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Web crippling design of modular construction optimised beams under interior-two-flange (ITF) loading

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Abstract

Modular construction is gaining prominence for its sustainability, speed of assembly, reduced material waste, and cost-effectiveness. Cold-formed steel (CFS) beams, such as the Modular Construction Optimised (MCO) beam, play a vital role in these structures due to their lightweight characteristics, high strength-to-weight ratio, and ease of fabrication. However, the thin-walled geometry of CFS beams introduces challenges in structural design, particularly due to complex buckling and failure modes. The structural behaviour of the MCO beam remains insufficiently explored, with no prior research focusing on its web crippling performance under interior two-flange (ITF) loading. Existing design codes provide equations for estimating web crippling capacity. However, these provisions have been shown to underestimate the actual capacity of complex CFS sections, resulting in overly conservative designs and inefficient material use. To address these limitations, this study investigates the web crippling behaviour of the MCO beam using finite element analysis (FEA). Numerical models were developed and validated against experimental web crippling data from similar beam types. A parametric study involving 162 FE models was conducted to assess the influence of key geometric parameters displaying an average reduction of 27% due to corner radius effects. All models assumed unfastened flanges, reflecting common modular construction practices. Based on the results, new design equations were proposed to improve the accuracy of web crippling capacity predictions, providing a mean value of 1.00 and COV value of 0.08 and 0.07. These findings support the development of more efficient design practices, reduce material overuse, and contribute to the optimisation of lightweight modular steel structures.

Keywords

modular construction optimised beam, web crippling, ITF loading, finite element analysis, design guidelines

Highlights

1. Comprehensive web crippling study of MCO beams under ITF loading
2. 164 FE models assessed design variables: depth, thickness, corner radius
3. An average of 27% reduction was noted with the inclusion of a 3 mm corner radius
4. Exiting design equations were assessed and proved overconservative for the MCO
5. Two design equations were proposed to provide a mean = 1.00 and COV = 0.08 & 0.07

Introduction

Modular construction has secured its spot in the construction industry as a solution to the common constraints of conventional construction methods. It is predicted that modular construction will play a significant role in reducing the UK housing crisis assisting with the construction in over 300,000 new homes (Wendy et al., 2023). Modular construction involves the construction of volumetric units or 'modules' which are developed and manufactured in a factory and transported to site for assembly only. Introducing benefits such as, higher quality control, safer

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working conditions and decreased construction time, making modular construction highly desirable for contractors and developers (Modular Building Institute, 2024). Aside from the UK housing market, commercial and healthcare industry equally benefit from the use of modular construction methods (NHS, 2023). Currently modular construction makes up around 7% of the construction within the UK, whilst in Sweden it is around 80% (Gatheeshgar et al., 2020), identifying that modular construction has large growth potential within the UK, and efforts to introduce its benefits to the UK have been shown within literature (Almashaqbeh and El-Rayes, 2021; Chatzimichailidou and Ma, 2022; Kamali and Hewage, 2016; Lacey et al., 2018). The main challenges to modular construction, however, is the structural efficiency and weight of the 'modules' due to transportation and assembly procedures. Typically, modules are transported to site via heavy goods vehicles and assembled using cranes, making lightweight materials such as CFS distinctly prudent to the modular industry due to providing a high strength-to-weight ratio (Thirunavukkarasu et al., 2021b). Currently, CFS design standards AISI S100 (American Iron and Steel Institute, 2016) and AS/NZS 4600 (Australian/New Zealand Standard, 2018) provide a unified design equation to predict the web crippling capacity of CFS sections whilst BS EN1993-1-3:2024 (British Standards Institution, 2024) provides its own independent equation.

CFS is manufactured in two main ways, cold-forming and press-forming with the chosen manufacturing method depending on the desired section complexity. The potential for complex shapes permitted the CFS industry to develop various innovative cross sectional shapes (Sigma, SupaCee and LiteSteel) which prove to exceed structural capacity of conventional CFS sections such as 'C' and 'Z' sections. CFS members, however, are generally thinner than hot-rolled members which creates complex buckling modes and burdening design processes for structural engineers. These complex buckling modes led to the development of innovative sections and dimension optimisations to reduce slenderness and delay the effects of buckling leading to a design controlled by yield strength rather than critical buckling loads. In addition, hollow flange sections were introduced as a way to reduce the number of free edges and provide torsional rigid flanges which proved to diminish the effects of distortional buckling and proved beneficial for improving flexural capacity (Anapayan et al., 2011; Avery et al., 2000; Keerthan et al., 2014a; Seo and Mahendran, 2011).

The developments within the CFS industry led to the development of a cross section guided towards to the use within modular structures. This section is known as the Modular Construction Optimised beam (MCO) developed by Ha et al. (2016) based upon a 'six sigma' and QFD (quality function deployment) method which proved to reduce floor weights to 0.25 kN/m^2 over a 7.5 m span. The MCO sections utilises triangular hollow flanges with a relatively slender web as shown in Figure 1. Gatheeshgar et al. (2021) performed a numerical study consisting of 126 advance numerical models, exploring the flexural capacity of the MCO section with various depths and thicknesses, choosing section sizes based upon the LiteSteel beam. This study proved that current design standards were unsuitable for the MCO and led to the development and proposal of new design equations based upon the direct strength method (DSM). Additionally, Thirunavukkarasu et al. (2021a) performed a numerical study consisting of 162 advanced numerical models exploring the web crippling capacity of the MCO section under one of the four web crippling failure modes, being ETF (end-two-flange). Similar to Gatheeshgar et al. (2021), Thirunavukkarasu et al. (2021a) proved that existing design equations were inaccurate in predicting the web crippling capacity of the MCO section under end ETF load conditions.

Web crippling failure is a common local failure mode that occurs at point of high concentrated (point) loads or near supports, where localized compressive stresses exceed the web's bearing capacity. Design standards such as the North American Specification (AISI S100) (American Iron and Steel Institute, 2016), Australian/New Zealand standard (AS/NZS 4600) (Australian/New Zealand Standard, 2018), Eurocode 3 part 1-3 (EN1993-1-3, 2024) (British Standards Institution, 2024) and AISI Standard web crippling test method (AISI S909) (American Iron and Steel Institute, 2017) categorise web crippling failure into four modes as shown in Figure 2. These modes are End-Two-Flange (ETF), End-One-Flange (EOF), Interior-Two-Flange (ITF) and finally Interior-One-Flange (IOF).

Previous studies on web crippling capacity have proven the inaccuracy in the existing design equations found

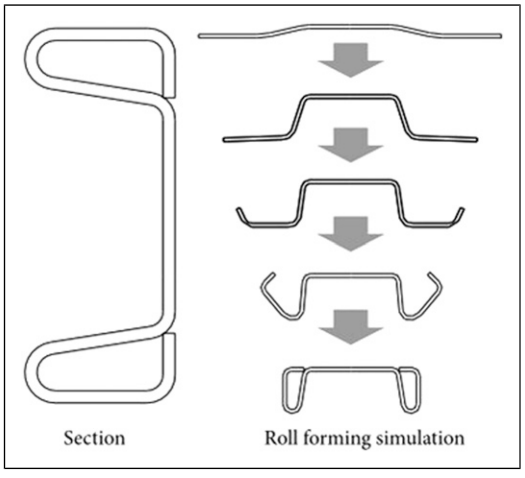

Figure 1. MCO section and roll forming process (Ha et al., 2016).

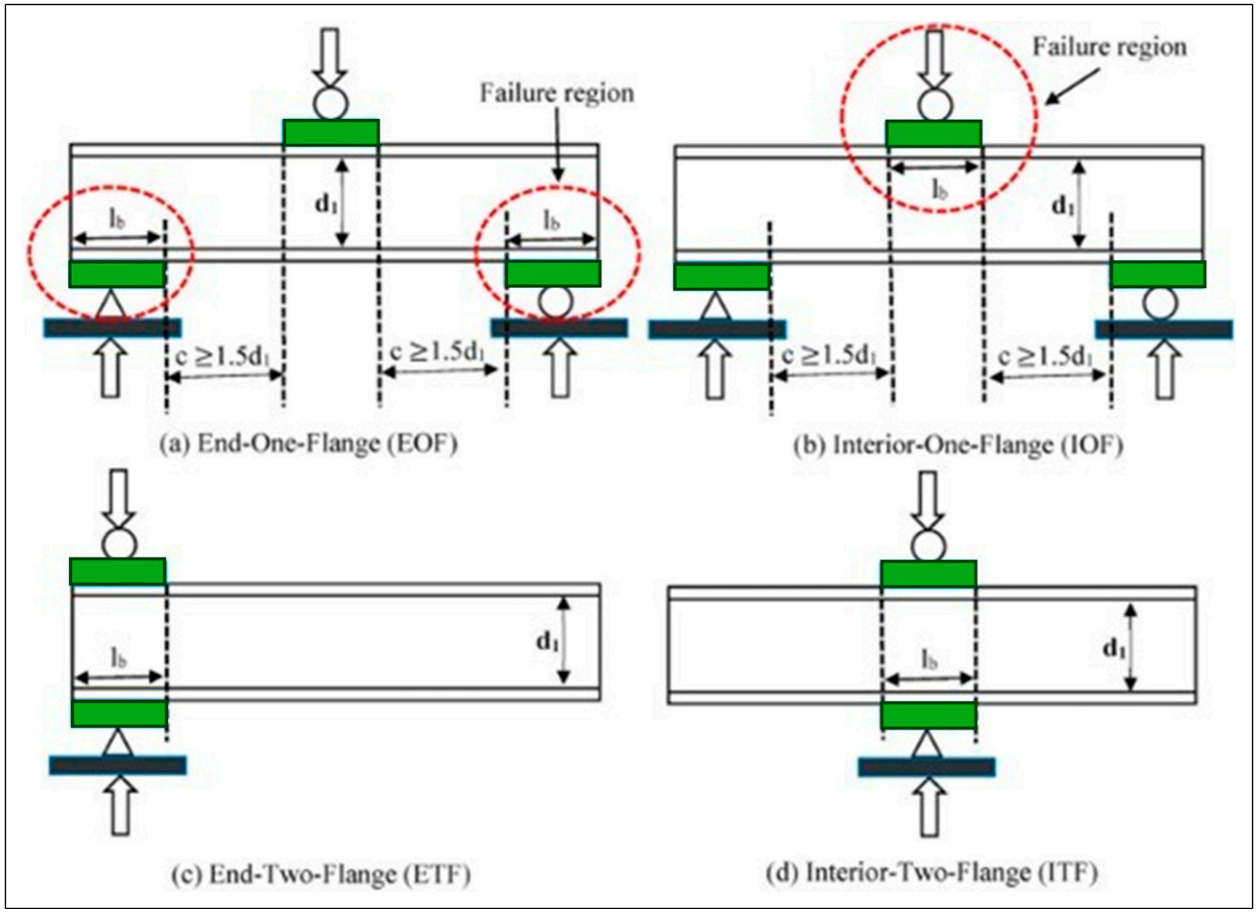

Figure 2. Web crippling failure load case (American Iron and Steel Institute, 2016).

