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Design of cold-formed high strength steel tubular beams

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ABSTRACT

A numerical investigation on cold-formed high strength steel (HSS) tubular beams is presented in this paper. The nominal 0.2% proof stresses of the HSS sections ranged from 700 MPa to 1100 MPa. In the complementary study [1], experimental investigation on the beam specimens have been performed. In the present study, numerical modelling methodology for beams was first validated and parametric study on the cold-formed HSS tubular beams was conducted. A total of 423 numerical data was obtained to investigate the structural performance of HSS tubular beams. The experimental and numerical results were then compared with the codified design guidelines from ANSI/AISC 360-10 [2], EN 1993-1-1 [3], AS 4100 [4] and AISI S100 [5] in addition to the predictions from Direct Strength Method (DSM) for square hollow sections (SHS), rectangular hollow sections (RHS) and circular hollow sections (CHS). The codified slenderness limits for sections subjected to bending were examined. Improvements on the design guidelines are proposed in this paper.

1. Introduction

Recently, High Strength Steel (HSS) materials become favorable choice for construction primarily due to their high strength-to-weight ratio and the associated low material cost. The current codes [2,6,7] allow the design of steel structures using steel with grade of 690 MPa but the design of steel structures having grades higher than 690 MPa has not yet been included. HSS materials usually have lower ductility than ordinary steel which leads to relatively low rotation capacities for HSS beams. Experimental investigations on fabricated HSS I-sections (with nominal yield stresses ranging from 570 MPa to 875 MPa) were conducted in the past decades [8–11] and results indicated that the strengths of the fabricated HSS I-sections are adequate for elastic design. However, for plastic design purposes, findings showed that their rotation capacities are marginal.

Cold-formed tubular members have great potential in structural application because of their outstanding torsion resistance, easy fabrication and aesthetic appearance. Jiao and Zhao [12] tested some cold-formed HSS circular hollow section (with $\sigma_{0.2}$ = 1300 MPa) beams with the nominal outer diameter ranging from 31.8 to 75 mm and the D/t ratios ranging from 16 to 48. Wang et al. [13] conducted tests on the hot-finished HSS square hollow section beams with steel grades of 460 and 690 MPa. Chan et al. [14] assessed the current yield slenderness limits for high strength steel tubular sections. In the literatures, different plastic slenderness limits $\bar{\lambda}_p$ and yield slenderness limits $\bar{\lambda}_y$ were proposed which could be applicable for high strength steel sections.

A series of experimental and numerical investigations on cold-formed HSS tubular members were initiated by the authors [1,15–17]. The experimental investigation on the bending behaviour of cold-formed HSS tubular beams in square hollow sections (SHS), rectangular hollow sections (RHS) and circular hollow sections (CHS) has been described in Ma et al. [1]. In the test program, the high strength steel tubular members were grouped into three series: H-series, V-series, and S-series, which have nominal 0.2% proof stresses of 700 MPa, 900 MPa and 1100 MPa, respectively. Research in cold-formed HSS square, rectangular and circular hollow section beams were scare in literatures and the data are not sufficient to develop reliable design rules for cold-formed HSS beams. Hence, a finite element model of HSS beams was developed and validated against the test results in this study. A systematic parametric study on cold-formed HSS tubular beams was carried out to supplement the existing data pool, in which a wide range of section slenderness was examined. Based on the Finite Element Analysis (FEA) results and the complementary experimental results [1], evaluation and modification of the current codes are performed in this paper.

