Fastened Aluminium Lipped Channel Sections Subjected to Web Crippling under Two-Flange Loading Conditions - Experimental Study

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ABSTRACT

Thin-walled members in structural systems are highly vulnerable to buckling instabilities including web crippling. Aluminium alloy members are more prone to this kind of failure due to their relatively low elastic moduli. As shown in the existing literature, limited research has been performed to investigate the web crippling failure of aluminium members. Therefore, this paper presents the details of an experimental investigation conducted to study the web crippling phenomenon of fastened (restrained flanges) aluminium lipped channel (ALC) sections. Two loading conditions of End-Two-Flange (ETF) and Interior-Two-Flange

(ITF) were considered. Two series of 40 tests were performed using roll-formed aluminium alloy 5052 H36 specimens with different web slenderness and load bearing lengths. A comparison between the ultimate capacities of the web crippling tests and the predictions from the currently available design rules was performed. The results show that the current web crippling design rules are mostly unsafe and unreliable for fastened ALC sections. Thus, a modified equation is needed to closely and accurately estimate the web crippling strengths for fastened ALC sections under two-flange loading conditions. Furthermore, the influence of restrained flanges on the web crippling mechanism was discussed in detail. It was observed that fastening the flanges considerably strengthened the section web crippling capacity; hence a new prediction approach was developed to estimate the increase of the web crippling capacity due to flange restraining.

Keywords: Web crippling; Aluminium lipped channel sections; Experimental study; Fastened; Two-flange loading conditions, Design rules.

INTRODUCTION

Aluminium alloy sections fabricated using roll-forming technique are becoming increasingly popular in structural applications including roofing and flooring systems, modular structures and various types of structures in corrosive environments. Figure 1 shows an application of roll-formed ALC section as purlins in Minto reservoir roof – NSW, Australia. Thin-walled flexural members may be loaded by inducing a concentrated load at either the load application point between supports or by way of the reactions at the supports. This could potentially lead to a localized web crippling failure. The AISI S909 (2008) Standard test method for determining the web crippling strength of cold-formed steel beams considers two loading conditions that thin-walled members may be subjected to in a structural system. End-

loading condition refers to when the distance between the end of the member and edge of the bearing plate is equal or less than to 1.5 times the flat portion of the web (h); otherwise, it is classified as interior-loading condition. Each load conditions are also classified into two groups according to the application of the transverse compression load on one-flange or two-flanges. The one-flange loading condition is considered if the distance between the edges of two opposite bearing plates is more than $1.5h$. Otherwise, it is considered as a two-flange loading condition. These prime loading conditions are classified as: end-one-flange (EOF), interior-one-flange (IOF), end-two-flange (ETF), and interior-two-flange (ITF) loading conditions. In addition, these cases can be further classified according to the flange connections, fastened and unfastened. Figures 2 (a) and (b) show the cases included in this study, fastened ETF and ITF loading conditions, while Figure 2 (c) presents the geometrical profile of a lipped channel section.

Extensive experimental research has been carried out to investigate the web crippling mechanism of thin-walled members. The majority of the previous studies were performed on cold-formed steel sections in which the sections were not attached (unfastened) to the supports (Sundararajah et al. ((2016), (2017)), Gunalan and Mahendran ((2015), (2019)), Keerthan et al (2014), Keerthan and Mahendran (2016) and Steau et al. ((2015), (2016), (2017) Uzzaman ((2012a), (2012b), (2012c), (2013)). However, this case may not fully represent the real practice as the flanges are typically attached (fastened) to the supports. Such a flange restraining has a significant impact on the web crippling failure of thin-walled members. Bhakta et al. (1992) investigated the influence of flange restraints on the web crippling capacity for conventional cold-formed steel members including channels (unlipped and lipped), I-Sections, Z-Sections, hat sections, and floor decks. A total of fifty-two web crippling tests were performed for fastened and unfastened member under EOF and IOF loading conditions.

Generally, it was found that restraining the flange makes a significant increase in the web crippling capacity of the section. Gerges and Schuster (1998), Macdonald et al. (2011) and Janarthanan et al. ((2015), (2019a), (2019b)) also carried out further experimental investigations and proposed several improved equations to determine the web crippling capacity for fastened cold-formed lipped channel steel beams under EOF and IOF loading conditions. For two-flange loading conditions (ETF and ITF), Beshara and Schuster (2000) reported the first experimental study in investigating the web crippling failure for fastened cold-formed steel sections. A series of 72 tests were performed on both C and Z sections and improved coefficients were established for fastened cold-formed steel sections under ETF and ITF loading conditions, which were later adopted in the AS/NZS 4600 (2018) and AISI S100 (2016).

Very limited research has been undertaken to study the web crippling instability of aluminium members. Tryland et al. (1999), Zhou and Young (2008), Young and Zhou (2008), Zhou et al. (2009) Chen et al (2015) and Su and Young (2018) conducted experimental and numerical studies on unfastened extruded aluminium hollow sections while Alsanat et al. ((2019a), (2019b)) conducted experimental and numerical investigations on unfastened roll-formed ALC sections under two-flange loading conditions. It should be noted that no experimental data is available in the literature related to the web crippling mechanism of fastened aluminium alloy sections.

