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Web crippling behavior of CFS built-up beams under end two-flange loading

Mohammad Adil Dar[1], Ahmad Fayeq Ghowsi[2], Seyed Mohammad Mojtabaei[3],
Iman Hajirasouliha[4], Jurgen Becque[5]

Abstract

Compared to a single cold-formed steel (CFS) channel beam, a built-up I-beam comprising of 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 Specifications (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. A finite element (FE) model was developed in ABAQUS of two plain channel sections, fastened through the web at discrete points cross-sectionally and longitudinally, and calibrated against relevant test data reported in the literature. The verified FE model was then used to conduct an extensive parametric study by varying critical parameters such as the web slenderness, the bearing length, and the corner radius-to-thickness ratio, under end two-flange loading. The accuracy of the North American and European design standards was also assessed by comparing their web crippling strength predictions against the FE results. It was concluded that both design codes made inconsistent predictions, overestimating the web crippling strengths in some cases, while significantly underestimating them in others.

1. Introduction

Cold-formed steel (CFS) sections have become popular in the construction of low- to mid-rise building systems. The desirable features of CFS include relatively straightforward fabrication, low self-weight, easy handling and convenient transportation, and off-site manufacturing, which substantially reduce construction time. As a result, CFS members are widely adopted by building industries world-wide. However, the limited wall thickness of CFS sections increases their vulnerability to various types of instabilities, thus limiting their application. This drawback has spurred extensive research into the stability of thin-walled CFS structural members, leading to novel cost-effective solutions with improved structural performance.

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[1] Marie Curie Fellow in Steel Structures, University of Sheffield, <dar.adil@sheffield.ac.uk>
[2] Postdoctoral Research Fellow, Istanbul Technical University, <ghowsi@itu.edu.tr>
[3] Lecturer, Loughborough University, <M.Mojtabaei@lboro.ac.uk>
[4] Professor, University of Sheffield, <i.hajirasouliha@sheffield.ac.uk>
[5] Associate Professor, University of Cambridge, < jab311@cam.ac.uk>

Beams constitute structural components of primary importance, and must effectively transfer loads from floor elements to adjacent columns. Single channel beams are asymmetric about their minor axis and exhibit an increased vulnerability to lateral-torsional buckling, as a result of the inevitable eccentricity of the loading relative to the shear centre of the cross-section. In contrast, built-up I-sections assembled from two web-connected channels display improved strength and stability characteristics. However, the web elements of CFS channels are typically very slender, and thus become susceptible to web crippling failure under concentrated loading, including support reactions. Previous research on web crippling has mostly concentrated on single CFS channel sections.

2. Previous research on CFS channel sections

Critical parameters such as the slenderness of the web, the corner radius, the bearing length, the yield strength of steel, the boundary conditions of the flange (fastened/unfastened), and the loading type were varied in early web crippling studies on CFS channel sections (Hetrakul & Yu 1978; Young & Hancock 1998; Rhodes & Nash 1998; Bhakta et al. 1992; Gerges & Schuster 1988; Lagan et al. 1994; Beshara & Schuster 2000). The results of these studies led to the development of several empirical design expressions to calculate the web crippling strength which were incorporated in earlier versions of the design standards (AISI 1996; S136; AS/NZS 4600; BS 5950-5), and to the fine-tuning of their coefficients. After 2000, this research was further extended by varying these 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; EC3), theoretical design models, and new design equations based on the Direct Strength Method. In addition to plain and lipped channel sections, recent analyses have also investigated the web crippling behaviour 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). Furthermore, the effect of web openings on the web crippling capacity of CFS channels was investigated (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 proposed to account for the reduction in strength due to the openings.

3. CFS built-up I-beams

The web crippling response of a single CFS channel may significantly differ from that of a built-up I-beam consisting of two such channels, due to interaction between the webs through contact and connectors in the latter. However, limited data is 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), with just three studies having explored built-up I-sections comprised of plain channels (He & Young 2022a-b, Dar et al., 2023c). These investigations concluded that the web crippling design equations in the current specifications (AISI S100 & EC3) are unsuitable for such beams, and proposed appropriate modifications. The current study expands on that work by investigating the web crippling behavior of CFS built-up I-beams over a wider range of critical parameters. A finite element (FE) model of CFS built-up I-beams assembled from plain channels was first constructed in ABAQUS, followed by validation against the experiments performed by He & Young (He & Young 2022a). An FE parametric study was subsequently performed by altering the slenderness of the web, the corner radius and the bearing length under the end two-flange loading case. In a next step, the web crippling strengths predicted by the current design specifications (AISI S100 & EC3) were calculated and compared against the FE-obtained web crippling strengths to assess the accuracy of these specifications.

