Finite Element Analysis on Hysteretic Behavior of H-shaped Columns of Thin-Walled Sections of 690 MPa High Strength Steel

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Abstract. High strength steel is widely used in engineering, especially in light steel structures. However, due to the material properties of high strength steel, its seismic performance has attracted wide attention. To study the hysteretic behavior of H-shaped members of thin-walled sections of Q690 high strength steel, a finite element model was built up by using the general finite element analysis software ABAQUS. Based on the finite element model, an extensive parametric analysis of H-shaped members of thin-walled sections of Q690 high strength steel was carried out. The results showed that the limiting flange width-thickness ratio and web height-thickness ratio for H-shaped members of Q690 high strength steel were recommended to be 11 and 65, respectively, in actual engineering. Also, an increase in web height-thickness ratio and axial compression ratio could lead to a significant decrease in the ductility of H-shaped members of thin-walled sections of Q690 high strength steel. The thinner and more flexible the section is, the larger the axial compression ratio is, further reducing the energy dissipation ability of the members.

1. Introduction

In recent years, with the widespread application of high-strength structural steels (with a yield strength of not less than 460 MPa, and hereinafter referred to as HSS) in construction projects, the seismic performance of high strength steels has been gaining prominent attention [1, 2]. Generally, in order to ensure the plastic rotation capacity of structural members under seismic actions, steel structures are usually designed as members with a small section width-thickness ratio. When the weight per unit length is certain, since HSS members with a larger section width-thickness ratio have greater bending stiffness, yield moment, and overall elastic stability than those with a smaller section width-thickness ratio, HSS members have good economic advantages and can be used in multi-story light steel structural systems [3]. However, due to their large width-thickness ratio, slabs usually are locally unstable, making it hard for the members to fully develop their plastic bending capacity. Besides, the members have low ductility and energy dissipation capacity, which greatly limits their applications in seismic design with high requirements for the plastic energy dissipation capacity of the members [4].

In the Chinese Code for Design of Steel Structures (GB50017-2017) [5], sections are divided into five classes, that is, S1, S2, S3, S4, and S5. Systematic studies on the hysteretic behavior of Q690 HSS H-shaped members with a section class of S1, S2, and S3 have been conducted. Chen et al [6-7] performed cyclic loading tests and finite element analysis for Q690D HSS welded H-section and box-
section columns. The results showed that the members had good energy dissipation capacity and the maximum inter-story displacement angle met the requirements of the Code for Design of Seismic Design of Buildings (GB 50011-2010) [4]. Through the study on Q690D HSS compact H-sections, Hai et al [8, 9] found that Class 1 and Class 2 H-sections had good plastic rotation capacity and could be used in seismic steel framing systems according to Eurocode [10] (EC3). However, few studies have been conducted for H-shaped members of Q690 thin-walled sections with a relatively large section width-thickness ratio.

In order to study the hysteretic behavior of H-shaped members of Q690 thin-walled sections, this paper established a finite element analysis model using the general finite element analysis software ABAQUS and conducted a parametric analysis for the hysteretic behavior of cantilever columns under constant axial force and horizontal cyclic load. In addition, the effects of web width-thickness ratio, flange width-thickness ratio, and axial compression ratio on the hysteretic behavior of H-shaped columns of Q690 thin-walled sections were analyzed.

2. Establishment of Finite Element Model

2.1 Material Model

The Mises yield criterion and the kinematic hardening model were used, and the trifold model was adopted in the material constitutive model. In parametric analysis, the measured values of 10mm Q690D steels in tensile testing in the literature [11] were used as the material strength. The yield strength $f_y$ of the steel plates was 823.7 MPa, the ultimate strength $f_u$ was 890.4 MPa, the elastic modulus $E$ was 207 GPa, and the tangential modulus in the strengthening phase was taken as $E_h=\frac{1}{100}E$ with a Poisson's ratio of 0.3.

2.2 Boundary Conditions and Mesh Division

The S4R element was used for building the model with a uniform mesh division pattern as shown in Fig. 1. The boundary conditions of the finite element analysis were the same as that of the test, with the top being the free end and the bottom being completely rigidly connected. The boundary conditions of the finite element analysis were used as shown in Fig. 2.

2.3 Division Initial Defects and Residual Stresses

Through eigenvalue buckling analysis, the first-order buckling mode of the members under the combined actions of axial and horizontal loads was obtained, which could be used as the geometric initial defect mode. Then the mode was applied to the overall model. The size of the geometric defects was taken as $B/100$ and the minimum value was 2 mm [12], where $B$ was the width of the flange of the H-shaped members. Considering the effects of residual stresses, the Q690 residual stress distribution model proposed by Li et al [13] was used and applied to the overall model.

