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WEB CRIPPLING BEHAVIOUR OF FASTENED ALUMINIUM LIPPED CHANNEL SECTIONS

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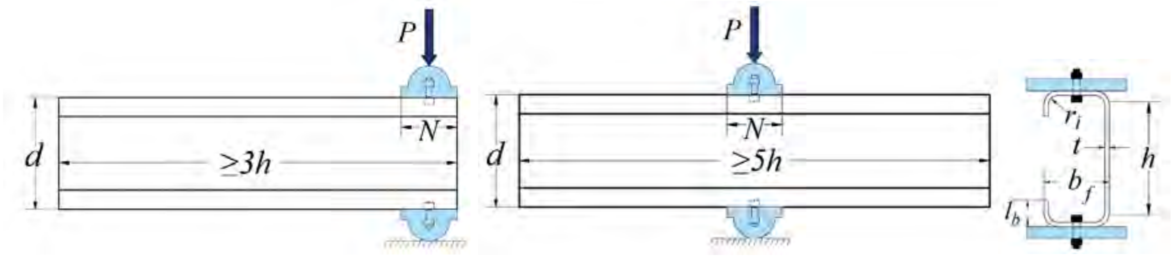
Abstract. *Web crippling is a form of localized failure that thin-walled members are susceptible to in structural systems. The available literature shows limited experimental studies conducted to investigate the web crippling behaviour of aluminium members. Hence, an experimental study was carried out herein to investigate the web crippling phenomenon of fastened (flanges restrained to supports) roll-formed aluminium lipped channel sections. A total of 40 web crippling tests were carried out under two-flange load cases of End Two-Flange (ETF) and Interior Two-Flange (ITF). This paper presents the test results including the load-displacement curves, failure modes, ultimate loads and the effect of restraining flanges to the support in the web crippling behaviour. It also presents the comparison of ultimate loads from tests with the current design rules and discuss the details of the development of the new design rules. The comparison showed that the current design rules are unconservative and unreliable to predict the web crippling capacities of fastened aluminium lipped channel sections, while the new design rules can accurately predict the web crippling strengths of fastened aluminium lipped channel sections under two-flange load cases.*

INTRODUCTION

In recent years, aluminium alloys have been considered as a competitive material to fabricate load-carrying members in construction industry. It has been successfully employed in various structural applications including flooring and roofing systems, pedestrian bridges. Typically, thin-walled flexural members may be loaded by inducing a concentrated load at either the load application point between supports, or by way of a reaction at the support. This could potentially lead to a localized web crippling failure. The AISI Specification [1] considers four loading conditions that flexural members can be prone to, namely End-One-Flange (EOF), Interior-One-Flange (IOF), End-Two-Flange (ETF), and Interior-Two-Flange (ITF) load cases. In addition, these cases can be further classified according to the flange connections, fastened and unfastened. Figures 1 (a) and (b) show the cases included in this study, fastened ETF and ITF load cases, while Figure 1 (c) shows the geometrical profile of a lipped channel section.



(a) Fastened-ETF (b) Fastened-ITF (c) Cross-section

Figure 1: Fastened two flange load cases configuration

A large number of experimental studies have been carried out to investigate the web crippling phenomenon of thin-walled members. Most of these studies were performed on cold-formed steel sections in which the sections were not attached to the support [2-10]. However, this case may not fully represent the real practice as the flanges are typically connected (fastened) to the supports. Such a flange restraining has a significant impact on the web crippling failure capacity of thin-walled members. Bhakta, et al. [11] investigated the effect of flange restraints on the web crippling strength for conventional cold-formed steel members. Following this study, several attempts were made to study the web crippling mechanism of fastened cold formed sections including C-sections, I-Sections, Z-Sections, hat sections, and floor decks [12-15].

For aluminium alloys, very limited research has been undertaken to investigate the web crippling failure. Several studies were conducted on unfastened extruded aluminium sections [16-22] while only one recent experimental investigation was carried out by Alsanat et al. [23] on unfastened roll-formed aluminium sections. It should be noted that no experimental data is available in the literature regarding the web crippling resistance of aluminium alloy sections with flanges fastened to supports.

This research, therefore, aims to investigate the web crippling behaviour and the capacity of fastened aluminium lipped channel sections under the ETF and ITF load cases. The tests were conducted on the same batch of specimens reported by Alsanat et al. [23]. Given no specific and standard web crippling testing method available for aluminium members, the test setup and specimen lengths were designed according to the AISI Specification [1] for cold-formed steel members. The experimental data obtained from this study and those from Alsanat et al. [23] were used to explore the influence of flange attachment on the capacity and behaviour of web crippling failure. Moreover, detailed assessment on the accuracy and reliability of the current web crippling design rules specified in AS/NZS 1664.1 [24], AS/NZS 4600 [25] and Eurocode 3 [26] was performed. An improved design equation was developed to predict the web crippling capacity of fastened aluminium lipped channel sections under two-flange load configuration.

