Web Crippling Behaviour of Aluminium Sigma Sections: One Flange Load Cases

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Abstract: Aluminium is recognized as a suitable material which is highly sustainable and needs less energy consumption to replace conventional materials such as steel, timber, and concrete in relevant areas of construction. However, aluminium has drawbacks such as low elastic modulus, low strength, and stability issues. To rectify the issues, researches are ongoing to introduce innovations or optimizations. Hence, various innovative sections including sigma sections have been introduced to enhance the structural capabilities of Cold-Formed (CF) aluminium structures. However, the new sections could be vulnerable to web crippling due to addition of longitudinal stiffeners which helps to improve shear and bending capacities. This paper intends to analyze the web crippling behaviour of aluminium sigma sections under one-flange load cases and provide design guidelines. On that note, comprehensive numerical analysis with the aid of ABAQUS CAE, was opted. Based on the industry demands, section properties were considered, and the results compared with the existing design equations, and finally, new modified design equations were proposed.
Keywords: Aluminium; Cold-Formed; Sigma sections; Web crippling; Numerical analysis; One-flange load case.

Introduction

Cold-Formed (CF) aluminium structures have emerged in the past two decades considering their advantages such as lightweight, corrosion resistance and high strength to weight ratio. Their applications as load carrying structures have been increased in the industry considering the sustainability aspects required. In addition, the CF method ensures that different section profiles can be introduced to the aluminium industry to enhance the structural ability of aluminium sections. Accordingly, numerous section profiles including Lipped Channel Beam (LCB), sigma section, hollow flange section, SupaCee and folded flange sections have been introduced in the industry. Researches have been ongoing from the past decade to enhance the structural ability of aluminium sections in terms of bending, shear, and web crippling. Although large number of researches have been focused on the improvement of structural abilities of the aluminium sections especially on bending and shear, due to their low elastic modulus compared to CF carbon steel and stainless steel, it is necessary to focus on their severe vulnerability against buckling scenarios

including web crippling.
Web crippling is defined as the failure in the web of the section due to the high concentrated loads on the section and the failure is categorized as four types (1) End Two Flange (ETF); (2) End One Flange (EOF); (3) Interior Two Flange (ITF) and (4) Interior One Flange (IOF) according to AISI S100 [1] considering the load applications and boundary conditions which replicated the actual conditions.