within standards, Sundararajah et al. (2017) performed both experimental and numerical tests on LCB sections under both ITF and ETF loading displaying that AISI S100 (American Iron and Steel Institute, 2016) and AS/NZS 4600 (Australian/New Zealand Standard, 2018) are highly unconservative. Additionally, it was found that the grade of steel (fy) plays a significant role in the web crippling capacity, therefore a new coefficient was added to the unified equation, $1 + C_s\sqrt{\frac{250}{f_y}}$, which proved to increase accuracy. Additionally Elilarasi and Janarthanan (2020) explored the web crippling capacity of LiteSteel beams under ETF load conditions and proposed the use of the following yield strength factor, $1 + C_s\frac{250}{f_y}$ where f_y is the material yield strength. Thirunavukkarasu et al. (2021a) investigated the web crippling capacity of the MCO beam under ETF loading conditions, from this study another factor was proposed $1 - C_h\sqrt{\frac{h}{t_w}}$ where h is the flat depth of the flange. This led to the current design formula equation (1) for the web crippling capacity of CFS beams where C denotes coefficients which vary depending on boundary conditions and geometrical properties.

$$R_b = Ct_w^2 f_y \sin\theta\left(1 - C_r\sqrt{\frac{r_i}{t_w}}\right)\left(1 + C_l\sqrt{\frac{l_b}{t_w}}\right)\left(1 - C_w\sqrt{\frac{d_1}{t_w}}\right)\left(1 + C_f\sqrt{\frac{250}{f_y}}\right)\left(1 - C_h\sqrt{\frac{h}{t_w}}\right) \quad (1)$$

To date, no published research has investigated the web crippling capacity of MCO beams under ITF loading conditions. To address this knowledge gap, this study performs a comprehensive numerical investigation of the web crippling behaviour of the MCO beam under ITF loading with flanges unfastened. Finite Element (FE) models are developed using ABAQUS version 6.26 (ABAQUS, 2020) and validated for similar hollow flange CFS sections. A parametric study of 162 FE models examines the influence of key geometric and material variables, including depth, thickness, bearing length, corner radius and yield strength. Based on the results, two improved design equations are proposed, achieving a Mean value of 1.00 and COV values of 0.08 and 0.07. These

equations aim to improve the reliability and efficiency of MCO beam design under ITF loading, contributing to the advancement of lightweight, high-performance modular structures.

Numerical analysis

This section details the methodology used to develop the FE models of the MCO beam under ITF loading. The nonlinear FE software ABAQUS (ABAQUS, 2020) was chosen, and the FE models were developed to simulate actual experimental set-ups with identical boundary conditions, loading, contacts and material properties.

Model description and element type

The FE models consisted of two main components: the MCO beam and a pair of interior bearing plates, as shown in Figure 3. In accordance with ABAQUS (ABAQUS, 2020) conventions for middle surface offset, the FE models were developed using centreline dimensions. Corner radii of 0 mm and 3 mm were adopted to explore its effects. This modelling setup was also used to replicate the LiteSteel beam (OneSteel Australian Tube Mills (OATM), 2008) tests during the validation process (Keerthan et al., 2014b). Figure 3 illustrates a typical MCO beam section showing centreline dimensions and thicknesses. The overall length was set to be five times the section depth, satisfying the minimum length requirements for ITF loading specified in AISI S909-17 (American Iron and Steel Institute, 2017). Given the slender geometry of the MCO sections, deformable shell elements were selected in ABAQUS (ABAQUS, 2020) to model the beam response. Specifically, the S4R element (general purpose four-node reduced integration shell element) was selected for its accuracy and computational efficiency. The bearing plates were modelled using a four noded R3D4 rigid element. These element types have previously demonstrated good agreement with experimental results (Thirunavukkarasu et al., 2021a; Wang et al., 2023, 2024a, 2024b).

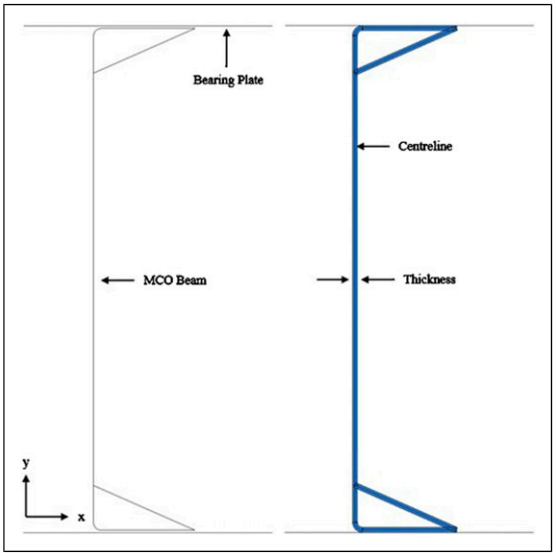

Figure 3. Cross-section of the MCO beam in FE software.

Meshing scheme

Meshing strategies from previous studies (Hareindirasarma et al., 2021; Thirunavukkarasu et al., 2021a) were reviewed to inform the meshing scheme adopted in this study. Figure 4 presents the results of the mesh sensitivity analysis, which highlight variation in output as mesh density is refined. While finer meshes generally yield more accurate results, they can also lead to convergence issues and significantly increased computation time. Based on the sensitivity analysis, a global mesh size of 5 × 5mm was adopted. A finer 1 × 5 mm mesh was applied in the corner regions near the web-flange junctions to capture localised plastic deformations. This meshing scheme provided a suitable balance between accuracy and computational cost. The bearing plates were assigned a course 10 × 10 mm mesh, as they were modelled as rigid elements and do not undergo deformation. The adopted meshing scheme is illustrated in Figure 5(a) and was used consistently throughout both the validation and parametric studies.

Material properties

The MCO beam is a CFS section, standard CFS material properties were adopted in the FE model, including density, Young's modulus, Poisson's ratio and yield strength. Although ABAQUS (ABAQUS, 2020) supports strain hardening, this feature was omitted as web crippling initiates at yield strength and strain hardening has negligible influence on peak capacity. A bilinear elastic-plastic material model was therefore used, defined by the nominal yield strength to represent the stress-strain behaviour of CFS. Young's modulus and Poisson's ratio were taken as 210 GPa and 0.3, respectively (Sifan et al., 2022a, 2022b).

Contact assignment

Bearing plates were positioned at the midspan of the MCO beam, with the top plate serving as the loading plate and the bottom as the support plate. A gap equal to half the beam thickness was introduced between the bearing plates and the beam to prevent overclosure during contact simulation. Surface-to-surface contact was defined between the beam and the bearing plates, with the plates designated as the rigid (master) surfaces and the beam as the deformable (slave) surface, as illustrated in Figure 5(b). Tangential and normal contact behaviour was defined, with a friction coefficient of 0.4 applied using the penalty method to

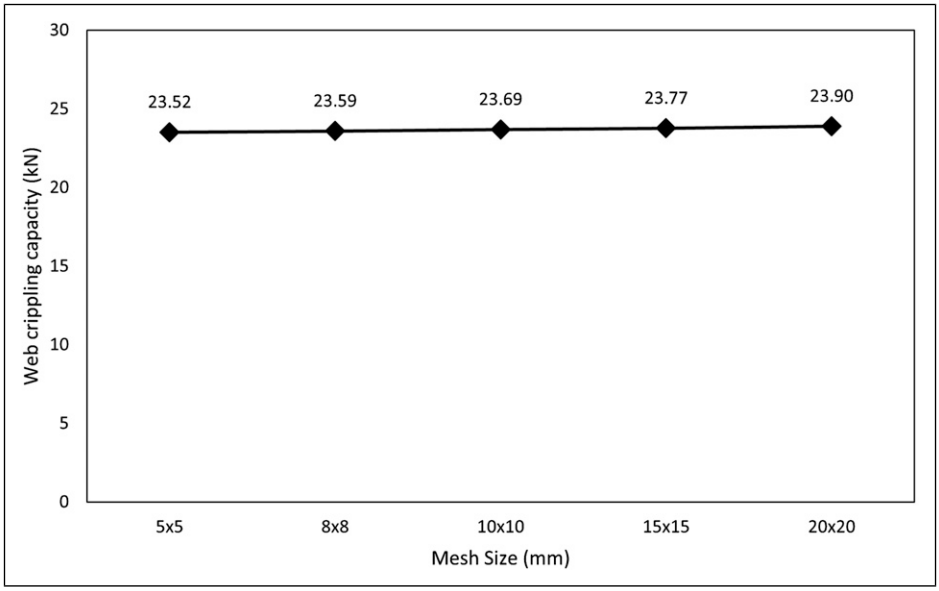

Figure 4. Mesh sensitivity analysis.

reduce the risk of slippage as the flange undergoes rotation under vertical loading.

