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Web crippling experiments of high strength lipped channel beams under one-flange loading

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A B S T R A C T

Web crippling is often a critical design problem in cold-formed steel flexural members. Lipped channel beams (LCBs) are commonly used as floor joists and bearers in the construction industry and are often subjected to concentrated loads. Design capacity predictions from most of the cold-formed steel design standards such as AISI S100 [1], AS/NZS 4600 [2] and Eurocode 3 Part 1-3 [3] are empirical, developed based on past experimental studies. They were found to be either unconservative or conservative in most cases. Inconsistencies in design capacity predictions are considered to be due to the fact that the specimen length and support conditions pertaining to the test set-up varied among past experimental studies. In 2008, American Iron and Steel Institute introduced a standard test method for conducting web crippling studies [4]. However, limited web crippling studies have been conducted to date for LCB sections under EOF and IOF load cases. Therefore a detailed experimental study consisting of 36 tests was conducted to investigate the web crippling behaviour of high strength cold-formed steel LCB sections under EOF and IOF load cases based on the AISI web crippling standard test method. This paper presents the details of this experimental study of LCBs unfastened to supports, using which it proposes suitable modifications to the current unified web crippling design equation. It also presents suitable direct strength method based design equations and associated predictive equations for elastic bucking and yield loads of LCBs under EOF and IOF load cases.

1. Introduction

Cold-formed steel sections are increasingly used as load bearing members in residential and commercial building construction due to their intrinsic characteristics such as high strength to weight ratio, easy fabrication and mass production when compared to conventional construction materials such as timber, concrete and masonry. However, these cold-formed steel sections which are generally made of thin steel sheets are prone to localized failures. Among them, web crippling is an important failure mode when the sections are exposed to concentrated loads or reactions and must be considered in their design.

A theoretical approach to predict web crippling strength has not been attained to date due to the complex nature of web crippling behaviour including non-uniform stress distribution along the web-flange juncture and adjoining web portions, elastic and inelastic buckling of web, non-linearity of steel properties (strain hardening), web plane eccentricity to loading or reaction points on flanges (due to corner radius), initial imperfections and flange curling (specially for unfastened flange to support conditions). Therefore, the current cold-formed steel design standards such as AISI S100 [1], AS/NZS 4600 [2] and Eurocode3 Part 1-3 [3] provide empirical formulae for predicting the web crippling capacity of cold-formed steel sections. Web crippling failures can occur in different ways based on the locations of applied concentrated forces or reaction forces, support conditions and length of the section. Currently available design rules simplify these web crippling failure modes into four main categories. They are End Two Flange (ETF) load case, Interior Two Flange (ITF) load case, End One Flange (EOF) load case and Interior Two Flange (IOF) load case. In this paper the web crippling failures of Lipped channel beam (LCB) sections under EOF and IOF load cases (as shown in Fig. 1) are investigated.

Web crippling design equations provided in the current design standards are based on experimental data obtained from past research studies consisting of different experimental studies starting from 1940s. These design equations are limited to the geometric and mechanical properties of sections used in the experimental studies. Inconsistences in design rule predictions are mainly due to the variations in the test set-up and specimen length used in these experimental studies. Recently American Iron and Steel Institute (AISI) published a standard test procedure for web crippling tests [4]. However, most of the past experimental studies have not fully followed the AISI standard test

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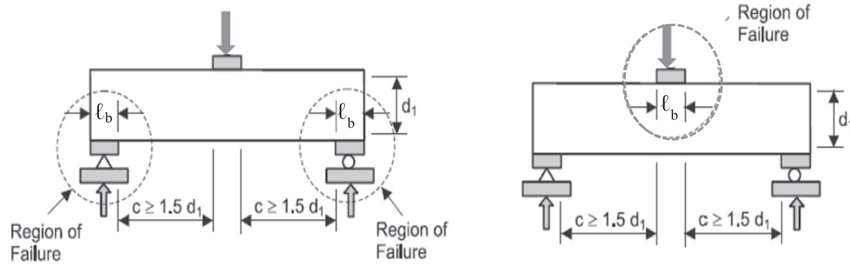

a) End One Flange (EOF) b) Interior One Flange (IOF)

Fig. 1. EOF and IOF load cases [4].

method. The web crippling capacities obtained from a series of recent experimental studies [5–7] also did not agree well with those predicted by the current design equations in AISI S100, AS/NZS 4600 and Eurocode 3 Part 1-3.Therefore, a detailed experimental study involving 36 EOF and IOF web crippling tests of LCBs unfastened to supports was conducted based on the AISI standard web crippling test method (AISI S909 [4]) and, this paper presents the details of this experimental study and the results.