4. Numerical modelling techniques and validation

An ABAQUS model was developed of two plain channels, oriented back-to-back and connected through the web at various discrete points along the specimen length (Fig. 1). Shell elements (S4R) and solid elements (R3D4) were used to model the channels and the bearing plates, respectively. Square meshes of 10 mm element size were used for the flat regions of the channels, while a finer mesh was adopted at the flange-web junctions, comprising four elements across the corner zone. The CFS material was modelled using Gardner and Yun's model (Gardner and Yun 2018), which is an improved version of the Ramberg–Osgood model (Ramberg and Osgood 1943). The engineering stress-strain curve was converted to true stresses and true plastic strains using the method specified in the ABAQUS manual (ABAQUS 2014). Reference points were established above the upper bearing plate and below the lower plate to aid in modelling the experimental setup used by He & Young (He & Young 2022a). Rigid body constraints were used to connect the bearing plates to their respective reference points. The fasteners were replicated using three-dimensional beam connector elements. Surface interactions were incorporated by adopting 'hard' contact between the contact surfaces in the normal direction, with small sliding allowed in the tangential direction. The coefficient of friction between the steel surfaces was adopted as 0.4. Previous studies have indicated that geometric imperfections have a small effect on the web crippling strength (Natario et al. 2014b; Sundararajah et al. 2017;2018). Therefore, the initial geometric imperfections were not modelled.

The FE model was verified using test data on CFS built-up I-beams composed of plain channels reported in the literature (He & Young 2022a). The specimens were formed using steel sheets (1.2 mm and 1.9 mm thick) of G450 and G500 grade, having a nominal yield strength of 450 MPa and 500 MPa, respectively. The longitudinal spacing between the fasteners (self-tapping screws) was adopted as three quarters of the cross-sectional depth. The vertical spacing of the screws were varied such that the ratio of the distance between the fastener and the flange to the web depth were achieved as 0.1, 0.3 and 0.5. Bearing lengths of 50 mm and 90 mm were used. The failure mode, the load-displacement behaviour and the ultimate load were compared in order to verify the accuracy of the FE model. Fig. 2 compares the failure mode of specimen ETF-120×80×1.9N50-0.1 with the FE-predicted equivalent. Fig. 3 compares the load-displacement behaviour of specimen ETF-200×140×1.9N90-0.5 with the FE output. Experimental and FE-predicted capacities are compared in Table 1. The ratio of the test strength to the FE-predicted strength was calculated to have a mean value of 1.02 and a standard deviation of 0.045 over a total of four data points. Comparing the FE analyses and the test results in terms of ultimate strength, load-displacement behaviour and failure mode revealed a good agreement. Consequently, the FE model can confidently be used to conduct parametric studies.

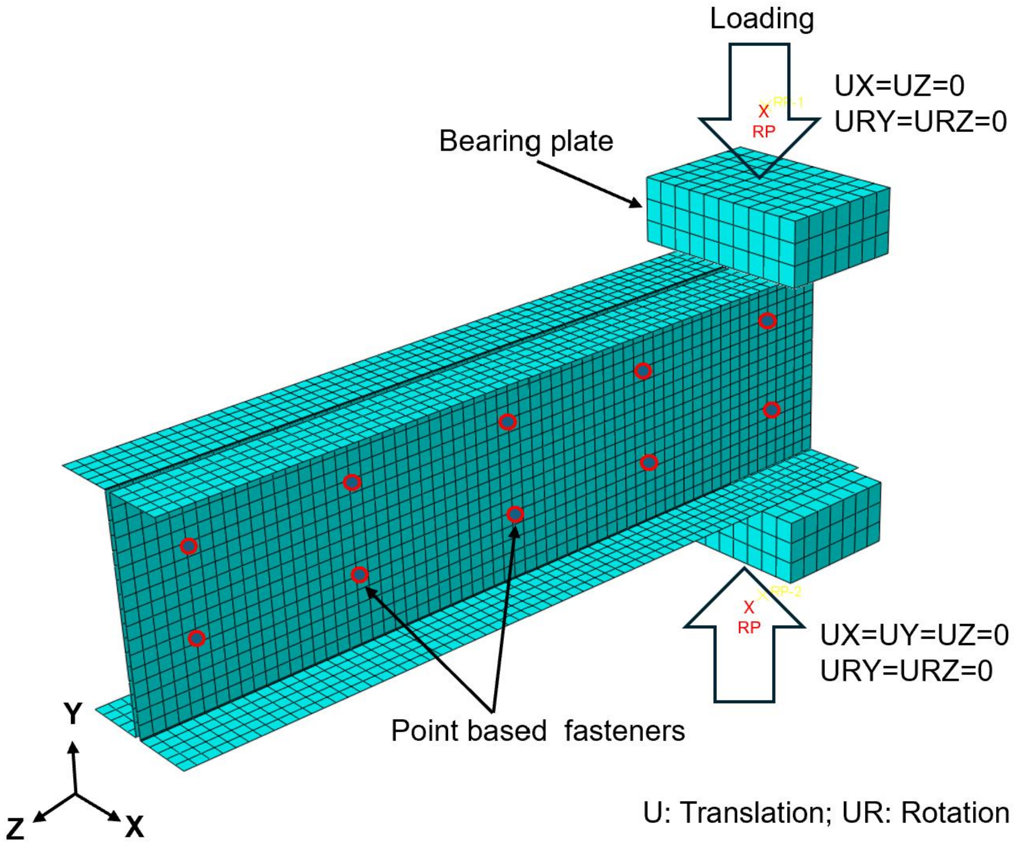

Figure 1: FE model of the built-up beam

Table 1: Comparison of test results and numerical strengths for validation (He & Young 2022a)