This research, therefore, aims to study the web crippling mechanism of fastened ALC sections under two-flange loading conditions. The tests were conducted on the same batch of specimens reported by Alsanat et al. (2019a). Given the unavailability of specific and standard web crippling testing methods for aluminium members, the specimen lengths and test set-up were designed following the AISI S909 (2008) guidelines for cold-formed steel members. A

detailed assessment on the accuracy and reliability of the current web crippling design rules provided by AS/NZS 1664.1 (1997), Aluminium design manual (AA 2015), AS/NZS 4600 (2018), AISI S100 (2016) and Eurocode 3 Part 1-3 (CEN 2006) was performed. As the predictions from the aforementioned specifications were found unconservative and unreliable, an improved design equation was then developed using a similar approach of the unified equation given in AS/NZS 4600 (2018) to predict the web crippling capacity of fastened ALC sections under two-flange load configurations. It should be noted that the web crippling design guidelines specified in the AS/NZS 1664.1 (1997) and Aluminium design manual (AA 2015) for aluminium structures are identical, and therefore only AS/NZS 1664.1 (1997) is considered in this paper. Similarly, The AS/NZS 4600 (2018) and AISI S100 (2016) design rules for cold-formed steel structures are identical, and hence only AS/NZS 4600 (2018) is examined herein. Moreover, the experimental data obtained from this study and those from Alsanat et al.'s (2019a) were used to explore the influence of flange attachment on the capacity and behaviour of the web crippling failure. A new prediction approach was subsequently proposed to estimate the increase of the web crippling capacity of restrained sections.

CURRENT DESIGN RULES

It is known that the nominal web crippling capacities of thin-walled sections can be predicted using AS/NZS 1664.1 (1997) and Eurocode 9 (CEN 2007) for aluminium structures, and AS/NZS 4600 (2018) and Eurocode 3 Part 1-3 (CEN 2006) for cold-formed steel structures. However, the predictions of web crippling capacities using these specifications except AS/NZS 4600 (2018) are not differentiated between sections with fastened and unfastened support conditions.

119 AS/NZS Specifications

120 AS/NZS 1664.1 for Aluminium Members

121 The web crippling design rules for thin-walled sections subjected to a concentrated
 122 transverse load are specified in the AS/NZS 1664 (1997) Part 1, Section 4.7.7 for aluminium
 123 structures. Equations (1) and (2) express the nominal web crippling capacity (P_{AS1664}) of ALC
 124 sections under the ETF and ITF loading conditions, respectively.

$$125 \quad P_{AS1664} = \frac{C_1 t^2 \sin \theta (0.46 f_y + 0.02 \sqrt{E f_y}) (N + C_{w2})}{C_{w3} + r_i (1 - \cos \theta)} \quad (\text{ETF}) \quad (1)$$

$$126 \quad P_{AS1664} = \frac{C_2 t^2 \sin \theta (0.46 f_y + 0.02 \sqrt{E f_y}) (N + C_{w1})}{C_{w3} + r_i (1 - \cos \theta)} \quad (\text{ITF}) \quad (2)$$

127 where $C_1 = 1.2$, $C_2 = 1.0$, $C_{w1} = 140\text{mm}$, $C_{w2} = 33\text{mm}$, $C_{w3} = 10\text{mm}$, t is the thickness of the web
 128 (mm), N is the bearing length (mm), r_i is the inside corner radius (mm), E is the elastic modulus
 129 (MPa), f_y is the static 0.2% yield stress (MPa), and θ is the angle between the web surface and
 130 the bearing surface plane. Note that θ is taken as 90° for the ALC sections used in this study.

131 Alsanat et al. (2019a) improved these equations to suitably predict the web crippling
 132 capacity of unfastened ALC sections under two-flange loading conditions. The effect of web
 133 slenderness was taken into consideration and the modified equations are:

$$134 \quad P_{AS1664 (Prop.)} = \frac{C_1 t^2 \sin \theta (0.46 f_y + 0.02 \sqrt{E f_y}) (N + C_{w2})}{C_{w3} + r_i (1 - \cos \theta)} \left(1 - C_{h1} \sqrt{\frac{h}{t}} \right) \quad (\text{ETF}) \quad (3)$$

$$135 \quad P_{AS1664 (Prop.)} = \frac{C_2 t^2 \sin \theta (0.46 f_y + 0.02 \sqrt{E f_y}) (N + C_{w1})}{C_{w3} + r_i (1 - \cos \theta)} \left(1 - C_{h2} \sqrt{\frac{h}{t}} \right) \quad (\text{ITF}) \quad (4)$$

where $C_1 = 0.31$, $C_2 = 258$, $C_{w1} = 780\text{mm}$, $C_{w2} = 238\text{mm}$, $C_{w3} = 10\text{mm}$, $C_{h1} = 0.05$ and $C_{h2} = 0.025$.

AS/NZS 4600 for Cold-Formed Steel Members

The AS/NZS 4600 (2018) provides a generalised design approach to estimate the web crippling capacity of various cold-formed steel sections. These sections include typical cold-formed steel sections including single web channels (lipped or unlipped), back-to-back channel sections, multi-web deck sections, single hat sections, and single web Z-sections. The unified Equation (5) given in the AS/NZS 4600 (2018) can be used to calculate the web crippling capacity (P_{AS4600}) of cold-formed steel members.

$$P_{AS4600} = Ct^2 f_y \sin \theta \left(1 - C_R \sqrt{\frac{r_l}{t}}\right) \left(1 + C_N \sqrt{\frac{N}{t}}\right) \left(1 - C_h \sqrt{\frac{h}{t}}\right) \quad (5)$$

Where C , C_R , 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 coefficients are summarised in Table 1. Note that in Equation (5), the following conditions $h/t \leq 200$, $N/t \leq 210$, $r_l/t \leq 3$, $N/h \leq 2$, and $\theta = 90^\circ$ must be satisfied.

