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Web crippling behaviour of cold-formed duplex stainless steel tubular sections at elevated temperatures

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ABSTRACT

This paper reports a numerical investigation of cold-formed high strength stainless steel square and rectangular hollow sections subjected to web crippling at elevated temperatures. Finite element analysis was conducted on cold-formed high strength austenitic and duplex stainless steel material. Four loading conditions specified in the American Specification and Australian/New Zealand Standard for cold-formed stainless steel structures were investigated in the numerical study. A non-linear finite element model which includes geometric and material non-linearities was developed and verified against experimental results. It was shown that the finite element model closely predicted the web crippling strengths and failure modes of the tested specimens under the four loading conditions. Hence, parametric study was carried out to investigate the web crippling behaviour of cold-formed high strength stainless steel square and rectangular hollow sections at elevated temperatures. The web crippling strengths predicted from the finite element analysis were compared with the design strengths obtained using the American, Australian/New Zealand and European specifications for stainless steel structures by substituting the reduced material properties in the current web crippling design equations. A unified web crippling equation for cold-formed high strength stainless steel square and rectangular hollow sections at elevated temperatures is proposed. It is demonstrated that the web crippling strength obtained using the proposed equation is safe and reliable using reliability analysis.

1. Introduction

Stainless steels are used in building applications for structural and decorative purpose. For examples, the St Paul's Cathedral in London and the roof of Chrysler Building in New York. Stainless steel does not only have decorative functions, but it can also provide more durable buildings, better fire resistance and better corrosion resistance. Hence, stainless steel has been increasingly used in structural applications in recent years. Significant progress has been made in recent years in the development of design guidance for stainless steel structures in ambient temperature (room temperature). However, investigation of the structural performance of stainless steel structural members at elevated temperatures is relatively limited [1–4].

It is recognised that stainless steel has better structural performance in terms of stiffness and strength than carbon steel at elevated temperatures. Material behaviour of cold-formed stainless steel at elevated temperatures has been reported by Chen and Young [1]. Tensile coupon tests were conducted at different temperatures ranged from approximately 20–1000 °C under both steady and transient state tests. The material properties of stainless steel types EN 1.4462 (Duplex) and EN 1.4301 (AISI 304) were obtained. A unified equation with different coefficients for yield strength, elastic modulus, ultimate strength and ultimate strain of stainless steel at elevated temperatures was proposed based on the test data. The material properties of stainless steel at elevated temperatures have also been conducted [5–8]. The findings of these investigations demonstrated the superior material properties of stainless steel at elevated temperatures, particularly in the temperature ranged approximately from 500 to 800 °C. For example, generally at 800 °C the strength retention of stainless steel is almost 4 times higher than those of carbon steel, and the stiffness retention is 7 times higher than those of carbon steel.

Web crippling is a form of localised buckling that occurs at points of concentrated loads or supports of structural members. Cold-formed stainless steel members that are unstiffened against this type of loading could cause structural failure by web crippling. Cold-formed stainless steel members subjected to web crippling have two different type failure modes. They are web buckling, where the web crippling capacity mainly depends on the stiffness of the material, and web yielding, where the web crippling capacity mainly depends on the yield strength of the material. The current web crippling design rules in most of the specifications for cold-

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Nomenclature

b_f	overall width of flange
b_{fc}	flange width between the midlines of the webs
C	web crippling coefficient
C_h	web slenderness coefficient
C_N	bearing length coefficient
C_R	inside corner radius coefficient
COV	coefficient of variation
d	overall depth of web
d_c	web depth between the midlines of the flanges
E	Young's modulus of elasticity
E_T	elastic modulus at temperature, T (°C)
F_m	mean value of fabrication factor
f_y	yield stress (0.2% proof stress)
$f_{y,T}$	yield stress (0.2% proof stress) at temperature, T (°C)
h	depth of flat portion of web measured along the plane of web
L	actual length of test specimen
M_m	mean value of material factor
N	length of bearing
P	nominal web crippling strength
P_{ASCE}	nominal web crippling strength obtained from ASCE Specification and AS/NAS Standard
P_{EC3}	nominal web crippling strength obtained from European code
P_{Exp}	experimental ultimate web crippling load per web
P_{FEA}	web crippling strength predicted from finite element analysis
$P_{FEA,T}$	web crippling strength predicted from finite element analysis at temperature, T (°C)
P_m	mean value of load ratio
P_{NAS}	nominal web crippling strength obtained from NAS Specification
P_p	proposed web crippling strength calculated
r_i	inside corner radius
r_c	midline corner radius
t	web thickness
V_F	coefficient of variation of fabrication factor
V_M	coefficient of variation of material factor
V_p	coefficient of variation of load ratio
β	reliability index
β_1	reliability index determined using, ϕ_{w1}
β_2	reliability index determined using, ϕ_{w2}
θ	angle between the plane of web and the plane of bearing surface
ε	strain
ε_f	elongation (longitudinal tensile strain) after fracture based on gauge length of 50 mm
σ	stress
σ_u	tensile strength
$\sigma_{0.2}$	0.2% tensile proof stress
ϕ_w	resistance (capacity) factor
ϕ_{w1}	resistance (capacity) factor specified in the current specifications
ϕ_{w2}	resistance (capacity) factor specified in the ASCE Specification

