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Comparative Study on Stability Theory of Steel-concrete Composite Beams in Negative Moment Region Based on ABAQUS

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Abstract: Steel-concrete composite beams are environmentally-friendly and cost-effective. The existing specifications have no calculation method for the stability of steel-concrete composite beams in the negative bending area, and the computational results of different theories put forward by scholars are quite different. In this paper, the finite element method is used to compare the three theoretical methods of the critical load in the negative bending moment zone when the length, thickness ratio and the reinforcement ratio of the concrete plate are changed. The analysis shows that the bending energy method is inaccurate and insecure, and the beam on elastic foundation method is more concise and simpler than the bending torsion energy method.

1. Introduction

Steel-concrete composite beams are widely used in industrial, civil buildings and bridge structures due to their good mechanical performance, convenient in construction and strong spanning ability^{[1],[2],[3]}. The upper flange of composite steel beam is restrained by the concrete floor. No matter what the force is, the concrete slab will provide reliable support for it, and it will not lose its stability. However, near the support, the steel beam is subjected to negative bending moment, and the lower flange may be unstable. When the structural load distribution makes a certain span under negative bending moment, the instability is more dangerous in some large span structures than strength and local stability. The standard does not provide the calculation method for the stability of the lower flange of the steel concrete composite beam, and it is not convenient for the designers to set the lateral support in the compression zone^{[4],[5],[6]}, also lateral support affects the appearance and the height of structure.

At present, the results calculated by various theoretical methods are quite different. How to choose a calculation method that satisfies the accuracy and is relatively simple to assist design has become an urgent problem at present. For this purpose, this paper conducts finite element comparative analysis of the currently accepted methods of bending energy method, bending and twisting energy method, and beam on elastic foundation method.

2. Three theoretical methods

2.1. Bending energy method

The calculation diagram is shown as in figure 1:



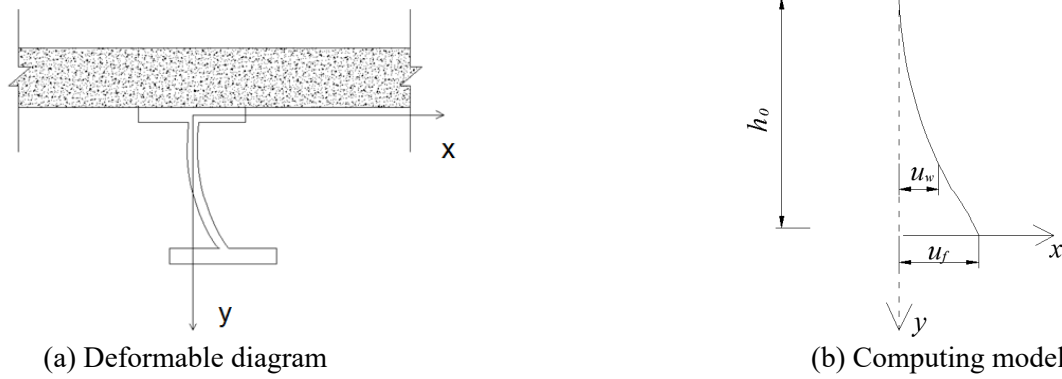


Figure 1. Deformable diagram of bending energy method

Assuming that the lateral displacement of the web is a cubic polynomial curve with respect to y ^[7], the lateral displacement of the bottom flange indicates that the lateral displacement of any point of the web is:

$$u_w = f(y)u_f(z)$$

Assume: $f(y) = ay^3 + by^2 + cy + d$

According to the principle of potential energy stationed, we can get the result by solving differential equations:

