experimental research and analysis can be further conducted, and relevant parameters can be further studied, such as the influence of concrete grade, prestress and section size on the shear performance of box beams.

Acknowledgments

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