EXPERIMENTAL STUDY

Test specimens

Two series of web crippling tests including 40 specimens of aluminium lipped channel sections with restrained flanges were conducted in the structural laboratory at Griffith University. The test specimens were roll-formed using a well proven marine grade structural aluminium alloy 5052 H36. The channel sections had five different sectional sizes, which are commonly used in aluminium structural applications, the section depth (d) ranged from 100 to 250 mm, and two nominal thicknesses (t) of 2.5 and 3 mm. The specimens were cut to specific length (L) according to the AISI Standard test method [1]. The specimen length (L) is three times the flat portion of the clear web height (*3h*) for the ETF, and *5h* for the ITF load cases. Four different loading bearing lengths (*N* = 25, 50, 100 and 150 mm) were used, and the flanges of lipped channel sections were fastened to them using a 12mm bolt per flange.

All of the above mentioned dimensions were accurately measured at three points on each sample using a vernier calliper, micrometre and tap meter. The specimen dimensional details, presented in Tables 1 and 2, were taken as the average values of these measured dimensions. The specimens were labelled in a way that the load case, web height and thickness, as well as, the length of bearing plate could be easily identified from the label. For example, the label "ITF-10030-N50" indicate that the specimen's load case is ITF, the web height is 100 mm and thickness is 3 mm and the bearing length is 50 mm.

Material properties

To investigate the material properties of the specimens including the yield stress, the elastic modulus, the ultimate strength and the stress strain-curve, tensile coupon tests were conducted. From each untested section (10030, 15030, 20025, 20030 and 25025), three coupons were taken from the upper, centre and bottom part of the web plate in the longitudinal direction (similar to roll forming direction). The tensile coupons were prepared and tested according to and AS 1391 [27] slandered for the tensile testing of materials. The material properties obtained from the tensile coupon tests are summarized in Table 3.

Table 1: Test specimen details and results for fastened ETF load case

Specimen	d (mm)	t (mm)	r_i (mm)	L (mm)	$P_{Exp.}$ (kN)	$P_{Exp.}/P_{AS1664}$	$P_{Exp.}/P_{AS4600}$	$P_{Exp.}/P_{EC3}$	$P_{Exp.}/P_P$
ETF-10030-N25	107.3	2.95	4.9	316	6.80	0.98	0.56	0.61	0.86
ETF-10030-N50	106.5	2.95	5.0	317	8.46	0.86	0.63	0.70	0.89
ETF-10030-N100	107.3	2.95	4.8	316	11.25	0.70	0.73	0.81	0.94
ETF-15030-N25	156.7	2.93	4.9	466	6.37	0.95	0.59	0.61	0.92
ETF-15030-N50	157.5	2.93	5.0	465	7.84	0.82	0.66	0.70	0.94
ETF-15030-N100	158.3	2.92	5.1	465	9.92	0.66	0.74	0.79	0.97
ETF-15030-N150	155.5	2.92	4.9	467	12.45	0.59	0.85	0.86	1.05
ETF-20025-N25	208.1	2.42	5.1	617	4.74	1.02	0.72	0.76	1.16
ETF-20025-N50	208.1	2.43	4.9	615	5.15	0.76	0.69	0.73	1.01
ETF-20025-N100	207.3	2.43	5.0	615	6.19	0.57	0.73	0.76	0.97
ETF-20025-N150	204.0	2.43	4.8	615	7.51	0.50	0.80	0.78	1.01
ETF-20030-N25	204.6	2.9	4.6	611	6.45	0.94	0.65	0.64	1.01
ETF-20030-N50	208.4	2.9	5.0	615	7.37	0.77	0.68	0.70	0.98
ETF-20030-N100	204.5	2.89	4.6	613	9.15	0.59	0.74	0.74	0.96
ETF-20030-N150	208.3	2.89	5.0	615	11.05	0.53	0.82	0.81	1.03
ETF-25025-N25	259.8	2.43	4.4	765	4.45	0.90	0.73	0.71	1.16
ETF-25025-N50	259.9	2.44	4.9	765	4.90	0.71	0.72	0.73	1.05
ETF-25025-N100	262.1	2.44	4.8	765	6.20	0.55	0.79	0.78	1.06
ETF-25025-N150	260.3	2.45	4.6	765	7.20	0.46	0.83	0.78	1.05
Mean						**0.73**	**0.72**	**0.74**	**1.00**
COV						**0.24**	**0.11**	**0.09**	**0.08**

