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# Web Crippling Investigations of Aluminium Lipped Channel Sections with Web holes – End-Two-Flange Loading Conditions

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## Abstract

The use of aluminium as a building material and load-bearing member has increased considerably due to their unique characteristics as a highly ductile, recyclable and corrosion-resistant material. While its structural potential is still being elucidated, its modulus of elasticity is inferior to that of steel. Hence it is more vulnerable to certain types of buckling instabilities such as web crippling. Web crippling failure occurs in thin-walled members including lipped channel beams, which can be found in the structural system as joists or rafters where transverse forces may arise. Recently the authors have thoroughly investigated the web crippling behaviour and design of roll-formed aluminium lipped channel sections subjected to web crippling. However, in real-life applications, holes in the web maybe required for the installation of electrical or plumbing services, which could have a great influence on the web crippling capacity of the member. Such influence has not been investigated yet, thus this study is conducted to experimentally explore the influence of web openings on the web crippling characteristics of these sections under the end-two-flange loading conditions. Fifteen specimens with various hole sizes are tested as specified by the American Institute of Steel and Iron (AISI) standard. Design recommendations in the form of web crippling strength reduction factor are proposed in this study.

**Keywords:** Aluminium; Lipped Channel Sections; Web Crippling; Web opening; Reduction Factor

## 1. Introduction

Over the last years, aluminium alloys have become more attractive in construction as a structural material. The high ductility, durability, corrosion resistance, strength-to-weight ratio, workability and many other inherent properties have led to significantly increase the aluminium production used in construction. Aluminium sections, such as Channels and Zed sections, fabricated using the roll-forming technique have been utilised as purlins, girts and beams in structural systems were harsh marine and industrial environments dominate. BlueScope Permalite Australia is producing these sections using 5052-H36 aluminium alloy grades due to the exceptional corrosion resistance against saltwater and spray.

To date, the buckling instabilities of roll-formed aluminium sections have not been thoroughly investigated. Alsanat et al [1-5] studied the localized buckling (web crippling) failure of aluminium lipped channels (ALC) sections under all possible load cases (end-one-flange (EOF), interior-one-flange (IOF), end-two-flange (ETF) and interior-two-flange (ITF)). These beams were also investigated against web shear buckling failure by Rouholamin et al. [6,7]. The mechanical properties and residual stresses of ALCB's were thoroughly explored by Pham and Rasmussen [8].

In practice, it might be necessary to punch in the web of structural members for the installation of the plumbing and/or electrical systems. The presence of such holes may lead to a significant reduction to the section strength and the prediction of reduced strength is needed. Uzzaman et al. [9–12] and Lian et al. [13–16] experimentally and numerically investigated the influence of web circular opening on the web crippling capacity of cold-formed steel channel sections under all load cases. Further, Uzzaman et al. [17-18] have recently reported web crippling tests and numerical analyses on cold-formed steel channel sections with edge-stiffened circular web holes under various loading conditions. For stainless-steel sections, Yousefi et al. [19,20] studied the reduction in the web crippling capacities of cold-formed lipped channel sections with circular web openings using both experimental and numerical scheme. Zhou and Young [21] performed a combination of experiments and numerical analyses on extruded aluminium hollow sections subjected to web crippling under two-flange loading conditions. All the aforementioned studies proposed reduction factors to estimate the reduced web crippling capacity due to the opening. In the literature, however, no research has been conducted to investigate the influence of web opening in the web crippling capacity of roll-formed aluminium lipped channel sections. It is also believed that the available design guidelines will fail to predict the actual capacities of these sections due to their empirical nature.

The present study aims to determine the effect of web opening on the web crippling capacity of roll-formed ALC sections under ETF loading condition with both unfastened and fastened flange scenarios. A Series of tests was carried out on the sections with holes located at the mid-depth of the web. The experimental data was then used to propose a reduction factor equation to determine the reduced capacity. Statistical verification was performed to confirm the accuracy of this factor, and showed a good agreement of data, with an acceptable coefficient of variation.

