Proceedings of the
Annual Stability Conference
Structural Stability Research Council
Atlanta, Georgia, April 21-24, 2026

Web crippling investigation of CFS open built-up sections subjected to exterior one-flange loading

Mohammad Adil Dar[1], S. Kavin Kumar[2], M. Anbarasu[3]

Abstract

Built-up I-beams formed by connecting two cold-formed steel (CFS) channel sections have emerged as an efficient structural solution for lightweight construction with high load demands, offering significantly higher flexural strength, stiffness, and overall stability than single-channel members. This improved performance results from more effective stress redistribution between the paired channels and enhanced resistance to global and local instability. Despite these advantages, the slender webs typical of CFS members make built-up I-beams particularly vulnerable to web crippling under concentrated loads at supports or load application points. Web crippling therefore remains a critical limit state governing the design and serviceability of CFS beams, especially in short-span members and modular construction systems. Most existing research on web crippling has focused on single CFS sections, with available experimental and analytical data largely restricted to individual lipped channel members. In contrast, the web crippling response of built-up I-beams is governed by additional mechanisms, including interaction between the two channel components, contact behavior between adjacent webs, and the presence of discrete fasteners that modify load transfer paths and failure modes. Consequently, the structural response of built-up beams differs fundamentally from that of single sections. Current design provisions in the North American Specification (AISI S100) and the Eurocode (EN 1993-1-3), which are primarily calibrated using single-section test data, may therefore be inadequate when applied to built-up CFS I-beams, potentially leading to overly conservative designs or unsafe strength predictions. To address this gap, a detailed finite element (FE) model of CFS built-up I-beams was developed using ABAQUS. The model explicitly represents two plain channel sections connected along their webs through discrete fasteners, with contact interactions defined to realistically capture force transfer and local deformation under concentrated loading. The FE model was rigorously validated against published experimental results to ensure accurate prediction of web crippling behavior and failure modes. Following validation, a comprehensive parametric study was conducted to examine the influence of key geometric parameters, including web slenderness, bearing length, and corner radius-to-thickness ratio, under exterior one-flange loading conditions commonly encountered in practice. The results demonstrate that web crippling resistance in built-up I-beams is highly sensitive to these parameters and that interaction between the channel components plays a dominant role in governing failure. Comparisons with predictions from AISI S100 and EN 1993-1-3 reveal significant inconsistencies, with both standards alternately overestimating and underestimating web crippling capacity.

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[1] Assistant Professor, Birla Institute of Technology & Science Pilani, <dar.adil@hyderabad.bits-pilani.ac.in>
[2] Structural Engineer, Thornton Tomasetti, <ksivakumar@thorntontomasetti.com>
[3] Associate Professor, Government College of Engineering Dharmapuri, <manbarasu@gcedpi.edu.in>

1. Introduction

Cold-formed steel (CFS) structural members have become an integral part of modern low- to mid-rise building systems due to their numerous technical and economic advantages. These members are manufactured through cold-working processes that allow precise control of geometry, resulting in efficient cross-sections with high strength-to-weight ratios. Additional benefits include ease of fabrication, reduced self-weight, simplified handling and transportation, and strong compatibility with off-site prefabrication and modular construction. These attributes collectively enable faster construction schedules and reduced labour requirements, contributing to the widespread adoption of CFS systems in the global construction industry.

Despite these advantages, the thin-walled nature of CFS sections makes them inherently susceptible to instability phenomena such as local buckling, distortional buckling, lateral–torsional buckling, and web crippling. These instability modes often govern the design and limit the full exploitation of material strength. Consequently, a substantial body of research has been devoted to improving the stability and structural efficiency of CFS members through section optimization, stiffening strategies, and improved design methodologies.

Beams represent one of the most critical structural elements in building systems, as they transfer loads from floor assemblies to supporting columns. Single CFS channel beams are asymmetric about their minor axis and are therefore particularly prone to lateral–torsional buckling due to the inevitable eccentricity between applied loads and the shear center. This inherent weakness significantly restricts their bending capacity. To overcome this limitation, built-up I-sections formed by connecting two CFS channels along their webs have been widely adopted. These built-up configurations exhibit superior flexural strength, torsional stability, and load distribution characteristics. However, the slender webs of the channel sections remain vulnerable to localized failures, particularly web crippling under concentrated loads at supports or load introduction points (Anbarasu et al., 2024). While web crippling has been extensively studied for single channel sections, the corresponding behavior of built-up I-sections has not been adequately explored.

2. Previous research on CFS channel sections

Early experimental and analytical studies on web crippling of CFS channel sections identified several key parameters influencing failure, including web slenderness, corner radius, bearing length, steel yield strength, flange restraint conditions, and loading configuration (Hetrakul & Yu, 1978; Young & Hancock, 1998; Rhodes & Nash, 1998; Bhakta et al., 1992; Gerges & Schuster, 1988; Lagan et al., 1994; Beshara & Schuster, 2000). These investigations provided the foundation for empirical web crippling design equations, which were subsequently adopted in early design standards such as AISI (1996), S136, AS/NZS 4600, and BS 5950-5. Continued refinement of experimental data allowed calibration and improvement of the associated coefficients.

Following 2000, research efforts expanded significantly to examine a broader range of geometric and material parameters and to improve predictive accuracy (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). These studies contributed directly to the development of the current web crippling provisions in AISI S100 and Eurocode 3 and also led to the proposal of analytical and semi-empirical formulations within the Direct Strength Method framework.

More recent investigations have extended web crippling research to modified CFS sections, including hollow-flange channels (Keerthan et al., a–b; Steau et al., a–c), intermittently web-stiffened channels with inclined lips (Sundararajah et al., a–b), and members incorporating web openings (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 and modified design approaches to account for strength reductions arising from such alterations, enhancing the applicability of CFS systems in practice.

3. CFS built-up I-beams

The web crippling response of built-up CFS I-beams differs fundamentally from that of single channel sections due to interaction between the paired channels through contact, fasteners, and shared load paths. These interactions influence stress distribution, deformation patterns, and failure mechanisms, making direct application of single-section design equations inappropriate. Despite the increasing use of built-up I-beams in practice, research on their web crippling behavior remains limited (Winter & Pian, 1946; Hetrakul & Wu, 1978; Bhakta & LaBoube, 1992; Cian et al., 1995; He & Young, 2022a–b; Dar et al. 2023; 2024; 2025). Only a small number of studies have focused on built-up sections formed from plain channels, and these have demonstrated that existing web crippling provisions in AISI S100 and Eurocode 3 are inadequate without modification.

Building upon this limited body of work, the present study investigates the web crippling behavior of CFS built-up I-beams over an expanded range of governing parameters. A finite element (FE) model of built-up I-beams assembled from plain channels was developed in ABAQUS and validated against experimental data reported by He and Young (2022a). The validated model was subsequently used to conduct a systematic parametric study examining the influence of web slenderness, corner radius, and bearing length under end two-flange loading conditions. The numerical predictions were compared with design strengths obtained using AISI S100 and Eurocode 3 to assess the reliability of existing provisions and to identify deficiencies requiring refinement.