Table 2: Test specimen details and results for fastened ITF load case

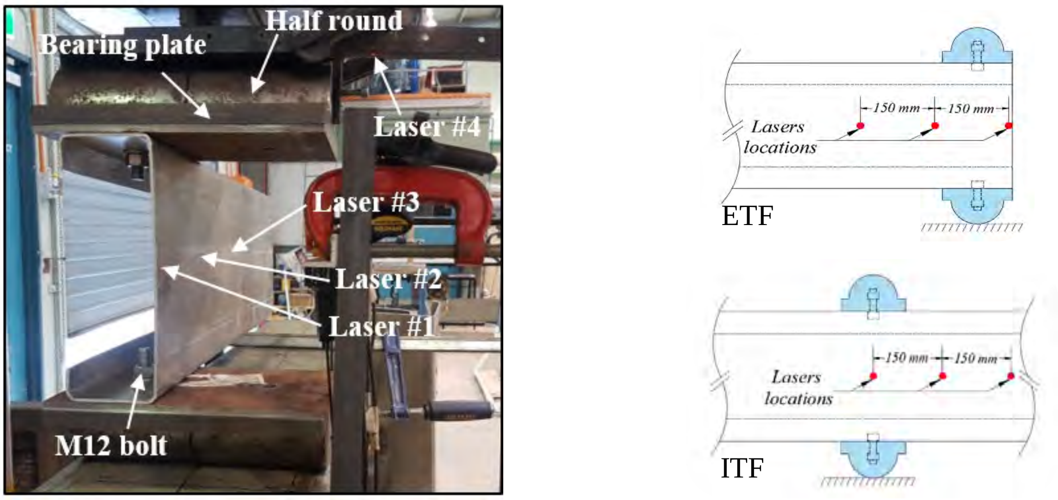
Specimen	d (mm)	t (mm)	r_i (mm)	L (mm)	$P_{Exp.}$ (kN)	$P_{Exp.}/P_{AS1664}$	$P_{Exp.}/P_{AS4600}$	$P_{Exp.}/P_{EC3}$	$P_{Exp.}/P_P$
ITF-10030-N25	106.9	2.94	4.8	527	19.99*	1.33	0.68	0.65	-
ITF-10030-N50(a)	106.4	2.95	4.9	525	19.34	1.10	0.59	0.60	0.94
ITF-10030-N100	106.1	2.94	4.8	523.5	22.99#	0.99	0.62	0.68	0.98
ITF-15030-N25	156.5	2.93	4.8	774	23.99*	1.25	0.67	0.64	-
ITF-15030-N50	156.7	2.92	4.9	775	13.41	1.06	0.61	0.62	0.95
ITF-15030-N100	156.2	2.92	4.8	776	13.93	0.99	0.65	0.72	1.01
ITF-15030-N150	156.6	2.93	4.9	774	15.83#	0.86	0.63	0.73	0.99
ITF-20025-N25	206.2	2.43	4.6	1028	16.52*	1.17	0.68	0.69	-
ITF-20025-N50	207.2	2.44	4.9	1022	19.46	1.06	0.65	0.71	1.01
ITF-20025-N100	207.3	2.43	5.0	1019	19.97#	0.97	0.67	0.79	1.05
ITF-20025-N150	207.4	2.44	4.6	1021	22.63#	0.81	0.64	0.79	0.99
ITF-20030-N25	205.6	2.9	4.4	1022	22.67*	1.18	0.67	0.66	-
ITF-20030-N50	206.6	2.93	4.8	102	14.21	1.05	0.63	0.66	0.97
ITF-20030-N100	206.5	2.9	4.8	1021	14.05#	0.97	0.66	0.75	1.02
ITF-20030-N150	206.5	2.89	4.6	1022	15.99#	0.80	0.62	0.73	0.96
ITF-25025-N25	259.9	2.43	4.4	1273	16.72*	1.21	0.74	0.79	-
ITF-25025-N50	260.0	2.42	4.5	1274	19.99	1.05	0.69	0.78	1.04
ITF-25025-N100	259.8	2.43	4.5	1269	19.34#	0.94	0.70	0.85	1.06
ITF-25025-N150	259.9	2.43	4.5	1275	22.99#	0.81	0.68	0.87	1.03
Mean						**1.03**	**0.66**	**0.72**	**1.00**
COV						**0.146**	**0.055**	**0.107**	**0.04**

Table 3: Mechanical properties of aluminum sections used in the experimental study

