Engineering Structures 62–63 (2014) 181–192

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

High strain rate behaviour of cold-formed rectangular hollow sections

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A R T I C L E I N F O

Article history:
Received 16 September 2013
Revised 9 December 2013
Accepted 17 January 2014
Available online 17 February 2014

Keywords:
High strain rate
Blast
Impact
Dynamic increase factor
Rectangular hollow section
Hollow structural section
Split-Hopkinson pressure bar

A B S T R A C T

For blast- or impact-resistant design of steel structures, it is important to use realistic properties of steel under high strain rate. In particular, the substantial rise in yield stress under high strain rate may have important effects on the dynamic behaviour of a steel structure. The high strain rate properties of some steels have been studied in the past; mostly reinforcing bars, plates and hot-rolled sections. The goal of this research is to remedy the lack of knowledge on the high strain rate behaviour of cold-formed steel hollow sections. In this study, four cold-formed Rectangular Hollow Sections (RHS) manufactured by two different cold-forming methods (direct-forming and continuous-forming) have been examined. The dynamic properties of the RHS specimens were determined by performing a total of 166 compressive and tensile Split-Hopkinson Pressure Bar (SHPB) tests at strain rates ranging from 100 to 1000 s^{-1} and their dynamic yield stresses were compared to their static yield stresses, to characterise the strength enhancement of cold-formed RHS under such loading rates.

1. Introduction

Recently, blast and impact loadings have been taken into consideration for the design of critical infrastructure. For structures under these severe loadings, their responses at high strain rates from 100 to 1000 s^{-1} are often sought [1–5]. It is estimated that the strain rates on the World Trade Centre steels, due to the aircraft impacts, were up to 1000 s^{-1} [3]. For blast- or impact-resistant design of steel structures, the specified static design strengths are commonly modified to dynamic design stresses using a Strength Increase Factor (SIF_y) and Dynamic Increase Factors (DIF_y and DIF_u).

According to AISC Steel Design Guide 26 [6], for steel grades of 345 MPa or less, the average yield stress of steels currently produced is approximately 10% larger than the nominal yield stress specified by the American Society for Testing and Materials (ASTM) specification. Hence, for blast design the nominal yield stress would be multiplied by a SIF_y of 1.10. For higher grades this average is claimed to be smaller than 5%, so no factor is used on those grades. Ultimate strength is not factored in any case. The same suggestions are given in [7–10]. It should be noted that the SIF_y value of 1.10 is intended for non-cold-formed steels. For cold-formed hollow sections, the ratio between the actual yield stress and the nominal value is typically higher. For example, SIF_y is taken as 1.4 for cold-formed hollow sections in the AISC Seismic Provisions for Structural Steel Buildings [11].

The mechanical properties of steel material vary with strain rate. Compared to the static values normally used in design, the properties vary for dynamic loading as follows: (1) the yield stress increases substantially; (2) the ultimate strength increases slightly; and (3) both modulus of elasticity and the elongation at rupture remain nearly constant [3,6]. Thus, DIF_y and DIF_u are commonly used to consider the increases in yield stress and ultimate strength due to blast loading [6–10]. The DIF_y and DIF_u values for various structural steels suggested by [6] are listed in Table 1. The values are based on an average strain rate of 0.1 s^{-1} which is characteristic of low pressure explosions. It can be seen in Table 1 that the ultimate strengths of various steels are in general less sensitive to the strain rate effect, compared to the yield stresses. Similar constant DIF values, independent of the strain rate, are given in [7–10]. If the strain rate can be determined, UFC 3-340-02 [7] recommends that the DIF_y for strain rates up to 100 s^{-1}, for ASTM A36 and A514 steels, be determined using Fig. 1. Another important effect of high strain rate on steel members is that the cross-section classification, and hence member behaviour, may be affected. The yield strength increase from the static to the dynamic value may cause a downgrading of cross-section classification, for example changing a section from compact to slender [12].

Based on the expected ductility ratio (ratio between the maximum displacement and the elastic displacement) or the expected support rotation angle (tangent angle at the support formed by the maximum beam deflection), it is suggested by [6] that the

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http://dx.doi.org/10.1016/j.engstruct.2014.01.023
0141-0296/