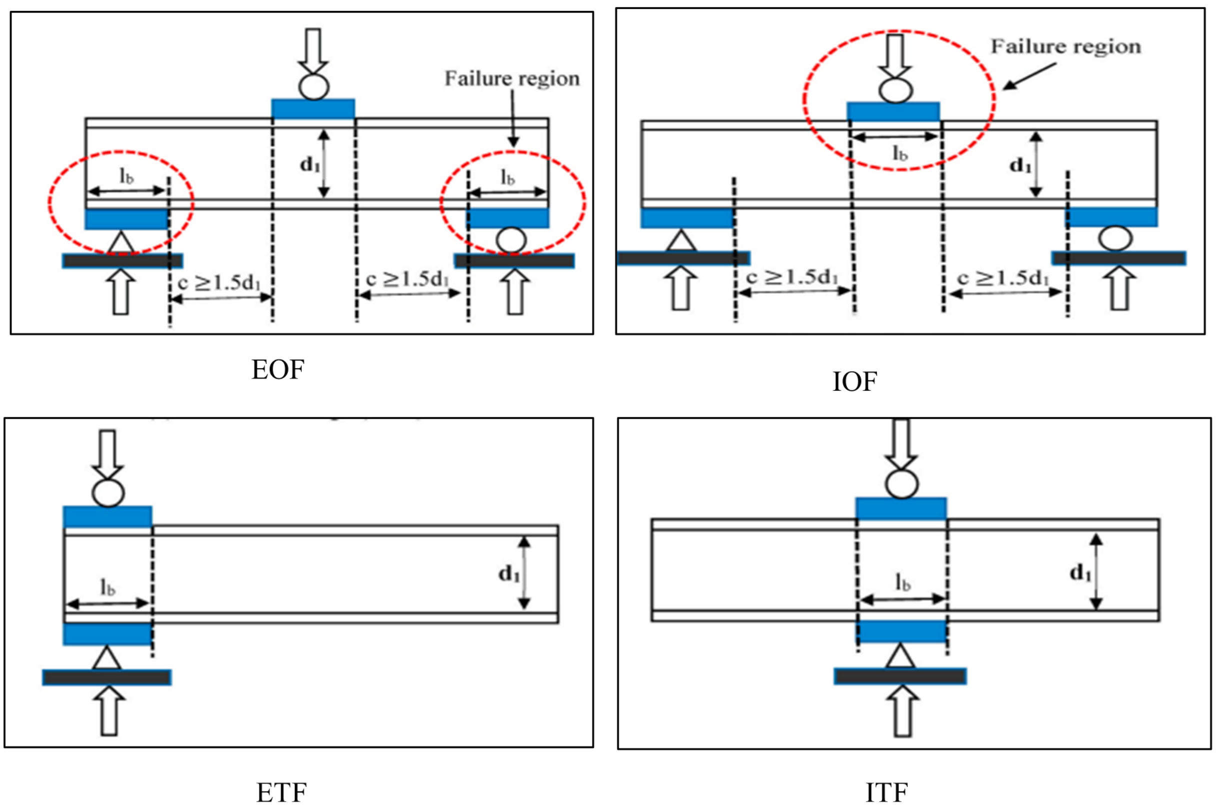


Figure 1: Web crippling failure types [2]

Figure 1 illustrates the web crippling failure types [2]. Researches have been carried out on different sections to find out the ultimate web crippling strength and design equations have been proposed by many researchers [3-6]. However, due to their empirical nature of proposed web crippling equations, for each new profile, experimental and numerical analysis have to be carried out to propose a design equation to predict its ultimate web crippling capacity.
Chen et al. [3] investigated the web crippling behaviour of aluminium tubular sections. Both experimental and numerical approach was followed for all web crippling failure types and the design equations were proposed. Similarly, Su and Young [4] experimentally and numerically analysed the web crippling performance of aluminium square and hollow sections and proposed new design provisions based on the results obtained from the studies. Later, Husam et al. [5-6] investigated the web

crippling behaviour of aluminium LCBs under one flange loading conditions for both stiffened and unstiffened flanges. The investigation was comprised of experimental and numerical approach and Husam et al. [5-6] compared the results with existing design standards such as AS/NZS 1664.1 [7], AS/NZS 4600 [8] and Eurocode 3 [9] and modified the existing equations to predict the web crippling capacity of aluminium LCBs under one flange loading conditions for both stiffened and unstiffened flanges.

Sigma sections are one of the innovative section profiles that have the capability of providing numerous benefits including enhanced stiffness compared to conventional CF sections. However, due to the lack of research studies conducted in regard to its web-crippling performances, the structural capabilities of sigma sections are not fully utilized. Hence, this paper intends to numerically investigate the web crippling behaviour of aluminium sigma sections under one flange loading conditions.

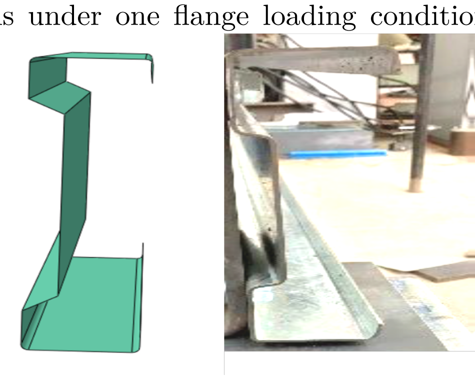


Figure 2: Sigma section profile and numerical model

Numerical Approach

The numerical model approach was opted in the study to explore the web crippling behaviour of aluminium sigma sections under EOF and IOF loading conditions. ABAQUS CAE [10] was employed as a Finite Element (FE) modelling and Analysis (FEA) software. Overall, three structural elements (1) sigma section; (2) loading/ supporting plate (bearing plate) and (3) web side plate were modelled and then assembled according to the actual loading setup. Figure 2 presents the actual and FE model of sigma section.

Deformable S4R element type was chosen for sigma sections while rigid R3D4 element type was employed to model loading/support plates and web side plates. S4R element was opted to allow finite stains in the sections while R3D4 was chosen to make them stiffer and not to fail during the loading. To increase the accuracy and maintain a sensible computational time 5 mm x 5 mm and 5 mm x 1 mm mesh schemes was opted for the flat and corner portions of the aluminium sigma section, respectively. A finer mesh is necessary in the corner regions to transmit the internal stresses properly from the flanges to web and similar mesh scheme was opted in previous numerical studies as well [11-17]. 10 mm x 10 mm mesh scheme was chosen for bearing plates and web side plates as a coarser mesh size in bearing plates will not affect the results.

