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Web crippling of cold-formed ferritic stainless steel square and rectangular hollow sections

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ABSTRACT

This paper presents experimental and numerical investigations on cold-formed ferritic stainless steel (CFFSS) square and rectangular hollow sections undergoing web crippling. A total of 44 web crippling tests was carried out under the four codified web crippling load cases as per the American cold-formed stainless steel specification. Numerical model of each load case was built and verified with the web crippling test results. After the verification, a parametric study comprised of 154 finite element analyses was undertaken thereafter to gain further insight into the behaviour of the CFFSS sections undergoing web crippling. The current design provisions in the American, Australian/New Zealand and European stainless steel codes of practice were assessed. Moreover, the North American Specification (NAS) provisions for carbon and low-alloy steel sections were evaluated. Furthermore, design recommendations in the literature for stainless steel sections were examined. Improved design rules are proposed in this study for CFFSS square and rectangular hollow sections by modifying NAS and Direct Strength Method. Reliability analysis was also undertaken to assess the reliability levels of the existing and modified provisions.

1. Introduction

Cold-formed stainless steel (CFSS) square and rectangular hollow sections (SHS and RHS) become increasingly appealing in structural applications owing to their favourable characteristics such as aesthetic appearance, recyclability, durability, high torsional stiffness and so forth. Under local transverse bearing forces, the webs of SHS/RHS may cripple and, hence, web crippling check is crucial in designing CFSS SHS/RHS structural members. Currently, web crippling provisions are available in the American Specification (ASCE) [1], Australian/New Zealand Standard (AS/NZS) [2] and European Code (EC3) [3] for stainless steel structural members. However, note that the codified web crippling design guidelines in these stainless steel codes of practice were adopted from provisions of carbon steel sections [4]. This is primarily owing to a lack of investigation carried out on CFSS sections undergoing web crippling.

The investigation of web crippling behaviour on CFSS sections was conducted since the 1990s at Rand Afrikaans University on stiffened C-sections subjected to Interior-One-Flange (IOF) [5] and End-One-Flange (EOF) [6] load cases. Talja and Salmi [7] pioneered the studies on stainless steel hollow sections. Six CFSS RHS specimens of austenitic grade (EN 1.4301) were investigated under the IOF load case [7]. Gardner et al. [8] studied the design of CFSS SHS/RHS of austenitic grade (EN 1.4318), and six experiments were carried out under the IOF load case. Zhou and Young [9,10] performed a set of experiments on CFSS SHS/RHS and design rules were proposed based on the North American Specification (NAS) [11] web crippling provisions with newly calibrated coefficients for austenitic [9] and high strength [10] stainless steels. It is noteworthy that the previous investigations on stainless steel members under web crippling have been mainly focused on austenitic stainless steels. On the other hand, ferritic stainless steels, having relatively lower initial material cost, may offer more viable alternatives for structural applications than other stainless steel grades [12,13]. Recently, a thorough project entitled Structural Applications of Ferritic Stainless Steels (SAFSS) was conducted in Europe for the purpose of increasing usage of ferritic grades in construction. In the SAFSS project, IOF and EOF tests were undertaken on ferritic SHS (two tests only) of grade EN 1.4509 [14]. A numerical study on ferritic hollow and hat sections under EOF and IOF loadings were undertaken by Bock et al. [15]. In addition, Islam and Young [16,17] investigated fibre reinforced polymer strengthening for ferritic (EN 1.4003) SHS/RHS undergoing web crippling. To date, however, investigations of ferritic SHS/RHS undergoing web crippling are still rather limited, especially under two-flange load cases, the End-Two-Flange (ETF) and Interior-Two-Flange (ITF).

