The weaken technique of bending moment for support beam of internal climb tower

C X Zhu¹, N Wang¹*, S Q Gu¹ and W B Ma¹

¹ School of Mechanical Engineering, Shenyang Jianzhu University, Shenyang, China

* i492166613y@gmail.com

Abstract. This paper develops a new analysis method to weaken bending moment at the end of support beam of the inner climbing tower crane. Firstly, the equivalent length of the variable cross-section beam is calculated according to the principle which the angular displacement of the variable cross-section beam is equal to that of the equal cross-section beam under the action of the unit bending moment. Then, the deformation of the variable cross-section can be calculated by using the calculation formula of the equal cross-section beam. Finally, Graphic multiplication is used to solve the stepped variable cross-section statically determinate beam and the function relation between bending moment and inertia moment ratio and variable cross-section length ratio is obtained by MATLAB. It is of great significance to the thin-walled supporting and protection by using the function between the bending moment and the parameter to determine the optimal supporting main beam.

1. Introduction

With the rapid development of science and technology, advanced structural theory, efficient computing technology, new construction techniques and high quality, lightweight construction materials have created favorable conditions for the further breakthrough of building height, and the fierce competition for building height has led to the upgrading of world architecture height ranking. Simultaneously, the requirements for crane support beams have also increased [1].

In recent years, there has been a lot of research on the bearing capacity of the beam itself. Cristian Vulcu [2] taking the joint between the support beam and the load-bearing column as the research object, the joint model was established and the numerical simulation of the beam-column joint strength was carried out by finite element simulation, the influence of factors such as concrete core on the joint strength of the supporting beam is also obtained.

Ayman El-Zohairy [3] tested the fatigue strength of four steel-concrete composite beams under different shear connection degrees and revealed that the range of shear stress is determined by the shear joint between concrete panels. This conclusion is playing an important role in controlling fatigue cracks. Hamdolah Behnam [4] did a set of comparative experiments which carried out on four large external wide beam-column connections of different sizes and different reinforcement ratios. The results showed that the well-reinforced wide-span beam can significantly enhance the shear resistance of the beam-column link surface and the overall connection beam. The torsional strength. Sweedan AMI, Rojob HN [5] discussed the numerical analysis of some composite steel-FRP beams and its performance. Through
the combination of finite element analysis and experiment, an analytical solution for the closed moment form of the nominal torque capability and related deflection of the steel-FRP beam system is obtained.

Xiaoqin Liu [6] taking the metal-plated wood truss as the research object, proposed the reliability research of the metal (MP) wooden truss web supported by single or double support and provides a reference for modifying the relevant regulations in the truss design specification. Many scholars are also working on the bearing capacity of supporting beams under different special circumstances.

The fatigue strength of cracked steel beams under different configurations and materials was investigated by Qian-Qian Yu [7]. Mohammad M. Kashani [8] considering the existence of a large number of old bridges in real life, and studied the residual bearing capacity of reinforced concrete bridges under corroded conditions. Through the simulation, Salem O. [9] studied the parameters on load ratio effect on the flexural bending behavior of axially-restrained HSS steel beams under fire condition.

In the optimization and improvement of the beam-based support system, E. Kaya, C [10] studied the effectiveness of two different modification technologies (NSM + NSM; NSM + ETS) in improving the bending strength of the beam support region with experiment. Both of the improvement can make bending resistance of the support beam better. Xie Shengrong [11] considering the stability of the roadway roof as a deep beam, the stability control of the roof of the roadway under the action of monorail is realized, and provides theoretical and technical references for the surrounding rock control under similar conditions. Sabahattin Aykac [12] studied the performance of reinforced concrete beams under monotonic lateral loads, and proposed a post-manufacturing method of RC beams for design and construction errors, as well as overcoming the strength and maintainability of structural systems under changing conditions. Nestor Iwankiw [13] improving steel beam torque connection details and related design criteria to Improved seismic performance. In order to calculate the dynamic resistance of reinforced concrete (RC) components, Foad Mohajeri Nav [14] developed a theoretical method and evaluated in three different stages, the theoretical method can provide a reliable framework for the gradual collapse analysis of reinforced concrete frames.

