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Material properties and compressive local buckling response of high strength steel square and rectangular hollow sections

J. Wang [a], S. Afshan [b,*], N. Schillo [c], M. Theofanous [d], M. Feldmann [c], L. Gardner [a]

[a] Imperial College London, London, UK
[b] Brunel University London, London, UK
[c] Institute of Steel Construction, RWTH Aachen University, Germany
[d] University of Birmingham, Birmingham, UK

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ABSTRACT

An experimental investigation into the structural performance of compressed high strength steel (HSS) square and rectangular hollow sections is described in this paper. Both hot-rolled and cold-formed HSS sections were examined. In total six S460NH and five S690QH hot-rolled section sizes and three S500MC, two S700MC and four S960QC cold-formed section sizes were tested. The experimental programme comprised tensile coupon tests on flat and corner material, measurements of geometric imperfections, full cross-section tensile tests and stub column tests. The results of the experiments presented in this paper have been combined with other available test data on high strength steel sections, and used to assess the existing design guidelines for high strength steels given in Eurocode 3. The focus has been on the material ductility requirements, the Class 3 slenderness limit for internal elements in compression and the effective width formula for Class 4 internal elements in compression.Reliability assessments of the Class 3 slenderness limit (both the current value of 42 and a proposed value of 38) and the effective width formula for Class 4 internal elements in compression were carried out. The analysis indicated that, based on the assembled test data considered in this study, and the assumptions made regarding the statistical distributions of material and geometric properties, a partial safety factor greater than unity is required for HSS. Similar findings have also recently been presented for ordinary strength steels.

1. Introduction

High strength steels offer a number of potential advantages over conventional steels, particularly in relation to reduced structural self-weight, as well as savings in the cost of material, transportation and handling. High strength steels have been applied in structural applications in the energy sector e.g. for parts of offshore platforms and in pipelines [1]. Recognising the benefits obtained from their enhanced strength, their use has been extended to building structures, and has grown in recent years [2–4]. With this trend set to increase, the development of codified design rules for high strength steels is imperative. While comprehensive design codes and standards exist for conventional steels, with nominal yield stress typically in the range of 235–355 N/mm^2, for high strength steels, with yield stress in excess of 460 N/mm^2, there is limited guidance available. Therefore, the aim of this paper is to examine the structural behaviour of high strength steel hollow sections from two principal production routes - hot-rolling and cold-forming, and to assess the applicability of existing design guidance. A comprehensive experimental programme, including material tests, stub column tests, full cross-section tensile tests and geometric imperfection measurements has been conducted, the results of which are presented and analysed.

The combination of chemical composition, heat treatment and manufacturing processes determine the mechanical properties of steel products. While the strength of steel can be increased by the additions of alloying elements, its other properties, such as ductility, toughness and weldability, can be adversely affected. Heat treatment, which involves cooling at a prescribed rate, refines the material grain size, enabling the manufacture of steels with both higher strength and improved fabrication properties. Hence, heat treatment has been of major importance in the development of new high strength steel grades, and may be used in conjunction with the addition of alloying elements to achieve optimum performance. Cold-working is another means of enhancing the strength of steel materials, and arises during the production of cold-formed structural steel sections. Structural steel products, as

* Corresponding author.
E-mail address: Sheida.Afshan@brunel.ac.uk (S. Afshan).

