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Web crippling instability response in CFS built-up open beams: Numerical study and design

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Abstract

The adoption of cold-formed steel (CFS) in structural systems has risen significantly in recent years due to various favourable features such as cost-effectiveness, speed of construction, and lightweight structures. As a result, CFS members are suitable for modular construction. Beams are primary structural members responsible for transferring loads from the floors to the adjacent columns. Built-up I-sections composed of two channel sections are preferred as flexural members owing to their higher torsional rigidity and other stability characteristics over mono-channel sections. The webs of CFS I-beams are vulnerable to web crippling deformation under the influence of localized loading due to their higher sectional slenderness. The past research on web crippling studies has mainly focused on CFS mono-sectional profiles. However, the web crippling instability response of a single CFS channel section may differ from that of an open built-up beam composed of two such channels. Limited findings on CFS built-up sections have been reported so far. Hence, the current web crippling design rules may not be adequate for CFS open built-up beams across a wide range of parameters and need to be explored in detail. The current study focuses on the web crippling response of CFS built-up I-beams composed of two plain channel sections fastened through the web at various distinct points across the cross-section and longitudinally. First, a numerical model was developed in ABAQUS, and validated against the relevant test data available in the literature. The validated model was used to carry out an extensive parametric study by varying critical parameters used in the web crippling design expression of the North American Specification (AISI S100). The effect of all these critical parameters on the web crippling behavoir has been explored. Lastly, the web crippling design strengths were determined using the current North American Specification (AISI S100) and Eurocode (EN1993-1-3). These web crippling design strengths were compared against the numerical web crippling strengths to assess the accuracy of the current design codes. Both these design codes showed inconsistency in the predictions, as they over-predicted the web crippling strengths in some cases and under-predicted in others. This clearly reflects the need for more studies on such built-up beams to bring out accurate design rules for the same.

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1. Introduction

In the recent decade, cold-formed steel (CFS) sections have been widely adopted in constructing framed systems, which are extensively used in low-rise to mid-rise structures. Key structural features in CFS members, like low self-weight, simple fabrication, easy handling/transportation result in faster construction, cutting the construction time significantly. This encourages the builders to use CFS members frequently. Since CFS structures only require assembling and connecting different structural elements at the site, they also offer great flexibility in constructing temporary structures. However, due to sectional thinness, CFS members are prone to different modes of buckling instabilities, restricting their application to limited adoption. This motivated steel researchers to work towards improving the buckling resistance of CFS sections. As a result, many research studies have brought out improved and cost-effective solutions for enhancing the buckling performance of different beams cross-sections (Dar et al. 2015;2018;2019a-c;2020a-b;2021;2022; Kumar& Sahoo 2016; Bian et al. 2016; Ye et al. 2019; Zhao et al. 2019; Anbarasu 2019; Selvaraj & Madhavan 3019;2021; Meza et al. 2020; Obst et al. 2022;), column cross-sections (Maderia et al. 2015; Leng et al. 2014; Li et al. 2016; Landesmann et al. 2016; Camotim et al. 2018; Anbarasu & Ashraf 2019; Rasmussen et al. 2020; Kechidi et al. 2020; Zhao et al.. 2022; Sippel et al. 2022; Fang et al. 2022), and shear-walls (Derveni et al. 2020; Zhang et al. 2021; Joorabchian et al. 2021; Liu et al. 2022; Yilmaz et al. 2023;). Beams are key structural members and must function adequately to transfer loads from the floors to the adjacent columns. Built-up I-sections comprising of two web-connected channel sections are preferred as flexural members primarily due to their superior torsional stiffness and other stability features over mono-channel sections. The thin webs of CFS I-beams are slender, therefore, susceptible to web crippling failure under the impact of localized loading. The past research on web crippling studies has mainly focused on CFS channel sections.