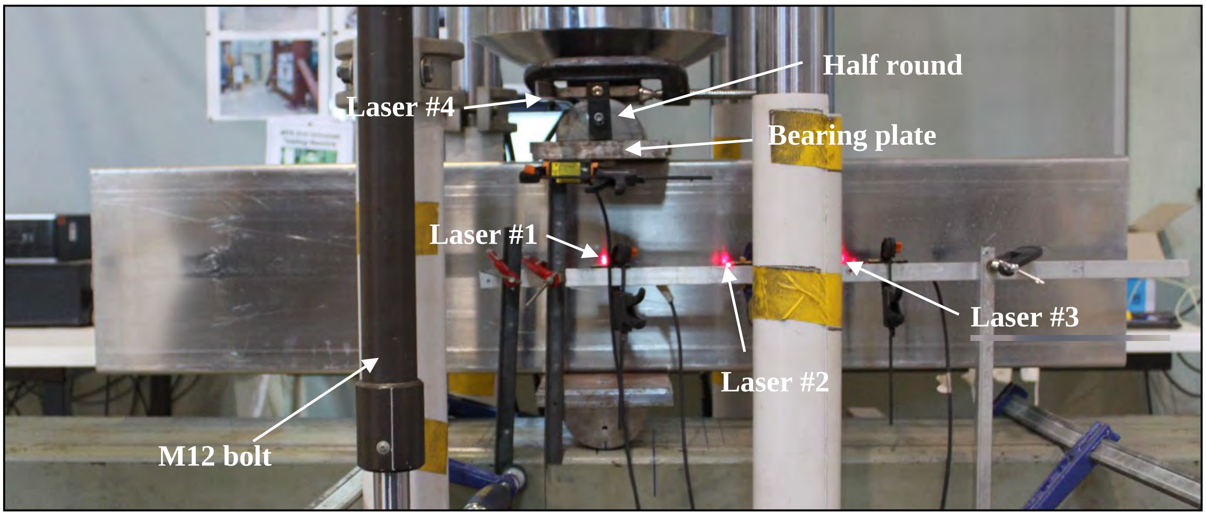
Section	E_0 (GPa)	$\sigma_{0.2}$ (MPa)	σ_u (MPa)	ε_u (%)
10030	65.05	210	259	6.15
15030	63.55	206	248	5.55
20025	63.95	214	260	5.05
20030	64.13	212	257	6.47
25025	64.34	216	265	6.68

Test set-up and procedure

Materials Test System (MTS) machine, with maximum compressive testing capacity of 500kN, was used to apply a compressive force to the specimens. Forty tests were conducted to investigate the web crippling capacity and behaviour of the aluminium lipped channel sections under the ETF and ITF load cases. Figures 2 (a) and (c) show the test set up for the ETF and ITF load cases, respectively. To ensure that the support at the bottom and the top are pinned, half rounds were used in the support system.



(a) Fastened ETF load case (b) Web lasers locations



(c) Fastened ITF load case

Figure 2: Fastened web crippling test setup

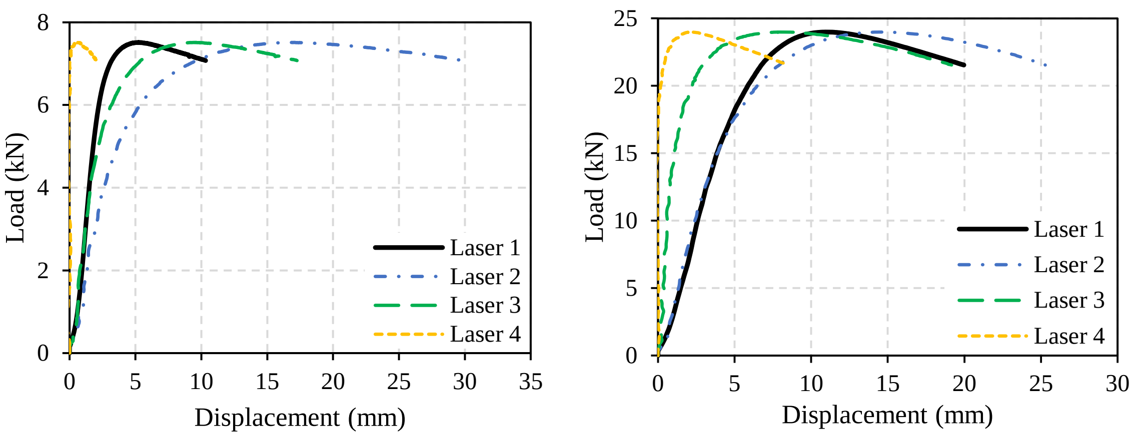
In both the ETF and ITF load cases, the specimens were positioned, respectively, at the edge and mid-span between two identical bearing plates of the same length. Then, the flanges were attached to the bearing plates using 12 mm bolts. The measured load was initialized with zero value before commencing each test. A displacement-controlled system was used to drive down the cross-head of the MTS machine at a constant speed of 2 mm/min for all test specimens until failure. The applied load, the vertical displacement of the section and the horizontal displacements of the web were recorded during the tests. As shown in Figure 2 (b), three laser displacement transducers were used to measure the lateral displacement of the web in three different positions (Laser 1, 2 and 3), whereas one laser (Laser 4) was used to measure the vertical displacement of the top bearing plate.

