International Journal of Applied Mathematics in Control Engineering 4 (2021) 142-150

Contents lists available at YXpublications

International Journal of Applied Mathematics in Control Engineering

Journal homepage: http://www.ijamce.com

Control and Research on the Overall Out-Of-Plane Stability of Beam-Column with Multi-Steel and Corrugated Web Mixtures

Ruipeng Gu, Qingyang Li, Wei Wei*

College of Civil Engineering, Hebei University of Engineering, Handan,056107, China

ARTICLE INFO

Article history:
Received 2 August 2021
Accepted 15 October 2021
Available online 22 October 2021

Keywords：
multi-steel
corrugated web
beam-column
critical moment
overall out-of-plane stability

ABSTRACT

Multi-steel components have high efficiency against normal stress, and the out-of-plane stiffness and torsional stiffness of corrugated web components are large. The two characteristics are combined, beam-column with multi-steel and corrugated web mixtures and its calculation method of out-of-plane stability bearing capacity is proposed. The ABAQUS software was used to study the influence of flange yield strength, flange width, web thickness, and initial defects on the overall out-of-plane stability of the component, And Comparing the calculation results of the numerical simulation with the suggested formula shows that: The flange yield strength and the width of flange ratio have a great influence on the overall out-of-plane stability of the member. The initial defects have a certain influence, while the thickness of the web has almost no influence, the numerical simulation and the calculation formula result are in good agreement.

1. Introduction

Unidirectional compression-bending components usually bend around the strong axis of the section. If the lateral fulcrum is not set, the component often undergoes lateral bending and torsion before reaching the ultimate load of in-plane instability and loses bearing capacity, that is, the overall bending moment is out of the plane. Instability (B. Kövesdi et al., 2016; Hongbo Zhou et al., 2021; Liying Lang, 2021). Research shows that compared with flat web I-shaped members, the out-of-plane stiffness and torsional stiffness of corrugated web I-shaped members are greatly improved, which can effectively improve the out-of-plane stability bearing capacity of bending moments; multi-steel mixed I-shaped member wings The strength of the flange is higher than that of the web, which can give full play to the advantages of the flange to resist bending moment and axial force and bear the axial stress (e.g., Moon J et al., 2009; R. Luo and B. Edlund., 1996). Since the axial stress of the corrugated web member is completely borne by the flange, the high-strength flange of the multi-steel mixed corrugated web member can greatly improve the ability of the flange to resist axial stress. The web is buckled and the flange is highly strengthened, it can be said to kill two birds with one stone (G. Kiymaz et al., 2010).

The existing specifications of hot-rolled I-beam and hot-rolled H-shaped steel, to ensure that the web does not buckle before yielding, the limit of the web height-to-thickness ratio is small (generally less than 80ε_k), and the thickness of the section must be increased while increasing the section height (Yong-Bo Shao et al., 2020; Nikoomanesh Mohammad and Reza, Goudarzi M. A., 2020). More steel is placed in the direction, and the web has little effect on resisting the normal stress, increasing the amount of "ineffective" steel; Research shows that compared with H-shaped steel with flat webs, H-shaped steel with corrugated webs greatly improves the out-of-plane stiffness and torsional stiffness due to its special web form, and the limit of height-to-thickness ratio is greatly improved (up to 600), can effectively improve the out-of-plane bending and torsion buckling performance, thereby forming a high-efficiency bending member with high webs and small plate thickness (Sayed-Ahmed E Y., 2007; Mohamed Elgaaly et al., 1996; Vladimir Zubkov et al., 2018).

Multi-steel mixed H-shaped steel refers to a new type of H-shaped steel that is combined with different strength grades of steel at the flange and web according to the stress state and failure mode, that is, the web is made of ordinary Q235 steel, and the flange is of relative strength. The higher steel material can give full play to the advantages of the flange to resist bending moment and bear the axial stress. The rational application of the concept of mixed steel to the design of steel structures such as bending and

* Corresponding author.
E-mail addresses: weiwei@hebeu.edu.cn (W. Wei)

bending can give full play to the material properties, effectively improve the bearing capacity and reduce the cost (John Papangelis et al., 2017).

Because there is little research on the application of corrugated webs and the mixed-use of multi-steel in compression-bending components, this paper combines the advantages of the two, adopts higher-strength steel for the flange, and uses Q235 steel for the web and makes it more corrugated. Compression-bending component of the corrugated web for steel grade mixing, and discuss the influence of the flange material yield strength, flange width, web thickness, and initial defects on the overall out-of-plane stability of the member. Combining related regulations and literature, it is proposed that the out-of-plane bending member of the multi-steel mixed corrugated web is proposed. The calculation method of the stable bearing capacity and the verification of the degree of agreement with the finite element results provide a reference for subsequent research.

2. Suggested calculation method for the out-of-plane overall stability of beam-column with multi-steel and corrugated web mixtures

2.1 Out-of-plane overall stability of single-steel corrugated web compression-bending members

The axial stiffness of the corrugated web in the corrugated web member is almost zero (Hassan H. Abbas et al., 2007; Qazi Inaam and Akhil U, 2020; Rao N N et al., 1972; Yong-Bo Shao et al., 2021).

Under the combined action of the axial force and the bending moment, the part of the web at the junction of the flange and the web is constrained by the axial deformation and there is small normal stress, The remaining 90% of the web section does not bear the axial pressure, so it is generally considered that the normal stress is all borne by the flange in the calculation. In some cases, it is often inconvenient to set up lateral support due to the shape of the building or the use function. At this time, out-of-plane instability due to bending moment will occur(Muslim A et al., 2020; Nikoomanesh Mohammad Reza et al., 2020; Xuqun Lin et al., 2019).

