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Lateral Torsional Buckling Investigation on Welded Q460GJ Structural Steel Unrestrained Beams under a Point Load

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***Abstract*—**This study aims to investigate the lateral torsional buckling of I-shaped cross-section beams fabricated from Q460GJ structural steel plates. Both experimental and numerical simulation results are presented in this paper. A total of eight specimens were tested under a three-point bending, and the corresponding numerical models were established to conduct parametric studies. The effects of some key parameters such as the non-dimensional member slenderness and the height-to-width ratio, were investigated based on the verified numerical models. Also, the results obtained from the parametric studies were compared with the predictions calculated by different design codes including the Chinese design code (GB50017-2003, 2003), the new draft version of Chinese design code (GB50017-201X, 2012), Eurocode 3 (EC3, 2005) and the North America design code (ANSI/AISC360-10, 2010). These comparisons indicated that the sectional height-to-width ratio does not play an important role to influence the overall stability load-carrying capacity of Q460GJ structural steel beams with welded I-shaped cross-sections. It was also found that the design methods in GB50017-2003 and ANSI/AISC360-10 overestimate the overall stability and load-carrying capacity of Q460GJ welded I-shaped cross-section beams.

***Keywords*—**Experimental study, finite element analysis, global stability, lateral torsional buckling, Q460GJ structural steel.

I. Introduction

HIGH Strength Steel (HSS) is a specific class of steel with yield stress greater than or equal to 460 MPa [1]. Compared with mild steel, HSS has higher yield strength, which means that using HSS in construction would generate comprehensive benefits, such as lightening deadweight, saving materials, and hence reducing construction time and protecting the environment. Due to those benefits, HSS has been increasingly used in many building and bridge constructions. HSS usually contains higher amounts of carbon equivalent and is prone to be quenched quickly after rolling. The mechanical properties of HSS may be different from mild steel due to the quenching process and/or the higher carbon equivalent.

Ban et al. [2] investigated the magnitude and distribution of residual stress in Q460 MPa steel welded I sections using sectioning method. Kubo and Fukumoto [3] conducted experimental tests and numerical simulations on cold-formed lean duplex stainless steel flexural members. Gao et al. [4] investigated the load-carrying capacity of thin-walled box-section stub columns fabricated by G550 with the nominal yield strength of 550 MPa. Ban et al. [5] investigated the overall buckling behaviour of 460 MPa HSS welded box and I-section columns, and finally they proposed the appropriate column curves and design formulae for each type of column. Liu and Gannon [6] conducted experimental tests on W-shaped beams under a four-point loading to investigate the behaviour and capacity of flexural members strengthened while under load. Gelera and Park [7] investigated the elastic lateral torsional buckling behaviour of stepped I-beams. Wang et al. [8] investigated the magnitude and distribution of residual stresses in 460 MPa HSS welded box sections fabricated from plates of 11 mm in thickness. Wang et al. [9] conducted experimental tests and numerical studies to find an appropriate design method for welded 460 MPa HSS H-section columns. Wang et al. [10] carried out an experimental study on welded box-columns fabricated from HSS with a nominal yield strength of 460 MPa under axial compression.

The research group of the authors is conducting a series of studies on GJ structural steel members. Yang et al. [11] investigated the lateral torsional buckling behaviour of welded H-section beams fabricated from Q345GJ structural steel under a concentrated load. It can be found in this paper that the predictions for flexural strengths of Q345GJ structural steel beams of GB50017-201X (2012) and EC3 (2005) are little conservative. Yang et al. [12] studied the magnitude and distribution of residual stress in Q460GJ structural steel welded I sections by using sectioning method. They found that the residual stresses on the tested sectional flanges were much smaller than the existing residual stress distribution models, and the flange tips were all under compression rather than tension. Xiong et al. [13] carried out experimental and numerical studies on the global stability behaviour of Q460GJ structural steel beams restrained at mid-span. They found that the global stability design methods for rolled sections or equivalent welded sections in GB50017-2003 (2003) [14] and ANSI/AISC360-10 (2010) [15] might not be conservative for Q460GJ structural steel beams with lateral restraints at mid-span, while it might be more appropriate/reasonable in GB50017-201X (2012) [16] and EC3 (2005) [17].