2. CFS channel sections

In the initial web-crippling studies on CFS channel sections (Hetrakul & Yu 1978; Young & Hancock 1998; Rhodes & Nash 1998; Bhakta et al. 1992; Gerges & Schuster; Lagan et al.; Beshara & Schuster), critical parameters like web slenderness, corner radius, bearing length, yield strength of steel, flange fixity (fastened/unfastened) and type of loading were varied. These findings resulted in developing various empirical design expressions for obtaining the web crippling strength for the previous design codes (AISI 1996;S136; AS/NZS 4600; BS 5950-5) and subsequently in improving the various coefficients for better predictions. Post 2000, significant research investigations on the web crippling response of CFS channels sections were carried out by expanding the critical parameters over a wider range (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 studies were instrumental in developing design rules for the current codes (AISI S100; EC3), theoretical design models and direct strength method based design equations. Apart from analysing plain and lipped channel sections, the recent studies also explored the web crippling behavior of improved channel sections like hollow flanged channel sections (Keerthan et al. a-b; Steau et al. a-c) and intermittently web stiffened channel sections with inclined lips (Sundararajah et al. a-b). Furthermore, the influence of web-openings on the web crippling resistance of CFS channel sections was also studied (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 recommended to account for the strength reduction (due to the web-openings).

3. CFS built-up I-beams

A single CFS channel section's web crippling behaviour may differ from that of an open built-up beam formed of two such channels. However, out of the substantial web-crippling research, limited studies have been conducted on built-up I-beams (Winter & Pian 1946; Hetrakul & Wu 1978; Bhakta & LaBoube 1992; Cian et al. 1995; He & Young 2022a-b), with only two studies being carried out on built-up sections composed on plain channel sections (He & Young 2022a-b). These studies indicated that the current web crippling design rules (AISI S100 & EC3) are not adequate for CFS open built-up beams composed of plain channel sections and accordingly brought out proposed design rules for the same. The current study extends that work by exploring the web crippling behavior of CFS built-up I-beams across a wide range of critical parameters.

The current study focuses on the web crippling response of CFS built-up I-beams composed of two plain channel sections, fastened through the web at various distinct points across the cross-section and longitudinally. First, a numerical model was developed in ABAQUS, and validated against the relevant test data available in the literature. Next, the validated model was used to carry out an extensive parametric study by varying critical parameters used in the web crippling design expression of the North American Specification (AISI S100). The effect of all these critical parameters on the web crippling behavoir has been explored. Lastly, the web crippling design strengths were determined using the current North American Specification (AISI S100) and Eurocode (EN1993-1-3). These web crippling design strengths were compared against the numerical web crippling strengths to assess the accuracy of the current design codes.

4. Numerical modelling technique and validation

ABAQUS platform was used to simulate the web-crippling response of CFS built-up I-beams composed of two plain channel sections, as shown in Fig.1. The channels were oriented in the back-to-back configuration and connected through the web at distinct locations along the beam span. The channel sections and bearing plates were simulated using shell elements (S4R) and solid elements (R3D4) respectively. A mesh convergence study favored the adoption of square meshes (10 mm) for the flat zones of channel sections. A finer mesh (3-4 parts) was adopted at the corner zones (flange-web junctions). The CFS material behavior with strain hardening effect was adopted through the material model (proposed by Gardner and Yun 2018). The engineering stress-strain was converted into the true stress and plastic strain, using the method given in the ABAQUS manual. Reference points were created above the top bearing plate and below the lower bearing plate. The bearing plates were connected to their respective reference points using rigid body constraints. The fasteners were simulated using 3D beam connecting elements. Surface interactions were considered by adopting hard contact between the contact surfaces, with small sliding, addressing both tangential and normal contact responses.

The numerical model developed was calibrated against the test results on CFS built-up I-beams composed on plain channels (He & Young 2022a) available in the literature. The failure modes and peak loads were validated, as shown in Fig. 2 for specimen ITF-120×80×1.9N50-0.1. Table 1 compares the numerical and test strengths on CFS built-up I-beams (He & Young 2022a). A mean value of 1.02 with a standard deviation of 0.045 was achieved for the ratio of test strength to numerical strength. Comparing the FEA results and test results in terms of peak strength and failure mode indicate a good match. Therefore, the numerical model can be adopted for the intended parametric studies.