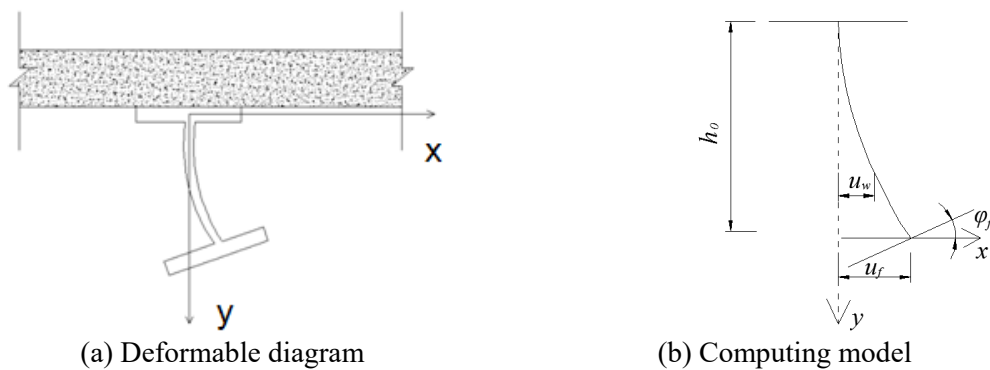
$$M_x = \frac{E\eta_1 I_{yb} \left(\frac{n\pi}{l}\right)^2 + \frac{Et^3}{(1-\mu^2)h_0^3} \left(\frac{l}{n\pi}\right)^2 + \frac{Et^3}{5(1-\mu^2)h_0}}{\beta_1} \quad (1)$$

$$\text{Among the equation (1), } \beta_1 = \frac{35y_c A_f + 13y_c h_0 t - 3h_0^2 t}{35I}, \quad n^4 = \frac{t^3 l^4}{\pi^4 (1-\mu^2) \eta_1 I_{yb} h_0^3}, \quad \eta_1 = 1 + \frac{13t^3 h_0}{420(1-\mu^2) I_{yb}}$$

The characteristic of this method is that the concrete plate is considered to be completely rigid, and the lateral bending deformation of the web is considered, but the torsion of the lower flange and the moment distribution on the lateral instability is not considered.

2.2. Bending and twisting energy method

The calculation diagram is shown as in figure 2:



(a) Deformable diagram

(b) Computing model

Figure 2. Deformable diagram of bending and twisting energy method

This method is similar as the bending energy method, the difference is that the bending and twisting energy method considers the twisting of the lower flange. The lateral displacement of any point on the web is^[8]:

$$u_w = f_1(y)u_f(z) + f_2(y)\phi_f(z) \quad (2)$$

The first variation of total potential energy is 0, we can obtain the critical moment:

$$M_x = EI_{yb} \left(\frac{n\pi}{l} \right)^2 \left[\beta - \sqrt{\beta^2 - \frac{\left(\frac{l}{n\pi} \right)^2}{(\beta_1\beta_3 - \beta_2^2)} \left[\frac{R_1 R_3 GJ_b}{n\pi I_{yb}} - \left(\frac{R_2 I_w l}{n\pi I_{yb}} \right)^2 \right]} \right] \quad (3)$$

Among the equation (2), $\beta = \frac{\beta_3 R}{2(\beta_1\beta_3 - \beta_2^2)} + \left[\frac{\beta_1 R_3 GJ_b}{2(\beta_1\beta_3 - \beta_2^2)EI_{yb}} - \frac{\beta_2 R_2 I_w}{(\beta_1\beta_3 - \beta_2^2)I_{yb}} \right] \left(\frac{l}{n\pi} \right)^2$

This method considers the torsional deformation of the lower flange of steel girder, but does not consider the effect of bending moment distribution on the lateral instability and the deformation of the concrete slab.

2.3. Beam on elastic foundation method

This method equates the lateral stability of the compressed flange to the stability of the compressive bar on the elastic foundation. The calculation diagram is shown in figure 3:

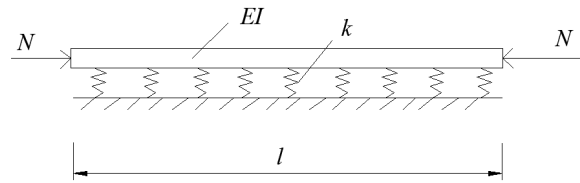


Figure 3. The calculation diagram of beam on elastic foundation method

The literature^[9] considers changes in the axial force along the length of the beam and the constraining contribution of the concrete slab, and proposes that the critical value of compressive failure for elastic foundation is:

$$N_{cr} = \frac{\pi^2 EI}{l_e^2} \quad (4)$$

l_e is the equivalent rod length:

$$l_e = 2.22 \left(\frac{EI}{c} \right)^{0.25} \quad (5)$$

This method considers the constrained contribution of the concrete slab, however, the l_e is actually related to the beam section parameters, and has no relation to the length of the negative moment zone.