Specimen	P_{Test} (kN)	P_{FEA} (kN)	P_{Test}/P_{FEA}
ETF-200×140×1.9N90-0.5	12.45	12.2	1.02
ITF-120×80×1.9N50-0.1	10.0	9.90	1.01
EOF-120×80×1.9N50-0.1	20.18	20.78	0.97
IOF-200×140×1.2N90-0.3	15.16	13.98	1.08
		Average	1.02
		Standard deviation	0.045

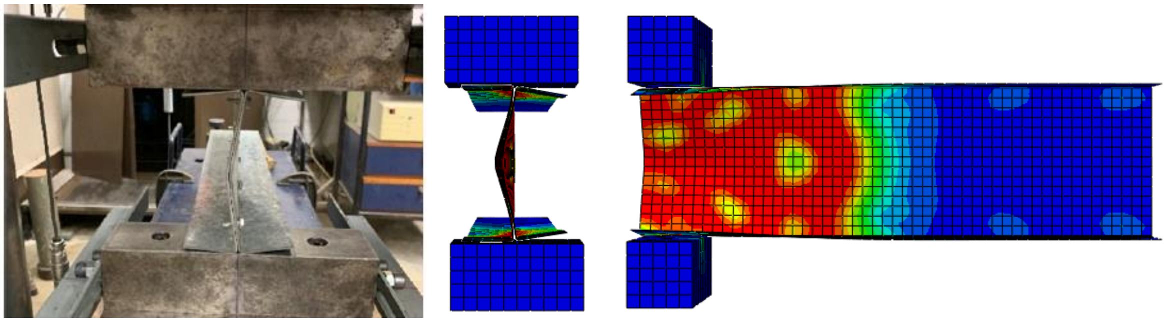

Figure 2: Failure mode comparison between test specimen ETF-120×80×1.9N50-0.1(He & Young 2022a) and the corresponding FE model

5. Parametric study

A built-up I-section identical to the one considered by He & Young (2022a), and consisting of two plain channels, was used in the parametric investigation. The web depth and flange width of the channel element were kept constant at 175 mm and 50 mm, respectively. The channel thickness was varied between 1.5 mm and 4 mm, the ratio of the corner radius to the channel thickness between 0.5 and 2.5, the ratio of the distance between the fastener and the flange to the web depth between 0.1 and 0.5, and the bearing length between 50 mm and 150 mm. Table 2 summarizes the parametric study. The yield strength of the steel was kept at 250 MPa. A specimen nomenclature was chosen so that it revealed the specimen specifics. For instance, for specimen IS-1.5-0.5-N50-0.1, the first part 'IS' indicates an I-section. The next part, '1.5', denotes the channel thickness in mm. The third part, '0.5', signifies the ratio of the corner radius to the wall thickness. The fourth part, 'N50', correspond to the bearing length in mm, and the final part, '0.1', stands for the ratio of the distance between the fastener and the flange to the web depth.

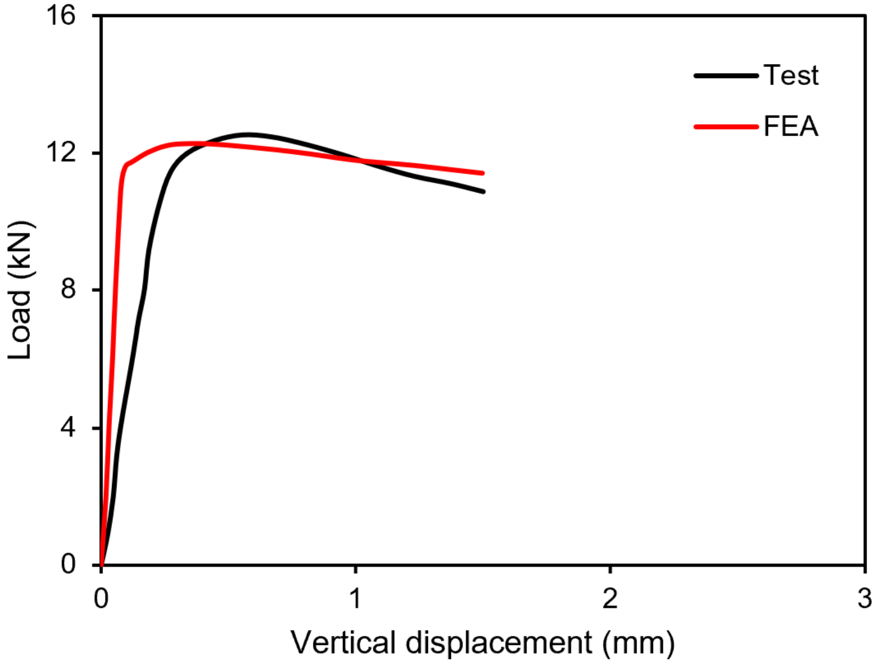

Figure 3: Comparison of the load-displacement plots for ETF-200×140×1.9N90-0.5(He & Young 2022a) and the corresponding FE model

All of the considered parameters had a significant influence on the web crippling strength of CFS built-up I-beams consisting of two plain channel sections. In general, it was noted that increasing the channel thickness and the bearing length enhanced the web crippling strengths, as expected. However, increasing the ratio of the distance between the fastener and the flange to the web depth led to a drop in the web crippling capacity. Table 3 presents the web crippling strengths of the various specimens.