The formula for out-of-plane stability bearing capacity of solid web beam-column is derived as follows:

According to the theory of stability, when the cross-section of the beam-column subjected to uniform bending moment is biaxial to form an I-shaped cross-section, the component buckles around the strong axis of the section, and the critical force N_{cr} of torsional buckling on the elastic side of the component can be solved by the following formula:

$$(N_y - N)(N_\omega - N) - (\frac{e}{i_0})N^2 = 0 \tag{1}$$

In the formula:

N_y is the Euler critical force for bending around the weak axis of the section, $N_y=n^2\pi^2 EI_y/l^2$, N_ω is the critical force of torsional buckling:

$$N_\omega = \frac{1}{i_0^2}(\frac{n\pi^2 EI_\omega}{l^2} + GI_t) \tag{2}$$

e is the eccentricity, $e=M/N$, i_0 is the polar radius of gyration, $i_0 = \sqrt{\frac{I_x + I_y}{A}} = \sqrt{i_x^2 + i_y^2}$, n is the half-wave number when the member buckles, often n=1, EI_ω and GI_t are respectively the warping stiffness and torsional stiffness of the section.

When a beam with a biaxially symmetrical section is subjected to pure bending, its critical bending moment is:

$$M_{cr} = \frac{\pi^2 EI_y}{l^2}\sqrt{\frac{I_\omega}{I_y} + \frac{l^2 GI_t}{\pi^2 EI_y}} \tag{3}$$

Substituting formula (1) and (2) into formula (3) can get:

$$M_{cr} = i_0\sqrt{N_y N_\omega} \tag{4}$$

Substituting formula (1), and taking $M=Ne$, we can get:

$$(1-\frac{N}{N_y})(1-\frac{N}{N_\omega}) - (\frac{M}{M_{cr}}) = 0 \tag{5}$$

Given different values of N_ω/N_y, the correlation curve of $N/N_y \sim M/M_{cr}$ can be drawn, as shown in Figure 1.

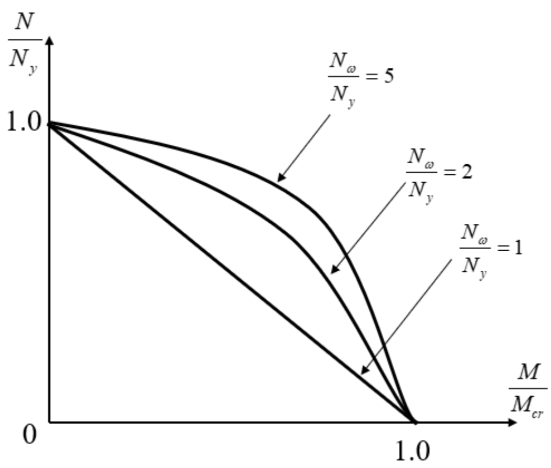

Fig. 1. Correlation curve during lateral torsional buckling

Because N_ω is often greater than N_y in general, the correlation curve is convex upward. If we use a straight line:

$$\frac{N}{N_y} + \frac{M}{M_{cr}} = 1 \tag{6}$$

Substituting formula (5) is biased towards safety obviously.

Now, set:

$$N_y = \varphi_y A f_y \tag{7}$$

$$M_{cr} = \varphi_b W_x f_y \tag{8}$$

And consider that the actual load situation is not necessarily the equivalent bending moment coefficient β_{tx} when uniform bending is introduced into lateral-torsional buckling, Substitute formulas (7) and (8) into formula (6), and change f_y to f, N and M take the design value, then the out-of-plane stability calculation formula of bending moment action can be obtained:

$$\frac{N}{\varphi_y A f}+\eta\frac{\beta_{tx}M_x}{\varphi_b W_{1x} f}\le 1.0 \tag{9}$$

Due to the "folding" effect of the corrugated web, Due to the "folding" effect of the corrugated web, the normal stress is not borne by the corrugated web at all. So it is stipulated in the " *Technical specification for steel structures with corrugated webs* " (hereafter referred to as "*Regulations*"), the overall stability outside the plane of bending moment action should be calculated as follows(China Association for Engineering Construction Standardization,2011):

$$\frac{N}{\varphi_y A_f}+\eta\frac{\beta_{tx}M_x}{\varphi_b W_{1x}}\le f \tag{10}$$

$$\varphi_b=\frac{2752.5\beta_b}{hl_1}\sqrt{0.064\frac{b_f}{t_f}I_t+1.64\frac{b_f}{t_f}\frac{I_\omega}{l_1^2}}\cdot\frac{235}{f_y} \tag{11}$$

$$I_t=\frac{2b_f t_f^3+h_w t_w^3}{3} \tag{12}$$

$$I_\omega=\frac{h^2 t_f b_f^3}{24}+\frac{t_w h^3 h_r^2}{48} \tag{13}$$

In the formula:

N is the axial pressure in the calculated rod section; M_x is the maximum bending moment in the range of the calculated member section; β_{tx} is the equivalent bending moment coefficient, When there is no end bending moment but there is a lateral load, β_{tx}=1.0; For non-closed section, η=1.0; φ_y is the stability coefficient of the axial compression member outside the bending moment action plane; φ_b is the overall stability coefficient of the flexural member with uniform bending; W_{1x} is the gross section modulus of the compressed fiber in the bending moment action plane (ignoring the contribution of the web); A_f is the gross cross-sectional area of the flange, β_b is the overall stable equivalent bending moment coefficient of the beam; I_t is the torsional moment of inertia of the corrugated web section; I_ω is the warpage constant of the corrugated web section; l_1 is the free length of the compression flange.

