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Experimental investigation of cold-formed high strength steel tubular beams

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ABSTRACT

This paper presents a test program on cold-formed high strength steel tubular beams. The nominal 0.2% proof stresses of the high strength steel were 700, 900 and 1100 MPa in this study. Twenty-five four-point bending tests on circular, rectangular and square hollow structural sections were conducted. Load-deformation histories and failure modes of the beams were reported. Experimental results were compared against design values calculated from European code, Australian standard and North American specification for hot-rolled and cold-formed steel structures. In addition, the test strengths were also compared with the Direct Strength Method predictions. The compactness criteria were assessed by comparing the section slenderness to the slenderness limits in codes.

1. Introduction

High Strength Steel (HSS) has considerable advantages over mild steel in terms of the strength-to-weight ratio and the material cost. Owning to the rapid development in material and manufacturing technologies, the yield strength of steel has increased in the last few decades. High strength steel tubes with nominal yield strengths (proof stresses) of 700, 900 and 1100 MPa are now commercially available. Their potential use should be exploited to achieve more economic design in steel structures. As part of a wider research program, this paper thus presents the experimental findings on the cross-sectional flexural behaviour of HSS tubes in 3 different grades: namely, H-Series, V-Series and S-Series (with nominal proof stresses of 700, 900 and 1100 MPa, respectively).

High strength steel beams behave differently from mild steel beams because of the high material strength and relatively lower ductility. In the past decades, investigations have been conducted on HSS fabricated I-section beams. Beg and Hladnik [1] conducted 10 tests on welded HSS I-beams with nominal yield stress f_y = 700 MPa (NIONICRAL 70) and results showed that the flange and web interaction can significantly affect the ultimate carrying capacities of the sections. Ricles et al. [2] and Green et al. [3] found there is less rotation capacity available in the HSS beams with nominal yield stress f_y = 552 MPa than their mild-steel counterparts (f_y = 250 MPa) through testing welded I beams. It was found that the rotation capacities for beams also vary from uniform moment loading conditions to moment gradient ones. Lee et al. [4] investigated the flexural behaviour of full-scale I-shaped beams built up from high-strength steels with nominal yield stresses of f_y = 650 MPa and f_y = 690 MPa and compared the results to the behaviour of ordinary steel beams fabricated from plates with nominal yield stress of f_y = 490 MPa. The specimens showed sufficient strength for elastic design whereas their rotation capacities for plastic design were marginal. Generally HSS beams have low residual stress to 0.2% proof stress ratios, good flexural resistances but limited rotation capacities. The rotation capacities were found to decrease with the increase in material strength, flange slenderness and web slenderness. Jiao and Zhao [5] tested cold-formed HSS circular hollow sections (CHS) with nominal 0.2% proof stress as high as 1300 MPa. The nominal outer diameter of the test specimens ranged from 31.8 mm to 75 mm while the D/t ratios ranged from 16 to 48. It was suggested that different plastic slenderness limits and yield slenderness limits might apply for HSS circular hollow sections. Further investigation is needed to determine the effect of yield stresses on the section slenderness limits.

2. Experimental investigation

2.1. Test specimens

The beam specimens were cut from the same batch of cold-formed HSS tubular sections as described in Ma et al. [6]. Nine

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Nomenclature

B	overall width of cross-section
b	width of flat portion in cross-section
D	outer diameter of circular hollow section
$d_{\max}$	measured maximum internal diameter
$d_{\min}$	measured minimum internal diameter
E	modulus of elasticity
f_y	yield stress of steel (0.2% proof stress)
H	overall depth of cross-section
h	depth of flat portion in cross-section
I	second moment of area
k	curvature of moment span
k_p	elastic curvature corresponding to the plastic moment
L_s	length of shear span in four-point-bending test
L_m	length of moment span in four-point-bending test
M_{exp}	experimental ultimate moment of cross-section
M_p	plastic moment of cross-section
M_y	yield moment of cross-section
M_u	ultimate 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
M_{EC3}	nominal strength (unfactored design strength) from EN 1993
M_{AISI}	nominal strength (unfactored design strength) from AISI S100
M_{DSM}	nominal strength (unfactored design strength) from Direct Strength Method without inelastic reserve
$M_{DSM\text{-}IR}$	nominal strength (unfactored design strength) from Direct Strength Method with inelastic reserve
P	applied load
R	outer corner radius of square and rectangular hollow sections
R_{eq}	equivalent radius of curvature on moment span
R_c	measured rotation capacity on moment span
r	inner corner radius of square and rectangular hollow sections
t	plate or wall thickness
U_r	out-of-roundness parameter
W_{pl}	plastic section modulus
W_{el}	elastic section modulus
y	measured deflection in moment span obtained from transducers
α	square/rectangular hollow section plate element slenderness
β	circular hollow section slenderness
δ	measured local geometric imperfection
σ_u	static ultimate tensile strength
$\sigma_{0.2}$	static 0.2% tensile proof stress
ε_{25mm}	non-proportional elongation at fracture based on gauge length of 25 mm
$\bar{\lambda}_p$	plastic slenderness limit
$\bar{\lambda}_{pf}$	plastic slenderness limit of flange
$\bar{\lambda}_{pw}$	plastic slenderness limit of web
$\bar{\lambda}_y$	yield slenderness limit
$\bar{\lambda}_{yf}$	yield slenderness limit of flange
$\bar{\lambda}_{yw}$	yield slenderness limit of web
$\theta_{\max}$	total end rotation at plastic moment during unloading response of beam
θ_p	elastic end rotation corresponding to plastic moment