Alsanat et al. (2019a) also modified this equation to accurately predict the web crippling capacity for unfastened ALC sections under the ETF and ITF loading conditions. The effect of elastic moduli of aluminium alloys was incorporated in the modified Equation (6), and the new coefficient factors (C , C_R , C_N and C_h) were proposed and given in Table 1.

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

Eurocode Specifications

Eurocode 9 for Aluminium Members

The Eurocode 9 (CEN 2007) Part 1.4, Section 6.1.7.2 provides Equation (7) to predict the web crippling capacity of roll-formed aluminium with unstiffened webs.

$$P_{EC9} = \alpha t^2 \sqrt{f_y E} \left(2.4 + \left(\frac{\theta}{90} \right)^2 \right) \left(1 - 0.1 \sqrt{\frac{r_i}{t}} \right) \left(0.5 + \sqrt{\frac{0.02N}{t}} \right) \quad (7)$$

where α is the coefficient for various categories of local loads and support for multi-web sections.

This equation follows the same approach of Equation (5) obtained from the AS/NZS 4600 (2018). However, it is only valid for multi-webs sections. Therefore, it is not considered in this paper and the Eurocode 3 Part 1-3 (CEN 2006) will be evaluated instead.

Eurocode 3 for Cold-formed Steel Members.

The Eurocode 3 Part 1-3 (CEN 2006) provides several equations derived based on the past experimental studies on cold-formed steel sections. Equations (8) and (9) are the design formulae for unstiffened single-web sections under ETF and ITF loading conditions, respectively.

$$P_{EC3} = \frac{k_1 k_2 k_3 f_y t^2}{\gamma_{M1}} \left[6.66 - \frac{d_w}{64t} \right] \left[1 + 0.01 \frac{N}{t} \right] \quad (8)$$

$$P_{EC3} = \frac{k_3 k_4 k_5 f_y t^2}{\gamma_{M1}} \left[21 - \frac{d_w}{16.3t} \right] \left[1 + 0.0013 \frac{N}{t} \right] \quad (9)$$

173 where $k_1 = 1.33 - \frac{f_y}{690.9}$; $k_2 = 1.15 - 0.15 \frac{r_i}{t}$ ($0.5 \leq k_5 \leq 1.0$); $k_3 = 0.7 + 0.3 \left(\frac{\theta}{90}\right)^2$;

174 $k_4 = 1.22 - \frac{f_y}{1036.4}$; $k_5 = 1.06 - 0.06 \frac{r_i}{t}$ ($k_5 \leq 1.0$); d_w is the web height between
 175 flange mid-lines in mm; γ_{M1} is the partial safety factor ($\gamma_{M1} = 1$) and θ is taken as 90° . Not
 176 that Equations (8) and (9) are limited for cold-formed steel sections with $d_w/t \leq 200$ and $r_i/t \leq 6$.

177

178 Taking into account the effect of elastic moduli of aluminium alloys, a slight
 179 modification was made to Equations (8) and (9) by Alsanat et al. (2019a) to enhance their web
 180 crippling predictions for unfastened ALC sections under two-flange loading conditions. The
 181 modified Equations (10) and (11) are:

$$182 \quad P_{EC3(Prop.)} = \frac{0.028k_1k_2k_3\sqrt{E}f_yt^2}{\gamma_{M1}} \left[6.66 - \frac{d_w}{64t} \right] \left[1 + 0.01 \frac{N}{t} \right] \quad (10)$$

$$183 \quad P_{EC3(Prop.)} = \frac{0.034k_3k_4k_5\sqrt{E}f_yt^2}{\gamma_{M1}} \left[21 - \frac{d_w}{16.3t} \right] \left[1 + 0.0013 \frac{N}{t} \right] \quad (11)$$

184 **EXPERIMENTAL STUDY**

185 **Test Specimens**

186 The web crippling experimental tests comprising 40 specimens of ALC sections with
 187 restrained flanges were performed in the structural laboratory at Griffith University. The test
 188 specimens were fabricated using aluminium alloy grade 5052 H36. The channel sections had
 189 five different sectional sizes, which are commonly used in aluminium structural systems. The
 190 section depth (d) varied from 100 to 250 mm, and two nominal thicknesses (t) of 2.5 and 3 mm
 191 were considered. The specimens were cut to specific lengths (L) according to AISI S909

(2008). The specimen length (L) is three times the clear web height ($3h$) for the ETF loading condition, and $5h$ for the ITF loading condition. All the specimens geometrical dimensions were accurately measured and summarised in Tables 2 and 3 for ETF and ITF, respectively

High-strength steel plates were used to apply the bearing load and to support the specimens. Four bearing plates with different lengths ranged from 25 mm to 150 mm were used to investigate the influence of bearing length on the web crippling capacity. During the test, the specimen flanges were fastened to the bearing plates using a 12mm bolt per flange.

The specimens were labelled to easily identify the loading condition, web height and thickness, and the bearing plate length. For instance, the label “ITF-10030-N50” indicates that the specimen’s loading condition is ITF, the nominal web height is 100 mm, the web thickness (t) is 3 mm and the bearing length (N) is 50 mm.

Material Properties

To investigate the material properties of the specimens, tensile coupon tests were conducted for each untested section (10030, 15030, 20025, 20030 and 25025). Three coupons per section were cut from the longitudinal direction of the upper, bottom and centre parts of the flat portion of the web. The coupons were then tested according to AS 1391 (SA 2007) for the material tensile testing. The material properties including the elastic modulus, yield stress, ultimate stress and ultimate strain obtained from the tensile coupon tests are summarised in Table 4. Figure 3 shows the typical stress-strain curve of structural aluminium alloy 5052 H36.

