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Web crippling analysis of CFS open built-up sections subjected to interior one-flange loading

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Abstract

Built-up I-beams composed of two cold-formed steel (CFS) channels offer significantly improved bending capacity and stability compared to single CFS channel beams. This enhancement is due to the combination of two channels, which results in better stress distribution and increased resistance to instability. However, the slender nature of CFS webs makes these beams vulnerable to web crippling under concentrated loads, particularly at points of applied force. Existing research predominantly focuses on the web crippling behavior of single CFS sections, leaving limited information on built-up sections. The response of built-up I-beams differs from single channels due to the interaction between the two components and the presence of fasteners, which alter the load transfer mechanisms. Consequently, the design rules provided in North American Specifications (AISI S100) and the Eurocode (EN1993-1-3), primarily developed for single sections, may not adequately address the unique behavior of built-up beams. This can lead to either overly conservative or unsafe designs. To bridge this gap, a finite element (FE) model of built-up I-beams was developed using ABAQUS. The model consisted of two plain CFS channels connected at discrete points along their webs, capturing the effects of contact and fasteners. The FE model was validated against experimental data from the literature to ensure its accuracy in predicting web crippling behavior under concentrated loads. The validated FE model was then used for a detailed parametric study, varying key parameters such as web slenderness, bearing length, and corner radius-to-thickness ratio. The study focused on interior one-flange loading conditions, a scenario often encountered in practice. The results revealed the critical influence of these parameters on the web crippling performance of built-up I-beams. When comparing the FE results to the predictions of AISI S100 and EN1993-1-3, significant inconsistencies were observed. Both standards often failed to accurately predict the web crippling strengths of built-up sections, with overestimations in some cases and underestimations in others. These discrepancies highlight the limitations of existing design codes when applied to built-up CFS I-beams. This study underscores the need for more focused research on the web crippling behavior of CFS built-up I-beams to establish a comprehensive dataset. Such efforts will support the development of revised design provisions that account for the distinctive characteristics of built-up sections. By addressing these gaps, the revised design standards can offer more accurate, reliable, and economical solutions for structural applications involving built-up CFS beams.

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1. Introduction

Cold-formed steel (CFS) sections are increasingly used in the construction of low- to mid-rise building systems due to their numerous advantages. These include simple fabrication processes, lightweight properties, ease of handling and transportation, and the potential for off-site manufacturing, which significantly reduces construction time. As a result, CFS members have gained widespread acceptance in the global building industry. However, the thin walls of CFS sections make them particularly susceptible to various forms of instability, limiting their broader application. This challenge has driven extensive research aimed at enhancing the stability of thin-walled CFS members, leading to innovative and cost-efficient solutions that improve their structural performance.

Beams are among the most critical structural components, responsible for efficiently transferring loads from floor systems to adjacent columns. Single CFS channel beams, being asymmetric about their minor axis, are especially prone to lateral-torsional buckling due to the inevitable eccentricity of loading with respect to the shear center of the cross-section. In contrast, built-up I-sections, formed by connecting two channels along their webs, exhibit significantly better strength and stability characteristics. Despite these advantages, the web elements of CFS channels are often very slender, making them vulnerable to web crippling failures under concentrated loads, such as those experienced at supports or other points of high stress (Anbarasu et al., 2024). Previous studies on web crippling behavior have predominantly focused on single CFS channel sections, with limited attention given to the behavior of built-up I-sections under similar loading conditions.

2. Previous research on CFS channel sections

Early research on web crippling in CFS channel sections examined critical parameters such as web slenderness, corner radius, bearing length, steel yield strength, flange boundary conditions (fastened/unfastened), and 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). These studies led to the development of empirical equations for calculating web crippling strength, which were incorporated into earlier design standards, including AISI (1996), S136, AS/NZS 4600, and BS 5950-5. The coefficients in these equations were also refined through these investigations.

Post-2000, research expanded to explore the impact of these parameters over a wider range (Young & Hancock, 2003, 2004; Ren et al., 2006; Duarte & Silvestre, 2013; Natário et al., 2014a-b; Gunalan & Mahendran, 2019; Janarthanan et al., 2019; Macdonald et al., 2011; Macdonald & Heiyantuduwa, 2012; Chen et al., 2015; Sundararajah et al., 2017, 2018; Heukens et al., 2018; Keerthan et al., 2014; Keerthan & Mahendran, 2016; Steau et al., 2015-2017). This body of work contributed to the development of updated design rules, which are now included in current standards such as AISI S100 and Eurocode 3 (EC3). Additionally, theoretical models and new equations based on the Direct Strength Method were proposed, further advancing the field.

Recent studies have also investigated web crippling behavior in modified CFS sections, including 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). Another area of focus has been the effect of web openings on web crippling capacity (Uzzaman et al., 2012-2020; Lian et al., 2016-

2017; Elilarasi & Janarthanan; Chen et al., 2021; Gatheeshgar et al., 2022). These studies proposed reduction factors to account for strength losses caused by the presence of web openings, offering practical solutions for incorporating such modifications into design practices.

3. CFS built-up I-beams

The web crippling behavior of a single CFS channel differs significantly from that of a built-up I-beam composed of two channels. This distinction arises from the interaction between the channels through contact and connectors, which alters the load transfer mechanisms in the latter. Despite its practical importance, research on the web crippling response of CFS built-up I-beams remains limited (Winter & Pian, 1946; Hetrakul & Wu, 1978; Bhakta & LaBoube, 1992; Cian et al., 1995; He & Young, 2022a-b), with only a few studies focusing on built-up I-sections made from plain channels (He & Young, 2022a-b). These studies highlighted the inadequacy of the web crippling design equations provided in current standards, such as AISI S100 and Eurocode 3 (EC3), for built-up I-beams and suggested necessary modifications.

Building upon this foundation, the present study investigates the web crippling behavior of CFS built-up I-beams across a broader range of critical parameters. A finite element (FE) model of built-up I-beams assembled from plain channels was developed using ABAQUS. This model was validated using experimental data reported by He and Young (2022a) to ensure its reliability in predicting web crippling behavior. The validated FE model was then employed for a parametric study, systematically varying key parameters such as web slenderness, corner radius, and bearing length under the end two-flange loading condition. Following the parametric analysis, the web crippling strengths predicted by the current design specifications (AISI S100 and EC3) were compared against the FE results to evaluate the accuracy and reliability of these standards for built-up I-beams. This study aims to provide deeper insights into the web crippling performance of CFS built-up I-beams and to identify potential areas for improvement in existing design codes to better account for the unique characteristics of these structural elements.