It should be noticed that the previous research on HSS focused mainly on the overall buckling behaviour of columns

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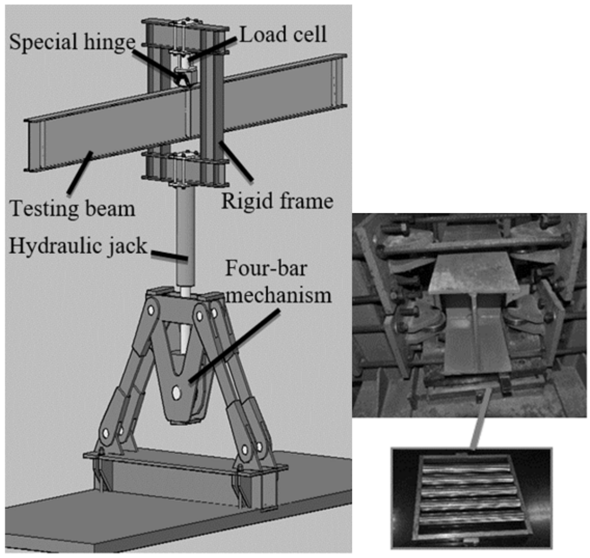
and only few papers investigated the overall buckling behaviour of beams. Beams play such an important role in the building structure that their overall buckling behaviour should be taken into consideration seriously. Several different calculation methods were put forward in the present design codes including China code (GB50017-2003, 2003; GB50017-201X, 2012), Eurocode 3 (EC3, 2005) and American code (ANSI/AISC360-10, 2010) to predict the overall buckling capacity of flexural members. The previous research outlined above showed wide variations in the predicted capacity of HSS-section members using the available design rules. Thus, it is necessary to investigate the overall buckling capacity and to determine the appropriate design curve for welded 460 MPa HSS H-section flexural members.

In order to find out the global stability behaviour of Q460GJ structural steel beams, a total of eight simply supported beam specimens with different slenderness and height-to-width ratios were tested. All the specimens failed by lateral-torsional buckling without any interaction of local buckling or bearing. In the loading system, the vertical force provided by a hydraulic jack can move freely along the lateral direction, which allows lateral torsional buckling of the tested beams to occur without mid-span restraint. The tested specimens were simply supported. To achieve the ideal loading and supporting boundary conditions, a special test set-up was designed. The stability load carrying capacities of the tested specimens can also be obtained by Finite Element Analysis (FEA) simulations. By comparing the test results with FEA results, the FEA models were verified. Subsequently, the verified FEA models were used in the parametric studies to obtain more data of the stability behaviour of welded Q460GJ structural steel simply-supported beams. Meanwhile, the results from parametric studies were compared with the values calculated from the present design codes including China code (GB50017-2003, 2003; GB50017-201X, 2012), Eurocode 3 (EC3, 2005) and American code (ANSI/AISC360-10, 2010). It is noteworthy that GB50017-2003 (2003) is the current steel structure design code in China, and GB50017-201X (2012) is a draft version of the code which is expected to be released in the near future. Based on these studies, some important conclusions on the global stability of Q460GJ structural steel simply-supported beams were drawn towards the end of the paper.

II. Experimental Studies

A. Test Setup

All the calculations for LTB load-carrying capacities in design codes are based on the theoretical formula which is obtained under the ideal boundary condition and the loading condition. Thus, a special test setup was designed and fabricated to achieve the ideal boundary condition and the loading condition. The load-carrying capacities obtained from the experiments would be close to the results which came from the design codes based on the theoretical formula by using the special test set-up above. The ideal loading condition is that the vertical force applied at mid-span must be kept vertical and move with the top flange of the beam specimen simultaneously. Fig. 1 (a) shows that the loading system is composed of a rigid loading frame, a four-bar mechanism, a load cell, a special hinge, and a hydraulic jack. A vertical load that can move freely along the lateral direction was provided by the hydraulic jack, and its magnitude could be measured by the load cell. Fig. 1 (b) shows a photograph of the supporting system. When the specimen sustains a vertical loading, the ends of the specimen can rotate freely in the plane of bending, but cannot rotate out of the plane of bending.