4. Numerical modelling techniques and validation

A detailed three-dimensional FE model was developed using ABAQUS to simulate built-up CFS I-beams formed by two plain channels placed back-to-back and connected along their webs at discrete intervals (Fig. 1). The channel sections were modeled using four-node shell elements (S4R), while bearing plates were represented using rigid solid elements (R3D4). A uniform mesh size of 10 mm was adopted for flat regions, with local mesh refinement applied at flange–web junctions using four elements across the corner regions to accurately capture stress concentrations and local deformations.

Material nonlinearity was represented using the constitutive model proposed by Gardner and Yun (2018), which extends the Ramberg–Osgood formulation (Ramberg & Osgood, 1943). Engineering stress–strain data were converted to true stress and true plastic strain following the procedures recommended in the ABAQUS documentation (ABAQUS, 2014). To replicate the experimental configuration of He and Young (2022a), reference points were introduced above and below the bearing plates, and rigid body constraints were used to connect these plates to the reference points. Mechanical fasteners were modeled using three-dimensional beam connector elements, while surface interactions between channel webs were defined using hard contact in the normal direction with limited tangential sliding. A friction coefficient of 0.4 was adopted for steel-to-steel interfaces. Consistent with previous studies (Natário et al., 2014b; Sundararajah et al., 2017, 2018), initial geometric imperfections were neglected due to their negligible influence on web crippling strength.

The FE model was validated against experimental results for built-up I-beams fabricated from 1.2 mm and 1.9 mm thick steel sheets with nominal yield strengths of 450 MPa and 500 MPa. Variations in screw spacing and bearing length were included to replicate the test configurations. Comparisons of failure modes, load–displacement responses, and ultimate capacities demonstrated excellent agreement between numerical and experimental results. The mean ratio of experimental to FE-predicted strength was 1.02, with a standard deviation of 0.045, confirming the robustness and suitability of the developed model for comprehensive parametric investigations.