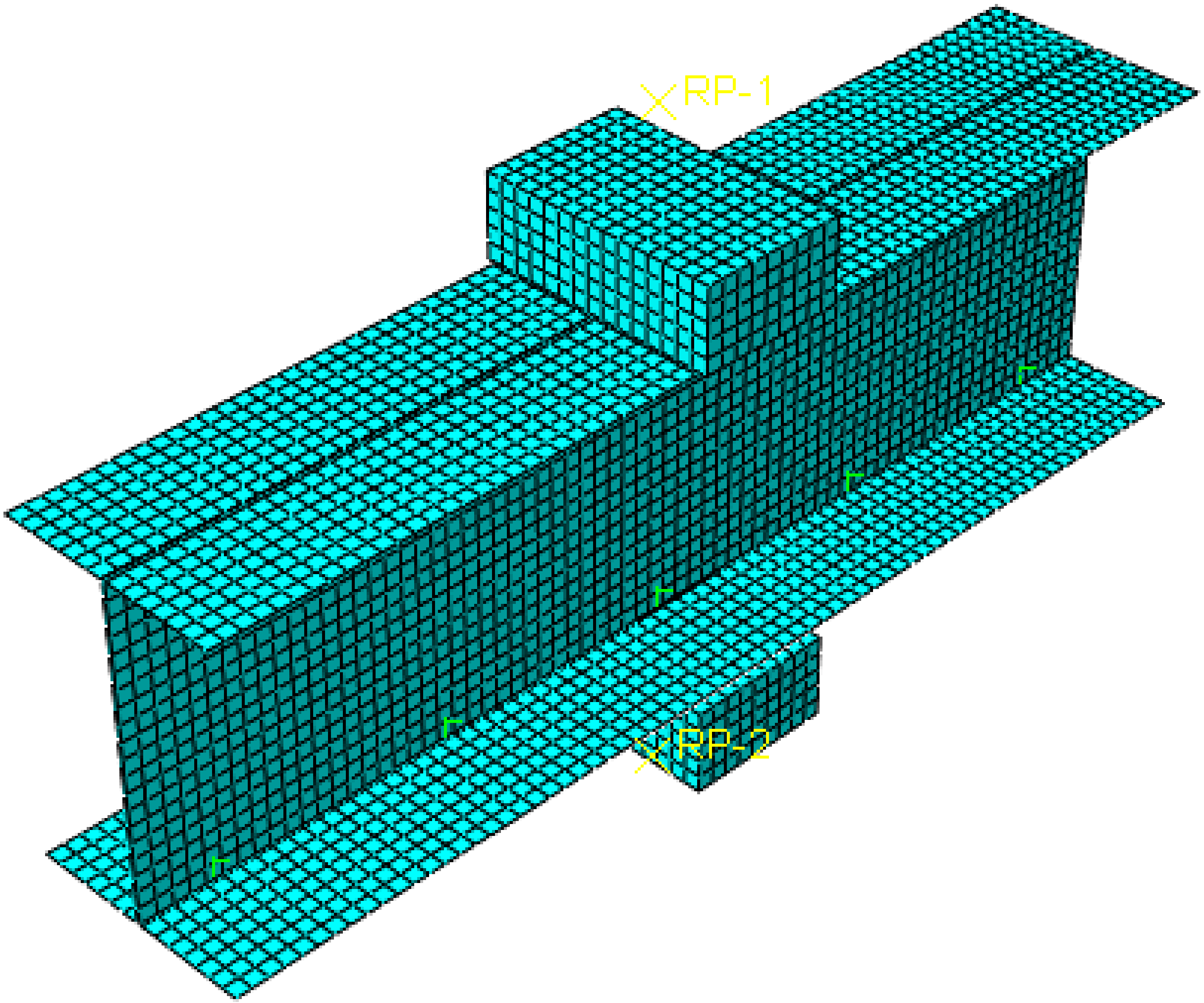

Figure 1: Cross-sectional details of the built-up

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}
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
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
		Ave.	1.02
		Std. dev.	0.045

