Numerical Analysis of the Ultimate Bearing Capacity of Thin-walled Rectangular-section Columns Using 18Mn2CrMoBA High Strength Steel in Bending and Axial Compression

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Abstract. The ultimate bearing capacity of thin-walled rectangular-section columns (which is welded by channel section steel plate) using 18Mn2CrMoBA high strength steel in bending and axial compression was studied by finite element method. The influence of slenderness ratio, flange width-thickness ratio and section side ratio on the ultimate bearing capacity of member was studied. The calculation method for ultimate bearing capacity of member was proposed on the basis of previous study (which can be found reference document) and many numerical calculation results. Results show that the moment-compression interactive curve changes downward concave from upward bulge with the increasing of slenderness ratio, the ultimate bearing capacity was reduced with the flange width-to-thickness ratio and section side ratio increased, the effects of these parameters were interactive. The proposed calculation formula is in good agreement with the finite element numerical results.

1. Introduction
High strength steel was applied to many actual projects widely for its excellent mechanics properties [1]. Currently, Australia, Japan, the United States and other countries have engaged in an increasing number of engineering projects employing high strength steel. The yield strength of high-strength steel mainly ranges between 460 MPa and 690 MPa [1-3]. In recent years, high-strength steel has been increasingly employed in constructions in China such as the National Stadium of China [4], the new headquarters of China Central Television [5] and so on. These buildings primarily employed Q460 high-strength structural steel as the construction material.

For the influence of load eccentricity, imperfections and so on, many members in structure were in bending and compression mechanics condition, so the members under bending and compression were studied by many researchers. Richard [6] studied the thin-walled box-section members under bending and compression by numerical integral and effective width method. Rasmussen [7] performed the stability test of weld box-section members whose nominal yield strength is 690MPa under bending and compression. Yan [8] studied the stability of box-section members whose nominal yield strength is 460MPa under bending and axial compression by test and numerical analysis, it can be found that the stability bearing capacity of studied members is higher than the value in Chinese code [9]. There are many research works in stability of beam-column [10] but the study of stability for high strength steel...
which nominal yield strength over 600MPa members under bending and compression was lacking. In this paper the ultimate bearing capacity of thin-walled rectangular-section columns (which is fabricated by welding channel plates) using 18Mn2CrMoBA high strength steel whose nominal yield strength is 745MPa under bending and compression was studied by numerical analysis method. The effect of slenderness ratio, flange width-thickness ratio and section side ratio on the ultimate bearing capacity of thin-walled box-section was studied. The proposed calculation equation of ultimate bearing capacity of thin-walled rectangular-section columns was put forward by previous studies [11, 12].

2. Finite element model
In order to consider the local buckling influence on ultimate load carrying capacity of member shell element (shell181) was employed in ANSYS software [13]. Two rigid steel plates having a very high elastic modulus were added to the ends of the member model, and the nodes at the middle of the two end plates were constrained. The established finite element model is shown in Figure 1. Basing on the stress-strain curve of the material from previous study [12], a multi-linear isotropic strengthening model was applied to the material model. Beginning with the basic model, the locations of nodes were altered according to a semi-sine wave, and the maximum initial deflection was equal to 1/1000 length of the member [9]. The consistent imperfection mode method was applied in local defect and the maximum local defect vale was determined by Equation (1), which proposed by Mateus [14].

$$\Delta_0=0.1\beta^2$$

Here, $\beta = \frac{b}{\sqrt{\sigma_y/E}}$, where b is the width to thickness ratio, and $\sigma_y$ is the yield strength.

The previous studied residual stress model was used [12] and the residual stress model was shown in Figure 2. The residual tension stress $\sigma_r$ is 0.8$\sigma_y$ and residual compression stress is 0.1$\sigma_y$.

![Figure 1. Calculation model.](image)

![Figure 2. Diagram of the residual stress model.](image)

The load of bending moment (M) and axial compression (N) was applied on the center of the rigid steel plate, the vale was shown in Equation (2)

$$N=\alpha N_y, \quad M=\beta M_p$$

Here, $\alpha$, $\beta$ is the load factor for every load in model, $N_y$ is the yield load of the entire section, $M_p$ is the yield moment of the entire section.