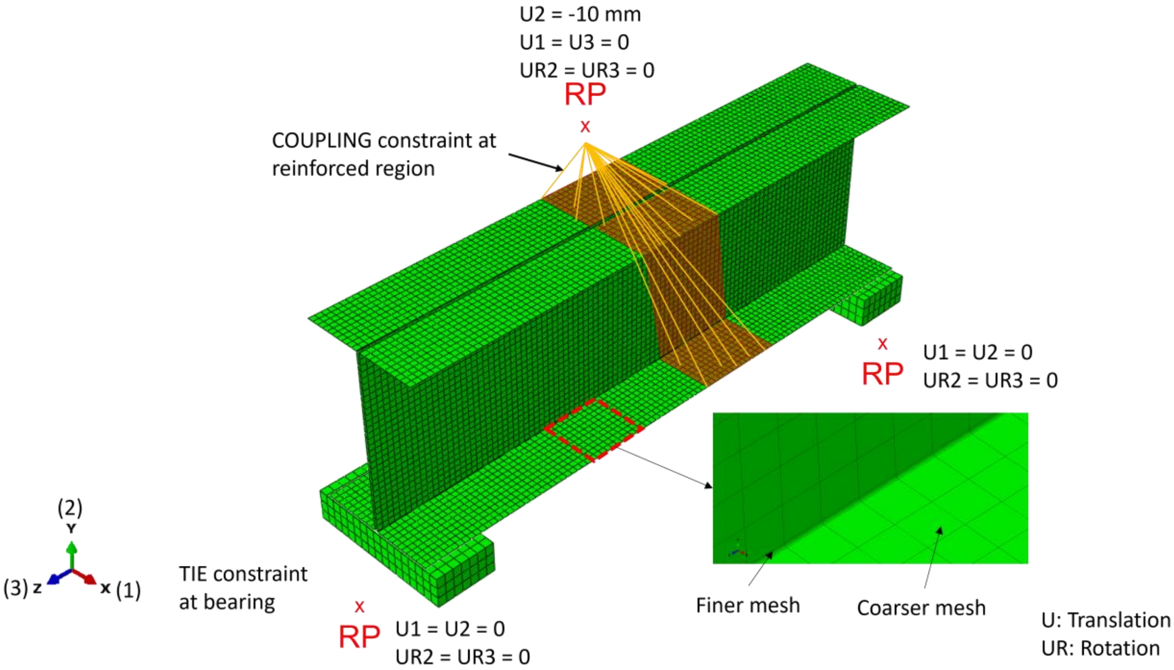


Figure 1: FE model of the built-up beam

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

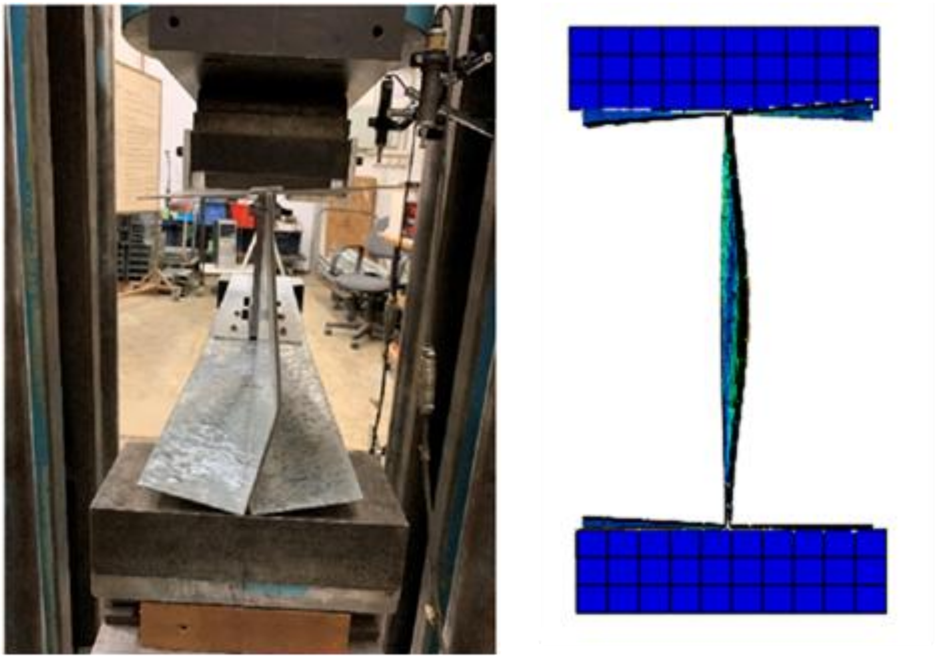


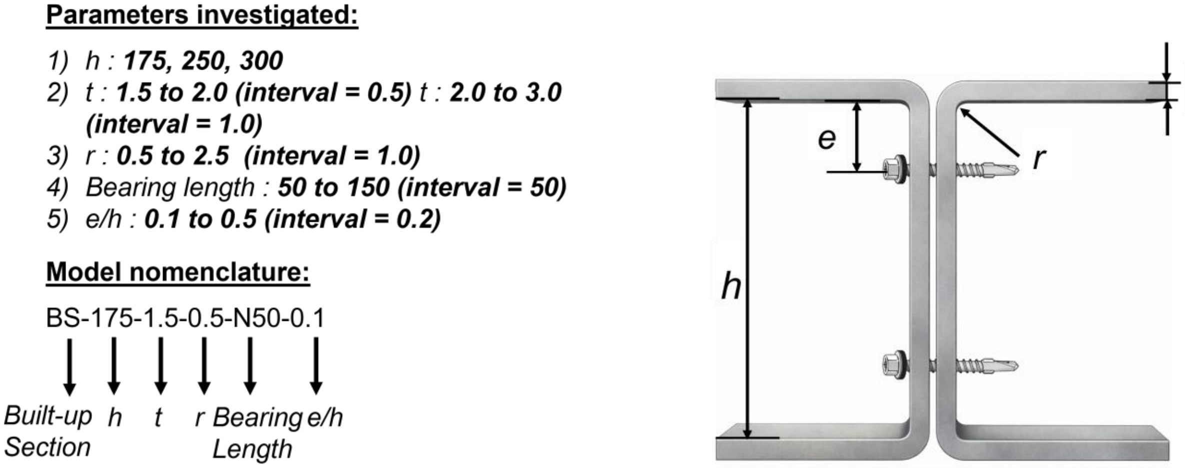
Figure 2: Failure mode comparison between test specimen EOF-120×80×1.9N50-0.1 (He & Young 2022a) and the corresponding FE model

5. Parametric study

A comprehensive parametric investigation was carried out on a CFS built-up I-beam configuration similar to that experimentally studied by He and Young (2022a). The built-up section consisted of two plain channel members connected through their webs using discrete fasteners. To isolate the influence of the selected parameters, the flange width of each channel section was maintained at 100 mm, and a built-up beam configuration was adopted by providing a 5 mm gap between the two channels, resulting in an overall section width of 205 mm. The web depth was varied as 175 mm, 250 mm, and 300 mm throughout the study. Key geometric and connection-related variables were systematically varied to examine their influence on web crippling behavior. The channel thickness was varied from 1.5 mm to 4.0 mm to represent both slender and relatively stocky sections. The ratio of corner radius to thickness (r/t) ranged from 0.13 to 1.67 to capture the effects of manufacturing-induced corner geometry. The ratio of the distance between the fastener and the flange to the web depth (e/h) was varied between 0.1 and 0.5 to investigate the sensitivity of load transfer mechanisms to fastener location. In addition, the bearing length was varied from 50 mm to 150 mm to represent different support conditions commonly encountered in practice. The primary parameters considered in the parametric study were web depth (h), thickness (t), corner radius (r), bearing length, and fastener position ratio (e/h), as illustrated in Fig. 3. The yield strength of steel was maintained at a constant value of 250 MPa to eliminate material strength variability.

A consistent specimen nomenclature was adopted to clearly identify each configuration. For instance, the designation BS-175-1.5-0.5-N50-0.1 denotes a built-up section (BS) with a web depth of 175 mm, thickness of 1.5 mm, internal corner radius of 0.5 mm, bearing length of 50 mm, and a fastener-to-web-depth ratio of 0.1. This nomenclature facilitates systematic interpretation of the results.

The parametric results demonstrated that all investigated parameters significantly influenced the web crippling strength of the built-up I-beams. As expected, increasing the channel thickness and bearing length led to substantial improvements in web crippling resistance due to enhanced load distribution and reduced local stresses. Conversely, increasing the e/h ratio consistently reduced web crippling capacity, indicating that fasteners positioned farther from the flange are less effective in restraining local deformations and facilitating load sharing between the channel components. The numerical web crippling strengths obtained for all configurations are summarized in Table 2.



Parameters investigated:

1) *h* : ***175, 250, 300***
2) *t* : ***1.5 to 2.0 (interval = 0.5)*** *t* : ***2.0 to 3.0 (interval = 1.0)***
3) *r* : ***0.5 to 2.5 (interval = 1.0)***
4) *Bearing length* : ***50 to 150 (interval = 50)***
5) *e/h* : ***0.1 to 0.5 (interval = 0.2)***

Model nomenclature:

BS-175-1.5-0.5-N50-0.1

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

6. Design strengths

The web crippling capacities of all parametric specimens were also calculated using the current North American Specification (AISI S100) and the Eurocode provisions (EN 1993-1-3). These code-based predictions were compared against the FE results to assess the applicability and accuracy of existing design equations for CFS built-up I-beams.

The comparison, presented in Table 2, indicates that both design codes yield inconsistent predictions when applied to built-up sections composed of two plain channels. In general, both AISI S100 and EN 1993-1-3 tend to overestimate the web crippling strength, often producing unconservative results. For AISI S100, the mean ratio of FE-predicted strength to code-predicted strength was 0.71, with a standard deviation of 0.15, reflecting substantial scatter and systematic overprediction. The Eurocode showed comparatively better agreement, with a mean ratio of 0.97 and a standard deviation of 0.25; however, the predictions still exhibited considerable variability.

These discrepancies clearly highlight the limitations of existing design provisions, which are primarily calibrated for single-section CFS members and do not adequately capture the interaction effects and altered load paths present in built-up configurations. The observed scatter underscores the need for targeted research on built-up I-beams to develop refined design models capable of delivering consistent and reliable strength predictions.