Material properties of aluminium sections were chosen based on similar numerical studies [11-12]. On that note, stress-strain behaviour of aluminium sigma section was represented by the bilinear continuous strength method. This method was employed in past researches [11-12] due to the excellent representation of material behaviour. In addition, density and elastic modules of the aluminium sigma sections were fixed as $2100 kg/m^3$ and 70,000 MPa, respectively.

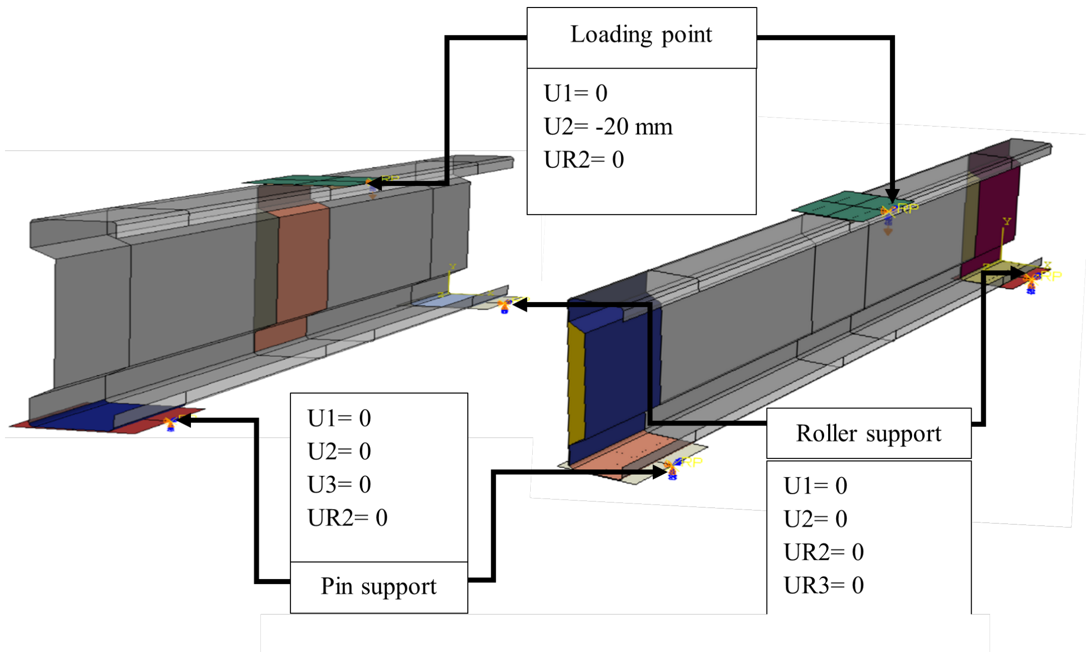
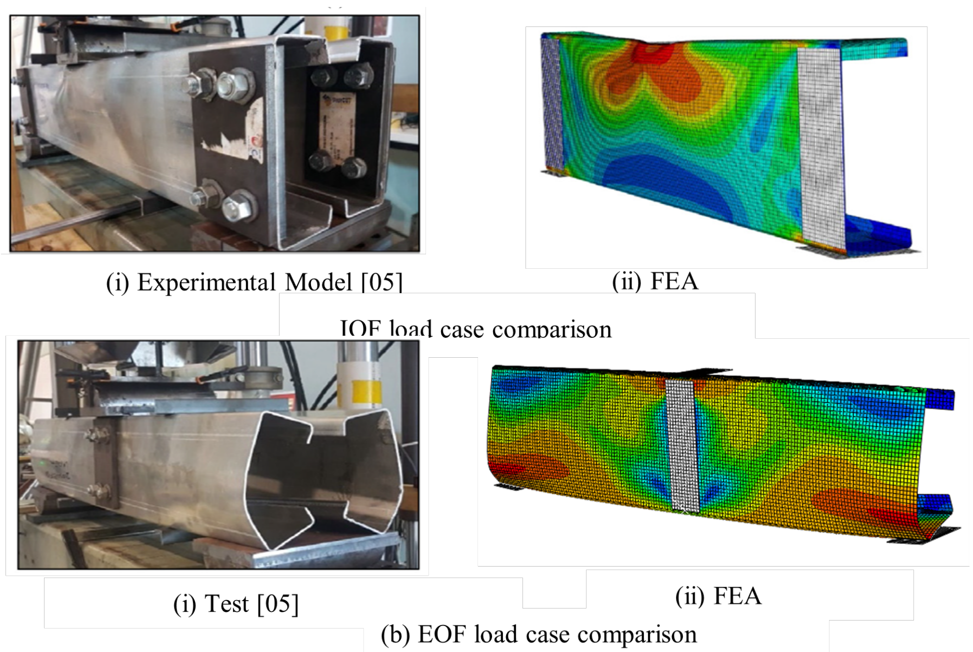