TEST RESULTS AND DISCUSSION

Tables 1 and 2 summarise the experimental ultimate web crippling load ($P_{Exp.}$) from the two series of tests, ETF and ITF load cases, respectively. Two tests were repeated, and the specimens were ETF-10030-N50 and ITF-10030-N50. The differences between the repeated tests were found to be small (0.5% for (ETF-10030-N50) and 1.0% for, (ITF-10030-N50), indicating that the test results are accurate and reliable.

Web crippling behavior

Figures 3 (a) and (b) shows the typical load versus deflection curves from the web crippling tests for specimens ETF-20025-N150 and ITF-25025-N150, respectively. As shown in Figure 4, web crippling is the only failure mode for all the ETF specimens, however two failure modes were observed in the ITF load case. The ITF specimens with 50, 100 and 150 mm bearing lengths failed in web crippling failure mode (see Figure 5) while those with a small bearing plate (25 mm) failed in combined flange crushing and web crippling failure due to the high concentrated load induced from the support, as shown in Figure 6. Figure 7 show the plot of applied load versus the vertical deflection for the ITF-25025-N25 section. The increased web bearing capacity of aluminium lipped channel section with small bearing plate (25 mm) can clearly be identified caused by flange crushing. Alsanat et al. [23], Gunalan and Mahendran [3] and Sundararajah et al. [4, 5] also observed this kind of failure during their experimental work on unfastened channel sections.