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-250-175-1.5-0.5-N50-0.1	9.45	13.38	9.84	0.71	0.96
BS-250-175-1.5-0.5-N50-0.3	9.42	13.38	9.84	0.70	0.96
BS-250-175-1.5-0.5-N50-0.5	7.25	13.38	9.84	0.54	0.74
BS-250-175-1.5-0.5-N100-0.1	14.75	16.81	11.54	0.88	1.28
BS-250-175-1.5-0.5-N100-0.3	13.07	16.81	11.54	0.78	1.13
BS-250-175-1.5-0.5-N100-0.5	10.59	16.81	11.54	0.63	0.92
BS-250-175-1.5-0.5-N150-0.1	19.99	19.44	12.86	1.03	1.56
BS-250-175-1.5-0.5-N150-0.3	18.21	19.44	12.86	0.94	1.42
BS-250-175-1.5-0.5-N150-0.5	15.20	19.44	12.86	0.78	1.18
BS-250-175-1.5-1.5-N50-0.1	9.42	12.52	9.84	0.75	0.96
BS-250-175-1.5-1.5-N50-0.3	9.80	12.52	9.84	0.78	1.00
BS-250-175-1.5-1.5-N50-0.5	7.18	12.52	9.84	0.57	0.73
BS-250-175-1.5-1.5-N100-0.1	14.72	15.73	11.54	0.94	1.28
BS-250-175-1.5-1.5-N100-0.3	13.40	15.73	11.54	0.85	1.16
BS-250-175-1.5-1.5-N100-0.5	10.80	15.73	11.54	0.69	0.94
BS-250-175-1.5-1.5-N150-0.1	18.60	18.19	12.86	1.02	1.45
BS-250-175-1.5-1.5-N150-0.3	16.45	18.19	12.86	0.90	1.28
BS-250-175-1.5-1.5-N150-0.5	14.15	18.19	12.86	0.78	1.10
BS-250-175-1.5-2.5-N50-0.1	9.28	11.93	9.84	0.78	0.94
BS-250-175-1.5-2.5-N50-0.3	8.55	11.93	9.84	0.72	0.87
BS-250-175-1.5-2.5-N50-0.5	6.82	11.93	9.84	0.57	0.69
BS-250-175-1.5-2.5-N100-0.1	14.33	14.98	11.54	0.96	1.24
BS-250-175-1.5-2.5-N100-0.3	12.54	14.98	11.54	0.84	1.09
BS-250-175-1.5-2.5-N100-0.5	10.37	14.98	11.54	0.69	0.90
BS-250-175-1.5-2.5-N150-0.1	18.11	17.33	12.86	1.05	1.41
BS-250-175-1.5-2.5-N150-0.3	17.03	17.33	12.86	0.98	1.33
BS-250-175-1.5-2.5-N150-0.5	14.04	17.33	12.86	0.81	1.09
BS-250-175-2-0.5-N50-0.1	16.44	22.11	15.95	0.74	1.03
BS-250-175-2-0.5-N50-0.3	18.64	22.11	15.95	0.84	1.17
BS-250-175-2-0.5-N50-0.5	13.44	22.11	15.95	0.61	0.84

Specimen	P_{FEA}	P_{NAS}	P_{EC3}	P_{FEA}/P_{NAS}	P_{FEA}/P_{EC3}
BS-250-175-2-0.5-N100-0.1	25.06	27.46	18.49	0.91	1.36
BS-250-175-2-0.5-N100-0.3	23.63	27.46	18.49	0.86	1.28
BS-250-175-2-0.5-N100-0.5	19.20	27.46	18.49	0.70	1.04
BS-250-175-2-0.5-N150-0.1	31.64	31.56	20.44	1.00	1.55
BS-250-175-2-0.5-N150-0.3	29.68	31.56	20.44	0.94	1.45
BS-250-175-2-0.5-N150-0.5	25.67	31.56	20.44	0.81	1.26
BS-250-175-2-1.5-N50-0.1	16.29	20.90	15.95	0.78	1.02
BS-250-175-2-1.5-N50-0.3	16.29	20.90	15.95	0.78	1.02
BS-250-175-2-1.5-N50-0.5	12.99	20.90	15.95	0.62	0.81
BS-250-175-2-1.5-N100-0.1	24.79	25.95	18.49	0.96	1.34
BS-250-175-2-1.5-N100-0.3	23.33	25.95	18.49	0.90	1.26
BS-250-175-2-1.5-N100-0.5	18.93	25.95	18.49	0.73	1.02
BS-250-175-2-1.5-N150-0.1	32.43	29.82	20.44	1.09	1.59
BS-250-175-2-1.5-N150-0.3	28.00	29.82	20.44	0.94	1.37
BS-250-175-2-1.5-N150-0.5	24.47	29.82	20.44	0.82	1.20
BS-250-175-2-2.5-N50-0.1	16.73	20.06	15.95	0.83	1.05
BS-250-175-2-2.5-N50-0.3	15.27	20.06	15.95	0.76	0.96
BS-250-175-2-2.5-N50-0.5	12.56	20.06	15.95	0.63	0.79
BS-250-175-2-2.5-N100-0.1	24.24	24.91	18.49	0.97	1.31
BS-250-175-2-2.5-N100-0.3	21.65	24.91	18.49	0.87	1.17
BS-250-175-2-2.5-N100-0.5	18.09	24.91	18.49	0.73	0.98
BS-250-175-2-2.5-N150-0.1	29.65	28.62	20.44	1.04	1.45
BS-250-175-2-2.5-N150-0.3	27.14	28.62	20.44	0.95	1.33
BS-250-175-2-2.5-N150-0.5	24.17	28.62	20.44	0.84	1.18
BS-250-175-3-0.5-N50-0.1	34.05	45.12	32.19	0.75	1.06
BS-250-175-3-0.5-N50-0.3	35.65	45.12	32.19	0.79	1.11
BS-250-175-3-0.5-N50-0.5	29.15	45.12	32.19	0.65	0.91
BS-250-175-3-0.5-N100-0.1	49.48	55.09	36.70	0.90	1.35
BS-250-175-3-0.5-N100-0.3	49.66	55.09	36.70	0.90	1.35
BS-250-175-3-0.5-N100-0.5	41.60	55.09	36.70	0.76	1.13
BS-250-175-3-0.5-N150-0.1	59.51	62.74	40.15	0.95	1.48
BS-250-175-3-0.5-N150-0.3	57.36	62.74	40.15	0.91	1.43
BS-250-175-3-0.5-N150-0.5	52.25	62.74	40.15	0.83	1.30
BS-250-175-3-1.5-N50-0.1	35.05	43.12	32.19	0.81	1.09
BS-250-175-3-1.5-N50-0.3	33.50	43.12	32.19	0.78	1.04
BS-250-175-3-1.5-N50-0.5	28.89	43.12	32.19	0.67	0.90
BS-250-175-3-1.5-N100-0.1	49.93	52.65	36.70	0.95	1.36
BS-250-175-3-1.5-N100-0.3	47.80	52.65	36.70	0.91	1.30
BS-250-175-3-1.5-N100-0.5	41.05	52.65	36.70	0.78	1.12
BS-250-175-3-1.5-N150-0.1	62.32	59.96	40.15	1.04	1.55
BS-250-175-3-1.5-N150-0.3	55.92	59.96	40.15	0.93	1.39
BS-250-175-3-1.5-N150-0.5	50.98	59.96	40.15	0.85	1.27
BS-250-175-3-2.5-N50-0.1	29.42	41.75	32.19	0.70	0.91
BS-250-175-3-2.5-N50-0.3	28.92	41.75	32.19	0.69	0.90
BS-250-175-3-2.5-N50-0.5	22.98	41.75	32.19	0.55	0.71