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Nomenclature

B	overall width of cross-section
b	width of flat portion in cross-section
b_e	effective width of flat portion
D	outer diameter of circular hollow section
E	modulus of elasticity
f_y	yield stress of steel (0.2% proof stress)
h	depth of flat portion on web
K	modular coefficient in constitutive model
L_s	length of shear span in four-point-bending test
L_m	length of moment span in four-point-bending test
m	exponent for the proposed constitutive model
$M_{cr\ell}$	critical elastic local buckling moment
M_{eff}	effective moment of cross-section
M_{exp}	experimental ultimate moment of cross-section
M_{FEA}	ultimate moment capacity from finite element model
M_n	nominal flexural strength of cross-section
M_{ne}	nominal flexural strength for overall buckling
$M_{n\ell}$	nominal flexural strength for local buckling
M_p	plastic moment of cross-section
M_u	ultimate moment of cross-section
M_y	yield moment of cross-section
M_{AISC}	nominal strength (unfactored design strength) from ANSI/AISC 360-10
M_{AS4100}	nominal strength (unfactored design strength) from AS 4100
$\hat{M}_{AS4100}$	nominal strength (unfactored design strength) from AS 4100 using the second method for slender sections
M_{EC3}	nominal strength (unfactored design strength) from EN 1993
M_{AISI}	nominal strength (unfactored design strength) from AISI S100
M^*_{AISI}	nominal strength (unfactored design strength) from modified AISI S100 method
M_{DSM}	nominal strength (unfactored design strength) from direct strength method
$M_{DSM\text{-}IR}$	nominal strength (unfactored design strength) from direct strength method with inelastic reserve
M^*_{DSM}	nominal strength (unfactored design strength) from modified direct strength method
n_0	strain-hardening exponent
P	applied load
R_c	rotation capacity on moment span
t	plate or wall thickness
W_{pl}	plastic section modulus
W'_{pl}	section modulus for compact section in AS4100
W_{eff}	effective section modulus
W_{el}	elastic section modulus
σ	stress
σ_u	ultimate stress
$\sigma_{x,Rk}$	characteristic buckling stress in EN1993-1-6
$\sigma_{0.2}$	static 0.2% tensile proof stress
ε	strain
ε_p	plastic strain
ε_{pu}	plastic strain at ultimate stress σ_u
λ	slenderness parameter
λ_ℓ	slenderness factor for local buckling in DSM
λ_s	section slenderness in AS4100
λ_{sp}	plastic slenderness limit in AS4100
λ_{sy}	yield slenderness limit in AS4100
$\bar{\lambda}$	slenderness parameter
$\bar{\lambda}_p$	plastic slenderness limit
$\bar{\lambda}_{pf}$	plastic slenderness limit of flange
$\bar{\lambda}_{pw}$	plastic slenderness limit of web
$\bar{\lambda}_{py}$	yield slenderness limit
$\bar{\lambda}_{yf}$	yield slenderness limit of flange
$\bar{\lambda}_{yw}$	yield slenderness limit of web
χ_x	buckling reduction factor in EN1993-1-6
θ_{max}	total end rotation at plastic moment during unloading response of beam
θ_p	elastic end rotation corresponding to plastic moment
ϕ	capacity factor
β	reliability index

2. Numerical modelling

2.1. General

In previous study, the bending behaviour of nine SHS beams, two RHS beams and six CHS beams were investigated. Four-point bending was adopted in this series of study. The schematic arrangement and the testing procedure are explained in Ma et al. [1], and the experimental results were collated to assess the codified predictions. The following sub-sections first present the validation results for the developed FE model of cold-formed HSS beams, and then explain the findings from the parametric study with an aim to developing suitable design rules for cold-formed HSS beams.

2.2. Validation

Since the current experimental work on cold-formed HSS tubular beams is limited, it is imperative to define a suitable finite element (FE) modelling methodology, which can help researchers generate more numerical data. Thus based on the available experimental results, the FE modelling methodology for cold-formed HSS tubular beams is explained in this section. The material properties used in this section have been reported in Ma et al. [15]. The 0.2% proof stresses of the cold-formed HSS sections ranged from 663 MPa to 1180 MPa and the proportional elongation ranged from 11% to 18%. It has been observed that the proportional elongations of HSS reduce gradually with the increase in material strength. The obtained constitutive model has been successfully adopted in the stub column finite element models. The local imperfection profiles and magnitudes have also been discussed in Ma et al. [16]

The S4R shell element with 4 nodes and reduced integration was used in this investigation. This element has been successfully adopted by Zhu and Young [18], Chan and Gardner [19], Huang and Young [20] and Zhao et al. [21] for different metallic materials and cross-sections under various loading cases. Mesh sensitivity studies have been conducted and the following mesh seed sizes were chosen: $(B+H)/30$ for RHS/SHS and $D/15$ for CHS. Structured mesh arrangement was adopted and the maximum aspect ratio was limited to 10:1 throughout the validation process.

The lowest elastic eigenmode shape was chosen as the local geometric imperfection profile. Measured maximum imperfection values were adopted. For specimens without local imperfection measurement, an assumed local imperfection value (δ_{asd}) was used, and the assumed value δ_{asd} is calculated as $\delta_{asd} = (\delta/\alpha)_{avg} \times \alpha$ (for SHS/RHS) and $\delta_{asd} = (\delta/\beta)_{avg} \times \beta$ (for CHS), where $(\delta/\alpha)_{avg}$ and $(\delta/\beta)_{avg}$ are shown in Table 1. Meanwhile, α and β are also defined in Table 1.