## 2. Experimental investigation

### 2.1. Test specimens

In total, 16 lipped channels with and without openings were prepared and tested. The test specimens were roll-formed using 5052-H36 aluminium sheets. Sections with 250 mm depth, 2.5 mm and 3 mm thicknesses and 5mm inside bent radius ($r_i$) were considered herein. To investigate the influence of the web opening on the web crippling capacity, opening with nominal diameters ($a$) ranging from 50, 120 and 190 mm were perforated in the web. The opening diameter $a$ to the flat portion of the web depth ($h$) ratios ($a/h$) were 0.2, 0.5, and 0.8. All openings were located, where their influence is optimal; the mid-depth of the webs and 50 mm fixed offsite between the opening perimeter and specimen's end. The specimens length ($L$) is three times the flat depth ($3h$), according to The AISI S909 [23] Standard test method. Table 1 summarises the measured sectional dimensions of the specimens which are accurately measured using a tap meter, micrometre vernier, and calliper. Figure 1 shows the typical sectional profile for lipped channel sections with holes.

For specimen designation, a label was given for each specimen as presented in Table 1. For example, the label F- 250-3-A0.5 can be explained as: fastened condition (F), loading condition (ETF), section depth (250), section thickness (3) and the hole ration (A0.5). The letter "U" indicates the unfastening loading conditions.

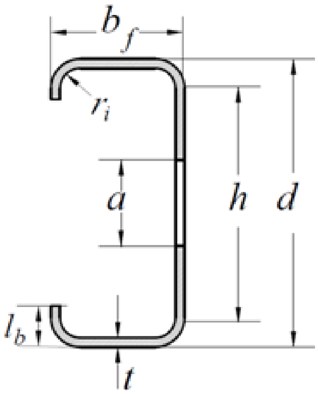



**Figure 1:** Typical sectional profile for lipped channel sections with holes

Note: specimen names end with (a) or (b) were repeated tests

### 2.2. Material properties

The mechanical properties of the roll-rolled channel sections were investigated using coupon tests. Flat coupons were taken from the flat portion of the web at different positions (upper middle and bottom). All coupons were cut in the longitudinal direction (parallel to the rolling direction), The dimensions of the coupons were 12.5mm wide and 50 mm long. The coupons were then tested in Instron tensile testing machine, and yield stress ($\sigma_{0.2}$) and Young's modulus ($E$) (given in Table 1) were acquired from the stress-strain curve, Figure 2 show the typical stress-strain curve for a typical coupon cut from section 250-2.5.

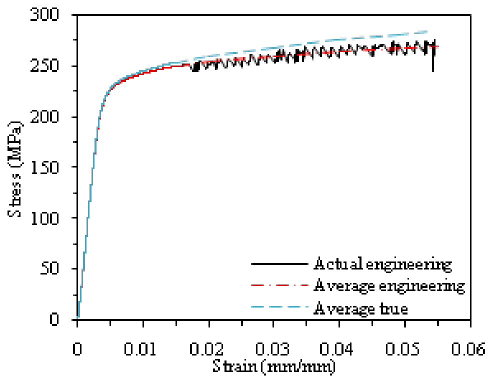



**Figure 2:** Typical stress-strain curve for 5052-H36t

### 2.3. Test rig and procedure

According to the AISI S909 [23] specification guidelines, the ALC sections were tested under ETF loading condition. Figures 3(a) and (b) depict the test set-up for unfastened and fastened tests, respectively. The specimen was first positioned between two identical and high strength bearing plates. The bottom and top flanges at the end of the specimen were attached to the bearing plates using M12 bolts for fastened scenario while they were kept unrestrained for the unfastened scenario. Half rounds were attached to the bearing plates to simulate hinge support. MTS machine with 500 kN capacity was used to apply a load by driving a hydraulic cross-head downward with a constant rate of 2mm/min. The applied force and the vertical movement were precisely recorded using a data-acquisition system. Figures 4 (a) and (b) present the load-vertical displacement curve for ALC sections with different hole ratios.