4. Numerical modelling techniques and validation

An ABAQUS FE model was developed to simulate built-up CFS I-beams composed of two plain channels oriented back-to-back and connected through their webs at discrete points along the specimen length (Fig. 1). The channels were modeled using shell elements (S4R), while the bearing plates were represented using solid elements (R3D4). A mesh size of 10 mm was applied to the flat regions of the channels, with a finer mesh in the flange-web junctions, consisting of four elements across the corner zones to capture local effects accurately.

The material behavior of the CFS was modeled using Gardner and Yun's constitutive model (Gardner and Yun, 2018), an enhancement of the Ramberg–Osgood model (Ramberg and Osgood, 1943). The engineering stress-strain data were converted to true stresses and true plastic strains following the method specified in the ABAQUS documentation (ABAQUS, 2014). To replicate the experimental setup reported by He and Young (2022a), reference points were established above and below the upper and lower bearing plates, respectively, and rigid body constraints were used to connect these plates to the reference points. Fasteners were modeled using three-dimensional beam connector elements, while surface interactions were defined with 'hard' contact in the normal direction and small sliding allowed tangentially. A friction coefficient of 0.4 was adopted for the steel interfaces. Based on prior studies (Natario et al., 2014b; Sundararajah et al., 2017; 2018), initial geometric imperfections were not included, as their influence on web crippling strength was found to be negligible.

The FE model was validated against experimental data on CFS built-up I-beams composed of plain channels (He & Young, 2022a). The tested specimens were constructed from steel sheets of 1.2 mm and 1.9 mm thickness, with nominal yield strengths of 450 MPa (G450) and 500 MPa (G500). The longitudinal spacing of self-tapping screws was set at three-quarters of the cross-sectional depth, while the vertical spacing was varied to achieve flange-to-web spacing ratios of 0.1, 0.3, and 0.5. Two bearing lengths (50 mm and 90 mm) were examined.

The failure modes, load-displacement responses, and ultimate loads from the FE simulations were compared with experimental results. Figure 2 illustrates the comparisons of failure modes for selected specimens, while Table 1 summarizes the ultimate load comparison. The mean ratio of experimental to FE-predicted strength was 1.02, with a standard deviation of 0.045 across four data points. The close agreement between the FE and experimental results confirms the reliability of the developed model, which is suitable for conducting parametric studies.