The arc-length method was applied for the solution. The time parameter of the highest point of the load-displacement curve indicates the ultimate bearing capacity of member. The ultimate load carrying compression $P_u$ and bending moment $M_u$ can be got by multiplying the time parameter with the initial axial compression N and bending moment M in numerical model.

3. Influence of the various factors on ultimate bearing capacity
Three factors which influence ultimate bearing capacity of members are mainly considered in this paper. In order to study influence of the various factors on ultimate bearing capacity of member stability analysis with different slenderness ratios, the width-thickness ratios of flange and the section side ratios were conducted. The thickness of the member plate is 6mm.

3.1. Influence of the slenderness ratio
In order to study the influence of the slenderness ratio on the ultimate bearing capacity of the members,
many members whose slenderness $\lambda$ is 10,30,50,60,80,100, width-thickness ratio of flange b/t is 10 and 30, section side ratio 1.5 were calculated, the moment-compression interactive curves were shown in Figure 3.

Figure 3. The moment-compression interactive curves under different slenderness ratios.

The slenderness ratio has great influence on the ultimate bearing capacity of the members from Figure 3. The ultimate bearing capacity $P_u/P_y$ decreases gradually in moment-compression interactive curve when $M_u/M_p$ approached zero. The moment-compression interactive curve changes approximate line or downward concave from upward bulge with the increasing of slenderness ratio. The phenomenon that moment-compression interactive curve becomes upward bulge when slenderness ratio is small indicated that out-plane anti-bending ability of the member is bigger, moment has bigger influence on ultimate bearing capacity of the member. It also can be found that $M_u/M_p$ in moment-compression interactive curve has little change when axial compression becomes smaller, especially $M_u/M_p$ changes nearly one point with different slenderness ratios when $P_u/P_y$ is zero.

### 3.2 Influence of the flange width-thickness ratio

In order to study the influence of the flange width-thickness ratio on the ultimate bearing capacity of the members, many members whose width-thickness ratio of flange b/t is 10, 30, 60, section side ratio is 1 and 1.5 , slenderness $\lambda$ is 50,100 were calculated, the interactive curves were shown in Figure 4.

Figure 4. The moment-compression interactive curves under different flange width-thickness ratios.

The flange width-thickness ratio has great influence on the ultimate bearing capacity of the members from Figure 4. It can be found that the moment-compression interactive curve becomes downward concave when flange width-thickness ratio becomes bigger. The reason is that the section anti-bending rigidity reduces when the flange local buckling appears for big flange width-thickness ratio. The influence of flange width-thickness ratio on the ultimate bearing capacity of the members is coupled with slenderness ratio and section side ratio. The moment-compression interactive curves nearly coincide when section side ratio is small because the member displays overall buckling. The moment-compression interactive curves divide gradually with the increasing of the section side ratio under different flange width-thickness ratios.

### 3.3 Influence of the section side ratio

In order to study the influence of the section side ratio on the ultimate bearing capacity of the members, many members whose section side ratio is 1,1.5,2, flange width-thickness ratio is 10 and 60, slenderness $\lambda$ is 50,100 were calculated, the interactive curves were shown in Figure 5.
The flange width-thickness ratio has little influence on the ultimate bearing capacity of the members when section side ratio is 10 from Figure 5. It indicates that the members display overall buckling because the flange or web doesn’t take place local buckling, so the moment-compression interactive curves come near. But the flange width-thickness ratio has great influence on the ultimate bearing capacity of the members when section side ratio is 60. In this case ultimate bearing capacity \( M_u/M_p \) and \( P_u/P_y \) decrease gradually because the flange or web take place local buckling. The influence of the section side ratio on ultimate bearing capacity reduces with the increasing of the slenderness ratio.