Test Set-up and Procedure

Forty tests were performed to investigate the web crippling mechanism of fastened ALC sections under the ETF and ITF loading conditions. A compressive force was applied to the specimens using the Materials Test System (MTS) machine with a compressive testing capacity of 500kN. Figures 4 (a) to (c) show the test set-up for the ETF and ITF loading conditions. High strength half-rounds were used at the bottom and the top of the specimen to simulate a simply supported beam scenario.

The specimens were first positioned between two bearing plates with similar lengths at the end and mid-span for both ETF and ITF loading conditions, respectively. Then, the flanges were attached to the bearing plates using 12 mm bolts. The measuring load was initialised with zero value and the test was then commenced. The cross-head of the MTS machine was driven down at a constant rate of 2 mm/min until the specimen failure. The applied load and both vertical and horizontal displacements of the ALC section were measured using a displacement control system. As shown in Figure 4 (b), the lateral displacement were measured using three laser displacement transducers (Lasers 1, 2 and 3) at three positions on the web, whereas the vertical displacement of the top bearing plate was measured using Laser 4 as shown in Figures 4(a) and (c).

TEST RESULTS AND DISCUSSION

The experimental web crippling capacities ($P_{F-Exp.}$) acquired from the two series of tests are presented in Tables 2 and 3. Note that the specimens ETF-10030-N50 and ITF-10030-N50 were both tested twice. 0.5% difference between the repeated tests was observed for ETF-10030-N50 specimens and 1.0% difference was found for ITF-10030-N50 specimens, signifying the accuracy and reliability of the test results.

Web Crippling Behaviour

Figures 5 (a) and (b) present the typical load-displacement responses for specimens ETF-20025-N150 and ITF-15030-N150, respectively. The curves of Lasers 1, 2 and 3 represent the lateral movements of the web in different longitudinal points while Laser 4 curve shows the vertical deformation of the ALC section during the test. As shown in Figure 6, web crippling failure was observed for all the ETF loading condition specimens. However, both web crippling and flange crushing failures were witnessed in the tests of ITF loading condition. The specimens loaded with 25 mm bearing plate experienced flange crushing failure as shown in Figure 7 while those loaded with 50, 100 and 150 mm bearing plates failed in web crippling failure (see Figure 8). Figure 9 (a) presents the applied load-vertical displacement responses for the ITF-25025-N25 section, while the influence of the bearing length on the web crippling failure capacities is illustrated in Figure 9 (b). The increased web crippling capacity for specimens experiencing flange crushing is due to the significant reduction in the corner radii of the deformed flange-web juncture and therefore the section became more resilient to the applied concentrated load. Alsanat et al. (2019a), Gunalan and Mahendran (2015) and Sundararajah et al. (2016) also observed a similar kind of failure during their experimental works on unfastened channel sections. It should be mentioned that this study does not consider the web crippling capacities obtained from the flange crushing tests when proposing design rules.

Specimen Length

Alsanat et al. (2019a) found that the ITF specimens loaded with 100 mm and 150 mm bearing plates were failed before reaching their maximum possible web crippling capacity due to the short length of the specimens. This was evidenced from the deformation of the specimen ends before reaching the maximum capacity of the sections. Alsanat et al. (2019b) numerically

investigated the influence of specimen length on the ultimate web crippling capacity of the section by conducting an extensive parametric study. Figure 10 shows the load-vertical displacement responses for unfastened ITF-25025-N150 specimen with different lengths ($L = 5d, 6d, 9d$ and $13d$). A significant drop of the $5d$ curve was observed comparing with $6d, 9d$, and $13d$ curves. Hence, it was recommended to increase the minimum specimen length to six times the section height for any future web crippling studies using aluminium sections. Similarly, in the current experimental study, it was found that the same specimens were also slightly failed prematurely even though the flanges were fastened to the supports. Figure 9 (b) shows the reduction in the capacities for the specimens loaded by 150 bearing length due to the short in specimen's length. This specifies that the specimen length (L) recommended by the AISI S909 (2008) should also be extended to $6d$ for the fastened ALC sections under the ITF loading condition.

The effect of restrained flanges

To investigate the effect of restrained flanges on the web crippling capacity, experimental data acquired from the present tests and those from Alsanat et al's (2019a) experiments for unfastened sections were analysed. It was observed that restraining the flanges has a considerable influence on the web crippling capacity of the ALC sections. In the case of unrestrained flanges, the out-of-plane bending moment (M_1) acting on the web plate due to the eccentric load (P_1) led to a large rotation to both the web and flanges, as shown in Figures 11 (a) and (b). Restraining the flanges, on the other hand, led to a significant reduction in M_1 due to the initiation of the opposite load (P_2) and moment (M_2) generated from the bolts, which eventually resulted in a substantial increase in the load carrying capability of the section as shown in Figures 11 (c) and (d). Figures 12 (a) to (d) display the differences in the experimental

web crippling failure modes for fastened and unfastened specimens under ETF and ITF loading conditions, respectively.

Figures 13 (a) and (b) compare the load-deflection curves for fastened and unfastened cases for ETF-20030N100 and ITF-20025N150 specimens, respectively. The overall behaviour is reasonably similar in both cases. Specifically, the displacement increased linearly with the load at a different slope up to the maximum load, and the ultimate failure in both cases practically occurred at the same vertical displacement. The maximum loads for the ETF-20030N100 specimens under fastened and unfastened conditions are 8.64 kN and 5.82 kN, respectively, with 33% difference while these values are 16.52 kN and 12.27 kN with 26% difference for the ITF-20025N150 specimens.