Fei Peng [15] studied a method of prestressed bending capacity which is based on concrete beams with external ribs. Compared with existing guidelines or models, the method has greater consistency and accuracy. Since the internal climbing tower crane can economize the tower body and reduce the vertical load, etc., it is an important equipment in the construction of high-rise and super high-rise buildings. Because of the climb of the inner climbing tower depends on its support system, it's very practical significance to create a research method of improving the high level support technology for the inner climbing tower crane and becomes a new subject. Internal climbing tower crane generally adopts two support, each is supported with two main girders to the elevator or to the reserved interval on the wall of the room. The tower crane transfers the vertical load to the two main girders via the connection frame, and the horizontal force of the tower at the supporting points is transferred to the side wall with horizontal strut which is supported on the connection points of the connecting frame, the main girder and the side wall. Both ends of the support girder are fixed to the wall mount by the flange seat, bending moment will generate simultaneous in body and the end of the beam, which is transferred to the wall and form a disadvantageous factor. So, it's very realistic to study the weaken technique of bending moment and reduce bending moment at the end of the beam to reduce the stress state of the wall.

2. Research on structure form of ZSL2700 tower support structure

2.1. The form of supporting structures

The internal climbing tower crane supporting system studied in this paper are composed of the following main components. As shown in figure 1: 1. main beam 1, 2. main beam 2, 3. first inclined supporting rod, 4. second inclined supporting rod, 5. third inclined supporting rod, 6. first ear plate, 7. second ear plate, 8. connection base, 9. wall, 10. embedded parts, 11. steel bone column, 12. pin axis, 13. connect frame.
The specific implementation plan is: when the tower crane is in working state, it is required to adopt a supporting structure with two sets of the same structure which above and below, and a spare supporting structure for climbing. The supporting structure comprises a connection frame 13, a main beam 1, a main beam 2, and first, second and third inclined supporting rod 3, 4, 5 which are connected to the main beam 1 in the horizontal direction.

One end of the main beam 1 is connected to the embedded parts 10 in the wall by the connecting base welded on the wall 9, and the other end is connected by connecting parts at the first, second and third inclined supporting rod, 3, 4, and 5, respectively.

The first inclined supporting rod 3 is connected with a pin shaft through the first ear plate 6 and the embedded parts in the wall 9, and the second and third inclined rods 4 and 5 are connected with the pin axis 12 through the second ear plate and the embedded parts in the wall 9. The main beam 2 is connected to the embedded parts 10 in the wall by the connecting base welded on the wall 9.

The side view of climbing tower crane is shown in figure 2 and the installation diagram of the supporting system showed as figure 3 [16].

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**Figure 1.** The supporting system of inner.

**Figure 2.** The side view of climbing tower crane.

**Figure 3.** The installation diagram of the supporting system of ZSL2700 tower crane.
After using in independent working conditions, the tower crane needs to be converted into the inner climbing condition. Firstly, the location of the embedded parts shall be welded in a pre-designed connection support which buried in the wall 9 of the building to complete the support welding. Secondly, the main beam 1 is connected with the first, second and third inclined supporting rods by pin shafts, and then the main beam 1 is lifted to form a combination with the supporting rods. After the corresponding position is reached, the main beam 1 is adjusted in a horizontal state, and the main beam 1 is fixed with the welded joint support on the wall 9 by the high strength bolt. Then the first ear plate 6 and the second ear plate 7 are welded. The main beam 2 is hoisted according to the same installation mode, and is less connected to the ear plate than the main beam 1. Finally, the connect frame 13 is installed, which completes the installation of a set of support frames.