![Graph](image)

**Figure 5.** The moment-compression interactive curves under different section side ratios.

### 4. Proposed calculation method

There is no design code for exceeding the allowed section width-thickness ratio in Chinese steel design code [9]. The local buckling maybe come true when section width-thickness ratio exceeds the allowed value, and in this case the member displays the interactive buckling of overall and local buckling. How to consider the interactive influence of local and overall buckling in design of beam-column was studied by many researchers. Hancock [7] gave the ultimate bearing capacity calculation of the square section beam-column as:

\[
\frac{P}{P_u} + \frac{M}{M_p} = 1
\]

Here \( P_u \) is ultimate bearing capacity of column, \( M_p \) is ultimate bearing capacity of beam.

The ultimate bearing capacity calculation of the box section beam-column is:

\[
\frac{P}{P_u} + \left( \frac{M}{M_u} \right) \alpha = 1
\]

Here \( P_u \) is ultimate bearing capacity of column, \( M_p \) is ultimate bearing capacity of beam.

The ultimate bearing capacity equations of the beam-column above mentioned are different and difficult to unify. The slenderness, the width-thickness ratio of flange and the section side ratio all affect ultimate bearing capacity of beam-column. So a equation for calculating ultimate bearing capacity of thin-walled rectangular-section columns using 18Mn2CrMoBA high strength steel in bending and axial compression was proposed on the basis of previous study [11,15], the equation is similar to equation 3 and 4 as:

\[
\left( \frac{P}{P_u} \right) \alpha + \frac{M}{M_u} \leq 1
\]

Where \( P \) is the axil compression, \( M \) is the bending moment, \( P_u^* \) is the axil compression ultimate bearing capacity which considers the local and overall interactive buckling, it can be got from the equation given by reference 16, \( M_u^* \) is the bending ultimate bearing capacity which considers the local and overall interactive buckling, it can be got from the equation given by reference 11, \( \alpha \) is a factor related with slenderness ratio. In order to get the value of \( \alpha \), two hundred and forty points with different slenderness ratios, flange width-thickness ratios and section side ratios were calculated.
According to the calculated datum $\alpha$ can be got in the following equation 6 by regression analysis.

$$\alpha = \begin{cases} -2.68 \times 10^{-6} \lambda^3 + 5.17 \times 10^{-3} \lambda^2 - 3.71 \times 10^{-2} \lambda + 1.817 & 0 < \lambda < 60 \\ 0.7 & \lambda \geq 60 \end{cases}$$

(6)

Many moment-compression interactive curves of thin-walled rectangular-section columns were calculated in order to verify the accuracy of the proposed equation. The calculated points were those points whose section side is 1.0 and 1.5, flange width-thickness ratio is 10, 20, 30, 40, slenderness ratio is 30, 80. The compared results were presented in Figure 6.

It can be found that the proposed equation 6 is adequate for calculating ultimate bearing capacity of thin-walled rectangular-section columns using 18Mn2CrMoBA high strength steel in bending and axial compression because the most points are located above the equation line.

5. Conclusions

The ultimate bearing capacity of thin-walled rectangular-section columns using 18Mn2CrMoBA high strength steel in bending and axial compression was studied by numerical method, the results of the study can be summarized as follows.

1. The slenderness ratio has great influence on the ultimate bearing capacity of the members. Axial compression has more influence on moment-compression interactive curve when the slenderness ratio is bigger.

2. The moment-compression interactive curve becomes downward concave when flange width-thickness ratio becomes bigger. The influence of flange width-thickness ratio on the ultimate bearing capacity of the members is coupled with slenderness ratio and section side ratio.

3. The influence of the section side ratio on ultimate bearing capacity is touched with the flange width-thickness ratio. Meanwhile the influence of the section side ratio on ultimate bearing capacity reduce with the increasing of the slenderness ratio.

4. The calculation method for ultimate bearing capacity of thin-walled rectangular-section columns using 18Mn2CrMoBA high strength steel in bending and axial compression was proposed on the basis of previous study and numerical calculation of many members. The accuracy of the proposed formula was verified by some calculated points.

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