formed stainless steel structures are generally empirical in nature and are based on the test results of cold-formed carbon steel. Furthermore, no web crippling design rules are given for stainless steel members at elevated temperatures. Hence, in this study, the web crippling design rules in the current American [9], Australian/New Zealand [10] and European [11] specifications for cold-formed stainless steel square and rectangular hollow sections are examined for the possibility of using the design rules at elevated temperatures. In doing so, the reduced material properties at elevated temperatures are used in calculating the web crippling strengths.

The objectives of this paper are to numerically investigate the behaviour of cold-formed high strength stainless steel square and rectangular hollow sections subjected to web crippling at elevated temperatures. The finite element analysis (FEA) program ABAQUS [12] was used for the numerical investigation. An accurate finite element model (FEM) that includes geometric and material nonlinearities was developed and verified against the web crippling tests conducted by Zhou and Young [13] at room temperature. Parametric study was carried out to study the structural performance of cold-formed stainless steel square and rectangular hollow sections subjected to web crippling at elevated temperatures. The stress–strain curves of cold-formed stainless steel tubular sections at elevated temperatures measured by Chen and Young [1] were used in the parametric study. The web crippling design rules in the current specifications [9–11] for cold-formed stainless steel square and rectangular hollow sections at elevated temperatures is assessed by comparing the web crippling strengths predicted from the finite element analysis. The reduced material properties were used to calculate the web crippling strengths. In addition, the NAS Specification [14] for cold-formed carbon steel structural members was also used to predict the design strengths. Furthermore, a unified web crippling equation is proposed for cold-formed high strength stainless steel tubular sections subjected to web crippling at elevated temperatures by considering the reduced yield strength and stiffness at elevated temperatures.

2. Summary of experimental investigation

The experimental investigation of cold-formed high strength stainless steel tubular sections subjected to web crippling was performed at room temperature by Zhou and Young [13]. The duplex and high strength austenitic stainless steel square hollow sections (SHS) and rectangular hollow sections (RHS) that included four SHS (Series SHS1, SHS2, SHS3 and SH4) and three RHS (Series RHS1, RHS2 and RHS3) were investigated. The nominal section sizes ($d \times b_f \times t$) were $40 \times 40 \times 2$, $50 \times 50 \times 1.5$, $150 \times 150 \times 3$, $150 \times 150 \times 6$, $140 \times 80 \times 3$, $160 \times 80 \times 3$ and $200 \times 110 \times 4$ for Series SHS1, SHS2, SHS3, SHS4, RHS1, RHS2 and RHS3, respectively, where d is the overall depth of web, b_f is the overall width of flange and t is the web thickness in millimetres as shown in Fig. 1(a). The measured cross-section dimensions of the test specimens are detailed in Zhou and Young [13].

The material properties of the flat portion of the specimens for each series were determined by tensile coupon tests. The coupons were taken from the centre of the face at 90° angle from the weld in the longitudinal direction of the untested specimens. The tensile coupons were prepared and tested according to the American Society for Testing and Materials Standard [15] and the Australian Standard AS 1391 [16] for the tensile testing of metals using 12.5 mm wide coupons of gauge length 50 mm. The measured Young's modulus (E), static 0.2% proof stress ($\sigma_{0.2}$) and ultimate tensile strength (σ_u) as well as the elongation after fracture (ε_f) for Series SHS1, SHS2, SHS3, SHS4, RHS1, RHS2 and RHS3 are shown in Table 1. The material properties of the corner portion of the specimens were also determined by tensile coupon tests for Series RHS2 and RHS3. The material properties of the corners