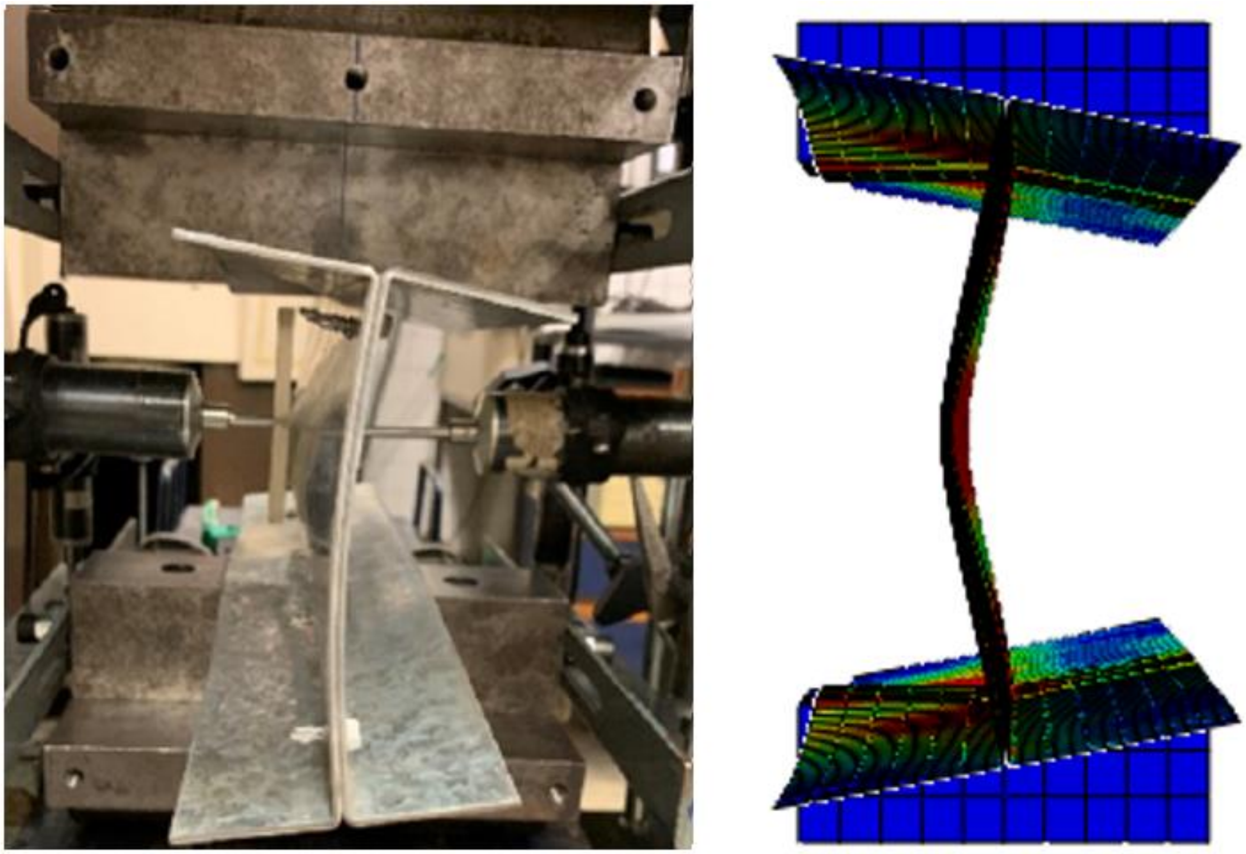

Figure 2: Comparison of the test failure mode with the numerical faiure mode (He & Young 2022a)