square hollow sections (SHS), two rectangular hollow sections (RHS) and six circular hollow sections (CHS) were investigated in this study. According to their nominal yield stress, f_y, they are categorized into: H-Series (f_y = 700 MPa), V-Series (f_y = 900 MPa) and S-Series (f_y = 1100 MPa). The nominal width and depth of the SHS and RHS ranged from 50 mm to 200 mm while the nominal outer diameter of the CHS varied from 89 mm to 139 mm. The nominal plate width-to-thickness and depth-to-thickness ratios of SHS and RHS ranged from 8 to 35 while the nominal outer diameter-to-thickness ratios of CHS ranged from 22 to 34. All SHS and RHS specimens are labelled as "Series, flange, web, thickness", and CHS specimens are labelled as "Series, outer diameter, thickness". The flexural behaviour of the beams was investigated through four-point bending tests. Both major-axis and minor-axis flexural tests were conducted for the RHS beams. RHS beam specimen H50 × 100 × 4-B refers to major axis bending and the 'B' indicates that it is a beam specimen. Tables 1 and 2 show the measured cross-section dimensions using the nomenclature from Fig. 1. The symbol '#' denotes that it is a repeated test. The calculated elastic section modulus W_{el}, the plastic section modulus W_{pl}, the shear span length L_s and the moment span length L_m are also tabulated in the last four columns of the tables.

Table 1
Measured SHS and RHS beam dimensions.

Specimen $B \times H \times t$ (mm)	B (mm)	D (mm)	t (mm)	R (mm)	r (mm)	W_{el} ($\times 10^3$ mm^3)	W_{pl} ($\times 10^3$ mm^3)	L_s (mm)	L_m (mm)
H80 × 80 × 4-B	80.3	80.1	3.92	9.5	5.0	26.9	32.1	500	450
H80 × 80 × 4-B[#]	80.2	80.1	3.93	9.5	5.0	26.9	32.0	500	450
H100 × 100 × 4-B	100.3	100.4	3.94	8.5	4.3	44.8	52.7	600	600
H120 × 120 × 4-B	121.0	121.4	3.95	8.0	4.0	67.7	79.0	600	600
H140 × 140 × 5-B	141.3	140.3	4.94	12.0	7.0	111.7	130.9	800	600
H140 × 140 × 5-B[#]	141.2	140.5	4.95	12.0	7.0	112.0	131.2	800	600
H140 × 140 × 6-B	140.9	141.2	5.98	13.0	7.0	132.6	156.8	800	600
H160 × 160 × 4-B	160.6	160.5	3.99	10.5	6.0	32.2	141.5	800	600
H100 × 50 × 4-B	100.3	50.3	3.93	8.5	3.5	17.9	20.6	500	450
H50 × 100 × 4-B	50.3	100.2	3.97	8.5	3.5	26.4	33.6	500	450
H200 × 120 × 5-B	200.4	121.5	4.95	13.0	7.5	124.1	140.5	800	600
H120 × 200 × 5-B	121.2	200.4	4.95	13.0	7.5	161.9	197.6	800	600
V80 × 80 × 4-B	80.3	80.2	3.95	10.0	6.0	27.1	32.3	500	450
V100 × 100 × 4-B	100.2	100.2	3.96	11.5	7.0	43.6	51.5	600	600
V120 × 120 × 4-B	120.9	121.1	3.93	9.5	6.0	66.9	78.1	600	600
V120 × 120 × 4-B[#]	120.9	121.1	3.91	9.5	6.0	66.6	77.7	600	600

[#] Repeated test.