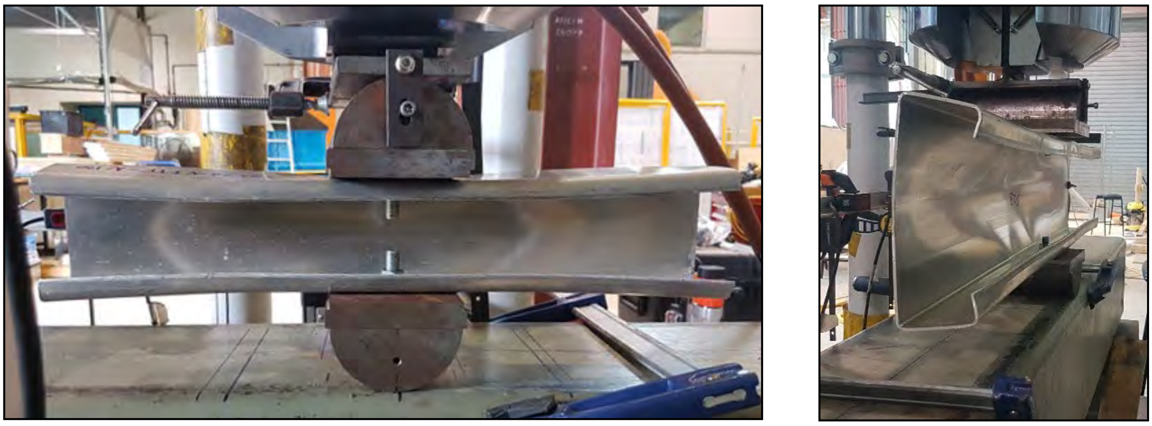


(a) ETF-20025-N150 (b) ITF-25025-N150

Figure 3: Typical load versus deflection curves

(a) ETF-20025-N25 (c) ETF-15030-N25

Figure 4: Web crippling failure modes for ETF load case



(a) ITF-10030-N100 (b) ITF-20030-N150

Figure 5: Web crippling failure modes for ITF load case

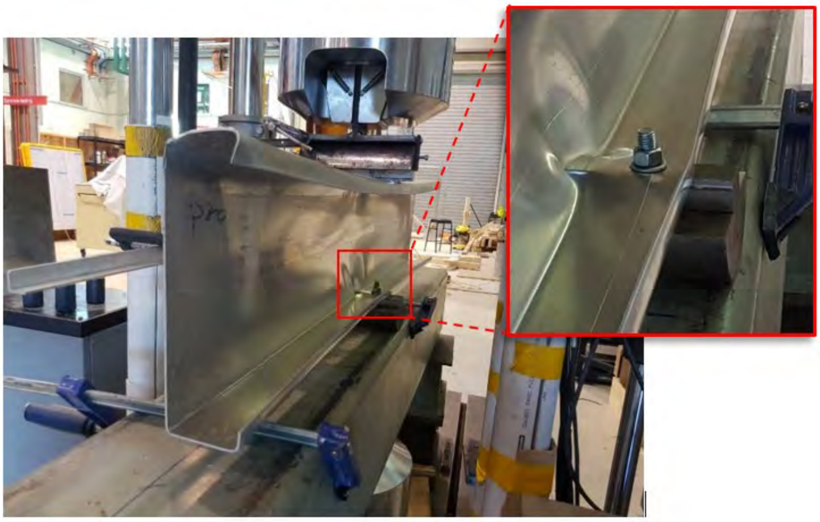
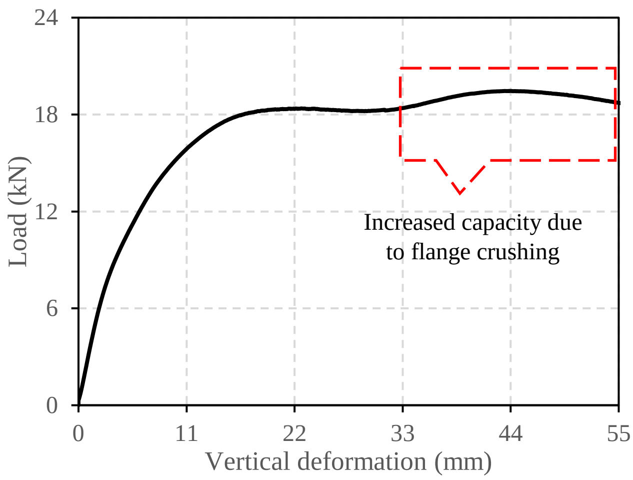


Figure 6: Combined flange crushing and web crippling failure for ITF-25025-N25

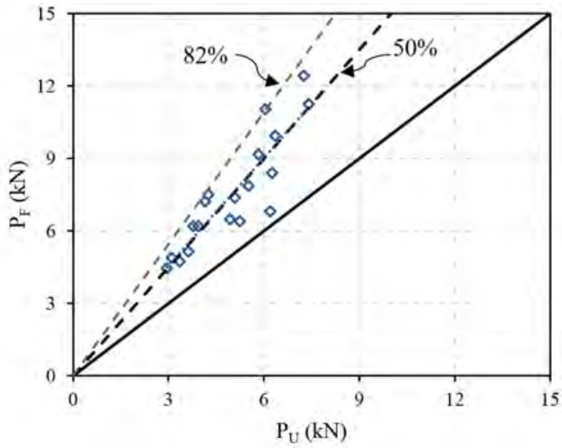


(a) Applied load versus vertical deflection.

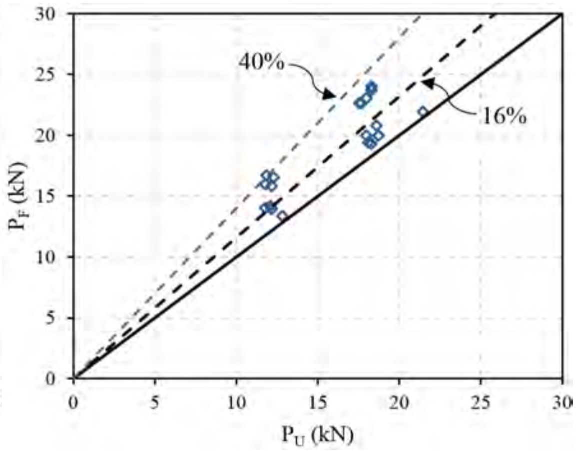
Figure 7: Flange crushing failure mechanism of ITF-25025-N25

The effect of restrained flanges

To investigate the effect of restrained flanges on the web crippling capacity, the data acquired from the experimental works were analysed with those from Alsanat et al's [23] experiments for unfastened sections. It was observed that restraining the flanges has a considerable influences in the section web crippling capacity. Figures 8 (a) and (b) present the web crippling capacity of fastened and unfastened sections and the ratios between them under ETF and ITF load cases, respectively. The vertical axis plots the test strengths for fastened sections while the horizontal axis represents the test strengths for unfastened sections. Generally, it was observed that fastening the flanges resulted in significant increase in the web crippling capacity of the sections under both cases. It has greater impact on sections under ETF load cases with up to 82% more capacity and average of 50% while for ITF load cases, the capacity rises to 40% with average of 16%.



(a) ETF load case



(b) ITF load case

Figure 8: Comparison between the fastened and unfastened web crippling capacities

DESIGN RULES

Current design rules

The nominal web crippling capacities of thin-walled sections could be predicted using AS/NZS 1664.1 [24] for aluminium structures, as well as AS/NZS 4600 [25] and Eurocode 3 [26] for cold-formed steel structures. It should be mentioned that the prediction of web crippling capacities from these specifications except AS/NZS 4600 [25] do not differentiate between sections with fastened and unfastened support conditions.