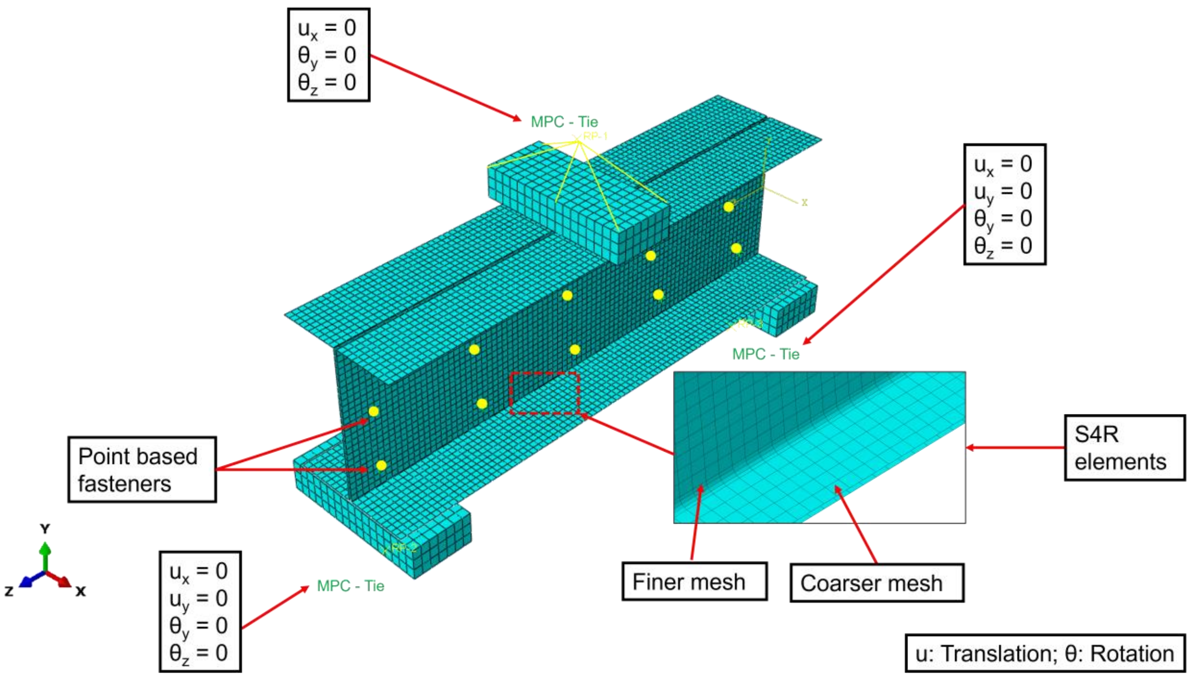

Figure 1: FE model of the built-up beam

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

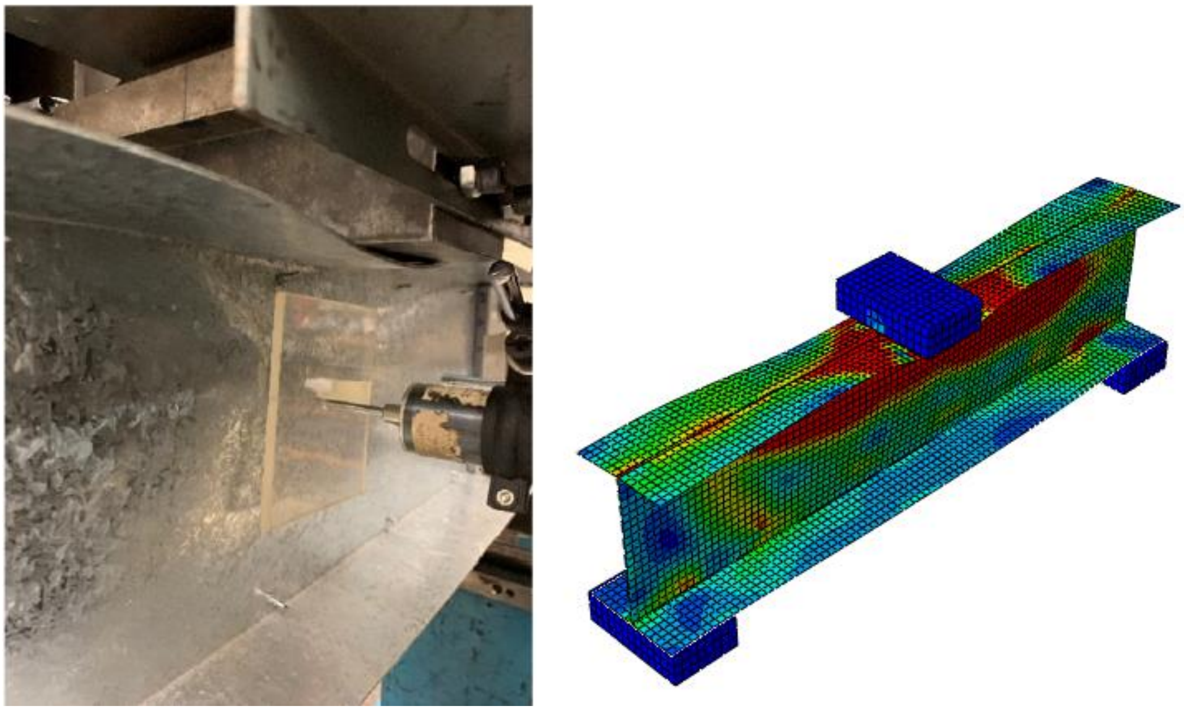

Figure 2: Failure mode comparison between test specimen IOF-200×140×1.9N50-0.5(He & Young 2022a) and the corresponding FE model

5. Parametric study

A parametric study was conducted using a built-up I-section similar to the one examined by He & Young (2022a), which comprised two plain channel sections. In this study, the web depth and flange width of the channel element were fixed at 175 mm and 50 mm, respectively. The thickness of the channel varied between 1.5 mm and 4 mm, the ratio of the corner radius to the channel thickness ranged from 0.5 to 2.5, the ratio of the distance from the fastener to the flange relative to the web depth ranged from 0.1 to 0.5, and the bearing length varied between 50 mm and 150 mm. The primary parameters adjusted in the parametric analysis included h, t, r, bearing length, and e/h, as shown in Fig. 3. The yield strength of the steel was kept constant at 250 MPa. A specific nomenclature for the specimens was developed to describe their characteristics. For example, for the specimen BS-175-1.5-0.5-N50-0.1, 'BS' refers to the Built-up Section, '175' indicates the section depth in mm, '1.5' is the section thickness in mm, '0.5' is the internal radius of the section in mm, 'N50' corresponds to the bearing length in mm, and '0.1' represents the ratio of the distance between the fastener and the flange to the web depth as shown in Fig. 3. The results showed that all the considered parameters had a significant impact on the web crippling strength of CFS built-up I-beams composed of two plain channel sections.

Overall, it was observed that increasing the channel thickness and bearing length resulted in improved web crippling strengths, as anticipated. On the other hand, an increase in the ratio of the distance between the fastener and the flange to the web depth caused a reduction in the web crippling capacity. The web crippling strengths of the different specimens are presented in Table 2.

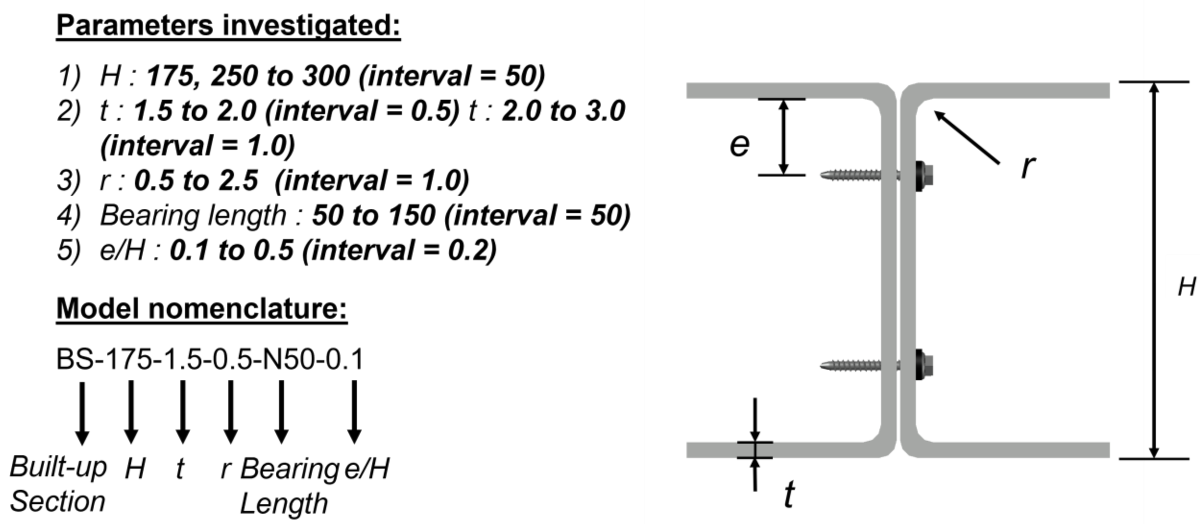

Figure 3: Geometric details of built-up adopted for the parametric study (Units: mm)

6. Design strengths

The web crippling strengths of all specimens were calculated using the current North American Specifications (AISI S100) and the latest Eurocode provisions (EN1993-1-3). These computed values were subsequently compared with the web crippling strengths derived from the FE models to evaluate the accuracy of both design codes, as presented in Table 2

Table 2: Comparison of code-predicted strengths and FE results.

Specimen	P_{FEA}	P_{NAS}	P_{EC3}	P_{FEA}/P_{NAS}	P_{FEA}/P_{EC3}
BS-175-1.5-0.5-N50-0.1	16.28	16.82	11.95	0.97	1.36
BS-175-1.5-0.5-N50-0.3	6.91	16.82	11.95	0.41	0.58
BS-175-1.5-0.5-N50-0.5	6.45	16.82	11.95	0.38	0.54
BS-175-1.5-0.5-N100-0.1	21.94	19.53	14.71	1.12	1.49
BS-175-1.5-0.5-N100-0.3	8.86	19.53	14.71	0.45	0.60
BS-175-1.5-0.5-N100-0.5	6.63	19.53	14.71	0.34	0.45
BS-175-1.5-0.5-N150-0.1	27.21	21.60	16.82	1.26	1.62
BS-175-1.5-0.5-N150-0.3	11.07	21.60	16.82	0.51	0.66
BS-175-1.5-0.5-N150-0.5	7.26	21.60	16.82	0.34	0.43

