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Strength enhancements in cold-formed structural sections — Part I: Material testing

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ABSTRACT

This paper describes a material test programme carried out as part of an extensive study into the prediction of strength enhancements in cold-formed structural sections. The experiments cover a wide range of cross-section geometries – twelve Square Hollow Sections (SHS), five Rectangular Hollow Sections (RHS) and one Circular Hollow Section (CHS), and materials – austenitic (EN 1.4301, 1.4571 and 1.4404), ferritic (EN 1.4509 and 1.4003), duplex (EN 1.4462) and lean duplex (EN 1.4162) stainless steel and grade S355J2H carbon steel. The experimental techniques implemented, the generated data and the analysis methods employed are fully described. The results from the current test programme were combined with existing measured stress–strain data on cold-formed sections from the literature and following a consistent analysis of the combined data set, revised values for Young's modulus E and the Ramberg–Osgood material model parameters n, $n'_{0.2,u}$ and $n'_{0.2,1.0}$ are recommended. A comparison between the recommended values and the codified values provided in AS/NZS 4673 (2001) [1], SEI/ASCE-8 (2002) [2] and EN 1993-1-4 (2006) [3] is also presented. The test results are also used in a companion paper Rossi et al. (submitted for publication) [4] for developing suitable predictive models to determine the strength enhancements in cold-formed structural sections that arise during the manufacturing processes.

1. Introduction

Cold-formed structural sections are formed from sheet material which may be either hot-rolled or cold-rolled, the latter being used for thinner gauges. The sheet material is typically rolled into coils for compact storage and transportation and is subsequently uncoiled prior to section forming. The processes of coiling and uncoiling of the sheet material and forming of the cross-section induce plastic deformations through the material thickness. Depending on the method of section forming employed — press-braking, where the sheet material is formed into the required shape by creating individual bends along its length, or cold-rolling, where gradual deformation of the uncoiled metal sheet through a series of successive rollers produces the final cross-section profile, different levels of plastic deformation are generated. The plastic deformations induced during the production processes influence the material response of the final cold-formed sections, with the key effects being an increase in yield strength, a reduction in ductility and the formation of residual stresses.

Predictive models for harnessing the increases in material strength caused by plastic deformations, experienced during the cold-forming production routes, have been developed for use in structural design. A comprehensive review of these models has been made in the companion paper [4], while a brief overview is presented herein.

Models for predicting the strength enhancement in the highly cold-worked corner regions of structural carbon steel cross-sections are provided in the following references: Karren [5], the AISI Specification for the Design of Cold-formed Steel Structural Members [6] and Gardner et al. [7]. A method for taking account of corner strength enhancements for cross-section design using an increased average yield strength is set out in EN 1993-1-3 [8].

For stainless steel, where the degree of non-linearity and the level of strain hardening are generally greater than carbon steel, separate predictive equations have been proposed. Experimental studies of cold-formed stainless steel sections were conducted by Coetzee et al. [9] and predictive equations were given by van den Berg and van der Merwe [10] for the corner regions of press-braked and cold-rolled sections. As part of their wider experimental study of the behaviour of austenitic stainless steels, Gardner and Nethercot [11] also developed an equation for predicting the increased 0.2% proof strength of the corner regions of cold-rolled box sections. Ashraf et al. [12] performed a comprehensive investigation into the behaviour of cold-formed stainless steel sections from a variety of fabrication processes and proposed a number of predictive models in terms of different material and geometric input parameters — allowing the wider applicability of the models. More recent predictive equations are provided in Cruise and Gardner [13] and Rossi [14], where the

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Table 1
Chemical compositions as stated in the mill certificates.