3. Finite element simulation analysis

3.1. The establishment of the finite element model

The constitutive relation of concrete in this paper is derived from the experiment of material properties, the strength of concrete is C30. Three section relationship is adopted in the constitutive relation of steel, as shown in the figure 4. The selection of the parameters is in table 1:

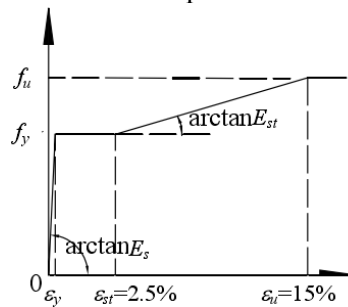
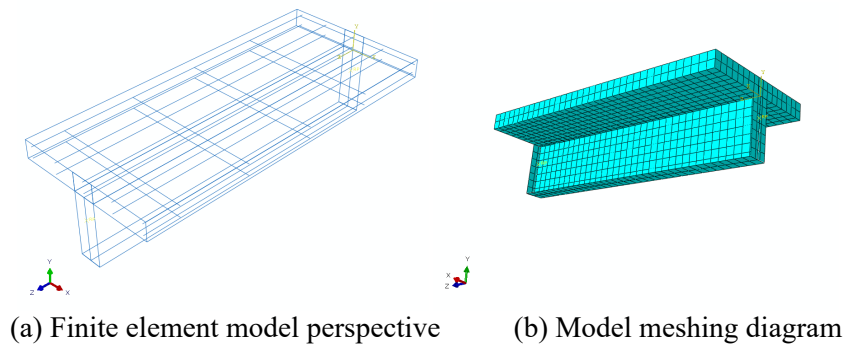
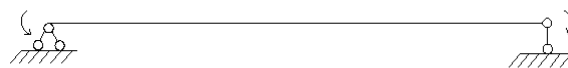


Figure 4. Steel constitutive relation diagram

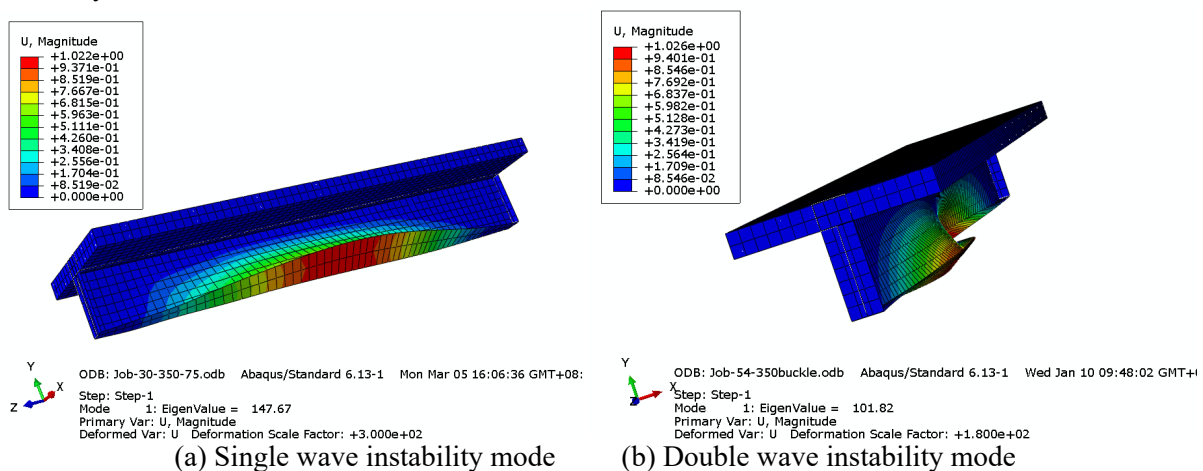
Table 1. Selection table for parameters of concrete material

Density kg/m ³	Elastic modulus	Poisson ratio	Dilation angle	Eccentricity	Biaxial compressive strength/ uniaxial compressive strength	Invariable stress ratio	Viscosity parameter
2500	0.2	0.2	30	0.1	1.16	0.6667	0.0005

The model applies the negative bending moment at the ends of simply supported steel beams at both ends. The tie type contact method is adopted between the concrete slab and the steel beam. The steel bar is embedded into the whole model. In order to facilitate the application of bending moments, assembling a rigid plate at the end of the beam to stiffening of the beam end cross section. First perform eigenvalue buckling analysis on the model, and taking 1% of the first order mode as an initial defect. The nonlinear finite element analysis of steel girders is carried out by arc length method. Model perspective and mesh diagram are shown in the figure 5, the calculation diagram is shown in the figure 6.