(a) (b)

Fig. 1 (a) The schematic diagram of the special loading system; (b) The photograph of the supporting system

Fig. 2 is the schematic diagram of four-bar mechanism. Rods AC and BD are connected to the rigid block CDE and foundation AB by using roller bearings, whereas the hydraulic jack and the rigid block CDE are joined together at the point E. Thus, the rigid block CDE could move and rotate by a number of forces applied by rods AC and BD and the hydraulic jack. The directions of the forces applied by rods AC and BD coincide with the axes of rods AC and BD. This means that only if the axis of hydraulic jack coincides with line EF, the rigid block CDE can be in equilibrium. So, the configuration of the four-bar mechanism was designed specially in order to satisfy the equilibrium condition. In Fig. 2, C`D`E` is the initial position of the rigid block CDE, F` is the intersection point of lines AC` and BD`, CDE is the final position of the rigid block CDE, and F is the intersection point of Lines AC and BD. Table I lists the reaction beams, which could release the longitudinal displacement of the tested beams.

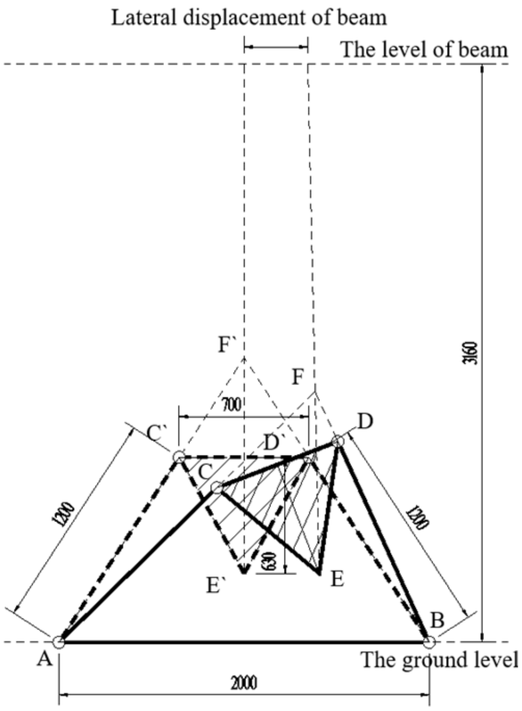


Fig. 2 The schematic diagram of four-bar mechanism

TABLE I
THE TILT OF LINE EF CHANGED WITH INCLINED ANGLE OF ROD AB

Lateral displacement of beam specimen (mm)	Tilt of Line EF (°)
0	0.00
6	0.09
11	0.18
17	0.27
22	0.36
28	0.45
33	0.53
39	0.62
44	0.70
50	0.78
55	0.86
60	0.94
66	1.02
71	1.09
77	1.16
82	1.24
87	1.31
93	1.38
98	1.44

B. Material Properties

The material properties of the beam were carried out by tensile coupon tests. The test coupons were cut from the plates used to weld the beam specimens. All the coupons were tested under the requirements of the code of tensile testing GB/T228.1-2010 (2010) [18]. And the method of the tensile coupon tests was descripted in the code above. The test results are listed in Table II, and the stress-strain curves are shown in Fig. 3.

TABLE II
MECHANICAL PROPERTIES OF THE PLATES

t [mm]	f_y [MPa]	ε_y [%]	f_u [MPa]	ε_u [%]	E [GPa]
8	541	1.33	669	9.67	204.74
10	525	2.77	613	11.55	202.49

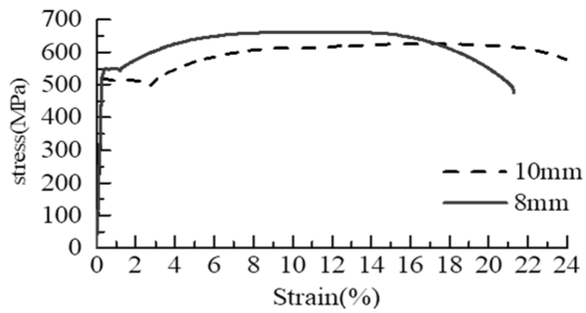
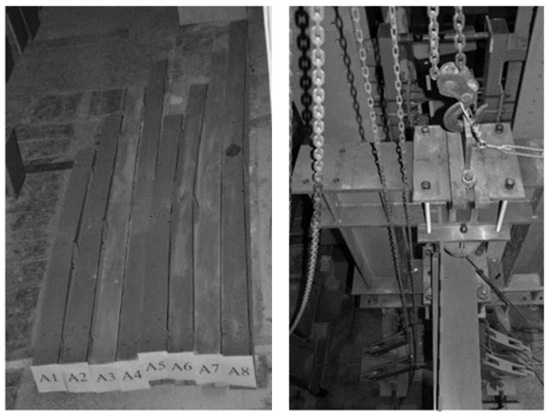