When the φ_b calculated by the above formula is greater than 0.45, the φ_b' calculated by the following formula is used instead of the φ_b value:

$$\varphi_b'=1.05-\frac{0.29}{\varphi_b}\le 1.0 \tag{14}$$

2.2 Overall out-of-plane stability of beam-column with multi-steel flat web mixed

At present, there are few studies on the stability of multi-steel mixed beam-column. Because of insufficient lateral stiffness, the out-of-plane instability of the bending member and the compression-bending member is the same exactly, and both are out-of-plane bending and torsion instability, so refer to the design method of the mixed beam in the American *AISC-LRFD-1999* specification: calculate the design value of bending moment and axial force according to a single steel grade, but considering the influence of the nonlinear stress distribution on the section, it should be multiplied by the following reduction factor (American Institute of Steel Construction, 1999):

$$R_e=\frac{12+\alpha_r(3m-m^3)}{12+2\alpha_r} \tag{15}$$

In the formula:

α_r is the ratio of the cross-sectional area of the web to the cross-sectional area of the compressed flange(≤ 10), calculate the stable bearing capacity, m is taken as $m=f_{yw}/(\varphi_b f_{yf})$, f_{yw} and f_{yf} and f_{yf} are the yield points of web and flange steel respectively, is the stability factor.

2.3 Suggested calculation formula for the out-of-plane overall stability of beam-column with multi-steel and corrugated web mixtures

Adopt the calculation formula for the overall stability outside the plane of bending moment action of single steel type corrugated web, refer to the simplified calculation method of single steel type of mixed beam in the American AISC specification, divide m in the reduction factor R_e formula by the stability factor φ_b, and multiply the maximum bending moment value and the maximum axial force value obtained by the single steel type corrugated web compression bending member by the reduction factor R_e, That is, the recommended calculation formula for the out-of-plane overall stability of beam-column with multi-steel and corrugated web mixtures:

$$\frac{N}{\varphi_y A_f}+\eta\frac{\beta_{tx}M_x}{\varphi_b W_{1x}}\le R_e f \tag{16}$$

3. Introduction to the finite element modeling process

3.1 Unit system determination

There is no fixed unit system in ABAQUS. For the convenience of calculation, the unit system selected in this article is shown in Table 1.

Tab. 1. ABAQUS finite element model unit

Length	Force	Stress/ Elastic Modulus
mm	N	Mpa(N/mm2)

3.2Constitutive relationship of materials

The beam-column studied in this paper adopt ideal elastoplastic constitutive models. The material strength is the yield strength value of Q235, Q355, Q390, Q420, Q460 grade steel, the steel elastic modulus E=2.06×105N/mm^2, Poisson's ratio ν=0.3. To study the stability of the beam-column, it is necessary to turn on the large deformation switch in the ABAQUS software, and its constitutive relationship obeys the yield criterion and related flow laws.

3.3 Model parameters

Single-steel flat webs, single-steel corrugated webs, and multi-steel mixed corrugated web beam-column was modeled by ABAQUS finite element software and numbered as A, B, C, as shown in Figure 2~4. Some parameters of the three groups of bending members are the same: flange width b_f=150mm, flange thickness t_f=10mm, web height h_w=320mm. The difference is that because the flat web H-shaped beam-column needs to meet the requirements of the web height-to-thickness ratio ($\le 80\varepsilon_k$), the web thickness of the flat web compression bending member is 4mm. The corrugated web can far exceed the limit of the height-to-thickness ratio of the flat web without local instability (the height-to-thickness ratio can reach 600), so the web thickness of the corrugated web beam-column is set to 2mm.

To prevent local instability before model A loses its overall stability, and to facilitate comparison, stiffeners are set at both ends and mid-span of the three groups of models. The width of the stiffener is the same as the flange and the height is the same as the web. Component length L=4m.

The corrugated web waveform adopts the common waveform in actual engineering, as shown in Figure 5.