Figures 14 (a) and (b) present the web crippling capacity ratios of the fastened and unfastened sections under ETF and ITF loading conditions, respectively. Generally, it was noticed that fastening the flanges resulted in a significant increase in the web crippling capacity of the sections under both cases. Flange restraining had a more significant impact on the sections under the ETF loading conditions with up to 82% more capacity with an average of 50%, however; for the ITF loading conditions, the capacity increased to 40% with an average of 16%.

DESIGN RULES

Comparison of Test Results with Current Design Rules

The web crippling capacities obtained from the experimental results of the specimens with flanges being restrained were compared with the design capacities predicted by the AS/NZS 1664.1 (1997) for aluminium structures, and AS/NZS 4600 (2018) and Eurocode 3

Part 1-3 (CEN 2006) for cold-formed steel structures. As mentioned earlier, the equations given by both AS/NZS 1664.1 (1997) and Eurocode 3 Part 1-3 (CEN 2006) are not differentiated between unfastened and fastened support conditions. Therefore their predictions are identical in both cases even though the experimental web crippling capacities with fastened and unfastened flanges are significantly different.

Tables 5 and 6 show the comparisons of the test strengths (P_{F-Exp}) with the design capacities predicted using the AS/NZS 1664.1 (1997) (P_{AS1664}), AS/NZS 4600 (2018) (P_{AS4600}) and Eurocode 3 Part 1-3 (CEN 2006) (P_{EC3}) for the ETF and ITF loading conditions, respectively. The average measured cross-section dimensions and the measured material properties as given in Tables 2-4 were used to calculate the design strengths of the test specimens. For the loading condition of ETF with restrained flanges, the mean values of test-to-predicted strength ratios P_{F-Exp}/P_{AS1664} , P_{F-Exp}/P_{AS4600} and P_{F-Exp}/P_{EC3} are 0.73, 0.72 and 0.74, with the corresponding COVs of 0.24, 0.11 and 0.092, respectively. For the fastened specimens under the loading condition of ITF, the mean values of P_{F-Exp}/P_{AS1664} , P_{F-Exp}/P_{AS4600} and P_{F-Exp}/P_{EC3} are 1.03, 0.66 and 0.72 with the corresponding COVs values of 0.15, 0.05 and 0.11, respectively. Generally, it is found that the predicted web crippling strengths using the currently available design rules are unconservative for both loading conditions, except for the capacities predicted by the AS/NZS 1664.1 (1997) specification under the ITF load case, with a reasonably acceptable mean value but an unreliable COV value. Therefore, accurate design rules are needed to predict the web crippling capacities of fastened ALC sections under two-flange loading conditions.

Modified Design Rules

The modified design equation presented in this study follows the same approach obtained from the AS/NZS 4600 (2018). This is due to the fact that: (i) this generalised approach is the only available one for both fastened and unfastened cases, (ii) it is also employed by other specifications, e.g. Eurocode 9 Part 1-4 (CEN 2007) and AISI S100 (2016), and (iii) it is suitable for both cold-formed steel and aluminium members as confirmed by Alsanat et al. (2019a). Table 1 summarises the proposed coefficients (C , C_R , C_N and C_h) associated with Equation (6) to predict the web crippling capacity of fastened ALC sections under two-flange loading conditions.

The web crippling strengths, predicted by Equation (6) implementing the proposed web crippling coefficients, agree well with the experimental results of fastened ALC sections under the ETF and ITF loading conditions, as evidenced in Tables 5 and 6. The mean value of test-to-predicted capacity ratios of the specimens under the ETF loading condition is 1.00 with a COV of 0.08 while these values are 1.01 and 0.04 for the ITF loading conditions. Figures 15 (a) and (b) show the comparison between the experimental web crippling capacities of the ALC sections with the predictions using the proposed equation under the ETF and ITF loading conditions, respectively; from which the suitability of the proposed equation is confirmed.

Proposed Design Rules Incorporating Flange Fastening Effect

To propose a reliable approach to predict the increase of the web crippling capacities of fastened sections, the effect of restraining flanges on the main web crippling parameters should be first investigated. Figures 16 (a) and (b) were plotted for the ETF and ITF loading conditions, respectively, to demonstrate the relationship between the web crippling capacity ratios (P_F/P_U) against the bearing length to thickness ratios (N/t) for web slenderness ratios

(h/t) ranging from 30 to 101. Increasing the bearing length to thickness ratios (N/t) leads to an increase in the capacity ratio (P_F/P_U) due to flange restraint. However, such an elevation reduces when the web slenderness (h/t) increases. For instance, the rising slope of the ETF specimens with the web slenderness (h/t) of 30 is 0.016, while the slope drops to 0.004 for the ETF specimens with h/t of 101. Therefore, it can be concluded that both the bearing length to thickness (N/t) and the web slenderness (h/t) ratios have a compound flange restraining effect on the web crippling capacity of aluminium lipped channel sections.

From this observation, the influence of fastening the flanges on the web crippling capacity of the ALC sections (P_F/P_U), was plotted against the geometrical factor Nh/t^2 for the ETF and ITF loading conditions in Figures 17 (a) and (b), respectively. It was observed that by increasing the Nh/t^2 factor, the effect of flange fastening increases considerably in a nonlinear manner. Using non-linear least-squares to curve fit the data in Figures 17 (a) and (b), a new equation was proposed to predict the increase on the web crippling capacity due to flange restraint.

$$K_F = 0.6 \left(\frac{Nh}{t^2} \right)^a \geq 1 \quad (12)$$

where K_F is the fastening factor, the coefficients $a = 0.126$ and 0.095 for the ETF and ITF loading conditions, respectively.