Fig. 3 Tensile stress-strain curves of Q460GJ structural steel

C. Test Results

All beam specimens failed by lateral-torsional buckling without any occurrence of local buckling. Fig. 4 (a) is the photograph of all eight beam specimens after testing. Fig. 4 (b) shows the photograph of one failed beam specimen. Those also indicate that the beam specimen failed in global buckling induced by the lateral bending of the top flange, while neither flange local buckling nor web local bearing failure was observed.



(a) (b)

Fig. 4 (a) All 8 tested beam specimens; (b) Failure mode of the tested specimen

Different from the Code for design of steel structures GB50017-2003 (2003), in the new version of the steel structure design code of China named by GB50017-201X (2012), rolled section beams and welded section beams have been distinguished, and the effect of beam height-to-width ratio on the beam global stability load carrying capacity has been specified. Table III lists the comparisons between experimental results and the results calculated by the methods of different design codes. It should be mentioned that the results of specimen A8 are not shown in Table III because the original sphere joint instead of the improved special joint was used in the loading system. It can be seen from Table III that the experimental results, except specimen A8, are on average 6.3% lower than the design strengths predicted by GB50017-2003 (2003), 12.8% higher than the strengths predicted by GB50017-201X (2012), 39.5% higher than the strength fromEC3 (2005), and 25.6% lower than the design strengths predicted by ANSI/AISC360-10 (2010). It illustrates that the overall stability calculation method for flexural members in GB50017-2003 (2003) and ANSI/AISC360-10 (2010) may not be suitable for the GJ structural steel beams, and the overall stability calculation method for flexural members in the new version of the steel structure design code of China GB50017-201X (2012) may be more suitable for GJ structural steel beams. It also illustrates that the overall stability calculation method for flexural members in EC3 (2005) for rolled sections or equivalent welded sections is conservative for overall stability design of grade Q460 GJ structural steel beams.

TABLE III
COMPARISON OF THE TEST BUCKLING STRENGTH WITH THE CORRESPONDING DESIGN STRENGTHS ACCORDING TO THE DIFFERENT CODES

	Experimental results	GB50017-2003 (2003)		GB50017-201X (2012)		EC3 (2005) for rolled or equivalent welded sections		ANSI/AISC360-10 (2010)	
	P_{exp}	P_{03}	P_{exp}/P_{03}	P_{1X}	P_{exp}/M_{1X}	P_{EC3}	P_{exp}/P_{EC3}	P_{AISC}	P_{exp}/P_{AISC}
A1	483.23	528.36	0.915	480.08	1.007	395.20	1.223	653.05	0.740
A2	345.82	273.68	0.865	251.04	0.979	286.83	1.206	495.14	0.698
A3	297.83	261.82	0.982	227.78	1.173	205.50	1.449	378.98	0.786
A4	216.87	251.31	0.922	210.45	1.135	154.42	1.404	299.15	0.725
A5	526.65	538.08	0.940	471.29	1.132	340.51	1.547	697.93	0.755
A6	383.78	509.60	0.925	420.57	1.171	275.80	1.392	525.41	0.730
A7	314.55	482.04	1.009	380.41	1.299	203.37	1.547	407.31	0.772
Average	—	—	0.937	—	1.128	—	1.395	—	0.744
Standard deviation	—	—	0.002	—	0.047	—	0.277	—	0.030

III. FINITE ELEMENT PARAMETRIC STUDIES

A. Finite Element Model

Finite element analysis (FEA) models were established by the finite element software ABAQUS [19]. The actual dimensions of the beam specimens and true stress-strain relationship of the steel plates were introduced in the FEA models, as shown in Fig. 2. Geometric imperfection, especially the initial bow of the top flanges, is an important characteristic of the beam specimens, which influences the LTB load carrying capacity. The initial bows of the top flanges were measured before the experiment, and the results are introduced in the FEA models to simulate the beam specimens. The initial bow of each beam specimen was approximately considered a half-sin wave, and 1/1000 of the beam span adopted as the peak of the half-sin wave. The magnitudes and distributions of residual stress were adopted as the results in another paper [12] written by the research group.