2.2. Structural forms of supporting beams

The box section has good structural performance and has been widely used in water conservancy, hydro power, civil building and bridge engineering. Large torsional rigidity and good stability in construction and use is the main advantages of box section. It can effectively resist negative bending moment and adapt to the structure with positive and negative bending moment, such as continuous beam, etc. The combination of load-bearing structure and transmission structure makes the components be forced together and the cross section be efficiency. What’s more it adapts to the requirements of modern construction methods.

The supporting beam of this paper is a box-shaped beam of variable cross-section, which is part of the end beam [17, 18]. Its height at the end is smaller than the main beam and shows a linear change from small to large, the height also within a certain range, as shown in figure 4, the thickness of the upper and lower cover plates and the web of the girder is unchanged. In this paper, the equivalent length calculation method of the equivalent variable cross-section beam in the small height beam at the end part is studied under the condition of the angular displacement is produced with the action of the unit bending moment.

![Figure 4. Schematic diagram of beam structure change of supporting.](image)

3. Calculation methods and principles

3.1. Calculation of equivalent length

We often encounter the calculation problem of variable cross-section beams deformation in daily engineering design [19 - 21]. For the deformation calculation of the equal cross-section beam, various design manuals and mechanics books can be examined.

However, there is no readily available formula for the deformation calculation of variable cross-section beams. Therefore, it is necessary to convert the variable cross-sections into the equivalent sections of the beam and transformed the main beam into a ladder deformation cross-section beam which can be calculated by using the diagrammatic multiplication method [22], and the desired unknown values can be obtained.

The method used in this paper is to calculate the stiffness of the cross-section beam by using the angle difference between the variable cross-section beam and the equal cross-section beam as the minimum value under the unit torque.
So that the beam of the variable cross-section is transformed into the equal cross-section beam. It provides a simple and practical new method for calculating the deformation of the variable cross-section beam, the principle of which is simple and easy to be mastered by engineering technician and convenient to be used in engineering design.

Figure 5 represents a variable cross-section cantilever beam whose cross-section is continuously changed, the moment of inertia of any cross-section is \( I(x) \). In order to transform the variable cross-section beam shown in figure 5 into the same equal cross-section beam with the same stiffness \( EI \) as shown in figure 6, under the action of bending moment, a certain angular displacement value \( \theta \) will be generated under the action of bending moment \( M \).

It can be assumed that there is an imaginary beam whose length value is the same as the end beam, and when it produces an angular displacement under the same bending moment, the length value of which is certain, and this length value is the equivalent calculation length of the variable cross-section beam.

The length of this equivalent end beam is solved below and the moment of inertia of any section on the variable cross-section end beam is set as \( I(x) \). The variable cross-section beam shown in figure 5. It produces angular displacement \( \theta \) under the action of the unit bending moment \( M = 1 \). Figure 6 shows a hypothetical end beam with a height \( h_0 \) as the height of the end, and it can be obtained a fixed length \( L_1 \) produces a rotational angle displacement \( \theta \) under the end bending moment of \( M = 1 \), then \( L_1 \) is the equivalent calculation length of the variable cross-section beam portion.

\[
\theta_a = \int_0^L \frac{M}{EI(x)} \, dx \quad \theta_b = \int_0^L \frac{M}{EI} \, dx = \frac{L_1}{EI}
\]

(1)

Expression of parameter of variable cross-section beam:
Height of cross-section beam:
\[
h(x) = h_0 + \frac{x}{L} (h_1 - h_0)
\]

(2)

Moment of inertia of cross-section beam:
\[
I(x) = \frac{th^3(x) - (t - 2t_1)(h(x) - 2t_1)^3}{12} = \frac{t[h_0 + \frac{x}{L} (h_1 - h_0)]^3 - (t - 2t_1)[h_0 + \frac{x}{L} (h_1 - h_0) - 2t_1]^3}{12}
\]

(3)

\[
I = \frac{th_0^3 - (t - 2t_1)(h_0 - 2t_1)^3}{12}
\]