Table 2: Matrix of the investigated parameters.

Parameter	Values
Thickness (mm)	1.5,2,3,4
Bearing length (mm)	50,100,150
Corner radius to thickness	0.5,1.5,2.5
Distance between the fastener and the flange to the web depth	0.1,0.3,0.5

6. Design strengths

The web crippling strengths of all specimens were also determined using the current North American Specifications (AISI S100) and the current Eurocode provisions (EN1993-1-3). These values were then compared to the web crippling strengths obtained from the FE models in order to assess the accuracy of both design codes, as shown in Table 3.

Table 3: Comparison of code-predicted strengths and FE results.

Specimen	P_{FEA}	P_{NAS}	P_{EC3}	P_{FEA} / P_{NAS}	P_{FEA} / P_{EC3}
IS-1.5-0.5-N50-0.1	7.14	6.92	11.43	1.03	0.62
IS-1.5-0.5-N50-0.3	7.06	6.92	11.43	1.02	0.62
IS-1.5-0.5-N50-0.5	4.02	6.92	11.43	0.58	0.35
IS-1.5-0.5-N100-0.1	11.46	7.83	14.07	1.46	0.81
IS-1.5-0.5-N100-0.3	10.42	7.83	14.07	1.33	0.74
IS-1.5-0.5-N100-0.5	5.88	7.83	14.07	0.75	0.42
IS-1.5-0.5-N150-0.1	15.42	8.52	16.09	1.81	0.96
IS-1.5-0.5-N150-0.3	14.31	8.52	16.09	1.68	0.89
IS-1.5-0.5-N150-0.5	7.72	8.52	16.09	0.91	0.48
IS-1.5-1.0-N50-0.1	7.12	6.67	11.43	1.07	0.62
IS-1.5-1.0-N50-0.3	7.11	6.67	11.43	1.07	0.62
IS-1.5-1.0-N50-0.5	4.04	6.67	11.43	0.61	0.35
IS-1.5-1.0-N100-0.1	11.65	7.55	14.07	1.54	0.83
IS-1.5-1.0-N100-0.3	10.67	7.55	14.07	1.41	0.76
IS-1.5-1.0-N100-0.5	8.10	7.55	14.07	1.07	0.58
IS-1.5-1.0-N150-0.1	15.45	8.22	16.09	1.88	0.96
IS-1.5-1.0-N150-0.3	15.56	8.22	16.09	1.89	0.97
IS-1.5-1.0-N150-0.5	7.90	8.22	16.09	0.96	0.49
IS-1.5-2.5-N50-0.1	7.35	6.51	11.43	1.13	0.64
IS-1.5-2.5-N50-0.3	7.21	6.51	11.43	1.11	0.63
IS-1.5-2.5-N50-0.5	4.12	6.51	11.43	0.63	0.36
IS-1.5-2.5-N100-0.1	11.96	7.36	14.07	1.62	0.85
IS-1.5-2.5-N100-0.3	10.76	7.36	14.07	1.46	0.76
IS-1.5-2.5-N100-0.5	6.11	7.36	14.07	0.83	0.43
IS-1.5-2.5-N150-0.1	17.51	8.02	16.09	2.18	1.09
IS-1.5-2.5-N150-0.3	14.76	8.02	16.09	1.84	0.92
IS-1.5-2.5-N150-0.5	8.08	8.02	16.09	1.01	0.50