Specimen	P_{FEA}	P_{NAS}	P_{EC3}	P_{FEA}/P_{NAS}	P_{FEA}/P_{EC3}
BS-250-175-3-2.5-N100-0.1	40.03	50.97	36.70	0.79	1.09
BS-250-175-3-2.5-N100-0.3	40.30	50.97	36.70	0.79	1.10
BS-250-175-3-2.5-N100-0.5	39.88	50.97	36.70	0.78	1.09
BS-250-175-3-2.5-N150-0.1	53.39	58.05	40.15	0.92	1.33
BS-250-175-3-2.5-N150-0.3	52.21	58.05	40.15	0.90	1.30
BS-250-175-3-2.5-N150-0.5	50.11	58.05	40.15	0.86	1.25
BS-250-175-4-0.5-N50-0.1	56.21	75.17	53.65	0.75	1.05
BS-250-175-4-0.5-N50-0.3	55.06	75.17	53.65	0.73	1.03
BS-250-175-4-0.5-N50-0.5	48.97	75.17	53.65	0.65	0.91
BS-250-175-4-0.5-N100-0.1	75.85	90.66	60.46	0.84	1.25
BS-250-175-4-0.5-N100-0.3	75.72	90.66	60.46	0.84	1.25
BS-250-175-4-0.5-N100-0.5	69.52	90.66	60.46	0.77	1.15
BS-250-175-4-0.5-N150-0.1	89.90	102.55	65.69	0.88	1.37
BS-250-175-4-0.5-N150-0.3	89.61	102.55	65.69	0.87	1.36
BS-250-175-4-0.5-N150-0.5	83.86	102.55	65.69	0.82	1.28
BS-250-175-4-1.5-N50-0.1	56.79	72.31	53.65	0.79	1.06
BS-250-175-4-1.5-N50-0.3	53.65	72.31	53.65	0.74	1.00
BS-250-175-4-1.5-N50-0.5	48.18	72.31	53.65	0.67	0.90
BS-250-175-4-1.5-N100-0.1	74.94	87.21	60.46	0.86	1.24
BS-250-175-4-1.5-N100-0.3	73.12	87.21	60.46	0.84	1.21
BS-250-175-4-1.5-N100-0.5	67.43	87.21	60.46	0.77	1.12
BS-250-175-4-1.5-N150-0.1	89.80	98.64	65.69	0.91	1.37
BS-250-175-4-1.5-N150-0.3	89.63	98.64	65.69	0.91	1.36
BS-250-175-4-1.5-N150-0.5	86.75	98.64	65.69	0.88	1.32
BS-250-175-4-2.5-N50-0.1	41.24	70.34	53.65	0.59	0.77
BS-250-175-4-2.5-N50-0.3	41.09	70.34	53.65	0.58	0.77
BS-250-175-4-2.5-N50-0.5	39.37	70.34	53.65	0.56	0.73
BS-250-175-4-2.5-N100-0.1	61.97	84.83	60.46	0.73	1.02
BS-250-175-4-2.5-N100-0.3	59.39	84.83	60.46	0.70	0.98
BS-250-175-4-2.5-N100-0.5	58.44	84.83	60.46	0.69	0.97
BS-250-175-4-2.5-N150-0.1	80.53	95.95	65.69	0.84	1.23
BS-250-175-4-2.5-N150-0.3	74.69	95.95	65.69	0.78	1.14
BS-250-175-4-2.5-N150-0.5	72.00	95.95	65.69	0.75	1.10
BS-250-250-1.5-0.5-N50-0.1	6.98	13.36	10.40	0.52	0.67
BS-250-250-1.5-0.5-N50-0.3	6.06	13.36	10.40	0.45	0.58
BS-250-250-1.5-0.5-N50-0.5	5.94	13.36	10.40	0.45	0.57
BS-250-250-1.5-0.5-N100-0.1	9.71	16.77	12.21	0.58	0.80
BS-250-250-1.5-0.5-N100-0.3	9.89	16.77	12.21	0.59	0.81
BS-250-250-1.5-0.5-N100-0.5	8.87	16.77	12.21	0.53	0.73
BS-250-250-1.5-0.5-N150-0.1	14.95	19.40	13.60	0.77	1.10
BS-250-250-1.5-0.5-N150-0.3	13.74	19.40	13.60	0.71	1.01
BS-250-250-1.5-0.5-N150-0.5	10.71	19.40	13.60	0.55	0.79
BS-250-250-1.5-1.5-N50-0.1	6.94	12.50	10.40	0.56	0.67
BS-250-250-1.5-1.5-N50-0.3	5.91	12.50	10.40	0.47	0.57
BS-250-250-1.5-1.5-N50-0.5	5.59	12.50	10.40	0.45	0.54

Specimen	P_{FEA}	P_{NAS}	P_{EC3}	P_{FEA}/P_{NAS}	P_{FEA}/P_{EC3}
BS-250-250-1.5-1.5-N100-0.1	10.60	15.69	12.21	0.68	0.87
BS-250-250-1.5-1.5-N100-0.3	8.74	15.69	12.21	0.56	0.72
BS-250-250-1.5-1.5-N100-0.5	8.59	15.69	12.21	0.55	0.70
BS-250-250-1.5-1.5-N150-0.1	12.80	18.15	13.60	0.71	0.94
BS-250-250-1.5-1.5-N150-0.3	13.92	18.15	13.60	0.77	1.02
BS-250-250-1.5-1.5-N150-0.5	11.42	18.15	13.60	0.63	0.84
BS-250-250-1.5-2.5-N50-0.1	7.06	11.90	10.40	0.59	0.68
BS-250-250-1.5-2.5-N50-0.3	6.34	11.90	10.40	0.53	0.61
BS-250-250-1.5-2.5-N50-0.5	5.39	11.90	10.40	0.45	0.52
BS-250-250-1.5-2.5-N100-0.1	9.83	14.95	12.21	0.66	0.81
BS-250-250-1.5-2.5-N100-0.3	7.88	14.95	12.21	0.53	0.65
BS-250-250-1.5-2.5-N100-0.5	7.38	14.95	12.21	0.49	0.60
BS-250-250-1.5-2.5-N150-0.1	12.43	17.29	13.60	0.72	0.91
BS-250-250-1.5-2.5-N150-0.3	11.71	17.29	13.60	0.68	0.86
BS-250-250-1.5-2.5-N150-0.5	10.30	17.29	13.60	0.60	0.76
BS-250-250-2-0.5-N50-0.1	14.44	22.07	16.66	0.65	0.87
BS-250-250-2-0.5-N50-0.3	12.54	22.07	16.66	0.57	0.75
BS-250-250-2-0.5-N50-0.5	10.97	22.07	16.66	0.50	0.66
BS-250-250-2-0.5-N100-0.1	18.97	27.41	19.32	0.69	0.98
BS-250-250-2-0.5-N100-0.3	19.03	27.41	19.32	0.69	0.99
BS-250-250-2-0.5-N100-0.5	16.95	27.41	19.32	0.62	0.88
BS-250-250-2-0.5-N150-0.1	27.48	31.50	21.36	0.87	1.29
BS-250-250-2-0.5-N150-0.3	22.77	31.50	21.36	0.72	1.07
BS-250-250-2-0.5-N150-0.5	22.52	31.50	21.36	0.71	1.05
BS-250-250-2-1.5-N50-0.1	13.68	20.86	16.66	0.66	0.82
BS-250-250-2-1.5-N50-0.3	11.72	20.86	16.66	0.56	0.70
BS-250-250-2-1.5-N50-0.5	10.64	20.86	16.66	0.51	0.64
BS-250-250-2-1.5-N100-0.1	19.32	25.90	19.32	0.75	1.00
BS-250-250-2-1.5-N100-0.3	19.08	25.90	19.32	0.74	0.99
BS-250-250-2-1.5-N100-0.5	15.92	25.90	19.32	0.61	0.82
BS-250-250-2-1.5-N150-0.1	24.99	29.76	21.36	0.84	1.17
BS-250-250-2-1.5-N150-0.3	24.91	29.76	21.36	0.84	1.17
BS-250-250-2-1.5-N150-0.5	22.52	29.76	21.36	0.76	1.05
BS-250-250-2-2.5-N50-0.1	13.66	20.02	16.66	0.68	0.82
BS-250-250-2-2.5-N50-0.3	11.25	20.02	16.66	0.56	0.67
BS-250-250-2-2.5-N50-0.5	10.42	20.02	16.66	0.52	0.63
BS-250-250-2-2.5-N100-0.1	19.18	24.86	19.32	0.77	0.99
BS-250-250-2-2.5-N100-0.3	16.91	24.86	19.32	0.68	0.88
BS-250-250-2-2.5-N100-0.5	15.39	24.86	19.32	0.62	0.80
BS-250-250-2-2.5-N150-0.1	24.41	28.57	21.36	0.85	1.14
BS-250-250-2-2.5-N150-0.3	21.90	28.57	21.36	0.77	1.03
BS-250-250-2-2.5-N150-0.5	20.49	28.57	21.36	0.72	0.96
BS-250-250-3-0.5-N50-0.1	30.80	45.05	33.19	0.68	0.93
BS-250-250-3-0.5-N50-0.3	28.05	45.05	33.19	0.62	0.85
BS-250-250-3-0.5-N50-0.5	27.02	45.05	33.19	0.60	0.81