(4)
Expression of rotation angle of variable cross-section fixed beam:

\[ \theta_\alpha = \int_0^L \frac{M}{EI(x)} \, dx = \frac{12}{E} \int_0^L \frac{1}{\left[ \left( h_x + \frac{x}{L} (h_l - h_r) \right)^3 - (t - 2t_1)(h_x + \frac{x}{L} (h_l - h_r) - 2t_1) \right]} \, dx \]  

(5)

It can be seen from the above formula that the solution to the rotation angle of the variable cross-section fixed beam is a integrate rational function. The direct solution itself is very troublesome. In this way, we can change our minds and simplify \( \theta_\alpha \) firstly, and it can be simplified into the form as

\[ \int_0^L \frac{1}{ax^3 + bx^2 + cx + d} \, dx \], among them, \( a, b, c, d \) are coefficients. Then:

\[ a = 2t_1 \left( \frac{h_l - h_r}{L} \right) \]

\[ b = 6(t_1 - h_1) \left[ h_0 t_1 + t_1^2 - 2t_1 t_2 \right] \]

\[ c = 6(h_1 - h_0) \left[ 2 t_1 (h_0 - t_1) + t_1 (h_0 - 2t_1)^2 \right] \]

\[ d = h_0 (t - (h_0 - 2t_1)(t - 2t_1)) \]  

(6)

The solution of \( \theta_\alpha \) can be converted to find the roots of a cubic equation.

Find the three roots of equation \( ax^3 + bx^2 + cx + d = 0 \) (\( a, b, c, d \) and \( a \neq 0 \)). It's solved by the Shengjin formula [23], a derivation of the Kardan formula. The heavy root discriminant:

\[ A = b^2 - 3ac \]

\[ B = bc - 9ad \]

\[ C = c^2 - 3bd \]  

(7)

General discriminant: \( \Delta = B^2 - 4AC \)

The root of the equation can be obtained according to the Shengjin formula. Then the general formula of \( \theta_\alpha \) can be solved by the deformation of the identity equation.

Identity distortion:

\[ \frac{1}{ax^3 + bx^2 + cx + d} = \frac{1}{a \left( x - x_1 \right) \left( x - x_2 \right) \left( x - x_3 \right)} = \frac{1}{a} \left( \frac{c_1}{x - x_1} + \frac{c_2}{x - x_2} + \frac{c_3}{x - x_3} \right) \]  

(8)

Among them:

\[ c_1 + c_2 + c_3 = 0 \]

\[ c_1 (x_1 x_2) + c_2 (x_1 x_3) + c_3 (x_2 x_3) = 1 \]

\[ c_1 (x_1 + x_2) + c_2 (x_1 + x_3) + c_3 (x_2 + x_3) = 0 \]  

(9)

\( c_1, c_2, c_3 \) are the setting coefficient.

Integrate:

\[ \int_0^L \frac{1}{ax^3 + bx^2 + cx + d} \, dx = \frac{1}{a} \left[ c_1 \ln(x - x_1) + c_2 \ln(x - x_2) + c_3 \ln(x - x_3) \right] \bigg|_0^L \]  

(10)

\( \theta_\alpha \) can be obtained by integrating rational function. The equivalent length \( L_\alpha \) of the cantilever beam can be solved by \( \theta_\alpha = \theta_b \).
3.2. Solution of fixed beam bending moment at both ends

Through the solution of the equivalent length above, the equivalent length $L_1$ of the cross section of the variable cross-section beam (as shown in figure 7) can be gained. Now, the trapezoidal cross section at both ends of the variable beam is equivalent to a fixed cross section. (as shown in figure 8). The length of the beam with small height is $L_1$, and the bending stiffness is $EI_1$.

The total length of the fixed beam at both ends is $L$, the bending stiffness of the high beam is, $EI_2$; a concentration force $F$ is applied perpendicular to the axis of the beam, the position of concentrated force is shown in figure 4, 5. The supporting main beam is simplified into the following form to analyze the end bending moment.