Figure 3:Boundary conditions for EOF and IOF load case

To replicate the actual loading scenario, contact method between the sigma section and bearing plate and web side plates has to be applied. Hence, surface to surface contact method was employed between the flange and bearing plates where the bearing plate surface was assigned as master surface and sigma sections flange was fixed as slave surface. Formulation of the contact was determined as Hard contact along with a penalty method to produce efficient solutions in the analysis. The friction coefficient value was defined as 0.4 between the contact surfaces to avoid any frictional slips. Web side plates were connected with the sigma sections web with Tie constraint to replicate the actual web stiffeners.

Loading and boundary conditions of assembled models were defined according to the experimental conditions. Reference points were assigned to apply the boundary conditions and similar boundary conditions were applied for both EOF and IOF load cases. Pin and roller boundary conditions were applied on the supporting plates. Loading of 20 mm/s with smooth step amplitude was applied on the loading plate based on the previous studies [18-19]. Figure 3 describes the boundary conditions applied on the models for both EOF and IOF load cases.

ABAQUS/Explicit analysis method was employed in this study for its proven credibility of being efficient in solving quasi-static problems [11-12]. In addition, the effect of geometrical imperfection was neglected in this study based on similar studies [2, 11-12] as the effect is negligible.



Failure load comparisons with experimental studies [5]

Validation and Parametric Plan

Validation

To check the reliability of the numerical models, the verification process was conducted with experiment studies. Hence, experiment studies on CF aluminium LCBs by Husam et al. [5] were considered for validation study. The numerical models were generated and validated with experiment results. Comparisons indicated that numerical models were coordinated well with the experimental results under IOF and EOF loading conditions. Figure 4 illustrates the failure pattern comparison of experimental and numerical studies. Table 1 and Table 2 present the ultimate web crippling capacity comparison between experiment and FE analysis. The mean and COV (coefficient of Variation) values of the comparison was 1.0 and 0.05 for EOF load case and 1.0 and 0.03 for IOF load case.

All three comparisons: ultimate web crippling capacity, failure pattern and load vs displacement were satisfactory and based on the successful comparison of numerical model with experimental results, proposed numerical approach was opted to carry out the parametric plan to analyse the web crippling behaviour of aluminium sections under one flange loading conditions.

Parametric plan

This parametric study intends to analyse the web crippling behaviour under one flange conditions. On that note, key parameters such as section depth, thickness, yield strength, radius, and bearing length were selected based on the previous studies [10-12]. Two section depths (140 mm, and 200 mm), three thicknesses (1 mm, 2 mm, and 3 mm), two different yield strengths (180 MPa and 220

Table 1:Ultimate web crippling capacity comparison under EOF load case - FE vs Experiment [5]

No.	Section	d (mm)	t (mm)	b_f (mm)	r_i (mm)	f_y (Mpa)	Bearing length (mm)	Rb, Exp (kN)	Rb, FE (kN)	Test/FEA
1	20025-N100	207.3	2.43	74.3	5.00	214	100	8.26	8.41	0.98
2	10030-N25	107.3	2.95	60.4	4.88	210	25	12.26	12.17	1.01
3	20030-N150	208.3	2.89	73.5	5.00	212	150	12.17	13.05	0.93
4	10030-N50	106.5	2.95	58.4	5.00	210	50	10.20	10.50	0.97
5	15030-N50	157.6	2.93	63.3	5.00	206	50	10.75	10.49	1.02
6	20030-N50	208.4	2.90	73.0	5.00	212	50	12.11	11.30	1.07
7	15030-N100	158.3	2.92	63.5	5.13	206	100	12.29	11.95	1.03
Mean										1.00
COV										0.05

MPa), three radii (3 mm, 5 mm, and 7 mm) and three bearing lengths (50 mm, 100 mm, and 150 mm) were included in the parametric plan. Table 3 presents the details of the parametric plan for both load cases. Overall, 216 numerical models were generated for both load cases.

