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Interior two-flange loading web crippling tests on CFS built-up I-beams composed of lipped channels

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Abstract

Compared to a single cold-formed steel (CFS) channel beam, a built-up I-beam comprising two such channels possesses a higher bending capacity and greatly increased stability. However, since CFS webs are typically slender elements, they are susceptible to web crippling under concentrated loading. Most of the previous research in this area has focused on single sections, with very limited data being available for built-up sections. The web crippling response of a single CFS channel may differ from that of an I-section, due to the presence of contact and connectors in the latter. Hence, the web crippling design rules in the current North American Specification (AISI S100) and the Eurocode (EN1993-1-3) for single sections may not be adequate for built-up beams and need further exploration across a wide range of parameters. Experimental results for CFS channel beams under Interior Two-Flange loading, with different base metal thicknesses and number of screws across the length, are presented in this paper. The accuracy of the North American Specification (NAS AISI S100) and European standard (EC3) is also assessed by evaluating their web crippling strength predictions. It is concluded that the NAS predictions are reasonably accurate, whereas the EC3 predictions are inconsistent and significantly underestimate the web crippling strengths

1. Introduction

In the construction of low- to mid-rise buildings cold-formed steel (CFS) sections have consistently gained popularity. Relatively simple fabrication, low self-weight, ease of handling and shipping, off-site manufacture and significantly shortened building times are all favorable aspects of CFS. As a result, building industries all across the world have embraced this type of construction. However, the limited wall thicknesses of CFS members make them more susceptible to several kinds of instabilities. Consequently, significant research has been invested in the stability of thin-walled CFS structural parts, which has resulted in new, economical alternatives with better structural performance.

Beams are essential structural elements that transfer loads from floors to supporting columns. Because of the inevitable eccentricity of the loading with respect to the shear center of the cross-section, single-channel beams become subject to torsion and an increased risk of lateral-torsional buckling when laterally unrestrained. Built-up I-sections made from two web-connected channels, on the other hand, exhibit higher strength and improved stability. However, under the concentrated action of point loads and support reactions, the slender web elements of CFS channels become

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vulnerable to web crippling failure. Prior studies on web crippling have primarily focused on individual CFS channels.

2. Previous web crippling research on CFS channel sections

Early web crippling tests on CFS channel sections examined critical factors such as the web slenderness, the corner radius, the bearing length, the yield strength of the steel, the flange boundary conditions (fastened or unfastened), and the loading type (Hetrakul & Yu 1978; Young & Hancock 1998; Rhodes & Nash 1998; Bhakta et al. 1992; Gerges & Schuster 1988; Lagan et al. 1994; Beshara & Schuster 2000). Several empirical design expressions to determine web crippling strength were developed as a result of these investigations, and were included in previous versions of the design guidelines (AISI 1996; S136; AS/NZS 4600; BS 5950-5). After 2000, this research was further extended by varying the relevant parameters over wider ranges (Young & Hancock 2003; 2004; Ren et al. 2006; Duarte & Silverstre 2013; Natario et al. 2014a-b; Gunalan & Mahendran 2019; Janathanan et al. 2019; Macdonald et al.2011; Macdonald & Heiyantuduwa 2012; Chen et al. 2015; Sundarajah et al. 2017; 2018; Heukens et al. 2018; Keerthan et al. 2014; Keerthan & Mahendran 2016; Steau et al. 2015; 2016; 2017). These investigations contributed to the development of the design rules included in the current codes (AISI S100; EN 1993-1-3), theoretical design models, and new design equations based on the Direct Strength Method (DSM). Recent analyses have examined the web crippling behavior of modified channel sections, such as hollow flanged channels (Keerthan et al. a-b; Steau et al. a-c) and intermittently web-stiffened channels with inclined lips (Sundararajah et al. a-b). Additionally, the impact of web openings on the web crippling capacity of CFS channels was examined (Uzzaman et al. 2012a-c; 2013; 2017; 2020a-b; Lian et al. 2016a-b; 2017a-b; Elilarasi and Janarthanan; Chen et al. 2021; Gatheeshgar et al. 2022), and various reduction factors were put forth to capture the strength reduction due to the openings.