As shown in figure 8, this beam is a statically indeterminate structures, and the force method is the first method to be developed in various statically indeterminate calculation methods, which is the most basic method of calculation and being widely used.

To solve the statically indeterminate structure, the redundant connection of the statically indeterminate structure should be removed to obtain the static structure, and the redundant unknown force is used as the basic unknown quantity. The redundant unknown force can be obtained by displacement condition which following the base system should deform in the same way as the original. Then the balance condition can be calculated for the remaining counter force and internal forces.

The simply supported beam is taken as the basic structure, the basic system is shown in figure 9, the redundant unknown force are the beam end bending moment $X_1$, $X_2$, and the horizontal counter force $X_3$. 
Figure 9. The simplify system of beam fixed at both ends.

It can be assumed that when the unit redundant unknown force $X_1=1$, $X_2=1$, $X_3=1$, and load $F$ are acting on the basic system respectively, the displacement of point $A$ along the direction of $X_1$ are $\delta_{11}$, $\delta_{12}$, $\delta_{13}$, and $\Delta_{1p}$, the displacement in the direction of $X_2$, are $\delta_{21}$, $\delta_{22}$, $\delta_{23}$ and $\Delta_{2p}$, the displacement along the direction of $X_1$, are $\delta_{31}$, $\delta_{32}$, $\delta_{33}$ and $\Delta_{3p}$ respectively, according to the principle of superposition, the displacement conditions of above can be written as:

$$
\Delta_1 = \delta_{11}X_1 + \delta_{12}X_2 + \delta_{13}X_3 + \Delta_{1p} = 0 \\
\Delta_2 = \delta_{21}X_1 + \delta_{22}X_2 + \delta_{23}X_3 + \Delta_{2p} = 0 \\
\Delta_3 = \delta_{31}X_1 + \delta_{32}X_2 + \delta_{33}X_3 + \Delta_{3p} = 0
$$

(11)

$\delta_{11}$, $\delta_{12}$, $\delta_{13}$ in the system of equations are called principal coefficients or principal displacements, whose values are always positive and not equal to zero.

The rest $\delta$ are called the auxiliary coefficient or the auxiliary displacement, and the last term in the formula $\Delta_p$ is called the free term. The values of the deputy coefficient and the free term may be positive,
negative or zero. According to the reciprocal theorem of displacement, the two deputy coefficients of the symmetric position on both sides of the main slant line \( \delta_{12} \) and \( \delta_{21} \) are equal to each other, namely, \( \delta_{ij} = \delta_{ji} \). The coefficients and the free items in the system are the displacement under the action of the already force, so it can be solved completely. For the plane structure, the calculation of these displacements can be written as:

\[
\delta_i = \sum \int \frac{M_i^2}{EI} ds + \sum \int \frac{F_{N_i}^2}{EA} ds + \sum \int kF_{u_i}^2 ds
\]

\[
\delta_j = \delta_{ji} = \sum \int \frac{M_j^2}{EI} ds + \sum \int \frac{F_{N_j}^2}{EA} ds + \sum \int kF_{u_j}^2 ds
\]

\[
\Delta_p = \sum \int \frac{M_p^2}{EI} ds + \sum \int \frac{F_{N_p}^2}{EA} ds + \sum \int kF_{u_p}^2 ds
\]

This is the calculation formula for displacement of the planar rod structure under load. The three items on the right of the upper equation are the calculation formula of bending deformation, axial deformation and shear deformation of the structure for the solved displacement.