Specimen	P_{FEA}	P_{NAS}	P_{EC3}	P_{FEA}/P_{NAS}	P_{FEA}/P_{EC3}
BS-250-250-3-0.5-N100-0.1	44.69	55.01	37.83	0.81	1.18
BS-250-250-3-0.5-N100-0.3	42.85	55.01	37.83	0.78	1.13
BS-250-250-3-0.5-N100-0.5	36.04	55.01	37.83	0.66	0.95
BS-250-250-3-0.5-N150-0.1	55.17	62.65	41.40	0.88	1.33
BS-250-250-3-0.5-N150-0.3	52.42	62.65	41.40	0.84	1.27
BS-250-250-3-0.5-N150-0.5	47.79	62.65	41.40	0.76	1.15
BS-250-250-3-1.5-N50-0.1	31.74	43.06	33.19	0.74	0.96
BS-250-250-3-1.5-N50-0.3	27.33	43.06	33.19	0.63	0.82
BS-250-250-3-1.5-N50-0.5	25.94	43.06	33.19	0.60	0.78
BS-250-250-3-1.5-N100-0.1	44.89	52.57	37.83	0.85	1.19
BS-250-250-3-1.5-N100-0.3	42.19	52.57	37.83	0.80	1.12
BS-250-250-3-1.5-N100-0.5	35.72	52.57	37.83	0.68	0.94
BS-250-250-3-1.5-N150-0.1	58.86	59.87	41.40	0.98	1.42
BS-250-250-3-1.5-N150-0.3	52.66	59.87	41.40	0.88	1.27
BS-250-250-3-1.5-N150-0.5	45.02	59.87	41.40	0.75	1.09
BS-250-250-3-2.5-N50-0.1	27.25	41.68	33.19	0.65	0.82
BS-250-250-3-2.5-N50-0.3	27.07	41.68	33.19	0.65	0.82
BS-250-250-3-2.5-N50-0.5	26.08	41.68	33.19	0.63	0.79
BS-250-250-3-2.5-N100-0.1	41.28	50.89	37.83	0.81	1.09
BS-250-250-3-2.5-N100-0.3	40.02	50.89	37.83	0.79	1.06
BS-250-250-3-2.5-N100-0.5	34.88	50.89	37.83	0.69	0.92
BS-250-250-3-2.5-N150-0.1	55.22	57.96	41.40	0.95	1.33
BS-250-250-3-2.5-N150-0.3	50.67	57.96	41.40	0.87	1.22
BS-250-250-3-2.5-N150-0.5	46.43	57.96	41.40	0.80	1.12
BS-250-250-4-0.5-N50-0.1	52.73	75.07	54.92	0.70	0.96
BS-250-250-4-0.5-N50-0.3	49.52	75.07	54.92	0.66	0.90
BS-250-250-4-0.5-N50-0.5	47.47	75.07	54.92	0.63	0.86
BS-250-250-4-0.5-N100-0.1	72.98	90.54	61.89	0.81	1.18
BS-250-250-4-0.5-N100-0.3	73.99	90.54	61.89	0.82	1.20
BS-250-250-4-0.5-N100-0.5	66.96	90.54	61.89	0.74	1.08
BS-250-250-4-0.5-N150-0.1	96.03	102.41	67.24	0.94	1.43
BS-250-250-4-0.5-N150-0.3	93.47	102.41	67.24	0.91	1.39
BS-250-250-4-0.5-N150-0.5	82.14	102.41	67.24	0.80	1.22
BS-250-250-4-1.5-N50-0.1	54.53	72.21	54.92	0.76	0.99
BS-250-250-4-1.5-N50-0.3	48.55	72.21	54.92	0.67	0.88
BS-250-250-4-1.5-N50-0.5	49.09	72.21	54.92	0.68	0.89
BS-250-250-4-1.5-N100-0.1	77.53	87.09	61.89	0.89	1.25
BS-250-250-4-1.5-N100-0.3	69.25	87.09	61.89	0.80	1.12
BS-250-250-4-1.5-N100-0.5	64.34	87.09	61.89	0.74	1.04
BS-250-250-4-1.5-N150-0.1	94.79	98.51	67.24	0.96	1.41
BS-250-250-4-1.5-N150-0.3	91.22	98.51	67.24	0.93	1.36
BS-250-250-4-1.5-N150-0.5	88.65	98.51	67.24	0.90	1.32
BS-250-250-4-2.5-N50-0.1	41.30	70.24	54.92	0.59	0.75
BS-250-250-4-2.5-N50-0.3	41.09	70.24	54.92	0.58	0.75
BS-250-250-4-2.5-N50-0.5	41.20	70.24	54.92	0.59	0.75