This paper presents a review of recent web crippling studies and an experimental study conducted for LCBs under EOF and IOF load cases and investigates the suitability of current web crippling design equations. Further, this paper also investigates the critical buckling loads of LCB subjected to web crippling and proposes a unified equation for calculating the buckling coefficients. Design equations for yield load predictions are also developed using a simplified yield mechanism. Finally direct strength method based design equations are developed using both critical buckling load and yield load to predict the web crippling capacities of LCBs.

2. AISI standard test method [4]

In 2008, American Iron and Steel Institute (AISI) published a standard test method in AISI S909 [4] to provide appropriate guidelines for web crippling tests. AISI S909 defines End One Flange (EOF) load case as a condition, where the distance from the edge of the bearing to the end of the member is equal to or $< 1.5d_1$, where d_1 is the flat portion of web depth and the clear distance between the bearing edges of adjacent opposite concentrated loads or reactions is equal to or $> 1.5d_1$. Interior One Flange (IOF) load case is defined as a condition where the distance from the edge of the bearing to the end of the member is $> 1.5d_1$, and the clear distance between the bearing edges of adjacent opposite concentrated loads or reactions is equal to or $> 1.5d_1$(see Fig. 1).

Specimen length is an important parameter in web crippling tests under EOF and IOF load cases. Increased specimen length will cause test specimen to fail in combined bending and web crippling. Therefore, AISI S909 standard test method recommends the overall minimum specimen length of $3d_1 + 3\ell_b$ for EOF and IOF load cases, where ℓ_b is the bearing length. Thus, in this study the overall specimen length was chosen as $3d + 3\ell_b$ to satisfy the minimum requirements, where d is the section depth.

To investigate the behaviour of cold-formed steel sections under pure web crippling, a laterally and torsionally stable test set-up is necessary. For channel sections where their section geometry does not allow simpler load application through the shear centre, AISI S909 recommends the use of two identical cross-sections in a stable test arrangement. These sections shall be connected toe to toe or back to back with appropriate connecting elements to form a box shape. It suggests 20 × 20 × 3 mm angle sections as connecting elements at approximately ¼ and ¾ points on the flanges along the longitudinal axis. The support system includes pin and roller supports to avoid any influence of axial force during testing.

3. Current web crippling design rules

3.1. AISI S100

American and Australian design standards [1,2] for cold-formed steel design provide a single unified equation (Eq. (1)) to predict web crippling capacities. This equation and relevant coefficients for different geometric sections were developed using detailed statistical analyses by Prabaharan [8] and Beshara and Schuster [9] based on past experimental studies. Appropriate coefficients provided in these design standards to predict the web crippling capacities of LCB sections under EOF and IOF load cases are given in Table 1.

$$R_b = Ct_w^2 f_y \sin\theta\left(1 - C_r\sqrt{\frac{r_i}{t_w}}\right)\left(1 + C_\ell\sqrt{\frac{\ell_b}{t_w}}\right)\left(1 - C_w\sqrt{\frac{d_1}{t_w}}\right) \quad (1)$$

where; t_w = web thickness, f_y = web yield stress, ℓ_b = bearing length, d_1 = flat portion of web depth, r_i = inside bent radius, θ = angle between the plane of the web and the plane of the bearing surface, C = coefficient, C_r = coefficient of inside bent radius, C_ℓ = coefficient of bearing length, C_w = coefficient of web slenderness.

3.2. Eurocode 3 Part 1-3

European design standard [3] gives a range of equations developed based on past experimental studies. Eqs. (2) to (6) give the design formulae given in [3] for single unstiffened web sections under EOF and IOF load cases, respectively. However, these design equations are

Table 1
AS/NZS 4600 web crippling coefficients for LCBs under EOF and IOF Load Cases.

Support conditions	Load cases	C	C_r	C_ℓ	C_w	ϕ_w	Limits
Flanges fastened to support	EOF IOF	4 13	0.14 0.23	0.35 0.14	0.02 0.01	0.85 0.90	$r_i/t_w \leq 9$ $r_i/t_w \leq 5$
Flanges unfastened to support	EOF IOF	4 13	0.14 0.23	0.35 0.14	0.02 0.01	0.80 0.90	$r_i/t_w \leq 5$

Note: The coefficients apply if $d_1/t_w \leq 200$, $\ell_b/t_w \leq 210$, $\ell_b/d_1 \leq 2.0$ and $\Theta = 90^0$; ϕ_w = capacity reduction factor.