1.1.1 AS/*NZS* 1664.1 for aluminum structures

The web design rules for thin walled sections subjected to a concentrated transverse load (web crippling) are specified in the AS/NZS 1664 standard [24] Part 1, Section 4.7.7 for aluminium structures. Equations (1) and (2) express the nominal web crippling capacity (P_{AS1664}) of aluminium lipped channel sections under the ETF and ITF load cases, respectively.

$$P_{AS1664} = \frac{C_1 t^2 \sin\theta (0.46 f_y + 0.02\sqrt{E f_y})(N + C_{w2})}{C_{w3} + r_i(1 - \cos\theta)} \text{ (ETF)} \quad (1)$$

$$P_{AS1664} = \frac{C_2 t^2 \sin\theta (0.46 f_y + 0.02\sqrt{E f_y})(N + C_{w1})}{C_{w3} + r_i(1 - \cos\theta)} \text{ (ITF)} \quad (2)$$

where $C_1 = 1.2$; $C_2 = 1.00$ $C_{w1} = 140mm$; $C_{w2} = 33\,mm$; $C_{w3} = 10\,mm$; t is the thickness of the web (mm), N is the bearing length (mm), r_i is the inside corner radius (mm), f_y is the static 0.2% yield stress (MPa), E is the elastic modulus (MPa), and θ is the angle that is calculated from the bearing surface plane to the plane of the web surface. θ is taken as 90 o degree for the lipped channel sections used in this experimental study.

1.1.2 AS/NZS 4600 for cold-formed steel structures

The AS/NZS 4600 [25] standard provides a generalized design approach to predict the bearing capacity of the most commonly used cold-formed steel sections. These sections include cold-formed steel typical sections such as single web channels (lipped or unlipped), back to back channel sections, multi-web deck sections, single hat sections, and single web Z-sections. The bearing capacity approach was developed based on Prabakaran's [28] research studies using large amount of experimental results. The specified web crippling strength according to AS/NZS 4600 (P_{AS4600}) is calculated according to Equation (3)

$$P_{AS4600} = Ct^2 f_y \sin\theta \left(1 - C_R\sqrt{\frac{r_i}{t}}\right)\left(1 + C_N\sqrt{\frac{N}{t}}\right)\left(1 - C_h\sqrt{\frac{h}{t}}\right) \quad (3)$$

Where C is the overall coefficient, C_R is the coefficient of the internal corner radius, C_N is the coefficient of the bearing length and C_h is the coefficient of the slenderness of the web. The values of these coefficient were summarised in Table 4. Note that in Equation (3), the following conditions $h/t \le 200$, $N/t \le 210$, $r_i/t \le 3$, $N/h \le 2$, and $\theta = 90^0$ must be satisfied.

Table 4: AS/NZS 4600 and proposed coefficients for fastened lipped channel sections

Equation	Load case	C	C_R	C_N	C_h
Current (AS/NZS 4600)	ETF	7.5	0.08	0.12	0.048
	ITF	20	0.10	0.08	0.031
Proposed	ETF	0.231	0.21	0.35	0.050
	ITF	0.78	0.20	0.08	0.020

1.1.3 Eurocode 3 for cold-formed steel structures

The Eurocode 3 Standard [26] Part 1.3 for cold-formed steel structures provides several equations derived based on past experimental studies on cold-formed steel sections. This standard specified generalized equations for single-web sections. Equations (4) and (5) show the design formulas given in the Eurocode 3 Standard [26] for cross sections with an unstiffened single web (channel sections) under ETF and ITF load cases, respectively. These equations are limited for cold-formed steel sections with $r_i/t \le 6$ and $d_w/t \le 200$.

$$P_{EC3} = \frac{k_1 k_2 k_3 f_y t^2}{\gamma_{M1}}\left[6.66 - \frac{d_w}{64t}\right]\left[1 + 0.01\frac{N}{t}\right] \quad (4)$$

$$P_{EC3} = \frac{k_3 k_4 k_5 f_y t^2}{\gamma_{M1}}\left[21 - \frac{d_w}{16.3t}\right]\left[1 + 0.0013\frac{N}{t}\right] \quad (5)$$

In which: k_1=1.33-f_y /690.9; k_2=1.15-0.15r_i /t $(0.5 \le k_5 \le 1.0)$; k_3=0.7+0.3$(\theta/\ 90)^2$; k_4=1.22-f_y/1036.4; k_5=1.06-0.06r_i/t $(k_5 \le 1.0)$; d_w is the web height between flange mid-lines in mm; γ_{M1} is the partial safety factor ($\gamma_{M1} = 1$) and θ is taken as 90 degree.