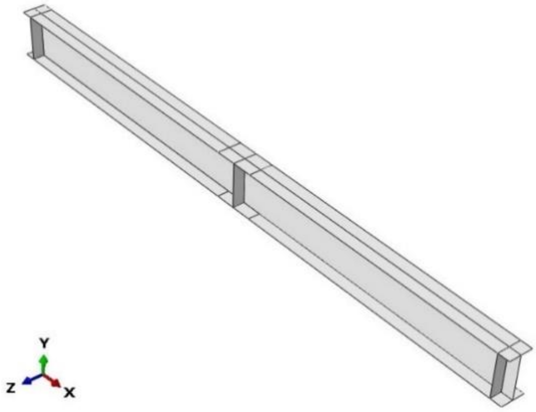

Fig. 2. Single steel grade flat web beam-column model A

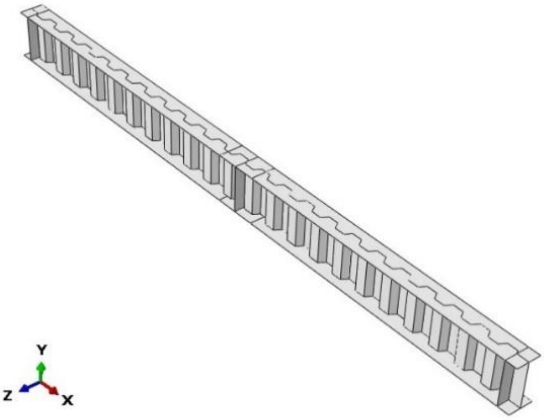

Fig. 3. Single steel corrugated web beam-column model B

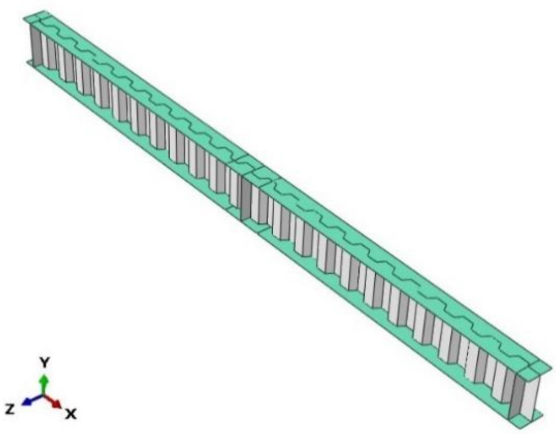

Fig. 4. Multi-steel corrugated web beam-column model C

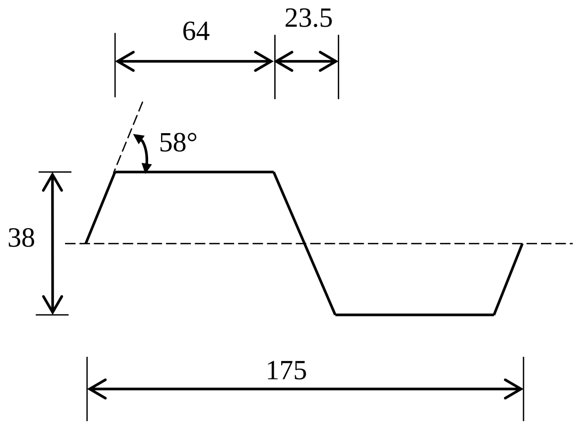

Fig. 5. Single steel grade flat web beam-column model A

3.4 *Determination of boundary conditions and application of load*

There are many load forms for beam-column. Here, the end part bears the axial load and the mid-span bears the transverse load. The ratio of the two always remains 1:1.

To avoid stress concentration caused by loading a single node, reference points are established at the center points of the two ends of the component as boundary constraint control points, and then all the six degrees of freedom of the two ends of the component are coupled to the control points. The boundary conditions of the two control points M and N are respectively set as U2=U3=UR1 and U1=U2=U3=UR1; Axial load and transverse load are respectively applied along the X direction at the boundary condition control point M and along the Y direction at the middle span of the upper flange of the member, and the ratio of the two is always kept at 1:1, Coupling is carried out along the rectangular area formed by the upper flange span direction of 150mm and the width direction of 200mm. The rigid surface formed after the coupling allows concentrated stress to be distributed to the slave nodes to effectively avoid local damage of components caused by stress concentration. The end coupling, boundary constraints, and load application established based on the above requirements are shown in Figures 6, 7, and 8.

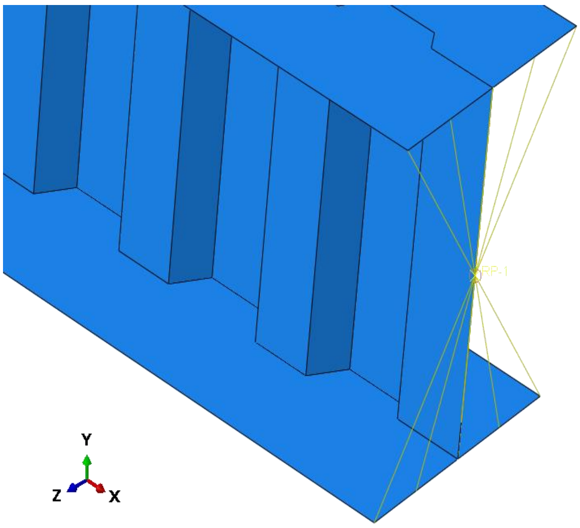

Fig. 6. End coupling

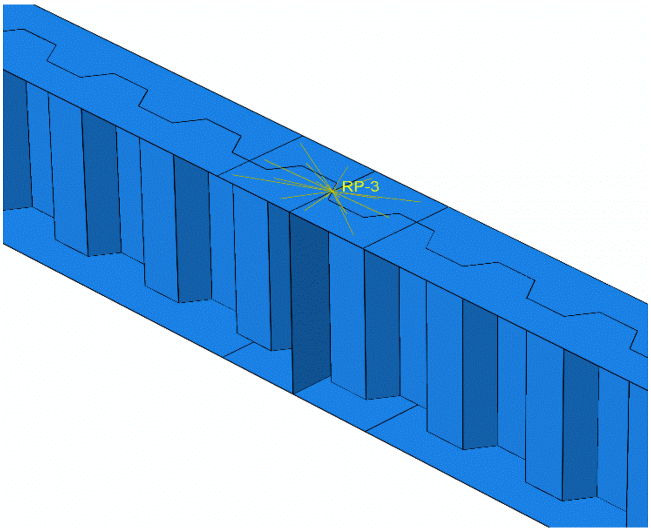

Fig. 7. Mid-span coupling

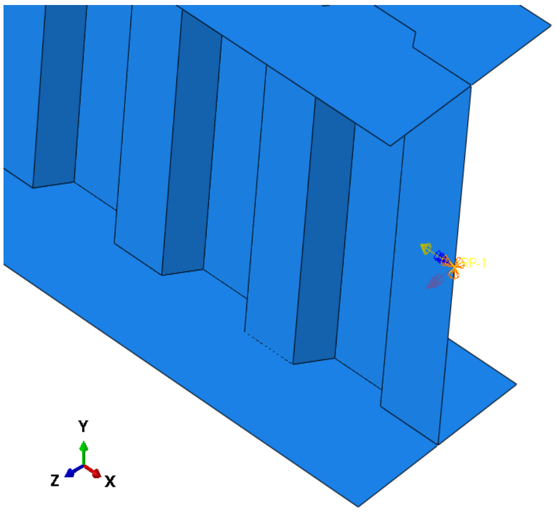

Fig. 8. Boundary constraints and load application

3.5 Grid division

Meshing is extremely important in the process of finite element analysis. It not only relates to whether the analysis can be carried out smoothly and quickly but also determines the accuracy of the analysis results. Meshing includes three parts: accurate element type, reasonable element shape, and suitable mesh density(Weicun Zhang., 2007)..