Specimen	P_{FEA}	P_{NAS}	P_{EC3}	P_{FEA}/P_{NAS}	P_{FEA}/P_{EC3}
BS-175-1.5-1.5-N50-0.1	16.30	15.48	11.95	1.05	1.36
BS-175-1.5-1.5-N50-0.3	6.95	15.48	11.95	0.45	0.58
BS-175-1.5-1.5-N50-0.5	6.56	15.48	11.95	0.42	0.55
BS-175-1.5-1.5-N100-0.1	21.82	17.97	14.71	1.21	1.48
BS-175-1.5-1.5-N100-0.3	8.94	17.97	14.71	0.50	0.61
BS-175-1.5-1.5-N100-0.5	6.78	17.97	14.71	0.38	0.46
BS-175-1.5-1.5-N150-0.1	29.65	19.88	16.82	1.49	1.76
BS-175-1.5-1.5-N150-0.3	10.99	19.88	16.82	0.55	0.65
BS-175-1.5-1.5-N150-0.5	7.43	19.88	16.82	0.37	0.44
BS-175-1.5-2.5-N50-0.1	16.20	14.56	11.95	1.11	1.36
BS-175-1.5-2.5-N50-0.3	10.32	14.56	11.95	0.71	0.86
BS-175-1.5-2.5-N50-0.5	6.52	14.56	11.95	0.45	0.55
BS-175-1.5-2.5-N100-0.1	22.15	16.90	14.71	1.31	1.51
BS-175-1.5-2.5-N100-0.3	7.03	16.90	14.71	0.42	0.48
BS-175-1.5-2.5-N100-0.5	6.90	16.90	14.71	0.41	0.47
BS-175-1.5-2.5-N150-0.1	30.83	18.70	16.82	1.65	1.83
BS-175-1.5-2.5-N150-0.3	11.37	18.70	16.82	0.61	0.68
BS-175-1.5-2.5-N150-0.5	7.56	18.70	16.82	0.40	0.45
BS-175-2-0.5-N50-0.1	13.81	28.80	18.87	0.48	0.73
BS-175-2-0.5-N50-0.3	11.89	28.80	18.87	0.41	0.63
BS-175-2-0.5-N50-0.5	12.13	28.80	18.87	0.42	0.64
BS-175-2-0.5-N100-0.1	18.65	33.04	22.94	0.56	0.81
BS-175-2-0.5-N100-0.3	14.95	33.04	22.94	0.45	0.65
BS-175-2-0.5-N100-0.5	13.77	33.04	22.94	0.42	0.60
BS-175-2-0.5-N150-0.1	24.19	36.29	26.07	0.67	0.93
BS-175-2-0.5-N150-0.3	23.90	36.29	26.07	0.66	0.92
BS-175-2-0.5-N150-0.5	15.10	36.29	26.07	0.42	0.58
BS-175-2-1.5-N50-0.1	13.69	26.84	18.87	0.51	0.73
BS-175-2-1.5-N50-0.3	11.56	26.84	18.87	0.43	0.61
BS-175-2-1.5-N50-0.5	12.03	26.84	18.87	0.45	0.64
BS-175-2-1.5-N100-0.1	18.84	30.79	22.94	0.61	0.82
BS-175-2-1.5-N100-0.3	17.34	30.79	22.94	0.56	0.76
BS-175-2-1.5-N100-0.5	14.02	30.79	22.94	0.46	0.61
BS-175-2-1.5-N150-0.1	25.81	33.82	26.07	0.76	0.99
BS-175-2-1.5-N150-0.3	21.83	33.82	26.07	0.65	0.84
BS-175-2-1.5-N150-0.5	15.74	33.82	26.07	0.47	0.60
BS-175-2-2.5-N50-0.1	13.63	25.50	18.87	0.53	0.72
BS-175-2-2.5-N50-0.3	11.73	25.50	18.87	0.46	0.62
BS-175-2-2.5-N50-0.5	12.29	25.50	18.87	0.48	0.65
BS-175-2-2.5-N100-0.1	19.30	29.24	22.94	0.66	0.84
BS-175-2-2.5-N100-0.3	19.18	29.24	22.94	0.66	0.84
BS-175-2-2.5-N100-0.5	14.23	29.24	22.94	0.49	0.62
BS-175-2-2.5-N150-0.1	26.85	32.12	26.07	0.84	1.03
BS-175-2-2.5-N150-0.3	23.04	32.12	26.07	0.72	0.88
BS-175-2-2.5-N150-0.5	16.21	32.12	26.07	0.50	0.62

Specimen	P_{FEA}	P_{NAS}	P_{EC3}	P_{FEA}/P_{NAS}	P_{FEA}/P_{EC3}
BS-175-3-0.5-N50-0.1	26.78	61.73	35.18	0.43	0.76
BS-175-3-0.5-N50-0.3	22.79	61.73	35.18	0.37	0.65
BS-175-3-0.5-N50-0.5	26.08	61.73	35.18	0.42	0.74
BS-175-3-0.5-N100-0.1	37.18	69.65	42.04	0.53	0.88
BS-175-3-0.5-N100-0.3	36.62	69.65	42.04	0.53	0.87
BS-175-3-0.5-N100-0.5	34.75	69.65	42.04	0.50	0.83
BS-175-3-0.5-N150-0.1	51.61	75.73	47.30	0.68	1.09
BS-175-3-0.5-N150-0.3	48.66	75.73	47.30	0.64	1.03
BS-175-3-0.5-N150-0.5	40.20	75.73	47.30	0.53	0.85
BS-175-3-1.5-N50-0.1	27.11	58.36	35.18	0.46	0.77
BS-175-3-1.5-N50-0.3	23.40	58.36	35.18	0.40	0.67
BS-175-3-1.5-N50-0.5	26.64	58.36	35.18	0.46	0.76
BS-175-3-1.5-N100-0.1	37.47	65.85	42.04	0.57	0.89
BS-175-3-1.5-N100-0.3	37.46	65.85	42.04	0.57	0.89
BS-175-3-1.5-N100-0.5	34.00	65.85	42.04	0.52	0.81
BS-175-3-1.5-N150-0.1	49.55	71.60	47.30	0.69	1.05
BS-175-3-1.5-N150-0.3	46.87	71.60	47.30	0.65	0.99
BS-175-3-1.5-N150-0.5	40.38	71.60	47.30	0.56	0.85
BS-175-3-2.5-N50-0.1	26.94	56.04	35.18	0.48	0.77
BS-175-3-2.5-N50-0.3	24.12	56.04	35.18	0.43	0.69
BS-175-3-2.5-N50-0.5	26.62	56.04	35.18	0.48	0.76
BS-175-3-2.5-N100-0.1	39.03	63.23	42.04	0.62	0.93
BS-175-3-2.5-N100-0.3	36.96	63.23	42.04	0.58	0.88
BS-175-3-2.5-N100-0.5	35.11	63.23	42.04	0.56	0.84
BS-175-3-2.5-N150-0.1	53.83	68.75	47.30	0.78	1.14
BS-175-3-2.5-N150-0.3	48.19	68.75	47.30	0.70	1.02
BS-175-3-2.5-N150-0.5	41.52	68.75	47.30	0.60	0.88
BS-175-4-0.5-N50-0.1	41.79	106.35	53.25	0.39	0.78
BS-175-4-0.5-N50-0.3	37.95	106.35	53.25	0.36	0.71
BS-175-4-0.5-N50-0.5	41.71	106.35	53.25	0.39	0.78
BS-175-4-0.5-N100-0.1	56.38	118.68	62.83	0.48	0.90
BS-175-4-0.5-N100-0.3	55.64	118.68	62.83	0.47	0.89
BS-175-4-0.5-N100-0.5	54.06	118.68	62.83	0.46	0.86
BS-175-4-0.5-N150-0.1	76.59	128.14	70.19	0.60	1.09
BS-175-4-0.5-N150-0.3	74.15	128.14	70.19	0.58	1.06
BS-175-4-0.5-N150-0.5	65.88	128.14	70.19	0.51	0.94
BS-175-4-1.5-N50-0.1	41.94	101.37	53.25	0.41	0.79
BS-175-4-1.5-N50-0.3	39.79	101.37	53.25	0.39	0.75
BS-175-4-1.5-N50-0.5	42.15	101.37	53.25	0.42	0.79
BS-175-4-1.5-N100-0.1	55.82	113.12	62.83	0.49	0.89
BS-175-4-1.5-N100-0.3	54.72	113.12	62.83	0.48	0.87
BS-175-4-1.5-N100-0.5	53.96	113.12	62.83	0.48	0.86
BS-175-4-1.5-N150-0.1	82.85	122.15	70.19	0.68	1.18
BS-175-4-1.5-N150-0.3	77.13	122.15	70.19	0.63	1.10
BS-175-4-1.5-N150-0.5	69.32	122.15	70.19	0.57	0.99