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Nomenclature

A	cross-sectional area
A_c	coupon cross-sectional area
A_{corner}	cross-sectional area of corner regions
A_{eff}	effective cross-sectional area
A_{flat}	cross-sectional area of flat faces
b	section breadth
b_{cl}	centreline width
$b_{eq,cl}$	equivalent centreline width
$b_{eq,flat}$	equivalent flat width
b_{flat}	flat width
COV	coefficient of variation
c	plate flat width
E	Young's modulus
FE	finite element
f_u	ultimate tensile stress
f_{uc}	ultimate tensile stress of corner coupon
$f_{u,cs}$	ultimate tensile stress of cross-section
f_y	yield stress
f_{yc}	yield stress of corner coupon
$f_{y,cs}$	yield stress of cross-section
$f_{y,mean}$	mean measured material yield stress
$f_{y,nom}$	nominal material yield stress
HSS	high strength steel
h	section height
$k_{d,n}$	design fractile factor for n data points
$k_{d,\infty}$	design fractile factor for n tending to infinity
k_σ	plate buckling coefficient
L	length of specimen
L_o	standard gauge length
MC	thermomechanically rolled and cold-formed section
M_{el}	elastic moment capacity
N	axial load
N_u	ultimate load
$N_{c,Rd}$	cross-section design compression resistance
NH	normalised hollow section
n	number of data points
Q	reliability parameter defined in EN 1990
QC	quenched and tempered and cold-formed section
QH	quenched and tempered hollow section
Q_δ	reliability parameter defined in EN 1990
Q_{rt}	reliability parameter defined in EN 1990
RHS	rectangular hollow section
r_d	design resistance
r_e	experimental resistance
r_i	internal corner radius
r_n	nominal resistance
r_t	theoretical resistance
SHS	square hollow section
t	thickness
V_{f_y}	coefficient of variation of material yield stress
V_r	combined coefficient of variation
V_δ	coefficient of variation of test results relative to resistance model
Z	area reduction factor
Z_c	corner coupon area reduction factor
α_δ	weighing factor for Q_δ
α_{rt}	weighing factor for Q_{rt}
γ_{M0}	partial safety factor for cross-section resistance
γ_{M1}	partial safety factor for member resistance
δ	end-shortening
δ_u	end-shortening at ultimate load
ε	strain and EN 1993-1-1 material parameter $\varepsilon = \sqrt{235/f_y}$
ε_f	plastic strain at fracture
ε_{fc}	plastic strain at fracture of corner coupon
$\varepsilon_{f,cs}$	plastic strain at fracture of cross-section
ε_u	strain at ultimate tensile stress
ε_{uc}	strain at ultimate tensile stress of corner coupon
$\varepsilon_{u,cs}$	strain at ultimate tensile stress of cross-section
$\bar{\lambda}_p$	plate slenderness
ν	Poisson's ratio
ρ	reduction factor
σ_{cr}	elastic buckling stress
$\sigma_{cr,cs}$	elastic buckling stress calculated using Direct Strength method (CUFSM software)
ω_{EN}	imperfection amplitude allowance defined by Eurocode
ω_0	measured imperfection amplitude

covered in EN 1993-1-1 [5] and EN 1993-1-12 [6], may be hot-rolled steels, normalised, quenched and tempered or thermo-mechanically rolled steels.

The conventional hot-rolled steels, with typical rolling finish temperatures of around 750 °C, and with no heat treatment, include the commonly used S235, S275 and S355 grades. Normalised steels, with additions of Carbon (C) and Manganese (Mn), are manufactured through conventional hot-rolling, followed by a normalising heat treatment, whereby the as-rolled material is heated back to and maintained at approximately 900 °C, before being allowed to cool naturally. This process results in a fine and homogeneous grain structure, improving the steel toughness. Similar material properties can also be achieved through a normalised rolling process, whereby the normalising heat treatment is included in the rolling process. The maximum yield stress of normalised steel products is however limited to 460 N/mm^2, beyond which the required steel composition is such that the balance of strength and fabrication properties diminishes [7]. The quenching and tempering process starts with the steel at about 900 °C; the steel is then rapidly cooled, normally in water, and subsequently tempered, where the material is reheated and maintained at about 600 °C before being allowed to cool naturally. Quenching and tempering can be used to produce steel grades with yield strengths up to as high as 1100 N/mm^2 while maintaining reasonable toughness and ductility, although only grades up to 690 N/mm^2 are currently standardised for structural use. Thermo-mechanically rolled steels utilise particular steel compositions, with lower carbon content, that permit lower rolling finish temperatures of about 700 °C. This results in improved weldability and ductility, which cannot generally be achieved by heat treatment alone. The high strength steels examined in this study include, hot-finished normalised and quenched and tempered hollow sections and cold-formed hollow sections from thermo-mechanically rolled sheets and quenched and tempered sheets, hence, allowing comparisons of the structural response of hollow sections from these different production routes to be made.

The material characteristics of high strength steels have been studied in references [1,8–10], where the influence of increasing yield strength on parameters including the ultimate tensile strength to yield strength ratio f_u/f_y, strain at fracture ε_f and strain at ultimate tensile strength ε_u, were investigated. These three parameters have traditionally been employed in EN 1993-1-1 [5] as measures of the material ductility, and minimum requirements are specified for each before the design rules set out in EN 1993-1-1 may be applied. A similar approach is adopted in EN 1993-1-12 [6], which is the part of Eurocode 3 that provides supplementary rules