Loading and boundary conditions

The boundary conditions used within this study were chosen to replicate loading conditions found within experimental studies. Translation about the X & *Z* axis and rotation about Z were restraint to zero for the loading plate, where translation in the Y axis was set to 20 mm. Similarly, for the support plate conditions remain the same with the Y axis also set to zero. This means that loading was applied to the beam using a displacement control approach with a smooth step applied to ensure a steady application of load throughout. The boundary conditions described are presented visually in Figure 5(c).

Analysis method and results extraction

Within ABAQUS (ABAQUS, 2020) there are two solvers available, ABAQUS/Implicit and ABAQUS/Explicit. The ABAQUS/Implicit solver is recommended for smooth nonlinear problems whereas, the ABAQUS/Explicit solver is recommended for dynamic issues. Previous research studies (Natário et al., 2014; Sundararajah et al., 2017; Thirunavukkarasu et al., 2021a) have successfully utilized the ABAQUS/Explicit solver for web crippling of CFS flexural members therefore, it was chosen for this study. It should be noted that, ABAQUS manual (ABAQUS, 2020) states that quasi-static contains a rule of ratio between kinetic energy and internal energy of which should be within 5–10% during the analysis. This was checked for each model upon completion.

The web crippling capacity for the modelled MCO beams within this parametric study was found based upon the load – vertical deflection curve where the peak value was taken as the capacity. It was noticed throughout the parametric study that the hard contact that was assigned between the bearing plate and MCO, was causing noise / fluctuations within the load-displacement curve. Therefore, when needed, the Butterworth filter was used on the graph, with a cut-off frequency of 10. Thirunavukkarasu et al. (2021a) displayed a similar process when investigating the MCO beam under ETF load conditions.

Initial geometric imperfections

Initial geometric imperfections can be neglected for web crippling studies (Thirunavukkarasu et al., 2021a), therefore, imperfection effect was not considered during this parametric study.

Validation of finite element models

Without verification of the methodology used to create and analyse the FE models, the accuracy remains unknown. Therefore experimental data was taken from Keerthan et al. (2014b), who performed a study consisting of 28 specimens to investigate the web crippling capacity of LiteSteel beam sections under ETF and ITF load conditions. As this study focuses on ITF load conditions, 7 tests were chosen to be replicated within ABAQUS (ABAQUS, 2020) using the aforementioned methodology. The section sizes used within this study for the MCO are directly related to the available sizes of the Litesteel beam, therefore this section

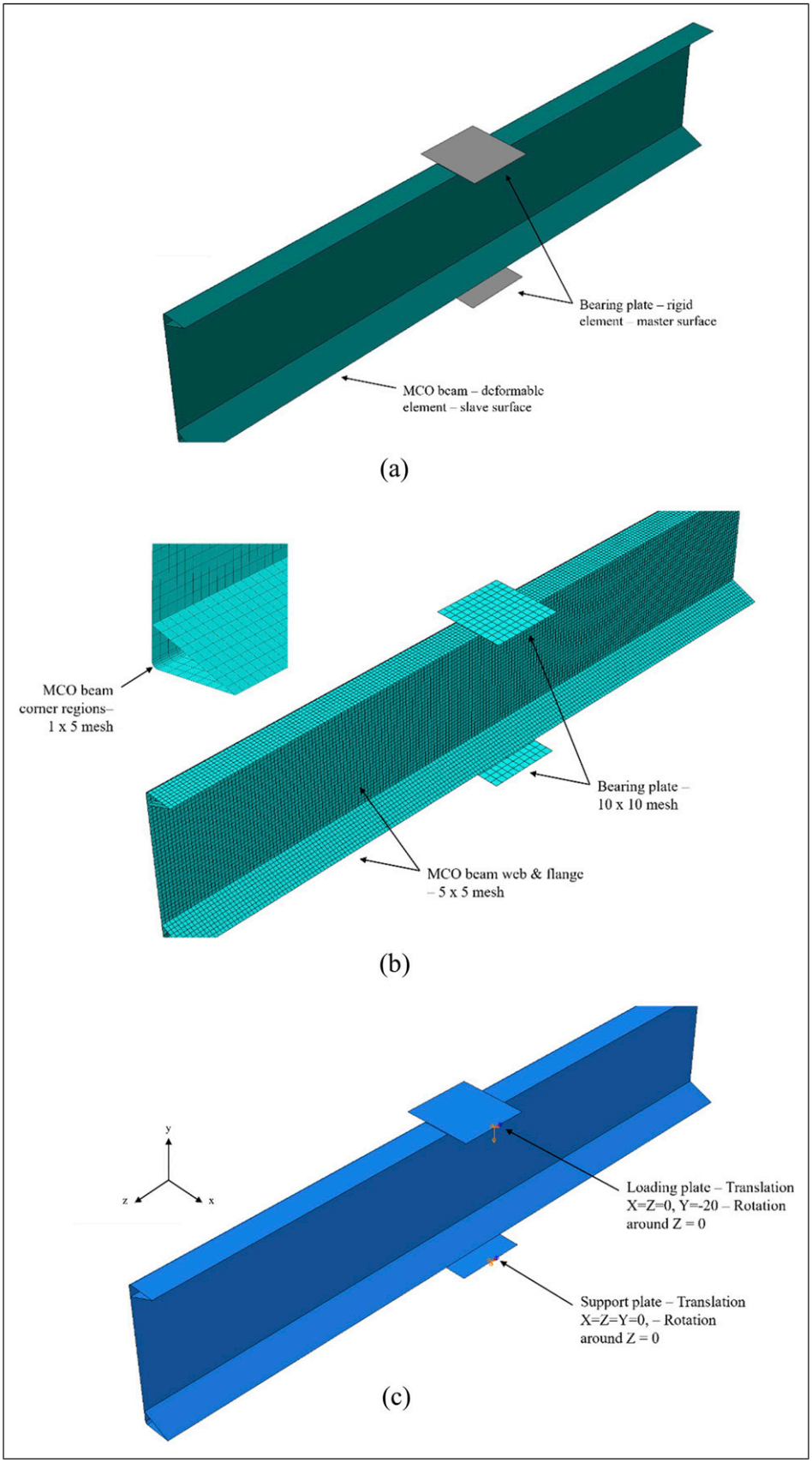

Figure 5. (a) Meshing scheme used in this study, (b) FE assemble and contact assignment, (c) Applied boundary conditions.

was chosen as a means to validate both geometrical shape with hollow-flanges and dimensions.

Table 1 presents the data sets used for the validation and comparison of web crippling capacities under ITF loading for the designated LSB section. The validation process covered three separate section depths (d = 150 mm, 200 mm and 250 mm), flange widths (b_f = 45 mm and 60 mm), flange depths (d_f = 15 mm and 20 mm), thicknesses (t = 1.6 mm, 2.0 mm and 2.5 mm) and finally yield stresses (443.3 MPa, 446.0 MPa, 452.1 MPa and 454.2 MPa). As the validation process covered a large variety of parameters it can be ensured that the developed FE models share similar accuracy. The web crippling capacities under ITF loading obtained from the FE analysis showed an excellent agreement with the experimental results from Keerthan et al. (2014b) with a mean value of 1.01 and a Coefficient of Variation (COV) value of 0.04. In addition, failure mode comparisons were performed between the experimental data from Keerthan et al. (2014b) and the FE models, showing similar characteristics as shown in Figure 6(a) and (b).

Although direct experimental data for MCO beams under ITF loading are currently unavailable, LSBs were used for model validation due to their comparable structural features. Both LSBs and MCO beams are cold-formed hollow-flange sections that exhibit similar local instability behaviour under concentrated transverse loads. In particular, the selected LSB sections share analogous web and flange slenderness characteristics with the MCO profiles studied. Moreover, the LSB tests were conducted under ITF loading conditions with unfastened flanges, directly aligning with the focus of this study. The strong agreement between experimental and numerical results (mean = 1.01, COV = 0.04), along with consistent failure modes, confirms the suitability of the LSB-based validation approach for capturing the web crippling response of MCO beams.

Parametric study

As an extension to the validated FE models, a comprehensive parametric plan was performed to investigate the web crippling behaviour of MCO beams under the ITF load case. The results from the parametric study were used to develop improved design equations based upon current design standards. It is clear from the results that the web crippling capacity relies on cross sectional and strength parameters such as, section depth, thickness and yield strength. In addition, bearing length plays a large role due to the increase in stress as the bearing length is shortened. Unlike common open channel CFS section, the MCO has hollow flanges which introduces flange depth.

This parametric study aimed to cover a wide range of sections depths (150 mm, 200 mm, & 250 mm), thicknesses (1.0 mm, 2.0 mm & 3.0 mm), and finally, inner radius (0 mm & 3 mm) concluding with a total model count of 162 FE models. A bearing plate width of 50 mm, 100 mm, and 150 mm was considered to explore thus effect on the web crippling capacity. The full parametric study of 162 is shown in Table 2. Previous studies have shown that when l_b < 50 mm, flange crushing is likely to occur therefore it was not included in this study (Sundararajah et al., 2017; Thirunavukkarasu et al., 2021a). Yield strengths of 300 MPa, 450 MPa and 600 MPa were considered to account for the range of yield strengths found in normal to high strength CFS.

Results and discussion

The web crippling behaviour of MCO under ITF loading conditions was investigated based on the numerical results of 162 total models. Figure 7 shows figuratively the failure mechanism of the MCO beam under ITF loading, displaying initial loading, pre failure, failure and post failure with reference to the load-vertical displacement graph. As previously discussed, this study observes the MCO under ITF loading therefore, failure is found at the midpoint of the beam. The apex

Table 1. Comparison of experimental and FE web crippling capacities of LSB sections under ITF loading (Keerthan et al., 2014b).