**Figure 5.** Finite element model**Figure 6.** Simple diagram of structure calculation

The eigenvalue instability analysis modality as the initial defect is shown in the figure 7, when the negative bending moment length changes from 1800mm~5400mm range, there are two kinds of instability modes of steel beam eigenvalue instability, single wave instability and double wave instability.

**Figure 7.** First order mode of eigenvalue buckling

The non-linear buckling analysis of steel beams using the arc-length method is shown in the figure 8 for the instability stress cloud.

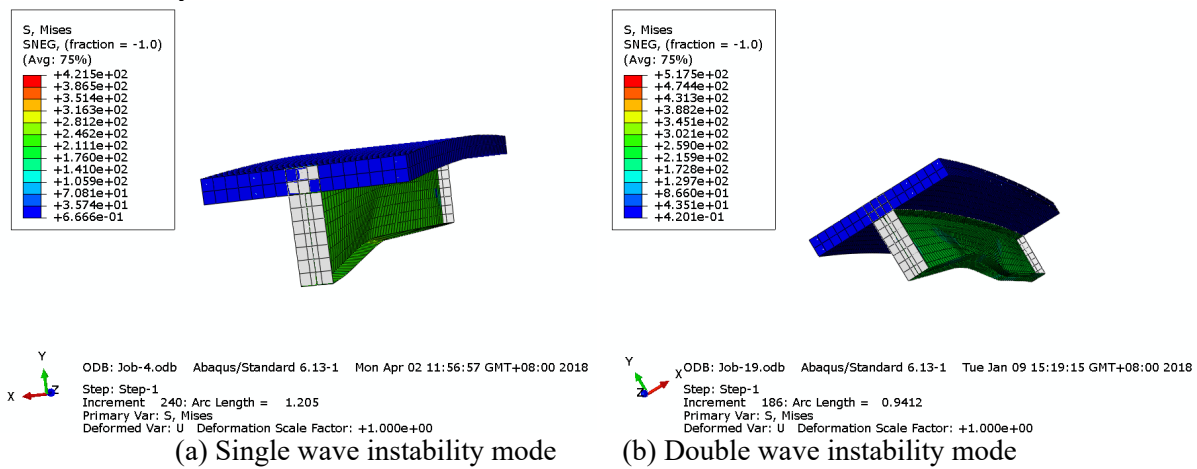


Figure 8. Analysis of stress cloud chart of lower flange of steel beam by arc length method

3.2. Comparative analysis of theoretical values and simulated values of various factors

3.2.1 The influence of the length bearing negative moment

In order to make the analysis more universal and eliminate the influence of section size on calculation results. In the analysis, the slenderness ratio is used as the variable of span variation for data organization. The three theories are calculated and sorted out with the change of span. The calculated results of theoretical and simulated critical moments are as in table 2:

Table 2. Theoretical and simulated critical moment of 350×125×6×8 cross section

Span	Slenderness ratio	Simulation value	Bending energy method	Bending and torsional energy method	Beam on elastic foundation method
1800	70.51	254.4	312.3	255.7	232.8
2400	90.01	287.9	350.5	214.7	232.8
3000	117.51	247.1	359.6	198.5	232.8
3600	141.01	319.5	363.9	300.8	232.8
4200	164.51	225.1	294.2	250.0	232.8
4800	188.01	278.7	350.5	235.0	232.8

Collate into a drawing line as in figure 9:

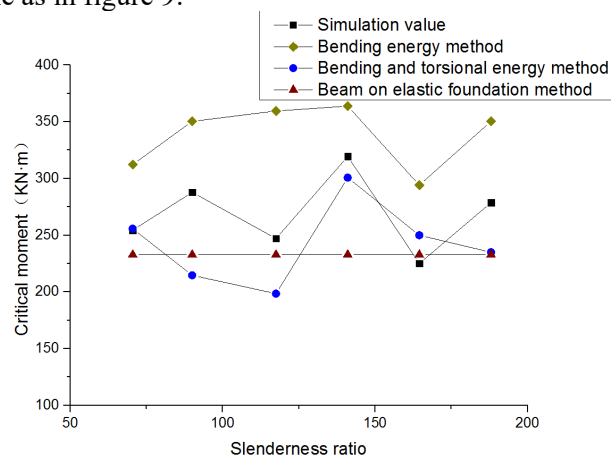


Figure 9. Relationship between critical moment and span of 350×125×6×8 section

To assess the degree of deviation and reliability of each theory relative to the simulated value, the error analysis of the three theories mentioned above is shown in Table 3.

