Thin-Walled Structures 133 (2018) 192–205

Contents lists available at ScienceDirect

Thin-Walled Structures

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

Full length article

# Design of cold-formed high strength steel tubular sections undergoing web crippling

Hai-Ting Li, Ben Young*

*Department of Civil Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong, China*

ARTICLE INFO

*Keywords:*
Cold-formed steel
Direct strength method
Finite element analysis
High strength steel
Tubular sections
Web crippling

ABSTRACT

Design of cold-formed high strength steel (HSS) tubular sections undergoing web crippling is examined in this study. Finite element (FE) models were developed and validated against available test results, showing the capability of replicating the experimental web crippling strengths, failure modes and load-web deformation histories. On validation of the FE models, an extensive parametric study comprised of 224 FE analyses was performed. The web crippling provisions in the current North American Specification, Australian/New Zealand Standard and European Code for cold-formed steel structures were assessed. The web crippling strengths obtained from the numerical investigation together with available experimental data from the literature were compared with the nominal strengths derived from the aforementioned specifications. Overall, the comparisons showed that the nominal strengths predicted by the existing codified provisions are either unconservative or overly conservative. Hence, improved design rules are proposed for cold-formed HSS tubular sections undergoing web crippling by means of modified unified equation and Direct Strength Method. The reliability of the modified design rules has been proven through reliability analysis.

## 1. Introduction

Web crippling may occur in cold-formed steel members due to high localized concentrated forces or reactions. Cold-formed steel tubular sections, which are often difficult and uneconomical to be stiffened by transverse stiffeners, are vulnerable to the web crippling failure under concentrated transverse forces. Many studies have been conducted to study the web crippling behaviour of cold-formed steel open sections [1–8], including recently introduced Direct Strength Method (DSM) based web crippling design rules by Gunalan and Mahendran [9], Natário et al. [10,11] and Heurkens et al. [12]. To date, however, investigation on cold-formed steel tubular sections undergoing web crippling is rather limited.

Kato and Nishiyama [13] tested cold-formed steel square hollow section (SHS) and rectangular hollow section (RHS) T-joints, and web crippling behaviour of the chord members was investigated. The results revealed that chord depth-to-thickness ratio was one of the most influential parameters to the web crippling strength. Web crippling strengths of cold-formed stress-relieved rectangular hollow sections under localized transverse compressive forces were examined by Packer [14]. It was found that the web crippling strengths of rectangular hollow section webs were not significantly affected by the presence of axial compressive force in the chord [14]. Zhao and Hancock [15] carried out web crippling tests under concentrated interior bearing force on cold-formed steel square and rectangular hollow sections. In the test program, the transverse bearing force was applied through steel plates that act across full-flange width of the sections. Based on experimental observations, a plastic mechanism model, which considered the eccentric loading of the webs, was proposed for the web crippling strength predictions [15]. Zhao and Hancock [16] further investigated the web crippling behaviour of cold-formed steel SHS/RHS and a mechanism model was proposed for the tubular sections subjected to concentrated end bearing force [16]. The nominal yield stress of the specimens tested by Zhao and Hancock [15,16] was 350 MPa. On the other hand, high strength steels have attracted attention in structural applications due to their excellent strength-to-weight ratios that could lead to lighter and elegant structures [17]. However, the behaviour and design of cold-formed high strength steel (HSS) tubular sections with 0.2% proof stress greater than 690 MPa undergoing web crippling have been largely unexplored.

The objective of this paper is to provide reliable design rules for cold-formed HSS tubular sections undergoing web crippling. Finite element (FE) models were developed and validated against the web crippling tests reported previously by the authors [18]. All four loading conditions, the End-One-Flange (EOF), Interior-One-Flange (IOF), End-Two-Flange (ETF) and Interior-Two-Flange (ITF), as specified in the

* Corresponding author.
*E-mail address:* young@hku.hk (B. Young).

https://doi.org/10.1016/j.tws.2018.09.005
Received 6 May 2018; Received in revised form 1 September 2018; Accepted 2 September 2018
0263-8231/ 