Note: Rb,Exp - Web crippling capacity obtained in experiment; Rb, FE- Web crippling capacity obtained in FE analysis.

Table 2: Web crippling strength comparison under IOF load case- FEA vs Test [5]

Specimen	No.	d (mm)	t (mm)	b_f (mm)	r_i (mm)	Bearing Length, l_b (mm)	Yield Strength, f_y (MPa)	Test (kN)	FEA (kN)	Test / FEA
IOF-15030	1	156.7	2.92	62.4	4.88	50	206	18.63	17.61	1.06
	2	156.2	2.92	62.1	4.75	100	206	22.22	21.88	1.02
	3	156.6	2.93	62.5	4.88	150	206	24.3	24.5	0.99
IOF-20030	4	206.5	2.90	74.4	4.75	100	212	22.56	22	1.03
	5	206.5	2.89	74.5	4.63	150	212	25.29	25.42	0.99
IOF-20025	6	207.2	2.44	73.3	4.88	50	214	13.77	12.91	1.07
	7	207.3	2.43	73.9	5.00	100	214	16.15	15.66	1.03
	8	207.4	2.44	73.4	4.63	150	214	18.2	18.65	0.98
Mean										1.02
COV										0.03

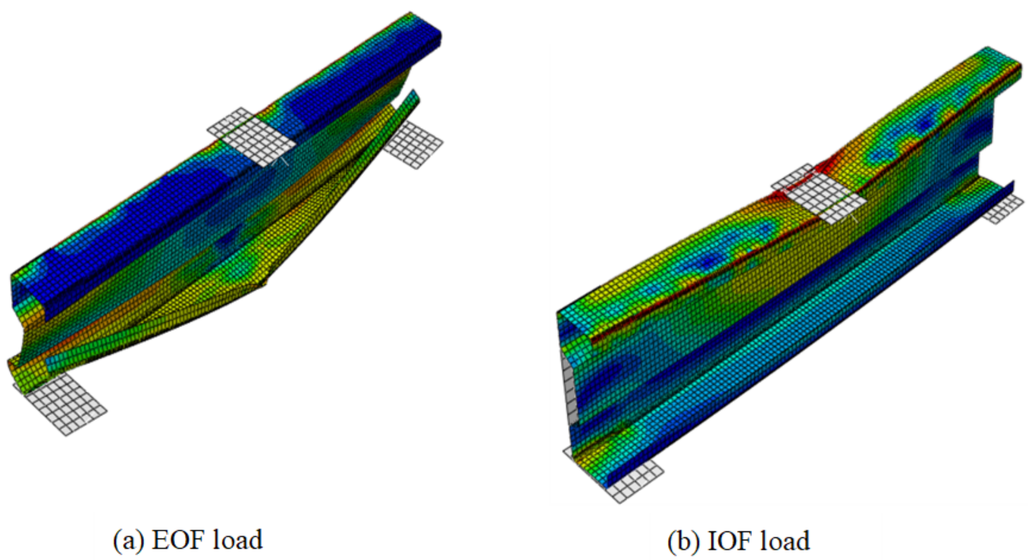


Figure 5: Failure type patterns of aluminium sigma sections under one flange loading conditions.

Table 3: Outline of parametric plan

Load cases	Material Grade	0.2% Proof Strength (MPa)	Ultimate Yield Strength (MPa)	Section Depth (mm)	Thickness (mm)	Radius (mm)	Bearing Length (mm)	No. Models
EOF IOF	5052-H14	180	230	140 200	1 2 3	3 5 7	50 100 150	216
	3004-H48	220	260					

Results and Discussion

Parametric study results were obtained from the numerical study which was carried out using ABAQUS/CAE 2017 [10] and results were analyzed with key parameters to study their effect on web crippling behaviour of sigma sections under one flange loading conditions. Thickness, bearing length and yield strength had a positive impact on web crippling capacity under one flange conditions when they were increased. Section depth and radius were opposite to other key parameters and effected negative impact on web crippling capacity of aluminium sigma sections under both EOF and IOF load cases when there was an increment. Web crippling capacity of aluminium sigma sections was higher under IOF load case compared to EOF load case while all the parameters were same. Figure 5 illustrates the failure pattern of aluminium sigma sections under both load cases. Table 4 presents the obtained numerical results of section 140 and section 200 under one flange loading conditions.