3. CFS built-up I-beams

Because of the interaction between the webs through contact and connectors, the web crippling response of a single CFS channel may be very different from that of a built-up I-beam made up of two such channels. Only a few studies have previously examined built-up I-sections made of plain channels (He & Young 2022a-b, Dar et al. 2023; 2024; 2025), with little further information available on web crippling of CFS built-up I-beams (Winter & Pian 1946; Hetrakul & Wu 1978; Bhakta & LaBoube 1992; Cian et al. 1995; He & Young 2022a-b). According to these previous studies, the web crippling design formulations in the present specifications (AISI S100 & EC3) are inaccurate for such beams.

The here presented study experimentally examined the web-crippling behavior of CFS built-up I-beams over a broader range of crucial parameters, building on the earlier research work. Additionally, the web crippling strengths predicted by the current design specifications (AISI S100 & EC3) were compared against the experimentally obtained web crippling strengths to assess their accuracy.

4. Codal Design Formulations Available

This section summarizes the analytical expressions used to predict the web crippling strength of CFS members subjected to Interior Two-Flange (ITF) loading. The predictions are based on the North American Specification (AISI S100) and the European Standard (EC3). These two approaches account for material yielding, geometric parameters and load dispersion effects in different ways.

4.1 North American Specification (AISI S100)

The North American Specification (AISI S100) provides an empirically based equation for predicting the nominal web crippling strength of CFS members. The formulation explicitly incorporates the effects of web thickness, bearing length, corner radius, web slenderness, and load inclination. For stiffened flanges under Interior Two-Flange loading, the nominal web crippling strength is given by Eq. (1):

$$P_n = Ct^2F_y sin\,\theta \left(1 - C_R\sqrt{\frac{R}{t}}\right)\left(1 + C_N\sqrt{\frac{N}{t}}\right)\left(1 - C_h\sqrt{\frac{h}{t}}\right) \tag{1}$$

Where,

P_n = Nominal web crippling strength
t = Web thickness
F_y = Design yield stress
R = Inside bend radius
N = Bearing length
θ = Angle between plane of web and plane of bearing surface
h = Flat dimension of web measured in plane of web
C = 36 for stiffened flanges, Interior Two-Flange loading
C_R = 0.14 for stiffened flanges, Interior Two-Flange loading
C_N = 0.08 for stiffened flanges, Interior Two-Flange loading
C_h = 0.04 for stiffened flanges, Interior Two-Flange loading

4.2 European Standard (EC3)

The EC3 predicted web crippling strength, given by Eq. (2), is expressed as a function of the web thickness, the 0.2% proof stress, and the bearing length. The coefficients k_8 and k_9 serve as modification factors to account for the influence of bearing length and web slenderness, respectively. The formulation distinguishes between short and long bearing lengths through different expressions for k_8, accounting for load distribution effects.

$$P_{EC3} = t^2 f_{0.2} k_8 k_9 \left(13.2 + 2.87\sqrt{\frac{N}{t}}\right) \tag{2}$$

Where,

P_{EC3} = Nominal web crippling strength
k_8 = $228/f_{0.2}$ if $N/t < 66.5$; $(1.1-h_w/(665\,t))/k$ if $N/t > 66.5$
k_9 = $0.82 + 0.15(t / 1.9)$
h_w = Web height
N = Bearing length
$F_{0.2}$ = Design yield stress

It should be noted that neither AISI S100 nor Eurocode 3 explicitly account for the influence of screw detailing on web crippling strength, despite prior studies (He & Young 2022a) demonstrating that fastener configuration can affect the web crippling response of built-up sections.