Test no	LSB section	t_w (mm)	d_1 (mm)	f_y (MPa)	l_b (mm)	Test (kN)	FE (kN)	Test/FE
1	150 × 45 × 1.6	1.6	119.3	454.2	50	15.43	16.18	0.95
2	150 × 45 × 1.6	1.6	119.3	454.2	100	16.14	15.37	1.05
3	150 × 45 × 1.6	1.6	118.2	454.2	150	16.91	16.79	1.01
4	200 × 45 × 1.6	1.6	168.5	452.1	100	13.26	13.91	0.95
5	200 × 45 × 1.6	1.6	168.4	452.1	150	14.18	14.11	1.00
6	200 × 60 × 2.5	2.5	160.0	443.3	100	22.48	21.63	1.04
7	250 × 60 × 2.0	2.0	210.0	446.0	50	43.68	41.36	1.06
Mean								1.01
COV								0.04

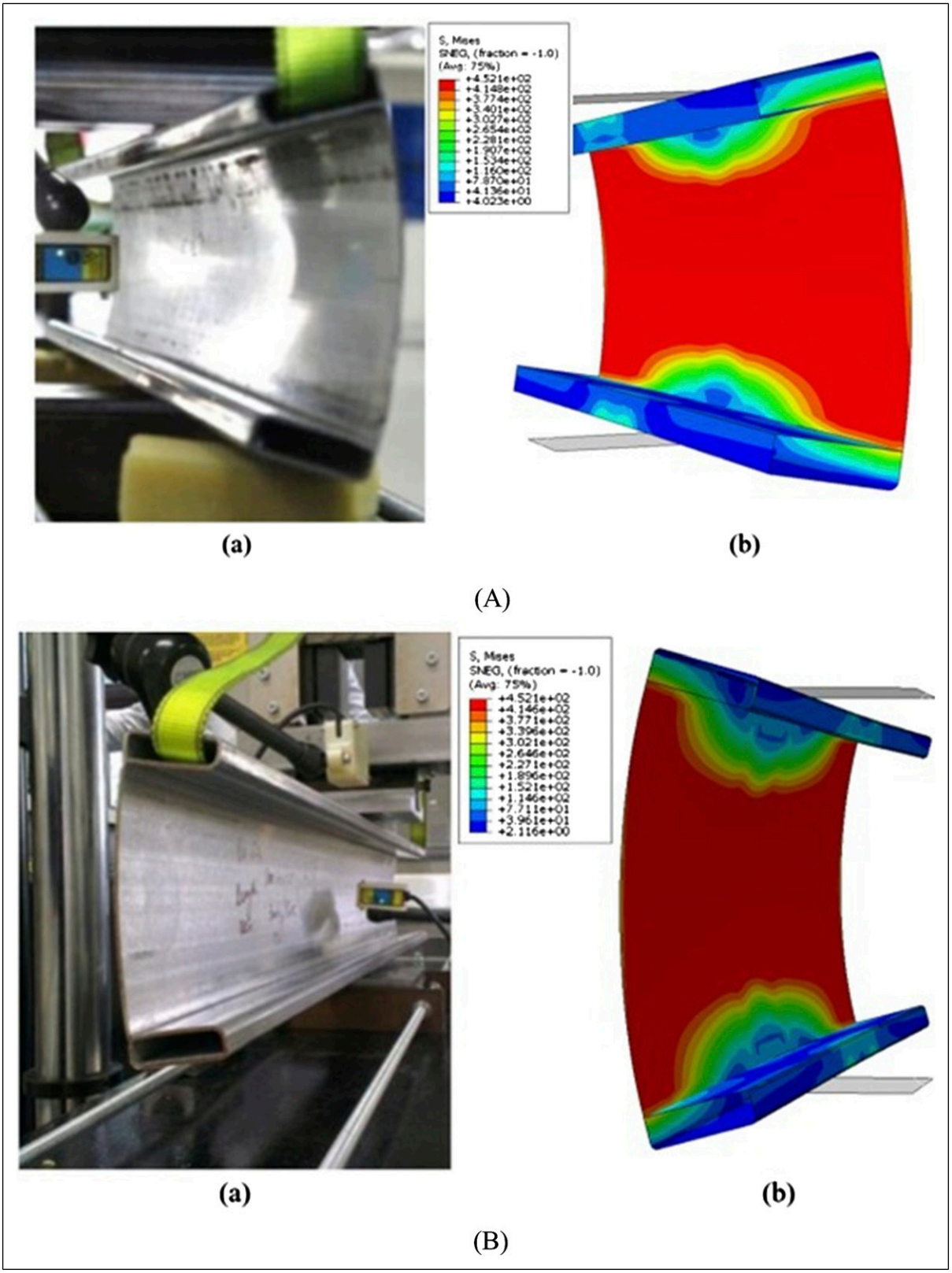

Figure 6. (A) Web crippling failure of 150 × 45 × 2.0 LSB (a) Experiment (b) FE. (B) Web crippling failure of 200 × 60 × 2.5 LSB (a) Experimental (b) FE.

Table 2. Parametric study.

H_w (mm)	W_f (mm)	H_f (mm)	t (mm)	f_y (MPa)	l_b (mm)	r_i (mm)	No. of models
150	45	15	1.0, 2.0, 3.0	300, 450, 600	50, 100, 150	0, 3	54
200	45	15	1.0, 2.0, 3.0	300, 450, 600	50, 100, 150	0, 3	54
250	60	20	1.0, 2.0, 3.0	300, 450, 600	50, 100, 150	0, 3	54
						Total	162

of the graph indicates the ultimate web crippling capacity of the relevant MCO section allowing for an improved understanding of the web crippling behaviour under ITF loading conditions. Tables 3, 4 and 5 display the values for the web crippling capacity of each section alongside the respective reduction due to corner radius effects. It is clear from the results that the corner radius has a direct effect on the web crippling capacity for example, a reduction of 23% between 0 mm and 3 mm radii for 200 mm section with a thickness of 2 mm, yield strength of 450 MPa and bearing length of 150 mm, an average of 27% reduction was noted between all results. Furthermore, it was noted that as the bearing length increases, so does the reduction in web crippling capacity due to corner radii effects. For example, for the 250 mm section with yield strength of 300 MPa and thickness of 3 mm, the reduction due to corner effects increased to 28% at 150 mm bearing length compared to 23% at 50 mm. Figure 8(a) presents graphically the effect of yield strength on the web crippling capacity, which proves a nonlinear relationship between yield strength and web crippling capacity, permitting the use of an additional yield strength factor. Figure 8(b) shows the effect of bearing length and Figure 8(c) displays the effect of web slenderness on the web crippling capacity. All factors displayed are proven to effect the web crippling capacity and are therefore present in the proposed design equations. Flange crushing was present within an insignificant quantity of models, additionally, convergence issues were found and therefore the models were deleted accordingly. A total model count of 14 models out of the 162 were removed from the analysis and it is recommended that experimental tests are performed for these sections, adaptation in the meshing scheme may overcome convergence issues however, was not performed in this study. Thirunavukkarasu et al. (2021a) and Sundararajah et al. (2017) identified the effects of flange crushing within their studies and similarly removed the results accordingly due to the increasing effects of web crippling capacity.

Design approach for MCO beams

AISI S100

As previously mentioned AISI S100 (American Iron and Steel Institute, 2016) and AS/NZS 4600 (Australian/New Zealand Standard, 2018) provide a unified design equation for the web crippling capacity of CFS beams (equation (2)) under all 4 load cases based upon experimental data from Prabakaran and Schuster (1998). Both AISI S100 (American Iron and Steel Institute, 2016) and AS/NZS 4600 (Australian/New Zealand Standard, 2018) provide the same coefficients with the only contrast being symbol notation. The web crippling capacity equation is given in equation (2) and identifies that the web crippling capacity (R_b) is directly dependent on the thickness of the web (t_w), yield stress (f_y), the angle between the web and flange or bearing surface in degrees (θ), corner radius (r_i), bearing length (l_b) and the clear web height (d_1). Where for ITF loading with partially stiffened flanges (torsional stiffness) the coefficient values (denoted C) are C = 24, C_r = 0.52, C_l = 0.15, and C_w = 0.04. The equation shows that web thickness and yield strength have the most significant effect on web crippling capacity.

$$R_b = C t_w^2 f_y \sin\theta \left(1 - C_r \sqrt{\frac{r_i}{t_w}}\right)\left(1 + C_l \sqrt{\frac{l_b}{t_w}}\right)\left(1 - C_w \sqrt{\frac{d_1}{t_w}}\right) \tag{2}$$

Thirunavukkarasu et al. (2021a) noted that it was clear from the results that the web crippling capacity for the MCO beam is highly dependent on the flat flange depth (h). A new design equation was proposed for MCO beams under ETF loading with the new factor and is shown in equation (3) where C = 2.056, C_r = 0.126, C_l = 0.065, C_w = 0.043, C_f = 8.468 and C_h = 0.105. This formula provided a mean and COV value of 1.0 and 0.13 respectively for the MCO under ETF loading (Thirunavukkarasu et al., 2021a) and included the yield strength factor from Elilarasi and Janarthanan (2020).

$$R_b = C t_w^2 f_y \sin\theta \left(1 - C_r \sqrt{\frac{r_i}{t_w}}\right)\left(1 + C_l \sqrt{\frac{l_b}{t_w}}\right)\left(1 - C_w \sqrt{\frac{d_1}{t_w}}\right)\left(1 + C_f \frac{250}{f_y}\right)\left(1 - C_h \sqrt{\frac{h}{t_w}}\right) \tag{3}$$

The suitability of using these two equations for MCO beams under ITF loading was analysed, comparing 148 FE models (14 No models removed due to flange crushing and convergence issues). For equation (2), from AISI S100 (American Iron and Steel Institute, 2016) and AS/NZS 4600 (Australian/New Zealand Standard, 2018) the mean