Cross-section	Material grade	C (%)	Si (%)	Mn (%)	P (%)	S (%)	Cr (%)	Ni (%)	N (%)	Mo (%)	Cu (%)	Nb (%)
SHS 100×100×5	1.4301	0.044	0.350	1.34	0.029	0.001	18.24	8.12	0.058	0.210	–	–
SHS 150×150×5	1.4301/1.4307	0.022	0.390	1.80	0.030	0.001	18.20	8.00	0.050	–	–	–
RHS 150×100×6	1.4301/1.4307	0.023	0.390	1.76	0.029	0.001	18.20	8.10	0.043	–	–	–
SHS 100×100×5	1.4571	0.010	0.400	1.79	0.033	0.001	16.60	10.70	0.010	2.070	–	–
SHS 120×120×5	1.4571	0.040	0.390	1.22	0.027	0.001	16.70	10.70	0.010	2.060	–	–
SHS 150×150×8	1.4404	0.025	0.530	1.75	0.030	0.000	17.20	10.10	0.044	2.090	–	–
RHS 150×100×8	1.4404	0.022	0.490	1.74	0.032	0.002	17.00	10.00	0.042	2.040	–	–
SHS 50×50×2	1.4509	0.013	0.430	0.22	0.021	0.001	18.26	0.19	0.013	0.020	–	0.38
SHS 40×40×2	1.4509	0.015	0.550	0.20	0.024	0.001	18.27	0.20	0.016	0.020	–	0.36
SHS 30×30×2	1.4509	0.015	0.560	0.20	0.024	0.001	18.27	0.20	0.016	0.020	–	0.36
RHS 120×80×3	1.4003	0.010	0.250	1.43	0.028	0.003	11.30	0.40	0.010	–	–	–
SHS 80×80×3	1.4003	0.007	0.230	1.39	0.025	0.002	11.20	0.40	0.010	–	–	–
SHS 150×150×8	1.4162	0.029	0.740	4.97	0.020	0.001	21.68	1.59	0.215	0.320	0.34	–
CHS 219.1×8.2	1.4462	0.016	0.450	1.66	0.025	0.001	22.38	5.35	0.190	3.070	–	–
SHS 150×150×6	S355J2H	0.200	0.017	1.48	0.009	0.008	0.016	0.018	0.007	0.002	0.036	0.033
RHS 200×100×5	S355J2H	0.130	0.017	1.40	0.015	0.003	0.030	0.010	0.006	0.010	0.010	0.034
RHS 150×100×6	S355J2H	0.143	0.176	0.92	0.009	0.006	0.024	0.047	–	0.002	0.028	–
SHS 200×200×6	S355J2H	0.155	0.216	1.05	0.013	0.007	0.022	0.019	0.005	0.008	0.035	0.002

strength enhancement of the flat faces of cold-rolled sections has also been studied. In an attempt to provide a unified predictive method for all cold-worked non-linear metallic material, Rossi's [14] model involves the determination of the associated plastic strains caused during the fabrication process and the evaluation of the corresponding stresses, through an appropriate material model.

The present study builds on previous research and describes an experimental programme carried out to measure the level of strength enhancement in a wide range of cold-formed structural sections, covering both carbon steel and a variety of stainless steel grades. The programme consists of tensile tests on coupons extracted from a series of cold-rolled tubular sections, together with full section tensile tests. The majority of test programmes and proposed predictive models from the literature have focused on austenitic stainless steel sections, since, to date, this class of stainless steel has been the most commonly used in structural applications. Material properties of structural sections are often obtained as part of wider experimental research programmes by performing longitudinal tensile coupon tests; material test data on other stainless steel grades — duplex, lean duplex and ferritic, may therefore be sourced from published experiments in the literature. In order to develop a comprehensive experimental database, both in terms of the material grades and section geometries, the tested specimens for this research programme were selected to fill in the gaps in the existing available test data.

A wide range of cross-section geometries and material grades were considered. All tubular sections were formed by the cold-rolling process, whereby the sheet material was first formed into a circle and welded closed, followed by subsequent crushing into the final cross-section geometry for the case of SHS and RHS specimens. The experimental techniques implemented, the resulting data and the analysis methods employed throughout this experimental programme and discussion of the results are presented herein. A review of the compound Ramberg–Osgood material model is provided and revised values for the model parameters and the Young's modulus for a series of stainless steel grades are also proposed. The suitability of the expression recommended in Annex C of EN 1993-1-4 [3] for determining the strain at the ultimate tensile stress has also been assessed. In the companion paper [4], the test results from this experimental programme, combined with relevant test data from the literature, are analysed and used for appraisal of the existing predictive models and development of a simple, accurate and universal predictive model for harnessing the strength enhancements in cold-formed structural sections.

Table 2
Mechanical properties as stated in the mill certificates.

Cross-section	Material grade	$\sigma_{0.2,mill}$ (N/mm^2)	$\sigma_{1.0,mill}$ (N/mm^2)	$\sigma_{u,mill}$ (N/mm^2)	A_5 (%)
SHS 100×100×5	1.4301	310	–[a]	670	51
SHS 150×150×5	1.4301/1.4307	289	342	621	53
RHS 150×100×6	1.4301/1.4307	284	328	603	56
SHS 100×100×5	1.4571	272	312	562	60
SHS 120×120×5	1.4571	268	315	584	53
SHS 150×150×8	1.4404	302	358	605	51
RHS 150×100×8	1.4404	285	336	590	53
SHS 50×50×2	1.4509	364	–[a]	501	30
SHS 40×40×2	1.4509	362	–[a]	476	33
SHS 30×30×2	1.4509	362	–[a]	476	33
RHS 120×80×3	1.4003	329	350	468	37
SHS 80×80×3	1.4003	324	342	467	45
SHS 150×150×8	1.4162	561	605	747	–[a]
CHS 219.1×8.2	1.4462	650	–[a]	819	33
SHS 150×150×6	S355J2H	420	–[a]	529	31
RHS 200×100×5	S355J2H	478	–[a]	546	27
RHS 150×100×6	S355J2H	384	–[a]	511	24
SHS 200×200×6	S355J2H	475	–[a]	549	–[a]

[a] Values were not provided.