The M diagrams and \( M_p \) diagrams of the basic structure are shown in the figure above. Due to \( M_3 = 0 \), \( F_{N3} = 0 \), and \( F_{N1} = F_{N2} = F_{NP} = 0 \), it can be obtained from the calculation formula of displacement that \( F_{N1} = F_{N2} = F_{NP} = 0 \), \( \delta_{23} = \delta_{32} = 0 \), \( \Delta_{3p} = 0 \). So, the third equation of the above equation becomes

\[
\delta_{33} X_3 = 0 \tag{13}
\]

In the calculation of \( \delta_{33} \), the influence of bending moment and axial force should be considered at the same time

\[
\delta_{33} = \sum \int \frac{M_3^2}{EI} ds + \sum \int \frac{F_{N3}^2}{EA} ds = 0 + \frac{L}{EI} = \frac{L}{EI} \neq 0
\]

Then,

\[
X_3 = 0 \tag{15}
\]

This indicates that the beams fixed at both ends do not produce a horizontal counter force with a load perpendicular to the beam axis. Therefore, it can be simplified to solve the problem of two redundant unknown forces, and the typical equation becomes:

\[
\delta_{11} X_1 + \delta_{12} X_2 + \Delta_{1p} = 0
\]

\[
\delta_{21} X_1 + \delta_{22} X_2 + \Delta_{2p} = 0 \tag{16}
\]

For the beam and the rigid frame, the displacement is mainly caused by the bending moment. The influence of axial force and shear force is too small, so it can be omitted (only the effect bending moment is considered). The coefficients and the free items can be obtained by the diagrammatic multiplication method.

\[
\delta_{11} = \sum \int \frac{M_i^2}{EI} ds
\]

\[
\delta_{12} = \sum \int \frac{M_i^2}{EI} ds
\]
As shown in figure 10, it can be assumed that in the two bending moments graph of the AB segment of the equal cross-section rod, the diagram of $M$ is a straight line, while the diagram of $M_p$ is in any shape. The rod axis is taken as the X axis, and the intersection of the extension of M diagram $\int M_p E I d s$ and the X axis is regarded as the origin, the y axis is set, then the integral form is written as, the $dx$ in the formula is available to be substituted with $dx$.

The image of $M$ varies according to the line, $\dot{M} = \tan x$, and $\tan \alpha$ is constant, so the integral form becomes:

$$\int \frac{M_p}{EI} dx = \tan \alpha \int x M_p dx = \tan \alpha \int xdA_w$$

(18)

In the formula $dA_w = M_p dx$, $dA_w$ is the differential area of the shadow line in the graph of $M_p$, so $xdA_w$ is the static moment of the differential area to the axis, and $\int xdA_w$ is the static moment of total area of the $M_p$ graph to the Y-axis, according to the theorem on moment of resultant force, it should be equal to the value which the area $A_w$ of the graph $M_p$ times the distance $x_c$ from the C to the Y-axis, substitute $\int xdA_w = A_w x_c$ into the upper formula, it can be obtained :

$$\int \frac{M_p}{EI} ds = \tan \alpha \frac{A_w x_c}{EI} = \frac{A_w y_c}{EI}$$

(19)

In the formula $y_c$ is the vertical coordinate of the M graph corresponding to the center C of $M_p$ graph. Since the use of the diagrammatic multiplication method is conditional, the division integration method is performed in order to find the coefficients in the equation. It can be gained:
Here $\delta_{11} = \delta_{22}$, $\delta_{12} = \delta_{21}$. In order to simplify the formula, the stiffness ratio of the step variable cross-section and the ratio of length of the variable cross-section are set as

$$\alpha = \frac{I_1}{I_2}, \quad \beta = \frac{L_1}{L}$$

The range of values of $\alpha$ and $\beta$ are: $\alpha \in (0,1]$, $\beta \in (0,0.5]$.