5. Experimental programme

5.1 Web crippling tests

The effects of the channel thickness and the screw arrangement along the channel length were experimentally investigated. Three CFS built-up beams, made of two equal-size lipped channels connected back-to-back through the web at various discrete points along the length, were tested under Interior-Two-Flange loading (ITF) conditions. The beams were formed from steel sheets of 3 mm and 5 mm thickness. Tensile coupon tests were performed to obtain the specimens' mechanical properties, including the Young's modulus (E), 0.2% proof stress ($f_{0.2}$), and ultimate strength (f_u), which are all listed in Table 1.

Table 1: Mechanical properties obtained from tensile tests

Coupon No.	Thickness (t)	Yield strength ($f_{0.2}$)	Ultimate strength (f_u)	Young's modulus (E)
	(mm)	(MPa)	(MPa)	(MPa)
Coupon 1	3.0	413.0	489.7	201169
Coupon 2	3.0	434.0	511.3	200954
Coupon 3	3.0	420.6	502.1	201026
Coupon 4	5.0	450.1	518.0	201450
Coupon 5	5.0	441.5	525.9	201583

Previous studies have reported that geometric imperfections have a negligible influence on the web crippling strength of CFS members (Natário et al., 2014b; Sundararajah et al., 2017, 2018). Accordingly, initial geometric imperfections were not explicitly measured in the present study. The nominal dimensions of the beams are summarized in Table 2, while the screw layouts and the corresponding labelling convention adopted for the test specimens are presented in Figure 1. All test beams were assembled using three horizontal rows of self-tapping screws, with the number of vertical rows (indicated as L.S. in Table 3) varied between specimens. The ratio of the distance between the flange and the center of the upper screw to the web depth, e/h, was maintained constant at 0.2 for all specimens, to ensure consistency. Similarly, the ratio of the bearing length to the web depth was fixed at 0.5, representing a typical value for interior loading conditions. The web crippling tests were conducted using a Shimadzu Universal Testing Machine, as shown in Figure 2. The actuator load was transferred to the specimens through high-strength steel bearing plates positioned at the top and bottom flanges at mid-length, ensuring even loading while establishing Interior Two-Flange loading conditions. Both the top and bottom bearing plates were hinge-supported and allowed flange rotations, while restraining horizontal movement. Two LVDTs were installed beneath each top flange to record vertical displacements, while an additional LVDT was placed on each side of the web to monitor lateral web deformations. To accurately measure this lateral displacement, a rigid plastic plate was attached to the tips of the LVDTs (Fig. 3b). An initial preload of 5 kN was applied to eliminate any initial misalignment and to ensure proper seating and engagement in the test set-up. The specimens were then loaded under displacement control at a constant rate of 0.5 mm per minute until failure.

Table 2: Nominal dimensions of the tested beam specimens

Beam ID.	Web height (h)	Thickness (t)	e/h	N/h	L.S.
	(mm)	(mm)			(Nos.)
ITF-0.2-3-0.5-3	350	3	0.2	0.5	3
ITF-0.2-5-0.5-3	350	3	0.2	0.5	5
ITF-0.2-3-0.5-5	350	5	0.2	0.5	3

5.2 Inferences from the experiments

The web crippling strengths obtained from the experimental programme are summarized in Table 3, while the corresponding failure modes are illustrated in Figure 3. All tested specimens ultimately failed by web crippling under the applied concentrated load, as desired.