Specimen	P_{FEA}	P_{NAS}	P_{EC3}	P_{FEA} / P_{NAS}	P_{FEA} / P_{EC3}
IS-2-0.5-N50-0.1	13.53	13.08	21.37	1.03	0.63
IS-2-0.5-N50-0.3	13.22	13.08	21.37	1.01	0.62
IS-2-0.5-N50-0.5	8.18	13.08	21.37	0.62	0.38
IS-2-0.5-N100-0.1	21.74	14.63	25.98	1.49	0.84
IS-2-0.5-N100-0.3	19.44	14.63	25.98	1.33	0.75
IS-2-0.5-N100-0.5	11.97	14.63	25.98	0.82	0.46
IS-2-0.5-N150-0.1	29.57	15.82	29.51	1.87	1.00
IS-2-0.5-N150-0.3	27.74	15.82	29.51	1.75	0.94
IS-2-0.5-N150-0.5	15.82	15.82	29.51	1.00	0.54
IS-2-1.0-N50-0.1	13.48	12.67	21.37	1.06	0.63
IS-2-1.0-N50-0.3	12.93	12.67	21.37	1.02	0.61
IS-2-1.0-N50-0.5	8.08	12.67	21.37	0.64	0.38
IS-2-1.0-N100-0.1	22.24	14.17	25.98	1.57	0.86
IS-2-1.0-N100-0.3	19.27	14.17	25.98	1.36	0.74
IS-2-1.0-N100-0.5	16.05	14.17	25.98	1.13	0.62
IS-2-1.0-N150-0.1	29.51	15.32	29.51	1.93	1.00
IS-2-1.0-N150-0.3	28.98	15.32	29.51	1.89	0.98
IS-2-1.0-N150-0.5	16.18	15.32	29.51	1.06	0.55
IS-2-2.5-N50-0.1	13.73	12.40	21.37	1.11	0.64
IS-2-2.5-N50-0.3	13.02	12.40	21.37	1.05	0.61
IS-2-2.5-N50-0.5	8.23	12.40	21.37	0.66	0.39
IS-2-2.5-N100-0.1	22.36	13.87	25.98	1.61	0.86
IS-2-2.5-N100-0.3	19.79	13.87	25.98	1.43	0.76
IS-2-2.5-N100-0.5	12.35	13.87	25.98	0.89	0.48
IS-2-2.5-N150-0.1	29.98	15.00	29.51	2.00	1.02
IS-2-2.5-N150-0.3	28.39	15.00	29.51	1.89	0.96
IS-2-2.5-N150-0.5	16.40	15.00	29.51	1.09	0.56
IS-3-0.5-N50-0.1	30.48	31.23	52.77	0.98	0.58
IS-3-0.5-N50-0.3	28.90	31.23	52.77	0.93	0.55
IS-3-0.5-N50-0.5	20.94	31.23	52.77	0.67	0.40
IS-3-0.5-N100-0.1	50.21	34.41	63.04	1.46	0.80
IS-3-0.5-N100-0.3	51.89	34.41	63.04	1.51	0.82
IS-3-0.5-N100-0.5	32.63	34.41	63.04	0.95	0.52
IS-3-0.5-N150-0.1	66.65	36.85	70.93	1.81	0.94
IS-3-0.5-N150-0.3	66.28	36.85	70.93	1.80	0.93
IS-3-0.5-N150-0.5	42.24	36.85	70.93	1.15	0.60
IS-3-1.0-N50-0.1	32.96	30.43	52.77	1.08	0.62
IS-3-1.0-N50-0.3	28.23	30.43	52.77	0.93	0.54
IS-3-1.0-N50-0.5	21.53	30.43	52.77	0.71	0.41
IS-3-1.0-N100-0.1	51.15	33.53	63.04	1.53	0.81
IS-3-1.0-N100-0.3	50.33	33.53	63.04	1.50	0.80
IS-3-1.0-N100-0.5	39.20	33.53	63.04	1.17	0.62
IS-3-1.0-N150-0.1	70.97	35.92	70.93	1.98	1.00
IS-3-1.0-N150-0.3	76.21	35.92	70.93	2.12	1.07

Specimen	P_{FEA}	P_{NAS}	P_{EC3}	P_{FEA} / P_{NAS}	P_{FEA} / P_{EC3}
IS-3-1.0-N150-0.5	42.27	35.92	70.93	1.18	0.60
IS-3-2.5-N50-0.1	33.12	29.91	52.77	1.11	0.63
IS-3-2.5-N50-0.3	28.85	29.91	52.77	0.96	0.55
IS-3-2.5-N50-0.5	20.88	29.91	52.77	0.70	0.40
IS-3-2.5-N100-0.1	49.72	32.96	63.04	1.51	0.79
IS-3-2.5-N100-0.3	47.81	32.96	63.04	1.45	0.76
IS-3-2.5-N100-0.5	32.52	32.96	63.04	0.99	0.52
IS-3-2.5-N150-0.1	67.94	35.30	70.93	1.92	0.96
IS-3-2.5-N150-0.3	67.43	35.30	70.93	1.91	0.95
IS-3-2.5-N150-0.5	43.30	35.30	70.93	1.23	0.61
IS-4-0.5-N50-0.1	48.23	57.16	102.45	0.84	0.47
IS-4-0.5-N50-0.3	50.33	57.16	102.45	0.88	0.49
IS-4-0.5-N50-0.5	40.24	57.16	102.45	0.70	0.39
IS-4-0.5-N100-0.1	82.61	62.38	120.89	1.32	0.68
IS-4-0.5-N100-0.3	94.13	62.38	120.89	1.51	0.78
IS-4-0.5-N100-0.5	60.46	62.38	120.89	0.97	0.50
IS-4-0.5-N150-0.1	108.27	66.39	135.05	1.63	0.80
IS-4-0.5-N150-0.3	108.43	66.39	135.05	1.63	0.80
IS-4-0.5-N150-0.5	76.18	66.39	135.05	1.15	0.56
IS-4-1.0-N50-0.1	49.25	55.90	102.45	0.88	0.48
IS-4-1.0-N50-0.3	54.91	55.90	102.45	0.98	0.54
IS-4-1.0-N50-0.5	38.77	55.90	102.45	0.69	0.38
IS-4-1.0-N100-0.1	83.15	61.01	120.89	1.36	0.69
IS-4-1.0-N100-0.3	84.06	61.01	120.89	1.38	0.70
IS-4-1.0-N100-0.5	75.08	61.01	120.89	1.23	0.62
IS-4-1.0-N150-0.1	110.37	64.93	135.05	1.70	0.82
IS-4-1.0-N150-0.3	119.23	64.93	135.05	1.84	0.88
IS-4-1.0-N150-0.5	84.70	64.93	135.05	1.30	0.63
IS-4-2.5-N50-0.1	48.86	55.07	102.45	0.89	0.48
IS-4-2.5-N50-0.3	48.45	55.07	102.45	0.88	0.47
IS-4-2.5-N50-0.5	38.52	55.07	102.45	0.70	0.38
IS-4-2.5-N100-0.1	86.56	60.10	120.89	1.44	0.72
IS-4-2.5-N100-0.3	81.90	60.10	120.89	1.36	0.68
IS-4-2.5-N100-0.5	64.68	60.10	120.89	1.08	0.54
IS-4-2.5-N150-0.1	111.16	63.96	135.05	1.74	0.82
IS-4-2.5-N150-0.3	119.34	63.96	135.05	1.87	0.88
IS-4-2.5-N150-0.5	83.24	63.96	135.05	1.30	0.62
			Ave.	1.27	0.67
			Std. dev.	0.41	0.20