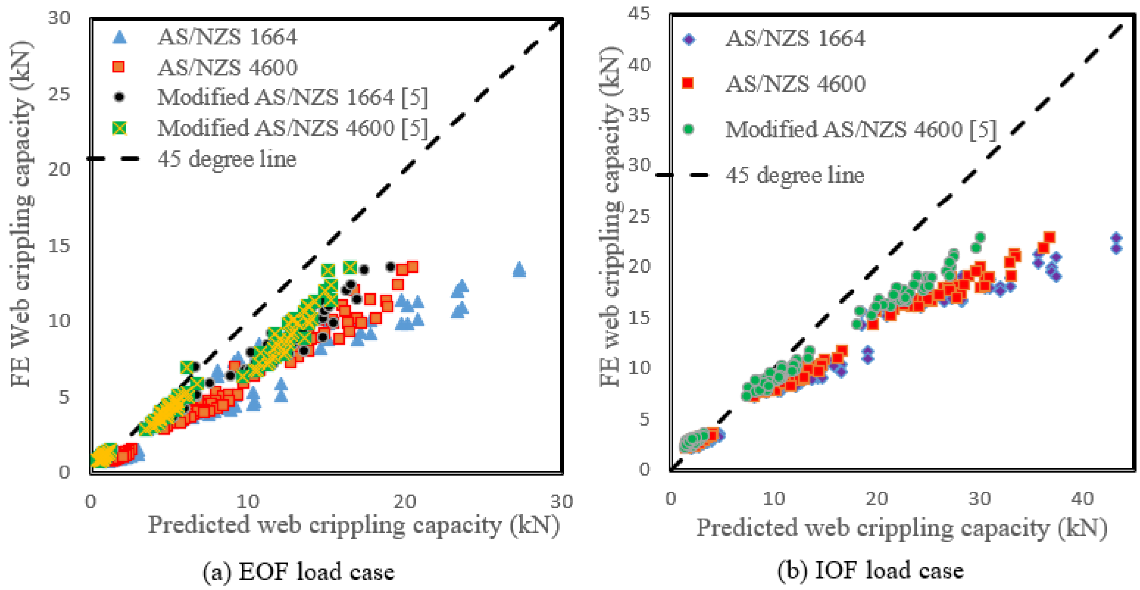


Figure 6: FE web crippling capacity comparison with existing design equations.

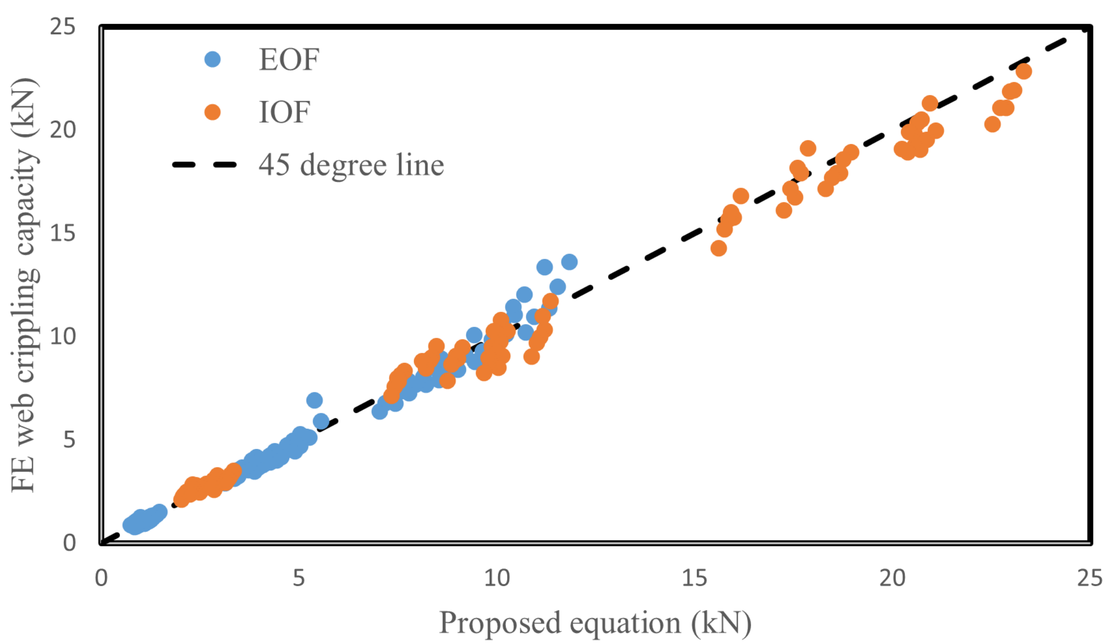


Figure 7: FE web crippling capacity comparison with proposed design modifications.