The expressions of the coefficients $\alpha$ and $\beta$ are obtained:

$$\delta_{11} = \delta_{22} = \frac{L}{EI} \left[ \frac{1}{\alpha} (\beta - \beta^2 + \frac{2}{3} \beta^3) + \frac{1}{3} \frac{2}{3} \beta^3 + \beta^2 - \beta \right]$$

(22)

$$\delta_{12} = \delta_{21} = \frac{L}{EI} \left[ \frac{1}{\alpha} (\beta^2 - \frac{2}{3} \beta^3) + \frac{1}{6} \frac{2}{3} \beta^3 - \beta^2 \right]$$

In addition, let $\gamma = a/L$.

$$\Delta_{1p} = -\frac{L^2 F}{EI} \left[ \frac{1}{\alpha} (4\gamma \beta^3 - 2\beta^3 + 3\beta^2 - 3\gamma \beta^2) \right]$$

$$+ (\gamma - \beta - \gamma^3 + \beta \gamma)(3\beta - 2\beta^2 - 2\beta \gamma + 3\gamma - 2\gamma^2)$$

$$+ (\gamma - \gamma^2 - \beta \gamma)(2 + 2\gamma^2 - 4\gamma + 2\beta - 2\beta \gamma + 2\beta^2)$$

(23)

$$\Delta_{2p} = -\frac{L^2 F}{EI} \left[ \frac{1}{\alpha} (2\beta^3 - 4\gamma \beta^3 + 3\gamma \beta^2) \right]$$

$$+ (\gamma - \gamma^2 - \beta \gamma)(\beta - 2\beta^2 + 2\beta \gamma + \gamma - 2\gamma^2 + 1)$$

$$+ (1 - \gamma)(\gamma - \beta)(2\gamma^2 + 2\beta \gamma + 2\beta^2)$$

(24)
Through the above process, the coefficients and the free items in the typical equation of the force method are solved by the diagrammatic multiplication method and represented by two parameters of design. In this way the end bending moment value of the fixed end beam be gained.

3.3. Simulation analysis

It appears that above expressions are complex, so the two-element equation system can be solved by MATLAB software and the expression for the end bending moment can be gotten immediately. Here are end bending moment of the main beam of a few concentrated forces in different points. A few special points of concentrated force are given in the following figure 11, in which the relationship between the end bending moment $M$ and the moment of inertia ratio $\alpha$ and the variable cross-section length ratio $\beta$ can be seen.

![Figure 11: Fixed beam end bending moment diagram.](image1)

![Figure 12: Fixed beam end bending moment diagram.](image2)

The bending moment value in the graph refers to the bending moment that is close to the central force $F$. The results given above will be discussed with a few special positions of concentrated force.

The concentrated force is applied at $1/2L$, when the ratio of the length of the variable cross-section is $\beta = 0$ or $\beta = 0.5$, at this time, the stepped variable cross-section beam which our research is the equivalent cross-section beam.

At which moment, the bending moment of the fixed ends achieve the maximum and have the equal value $1/8FL$, when the moment of inertia $\alpha$ is closer to 1, that is, the bending stiffness of the two step
beams is not quite different, so that it can be regarded as the equal cross-section beam, and the bending moment value is the most significant 1/8FL. It can be seen from the structure mechanics book, when a=b=1/2L, the bending moment at both ends of AB are 1/8FL. From the figure 12(a) above, it can be seen that the maximum value of the bending moment is also 1/8FL. When $\alpha \in (0, 0.2)$, $\beta \in (0.05, 0.2)$, the end bending moment is minimized.

The concentrated force is applied at 1/4L and 1/5L, as shown in figure 12(b), under the same condition of equal cross-section beam, the influence of the variable cross-section length ratio $\beta$ on the fixed end bending moment is greater than that of the moment of inertia ratio $\alpha$. In the area of $\alpha \in (0, 0.2)$ and $\beta \in (0.4, 0.5)$, the maximum bending moment occurred in the inner end of the region. The design of the main beam should avoid the selection of parameters in this area.

From this we can conclude that the dark blue area of the bending moment diagram is the main beam design zone, the light blue area is the optional zone, the green and yellow area is the reference selection zone, and the red area is the design rejection zone. In this way, we can obviously know that magnitude of the end bending moment when the main beam is designed by the bending moment diagram [24], and it is important to design the wall body with special requirement for some bearing capacity.