It is evident from Table 3 that the current design codes provide inconsistent predictions of the web crippling strengths of CFS built-up beams composed of two plain channel sections. The North American Specifications (AISI S100) mostly under-predict the web crippling strengths, while as the Eurocode (EN1993-1-3) overpredict the same. The mean and standard deviation of the ratio of the numerically obtained strength to the predicted strength are 1.27 and 0.41, respectively, for the North American Specifications (AISI S100). The corresponding values for the Eurocode (EN1993-1-3) are 0.69 and 0.20, in the same order. These fairly inconsistent results with a large scatter call for more research on built-up configurations to facilitate the development of modified design rules for an accurate strength prediction.

7. Conclusions

The present study investigated the web crippling behavior of CFS built-up I-beams assembled from two plain channels fastened through the web at various positions within the cross-section and along the beam span. An ABAQUS FE model was developed, which was validated against relevant test data from the literature. The verified model was subsequently employed to undertake extensive parametric research by altering the relevant variables, as indicated by the North American Specifications' web crippling design equation. In general, reducing the bearing length reduced the web crippling strength, whereas increasing the wall thickness greatly increased the web crippling resistance, as expected. However, increasing the distance between the fastener and the flange for a given web depth resulted in a decrease in the web crippling strength. The web crippling design strengths were also determined using the current North American Specifications (AISI S100) and the Eurocode (EN1993-1-3). To determine the accuracy of these design codes, their predictions were compared against the FE-obtained web crippling strengths. The North American Specifications (AISI S100) provided quite conservative predictions of the web crippling strength in most cases, while the Eurocode (EN1993-1-3) predictions were highly unconservative. This clearly demonstrates the necessity for additional research on such built-up beams in order to provide more accurate design provisions.

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References

ABAQUS (2014) Analysis User's Manual, Version 6.14. Dassault Systemes Simulia, Inc.

AISI:1996. Specification for the design of cold formed steel structural members. Washington, D.C; American Iron and Steel Institute; 1996.

S136. Cold Formed Steel Structural Members, Etobicoke, Ontario, Canadian Standards Association; 1994.

AS/NZS 4600: 1996. Australia/New Zealand Standard Cold-formed steel structures. Sydney, Australia; Standard Australian/Standard New Zealand; 1996.

BS 5950-5:1998. Structural use of steelwork in building, Part 5: Code of practice for design of cold formed thin gauge sections, British Standard Institution; 1998.

AISI S100-16 North American specification for the design of cold-formed steel structural members. Washington, DC: American Iron and Steel Institute; 2016.

Ayhan, D., Schafer, B.W. (2017) "Characterization of in-plane backbone response of cold-formed steel beams", *Journal of Constructional Steel Research*, 132,141-150.

Beshara, B., Schuster, R. (2000) "Web crippling of cold formed steel C-and Z-sections" *Proceedings of 14th International Specialty Conference on Cold-formed Steel Design and Construction*, Missouri, 23–42.

Bhakta, B.H., LaBoube, R.A., Yu, W.W. (1992) "The effect of flange restraint on web crippling strength", *Final report, Civil Engineering Study* , University of Missouri-Rolla, Missouri, USA.

BS EN1993-1-3 (2006), Design of steel structures. Part1-3: General rules – Supplementary rules for cold-formed members and sheeting, Brussels: European Committee for Standardization.

Chen, Y., Chen, X., Wang, C. (2015) “Experimental and finite element analysis research on cold-formed steel lipped channel beams under web crippling”, *Thin-Walled Structures,*87:41–52.

Chen, M.T., Young, B., Martins, A.D., Camotim, D., Dinis, P.B. (2021) “Experimental investigation on cold-formed steel lipped channel beams affected by local-distortional interaction under non-uniform bending”, *Thin-Walled Structures,* 161, 107494.

Chen, B., Roy, K., Fang, Z., Uzzaman, A., Chi, Y., Lim, J.B. (2021) “Web crippling capacity of fastened cold-formed steel channels with edge-stiffened web holes, un-stiffened web holes and plain webs under two-flange loading”, *Thin-Walled Structures*, 163, 107666.