**Notation**

| | |
|---|---|
| $B$ | Overall width of cross-section; |
| $C_P$ | Correction factor; |
| $C_\phi$ | Calibration coefficient; |
| $E$ | Young's modulus; |
| $E_{corner}$ | Young's modulus obtained from tensile corner coupon test; |
| $F_m$ | Mean value of fabrication factor; |
| $H$ | Overall depth of cross-section; |
| $h$ | Depth of web flat portion; |
| $L$ | Specimen length; |
| $M_m$ | Mean value of material factor; |
| $N$ | Bearing length; |
| $n_{corner}$ | Ramberg-Osgood parameter obtained from tensile corner coupon test; |
| $N_m$ | Mechanism length; |
| $P_{cr}$ | Nominal bearing buckling strength per web; |
| $P^C_{DSM}$ | Nominal web crippling strength per web obtained from modified direct strength method using compressive flat material properties; |
| $P^T_{DSM}$ | Nominal web crippling strength per web obtained from modified direct strength method using tensile flat material properties; |
| $P^C_{EC3}$ | Nominal web crippling strength per web obtained from European Code using compressive flat material properties; |
| $P^T_{EC3}$ | Nominal web crippling strength per web obtained from European Code using tensile flat material properties; |
| $P^C_{EC3\#}$ | Nominal web crippling strength per web obtained from European Code using actual bearing length and compressive flat material properties; |
| $P^T_{EC3\#}$ | Nominal web crippling 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; |
| $P_m$ | Mean value of test and finite element strength to design prediction ratios; |
| $P^C_{MUE}$ | Nominal web crippling strength per web obtained from modified unified equation using compressive flat material properties; |
| $P^T_{MUE}$ | Nominal web crippling strength per web obtained from modified unified equation using tensile flat material properties; |
| $P^C_{NAS}$ | Nominal web crippling strength per web obtained from North American Specification using compressive flat material properties; |
| $P^T_{NAS}$ | Nominal web crippling strength per web obtained from North American Specification using tensile flat material properties; |
| $P^C_{pred}$ | Nominal web crippling strength per web calculated using compressive flat material properties; |
| $P^T_{pred}$ | Nominal web crippling strength per web calculated using tensile flat material properties; |
| $P_u$ | Test and finite element strengths per web; |
| $P_y$ | Nominal bearing yield strength per web; |
| $R$ | Outer corner radius; |
| $r$ | Inner 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 test and finite element strength to design prediction ratios; |
| $V_Q$ | Coefficient of variation of load effect; |
| $\beta$ | Reliability index; |
| $\varepsilon$ | Factor depending on 0.2% proof stress; |
| $\varepsilon_{f,corner}$ | Fracture strain obtained from tensile corner coupon test; |
| $\varepsilon_{u,corner}$ | Ultimate strain obtained from tensile corner coupon test; |
| $\lambda$ | Web crippling slenderness ratio; |
| $\sigma_{0.2}$ | 0.2% proof stress (yield stress); |
| $\sigma_{0.2,corner}$ | 0.2% proof stress obtained from tensile corner coupon test; |
| $\sigma_{u,corner}$ | Tensile strength obtained from tensile corner coupon test; |
| $\phi$ | Resistance factor. |

North American Specification (NAS) [19] and Australian/New Zealand Standard (AS/NZS) [20], were investigated. Upon validation of the FE models, an extensive parametric study was performed. The applicability of the codified web crippling provisions in the NAS [19], AS/NZS [20] and European Code (EC3) [21] to cold-formed HSS tubular sections was assessed. A modified unified equation is proposed based on the web crippling design formula in the NAS [19]. Web crippling design rules based on DSM are also proposed for cold-formed HSS tubular sections under the four codified loading conditions.

## 2. Experimental investigation

### 2.1. Summary of test program

An experimental investigation on cold-formed HSS square and rectangular hollow sections undergoing web crippling was conducted by the authors [18]. The tests were carried out on the HSS tubular sections with measured 0.2% proof stresses ranging from 679 to 1025 MPa (obtained from longitudinal tensile flat coupon tests). The measured section web slenderness ratios $h/t$ ranging from 8.3 to 35.8, in which $h$ is the depth of the web flat portion and $t$ is the web thickness. The tests were conducted under the four codified web crippling loading conditions in the NAS [19] and AS/NZS [20], namely, the EOF, IOF, ETF and ITF. The specimen lengths $L$, as indicated in Fig. 1, were determined as per the NAS [19] and AS/NZS [20]. The loading or reaction forces were applied through steel bearing plates and the bearing plates were acted across full-flange widths excluding the corners of the sections. All flanges of the HSS tubular specimens were not fastened to the bearing plates. The web crippling test program is detailed in Li and Young [18].

### 2.2. Corner coupon tests

The material properties of the cold-formed HSS tubular specimens were obtained by coupon tests. Longitudinal tensile and transverse compressive flat coupon tests were conducted [18]. It should be noted that, due to cold-working, the corner regions of the cold-formed HSS tubular sections were strengthened, and therefore, exhibited enhanced yield stresses and ultimate strengths compared to their flat counterparts. Hence, longitudinal tensile corner coupon tests were conducted and are reported in the present study in order to obtain material properties of the highly cold-worked corners, and the corner material properties were also incorporated in FE modelling. The corner coupons were extracted from the HSS sections (opposite to the weld) in the longitudinal direction and an MTS material testing machine was used to conduct the tensile corner coupon tests in this study. For each coupon test, the instrumentation comprised of two strain gauges and a calibrated 25 mm gauge length MTS extensometer. The tensile corner coupon test procedures were in accordance with those described by Li and Young [18] for tensile flat coupon tests, but the corner coupon specimens were loaded through two pins. Table 1 summarises the