B. Simulations

Thus, parametric studies are necessary in order to have complete comparisons and cover all the range of non-dimensional slenderness. The key parameters considered in this study are the non-dimensional slenderness parameter and the height-to-width ratios. In order to obtain the relationship between stability load carrying capacities and key parameters, a series of FEA models were established.

In order to study the relationship between the stability load carrying capacities of the Q460GJ structural steel beams and key parameters including the non-dimensional slenderness and the height-to-width ratios, beam specimens simulations with different non-dimensional slenderness and different height-to-width ratios were established by using the FEA models introduced above. Non-dimensional slenderness varying from 0.6 to 2.0 and the height-to-width ratios varying from 1.5 to 2.5 were considered in the parametric study.

C. Comparisons

The comparisons of the parametric study results with the buckling curves from design codes are presented in Fig. 5. The comparisons are very helpful for designer to choose the suitable design code when the GJ structural steel beams are used. This indicates that the overall stability calculation method for flexural members in GB50017-2003 (2003) may not be suitable for the Q460GJ structural steel beams, which failed in the inelastic overall buckling mode, while the overall stability calculation method for flexural members in the new version of the steel structure design code of China (GB50017-201X, 2012) is conservative and may be more suitable than the previous version (B50017-2003, 2003) for Q460GJ structural steel beams. For H270×180×8×10 and H360×180×8×10, of which the height-to-width ratios are equal to or less than 2.0, the buckling curve c is used for stability design, whereas the buckling curve d is used for stability design of H450×180×8×10. It can be seen from Fig. 5 (c) that most stability coefficients of all kinds of beams obtained by parametric studies are much greater than the buckling curves from EC3 (2005). It illustrates that overall stability calculation method of flexural members in EC3 (2005) for rolled sections or equivalent welded sections is conservative for overall stability design of Q460GJ structural steel beams. The comparisons of the parametric study results with the buckling curve from the American code (ANSI/AISC360-10, 2010) for rolled sections or equivalent welded sections are presented in Fig. 5 (d). It can be seen from Fig. 5 (d) that most stability coefficients of H360×180×8×10 and H450×180×8×10 obtained by parametric studies are lower than the buckling curve from ANSI/AISC360-10 (2010), while some stability coefficients of H270×180×8×10 obtained by parametric studies are higher than the buckling curve from ANSI/AISC360-10 (2010). Meanwhile, when the non-dimensional slenderness ratios are in the range of 0.7 to 1.2, almost all of the stability coefficients obtained by parametric studies are lower than the buckling curve from ANSI/AISC360-10 (2010). This indicates that buckling curve from ANSI/AISC360-10 (2010) may not be suitable for the Q460GJ structural steel beams, especially its inelastic transition range. The conclusions obtained by parametric study are similar to the conclusions obtained by the experimental study.