Cain, D.E., LaBoube, R.A., Yu, W.W. (1995) “The effect of flange restraint on web crippling strength of cold-formed steel Z- and I-sections”, Final Report, Civil Engineering Study, University of Missouri-Rolla, Missouri, USA.95-2

Dar, M.A., Ghowsi, A.F., Anbarasu, M., Celik, O.C., Hajirasouliha, I. (2023), “Web crippling instability response in CFS built-up open beams: Numerical study and design”, *Annual Stability Conference, Structural Stability Research Council*, Charlotte, North Carolina, USA, April 12-14.

Duarte, A., Silvestre, N. (2013) “A new slenderness-based approach for the web crippling design of plain channel steel beams” *International Journal of Steel Structures,* 13:421–34.

Gardner, L., Yun, X. (2018) “Description of stress-strain curves for cold-formed steels”, *Construction and Building Materials,* 189, 527-538.

Gatheeshgar, P., Poologanathan, K., Gunalan, S., Konstantinos, D.T., Nagaratnam, G., Iacovidou, E. (2020) “Optimised Cold-Formed Steel Beams in Modular Building Applications”, *Journal of Building Engineering,* 32 101607.

Gatheeshgar, P., Alsanat, H., Poologanathan, K., Gunalan, S., Degtyareva, N., Hajirasouliha, I. (2022) “Web crippling behaviour of slotted perforated cold-formed steel channels: IOF load case”, *Journal of Constructional Steel Research*, 188,106974.

Gerges, R.R., Schuster, R. (1988) “Web crippling of single web cold formed steel members subjected to end one-flange loading”, *Proceedings of 14th International Specialty Conference on Cold-formed Steel Design and Construction*, Missouri, USA.

Gunalan, S., Mahendran, M. (2019) “Experimental study of unlipped channel beams subject to web crippling under one flange load cases”, *Advanced Steel Construction,* 15:165–72

He, J., Young, B. (2022a) “Web crippling design of cold-formed steel built-up I-sections”, *Engineering Structures,* 252,113731.

He, J., Young, B. (2022b) “Behaviour of cold-formed steel built-up I-sections with perforated web under localized forces”, *Journal of Constructional Steel Research*, 190, 107129.

Hetrakul, N., Yu, W.W. (1978) “Structural behavior of beam webs subjected to web crippling and a combination of web crippling and bending”, *Final report, Civil Engineering Study*, University of Missouri-Rolla, Missouri, USA, 78-4.

Heurkens, R., Hofmeyer, H., Mahendran, M., Snijder, H. (2018) “Direct strength method for web crippling–lipped channels under EOF and IOF loading”, *Thin-Walled Structures*,123,126–41.

Janarthanan, B., Mahendran, M., Gunalan, S. (2019) “Numerical modelling of web crippling failures in cold-formed steel unlipped channel sections”, *Journal of Constructional Steel Research*;158:486–501.

Keerthan, P., Mahendran, M., Steau, E. (2014) “Experimental study of web crippling behaviour of hollow flange channel beams under two flange load cases”, *Thin-Walled Structures*, 85,207–19.

Keerthan, P., Mahendran, M. (2016) “Experimental study on web crippling strength of hollow flange channels under end-one-flange and interior-one-flange load cases”, *Advances in Structural Engineering,* 19,966–81.

Langan, J.E., LaBoube, R.A., Yu, W.W. (1994) “Structural behavior of perforated web elements of cold-formed steel flexural members subjected to web crippling and a combination of web crippling and bending”, *Final report, Civil Engineering Series*, University of Missouri, Rolla, USA.

Liu, X., Zhang, W., Yu, C., Li, Y., Jiang, Z., Yu, S. (2022) “Experimental study on cold-formed steel shear walls with different corrugated steel sheathings”, *Journal of Constructional Steel Research*, 199, 107639.

Macdonald, M., Don, M.H., KoteŁko, M., Rhodes,J. (2011) “Web crippling behaviour of thinwalled lipped channel beams”, *Thin-Walled Structures,*49:682–90.

Macdonald, M., Heiyantuduwa, M. (2012) “A design rule for web crippling of cold-formed steel lipped channel beams based on nonlinear FEA”, *Thin-Walled Structures,* 53,123–30.

Natario, P., Silvestre, N., Camotim, D. (2014a) “Computational modelling of flange crushing in cold-formed steel sections”, *Thin-Walled Structures,* 84:393–405.

Natario, P., Silvestre, N., Camotim, D. (2014b) “Web crippling failure using quasi-static fe models. *Thin-Walled Structures*, 84:34–49.

Neves, M., Basaglia, C., Camotim, D. (2022) “Stiffening optimisation of conventional cold-formed steel cross-sections based on a multi-objective Genetic Algorithm and using Generalised Beam Theory”, *Thin-Walled Structures,* 179,109713.

Ramberg, W. and Osgood, W.R., (1943) “Description of stress-strain curves by three parameters” (No. NACA-TN-902).

Ren, W.X., Fang, S.E, Young, B. (2006) “Finite-element simulation and design of cold-formed steel channels subjected to web crippling”. *Journal of Structural Engineering*,132:1967–75.