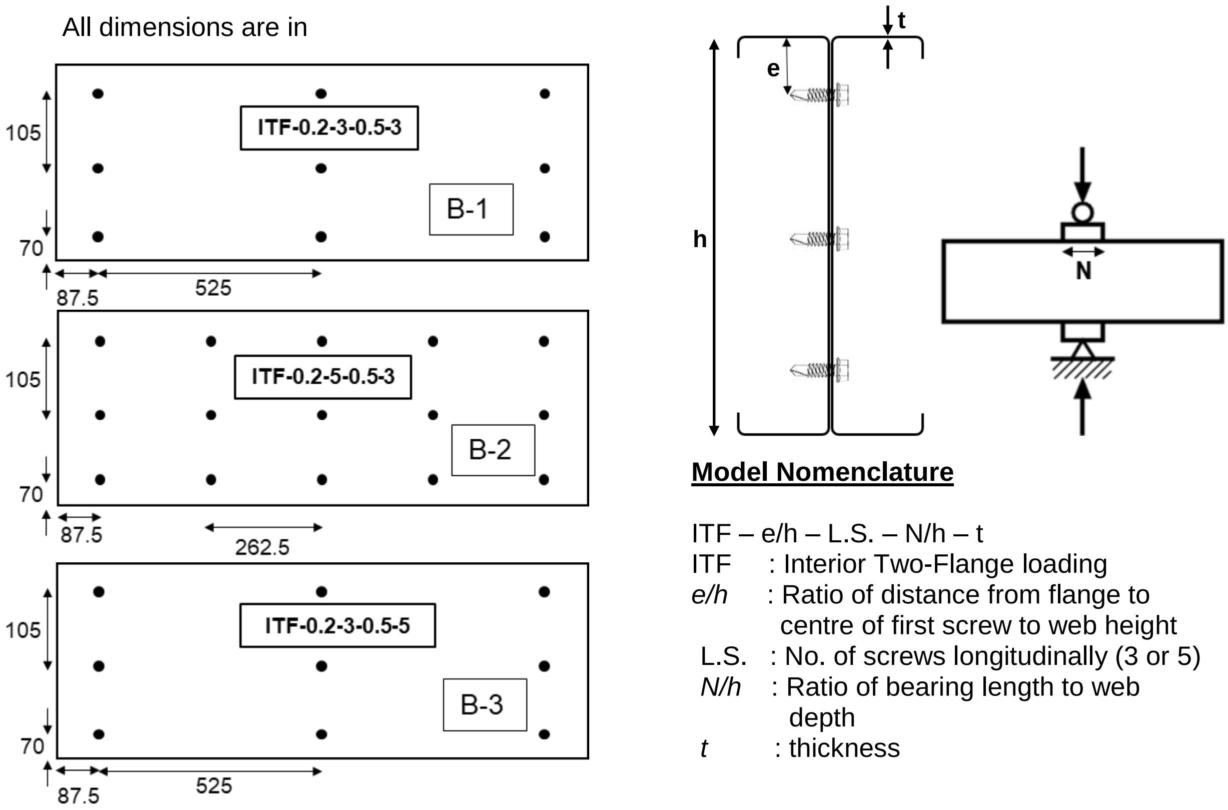
A clear influence of base metal thickness on web crippling strength was observed. The specimens with 5 mm thickness displayed a capacity that was, on average, three times higher than that of the 3 mm thick specimens. In contrast, the variation in the number of rows of screws provided along the longitudinal direction of the beam had a negligible effect on the measured web crippling strength for the configurations tested. This indicates that, once adequate shear transfer and composite action between the built-up components are ensured, further increasing the screw density does not contribute meaningfully to improving the web crippling resistance.

No separation between the webs of the channels or screw pull-out was observed during the out-of-plane bending of the webs in any of the specimens. This indicated that the mechanical fasteners provided sufficient connectivity to maintain composite action up to failure. However, screw failure was observed in one of the specimens, namely ITF-0.2-3-0.5-5, wherein three screws failed. Additionally, plastic rotation of one or both flanges about the web–flange junction was observed under the load in all the specimens.

Figure 4 shows the load–displacement responses of all tested specimens, which were in line with trends reported in earlier studies (He & Young 2022a). The overall behavior consisted of an initial linear elastic region, followed by progressive stiffness degradation as local web deformations developed. For specimen ITF-0.2-3-0.5-5, three distinct kinks were evident in the load–displacement curve. These are attributed to the sequential failure of individual screw fasteners, resulting in sudden drops in load, followed by a recovery phase. This phenomenon was not observed in the other two specimens, which displayed comparatively smoother and more continuous load–displacement curves.