Table 3. Error analysis of theoretical value and simulation value of span change

Computing method	Maximum error	Average error	Error standard deviation
Bending energy method	45.5%	26.7%	0.107
Bending and torsional energy method	-25.4%	-9.8%	0.133
Beam on elastic foundation method	-27.1%	-12.3%	0.108

The following conclusions can be obtained through the above chart:

- 1) The bending energy method does not take into account of the torsional deformation of the lower flange, this is equivalent to applying a restraint to the torsional deformation in the structure, so the critical bending moment calculated is larger. This will makes the result of the calculation unsafe.
- 2) Beam on elastic foundation method does not take into account the effect of negative moment area length on critical moment. We can know from table 3 that the simulation values are oscillating in a certain range, so this method has small standard deviation error. However, the maximum error and average error of this method are large, therefore, under the premise of ensuring the safety of the structure, the calculation is more conservative.
- 3) The trend of the bending torsion energy method is basically the same as that of the simulation value. It can be seen from table 3 that the average error is minimal, the maximum error is also small. This method has good precision, but the computing process is also the most complex.

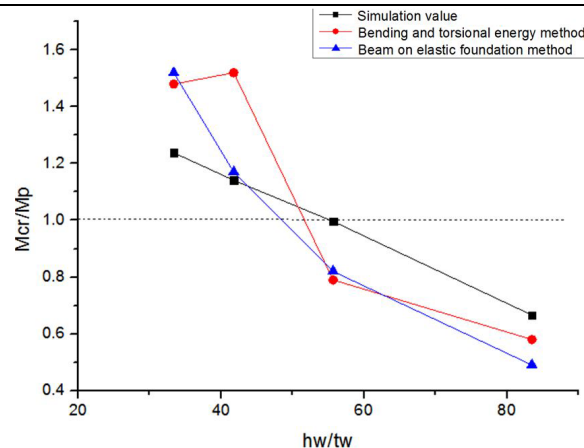
3.2.2 Contrast of height to thickness ratio

The influence of height to thickness ratio on critical bearing capacity is studied when the composite beam with span 3000mm changed with different web thickness. When calculating the effect of height thickness ratio on buckling load, the influence of sectional area change should be excluded. Therefore, the influence degree of this section will be described by the critical moment divided by the plastic bending moment (M_{cr}/M_p) of the whole section.

From the analysis of the previous section we know that the critical moment calculated by the bending energy method may makes the calculation result unsafe. Therefore, this section only carries out the analysis of the bending torsion energy method and the beam on elastic foundation method. The results of the calculation are as in table 4 and figure 10:

Table 4. Comparison of relative critical bending moment between theoretical value and simulated value when height thickness ratio changes

Section	h_w/t_w	Simulation value	Bending and torsional energy method	Beam on elastic foundation method
B3-350×125×4×8	83.5	0.666	0.58 (-12.9%)	0.49 (-26.4)
B3-350×125×6×8	55.7	0.996	0.79 (-20.7%)	0.82 (-17.7%)
B3-350×125×8×8	41.8	1.141	1.52 (33.2%)	1.17 (2.5%)
B3-350×125×10×8	33.4	1.238	1.48 (19.5%)	1.52 (22.8%)

**Figure 10.** Comparison of the high thickness ratio changes on relative critical bending moment

According to the graph, the theoretical value basically accords with the rule that the higher the thickness ratio is, the smaller the critical bending moment is. The theoretical value is larger than that of the simulated value when the high thickness ratio is small. When M_{cr}/M_p is greater than 1, the structural failure is controlled by intensity. When M_{cr}/M_p is less than 1, the structural failure is controlled by stability. In the case of the fact that M_{cr}/M_p is less than 1, the two theories can meet the conditions that M_{cr}/M_p are less than the simulated value in the meanwhile closer to the simulated value. The security of the structure can be guaranteed, and in contrast, the beam on elastic foundation method is closer to the simulation value.