This equation can be used in conjunction with any web crippling design rules for unfastened lipped channel sections to predict the increased web crippling capacity for fastened sections. The modified web crippling equations reported by Alsanat et al. (2019a) (Equations (3), (4), (6), (10) and (11)) for unfastened ALC sections under two-flange loading conditions were used in this study to assess the accuracy and reliability of the proposed fastening factor.

Tables 5 and 6 give the ratios of the test results to the predictions of Alsanat et al.'s (2019a) modified equations multiplied by the fastening factor (k_F). For the ETF loading condition (modified Equations (3), (6) and (10) multiplied by the K_F), the mean values of the test-to-predicted web crippling capacities of fastened ALC sections are 1.00, 1.00 and 0.99 while the corresponding COV values are 0.05, 0.08 and 0.07, respectively. For the ITF loading condition (modified Equations (4), (6) and (11) multiplied by the K_F), the mean values are 1.00, 1.01 and 0.98 and the corresponding COV values are 0.04, 0.03 and 0.03, respectively. It can be concluded that the web crippling capacity formulae incorporating the fastening factor is able to accurately predict the increased capacities of the ALC sections under two-flange loading conditions when the flanges are restrained to the supports (see Figures 15(a) and (b)).

Capacity Reduction Factor (ϕ_w)

The capacity reduction factor (ϕ_w) can be determined using the statistical model specified in the AISI S100 (2016) specification. This model considers various fabrication, material, and loading effects. Equation (13) is generally used to determine the capacity reduction factor for the capacity ratios gained from the international specifications and the proposed design rules.

$$\phi_w = 1.5M_mF_mP_me^{-\beta_0\sqrt{V_M^2+V_F^2+C_nV_P^2+V_Q^2}} \quad (13)$$

where ϕ_w is the resistance factor; $M_m = 1.1$ and $V_m = 0.06$ are respectively the mean and coefficient of variation of the material factor; $\beta_0 = 2.5$ is the target reliability index for beams; $F_m = 1.0$ and $V_F = 0.05$ are respectively the mean and coefficient of variation of the fabrication factor r ; $C_n = \frac{n^2-1}{n^2-3n}$ is the correction factor depending on the number of tests; $V_Q = 0.21$ is the coefficient of variation of load effect; P_m is the mean value of the test-to-predicted load

ratios; V_p is the coefficient of variation of the test-to-predicted load ratios and n is the number of tests.

Tables 5 and 6 show the capacity reduction factors (ϕ_w) for the proposed design rules. They are ranging between 0.90 and 0.94 and thus it is suggested to consider a ϕ_w factor of 0.90 for all the proposed design rules to estimate the web crippling capacities of the ALC sections under the two-flange loading conditions.

CONCLUSIONS

This paper described the details of an experimental investigation of fastened roll-formed aluminium lipped channel (ALC) sections under web crippling action with End-Two-Flange (ETF) and Interior-Two-Flange (ITF) loading conditions. Forty tests were performed with different geometrical cross-section parameters and bearing lengths. The details of web crippling results in terms of ultimate loads, load-deformation responses, and failure modes were discussed in detail. Web crippling is the prominent failure for both loading conditions however, the ITF specimens loaded with 25 mm bearing plates experienced a combined flange crushing and web crippling failure. Comparisons with the experimental results of fastened ALC sections showed that the nominal web crippling capacities predictions of the design guidelines obtained from the AS/NZS 1664.1 (1997), AS/NZS 4600 (2018) and Eurocode 3 Part 1-3 (CEN 2006) are mostly unconservative and unreliable. Hence, a modified design rule was proposed based on the experimental results to precisely predict the ultimate web crippling capacities of fastened ALC sections. Furthermore, the effect of restrained flanges on the web crippling capacity was discussed in detail. Fastening the flanges led to a significant increase in the web crippling capacity of the sections under both loading conditions (up to 82% more capacity for the ETF load case, and 40% for the ITF load case). A new design approach, incorporating the

fastening factor (k_f), was developed in this paper to predict the increased web crippling capacity due to fastened flanges. The results showed that this novel approach can be used in conjunction with the unfastened web crippling design guidelines to estimate the capacities of fastened ALC sections.

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Table 1. AS/NZS 4600 and proposed coefficients for lipped channel sections.

Equation	Flange condition	Load case	C	C_R	C_N	C_h	ϕ_w
Current (AS/NZS 4600)	Fastened	ETF	7.5	0.08	0.12	0.048	0.85
		ITF	20	0.10	0.08	0.031	0.85
Alsanat et al. (2019a)	Unfastened	ETF	0.273	0.21	0.16	0.06	0.90
		ITF	0.78	0.17	0.04	0.03	0.93
Proposed	Fastened	ETF	0.231	0.21	0.35	0.05	0.91
		ITF	0.78	0.20	0.08	0.02	0.93

Table 2. Specimen details and test results for fastened ETF load case.