(1) Element type: the analysis process in this paper includes buckling analysis and RIKS analysis. The ultimate bearing capacity needs to be obtained through analysis. Because the thickness of the model webs is all thin, the 4-node linear reduced integral shell element S4R is selected to build the model. This unit is a universal shell unit type, and its applicability is very wide.

(2) Element shape: for steel columns with flat webs and corrugated webs, because the upper and lower flange shapes are relatively regular, the quadrilateral free mesh of advanced algorithms are used when dividing the mesh. When dividing the web mesh, the free mesh with the same shape as the flange element is still selected for the flat web, for the corrugated web due to its irregularity, a triangular free grid is selected for division, and a mapped grid is used where appropriate to improve its accuracy.

(3) Mesh density: after many simulations, it is found that for the beam-column model of this specification, selecting a larger mesh density will cause too much error in the calculation results, while a smaller mesh density will greatly increase the calculation time and is of little significance, finalize the grid size of 40mm.

3.6 Initial defect

For beam-column without sufficient lateral support, if the initial defects are not considered, no plane displacement or torsional deformation will occur when the load is small, and the lateral-torsional buckling can occur after the load is added to N_{cr} and be damaged; however, in actual engineering, initial defects will inevitably occur due to manufacturing, installation, transportation and other reasons. When subjected to bending loads, small displacements and torsional deformations will occur once the load is applied. At this time, it cannot be considered by the problem of balanced bifurcation. This paper mainly considers the effect of initial defects on the out-of-plane stability of beam-column with multi-steel and corrugated web mixtures under the dual effects of geometric nonlinearity and material nonlinearity.

According to relevant regulations, the initial defect of the bending vector height of the column shall not be greater than 1/1000 of the length of the member, and shall not be greater than 10mm. In this paper, L/1000 is selected as the initial defect of the beam-column. The method of adding the initial defect in ABAQUS is as follows:

(1) Build the model and set the analysis step to Linear Perturbation-Buckle.

(2) After completing the establishment of the model, edit the keywords and add keywords at the end of the buckling analysis model:
*NODE FILE, GLOBAL=YES, LAST MODE=1
U
Add this keyword to perform eigenvalue buckling analysis, and select the first-order mode as the initial geometric defect to be added.

(3) Copy the above model, change the analysis step to Static—Riks, edit the keywords again:
*IMPERFECTION, FILE=Job-1, STEP=1
1, 6
The meaning of the keyword is to add the initial bending value of 4mm, which is 1/1000 of the length of the bending member.

4. Parametric analysis

The web thickness of the model is 2mm, and the steel grade of the web is Q235. Except for section 3.1, the flange steel is Q355, and the other parameters remain the same as above.

4.1 Yield strength of flange material

Adjust the flange steel yield strength of model C to Q235, Q355, Q390, Q420, Q460, and the web steel to keep Q235 unchanged, establish 5 models for nonlinear buckling analysis, extract the load point data, and plot the mid-span load of each model Load-in-plane displacement and load-out-of-plane displacement curves, as shown in Figure 9 and Figure 10 (because the ratio of the mid-span and end load values is always 1:1, only one load is considered here).

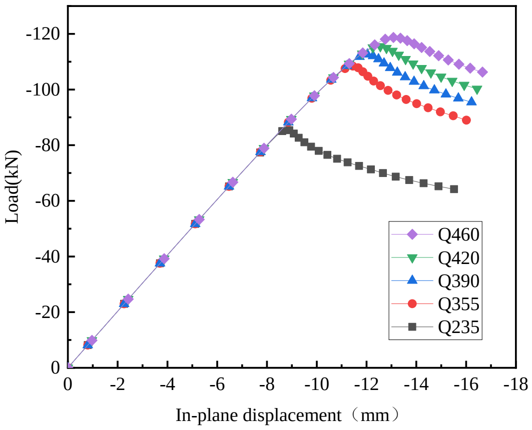

Fig. 9. Different flange yield strength load-In-plane displacement curves

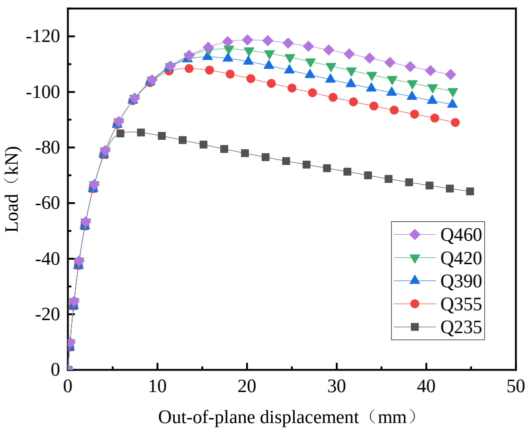

Fig. 10. Different flange yield strength load-Out-of-plane displacement curves

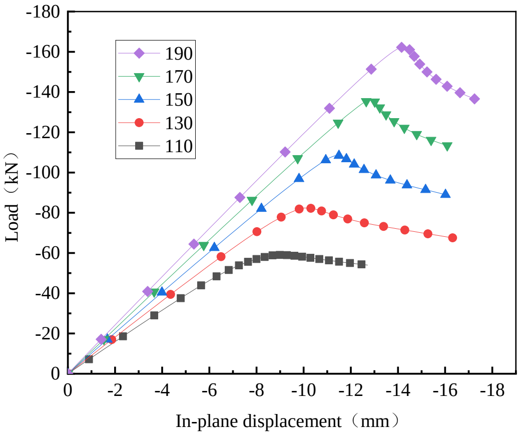

Fig. 11. Load-In-plane displacement curves of different flange widths

It can be seen from Figures 9 and 10 that as the flange yield strength increases, the out-of-plane stability bearing capacity of the member continues to increase; the slopes of the load-in-plane displacement and load-out-of-plane displacement curves at the elastic stage of each model are unchanged basically, it shows that the change of flange strength has little effect on the stiffness of the member in the elastic stage

4.2 Flange width

Adjust the flange width of model C to 110mm, 130mm, 150mm, 170mm, 190mm, establish 5 models for analysis, draw the load-in-plane displacement and load-out-of-plane displacement curves of each model at the mid-span position according to the loading point data. As shown in Figures 11 and 12.