Design Approach

Design of aluminium sections for web crippling under one flange loading is based on the current design guidelines such as AS/NZS 1664.1 [18], AS/NZS 4600[8], and AISI S100 [1]. AS/NZS 1664.1 [20] provides separate web crippling capacity equations (Eq. 1 - 2) under EOF and

Table 4: Web crippling capacities of section 140 and 200

Section 140							Section 200						
t	b_l	r	Web crippling capacity (kN)				t	b_l	r	Web crippling capacity (kN)			
			EOF		IOF					EOF		IOF	
			f_y(MPa)		f_y(MPa)					f_y(MPa)		f_y(MPa)	
mm	mm	mm	180	220	180	220	mm	mm	mm	180	220	180	220
1	50	3	1.10	1.26	2.50	2.81	1	50	3	0.88	0.83	2.31	2.60
1	50	5	1.03	1.17	2.50	2.77	1	50	5	0.92	0.78	2.24	2.50
1	50	7	0.93	1.04	2.51	2.83	1	50	7	0.88	0.88	2.12	2.37
1	100	3	1.20	1.32	2.88	3.29	1	100	3	0.95	1.05	2.69	3.06
1	100	5	1.14	1.26	2.74	3.07	1	100	5	0.92	1.02	2.54	2.87
1	100	7	1.07	1.18	2.68	3.05	1	100	7	0.87	0.96	2.47	2.73
1	150	3	1.35	1.50	3.07	3.50	1	150	3	1.09	1.22	2.91	3.30
1	150	5	1.25	1.38	2.90	3.31	1	150	5	1.02	1.13	2.73	3.09
1	150	7	1.20	1.32	2.80	3.16	1	150	7	0.95	1.06	2.60	2.92
2	50	3	3.65	4.16	8.34	9.53	2	50	3	3.25	3.66	7.84	8.83
2	50	5	3.52	4.00	8.16	8.99	2	50	5	3.11	3.54	7.57	8.45
2	50	7	3.11	3.54	8.00	8.86	2	50	7	2.91	3.26	7.13	8.81
2	100	3	4.46	4.97	9.47	10.79	2	100	3	3.80	4.26	9.05	10.25
2	100	5	4.24	4.72	8.94	10.22	2	100	5	3.65	4.07	8.66	8.96
2	100	7	3.98	4.39	8.85	9.52	2	100	7	3.47	3.90	7.85	8.23
2	150	3	5.27	5.92	10.27	11.71	2	150	3	4.51	5.14	9.77	10.99
2	150	5	4.75	6.93	9.06	10.33	2	150	5	4.18	4.71	9.28	9.69
2	150	7	4.55	5.12	8.49	9.99	2	150	7	4.00	4.46	8.67	9.04
3	50	3	7.87	8.93	16.80	19.12	3	50	3	7.11	8.04	16.02	18.17
3	50	5	7.35	8.50	15.75	17.91	3	50	5	6.78	7.66	15.19	17.17
3	50	7	6.77	7.66	15.66	16.73	3	50	7	6.38	7.26	14.27	16.10
3	100	3	10.07	11.43	18.92	21.29	3	100	3	8.78	9.86	17.90	20.36
3	100	5	9.14	10.21	17.58	18.82	3	100	5	8.24	9.28	16.69	17.91
3	100	7	8.39	9.84	16.41	17.35	3	100	7	7.89	8.78	16.16	16.89
3	150	3	12.05	13.61	19.96	22.84	3	150	3	10.63	13.36	19.51	21.87
3	150	5	11.06	12.43	18.14	20.92	3	150	5	9.83	10.95	17.61	19.07
3	150	7	10.10	11.37	16.59	18.99	3	150	7	9.20	10.19	16.77	18.06

IOF load cases for aluminium structures while AS/NZS 4600 [8] reports a unified web crippling capacity equation under one flange load cases (Eq. 3) for CF lipped channel sections which is identical to AISI S100 [1]. Later, Husam et al. [5] carried out experimental and numerical program to analyze the web crippling behaviour of aluminium LCBs and modified the equations of AS/NZS 1664.1 (EOF) [20] and AS/NZS 4600 [8] to predict the ultimate web crippling capacity of aluminium LCBs under one flange load cases.