In the present study, experimental and numerical investigations

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Nomenclature

B	overall flange width
E	elastic modulus
E^C	elastic modulus from transverse compressive flat coupon test
E^T	elastic modulus from longitudinal tensile flat coupon test
E_{corner}	elastic modulus from longitudinal tensile corner coupon test
H	overall web height
L	specimen length
N	bearing length
P^C	nominal strength per web calculated using transverse compressive flat material properties
P^T	nominal strength per web calculated using longitudinal tensile flat material properties
P^C_{ASCE}	nominal strength per web obtained from ASCE Specification using compressive flat material properties
P^T_{ASCE}	nominal strength per web obtained from ASCE Specification using tensile flat material properties
P^C_{DSM}	nominal strength per web obtained from modified direct strength method using compressive flat material properties
P^T_{DSM}	nominal strength per web obtained from modified direct strength method using tensile flat material properties
P^C_{EC3}	nominal strength per web obtained from European Code using compressive flat material properties
P^T_{EC3}	nominal strength per web obtained from European Code using tensile flat material properties
$P^C_{EC3\#}$	nominal strength per web obtained from European Code using actual bearing length and compressive flat material properties
$P^T_{EC3\#}$	nominal strength per web obtained from European Code using actual bearing length and tensile flat material properties
P_{Exp}	experimental web crippling strength per web
P_{FEA}	web crippling strength per web obtained from finite element analysis by using both tensile and compressive material properties
$P^\#_{FEA}$	web crippling strength per web obtained from finite element analysis by using tensile material properties only
P^C_{NAS}	nominal strength per web obtained from North American Specification using compressive flat material properties
P^T_{NAS}	nominal strength per web obtained from North American Specification using tensile flat material properties
$P^C_{NAS\#}$	nominal strength per web obtained from modified North American Specification using compressive flat material properties
$P^T_{NAS\#}$	nominal strength per web obtained from modified North American Specification using tensile flat material properties
$P^C_{Z\&Y}$	nominal strength per web obtained from design rules suggested by Zhou and Young [10] using compressive flat material properties
$P^T_{Z\&Y}$	nominal strength per web obtained from design rules suggested by Zhou and Young [10] using tensile flat material properties
P_{cr}	nominal bearing buckling strength per web
P_m	mean value of test/FE strength to design prediction ratios
P_u	test/FE web crippling strength per web
P_y	nominal bearing yield strength per web
R	outer corner radius
V_P	coefficient of variation of test/FE strength to design prediction ratios
h	depth of web flat portion
r	inner corner radius
t	web thickness
β	reliability index
ε^T_f	fracture strain from longitudinal tensile flat coupon test
$\varepsilon_{f,corner}$	fracture strain from longitudinal tensile corner coupon test
$\sigma_{0.2}$	0.2% proof stress (yield stress)
$\sigma^C_{0.2}$	0.2% proof stress from transverse compressive flat coupon test
$\sigma^T_{0.2}$	0.2% proof stress from longitudinal tensile flat coupon test
$\sigma_{0.2,corner}$	0.2% proof stress from longitudinal tensile corner coupon test
σ^T_u	tensile strength from longitudinal tensile flat coupon test
$\sigma_{u,corner}$	tensile strength from longitudinal tensile corner coupon test
ϕ	resistance factor

were undertaken in order to study the behaviour of cold-formed ferritic stainless steel (CFFSS) SHS/RHS undergoing web crippling. In total, 44 web crippling experiments were performed, which covered all four load cases as codified in the ASCE [1] and AS/NZS [2]. These four codified load cases are the EOF, IOF, ETF and ITF. Finite element (FE) models were built and verified with the experimental results. Upon verification, a parametric study was undertaken utilizing the verified FE models to expand the database. The applicability of the codified provisions in the ASCE [1], AS/NZS [2], EC3 [3] and NAS [11] was evaluated. Furthermore, the web crippling design rules suggested by Zhou and Young [10] were assessed to investigate their feasibility to be applied for CFFSS sections. Modified design rules are provided in this study for CFFSS SHS/RHS undergoing web crippling.

Table 1
Measured specimen dimensions and web crippling strengths per web for EOF load case.

Specimens	H (mm)	B (mm)	t (mm)	r (mm)	R (mm)	L (mm)	P_{Exp} (kN)	$\frac{P_{Exp}}{P^\#_{FEA}}$	$\frac{P_{Exp}}{P_{FEA}}$
EOF-80 × 80 × 3 N50	80.0	80.0	2.803	3.0	5.8	441	37.8	1.19	1.11
EOF-60 × 40 × 3 N30	60.0	40.1	2.716	3.1	5.9	300	22.4	1.13	1.02
EOF-60 × 40 × 3 N30-R†	60.0	40.0	2.716	3.1	5.9	301	22.3	1.12	1.01
EOF-100 × 40 × 2 N50	99.8	40.3	1.931	3.8	5.7	499	12.1	0.98	0.97
EOF-100 × 40 × 2 N30	99.8	40.2	1.925	3.8	5.7	420	9.0	0.95	0.94
EOF-100 × 50 × 3 N50	100.2	50.0	2.796	2.6	5.4	500	32.9	1.10	1.04
EOF-100 × 50 × 3 N30	100.2	49.9	2.792	2.6	5.4	419	23.9	1.11	1.06
							Mean	1.08	1.02
							COV	0.078	0.057

Note: †Repeated test; #FE model using material properties obtained from longitudinal tensile coupon tests only.