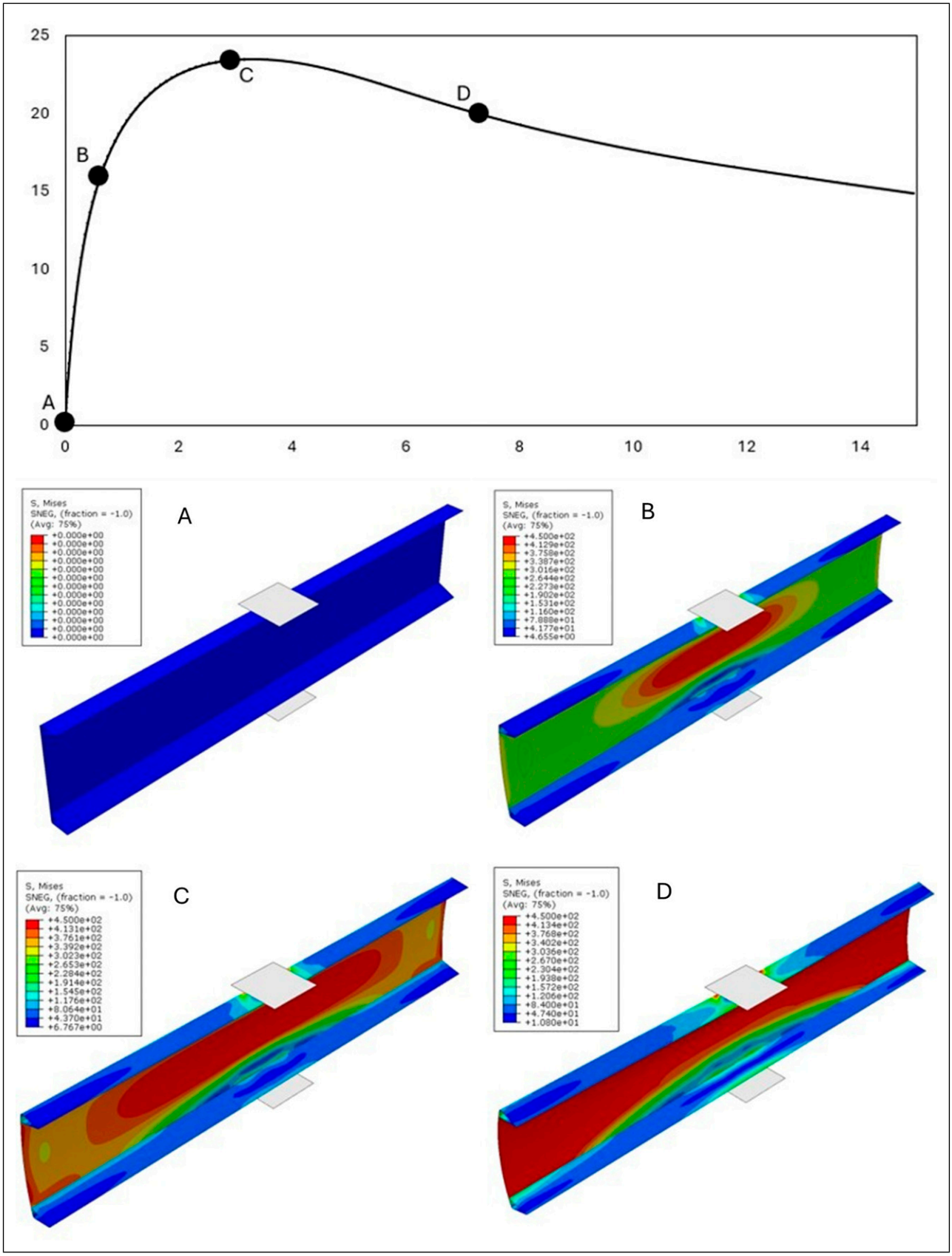

Figure 7. Comparison of failure mode and load-vertical displacement behaviour (Hw = 200 mm, t = 2.0 mm fy = 450 MPa, ri = 3.0 mm and lb = 100 mm).

Table 3. FE ultimate web crippling value of MCO beam (H_w = 150 mm).

						FE (kN)		
H_w (mm)	W_f (mm)	H_f (mm)	f_y (MPa)	t (mm)	l_b (mm)	r_i = 0 (mm)	r_i = 3 (mm)	Reduction due to corner radii
150	45	15	300	1	50	5.53	3.98	28%
150	45	15	300	1	100	6.07	4.00	34%
150	45	15	300	1	150	6.67	4.04	39%
150	45	15	300	2	50	35.55	20.16	43%
150	45	15	300	2	100	39.18	23.19	41%
150	45	15	300	2	150	N/A	23.96	N/A
150	45	15	300	3	50	76.49	N/A	N/A
150	45	15	300	3	100	N/A	59.96	N/A
150	45	15	300	3	150	N/A	62.97	N/A
150	45	15	450	1	50	5.75	4.47	22%
150	45	15	450	1	100	6.06	4.51	26%
150	45	15	450	1	150	6.66	4.57	31%
150	45	15	450	2	50	38.82	26.59	32%
150	45	15	450	2	100	41.80	27.26	35%
150	45	15	450	2	150	44.52	28.13	37%
150	45	15	450	3	50	102.60	64.10	38%
150	45	15	450	3	100	N/A	72.43	N/A
150	45	15	450	3	150	N/A	76.21	N/A
150	45	15	600	1	50	5.94	4.81	19%
150	45	15	600	1	100	6.06	4.87	20%
150	45	15	600	1	150	6.66	4.95	26%
150	45	15	600	2	50	40.12	29.52	26%
150	45	15	600	2	100	42.49	30.16	29%
150	45	15	600	2	150	44.90	31.10	31%
150	45	15	600	3	50	114.80	77.47	33%
150	45	15	600	3	100	N/A	81.52	N/A
150	45	15	600	3	150	N/A	85.91	N/A

Note: H_w – section depth, W_f – flange width, H_f – flange height, t – thickness, f_y – yield strength, l_b – bearing length, r_i – inside corner radius.

value and COV value of the comparison between FE results and equation predictions were 1.29 and 0.61, respectively. This comparison as shown in Figure 9(a) and clearly display the inaccuracy of this equation and concludes with this equation being unsuitable to predict the web crippling capacity of MCO beams under ITF load conditions. Equation (3), with coefficients from Thirunavukkarasu et al. (2021a) was compared and displayed in Figure 9(b), although the given coefficients are based upon ETF loading. The received mean was 0.41 and COV was 0.13 deeming this equation with the corresponding coefficients to be inaccurate although a more linear spread was noted.

An attempt was made to adapt the coefficients found within AISI S100 (American Iron and Steel Institute, 2016) and AS/NZS 4600 (Australian/New Zealand Standard, 2018) to provide more accurate predictions of the web crippling of MCO beams under ITF load conditions using equation (2). A two-step numerical optimization strategy was used to find the appropriate coefficients, Firstly, a genetic algorithm was used to provide an adequate range of coefficients then the Generalised Reduced Gradient (GRG) method to refine the coefficients to provide a mean value of 1.00 and COV as close to 0.00 as possible. From this the following coefficients were found, C = 29.549, C_r = 0.175, C_l = 0.008 and C_w = 0.048, providing a mean of 1.00 and COV of 0.24 although more accurate than the coefficients found within AISI S100 (American Iron and Steel Institute, 2016) and AS/NSZ 4600 (Australian/New Zealand Standard, 2018), equation (2) was deemed to be still inaccurate and further equation optimisations began.

BS EN 1993-1-3:2024

BS EN 1993-1-3:2024 (British Standards Institution, 2024) or commonly referred to as Eurocode 3, provides a design equation for the web crippling capacity of CFS beams with varying coefficients depending on section type, boundary conditions and load case. For stiffened C sections with unfastened supports, equation (3) is to be used. Where, $R_{w,Rd}$ is the web crippling capacity, t is the design thickness, E is the elastic modulus, f_{yb} is the yield strength, h is the

Table 4. FE ultimate web crippling value of MCO beam (H_w = 200 mm).

						FE (kN)		
H_w (mm)	W_f (mm)	H_f (mm)	F_y (MPa)	t (mm)	l_b (mm)	r_i = 0 (mm)	r_i = 3 (mm)	Reduction due to corner radii
200	45	15	300	1	50	4.43	3.41	23%
200	45	15	300	1	100	4.81	3.48	28%
200	45	15	300	1	150	5.23	3.44	34%
200	45	15	300	2	50	27.95	19.91	29%
200	45	15	300	2	100	29.52	20.64	30%
200	45	15	300	2	150	31.26	21.11	32%
200	45	15	300	3	50	71.80	N/A	N/A
200	45	15	300	3	100	82.37	54.04	34%
200	45	15	300	3	150	89.03	56.36	37%
200	45	15	450	1	50	N/A	3.74	N/A
200	45	15	450	1	100	4.82	3.75	22%
200	45	15	450	1	150	5.23	3.76	28%
200	45	15	450	2	50	29.30	23.22	21%
200	45	15	450	2	100	30.09	23.52	22%
200	45	15	450	2	150	31.38	24.01	23%
200	45	15	450	3	50	83.94	61.16	27%
200	45	15	450	3	100	90.00	63.32	30%
200	45	15	450	3	150	95.90	65.80	31%
200	45	15	600	1	50	N/A	4.03	N/A
200	45	15	600	1	100	N/A	4.03	N/A
200	45	15	600	1	150	5.23	4.04	23%
200	45	15	600	2	50	30.58	25.22	18%
200	45	15	600	2	100	31.20	25.52	18%
200	45	15	600	2	150	32.30	26.01	19%
200	45	15	600	3	50	87.82	68.26	22%
200	45	15	600	3	100	92.78	70.00	25%
200	45	15	600	3	150	97.75	72.58	26%

Note: H_w – section depth, W_f – flange width, H_f – flange height, t – thickness, f_y – yield strength, l_b – bearing length, r_i – inside corner radius.

overall depth of the cross sections (unlike previous), r is the internal radius, and l_{sb} is the bearing length. The coefficients represented by k, for stiffened C-sections with unfastened supports under ITF loading were extracted from BS EN 1993-1-3:2024 (British Standards Institution, 2024) to assess the suitability for the MCO, where $k_{0,sb}$ = 1.202, $k_{r,sb}$ = 0.232, $k_{1,sb}$ = 0.000 and $k_{h,sb}$ = 0.051. Results showed that equation (3) estimated the ITF web crippling capacity with a mean of 0.65 and COV of 0.18 displaying a underestimation throughout as shown in Figure 10.

$$R_{w,Rd} = k_{0,sb}.\frac{t^2\sqrt{Ef_{yb}}}{\gamma_{M1}}\left(1 - k_{r,sb}\sqrt{\frac{r}{t}}\right)\left(1 + k_{1,sb}\sqrt{\frac{l_{sb}}{t}}\right)\left(1 - k_{h,sb}\sqrt{\frac{h}{t}}\right) \quad (4)$$

An attempt was made to modify the coefficients given in BS EN 1993-3-1:2024 (British Standards Institution, 2024) to deliver a more accurate prediction, a classic genetic algorithm was used with the GRG method to minimise the COV and provide a mean of 1.00. With this method the following coefficients were found, $k_{0,sb}$ = 1.368, $k_{r,sb}$ = 0.183, $k_{1,sb}$ = 0.005 and $k_{h,sb}$ = 0.042 giving a mean of 1.00 and COV of 0.11. Although more accurate, the proposed coefficients were still deemed inaccurate and further progression was performed.