Table 3: Web crippling test results

Beam ID.	Thickness (mm)	L.S. (Nos.)	Failure load, P_{Test} (kN)
ITF-0.2-3-0.5-3	3	3	123.3
ITF-0.2-5-0.5-3	3	5	126.2
ITF-0.2-3-0.5-5	5	3	377.5



Model Nomenclature

ITF – e/h – L.S. – N/h – t

ITF	: Interior Two-Flange loading
e/h	: Ratio of distance from flange to centre of first screw to web height
L.S.	: No. of screws longitudinally (3 or 5)
N/h	: Ratio of bearing length to web depth
t	: thickness

Figure 1: Geometric parameters of the tested built-up beams

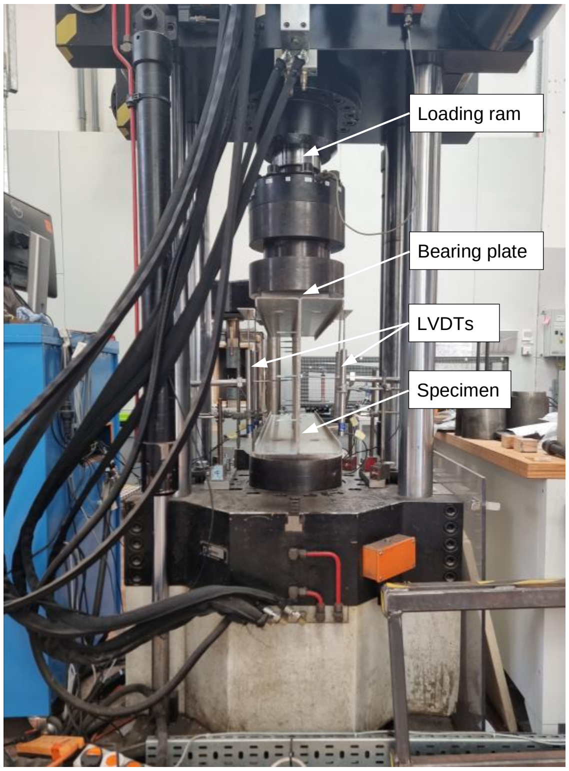


Figure 2: Experimental set-up


(a) ITF-0.2-3-0.5-3 (b) ITF-0.2-3-0.5-5 (c) ITF-0.2-5-0.5-3

Figure 3: Failure modes of tested beams

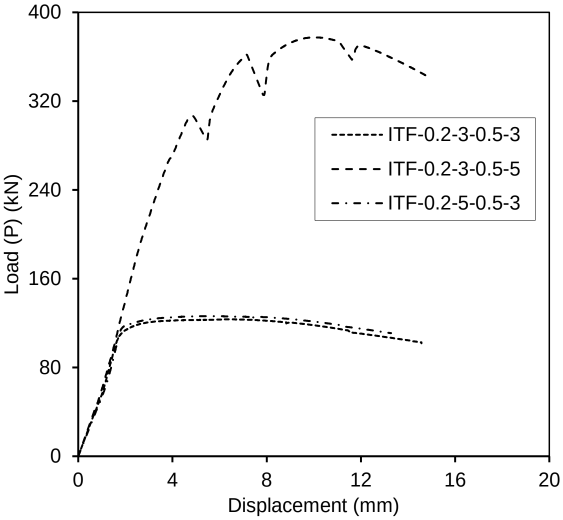


Figure 4: Load – displacement curves of the tested specimens

5. Design strength comparisons

The web crippling strengths of all specimens were predicted using the current North American Specification (AISI S100), and the current Eurocode provisions (EN1993-1-3). The resulting values were then compared to the web crippling strengths obtained from the tests to assess the accuracy of both design codes. The results are summarized in Table 4.

Table 4: Comparison of code-predicted strengths and test results.