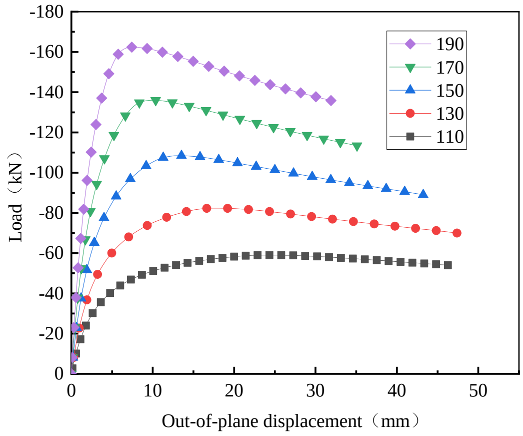

Fig. 12. Load-Out-of-plane displacement curves of different flange widths

It can be seen from Figures 11 and 12 that as the width of the flange increases, the out-of-plane stability bearing capacity of the component is greatly improved. The slopes of the load-in-plane displacement and load-out-of-plane displacement curves in the elastic stage increase with the increase of the flange width, indicating that increasing the flange width greatly improves the in-plane and out-of-plane stiffness in the elastic stage; Although the in-plane displacement increases when the member reaches the ultimate load, the out-of-plane displacement decreases a lot. It means that after increasing the flange width, the out-of-plane stiffness increases, the out-of-plane deformation decreases, and the ultimate bearing capacity increases, which can be described as " Get three kills with one stone."

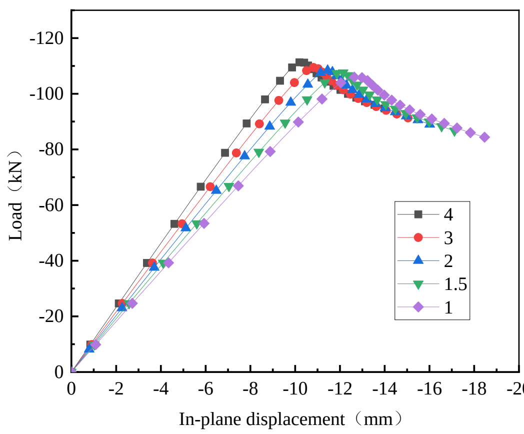

Fig. 13. Load-In-plane displacement curve of different web thickness

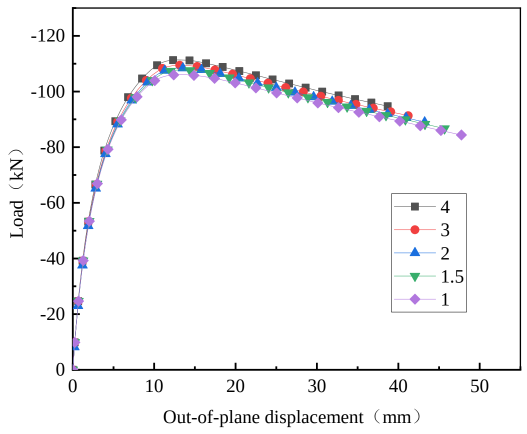

Fig. 14. Load-Out-of-plane displacement curve of different web thickness

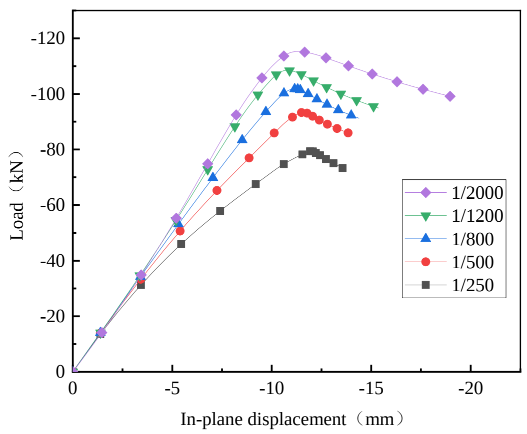

Fig. 15. Different initial defect load-In-plane displacement curves

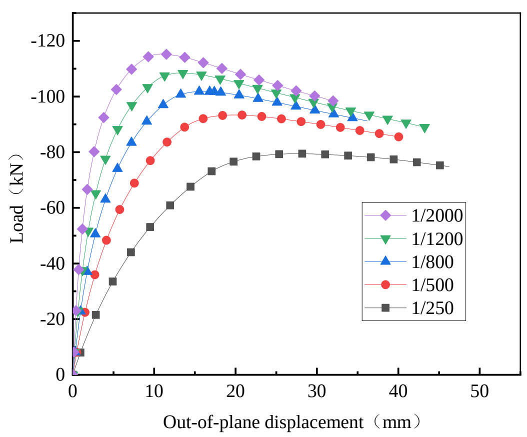

Fig. 16. Different initial defect load-Out-of-plane displacement curves

4.3 Web thickness

Adjust the web thickness of model C to 1mm, 1.5mm, 2mm, 3mm, 4mm, and establish 5 models for analysis. The load-in-plane displacement and load-out-of-plane displacement curves of each model are shown in Figures 13 and 14.