Proposed equation 1

An attempt was made to adapt the coefficients to provide a more accurate prediction on the web crippling capacity of MCO beams under ITF load conditions using equation (3). Utilising the same methodology as previous, a genetic algorithm was used with the GRG method. With the aim of having a mean value of 1.00 and COV as close to 0.00 as possible, the following coefficients were found, C = 7.886, C_r = 0.187, C_l = 0.01, C_w = 0.039, C_f = 5.625 and C_h = 0.073, providing a mean value of 1.00 and COV of 0.08. Displayed in Figure 11, this equation is deemed accurate for predicting the web crippling capacity of MCO beams under the ITF load conditions.

Table 5. FE ultimate web crippling value of MCO beam (H_w = 250 mm).

						FE (kN)		
H_w (mm)	W_f (mm)	Hf (mm)	f_y (MPa)	t (mm)	l_b (mm)	r_i = 0 (mm)	r_i = 3 (mm)	Reduction due to corner radii
250	60	20	300	1	50	4.70	3.03	36%
250	60	20	300	1	100	5.07	3.03	40%
250	60	20	300	1	150	N/A	3.03	N/A
250	60	20	300	2	50	24.23	18.69	23%
250	60	20	300	2	100	25.70	19.33	25%
250	60	20	300	2	150	27.25	19.54	28%
250	60	20	300	3	50	68.62	N/A	N/A
250	60	20	300	3	100	74.08	52.92	29%
250	60	20	300	3	150	78.75	54.14	31%
250	60	20	450	1	50	4.70	3.28	30%
250	60	20	450	1	100	5.07	3.29	35%
250	60	20	450	1	150	5.55	3.30	41%
250	60	20	450	2	50	25.59	21.39	16%
250	60	20	450	2	100	25.96	21.52	17%
250	60	20	450	2	150	27.24	21.69	20%
250	60	20	450	3	50	74.29	58.95	21%
250	60	20	450	3	100	77.23	60.68	21%
250	60	20	450	3	150	80.83	61.87	23%
250	60	20	600	1	50	4.70	3.55	24%
250	60	20	600	1	100	5.08	3.55	30%
250	60	20	600	1	150	5.55	3.54	36%
250	60	20	600	2	50	26.21	22.79	13%
250	60	20	600	2	100	26.47	22.93	13%
250	60	20	600	2	150	27.24	23.11	15%
250	60	20	600	3	50	74.08	65.28	12%
250	60	20	600	3	100	79.62	66.09	17%
250	60	20	600	3	150	81.88	67.23	18%

Note: H_w – section depth, W_f – flange width, H_f – flange height, t – thickness, f_y – yield strength, l_b – bearing length, r_i – inside corner radius.

Proposed equation 2

A further attempt was made to provide a more accurate prediction of the web crippling capacity of MCO beams under ITF load conditions. An equation developed by Thirunavukkarasu et al. (2021a) was introduced as an accurate method to predict the web crippling capacity of the MCO under ETF load conditions, therefore it was chosen to provide modified coefficients for ITF load conditions. A classic genetic algorithm and GRG method was used to achieve a mean value of 1.00 and minimum COV value. The developed equation is given in equation (5). Where all notations are similar to the previous equations. The proposed equation resulted in a mean value of 1.00 and COV of 0.07 for the FE results-to-predicted capacity ratios as shown in Figure 12. Therefore, equation (5) is deemed appropriate for predicting the web crippling capacity of MCO beams under ITF load conditions. Figure 13 illustrates the accuracy of both proposed equations (1) and (2) in comparison to the unified equation found with modified coefficients for in AISI S100 (American Iron and Steel Institute, 2016).

$$R_b = 161.41 t_w^2 f_y \left[\frac{\left(\left(\frac{l_b}{t_w}\right)^{0.047} \left(\frac{h}{t_w}\right)^{-0.097} \left(\frac{250}{fy}\right)^{0.766} \right)}{\left(1+\frac{r_i}{t_w}\right)^{0.295} \left(\frac{d_1}{t_w}\right)^{0.402}} \right] \quad (5)$$

Reliability analysis

The reduction factors for the two proposed equations were calculated based on their mean and COV values using equation (4) with a reliability index (β_0) of 2.5, and C equal to 1.521 as stated within AISI S100 (American Iron and Steel Institute, 2016). M_m and V_m are the mean and COV of the material factor being 1.1 and 0.1 respectively. Furthermore, F_m and V_f are the mean and COV of the fabrication factor being 1.0 and 0.05 respectively. V_q represents the COV of load effects which depends on the ratio between dead and live loading, from AISI S100 (American Iron and Steel Institute, 2016) this value was derived to be 0.21. C_p is the correction factor and is calculated as $\left[1+\frac{1}{N}\right]\left[\frac{m}{m-2}\right]$ where N is the number of FE tests conducted, and

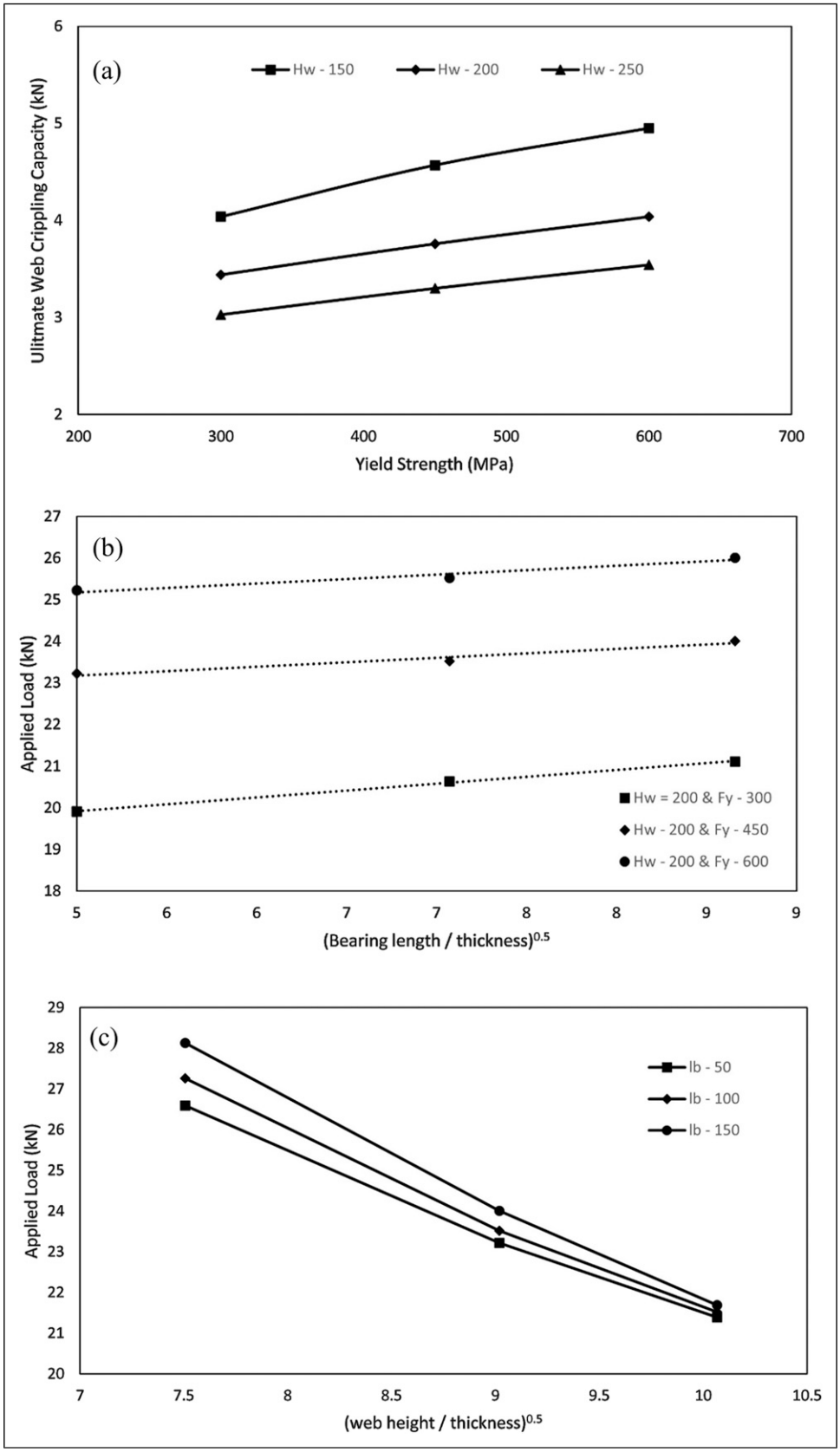

Figure 8. (a) Strength effect on web crippling capacity of MCO beams, (b) Bearing length effect on web crippling capacity of MCO beams, (c) Web slenderness effect on web crippling capacity of MCO beams.