3. Parametric Analysis

3.1 Parameter Setting

Based on the verified finite element model, an extensive parametric analysis was performed on the H-shaped members of Q690 HSS thin-walled sections. According to the classification of plate sections in GB 20017-2017 [5], the sections with a section class of S5 are called thin-walled sections ($M_u < M_y$). Therefore, the limiting width-thickness ratio of S5 sections was used for the parametric analysis (Table 1). For the parametric analysis, five groups of members were selected in terms of flange width-thickness ratio and web width-thickness ratio, that is, 11, 13, 15, 17, 19 and 55, 60, 65, 70, 75, respectively. The axial compression ratio was 0.2 and 0.35, and a total of 50 members was selected, and all the members were of the S5 section. The naming rule of the members is H-x-y-z, where H stands for H-shaped section member, x stands for flange width-thickness ratio, y stands for web height-thickness ratio, and z stands for axial compression ratio.
3.2 Ultimate Bearing Capacity

Table 2 shows the calculation results of the members through the parametric analysis. The ultimate flexural bearing capacity $M_u$ can be obtained from the peak value of the $M$-$\theta$ curve. The nondimensionalized ultimate bearing capacity ($M_u/M_p$, $M_u/M_y$) reflects the plastic development capacity of the section to a certain extent, where $M_p$ is the plastic moment of the full section with the influence of the axial force into consideration and $M_f$ is the elastic yield moment calculated according to the elastic theory. The $M_u/M_p$ value of all members is summarized in Fig. 3 and Fig. 4. Fig. 3 shows the effect of flange width-thickness ratio and axial compression ratio on $M_u/M_p$, from which it can be seen that $M_u/M_p$ decreases with the increase of flange width-thickness ratio. As we can see from Fig. 4, the effect of web height-thickness ratio on $M_u/M_f$ of the members is significantly smaller than that of the flange width-thickness ratio and shows a slowly decreasing trend, indicating that the flange width-thickness ratio is a decisive factor affecting the ultimate bearing capacity of the members. In addition, from Table 2, it can be seen that $M_u/M_p$ is either greater than 1 or less than 1, which means that the members are in an elastic state or can only develop limited plastic capacity when reaching the ultimate bearing capacity. In this case, the members belong to an S4 section or S5 section, which is because the current code does not consider the interaction between the plates. Under the premise of considering the interaction between the plates, the limiting width-thickness ratio of the plates of the compression-bending members of Q690 HSS H-shaped sections can be extended appropriately. Based on the calculated data in Table 2, in order to ensure that the members can enter the plastic stage under the compression-bending load state and give full play to the plastic capacity of the sections, it is recommended that the limiting flange width-thickness ratio of Q690 HSS H-shaped members in engineering is 11, and the limiting web height-thickness ratio is 65, and the latter can be extended to 75 when the frame column is subjected to a relatively smaller axial force.

Table 1 Limiting Width-Thickness Ratio of Q690 HSS Compression-Bending Members

| Section Class | S4 | S5 |
|---------------|----|----|
| Flange $h/t_f$ | 15$\delta_k$ | 20$\delta_k$ |
| Web $h/t_w$   | $(45+25\alpha_0^{1.66})\delta_k$ | 250$\delta_k$ |

Table 2 Calculation Results of Members

| Member No.     | $M_u/M_y$ | $M_u/M_p$ | $M_u/M_f$ |
|----------------|-----------|-----------|-----------|
| Axial Compression Ratio | 0.2 | 0.35 | 0.2 | 0.35 |
| H-11-55-0.2/0.35 | 1.15 | 1.10 | 0.84 | 0.67 |
| H-13-55-0.2/0.35 | 1.05 | 0.97 | 0.77 | 0.60 |
| H-15-55-0.2/0.35 | 0.97 | 0.84 | 0.72 | 0.54 |
| H-17-55-0.2/0.35 | 0.89 | 0.80 | 0.67 | 0.51 |
| H-19-55-0.2/0.35 | 0.84 | 0.73 | 0.64 | 0.47 |
| H-11-60-0.2/0.35 | 1.16 | 1.06 | 0.83 | 0.64 |
| H-13-60-0.2/0.35 | 1.04 | 0.95 | 0.76 | 0.58 |
| H-15-60-0.2/0.35 | 0.95 | 0.83 | 0.70 | 0.52 |
3.3 Ductility