Specimen	P_{FEA}	P_{NAS}	P_{EC3}	P_{FEA}/P_{NAS}	P_{FEA}/P_{EC3}
BS-250-250-4-2.5-N100-0.1	63.13	84.72	61.89	0.75	1.02
BS-250-250-4-2.5-N100-0.3	60.12	84.72	61.89	0.71	0.97
BS-250-250-4-2.5-N100-0.5	60.10	84.72	61.89	0.71	0.97
BS-250-250-4-2.5-N150-0.1	81.01	95.82	67.24	0.85	1.20
BS-250-250-4-2.5-N150-0.3	73.20	95.82	67.24	0.76	1.09
BS-250-250-4-2.5-N150-0.5	72.89	95.82	67.24	0.76	1.08
BS-250-300-1.5-0.5-N50-0.1	6.93	13.34	10.78	0.52	0.64
BS-250-300-1.5-0.5-N50-0.3	5.56	13.34	10.78	0.42	0.52
BS-250-300-1.5-0.5-N50-0.5	4.89	13.34	10.78	0.37	0.45
BS-250-300-1.5-0.5-N100-0.1	8.88	16.75	12.66	0.53	0.70
BS-250-300-1.5-0.5-N100-0.3	8.40	16.75	12.66	0.50	0.66
BS-250-300-1.5-0.5-N100-0.5	7.44	16.75	12.66	0.44	0.59
BS-250-300-1.5-0.5-N150-0.1	11.78	19.37	14.09	0.61	0.84
BS-250-300-1.5-0.5-N150-0.3	11.98	19.37	14.09	0.62	0.85
BS-250-300-1.5-0.5-N150-0.5	7.94	19.37	14.09	0.41	0.56
BS-250-300-1.5-1.5-N50-0.1	5.98	12.48	10.78	0.48	0.55
BS-250-300-1.5-1.5-N50-0.3	5.20	12.48	10.78	0.42	0.48
BS-250-300-1.5-1.5-N50-0.5	4.78	12.48	10.78	0.38	0.44
BS-250-300-1.5-1.5-N100-0.1	8.51	15.67	12.66	0.54	0.67
BS-250-300-1.5-1.5-N100-0.3	8.50	15.67	12.66	0.54	0.67
BS-250-300-1.5-1.5-N100-0.5	6.52	15.67	12.66	0.42	0.52
BS-250-300-1.5-1.5-N150-0.1	9.99	18.13	14.09	0.55	0.71
BS-250-300-1.5-1.5-N150-0.3	11.16	18.13	14.09	0.62	0.79
BS-250-300-1.5-1.5-N150-0.5	7.74	18.13	14.09	0.43	0.55
BS-250-300-1.5-2.5-N50-0.1	6.23	11.89	10.78	0.52	0.58
BS-250-300-1.5-2.5-N50-0.3	5.14	11.89	10.78	0.43	0.48
BS-250-300-1.5-2.5-N50-0.5	4.72	11.89	10.78	0.40	0.44
BS-250-300-1.5-2.5-N100-0.1	7.98	14.93	12.66	0.53	0.63
BS-250-300-1.5-2.5-N100-0.3	9.13	14.93	12.66	0.61	0.72
BS-250-300-1.5-2.5-N100-0.5	5.94	14.93	12.66	0.40	0.47
BS-250-300-1.5-2.5-N150-0.1	10.24	17.27	14.09	0.59	0.73
BS-250-300-1.5-2.5-N150-0.3	9.35	17.27	14.09	0.54	0.66
BS-250-300-1.5-2.5-N150-0.5	8.94	17.27	14.09	0.52	0.63
BS-250-300-2-0.5-N50-0.1	12.81	22.05	17.14	0.58	0.75
BS-250-300-2-0.5-N50-0.3	11.08	22.05	17.14	0.50	0.65
BS-250-300-2-0.5-N50-0.5	10.30	22.05	17.14	0.47	0.60
BS-250-300-2-0.5-N100-0.1	17.51	27.38	19.87	0.64	0.88
BS-250-300-2-0.5-N100-0.3	16.77	27.38	19.87	0.61	0.84
BS-250-300-2-0.5-N100-0.5	14.51	27.38	19.87	0.53	0.73
BS-250-300-2-0.5-N150-0.1	23.88	31.46	21.97	0.76	1.09
BS-250-300-2-0.5-N150-0.3	19.72	31.46	21.97	0.63	0.90
BS-250-300-2-0.5-N150-0.5	16.02	31.46	21.97	0.51	0.73
BS-250-300-2-1.5-N50-0.1	12.60	20.83	17.14	0.60	0.74
BS-250-300-2-1.5-N50-0.3	10.84	20.83	17.14	0.52	0.63
BS-250-300-2-1.5-N50-0.5	9.39	20.83	17.14	0.45	0.55