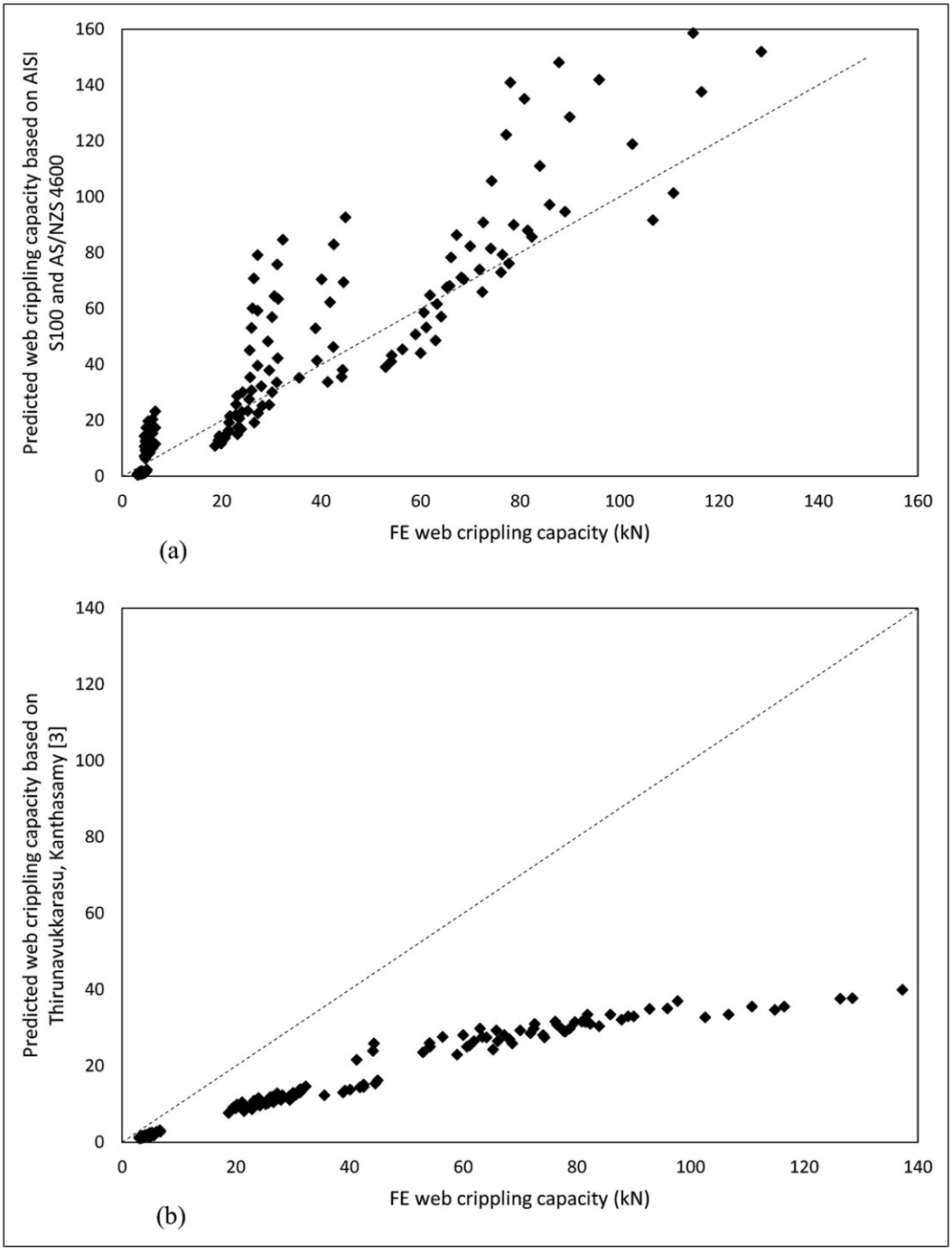

Figure 9. (a) Comparison of FE parametric results and AISI S100 unified equation (American Iron and Steel Institute, 2016; Australian/New Zealand Standard, 2018). (b) Comparison of FE parametric results and (Thirunavukkarasu et al., 2021a).

m is the degree of freedom identified as N − 1. P_m and V_p are the mean and COV of the FE values to predicted values from the proposed equation. Equations (3) and (5) proposed in this study to predict the web crippling capacity of MCO beams under ITF load conditions gave a resistance factor value of 0.89 and 0.90 respectively calculated using equation (6). The application limits based upon the performed parametric study for both proposed equations (3) and (5) are $0 \le \frac{r_i}{t_w} \le 3, 16.67 \le \frac{l_b}{t_w} \le 150, 36.3 \le \frac{d_1}{t_w} \le 206.3$ *and* $4.5 \le \frac{h}{t_w} \le 24$ and is only applicable to the MCO section.

$$\varphi_w = CM_m F_m P_m e^{-\beta_0 \sqrt{\left\{V_m^2 + V_f^2 + C_p V_p^2 + V_q^2\right\}}} \quad (6)$$

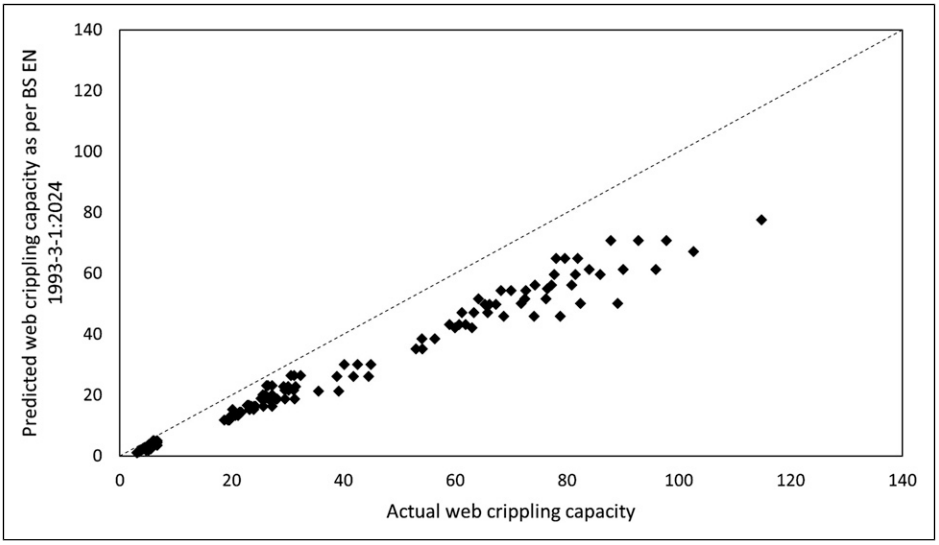

Figure 10. Comparison of FE parametric results and BS EN 1993-3-1:2024 (British Standards Institution, 2024).

Comparison of web crippling capacity between the MCO and LCB

A numerical study was performed to compare the web crippling capacity of MCO beams with LCB of the same coil length. This study was performed using the same modelling process presented in this paper and under the same load case, being ITF with unfastened flanges. Two coil lengths of 388 and 514 mm, and thicknesses of 1,2 and 3 mm were chosen to be compared whilst the yield strength and corner radius was kept constant at 450 MPa and 3 mm respectively. For the LCB sections, it was chosen to choose two sections that are readily available in industry. METSEC (2024) have a range of available LCB sizes and for this study the 232C and 302C designated sections were chosen.

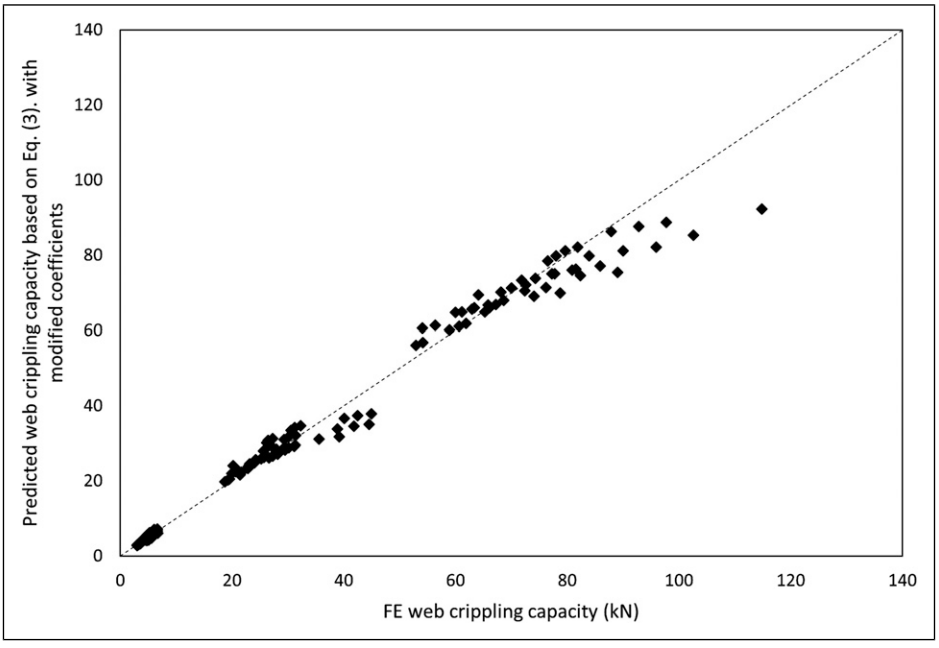

Figure 11. Comparison of FE parametric results and equation (3) with modified coefficients.