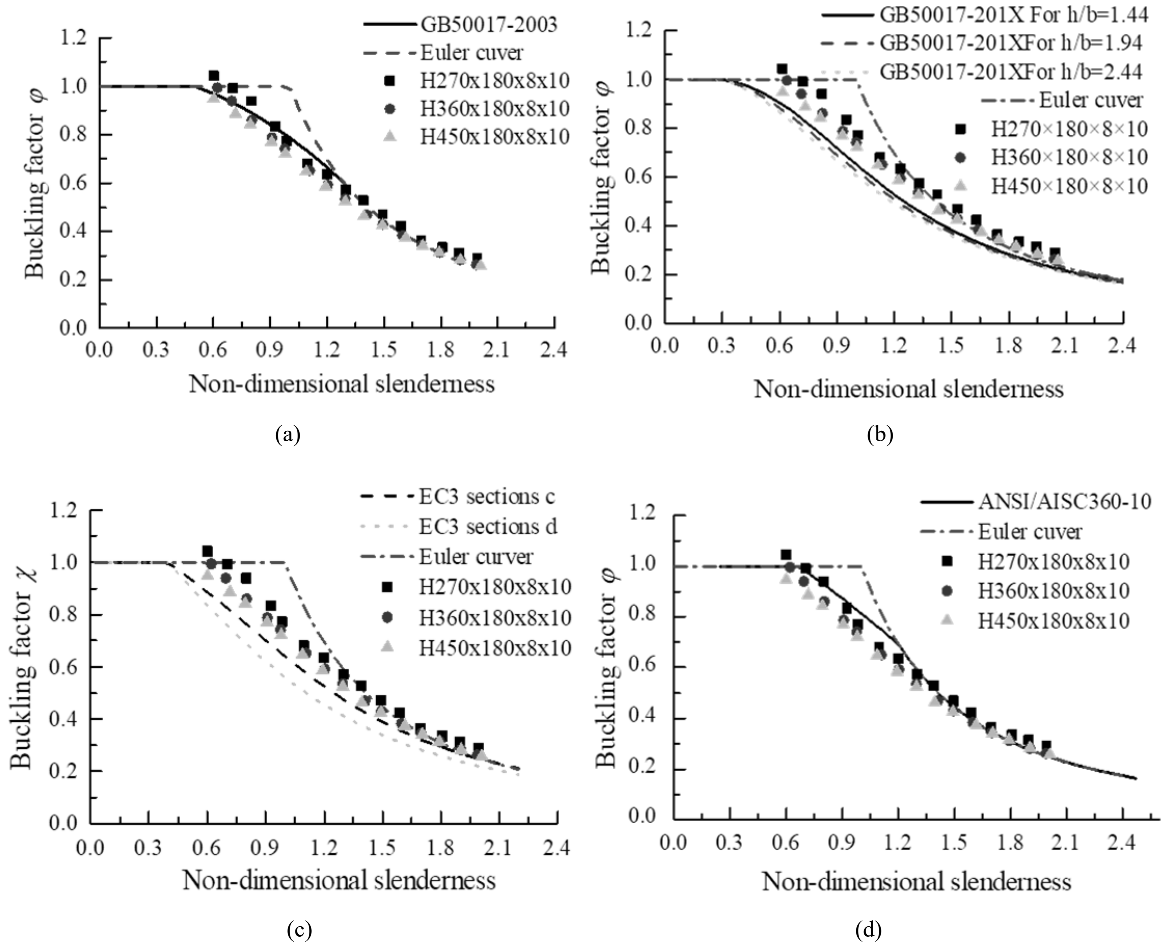


Fig. 5 (a) Comparison of parametric study results with the design curve from GB50017-2003 (2003); (b) Comparison of parametric study results with the design curve from GB50017-201X (2012); (c) Comparison of parametric study results with the design curves from EC3 (2005) for rolled or equivalent welded sections; (d) Comparison of parametric study results with the design curve from American code (ANSI/AISC360-10, 2010)

IV. Conclusions

In this study, the global stability behaviours of welded H-shaped beams fabricated from Q460GJ structural steel plates were investigated. A series of experimental tests by using a special loading device to investigate the lateral-torsional stability of Q460GJ structural steel beams were carried out first. Numerical studies include validations FEA models, and parametric analyses were conducted as well. Moreover, the test results and parametric study results were compared with different design codes including GB50017-2003 (2003), GB50017-201X (2012), EC3 (2005), and ANSI/AISC360-10 (2010). Based on the experimental and numerical studies, the following conclusions may be drawn:

(1) The special loading system can provide a vertical load effectively, which can move freely along the lateral direction. Meanwhile, the tested beams could buckle along out of-plane direction under the vertical load provided by this special loading system. These mean that the special loading system can achieve the ideal loading condition.
(2) Inelastic overall buckling is the typical failure mode for all the test specimens, and no local buckling or local bearing failure was observed. The global stability design methods of GB50017-2003 (2003) and American code (ANSI/AISC360-10, 2010) both overestimated the stability load carrying capacities of Q460GJ structural steel beam specimens. Meanwhile, the design methods of GB50017-201X (2012) and EC3 (2005) for rolled sections or equivalent welded sections are both favorably conservative for the global stability load carrying capacities of Q460GJ structural steel beam specimens.
(3) The validated FEA model established in this paper can be

used for further parametric studies on the overall buckling behavior of Q460GJ structural steel welded I-section beams, which is helpful to study the high strength structural steel buckling design theory.

(4) It was also found that the section height-to-width ratio influences the overall stability load carrying capacities of Q460GJ structural steel flexural members, and the stability coefficient reduces with the increase of the section height-to-width ratio.

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