Specimen	Depth d (mm)	Thickness t (mm)	Radius r_i (mm)	Flange b_f (mm)	Lip l_b (mm)	Length L (mm)	Load $P_{F-Exp.}$ (kN)
ETF-10030-N25	107.2	2.95	4.9	60.5	14.8	316	6.80
ETF-10030-N50(a)	106.4	2.95	5.0	58.3	16.2	317	8.46
ETF-10030-N50(b)	107.2	2.97	4.9	59.6	15.0	317	8.42
ETF-10030-N100	107.2	2.95	4.8	59.3	15.1	316	11.25
ETF-15030-N25	156.8	2.93	4.9	62.9	23.0	466	6.37
ETF-15030-N50	157.6	2.93	5.0	63.2	22.3	465	7.84
ETF-15030-N100	158.4	2.92	5.1	63.3	21.8	465	9.92
ETF-15030-N150	155.4	2.92	4.9	63.4	23.0	467	12.45
ETF-20025-N25	208.2	2.42	5.1	74.5	25.4	617	4.74
ETF-20025-N50	208.0	2.43	4.9	74.3	25.3	615	5.15
ETF-20025-N100	207.2	2.43	5.0	74.2	25.8	615	6.19
ETF-20025-N150	204.1	2.43	4.8	75.9	26.4	615	7.51
ETF-20030-N25	204.5	2.9	4.6	74.9	27.5	611	6.45
ETF-20030-N50	208.3	2.9	5.0	73.1	27.6	615	7.37
ETF-20030-N100	204.4	2.89	4.6	75.5	27.6	613	8.64
ETF-20030-N150	208.2	2.89	5.0	73.4	27.2	615	11.05
ETF-25025-N25	259.9	2.43	4.4	80.7	23.5	765	4.45
ETF-25025-N50	259.8	2.44	4.9	76.2	23.8	765	4.90
ETF-25025-N100	262.2	2.44	4.8	76.1	22.6	765	6.20
ETF-25025-N150	260.4	2.45	4.6	76.2	23.5	765	7.20

Note: ETF-10030-N50(a) and ETF-10030-N50(b) were repeated tests

Table 3. Specimen details and test results for fastened ITF load case.

Specimen	Depth d (mm)	Thickness t (mm)	Radius r_i (mm)	Flange b_f (mm)	Lip l_b (mm)	Length L (mm)	Load $P_{F-Exp.}$ (kN)
ITF-10030-N25	106.8	2.94	4.8	59.3	14.3	527	21.88
ITF-10030-N50(a)	106.5	2.95	4.9	59.4	14.8	525	20.69
ITF-10030-N50(b)	106.8	2.94	4.9	59.0	14.4	521	20.90
ITF-10030-N100	106.2	2.94	4.8	59.6	14.4	523.5	23.68
ITF-15030-N25	156.6	2.93	4.8	62.6	22.6	774	19.99
ITF-15030-N50	156.8	2.92	4.9	62.4	22.7	775	19.34
ITF-15030-N100	156.3	2.92	4.8	62.1	22.7	776	22.99
ITF-15030-N150	156.7	2.93	4.9	62.5	22.8	774	23.99
ITF-20025-N25	206.3	2.43	4.6	74.0	26.3	1028	13.41
ITF-20025-N50	207.3	2.44	4.9	73.3	26.0	1022	13.93
ITF-20025-N100	207.4	2.43	5.0	73.9	26.3	1019	15.83
ITF-20025-N150	207.5	2.44	4.6	73.4	26.9	1021	16.52
ITF-20030-N25	205.5	2.9	4.4	74.5	31.6	1022	19.46
ITF-20030-N50	206.7	2.93	4.8	75.3	27.4	102	19.97
ITF-20030-N100	206.4	2.9	4.8	74.4	26.7	1021	22.63
ITF-20030-N150	206.6	2.89	4.6	74.5	26.7	1022	22.67
ITF-25025-N25	259.8	2.43	4.4	76.1	22.1	1273	14.21
ITF-25025-N50	260.1	2.42	4.5	76.0	22.4	1274	14.05
ITF-25025-N100	259.9	2.43	4.5	76.3	22.5	1269	15.99
ITF-25025-N150	259.8	2.43	4.5	76.2	22.2	1275	16.72

Note: ITF-10030-N50(a) and ITF-10030-N50(b) were repeated tests

Table 4. Mechanical properties of aluminium sections used in the experimental study.

Section	E (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

Note: E = elastic modulus, $\sigma_{0.2}$ = static 0.2% tensile proof stress, σ_u = tensile strength and ε_u = ultimate strain

Table 5. Experimental ultimate loads and comparisons with current and proposed design rules – fastened ETF load case.