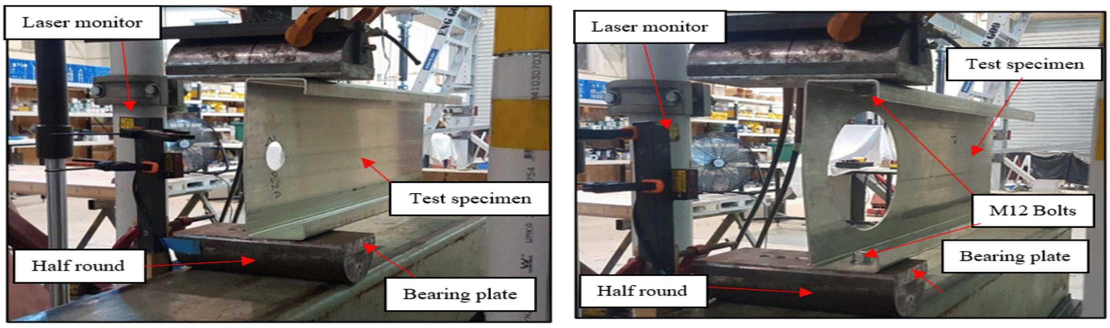
## 3. Proposed web crippling reduction factor

Alsanat et al. [1,3] modified the equation provided by AISI S100(Equation (1)) for cold-formed steel lipped channel sections to accurately predict the web crippling capacity for unfastened and fastened ALC sections with no holes under the ETF. The effect of elastic moduli of aluminium alloys was incorporated in the modified Equation (2), and the new coefficient factors $C$, $C_R$, $C_N$ and $C_h$)were proposed and given in Table 2.

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

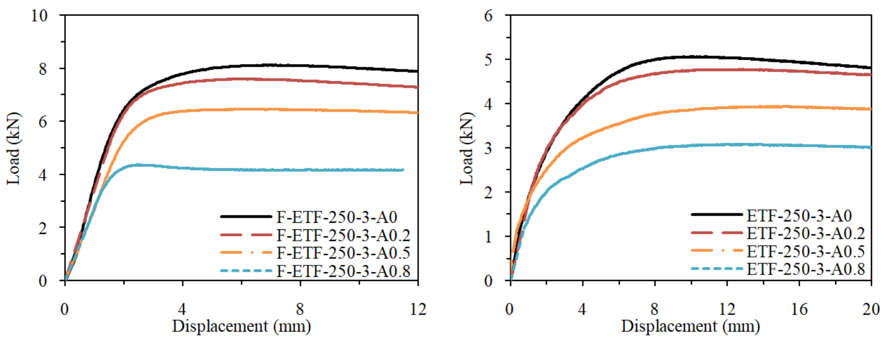
**Table 1:** Geometric and mechanical properties of tested ALC sections