Rhodes, J., Nash, D. (1998) “An investigation of web crushing behaviour in thin-walled beams. *Thin-Walled Structures*, 32:207–30.

Steau, E., Mahendran, M., Keerthan, P. (2015) “Web crippling tests of rivet fastened rectangular hollow flange channel beams under two flange load cases”, *Thin-Walled Structures,*95,262–75.

Steau, E., Mahendran, M., Keerthan, P. (2016) “Web crippling capacities of rivet fastened rectangular hollow flange channel beams under one flange load cases” *Steel Construction,* 9:222–39.

Steau, E., Mahendran, M., Keerthan, P. (2017) “Web crippling study of rivet fastened rectangular hollow flange channel beams with flanges fastened to supports”, *Advances in Structural Engineering*, 20:1059–73.

Sundararajah, L., Mahendran, M., Keerthan, P. (2017) “Web crippling studies of SupaCee sections under two flange load cases”, *Engineering Structures*, 153:582–97.

Sundararajah, L., Mahendran, M., Keerthan, P. (2018) “Design of SupaCee sections subject to web crippling under one-flange load cases”, *Journal of Structural Engineering*,144:04018222.

Uzzaman, A., Lim, J.B., Nash, D., Rhodes, J., Young, B. (2012a) “Cold-formed steel sections with web openings subjected to web crippling under two-flange loading conditions–Part I: Tests and finite element analysis”, *Thin-Walled Structures,* 56,38–48.

Uzzaman, A., Lim, J.B., Nash, D., Rhodes, J., Young, B. (2012b) “Cold-formed steel sections with web openings subjected to web crippling under two-flange loading conditions–Part II: Parametric study and proposed design equations”, *Thin-Walled Structures,* 56,79–87.

Uzzaman, A., Lim, J.B., Nash, D., Rhodes, J., Young, B. (2012c) “Web crippling behaviour of coldformed
steel channel sections with offset web holes subjected to interior-two flange loading’, *Thin-Walled Structures,* 50,76–86.

Uzzaman, A., Lim, J.B., Nash, D., Rhodes, J., Young, B. (2013) “Effect of offset web holes on web crippling strength of cold-formed steel channel sections under end-two-flange loading condition. *Thin-Walled Structures,* 65:34–48.

Uzzaman, A., Lim, J.B., Nash, D., Young, B. (2017) “Effects of edge-stiffened circular holes on the web crippling strength of cold-formed steel channel sections under one-flange loading conditions”, *Engineering Structures,* 139:96–107.

Uzzaman, A., Lim, J.B., Nash, D., Roy, K. (2020a) “Cold-formed steel channel sections under end-two-flange loading condition: Design for edge-stiffened holes, unstiffened holes and plain webs”, *Thin-Walled Structures,* 147:106532.

Uzzaman, A., Lim, J.B., Nash, D., Roy, K. (2020b) “Web crippling behaviour of cold-formed steel channel sections with edge-stiffened and unstiffened circular holes under interior two-flange loading condition”, *Thin-Walled Structures,* 154:106813.

Lian, Y., Uzzaman, A., Lim, J.B., Abdelal, G., Nash, D., Young, B. (2016a) “Effect of web holes on web crippling strength of cold-formed steel channel sections under end-one flange loading condition–Part I: Tests and finite element analysis”, *Thin-Walled Structures*, 107,443–52.

Lian, Y., Uzzaman, A., Lim, J.B., Abdelal, G., Nash, D., Young, B. (2016b) “Effect of web holes on web crippling strength of cold-formed steel channel sections under end-one flange loading condition-Part II: Parametric study and proposed design equations”, *Thin-Walled Structures*, 107,489–501.

Lian, Y., Uzzaman, A., Lim, J.B., Abdelal, G., Nash, D., Young, B. (2017a) “Web crippling behaviour of cold-formed steel channel sections with web holes subjected to interior-one flange loading condition-Part I: Experimental and numerical investigation”, *Thin-Walled Structures,* 100:103–12.

Lian, Y., Uzzaman, A., Lim, J.B., Abdelal, G., Nash, D., Young, B. (2017b) “Web crippling behaviour of cold-formed steel channel sections with web holes subjected to interior-one flange loading condition–Part II: parametric study and proposed design equations”, *Thin-Walled Structures,* 114:92–106.

Elilarasi, K., Janarthanan, B. (2020) “Effect of web holes on the web crippling capacity of cold-formed litesteel beams under End-Two-Flange load case” *Structures*, 25, 411–25.

Young, B., Hancock, G.J. (1998) “Web crippling behaviour of cold-formed unlipped channels”, *Proceedings of 14th International specialty conference on cold-formed steel design and construction*, Missouri, USA, 127–50.

Young, B., Hancock, G.J. (2003) “Cold-formed steel channels subjected to concentrated bearing load”, *Journal of Structural Engineering*, 129,1003–10.

Young, B., Hancock, G.J. (2004) “Web crippling of cold-formed unlipped channels with flanges restrained”, *Thin-Wall Structures,* 42,911–30.

Winter, G., Pian, R. (1946) “Crushing strength of thin steel webs, engineering experiment”, *Bulletin 35*, Cornell University, New York, USA.

Notations

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