Specimen	P_{FEA}	P_{NAS}	P_{EC3}	P_{FEA}/P_{NAS}	P_{FEA}/P_{EC3}
BS-250-300-2-1.5-N100-0.1	16.13	25.87	19.87	0.62	0.81
BS-250-300-2-1.5-N100-0.3	15.09	25.87	19.87	0.58	0.76
BS-250-300-2-1.5-N100-0.5	13.50	25.87	19.87	0.52	0.68
BS-250-300-2-1.5-N150-0.1	20.00	29.73	21.97	0.67	0.91
BS-250-300-2-1.5-N150-0.3	20.11	29.73	21.97	0.68	0.92
BS-250-300-2-1.5-N150-0.5	19.03	29.73	21.97	0.64	0.87
BS-250-300-2-2.5-N50-0.1	12.32	20.00	17.14	0.62	0.72
BS-250-300-2-2.5-N50-0.3	10.54	20.00	17.14	0.53	0.62
BS-250-300-2-2.5-N50-0.5	9.27	20.00	17.14	0.46	0.54
BS-250-300-2-2.5-N100-0.1	16.67	24.83	19.87	0.67	0.84
BS-250-300-2-2.5-N100-0.3	15.15	24.83	19.87	0.61	0.76
BS-250-300-2-2.5-N100-0.5	13.43	24.83	19.87	0.54	0.68
BS-250-300-2-2.5-N150-0.1	20.35	28.54	21.97	0.71	0.93
BS-250-300-2-2.5-N150-0.3	18.45	28.54	21.97	0.65	0.84
BS-250-300-2-2.5-N150-0.5	15.51	28.54	21.97	0.54	0.71
BS-250-300-3-0.5-N50-0.1	30.48	45.01	33.85	0.68	0.90
BS-250-300-3-0.5-N50-0.3	26.36	45.01	33.85	0.59	0.78
BS-250-300-3-0.5-N50-0.5	23.76	45.01	33.85	0.53	0.70
BS-250-300-3-0.5-N100-0.1	39.60	54.96	38.59	0.72	1.03
BS-250-300-3-0.5-N100-0.3	39.01	54.96	38.59	0.71	1.01
BS-250-300-3-0.5-N100-0.5	34.90	54.96	38.59	0.63	0.90
BS-250-300-3-0.5-N150-0.1	50.25	62.59	42.22	0.80	1.19
BS-250-300-3-0.5-N150-0.3	49.92	62.59	42.22	0.80	1.18
BS-250-300-3-0.5-N150-0.5	45.11	62.59	42.22	0.72	1.07
BS-250-300-3-1.5-N50-0.1	30.23	43.02	33.85	0.70	0.89
BS-250-300-3-1.5-N50-0.3	25.36	43.02	33.85	0.59	0.75
BS-250-300-3-1.5-N50-0.5	23.35	43.02	33.85	0.54	0.69
BS-250-300-3-1.5-N100-0.1	39.91	52.52	38.59	0.76	1.03
BS-250-300-3-1.5-N100-0.3	36.68	52.52	38.59	0.70	0.95
BS-250-300-3-1.5-N100-0.5	31.97	52.52	38.59	0.61	0.83
BS-250-300-3-1.5-N150-0.1	50.89	59.82	42.22	0.85	1.21
BS-250-300-3-1.5-N150-0.3	45.26	59.82	42.22	0.76	1.07
BS-250-300-3-1.5-N150-0.5	39.78	59.82	42.22	0.67	0.94
BS-250-300-3-2.5-N50-0.1	27.23	41.64	33.85	0.65	0.80
BS-250-300-3-2.5-N50-0.3	25.31	41.64	33.85	0.61	0.75
BS-250-300-3-2.5-N50-0.5	23.72	41.64	33.85	0.57	0.70
BS-250-300-3-2.5-N100-0.1	40.10	50.84	38.59	0.79	1.04
BS-250-300-3-2.5-N100-0.3	36.61	50.84	38.59	0.72	0.95
BS-250-300-3-2.5-N100-0.5	31.92	50.84	38.59	0.63	0.83
BS-250-300-3-2.5-N150-0.1	54.60	57.90	42.22	0.94	1.29
BS-250-300-3-2.5-N150-0.3	49.86	57.90	42.22	0.86	1.18
BS-250-300-3-2.5-N150-0.5	42.13	57.90	42.22	0.73	1.00
BS-250-300-4-0.5-N50-0.1	51.16	75.01	55.76	0.68	0.92
BS-250-300-4-0.5-N50-0.3	46.75	75.01	55.76	0.62	0.84
BS-250-300-4-0.5-N50-0.5	44.23	75.01	55.76	0.59	0.79

Specimen	P_{FEA}	P_{NAS}	P_{EC3}	P_{FEA}/P_{NAS}	P_{FEA}/P_{EC3}
BS-250-300-4-0.5-N100-0.1	71.37	90.47	62.84	0.79	1.14
BS-250-300-4-0.5-N100-0.3	68.83	90.47	62.84	0.76	1.10
BS-250-300-4-0.5-N100-0.5	61.27	90.47	62.84	0.68	0.98
BS-250-300-4-0.5-N150-0.1	88.99	102.33	68.28	0.87	1.30
BS-250-300-4-0.5-N150-0.3	81.62	102.33	68.28	0.80	1.20
BS-250-300-4-0.5-N150-0.5	76.93	102.33	68.28	0.75	1.13
BS-250-300-4-1.5-N50-0.1	52.80	72.16	55.76	0.73	0.95
BS-250-300-4-1.5-N50-0.3	46.10	72.16	55.76	0.64	0.83
BS-250-300-4-1.5-N50-0.5	43.92	72.16	55.76	0.61	0.79
BS-250-300-4-1.5-N100-0.1	71.83	87.02	62.84	0.83	1.14
BS-250-300-4-1.5-N100-0.3	66.38	87.02	62.84	0.76	1.06
BS-250-300-4-1.5-N100-0.5	59.14	87.02	62.84	0.68	0.94
BS-250-300-4-1.5-N150-0.1	97.72	98.43	68.28	0.99	1.43
BS-250-300-4-1.5-N150-0.3	80.28	98.43	68.28	0.82	1.18
BS-250-300-4-1.5-N150-0.5	76.28	98.43	68.28	0.77	1.12
BS-250-300-4-2.5-N50-0.1	41.08	70.19	55.76	0.59	0.74
BS-250-300-4-2.5-N50-0.3	40.69	70.19	55.76	0.58	0.73
BS-250-300-4-2.5-N50-0.5	40.46	70.19	55.76	0.58	0.73
BS-250-300-4-2.5-N100-0.1	63.19	84.65	62.84	0.75	1.01
BS-250-300-4-2.5-N100-0.3	60.09	84.65	62.84	0.71	0.96
BS-250-300-4-2.5-N100-0.5	58.17	84.65	62.84	0.69	0.93
BS-250-300-4-2.5-N150-0.1	80.31	95.75	68.28	0.84	1.18
BS-250-300-4-2.5-N150-0.3	72.91	95.75	68.28	0.76	1.07
BS-250-300-4-2.5-N150-0.5	72.24	95.75	68.28	0.75	1.06
			Ave.	0.71	0.97
			Std. dev.	0.15	0.25

7. Conclusions

This study investigated the web crippling behavior of CFS built-up I-beams constructed from two plain channel sections connected through their webs using discrete fasteners. A detailed FE model was developed in ABAQUS and validated against available experimental data from the literature, demonstrating excellent agreement in terms of failure modes and ultimate strengths. The validated model was subsequently employed to conduct an extensive parametric study covering a broad range of geometric and connection-related variables relevant to web crippling design.

The results confirmed that bearing length and section thickness play dominant roles in governing web crippling resistance. Reductions in bearing length resulted in notable decreases in capacity, while increases in wall thickness significantly enhanced resistance to localized crushing and instability. In contrast, increasing the distance between the fastener and the flange for a given web depth consistently reduced web crippling strength, highlighting the importance of fastener placement in facilitating effective load transfer and restraint.

The web crippling strengths predicted using the current North American Specification (AISI S100) and Eurocode provisions (EN 1993-1-3) were evaluated against the FE-based results. The AISI S100 design equations were found to yield predominantly unconservative predictions for the built-up configurations considered, with considerable scatter observed across the investigated parametric range. In contrast, the Eurocode provisions generally produced conservative estimates, although significant variability was still evident. These results indicate that the existing web crippling design provisions, developed primarily for single cold-formed members, are not directly applicable to cold-formed steel built-up I-beams without appropriate modification or calibration to account for the effects of built-up action and load sharing between components.

Overall, the study emphasizes the need for further focused research on built-up CFS members to establish a comprehensive database and to develop improved design provisions that explicitly account for interaction effects and connection details. Such developments are essential to ensure safe, reliable, and economical design of CFS built-up I-beams in practical structural applications.

Acknowledgement

The authors gratefully acknowledge the financial support provided by BITS Pilani under the New Faculty Seed Grant programme (Grant Reference: N5/25/1051).

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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