Ductility is an important characteristic of the seismic performance of the member, characterizing the plastic deformation capacity of the member under seismic loading. $\theta_u$ is used to describe the ductility of the member [10], where $\theta_u$ is the angle of rotation when the load drops to 0.85 times the ultimate load after the member reaches its limit. The $\theta_u$ value of all members is divided into four groups in terms of the flange width-thickness ratio, web height-thickness ratio, and axial compression ratio, as shown in Fig. 5 and Fig. 6. By comparing Fig. 6 and Fig. 7, it can be seen that the web height-thickness ratio is the decisive factor affecting the ductility of the members. The ductility of the members decreases significantly with the increase of the web height-thickness ratio, with an average decrease rate of 25.3%, while that of the flange width-thickness ratio is only 6.4%. By comparing Fig. 5(a) and Fig. 5(b), Fig. 6(a) and Fig. 6(b), respectively, it can be seen that with the increase of the axial compression ratio, the ductility of the members decreases significantly, with an average decrease rate of 24.4% and 25.7%, respectively. In summary, increasing the web height-thickness ratio and axial compression ratio will cause a significant decrease in the ductility of the members, which is not conducive to the development of plastic deformation.

![Graph](image-url)

(a) Member with Axial Compression Ratio of 0.2  (b) Member with Axial Compression Ratio of 0.35

Fig. 3. Effect of Flange Width-Thickness Ratio and Axial Compression Ratio on $M_u/M_p$.
Fig. 4. Effect of Web Height-Thickness Ratio and Axial Compression Ratio on $M_u/M_p$

Fig. 5. Effect of Flange Width-Thickness Ratio and Axial Compression Ratio on Ductility

Fig. 6. Effect of Web Height-Thickness Ratio and Axial Compression Ratio on Ductility
3.4 Energy Dissipation Capacity

The energy dissipation capacity is an important indicator for evaluating the seismic performance of
the members. In this paper, the energy dissipation capacity of the members and their development
trend are evaluated by using the whole-process nondimensionalized energy dissipation coefficient. The
sum of the area enclosed by each hysteresis loop in the \( M-\theta \) curve is nondimensionalized by the yield
rotation angle and yield bending moment. The nondimensionalized energy dissipation coefficient \( h_e \)
can be obtained as follows.

\[
h_e = \frac{\sum_{i=1}^{n} E_i}{M_i \theta_i}
\]  

where \( E_i \) is the energy consumed by each cycle of the member.

The effects of flange width-thickness ratio, web height-thickness ratio, and axial compression ratio
on the energy dissipation coefficient are shown in Figs. 7, 8, and 9, respectively. It can be found that
the energy dissipation coefficient decreases with the increase of the flange width-thickness ratio. This
is because the larger the flange width-thickness ratio is, the earlier the local buckling appears, and the
more significantly the bearing capacity decreases. However, it can be seen from Fig. 8 that the increase of web height-thickness ratio has a favorable effect on the energy dissipation coefficient to some extent. But when the number of cycles continues to increase, the energy dissipation coefficient starts to decrease with the increase of the web height-thickness ratio. The reason is that with the increase of the web height-thickness ratio, the sectional area of the member will grow, thus increasing the ultimate bearing capacity of the member. Therefore, there is an increase in the energy dissipation coefficient during the first few cycles, but after exceeding the limit, the excessive width-thickness ratio will accelerate the degradation of the bearing capacity of the member, which will have a negative impact on the energy dissipation. The effect of axial compression ratio on the energy dissipation coefficient is shown in Fig. 9. The increase of axial compression ratio enables the member to enter the energy dissipation stage in advance, but with the increase of the number of cycles, after exceeding the limit, the excessive axial compression ratio will accelerate the degradation of the member, further leading to the loss of the bearing capacity so that the member cannot dissipate energy.

![Graph](image)

Fig. 9. Effect of Axial Compression Ratio on Energy Dissipation Coefficient

4. Conclusions
In order to fully understand the seismic performance of thin-walled high-strength steel members, based on the established finite element model, a parametric study of H-shaped members of Q690 HSS thin-walled sections was conducted to analysed the effects of flange width-thickness ratio, web height-thickness ratio, and axial compression ratio on the ultimate bearing capacity, ductility, and energy dissipation capacity. The main conclusions are as follows.

1. Under the category of the S5 section, the flange width-thickness ratio is the decisive factor affecting the ultimate bearing capacity of Q690 HSS H-shaped members, and the impact of web height-thickness ratio on the ultimate bearing capacity is relatively weaker.

2. In the actual engineering with regard to Q690 HSS H-shaped members, it is recommended that the limiting flange width-thickness ratio and web height-thickness ratio are 11 and 65, respectively. Further study on the interaction between flange and web of high strength steel members is needed to guide engineering practice.

3. The increase of axial compression ratio and web height-thickness ratio will significantly reduce the ductility of the members. The thinner and more flexible the sections are, the larger the axial compression ratio is, and the more negative the impacts on the energy dissipation of the members are.

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