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Experimental and numerical study on the behavior of axially compressed high strength steel box-columns

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ABSTRACT

The establishment of current design curves for predicting the maximum strengths of centrally loaded columns was mostly based on the experimental and analytical studies of mild carbon steels. In order to study the overall buckling behavior of welded high strength steel (HSS) box-columns, an experimental study on the ultimate strength of welded box-columns with a nominal yield strength of 460 MPa under axial compression was conducted. This experiment program includes six welded box-columns with slenderness varying from 38 to 80. A nonlinear finite element model considering the actually measured geometric imperfections and residual stresses was developed and verified in order to perform an extensively parametric study. The effect of residual stresses on the ultimate bearing capacity and the sensitivity of yield strength to initial geometric imperfections were investigated and discussed. The purpose of the parametric study is to select an appropriate design curve for welded 460 MPa HSS box-columns. By comparing the theoretical curves with the design curves specified in Eurocode3 and GB 50017-2003, it is found that the currently adopted design curves underestimate the ultimate bearing capacity of the welded box-columns fabricated from 460 MPa HSS plates by 18.7% and 23.2% in average, respectively. The curves b in both Eurocode3 and GB 50017-2003 show a good agreement with the generated theoretic curve for the welded box-columns with the nominal yield strength of 460 MPa buckling about both principle axes.

1. Introduction

Due to the architectural and structural advantages, high strength steel (HSS, yield strength ⩾460 MPa) members have been increasingly used in high-rise buildings, large span buildings and bridges in the past two decades. Compared with conventional mild carbon steel members, the use of HSS members could not only reduce member size and save building space, but also shows considerable economic benefits through reducing the workloads of transportation and welding and shortening the time of construction. With the recent development of high strength steel and advances in welding techniques, HSS members now can be produced at a reasonable cost and quality in China. However, the current Chinese steel structures design code GB 50017-2003 [1] limits steel strength grade up to Q420 (nominal yield strength 420 MPa). HSS has been located in the research scope of the introduction of multiple column curves to the design codes, and which were selected for different combinations of shape, steel grade, bending axis and manufacturing method [2–4]. European and American specifications for steel structures allow the use of HSS up to steel grades of S700 (700 MPa) and A514 (690 MPa) [5,6], but the current column curves for predicting the maximum strengths of centrally loaded columns were selected based on the available experimental and analytical studies of mild carbon steels usually with nominal yield strengths from 235 MPa to 345 MPa [4,7]. Bjorhovde [2,3] has generated a total of 112 maximum strength column curves, which form the theoretic basis for the American column curves. Nevertheless, some combinations of shape and HSS were limited due to lack of test data of residual stresses, which is needed for establishing the American column curves. Therefore, a tentative choice of columns curves for the steel grade A572 (Grade 65) with nominal yield strength of 460 MPa has been made without an experimental confirmation. The determination of European column curves was based on the theoretical and experimental studies by European Convention for Constructional Steelwork (ECCS) [4]. Unlike the actually measured residual stresses considered in Ref. [3], ECCS [4] assumed a compressive residual stress level of 10% of the yield strength for fabricated HSS box and H sections with moderate sized weld in the absence of experimental confirmation. As a major factor influencing the buckling behavior of the columns, emphases should be imposed on the effect of residual stresses on the maximum strength of the HSS welded columns. Moreover, the assumption of the residual stress distributions for

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different shapes of HSS should be validated by actual measurements. Consequently, more work should be done to investigate whether the members fabricated from HSS can be designed according to the existing codes or whether the codes need to be modified to include HSS columns.