5. Parametric study

For the parametric study, a built-up beam similar to He & Young (2022a), i.e., composed of two plain channel sections was adopted. The flange width and web depth of each channel were fixed at 50 mm and 175 mm respectively. The thickness of the channel was varied from 1 mm to 3 mm. The ratio of the corner radius to the wall thickness was varied from 0.5 to 2.5. The ratio of the distance of the fastener from the flange to the web depth was varied from 0.1 to 0.5. The bearing lengths were varied from 50 mm to 150 mm. The yield strength of the steel was adopted as 250 MPa. The nomenclature of the specimens was adopted in such a way that important details get reflected. For example, in BS-250-175-1-0.5-N50-0.1, the first term BS stands for built-up section. The second term 175 represents the yield strength (MPa) of the steel used. The third term 175 indicates the web depth in mm. The forth term 1 represents the wall thickness in mm. The fifth term 0.5 indicates the ratio of the corner radius to the wall thickness. The sixth term N50 represents the bearing length in mm. The last term 0.1 stands for the ratio of the distance of the fastener from the flange to the web depth. All these critical parameters affected the web crippling strength of CFS built-up beams composed of two plain channel sections. Generally, a reduction in the bearing length resulted in lowering the web crippling strength, while as increasing the wall thickness improved the web crippling resistance significantly. Also, the increase in the ratio of the distance of the fastener from the flange to the web depth, overall resulted in a drop in the web crippling strengths.

6. Design strengths

The web crippling strengths of the various specimens were quantified using the current North American Specification (AISI S100) and Eurocode (EN1993-1-3), and were compared against the numerical web crippling strengths to assess the accuracy, and are presented in Table 2.

Table 2: Comparison of design strengths and the numerical strengths.

Specimen	P_{FEA}	P_{NAS}	P_{EC3}	P_{FEA} / P_{NAS}	P_{FEA} / P_{EC3}
BS-250-175-1-0.5-N50-0.1	6.53	6.04	3.76	1.08	1.73
BS-250-175-1-0.5-N50-0.3	4.79	6.04	3.76	0.79	1.27
BS-250-175-1-0.5-N50-0.5	3.13	6.04	3.76	0.52	0.83
BS-250-175-1-0.5-N100-0.1	5.10	6.94	4.71	0.74	1.08
BS-250-175-1-0.5-N100-0.3	5.14	6.94	4.71	0.74	1.09
BS-250-175-1-0.5-N100-0.5	3.43	6.94	4.71	0.49	0.73
BS-250-175-1-0.5-N150-0.1	5.96	7.63	5.43	0.78	1.10
BS-250-175-1-0.5-N150-0.3	5.87	7.63	5.43	0.77	1.08
BS-250-175-1-0.5-N150-0.5	3.75	7.63	5.43	0.49	0.69
BS-250-175-1-1.0-N50-0.1	4.05	5.78	3.76	0.70	1.08
BS-250-175-1-1.0-N50-0.3	5.11	5.78	3.76	0.88	1.36
BS-250-175-1-1.0-N50-0.5	3.14	5.78	3.76	0.54	0.83
BS-250-175-1-1.0-N100-0.1	4.44	6.64	4.71	0.67	0.94
BS-250-175-1-1.0-N100-0.3	5.68	6.64	4.71	0.85	1.21
BS-250-175-1-1.0-N100-0.5	3.44	6.64	4.71	0.52	0.73
BS-250-175-1-1.0-N150-0.1	4.85	7.31	5.43	0.66	0.89
BS-250-175-1-1.0-N150-0.3	6.34	7.31	5.43	0.87	1.17
BS-250-175-1-1.0-N150-0.5	3.78	7.31	5.43	0.52	0.69
BS-250-175-1-2.5-N50-0.1	4.15	5.28	3.76	0.79	1.10
BS-250-175-1-2.5-N50-0.3	4.60	5.28	3.76	0.87	1.22
BS-250-175-1-2.5-N50-0.5	3.19	5.28	3.76	0.60	0.85
BS-250-175-1-2.5-N100-0.1	4.50	6.07	4.71	0.74	0.96
BS-250-175-1-2.5-N100-0.3	5.91	6.07	4.71	0.97	1.26
BS-250-175-1-2.5-N100-0.5	3.51	6.07	4.71	0.58	0.75
BS-250-175-1-2.5-N150-0.1	4.93	6.68	5.43	0.74	0.91
BS-250-175-1-2.5-N150-0.3	6.23	6.68	5.43	0.93	1.15
BS-250-175-1-2.5-N150-0.5	3.84	6.68	5.43	0.58	0.71
BS-250-175-2-0.5-N50-0.1	29.39	29.59	12.38	0.99	2.37
BS-250-175-2-0.5-N50-0.3	24.79	29.59	12.38	0.84	2.00
BS-250-175-2-0.5-N50-0.5	16.67	29.59	12.38	0.56	1.35
BS-250-175-2-0.5-N100-0.1	30.64	33.09	15.06	0.93	2.04
BS-250-175-2-0.5-N100-0.3	29.13	33.09	15.06	0.88	1.93
BS-250-175-2-0.5-N100-0.5	18.79	33.09	15.06	0.57	1.25
BS-250-175-2-0.5-N150-0.1	36.78	35.77	17.11	1.03	2.15
BS-250-175-2-0.5-N150-0.3	33.84	35.77	17.11	0.95	1.98
BS-250-175-2-0.5-N150-0.5	21.26	35.77	17.11	0.59	1.24
BS-250-175-2-1.0-N50-0.1	25.88	28.71	12.38	0.90	2.09
BS-250-175-2-1.0-N50-0.3	17.88	28.71	12.38	0.62	1.44