3.2.3 Comparison of changes in reinforcement rate of concrete plates

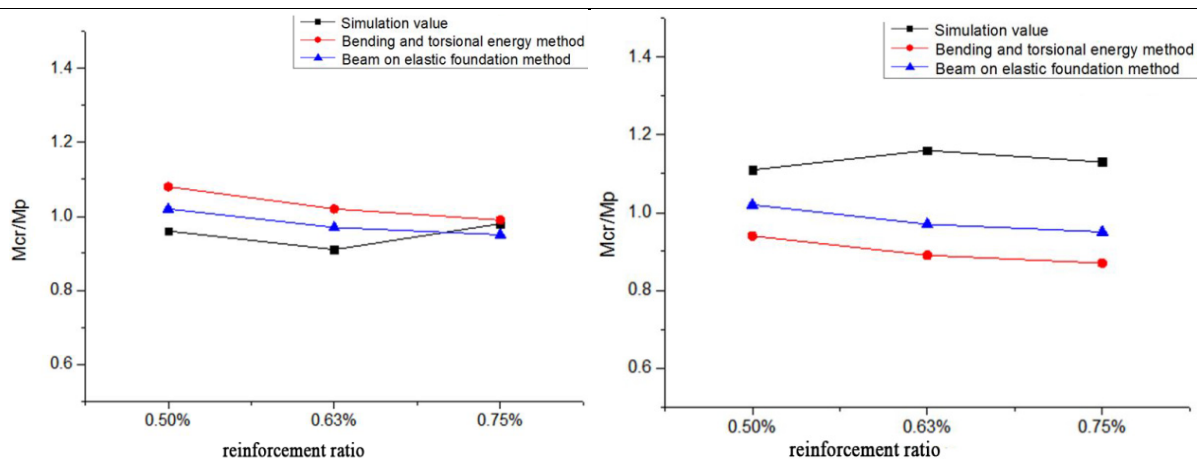
The bending and torsion energy method and the beam on elastic foundation method all consider the influence of the reinforcement ratio of the concrete slab on the calculation of ultimate bending moment. On the one hand, they considering the effect of steel bar on the moment of inertia of the section when calculating the moment of inertia of the section, on the other hand, the contribution of the ribs in the plate is also taken into account when calculating the section neutral axis. The calculation results of the relative critical moment (M_{cr}/M_p) are as in table 5, table 6 and figure 11:

Table 5. Comparison of relative critical moment of $350 \times 125 \times 8 \times 6$ cross section with span of 4200mm

Reinforcement ratio	M_p	Simulation value	Bending and torsional energy method	Beam on elastic foundation method
0.50%	227.6	0.96	1.08	1.02
0.63%	248.0	0.91	1.02	0.97
0.75%	262.7	0.98	0.99	0.95

Table 6. Comparison of relative critical moment of $350 \times 125 \times 8 \times 6$ cross section with span of 2400mm

Reinforcement ratio	M_p	Simulation value	Bending and torsional energy method	Beam on elastic foundation method
0.50%	227.6	1.11	0.94	1.02
0.63%	248.0	1.16	0.89	0.97
0.75%	262.7	1.13	0.87	0.95



(a) $350 \times 125 \times 8 \times 6$ with span of 4200mm

(b) $350 \times 125 \times 8 \times 6$ with span of 2400mm

Figure 11. Comparison of changes in reinforcement rate of concrete plates on relative critical bending moment

The following conclusions are drawn by comparing the two theoretical methods: (1) The two theories have large errors when the span is large. Even a little larger than the simulation value. The critical moment of the two theories is smaller than the simulated value when the span is small. (2) The

calculation of beam on elastic foundation method is relatively conservative, the maximum error is 6.6%, the average error and standard error deviation are less than the bending torsion energy method.

4. Conclusion

In this paper, the three theories are compared with the simulated values in the changes of negative bending moment area, the ratio of height to thickness and the reinforcement ratio of the concrete slab. It is found that the bending energy method is inaccurate and insecure. When the length of the negative moment region changes, the average error of the beam on elastic foundation method and the bending torsion energy method is 12.3% and 9.8% respectively, the maximum deviation of the two method is small, and the result is safe. When the ratio of height to thickness changes, for the situation that the destruction of the cross section is controlled by stability, the critical moment of bending torsion energy method and beam on elastic foundation method are very precise. When the reinforcement ratio of the concrete plate is changed, the two theories have some data larger than the simulation values, In comparison, under the change of a variety of factors, the results of beam on elastic foundation method is closest, and the calculation process is relatively simple.

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