Local and overall interaction buckling of columns and beam-columns has been widely investigated in the fields of cold-formed [8–11] and welded built-up steel compression members [12–16]. The restrictions of current design codes specified on the design of beam to column joints and connections of steel grade up to S460 have been reevaluated [17–20]. However, only a few studies have concentrated on the overall buckling behavior and the maximum strength of centrally loaded columns fabricated from HSS. For 690 MPa steel, the research project on welded built-up A514 (nominal yield strength 690 MPa) HSS columns was carried out at Lehigh University [21,22] at first. This research project was composed of three parts: evaluation of residual stresses, short column test and long column test. It was found that the measured compressive residual stress in welded A514 steel section was slightly higher than those in welded A7 (nominal yield strength 250 MPa) steel sections, nevertheless, it was a much smaller fraction of the yield strength and less detrimental to the maximum strength of HSS columns than normal strength steel columns [21,22]. Then, Rasmussen and Hancock [23] found a similar result that the columns fabricated from HSS are stronger than columns fabricated form normal strength steel when compared on a non-dimensionalized basis. On the basis of tests on the ultimate bearing capacity of HSS box and I-section columns (nominal yield strength 690 MPa) and the comparison between the tests and column design strengths of the Australian steel structures standard AS4100, they found that the higher curve (α_b = -0.5) was the appropriate curve for columns fabricated from flame-cut HSS plates with a nominal yield strength 690 MPa. For 460 MPa steel, recently, Ban and Shi et al. [24] conducted a lot of valuable experimental and numerical works on the buckling behavior of 460 MPa HSS welded H and box section columns and proposed a design method. However, the cylindrical hinge used in their experiment as pin-ended support did not perform as a perfect hinged connection as expected. The bending deformations of the test columns were partially restrained by the friction between the two contact surfaces of the cylindrical hinge, which resulted in a significant enhancing on the overall buckling behavior of the axially loaded specimens. Because of the uncertainties of the rotational stiffness of the cylindrical hinge, there is a need to develop an ideally pin-ended support and further verify the proposed design method of centrally loaded box and H-section columns fabricated from 460 MPa HSS. Wang and Li et al. [25] designed and fabricated a pair of curved surface supports, which are able to rotate without any friction as a perfect hinge connection, to conduct experimental and analytical studies on the maximum strength of flame-cut welded H-section columns with a nominal yield strength of 460 MPa. The comparison with Eurocode3 and GB 50017-2003 indicated that the currently adopted design curves were appropriate for the design of 460 MPa welded flame-cut H-section columns, although the curve c specified in Eurocode3 was very conservative for predicting the maximum strength of such columns in case of buckling about weak axis. Most of the studies referred the improved overall buckling behavior of HSS columns to the decrease in compressive residual stress to yield strength ratio [22–25]. However, the differences in the influence of residual stresses on the overall buckling behavior and the maximum strength for short, intermediate and long HSS columns, which is very important to evaluate the effect of residual stresses on the maximum strength of steel columns, have not been reported in the literature.

This paper extends the previously cited work [25] to welded box-columns with the nominal yield strength of 460 MPa. Six welded box columns with intermediate slenderness ratios of 38–80 were fabricated from flame-cut Q460 HSS plates and tested to failure under axial loading by using perfect pin-ended supports. The ultimate bearing capacities and load-deformation curves were obtained from the test and compared with the design columns strength of GB 50017-2003 and Eurocode3. An extensive parametric analysis was carried out based on the experimentally verified nonlinear finite element model to select an appropriate design curve for welded 460 MPa box-columns. In addition, the influence of initial geometric imperfection and the differences in the effect of residual stresses on the overall buckling behavior and the maximum strength for short, intermediate and long HSS columns were discussed.

2. Experiment program

2.1. Test specimen data and fabrication procedure

In order to study the behavior of HSS box-columns under axial compression, six specimens with various sectional width to thickness ratios of 7.7–17.3 were fabricated from flame-cut Q460 steel plate. Q460 steel with the nominal yield strength of 460 MPa is equivalent to S460 of EN 10025. The Q460 steel plates with a nominal thickness of 11 mm were flame-cut into strips. Four 11 mm component plates were welded together to form a box-section specimen by manual gas metal arc welding, as shown in Fig. 1. The electrode ER55-D2 with the same nominal yield strength of the Q460 steel was used. As current practice does not employ complete penetration welding for columns except in the beam-to-column connection zone, the component plates were connected by incomplete penetration welding except the 500 mm length from each end. In order to reduce the effect of shrinkage deformation caused by welding heating and cooling, the optimized welding sequence (1 → 3 → 2 → 4) was adopted, as shown in Fig. 1. The measured geometric dimensions of the six test specimens are shown in Table 1. Symbols in Table 1 are illustrated in Fig. 1. The specimens were designed to investigate the overall buckling behavior of the welded HSS box-columns under axially loading. Thus, the plate slenderness ratios of all specimens were designed to prevent the occurrence of the local buckling.

In the Chinese code for design of steel structures GB 50017-2003 [1]:

$$d/t \leqslant (25+0.5\lambda)\sqrt{\frac{235}{f_y}}, \quad 30 \leqslant \lambda \leqslant 100 \tag{1}$$

where λ is the column slenderness ratio, f_y is the nominal yield strength, which is equal to 460 MPa herein. The plate slenderness limits are ranging from 28.6 to 53.6 with λ varying from 30 to 100.

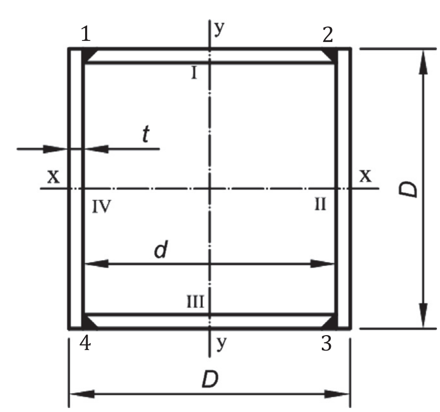

Fig. 1. Definition of symbols.