Nomenclature

$\sigma(t)$	stress-time history of SHPB sample
$\varepsilon(t)$	strain-time history of SHPB sample
$\varepsilon_i(t)$	incident wave in the pressure bar
$\varepsilon_r(t)$	reflected wave in the pressure bar
$\varepsilon_t(t)$	transmitted wave in the pressure bar
$\dot{\varepsilon}$	strain rate
f_{ds}	dynamic design stress for tension, compression and bending
f_{dv}	dynamic design stress for shear
f_{dy}	measured dynamic yield stress, or predicted dynamic yield stress
f_{du}	predicted dynamic ultimate strength
f_y	measured static yield stress of tensile coupon
$f_{y,avg}$	average of measured static yield stresses of tensile coupons
$f_{y,nom}$	nominal yield stress
f_u	measured static ultimate strength of tensile coupon
$f_{u,avg}$	average of measured ultimate strengths of tensile coupons
$f_{u,nom}$	nominal ultimate strength
l_s	length of compressive SHPB sample
q	Cowper–Symonds parameter
t_{nom}	nominal wall thickness of RHS
A_b	cross-sectional area of pressure bar
A_s	cross-sectional area of compressive SHPB sample, or cross-sectional area of the test region of tensile SHPB sample
B_{nom}	nominal external width of RHS
C	Cowper–Symonds parameter
C_b	longitudinal elastic wave speed in pressure bar
CF	continuous-formed
DF	direct-formed
DIF_y	dynamic increase factor for yield stress = measured dynamic yield stress/measured static yield stress
DIF_u	dynamic increase factor for ultimate strength = measured dynamic ultimate strength/measured static ultimate strength
E	Young's modulus
F	ratio of flat face area to total cross-sectional area of RHS
RHS	rectangular hollow section
R^2	coefficient of determination
SHPB	split-Hopkinson pressure bar
SIF_y	strength increase factor for yield stress = measured static yield stress/nominal yield stress
SIF_u	strength increase factor for ultimate strength = measured static ultimate strength/nominal ultimate strength

dynamic design stress for tension, compression and bending (f_{ds}) can be calculated as follows:

For ductility ratio ⩽10 or support rotation angle ⩽2°,

$$f_{ds} = f_{dy} = (SIF_y)(DIF_y)(f_{y,nom}) \quad (1)$$

For ductility ratio >10 or support rotation angle >2°,

$$f_{ds} = f_{dy} + \frac{f_{du} - f_{dy}}{4} \quad (2)$$

where

$$f_{du} = (DIF_u)(f_{u,nom}) \quad (3)$$

The dynamic design stress for shear is:

$$f_{dv} = 0.55 f_{ds} \quad (4)$$

It should be noted that the constant DIF_y and DIF_u values suggested by the above design guides and technical manuals are in general intended for low pressure explosions (for strain rates in the order of $10^{-1}\,s^{-1}$). Thus, they may not be accurate for blast loading in close proximity or impact loading where the strain rate may be much higher (in the order of 10^2–$10^3\,s^{-1}$).

2. Previous investigations

The effect of strain rate on the mechanical behaviour of steels has long been a subject of interest to researchers. Early research on the influence of strain rate on the yield stresses of three structural steels (ASTM A36 and A441 steels and one quenched and tempered steel) was conducted by Rao et al. [13]. Tensile coupons were tested quasi-statically and dynamically to obtain the experimental results. The measured static tensile yield stresses of the steels tested ranged from 238 MPa to 778 MPa. The dynamic test strain rates were up to $1.4 \times 10^{-3}\,s^{-1}$. Based on 189 tests on A36 steel, 39 tests on A441 steel and 29 tests on the quenched and tempered steel (Q–T), (Eqs. (5)–(7)) were established to describe the relationships between DIF_y and strain rate for the three tested steels. The equations are functions of the strain rates only.

$$\text{A36}: \; DIF_y = 1 + 0.021\dot{\varepsilon}^{0.26} \quad (5)$$

$$\text{A441}: \; DIF_y = 1 + 0.020\dot{\varepsilon}^{0.18} \quad (6)$$

Table 1
DIF_y and DIF_u values for various structural steels under low pressure explosion [6].

ASTM specifications	DIF_y		DIF_u
	Bending/shear	Tension/compression	
A36	1.29	1.19	1.10
A588	1.19	1.12	1.05
A514	1.09	1.05	1.00
A446/A653	1.10	1.10	1.00
A572	1.19	1.10	1.00
A992	1.19	1.10	1.00

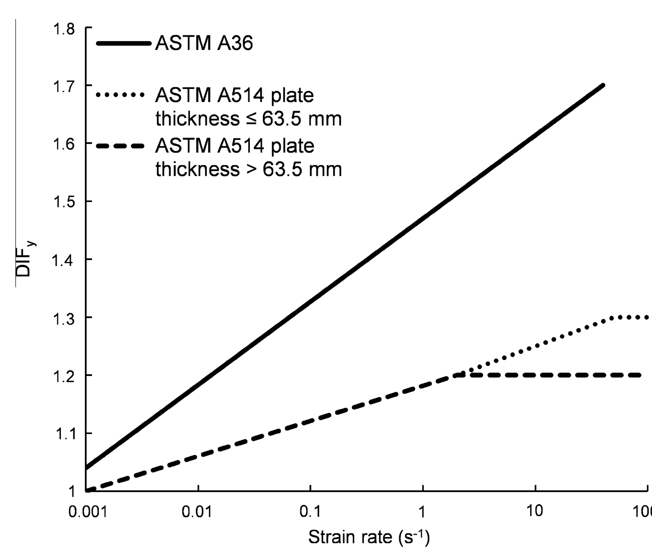

Fig. 1. DIF_y values at various strain rates for ASTM A36 and A514 steels in [7].