Specimen	P_{FEA}	P_{NAS}	P_{EC3}	P_{FEA}/P_{NAS}	P_{FEA}/P_{EC3}
BS-175-4-2.5-N50-0.1	42.25	97.94	53.25	0.43	0.79
BS-175-4-2.5-N50-0.3	41.79	97.94	53.25	0.43	0.78
BS-175-4-2.5-N50-0.5	41.90	97.94	53.25	0.43	0.79
BS-175-4-2.5-N100-0.1	55.05	109.30	62.83	0.50	0.88
BS-175-4-2.5-N100-0.3	54.14	109.30	62.83	0.50	0.86
BS-175-4-2.5-N100-0.5	53.19	109.30	62.83	0.49	0.85
BS-175-4-2.5-N150-0.1	77.30	118.02	70.19	0.66	1.10
BS-175-4-2.5-N150-0.3	75.03	118.02	70.19	0.64	1.07
BS-175-4-2.5-N150-0.5	68.54	118.02	70.19	0.58	0.98
BS-250-1.5-0.5-N50-0.1	15.65	16.79	11.95	0.93	1.31
BS-250-1.5-0.5-N50-0.3	7.00	16.79	11.95	0.42	0.59
BS-250-1.5-0.5-N50-0.5	4.86	16.79	11.95	0.29	0.41
BS-250-1.5-0.5-N100-0.1	9.59	19.49	14.71	0.49	0.65
BS-250-1.5-0.5-N100-0.3	8.23	19.49	14.71	0.42	0.56
BS-250-1.5-0.5-N100-0.5	5.11	19.49	14.71	0.26	0.35
BS-250-1.5-0.5-N150-0.1	11.09	21.56	16.82	0.51	0.66
BS-250-1.5-0.5-N150-0.3	9.16	21.56	16.82	0.42	0.54
BS-250-1.5-0.5-N150-0.5	5.33	21.56	16.82	0.25	0.32
BS-250-1.5-1.5-N50-0.1	15.79	15.45	11.95	1.02	1.32
BS-250-1.5-1.5-N50-0.3	7.13	15.45	11.95	0.46	0.60
BS-250-1.5-1.5-N50-0.5	4.75	15.45	11.95	0.31	0.40
BS-250-1.5-1.5-N100-0.1	9.68	17.93	14.71	0.54	0.66
BS-250-1.5-1.5-N100-0.3	8.25	17.93	14.71	0.46	0.56
BS-250-1.5-1.5-N100-0.5	5.12	17.93	14.71	0.29	0.35
BS-250-1.5-1.5-N150-0.1	11.19	19.84	16.82	0.56	0.67
BS-250-1.5-1.5-N150-0.3	8.83	19.84	16.82	0.44	0.52
BS-250-1.5-1.5-N150-0.5	5.40	19.84	16.82	0.27	0.32
BS-250-1.5-2.5-N50-0.1	15.71	14.53	11.95	1.08	1.31
BS-250-1.5-2.5-N50-0.3	7.28	14.53	11.95	0.50	0.61
BS-250-1.5-2.5-N50-0.5	4.84	14.53	11.95	0.33	0.41
BS-250-1.5-2.5-N100-0.1	9.59	16.86	14.71	0.57	0.65
BS-250-1.5-2.5-N100-0.3	8.43	16.86	14.71	0.50	0.57
BS-250-1.5-2.5-N100-0.5	5.20	16.86	14.71	0.31	0.35
BS-250-1.5-2.5-N150-0.1	11.42	18.66	16.82	0.61	0.68
BS-250-1.5-2.5-N150-0.3	8.95	18.66	16.82	0.48	0.53
BS-250-1.5-2.5-N150-0.5	5.50	18.66	16.82	0.29	0.33
BS-250-2-0.5-N50-0.1	13.55	28.75	18.87	0.47	0.72
BS-250-2-0.5-N50-0.3	12.08	28.75	18.87	0.42	0.64
BS-250-2-0.5-N50-0.5	11.15	28.75	18.87	0.39	0.59
BS-250-2-0.5-N100-0.1	17.01	32.98	22.94	0.52	0.74
BS-250-2-0.5-N100-0.3	14.46	32.98	22.94	0.44	0.63
BS-250-2-0.5-N100-0.5	11.60	32.98	22.94	0.35	0.51
BS-250-2-0.5-N150-0.1	20.30	36.22	26.07	0.56	0.78
BS-250-2-0.5-N150-0.3	16.97	36.22	26.07	0.47	0.65
BS-250-2-0.5-N150-0.5	11.94	36.22	26.07	0.33	0.46