It can be seen from Figures 13 and 14 that when the web thickness is increased, the out-of-plane stability bearing capacity of the beam-column with multi-steel and corrugated web mixtures slightly increases. In the elastic stage of the component, as the thickness increases, the slope of the load-in-plane displacement curve increases to a certain extent, while the slope of the load-out-of-plane displacement curve remains unchanged basically; It shows that the change of the web thickness has little effect on the out-of-plane stiffness of the member, and has almost no effect on the ultimate bearing capacity, which verifies that the corrugated web hardly bears normal stress.

4.4 Initial defect

Apply the initial bending of the member length 1/250, 1/500, 1/800, 1/1200, 1/2000 (that is, 16, 8, 5, 3.3, 2mm respectively) as initial defects to model C, and establish 5 types of Model analysis, drawing the load-in-plane displacement and load-out-of-plane displacement curves at the mid-span position of each model, as shown in Figures 15 and 16.

It can be seen from Figures 15 and 16 that when the initial defects continue to decrease, the critical load continues to increase. In the elastic stage, the slope of the load-in-plane displacement curve of the component increases to a certain extent, and the slope of the load-out-of-plane displacement curve increases greatly, indicating that with the reduction of the initial defect, the in-plane and out-of-plane stiffness of the component gradually increasing, and the in-plane and out-of-plane displacements that reach the ultimate load are continuously decreasing.

5. Verification of the proposed calculation formula for the out-of-plane overall stability of beam-column with multi-steel and corrugated web mixtures

Post-processing, the mid-span load F_{n1}, axial load F_{n2}, and the mid-span critical bending moment value M_1 of the out-of-plane instability of beam-column with multi-steel and corrugated web mixtures are calculated by using ABAQUS.

Equation (1) is the formula for out-of-plane stability of the (Single steel type) corrugated web in the "Specifications", and the calculated maximum mid-span bending moment is represented by M_2. Taking into account that the webs of beam-column with multi-steel and corrugated web mixtures may yield earlier than the flanges, thereby reducing the out-of-plane stability of the beam-column, the maximum bending moment value M_2 for a single steel type is multiplied by the reduction factor R_e of formula (6) and set it as the maximum bending moment value of beam-column with multi-steel and corrugated web mixtures, denoted by M_3. The critical bending moment value M_1 obtained by each model is compared with the theoretical values M_2 and M_3, as shown in Table 2 below.

Finite element analysis was carried out for a total of 15 components in 3 groups, and compared with the maximum mid-span bending moment calculated by the formula, it was found that: except for the extremely small width of individual flanges that rarely occurs in actual engineering, Most of M_1/M_2 and M_1/M_3 is concentrated between 1.0 and 1.2. The finite element analysis result is always greater than the calculation result of the formula in the *Regulations*, which shows that it is feasible to use formula (1) to check the out-of-plane stability bearing capacity of the beam-column with multi-steel and corrugated web mixtures. However, considering the low strength of the web material and the high strength of the flange material in the mixed component, when the component is out-of-plane instability, the web may have yielded, thereby reducing the stability bearing capacity. Therefore, when calculating the maximum out-of-plane overall stability of the beam-column with multi-steel and corrugated web mixtures, the reduced maximum bending moment value M_3 is closer to the actual situation and has higher safety.

Tab.2 Comparison of finite element results and theoretical results of out-of-plane stabilizing capacity of beam-column with multi-steel and corrugated web mixtures

Serial number	Variable	Variable value	Fn_1 ,Fn_2(kN)	M_1(kN・m)	M_2(kN・m)	R_e	M_3(kN・m)	M_1/M_2	M_1/M_3
1	Yield strength of flange material （N/mm2）	235	85.58	82.37	75.06	0.998	74.91	1.10	1.10
2		355	108.45	104.38	99.07	0.998	98.87	1.05	1.06
3		390	112.62	108.40	104.98	0.996	104.56	1.03	1.04
4		420	115.52	111.19	109.34	0.995	108.79	1.02	1.02
5		460	118.70	114.25	114.46	0.994	113.77	1.00	1.00
6	Flange width (mm)	110	59.02	56.81	41.32	0.990	40.91	1.37	1.39
7		130	82.37	79.28	64.68	1.000	64.68	1.23	1.23
8		150	108.45	104.38	89.21	0.998	89.03	1.17	1.17
9		170	136.01	130.91	117.51	0.996	117.04	1.11	1.12
10		190	162.41	156.32	147.29	0.995	146.55	1.06	1.07
11	Web thickness (mm)	4	111.35	107.17	98.17	0.996	97.78	1.09	1.10
12		3	109.43	105.33	98.77	0.997	98.47	1.07	1.07
13		2	108.45	104.38	99.07	0.998	98.87	1.05	1.06
14		1.5	107.74	103.70	99.29	0.998	99.09	1.04	1.05
15		1	106.11	102.13	99.79	0.999	99.69	1.02	1.02

6. Conclusion

The advantages of corrugated web components and multi-steel components are introduced. Combining the two, beam-column with multi-steel and corrugated web mixtures is proposed. Using ABAQUS finite element software to model, analyze the advantages of this new type of beam-column in terms of bearing capacity and steel consumption; and through theoretical analysis, the calculation method of the out-of-plane overall stability of this beam-column is put forward, compared with the finite element results, the correctness of the formula is verified; and it provides a reference for the design of columns that mainly bear compressive and bending loads in actual engineering, and draws the following conclusions:

(1) Compared with single-steel flat webs and corrugated web compression-bending components, beam-column with multi-steel and corrugated web mixtures have better performance in terms of load-bearing capacity and steel consumption.