Beam ID.	P_{Test} (kN)	P_{Test} / P_{EC3}	P_{Test} / P_{NAS}
ITF-0.2-3-0.5-3	123.31	1.62	1.13
ITF-0.2-5-0.5-3	126.21	1.66	1.16
ITF-0.2-3-0.5-5	377.53	1.81	1.10
	Average	1.69	1.13
	Std. dev.	0.08	0.02

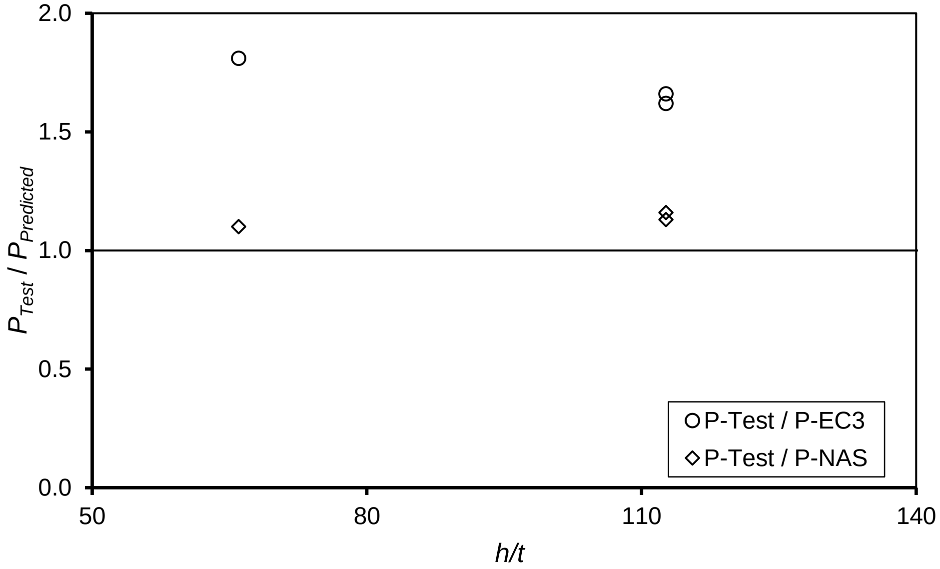


Figure 5: Comparison of design strength predictions

It is evident from Figure 5 and Table 4 that the North American Specification (AISI S100) provides reasonably accurate and slightly conservative predictions of the web crippling strengths. The Eurocode (EN 1993-1-3), on the other hand, yields rather inconsistent and overly conservative predictions. The mean and standard deviation of the ratio of the experimentally obtained strength to the predicted strength are 1.13 and 0.02, respectively, for the North American Specification (AISI S100). The corresponding values for the Eurocode (EN1993-1-3) are 1.69 and 0.08, respectively.

6. Conclusions

The presented study examined the web crippling behavior of CFS built-up I-beams formed by fastening two lipped channel sections together through the web at various locations in the cross-section and along the beam length. An experimental investigation was carried out to evaluate the influence of screw arrangement and channel thickness on the web crippling response and ultimate strength. The experimentally obtained web crippling strengths were compared with the design predictions obtained from the North American Specification (AISI S100), and the Eurocode (EN 1993-1-3). The comparison revealed that the AISI S100 provisions provided reasonably accurate, consistent and conservative predictions of the web crippling strength for all tested beams. In contrast, the predictions from EN 1993-1-3 were found to be overly conservative. These findings highlight the limitations of current EC3 design provisions when applied to CFS lipped channel built-up beams and demonstrate the need for further investigations to develop improved and reliable Eurocode design equations specifically tailored for built-up CFS I-beams.

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Notations

CFS	: Cold-formed steel
P_{NAS}	: Design strength predicted by North American Specification (AISI S100:2020)
P_{EC3}	: Design strength predicted by European Standard EN1993-1-3 (2006)
P_{Test}	: Peak test strength
Std. dev.	: Standard deviation