Specimen	P_{FEA}	P_{NAS}	P_{EC3}	P_{FEA} / P_{NAS}	P_{FEA} / P_{EC3}
BS-250-175-2-1.0-N100-0.1	30.91	32.11	15.06	0.96	2.05
BS-250-175-2-1.0-N100-0.3	26.55	32.11	15.06	0.83	1.76
BS-250-175-2-1.0-N100-0.5	18.90	32.11	15.06	0.59	1.26
BS-250-175-2-1.0-N150-0.1	36.92	34.72	17.11	1.06	2.16
BS-250-175-2-1.0-N150-0.3	31.56	34.72	17.11	0.91	1.84
BS-250-175-2-2.5-N50-0.1	26.92	27.02	12.38	1.00	2.17
BS-250-175-2-2.5-N50-0.3	24.29	27.02	12.38	0.90	1.96
BS-250-175-2-2.5-N50-0.5	17.20	27.02	12.38	0.64	1.39
BS-250-175-2-2.5-N100-0.1	31.64	30.22	15.06	1.05	2.10
BS-250-175-2-2.5-N100-0.3	27.38	30.22	15.06	0.91	1.82
BS-250-175-2-2.5-N100-0.5	19.52	30.22	15.06	0.65	1.30
BS-250-175-2-2.5-N150-0.1	38.37	32.67	17.11	1.17	2.24
BS-250-175-2-2.5-N150-0.3	36.76	32.67	17.11	1.13	2.15
BS-250-175-2-2.5-N150-0.5	22.14	32.67	17.11	0.68	1.29
BS-250-175-3-0.5-N50-0.1	52.77	70.99	25.20	0.74	2.09
BS-250-175-3-0.5-N50-0.3	56.61	70.99	25.20	0.80	2.25
BS-250-175-3-0.5-N50-0.5	41.66	70.99	25.20	0.59	1.65
BS-250-175-3-0.5-N100-0.1	63.44	78.23	30.11	0.81	2.11
BS-250-175-3-0.5-N100-0.3	65.22	78.23	30.11	0.83	2.17
BS-250-175-3-0.5-N100-0.5	47.10	78.23	30.11	0.60	1.56
BS-250-175-3-0.5-N150-0.1	82.68	83.78	33.88	0.99	2.44
BS-250-175-3-0.5-N150-0.3	93.51	83.78	33.88	1.12	2.76
BS-250-175-3-0.5-N150-0.5	55.81	83.78	33.88	0.67	1.65
BS-250-175-3-1.0-N50-0.1	53.63	69.29	25.20	0.77	2.13
BS-250-175-3-1.0-N50-0.3	43.87	69.29	25.20	0.63	1.74
BS-250-175-3-1.0-N50-0.5	52.49	69.29	25.20	0.76	2.08
BS-250-175-3-1.0-N100-0.1	67.26	76.36	30.11	0.88	2.23
BS-250-175-3-1.0-N100-0.3	51.16	76.36	30.11	0.67	1.70
BS-250-175-3-1.0-N100-0.5	48.20	76.36	30.11	0.63	1.60
BS-250-175-3-1.0-N150-0.1	82.11	81.78	33.88	1.00	2.42
BS-250-175-3-1.0-N150-0.3	65.55	81.78	33.88	0.80	1.93
BS-250-175-3-1.0-N150-0.5	55.23	81.78	33.88	0.68	1.63
BS-250-175-3-2.5-N50-0.1	58.52	66.00	25.20	0.89	2.32
BS-250-175-3-2.5-N50-0.3	59.99	66.00	25.20	0.91	2.38
BS-250-175-3-2.5-N50-0.5	43.32	66.00	25.20	0.66	1.72
BS-250-175-3-2.5-N100-0.1	71.82	72.73	30.11	0.99	2.39
BS-250-175-3-2.5-N100-0.3	71.87	72.73	30.11	0.99	2.39
BS-250-175-3-2.5-N100-0.5	50.60	72.73	30.11	0.70	1.68
BS-250-175-3-2.5-N150-0.1	89.37	77.90	33.88	1.15	2.64
BS-250-175-3-2.5-N150-0.3	92.07	77.90	33.88	1.18	2.72
BS-250-175-3-2.5-N150-0.5	61.90	77.90	33.88	0.79	1.83
			Ave.	0.80	1.63
			Std. dev.	0.18	0.56