Specimen	P_{FEA}	P_{NAS}	P_{EC3}	P_{FEA}/P_{NAS}	P_{FEA}/P_{EC3}
BS-250-2-1.5-N50-0.1	13.61	26.80	18.87	0.51	0.72
BS-250-2-1.5-N50-0.3	12.12	26.80	18.87	0.45	0.64
BS-250-2-1.5-N50-0.5	10.79	26.80	18.87	0.40	0.57
BS-250-2-1.5-N100-0.1	16.94	30.73	22.94	0.55	0.74
BS-250-2-1.5-N100-0.3	14.71	30.73	22.94	0.48	0.64
BS-250-2-1.5-N100-0.5	11.72	30.73	22.94	0.38	0.51
BS-250-2-1.5-N150-0.1	20.35	33.76	26.07	0.60	0.78
BS-250-2-1.5-N150-0.3	16.99	33.76	26.07	0.50	0.65
BS-250-2-1.5-N150-0.5	12.02	33.76	26.07	0.36	0.46
BS-250-2-2.5-N50-0.1	13.65	25.45	18.87	0.54	0.72
BS-250-2-2.5-N50-0.3	12.34	25.45	18.87	0.48	0.65
BS-250-2-2.5-N50-0.5	10.96	25.45	18.87	0.43	0.58
BS-250-2-2.5-N100-0.1	17.08	29.19	22.94	0.59	0.74
BS-250-2-2.5-N100-0.3	14.82	29.19	22.94	0.51	0.65
BS-250-2-2.5-N100-0.5	13.05	29.19	22.94	0.45	0.57
BS-250-2-2.5-N150-0.1	20.01	32.06	26.07	0.62	0.77
BS-250-2-2.5-N150-0.3	17.60	32.06	26.07	0.55	0.68
BS-250-2-2.5-N150-0.5	12.12	32.06	26.07	0.38	0.47
BS-250-3-0.5-N50-0.1	27.34	61.64	35.18	0.44	0.78
BS-250-3-0.5-N50-0.3	27.23	61.64	35.18	0.44	0.77
BS-250-3-0.5-N50-0.5	25.53	61.64	35.18	0.41	0.73
BS-250-3-0.5-N100-0.1	36.33	69.55	42.04	0.52	0.86
BS-250-3-0.5-N100-0.3	31.05	69.55	42.04	0.45	0.74
BS-250-3-0.5-N100-0.5	32.83	69.55	42.04	0.47	0.78
BS-250-3-0.5-N150-0.1	44.51	75.62	47.30	0.59	0.94
BS-250-3-0.5-N150-0.3	40.62	75.62	47.30	0.54	0.86
BS-250-3-0.5-N150-0.5	34.49	75.62	47.30	0.46	0.73
BS-250-3-1.5-N50-0.1	27.82	58.27	35.18	0.48	0.79
BS-250-3-1.5-N50-0.3	24.83	58.27	35.18	0.43	0.71
BS-250-3-1.5-N50-0.5	26.12	58.27	35.18	0.45	0.74
BS-250-3-1.5-N100-0.1	36.78	65.75	42.04	0.56	0.87
BS-250-3-1.5-N100-0.3	31.38	65.75	42.04	0.48	0.75
BS-250-3-1.5-N100-0.5	31.10	65.75	42.04	0.47	0.74
BS-250-3-1.5-N150-0.1	44.18	71.49	47.30	0.62	0.93
BS-250-3-1.5-N150-0.3	41.54	71.49	47.30	0.58	0.88
BS-250-3-1.5-N150-0.5	37.42	71.49	47.30	0.52	0.79
BS-250-3-2.5-N50-0.1	28.14	55.95	35.18	0.50	0.80
BS-250-3-2.5-N50-0.3	25.13	55.95	35.18	0.45	0.71
BS-250-3-2.5-N50-0.5	25.95	55.95	35.18	0.46	0.74
BS-250-3-2.5-N100-0.1	37.44	63.14	42.04	0.59	0.89
BS-250-3-2.5-N100-0.3	32.28	63.14	42.04	0.51	0.77
BS-250-3-2.5-N100-0.5	32.99	63.14	42.04	0.52	0.78
BS-250-3-2.5-N150-0.1	45.17	68.65	47.30	0.66	0.95
BS-250-3-2.5-N150-0.3	42.69	68.65	47.30	0.62	0.90
BS-250-3-2.5-N150-0.5	38.33	68.65	47.30	0.56	0.81