4. Optimization analysis of main beam structure

4.1. Structure of ZSL2700 main beam

Many scholars have done research on the simulation of real tower cranes [25 - 26]. The structure of ZSL2700 supporting main beam designed in the above chapter is analyzed as an example. The main beam is a rectangular box type structure welded with steel plate. The structure is shown in figure 13 below: we apply the bending moment weakening technique which is described above to give end bending moment value of the main beam.

![Figure 13. Schematic diagram of ZSL2700 main beam structure.](image)

According to the design dimension parameters of the main beam, and the equivalent method of the variation cross-section of the upper section, the equal cross-section length of the oblique cross-section of ZSL2700 main beam can be obtained: $L_1=550/2+738=1013$ since the main beam is designed as $L=9320$mm, the moment of inertia of main beam in small cross-section height and that in large cross-section height can obtained.

$$I_1 = \frac{1}{12} \times (400 \times 1200^3 - 350 \times 1100^3) = 1877916666 mm^2$$

$$I_2 = \frac{1}{12} \times (400 \times 600^3 - 350 \times 500^3) = 3554166667 mm^2$$  \hspace{1cm} (25)

The moment of inertia ratio and the variable cross section ratio of the two trapezoidal beams:

$$\alpha = \frac{I_1}{I_2} = 0.189 \quad \beta = \frac{L_1}{L} = 0.109$$  \hspace{1cm} (26)
In the case of the main beam, the concentration force is applied at 1/6L, and the relationship between the bending moment \( X \) of the main beam and the ratio of the moment of inertia \( \alpha \) and the length ratio of the variable cross-section \( \beta \) is shown in figure 14.

Value of special point, if \( \alpha = 1, \beta = 0 \), the beam is equal cross-section beam at this time. It can be seen from structural mechanics:

Bending moment of both ends:

\[
X_1 = \frac{Fa b^2}{L^2} \quad X_2 = \frac{Fa a b}{L^2}
\]  

(27)

If \( a = 1/6L, b = 5/6L \), substitute them into the formula:

\[
X_1 = \frac{F \frac{1}{6}L \left( \frac{5}{6}L \right)^2}{L^2} = 0.12FL
\]

\[
X_2 = \frac{F \frac{1}{6}L \left( \frac{1}{6}L \right)^2}{L^2} = 0.02FL
\]  

(28)

If \( \alpha = 0.189, \beta = 0.109, a = 1/6L \) substitute them into the equation system:

Bending moment of both ends of variable cross section beam:

\[
X_1 = 0.0769FL \quad X_2 = 0.0213FL
\]  

(29)

When \( \beta = 0.109 \), the relationship between bending moment \( X_1 \) and \( \alpha \) is given below: at the time \( \alpha = 0.189 \), the diagram of the relationship between bending moment \( X_1 \) and \( \beta \) is shown as follows:
We can see the value of bending moment transmitted by the main beam end to the wall during the solving process as described above. The design of the structural parameters of the main beam is within the allowable range, which is basically the optimized parameter.

5. Conclusions

Based on the study of the supporting structure of ZSL2700 tower, in order to reduce the force transformed from the structure of the main beam to the building, the innovation technology of end bending moment weakening is used in the main beam of the structure, which is proposed for the first time to reduce the bending moment effect of the main beam end to the wall.

There is a certain function relation between the end bending moment and the main beam parameter $\alpha$, $\beta$: $M=f(\alpha, \beta)$, that is, given suitable $\alpha$, $\beta$, the bending moment of the wall can be reduced to a certain extent, which is of great significance to the thin wall support, among them, $\alpha$ is the ratio between the small height of the main beam end and the height of the large end, $\beta$ is the ratio of the small height of the main beam end to the overall length of the main beam.

The proposition of this technique can ensure the safety of the tower in the thin walls of the building and the research method adopted in the project provides the design idea and theoretical support for the support of tower crane in similar building construction.

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