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Numerical investigation into high strength Q690 steel columns of welded H-sections under combined compression and bending

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ABSTRACT

In conjunction with the experimental investigation described in the paper [1], a numerical modeling programme has been carried out to investigate further the structural behaviour of high strength Q690 steel columns of welded H-sections under combined compression and bending. Finite element (FE) models were developed by using the FE package ABAQUS. Geometrical and material non-linearities were incorporated in the FE models. Through the validation against the experimental results, these FE models showed excellent capability of replicating the key test results, including failure modes, failure loads and full load-axial deformation and load-lateral deflection histories. Upon validation of the FE models, parametric studies were conducted focusing on the effect of member residual stresses and material yield to tensile strength ratios. Then a large number of FE models were established to generate additional structural performance data over a wide range of cross-section dimensions, member slenderness and initial loading eccentricity ratios. The FE model results were then compared with the design buckling resistances of columns under combined compression and bending according to the current European Standard EN 1993-1-1, American Specification ANSI/AISC 360-16 and Chinese Standard GB 50017-2003. The comparisons revealed that by properly selecting design parameters, the design rules in EN 1993-1-1 and GB 50017-2003 could provide close and safe predictions to the buckling resistances of Q690 steel columns of welded H-sections while the design rules in ANSI/AISC 360-16 was readily applicable to the design of Q690 steel columns of welded H-sections.

1. Introduction

Structural steel materials with nominal yield strengths equal to or higher than 460 N/mm^2, widely known as high strength steels, can potentially lead to slenderer and lighter structures. In the recent decades, high strength steel materials with various steel grades have been innovatively used in many heavily loaded and long spanned structures. The reduced deadweight of high strength steel structures allows for lower construction costs and transportation workloads. Compared with those conventional steel materials, high strength steel materials exhibit a reduced ductility with a smaller elongation at fracture and a limited degree of strain hardening after yielding. Moreover, the values of tensile to yield strength ratios are also decreased. Some structural design codes have covered the design of steelworks made of high strength steel materials with some restrictions due to their inferior ductility and strain-hardening characteristics. However, these recommended design rules are mainly based on test data for conventional strength steel materials and further investigation on the applicability of such design rules to high strength steel materials is required.

Recently, several researchers have investigated the structural behavior of high strength steel columns under compression. Through the tests on stocky columns of welded sections, it was preliminarily concluded that the plate slenderness limits for yielding obtained from conventional steel sections were also applicable to similar sections made of high strength steel [2–5], however, sufficient deformation capacities could not be guaranteed if the plate slenderness limits for conventional steel compact sections were simply extended to high strength steel sections [6]. Some compression tests were conducted on slender columns of welded sections with steel grades from 460 to 960 N/mm^2 [7–13]. Those sections with steel grades higher than 460 N/mm^2 exhibited significantly higher buckling resistances than those similar sections made of conventional steel materials on a non-dimensional basis. Those resistance improvements were mainly attributed to higher yield strengths and lower residual stress to yield strength ratios. Besides, the end restraints and limited initial out-of-straightness also contributed to the resistance improvements.

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The investigations on structural behavior of high strength steel columns under combined compression and bending remain scarce. Kim et al. [14] tested stocky columns of welded sections with 650 N/mm^2 steel and found that the design code ANSI/AISC 360-10 [15] adopted a fairly conservative method to evaluate the sectional resistances of high strength steel welded sections. Nie et al. [16] examined the overall buckling behavior of slender columns of welded box sections with 460 N/mm^2 steel and made design recommendations based on the comparisons between numerical results and column curves in different codes. Usami et al. [17,18] conducted eccentric compression tests on columns with slender sections made of 460 and 690 N/mm^2 and verified an effective width approach with respect to interaction between local and overall buckling. Shen [19] proposed a modification factor to the design of 460 N/mm^2 steel welded box-sections with slender webs based on the design rules in GB 50017-2003 [20].

Currently, there are a number of design codes whose scopes of applicability cover or may be readily expanded to cover steel sections made of high strength Q690 steel materials. Based on the design rules applicable to steel grades from S235 to S460 given in EN 1993-1-1 [21], EN 1993-1-12 [22] gives supplementary rules to steel grades up to S700. ANSI/AISC 360-16 [23] covers steel grades up to 690 N/mm^2 (ASTM A514 and A709 steel) while GB 50017-2003 [20] only applies to steel grades from Q235 to Q420. As the development of these design codes was based on the studies on conventional strength steel materials, there is a concern on the applicability of those rules to high strength steel materials.