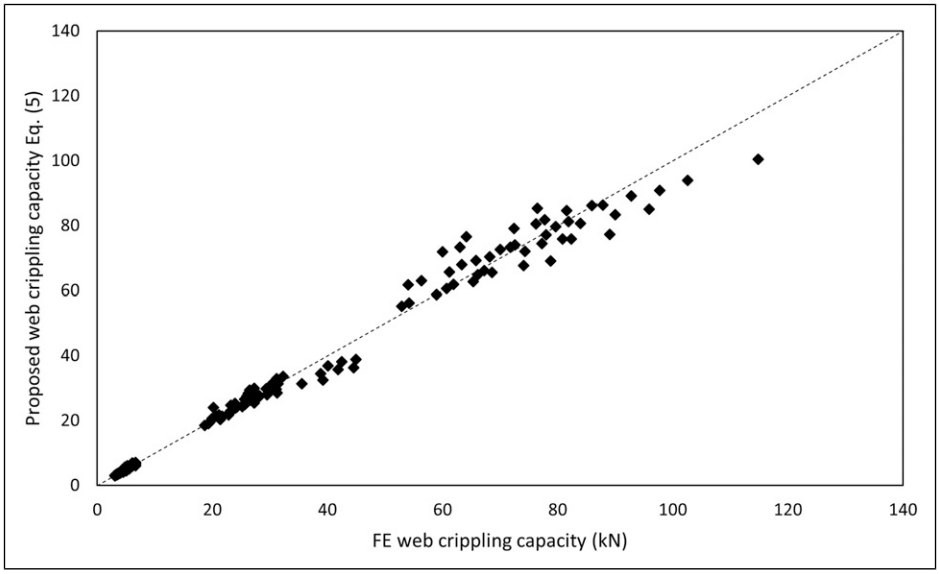

Figure 12. Comparison of FE parametric results and equation (5) with modified coefficients.

The results displayed that as slenderness (h/t) decreases, the increase in web crippling capacity of the MCO is more apparent. A maximum increase of 29% was noted of the MCO in comparison to the LCB with the same coil length, minimum of 5% and an average increase of 16%. Figure 14(a) displays the results for a coil length of 388 mm and Figure 14(b) displays the results for a coil length of 514 mm it should be noted that all comparisons presented an increase in capacity using the MCO over the LCB.

Future research recommendations

The improved design equations developed in this study offer a more accurate prediction of the web crippling capacity of MCO beams under ITF loading. For practicing

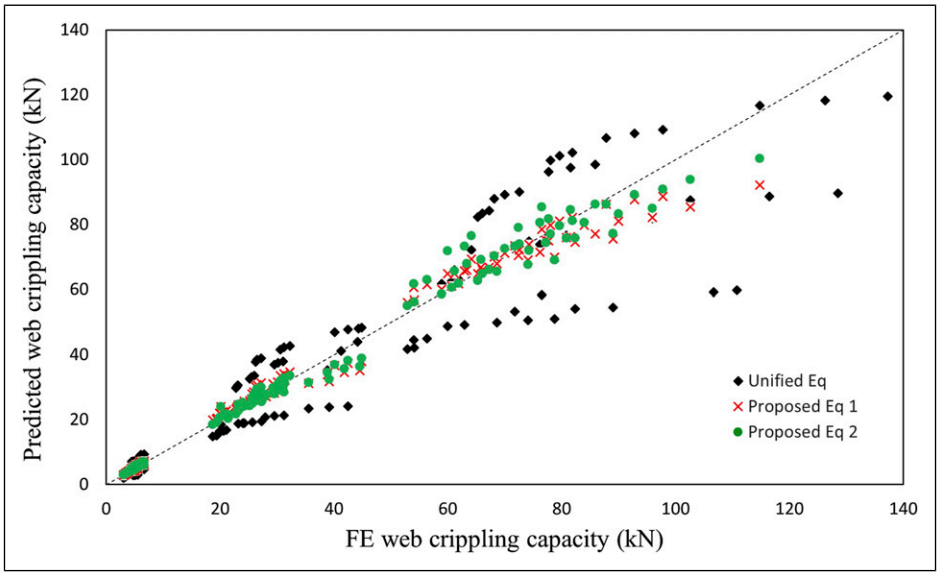

Figure 13. Comparison of FE parametric results and, AISI S100 unified equation with modified coefficients (American Iron and Steel Institute, 2016; Australian/New Zealand Standard, 2018), Proposed equation 1 and Proposed equation 2.

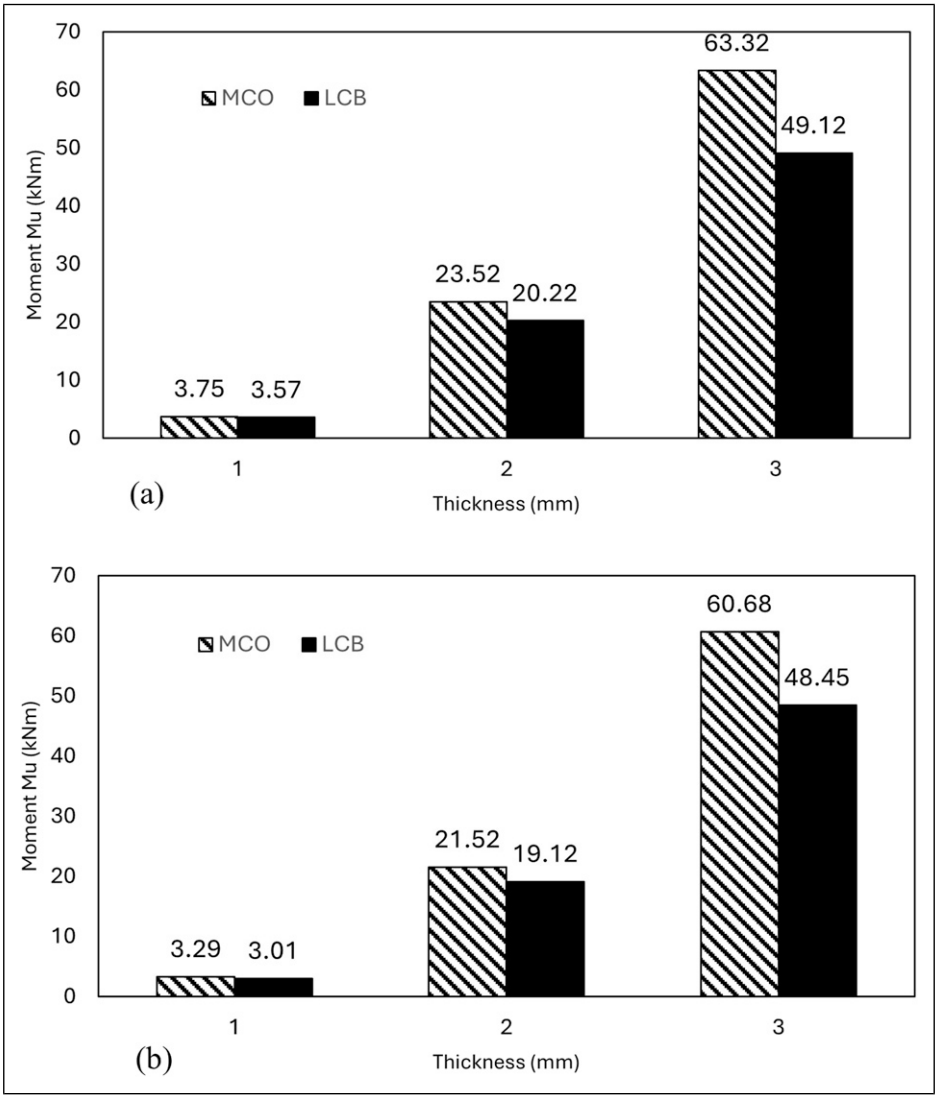

Figure 14. (a) Web crippling capacity vs thickness, coil length = 388 mm, yield strength = 450 MPa. (b) Web crippling capacity vs thickness, coil length = 514 mm, yield strength = 450 MPa.

engineers, these equations can be integrated into their designs to help optimise material use, reduce unnecessary conservatism, and enhance the sustainability of modular construction.

Conclusion

This paper presented the investigation into the web crippling behaviour of MCO beams under the ITF load condition. FE numerical analysis was undertaken to perform the investigation with a validation process completed to ensure the accuracy of the numerical models. A total model count of 164 FE models was developed. The effect of yield strength, corner radii and geometrical properties was investigated to get a wide range of results. It was deemed throughout this paper that current design standards are inaccurate in predicting the web crippling capacity of MCO beams under the ITF load conditions and new coefficients were proposed to improve their accuracy. Based on the study, the following conclusions are made:

1. The developed FE methodology demonstrated a strong agreement with past experimental data, with an overall mean of 1.01 and COV of 0.04. This confirms the accuracy of the numerical models.
2. An extensive parametric study examined how varying parameters effect the web crippling capacity of MCO section under ITF load conditions. The results indicated that web height, flange width,

thickness, yield strength and bearing length all effect the web crippling capacity. An average reduction is 27% was noted due to corner radii effects.
3. The results from the parametric study were compared against the design equation from current standards and proved to be inaccurate in predicting. Therefore, two new design equations were proposed with new coefficients for ITF loading with unfixed supports to prevent over conservatism in design. The developed design equations successfully predicted the web crippling capacity of MCO sections under ITF loading with a mean value of 1.00 and COV of 0.08 & 0.07 based upon 150 FE models and two justified design methodologies.
4. These equations proposed within this paper can be used by structural engineers and design software to accurately predict the web crippling capacity of MCO beams under ITF load conditions with unfastened flanges.

This study is limited to numerical FE models only, although validated against experimental results on the LiteSteel beam, it is recommended that experimental studies are performed to provide further justification for the proposed equations. The authors welcome collaboration in performing experimental tests under the guidance of AISI S909-17 (American Iron and Steel Institute, 2017) to further validate the FE methodology and results presented in this paper. Additionally, this study has utilized quasi-static loading, a further assessment would need to be done to investigate the MCOs behaviour under dynamic or cyclic loading. Furthermore, environmental or fatigue effects have not been considered. As of current, including this paper, two of the four categories of web crippling loading have been investigated. It would be prudent to investigate the remaining load cases being IOF and EOF to gain a full set of coefficients for the MCO section.

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Data Availability Statement

Data will be made available upon request.

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