Specimen	h/t	$P_{F-Exp.}$ (kN)	Ultimate load ratios (Test-to-predicted)						
			P_{AS1664}	P_{AS4600}	P_{EC3}	$K_F \cdot$ $P_{U-AS1664}$	$K_F \cdot$ $P_{U-AS4600}$	$K_F \cdot$ P_{U-EC3}	P_P
F-ETF-10030-N25	31.1	6.80	0.98	0.56	0.61	0.96	0.90	0.94	0.86
F-ETF-10030-N50	30.7	8.44	0.86	0.63	0.70	1.00	0.91	1.00	0.89
F-ETF-10030-N100	31.1	11.25	0.70	0.73	0.81	1.03	0.94	1.05	0.94
F-ETF-15030-N25	48.1	6.37	0.95	0.59	0.61	0.97	0.94	0.92	0.92
F-ETF-15030-N50	48.4	7.84	0.82	0.66	0.70	1.01	0.94	0.97	0.94
F-ETF-15030-N100	48.7	9.92	0.66	0.74	0.79	1.01	0.95	1.00	0.97
F-ETF-15030-N150	47.9	12.45	0.59	0.85	0.86	1.03	1.01	1.04	1.05
F-ETF-20025-N25	79.8	4.74	1.02	0.72	0.76	1.13	1.17	1.13	1.16
F-ETF-20025-N50	79.6	5.15	0.76	0.69	0.73	1.00	1.01	1.00	1.01
F-ETF-20025-N100	79.2	6.19	0.57	0.73	0.76	0.94	0.95	0.95	0.97
F-ETF-20025-N150	78.0	7.51	0.50	0.80	0.78	0.93	0.96	0.93	1.01
F-ETF-20030-N25	65.3	6.45	0.94	0.65	0.64	1.01	1.03	0.97	1.01
F-ETF-20030-N50	66.4	7.37	0.77	0.68	0.70	1.00	0.97	0.96	0.98
F-ETF-20030-N100	65.6	8.64	0.59	0.74	0.74	0.94	0.94	0.94	0.96
F-ETF-20030-N150	66.6	11.05	0.53	0.82	0.81	0.97	0.99	0.98	1.03
F-ETF-25025-N25	101.3	4.45	0.90	0.73	0.71	1.07	1.19	1.07	1.16
F-ETF-25025-N50	100.5	4.90	0.71	0.72	0.73	1.01	1.07	1.01	1.05
F-ETF-25025-N100	101.5	6.20	0.55	0.79	0.78	0.99	1.05	1.00	1.06
F-ETF-25025-N150	100.4	7.20	0.46	0.83	0.78	0.93	1.02	0.94	1.05
Mean			0.73	0.72	0.74	1.00	1.00	0.99	1.00
COV			0.24	0.11	0.09	0.05	0.08	0.05	0.08
ϕ_w						0.92	0.90	0.92	0.91

Table 6. Experimental ultimate loads and comparisons with current and proposed design rules - fastened ITF load case.

Specimen	h/t	$P_{F-Exp.}$ (kN)	Ultimate load ratios (Test/Prediction)						
			P_{AS1664}	P_{AS4600}	P_{EC3}	$K_F \times$ $P_{U-AS1664}$	$K_F \times$ $P_{U-AS4600}$	$K_F \times$ P_{U-EC3}	P_P
ITF-10030-N25	31.1	21.88 ^a	1.33	0.68	0.65	-	-	-	-
ITF-10030-N50	30.8	20.79	1.10	0.59	0.60	1.04	1.00	0.97	0.94
ITF-10030-N100	30.9	23.68	0.99	0.62	0.68	1.04	1.02	1.02	0.98
ITF-15030-N25	48.2	19.99 ^a	1.25	0.67	0.64	-	-	-	-
ITF-15030-N50	48.3	19.34	1.06	0.61	0.62	1.00	0.98	0.93	0.95
ITF-15030-N100	48.2	22.99	0.99	0.65	0.72	1.05	1.03	1.01	1.01
ITF-15030-N150	48.1	23.99 ^b	0.86	0.63	0.73	1.00	0.99	0.99	0.99
ITF-20025-N25	79.0	13.41 ^a	1.17	0.68	0.69	-	-	-	-
ITF-20025-N50	78.9	13.93	1.06	0.65	0.71	1.00	1.02	0.95	1.01
ITF-20025-N100	79.2	15.83	0.97	0.67	0.79	1.02	1.03	1.00	1.05
ITF-20025-N150	79.2	16.52 ^b	0.81	0.64	0.79	0.94	0.97	0.96	0.99
ITF-20030-N25	65.9	19.46 ^a	1.18	0.67	0.66	-	-	-	-
ITF-20030-N50	65.3	19.97	1.05	0.63	0.66	1.00	1.00	0.94	0.97
ITF-20030-N100	65.9	22.63	0.97	0.66	0.75	1.02	1.02	1.00	1.02
ITF-20030-N150	66.3	22.67 ^b	0.80	0.62	0.73	0.93	0.95	0.94	0.96
ITF-25025-N25	101.3	14.21 ^a	1.21	0.74	0.79	-	-	-	-
ITF-25025-N50	101.7	14.05	1.05	0.69	0.78	1.01	1.05	0.98	1.04
ITF-25025-N100	101.2	15.99	0.94	0.70	0.85	1.00	1.04	1.01	1.06
ITF-25025-N150	101.3	16.72 ^b	0.81	0.68	0.87	0.96	1.00	0.99	1.03
Mean			1.03	0.66	0.72	1.00	1.01	0.98	1.00
COV			0.15	0.05	0.11	0.04	0.03	0.03	0.04
ϕ_w						0.93	0.94	0.92	0.93

Note: ^a The specimen failed in combined web crippling and flange crushing.

^b The ends of specimen started to deform before reaching the ultimate load.

(a) Fastened ETF load case

(b) Locations of web lasers

(c) Fastened ITF load case

(a) ETF-20025-N25

(b) ETF-20030-N150

(c) ETF-15030-N25

(d) ETF-25025-N100

(a) ITF-10030-N100

(b) ITF-20030-N150

(c) ITF-15030-N50

(a) Applied load versus vertical deflection (ITF-25025-N25)

(b) Failure load versus bearing length – ITF load case

(a) Initial configuration
(Unfastened)

(b) Web and flange
rotations (Unfastened)

(c) Initial configuration
(Fastened)

(d) Web rotation
(Fastened)

(a) ETF Unfastened

(b) ETF Fastened

(c) ITF Unfastened

(d) ITF Fastened

a) ETF load case

(b) ITF load case

(a) ETF load case

(b) ITF Load case

(a) ETF load case

(b) ITF load case

- Fig. 1.** Application of roll-formed aluminium purlins, Minto reservoir – NSW, Australia
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