In order to promote an effective use of high strength steel sections in building construction, a comprehensive research programme was undertaken to investigate structural behavior of Q690 steel columns of welded H-sections. The experimental programme has been presented in the companion paper [1] and the parallel numerical programme is presented in this paper. In this numerical programme, validated numerical models were initially developed through accurate replication of the test results presented in paper [1]. Parametric studies were performed subsequently to examine further the influences of member residual stresses and material tensile to yield strength ratios on the structural response of high strength Q690 columns of welded H-sections under combined compression and bending. Finally, the assessment on the applicability of design rules in different design codes was conducted through the comparison with FE model results.

2. Finite element model

In the experimental programme, a total of 8 slender columns with four sections of different cross-sectional dimensions were tested successfully under eccentric loads. The nominal dimensions for those sections and their section classifications according to EN 1993-1-1 and ANSI/AISC 360-16 are shown in Fig. 1.

In this section, the key characteristics of the finite element models are presented. Geometrical and material non-linearities were incorporated in the FE models in order to replicate the structural behavior observed in the experimental programme. Those FE models were validated through the comparison of numerical results with the relevant test data.

2.1. Elements and basic modeling assumptions

The general purpose finite element analysis package ABAQUS (version 6.11) was employed throughout this study. Shell elements were adopted to discretize the high strength Q690 steel columns of welded H-sections. Shell elements are frequently used in the modeling of thin-walled metallic sections and they have been successfully implemented in other studies [10,24–26]. The finite element type S4R was selected from the ABAQUS element library and it was a four-noded, doubly curved general-purpose shell element with reduced integration and finite membrane strains. A mesh convergence study was carried out to establish a sufficiently refined mesh size which provides accurate results with practical computational times. For each flange and web, the adopted mesh size along the lateral direction of the plate was 1/20 of the plate width while the adopted mesh size along the longitudinal direction was 1/40 of the plate length. The measured geometrical and material mechanical properties obtained prior to testing were used in the finite element models. The initial out-of-straightness was incorporated into the models in the form of the lowest elastic overall buckling mode shape, obtained from a linear perturbation buckling analysis. The initial out-of-straightness was applied by using the "*IMPERFECTIONS" command with amplitudes equal to the measured values prior to testing. The modeling of residual stresses was achieved by setting the initial stresses of the shell elements. Boundary conditions were applied to model the pin-ended conditions at both ends of the columns.

For each finite element model, the simulation consisted of two analyses. The first analysis was a linear perturbation buckling analysis, which was performed on a "perfect" column. The purpose of this analysis was to obtain the lowest elastic overall buckling mode shape, which would be employed as the shape of the initial out-of-straightness of the column in subsequent analysis. The second analysis was a static analysis using the modified Riks method, which was performed on an "imperfect column" with both material and geometrical non-linearities. The purpose of this analysis was to trace the full load-deformation response of the specimens, including the post-ultimate path.

2.2. Material modeling

The measured Q690 steel stress-strain curves were utilized in the development of the finite element models. The material behaviour was modeled as an elastic-linear hardening relationship with a Von

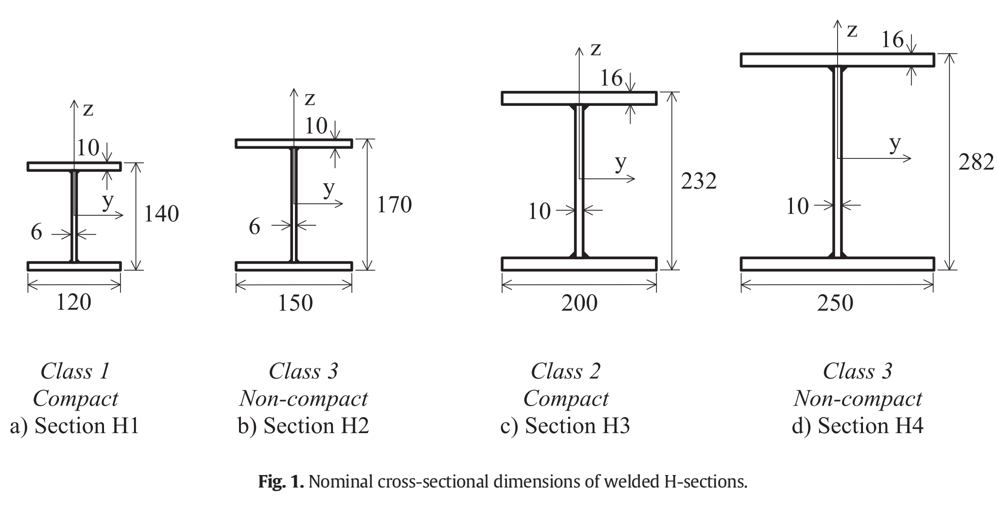

Fig. 1. Nominal cross-sectional dimensions of welded H-sections.