(2) Increasing the flange strength of the beam-column with multi-steel and corrugated web mixtures, the out-of-plane stability bearing capacity of the member is greatly improved, but it has almost no effect on the out-of-plane stiffness of the member in the elastic stage.

(3) Increasing the flange width can not only increase the out-of-plane stability bearing capacity and out-of-plane rigidity but also greatly reduce the out-of-plane displacement, indicating that increasing the flange width is an effective way to improve its overall out-of-plane stability.

(4) The web thickness has little effect on the overall out-of-plane stability; initial defects have a certain impact on the overall out-of-plane stability.

(5) The proposed calculation method for the out-of-plane overall stability of beam-column with multi-steel and corrugated web mixtures is proposed.

Acknowledgements

This work was supported by the Science and Technology Development Programs of Handan City (Grant No.19422111008-23).

References

American Institute of Steel Construction, 1999.AISC1999:Load and resistance factor design specification for structural steel buildings. American: American Institute of Steel Construction, Inc., 108.

B. Kövesdi, B. Jáger, L. D.,2016. Bending and shear interaction behavior of girders with trapezoidally corrugated webs. Journal of Constructional Steel Research, 121.

China Association for Engineering Construction Standardization,2011. CECS291-2011: Technical specification for steel structures with corrugated webs. Beijing: China Planning Press, 9-14.

Construction Engineering,2016; Report Summarizes Construction Engineering Study Findings from Budapest University of Technology and Economics (Bending and shear interaction behavior of girders with trapezoidally corrugated webs). Journal of Engineering.

G. Kiymaz, E. Coskun, C. Cosgun, E. S.,2010. Transverse load carrying capacity of sinusoidally corrugated steel web beams with web openings. Steel and Composite Structures, 10(1).

Hassan H. Abbas,Richard S.,Robert G. D.,2007. Analysis of Flange Transverse Bending of Corrugated Web I-Girders under In-Plane Loads. Journal of Structural Engineering, 133(3).

Hongbo Zhou, Junjie Zhou, Aiping Pang .,2021.Adaptive Control Design for a Class of Systems with Modal Uncertainty. International Journal of Applied Mathematics in Control Engineering (IJAMCE) Vol.4, No.1, (40-45).

John Papangelis, Nicholas T., Gregory H.,2017. Direct strength method for shear capacity of beams with corrugated webs. Journal of Constructional Steel Research,137.

Liying Lang, Aihong Kang , Xueguang Wang , Hui Zhao.,2020. Research on Theoretical Analysis Method Based on Maximizing Deviation International Journal of Applied Mathematics in Control Engineering (IJAMCE), Vol.3, No.1, (72-77).

Mohamed Elgaaly, Robert W. H, A. S., 1996. Shear Strength of Beams with Corrugated Webs.Journal of Structural Engineering. 122,4.

Moon J, Yi J W, Choi B H . et al.,2009 Lateral–torsional buckling of I-girder with corrugated webs under uniform bending. Thin-Walled Structures, 47(1):21-30.

Muslim A. Al Kannoon,Al K. M. A.,Suhiel I. A..,2020. Experimentally Flexural Behaviour Study of Steel Beams with Corrugated Webs. IOP Conference Series: Materials Science and Engineering, 888(1).

Nikoomanesh Mohammad Reza, Goudarzi M. A.,2020. Experimental and numerical evaluation of shear load capacity for sinusoidal corrugated web girders[J]. Thin-Walled Structures, 153.

Qazi Inaam, Akhil U..,2020. Flexural behaviour of steel I-girder having corrugated webs and slender flanges. Structures, 27.

Rao N N, Marek P ,Tall L .,1972. Welded hybrid steel columns. Welding Journal, 51:462s-472s.

R. Luo, B. Edlund.,1996. Shear capacity of plate girders with trapezoidally corrugated webs. Thin-Walled Structures.26(1).

Sayed-Ahmed E Y. . , 2007. Design aspects of steel I-girders with corrugated steel webs.Electronic Journal of Structural Engineering, 7,27-40.

Veljkovic M,Johansson B.,2004. Design of hybrid steel girders. Journal of Constructional Steel Research, 60(3/5):535-547.

Vladimir Zubkov,Alexey L.,Vadim A.,2018. Experimental research of beams with corrugated web. MATEC Web of Conferences, 196.

Weicun Zhang .,2021.Stability Analysis of Switching Multiple Model Adaptive Control. International Journal of Applied Mathematics in Control Engineering (IJAMCE), Vol. 4, No.1, (74-79).

Xuqun Lin, Harry F., Ali S.,2019. Structural Behaviour and Mechanical Properties of Welded Steel I-Girders with Corrugated Webs. International Journal of Steel Structures, 19(4).

Yong-Bo Shao,Refat E. A.,Hassanein M.F..,2021. On the out-of-plane stiffness of I-section girders with corrugated webs using elastic finite element analyses. , 29.

Yong-Bo Shao,Yu-Mei Zhang,M.F. Hassanein.,2020. Strength and behaviour of laterally-unrestrained S690 high-strength steel hybrid girders with corrugated webs.Thin-Walled Structures.150.

Gu Ruipeng is currently pursuing his master's study at the College of Civil Engineering, Hebei University of Engineering, Handan, China. He obtained his Bachelor of Engineering degree from Hebei University of Engineering in 2019. His main research interests are steel structures. Email: 747820621@qq.com

Li Qingyang is a master tutor, she has the title of professor and senior engineer. Her research interest is steel structure.
Email: liqingyang1111@126.com

Wei Wei received his MS Degree in Solid mechanics from Yanshan University, Qinhuangdao, China, in 2005. He later received the PhD degree in mechanics at Beijing University of technology, Beijing, China, in 2017. His research interest is computational mechanics.
Email: weiwei@hebeu.edu.cn