The parametric study results of aluminium sigma sections under one flange loading

Table 5: Existing and proposed coefficients for Eq. 5

Design rule	Load case	C	C_R	C_N	C_h
AS/NZS 4600 [8]	EOF	4.00	0.14	0.35	0.85
	IOF	13.00	0.23	0.14	0.90
Husam et al. [5]	EOF	0.5	0.22	0.10	0.045
	IOF	0.62	0.23	0.13	0.01
Proposed	EOF	0.16	0.09	0.26	0.03
	IOF	0.33	0.04	0.18	0.01

conditions were compared with the existing design equations from the standards and the equations (Eq. 4 -5) modified by Husam et al. [5] for aluminium lipped channel sections.

The comparisons indicated that existing standard design equations and modified equations by Husam et al. [5] for aluminium lipped channels were unconservative for aluminium sigma sections. The comparisons are illustrated in Figure 6 for both EOF and IOF load cases. Since, the existing design equations were not suitable to predict the web crippling capacity of sigma sections under one flange load cases, modified equations were proposed to accurately predict the ultimate web crippling strength of sigma sections under EOF and IOF loading conditions. Coefficients of Eq. 5 were modified to predict the web crippling capacity of aluminium sigma sections under one flange load cases and Table 5 presents the proposed coefficients for aluminium sigma sections under both EOF and IOF loading conditions. Figure 7 presents the comparison of proposed equation with the FE results, and it shows that they coordinated well with the mean value of 1.0 and COV value of 0.09 for EOF load case and mean value of 1.0 and COV value of 0.08 for IOF load case.

Conclusions

This paper presents a comprehensive numerical analysis of aluminium sigma sections under one flange loading conditions. Generated numerical model was validated against experimental results for both load cases and upon a successful validation analysis, parametric plan was developed consisting key parameters such as section depth, thickness, bearing length, yield strength and radius.

$$P_{AS/NZS\ 1664} = \frac{1.2t^2 \sin(\theta)\left(0.46f_y + 0.02\sqrt{Ef_y}\right)(N+33)}{10 + r_1(1-\cos(\theta))} \quad \text{(EOF)} \tag{9}$$

$$P_{AS/NZS\ 1664} = \frac{1.2t^2 \sin(\theta)\left(0.46f_y + 0.02\sqrt{Ef_y}\right)(N+140)}{10 + r_i(1-\cos(\theta))} \quad \text{(IOF)} \tag{10}$$

$$P_{AS/NZS\ 4600} = Ct^2 f_y \sin(\theta)\left(1 - C_R\sqrt{\frac{r_i}{t}}\right)\left(1 + C_N\sqrt{\frac{N}{t}}\right)\left(1 - C_h\sqrt{\frac{h}{t}}\right) \quad (11)$$

$$P_{AS/NZS\ 1664-modified} = \frac{0.48t^2\sin(\theta)\left(0.46f_y + 0.02\sqrt{Ef_y}\right)(N + c_{w2})}{c_{wx} + r_i(1-\cos(\theta))}\cdot\left(1 - C_{n1}\sqrt{\frac{h}{t}}\right) \quad \text{(EOF)} \quad (12)$$

$$P_{AS/NZS\ 1664-modified} = Ct^2 E f_y \sin(\theta)\left(1 - C_R\sqrt{\frac{r_i}{t}}\right)\left(1 + C_N\sqrt{\frac{N}{t}}\right)\left(1 - C_h\sqrt{\frac{h}{t}}\right) \quad (13)$$

Where: f_y-Yield strength; E- Elastic modulus; N-Bearing length; r_i- Radius; t- Thickness; h-Section effective depth; C, C_R, C_N and C_h-Geometrical coefficients; C_{w2}=300; C_{W3}=10 and C_{h1}= 0.044.

Overall, 216 numerical models were generated, and results were obtained from numerical analysis. The results were compared with key parameters and observations were stated. In addition, the results were compared with existing design standard equations and proposed equations to check the validity of those equations to predict the web crippling capacity of aluminium sigma sections under EOF and IOF load cases. The comparisons indicated that the existing design equations were unconservative and hence, the equations were modified to predict the web crippling strength of aluminium sigma section under one flange load cases. Since the modified equations accurately predicted the web crippling capacity of aluminium sigma sections, it is concluded that the modified equations should be applicable to figure out the ultimate web crippling strength aluminium sigma sections under one flange loading conditions.

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