Specimen	P_{FEA}	P_{NAS}	P_{EC3}	P_{FEA}/P_{NAS}	P_{FEA}/P_{EC3}
BS-250-4-0.5-N50-0.1	44.44	106.21	53.25	0.42	0.83
BS-250-4-0.5-N50-0.3	42.22	106.21	53.25	0.40	0.79
BS-250-4-0.5-N50-0.5	44.01	106.21	53.25	0.41	0.83
BS-250-4-0.5-N100-0.1	59.44	118.52	62.83	0.50	0.95
BS-250-4-0.5-N100-0.3	53.31	118.52	62.83	0.45	0.85
BS-250-4-0.5-N100-0.5	55.49	118.52	62.83	0.47	0.88
BS-250-4-0.5-N150-0.1	73.65	127.98	70.19	0.58	1.05
BS-250-4-0.5-N150-0.3	78.87	127.98	70.19	0.62	1.12
BS-250-4-0.5-N150-0.5	69.23	127.98	70.19	0.54	0.99
BS-250-4-1.5-N50-0.1	44.75	101.23	53.25	0.44	0.84
BS-250-4-1.5-N50-0.3	43.06	101.23	53.25	0.43	0.81
BS-250-4-1.5-N50-0.5	45.95	101.23	53.25	0.45	0.86
BS-250-4-1.5-N100-0.1	60.19	112.98	62.83	0.53	0.96
BS-250-4-1.5-N100-0.3	54.22	112.98	62.83	0.48	0.86
BS-250-4-1.5-N100-0.5	58.49	112.98	62.83	0.52	0.93
BS-250-4-1.5-N150-0.1	73.01	121.99	70.19	0.60	1.04
BS-250-4-1.5-N150-0.3	75.26	121.99	70.19	0.62	1.07
BS-250-4-1.5-N150-0.5	67.11	121.99	70.19	0.55	0.96
BS-250-4-2.5-N50-0.1	45.22	97.81	53.25	0.46	0.85
BS-250-4-2.5-N50-0.3	42.34	97.81	53.25	0.43	0.80
BS-250-4-2.5-N50-0.5	44.93	97.81	53.25	0.46	0.84
BS-250-4-2.5-N100-0.1	60.17	109.16	62.83	0.55	0.96
BS-250-4-2.5-N100-0.3	56.16	109.16	62.83	0.51	0.89
BS-250-4-2.5-N100-0.5	56.84	109.16	62.83	0.52	0.90
BS-250-4-2.5-N150-0.1	79.41	117.86	70.19	0.67	1.13
BS-250-4-2.5-N150-0.3	81.09	117.86	70.19	0.69	1.16
BS-250-4-2.5-N150-0.5	64.64	117.86	70.19	0.55	0.92
BS-300-1.5-0.5-N50-0.1	6.65	16.76	11.95	0.40	0.56
BS-300-1.5-0.5-N50-0.3	5.87	16.76	11.95	0.35	0.49
BS-300-1.5-0.5-N50-0.5	3.84	16.76	11.95	0.23	0.32
BS-300-1.5-0.5-N100-0.1	8.56	19.46	14.71	0.44	0.58
BS-300-1.5-0.5-N100-0.3	7.27	19.46	14.71	0.37	0.49
BS-300-1.5-0.5-N100-0.5	4.11	19.46	14.71	0.21	0.28
BS-300-1.5-0.5-N150-0.1	9.31	21.53	16.82	0.43	0.55
BS-300-1.5-0.5-N150-0.3	8.25	21.53	16.82	0.38	0.49
BS-300-1.5-0.5-N150-0.5	4.37	21.53	16.82	0.20	0.26
BS-300-1.5-1.5-N50-0.1	13.00	15.43	11.95	0.84	1.09
BS-300-1.5-1.5-N50-0.3	6.17	15.43	11.95	0.40	0.52
BS-300-1.5-1.5-N50-0.5	3.85	15.43	11.95	0.25	0.32
BS-300-1.5-1.5-N100-0.1	8.51	17.91	14.71	0.48	0.58
BS-300-1.5-1.5-N100-0.3	7.37	17.91	14.71	0.41	0.50
BS-300-1.5-1.5-N100-0.5	4.14	17.91	14.71	0.23	0.28
BS-300-1.5-1.5-N150-0.1	9.48	19.82	16.82	0.48	0.56
BS-300-1.5-1.5-N150-0.3	7.89	19.82	16.82	0.40	0.47
BS-300-1.5-1.5-N150-0.5	4.40	19.82	16.82	0.22	0.26

Specimen	P_{FEA}	P_{NAS}	P_{EC3}	P_{FEA}/P_{NAS}	P_{FEA}/P_{EC3}
BS-300-1.5-2.5-N50-0.1	13.02	14.51	11.95	0.90	1.09
BS-300-1.5-2.5-N50-0.3	6.11	14.51	11.95	0.42	0.51
BS-300-1.5-2.5-N50-0.5	3.93	14.51	11.95	0.27	0.33
BS-300-1.5-2.5-N100-0.1	8.76	16.84	14.71	0.52	0.60
BS-300-1.5-2.5-N100-0.3	7.42	16.84	14.71	0.44	0.50
BS-300-1.5-2.5-N100-0.5	4.18	16.84	14.71	0.25	0.28
BS-300-1.5-2.5-N150-0.1	9.45	18.63	16.82	0.51	0.56
BS-300-1.5-2.5-N150-0.3	7.94	18.63	16.82	0.43	0.47
BS-300-1.5-2.5-N150-0.5	4.45	18.63	16.82	0.24	0.26
BS-300-2-0.5-N50-0.1	13.00	28.72	18.87	0.45	0.69
BS-300-2-0.5-N50-0.3	11.68	28.72	18.87	0.41	0.62
BS-300-2-0.5-N50-0.5	9.41	28.72	18.87	0.33	0.50
BS-300-2-0.5-N100-0.1	15.90	32.94	22.94	0.48	0.69
BS-300-2-0.5-N100-0.3	13.53	32.94	22.94	0.41	0.59
BS-300-2-0.5-N100-0.5	9.52	32.94	22.94	0.29	0.41
BS-300-2-0.5-N150-0.1	18.15	36.18	26.07	0.50	0.70
BS-300-2-0.5-N150-0.3	14.92	36.18	26.07	0.41	0.57
BS-300-2-0.5-N150-0.5	20.44	36.18	26.07	0.57	0.78
BS-300-2-1.5-N50-0.1	13.10	26.77	18.87	0.49	0.69
BS-300-2-1.5-N50-0.3	11.80	26.77	18.87	0.44	0.63
BS-300-2-1.5-N50-0.5	8.94	26.77	18.87	0.33	0.47
BS-300-2-1.5-N100-0.1	16.15	30.70	22.94	0.53	0.70
BS-300-2-1.5-N100-0.3	13.63	30.70	22.94	0.44	0.59
BS-300-2-1.5-N100-0.5	9.56	30.70	22.94	0.31	0.42
BS-300-2-1.5-N150-0.1	18.42	33.72	26.07	0.55	0.71
BS-300-2-1.5-N150-0.3	15.23	33.72	26.07	0.45	0.58
BS-300-2-1.5-N150-0.5	20.36	33.72	26.07	0.60	0.78
BS-300-2-2.5-N50-0.1	13.23	25.42	18.87	0.52	0.70
BS-300-2-2.5-N50-0.3	11.94	25.42	18.87	0.47	0.63
BS-300-2-2.5-N50-0.5	9.17	25.42	18.87	0.36	0.49
BS-300-2-2.5-N100-0.1	15.88	29.16	22.94	0.54	0.69
BS-300-2-2.5-N100-0.3	13.97	29.16	22.94	0.48	0.61
BS-300-2-2.5-N100-0.5	9.96	29.16	22.94	0.34	0.43
BS-300-2-2.5-N150-0.1	18.44	32.03	26.07	0.58	0.71
BS-300-2-2.5-N150-0.3	14.95	32.03	26.07	0.47	0.57
BS-300-2-2.5-N150-0.5	18.19	32.03	26.07	0.57	0.70
BS-300-3-0.5-N50-0.1	27.38	61.58	35.18	0.44	0.78
BS-300-3-0.5-N50-0.3	24.78	61.58	35.18	0.40	0.70
BS-300-3-0.5-N50-0.5	25.48	61.58	35.18	0.41	0.72
BS-300-3-0.5-N100-0.1	34.89	69.49	42.04	0.50	0.83
BS-300-3-0.5-N100-0.3	28.98	69.49	42.04	0.42	0.69
BS-300-3-0.5-N100-0.5	30.22	69.49	42.04	0.43	0.72
BS-300-3-0.5-N150-0.1	42.23	75.55	47.30	0.56	0.89
BS-300-3-0.5-N150-0.3	35.45	75.55	47.30	0.47	0.75
BS-300-3-0.5-N150-0.5	30.42	75.55	47.30	0.40	0.64