Comparison of test results with current design rules

The web crippling capacities obtained from the experimental results of the fastened aluminium lipped channel sections were compared with the design rules predicted using the AS/NZS 1664.1 [24] for aluminium structures, as well as, AS/NZS 4600 [25] and Eurocode 3 [26] for cold-formed steel structures. As mentioned earlier, the equations provided by both AS/NZS 1664.1 [24] and Eurocode 3 [26] standards do not differentiate between fastened and unfastened support conditions, therefore their predictions are identical in both cases even though the experimental web crippling capacities with fastened and unfastened flanges are considerably different. Tables 1 and 2 show the comparisons of the test strengths ($P_{Exp.}$) with the design capacities predicted using the AS/NZS 1664.1 Standard (P_{AS1664}), AS/NZS 4600 Standard (P_{AS4600}) and Eurocode 3 (P_{EC3}) for the ETF and ITF load cases, respectively.

The average measured cross-section dimensions and the measured material properties as shown in Tables 1 -3 were used to calculate the design strengths of the test specimens. For the loading condition of ETF with restrained flanges, the mean values of tested-to-predicted strength ratio of $P_{Exp.}$ /P_{AS1664}, $P_{Exp.}$ /P_{AS4600} and $P_{Exp.}$ /P_{EC3} are 0.73, 0.72 and 0.74, with the corresponding COV values 0.24, 0.11 and 0.09, respectively. For the fastened specimens with loading condition of ITF, the mean values of $P_{Exp.}$ /P_{AS1664}, $P_{Exp.}$ /P_{AS4600} and $P_{Exp.}$ /P_{EC3} are 1.03, 0.66 and 0.72 with the corresponding COV values of 0.15, 0.06 and 0.11, respectively. Generally, it was found that the predicted web crippling strengths using the currently available design rules were unconservative for both load cases, except for the strengths predicted by the AS/NZS 1664 specification under the load case of ITF which was reasonably acceptable mean value with unreliable COV value. Hence there is a need to modify the current design rules or develop new design rules to accurately predict the web crippling capacities of fastened aluminium lipped channel sections.

Proposed unified design rule.

The proposed unified equation in this study follows the same approach obtained from AS/NZS 4600 [25] standard. This is due to the facts that (i) this generalized approach is the only one available for both fastened and unfastened cases, (ii) same approach is employed by few other specifications, e.g. Eurocode 9 [29] and AISI S100 [30], and (iii) it could be suitable for both cold-formed steel and aluminium members as approved by Alsanat et al. [23]. Table 4 summarizes the proposed coefficients ($C, C_R, C_N\ and\ C_h$) which can be associated with Equation (6) to predict the web crippling capacity of fastened aluminum lipped channel sections under two flange load cases.

$$P_p = Ct^2\sqrt{Ef_y}\sin\theta\left(1 - C_R\sqrt{\frac{r_i}{t}}\right)\left(1 + C_N\sqrt{\frac{N}{t}}\right)\left(1 - C_h\sqrt{\frac{h}{t}}\right) \quad (6)$$

The web crippling strengths predicted by Equation (6) with implementing the modified web crippling coefficients agree well with the experimental web crippling capacities of fastened aluminum lipped channel sections under ETF and ITF load cases as shown in Tables 1 and 2. The mean value of test-to-predicted web crippling capacities of the sections under the ETF load case is 1.00 and the COV value is 0.08. For the ITF load case, these values are 1.00 and 0.04.

Conclusion

An experimental investigation of fastened aluminium lipped channel sections subjected to web crippling under the ETF and ITF load cases was presented in this paper. Forty tests were conducted with different section heights, thicknesses and bearing lengths. A full description of the web crippling behaviour including the ultimate loads, the failure modes and the load-deformation curves was discussed. It was observed that fastening the flanges lead to a significant increase in the web crippling capacity of the sections under both cases, up to 82% more capacity for ETF load case and 40% for ETF load case. Furthermore, The test web crippling capacities of fastened aluminium lipped channel sections were compared with the nominal strengths calculated using AS/NZS 1664.1 [24], AS/NZS 4600 [25], Eurocode 3 [26] specifications. It was found that the design strengths predicted by the aforementioned specifications are mostly unconservative and unsafe. Therefore, a modified equation was developed based on the experimental results to accurately predict the web crippling capacities of fastened aluminium lipped channel sections. Generally, it was shown that the modified design rule was capable to predict the ultimate strengths for fastened aluminium lipped channel sections with good agreement with the experimental results.

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