Table 2 shows that the current design codes predict the web crippling strengths of CFS built-up beams composed of two plain channel sections inconsistently. The North American Specification (AISI S100) mostly over-predicted the web crippling strengths. The mean and standard deviation of the ratio of numerical strength to predicted strength are 0.8 and 0.18 respectively. On the contarary the Eurocode (EN1993-1-3) mostly under-predicted the web crippling strengths. In this case the mean and standard deviation of the ratio of numerical strength to predicted strength are 1.63 and 0.56 respectively. The outcomes of this comparison indeed call for more research on such configurations and the need to bring out modified design rules for the same.

7. Conclusions

The current study presented the web crippling behavior of CFS built-up I-beams composed of two plain channel sections fastened through the web at various distinct points across the cross-section and longitudinally. First, a numerical model was created in ABAQUS, then it was validated using test data from the literature pertinent to the model. The verified model was utilised to conduct a thorough parametric research by modifying crucial parameters used in the North American Specification's web crippling design expression. The influence of all these critical parameters on the web crippling behavoir has been assessed. Finally, the web crippling design strengths were calculated using the most recent North American Specification (AISI S100) and Eurocode (EN1993-1-3). To assess the accuracy of the current design codes, these web crippling design strengths were compared to numerical web crippling strengths. All the critical parameters affected the web crippling strength of CFS built-up beams composed of two plain channel sections. Generally, a reduction in the bearing length lowered the web crippling strength, while increasing the wall thickness improved the web crippling resistance significantly. Also, the increase in the ratio of the distance of the fastener from the flange to the web depth, overall resulted in a drop in the web crippling strengths. The North American Specification (AISI S100) estimated the web crippling strengths unconservatively for the full sectional slenderness range of the web. The Eurocode (EN1993-1-3) predicted the web crippling strength conservatively in some circumstances and unconservatively in others, indicating variation in accuracy. This clearly demonstrates the necessity for additional research on such built-up beams in order to provide proper design criteria for the same.

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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