Specimen	P_{FEA}	P_{NAS}	P_{EC3}	P_{FEA}/P_{NAS}	P_{FEA}/P_{EC3}
BS-300-3-1.5-N50-0.1	27.86	58.22	35.18	0.48	0.79
BS-300-3-1.5-N50-0.3	24.56	58.22	35.18	0.42	0.70
BS-300-3-1.5-N50-0.5	25.52	58.22	35.18	0.44	0.73
BS-300-3-1.5-N100-0.1	36.58	65.69	42.04	0.56	0.87
BS-300-3-1.5-N100-0.3	29.53	65.69	42.04	0.45	0.70
BS-300-3-1.5-N100-0.5	30.88	65.69	42.04	0.47	0.73
BS-300-3-1.5-N150-0.1	41.58	71.43	47.30	0.58	0.88
BS-300-3-1.5-N150-0.3	35.90	71.43	47.30	0.50	0.76
BS-300-3-1.5-N150-0.5	34.16	71.43	47.30	0.48	0.72
BS-300-3-2.5-N50-0.1	28.13	55.90	35.18	0.50	0.80
BS-300-3-2.5-N50-0.3	25.18	55.90	35.18	0.45	0.72
BS-300-3-2.5-N50-0.5	26.32	55.90	35.18	0.47	0.75
BS-300-3-2.5-N100-0.1	35.70	63.08	42.04	0.57	0.85
BS-300-3-2.5-N100-0.3	30.18	63.08	42.04	0.48	0.72
BS-300-3-2.5-N100-0.5	31.51	63.08	42.04	0.50	0.75
BS-300-3-2.5-N150-0.1	42.88	68.59	47.30	0.63	0.91
BS-300-3-2.5-N150-0.3	41.29	68.59	47.30	0.60	0.87
BS-300-3-2.5-N150-0.5	33.62	68.59	47.30	0.49	0.71
BS-300-4-0.5-N50-0.1	43.31	106.12	53.25	0.41	0.81
BS-300-4-0.5-N50-0.3	41.86	106.12	53.25	0.39	0.79
BS-300-4-0.5-N50-0.5	77.70	106.12	53.25	0.73	1.46
BS-300-4-0.5-N100-0.1	59.39	118.43	62.83	0.50	0.95
BS-300-4-0.5-N100-0.3	53.36	118.43	62.83	0.45	0.85
BS-300-4-0.5-N100-0.5	54.42	118.43	62.83	0.46	0.87
BS-300-4-0.5-N150-0.1	71.16	127.88	70.19	0.56	1.01
BS-300-4-0.5-N150-0.3	65.22	127.88	70.19	0.51	0.93
BS-300-4-0.5-N150-0.5	43.74	127.88	70.19	0.34	0.62
BS-300-4-1.5-N50-0.1	73.14	101.16	53.25	0.72	1.37
BS-300-4-1.5-N50-0.3	41.64	101.16	53.25	0.41	0.78
BS-300-4-1.5-N50-0.5	43.76	101.16	53.25	0.43	0.82
BS-300-4-1.5-N100-0.1	58.82	112.89	62.83	0.52	0.94
BS-300-4-1.5-N100-0.3	52.30	112.89	62.83	0.46	0.83
BS-300-4-1.5-N100-0.5	55.07	112.89	62.83	0.49	0.88
BS-300-4-1.5-N150-0.1	44.83	121.89	70.19	0.37	0.64
BS-300-4-1.5-N150-0.3	65.15	121.89	70.19	0.53	0.93
BS-300-4-1.5-N150-0.5	66.06	121.89	70.19	0.54	0.94
BS-300-4-2.5-N50-0.1	45.25	97.74	53.25	0.46	0.85
BS-300-4-2.5-N50-0.3	42.09	97.74	53.25	0.43	0.79
BS-300-4-2.5-N50-0.5	44.81	97.74	53.25	0.46	0.84
BS-300-4-2.5-N100-0.1	59.73	109.07	62.83	0.55	0.95
BS-300-4-2.5-N100-0.3	53.55	109.07	62.83	0.49	0.85
BS-300-4-2.5-N100-0.5	56.12	109.07	62.83	0.51	0.89
BS-300-4-2.5-N150-0.1	68.68	117.77	70.19	0.58	0.98
BS-300-4-2.5-N150-0.3	70.25	117.77	70.19	0.60	1.00
BS-300-4-2.5-N150-0.5	60.59	117.77	70.19	0.51	0.86

Specimen	P_{FEA}	P_{NAS}	P_{EC3}	P_{FEA}/P_{NAS}	P_{FEA}/P_{EC3}
			Ave.	0.51	0.76
			Std. dev.	0.17	0.24

Table 2 clearly shows that the current design codes provide inconsistent predictions of the web crippling strengths for CFS built-up beams made of two plain channel sections. Both the North American Specifications (AISI S100) and Eurocode (EN1993-1-3) tend to overestimate the web crippling strengths. The mean and standard deviation of the ratio of the numerically obtained strength to the predicted strength are 0.51 and 0.17, respectively, for the North American Specifications (AISI S100). For the Eurocode (EN1993-1-3), the corresponding values are 0.76 and 0.24. These relatively inconsistent results, with considerable scatter, highlight the need for further research on built-up configurations to support the development of refined design guidelines for more accurate strength predictions.

7. Conclusions

The present study examined the web crippling behavior of CFS built-up I-beams, which were constructed using 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 and validated against relevant experimental data from the literature. Once verified, the model was used to conduct extensive parametric investigations by varying key variables, as outlined by the web crippling design equation in the North American Specifications. In general, it was found that reducing the bearing length led to a decrease in web crippling strength, while increasing the wall thickness significantly enhanced the web crippling resistance, as expected. However, increasing the distance between the fastener and the flange for a given web depth resulted in a reduction in web crippling strength. Web crippling strengths were also determined using the current North American Specifications (AISI S100) and the Eurocode (EN1993-1-3). When comparing the design code predictions with the FE-based web crippling strengths, both the North American Specifications (AISI S100) and the Eurocode (EN1993-1-3) tended to provide overly unconservative predictions in most cases. This highlights the need for further research on such built-up beams to develop more accurate and reliable design provisions.

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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