| Specimen | *N* (mm) | *d* (mm) | *t* (mm) | $b_f$ (mm) | $r_i$ (mm) | $l_b$ (mm) | *L* (mm) | *E* (MPa) | $f_y$ (MPa) | $P_{Exp.}$ (kN) |
|---|---|---|---|---|---|---|---|---|---|---|
| U-ETF-250-3-A0(a) | 100 | 253.2 | 2.95 | 72.2 | 5.0 | 25.0 | 716 | 65050 | 210 | 5.1 |
| U-ETF-250-3-A0(b) | 100 | 253.7 | 2.93 | 76.7 | 4.8 | 24.8 | 716 | 65050 | 210 | 5.0 |
| U-ETF-250-3-A0.2(a) | 100 | 252.4 | 2.94 | 76.7 | 4.8 | 24.9 | 716 | 65050 | 210 | 4.8 |
| U-ETF-250-3-A0.2(b) | 100 | 252.3 | 2.94 | 76.9 | 5.0 | 23.7 | 714 | 65050 | 210 | 4.7 |
| U-ETF -250-3-A0.5 | 100 | 253.5 | 2.97 | 77.2 | 4.8 | 23.6 | 715 | 63555 | 206 | 3.9 |
| U-ETF -250-3-A0.8(a) | 100 | 254.0 | 2.94 | 77.7 | 4.8 | 25.6 | 714 | 63555 | 206 | 3.0 |
| U-ETF -250-3-A0.8(b) | 100 | 262.1 | 2.44 | 76.2 | 4.8 | 22.7 | 715 | 63555 | 206 | 3.1 |
| U-ETF -250-2.5-A0 | 100 | 252.8 | 2.44 | 76.2 | 5.0 | 25.1 | 713 | 63555 | 206 | 3.8 |
| U-ETF -250-2.5-A0.2 | 100 | 252.4 | 2.55 | 76.0 | 5.0 | 25.3 | 714 | 63955 | 214 | 3.1 |
| U-ETF -250-2.5-A0.5 | 100 | 252.2 | 2.44 | 76.2 | 5.0 | 25.1 | 1440 | 63955 | 214 | 2.4 |
| U-ETF -250-2.5-A0.8 | 100 | 252.5 | 2.94 | 76.8 | 5.0 | 25.6 | 714 | 63955 | 214 | 2.0 |
| F-ETF -250-3-A0 | 100 | 253.7 | 3.00 | 76.5 | 4.8 | 24.6 | 711 | 63955 | 214 | 8.1 |
| F-ETF -250-3-A0.2 | 100 | 252.9 | 2.99 | 76.9 | 4.8 | 25.6 | 714 | 64125 | 212 | 7.6 |
| F-ETF -250-3-A0.5 | 100 | 253.2 | 2.93 | 76.6 | 5.0 | 24.5 | 716 | 64125 | 212 | 6.5 |
| F-ETF -250-3-A0.8 | 100 | 253.7 | 2.95 | 72.2 | 5.0 | 25.0 | 716 | 64125 | 212 | 4.4 |




(a) Unfastened - ETF (b) Fastened - ETF

Figures 3: web crippling test set-up




(a) unfastened - ETF (b) Fastened - ETF

Figures 4: load-vertical displacement curves for ALC specimens with different hole ratios

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

Where $C$ is the web crippling 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 coefficients are summarised in Table 2. Note that in Equation (1), 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 2:** Alsanat et al.'s [1,3] web crippling coefficients for ALC sections

| Flange condition | Load case | $C$ | $tC_R$ | $C_N$ | $C_h$ | $\phi_w$ |
|---|---|---|---|---|---|---|
| Unfastened | ETF | 0.273 | 0.21 | 0.16 | 0.06 | 0.90 |
| Fastened | ETF | 0.231 | 0.21 | 0.35 | 0.05 | 0.91 |

For the test specimens, the web crippling strengths of the sections without the web holes were obtained. Thus, the ratio of the web crippling strengths for sections with the web holes divided by the sections without the web holes, which is the strength reduction factor ($R$), was used to quantify the degrading influence of the web holes on the web crippling strengths under the end-two-flange loading condition. Evaluation of the experimental results shows that the ratios $a/h$is the primary parameters influencing the web crippling behaviour of the sections with web holes as shown in Figure 5. The reduction in the web crippling capacity can reach up to 43% of specimens without web holes. Based on the experimental results obtained from this study; strength reduction factor ($R_{prop}$) is proposed using bivariate linear regression analysis for the end-two-flange loading condition.

$$R_{prop} = \left[1.05 - 0.57\left(\frac{a}{h}\right)^{1.5} + 0.06\left(\frac{N}{h}\right)\right] \times \left(1 - 0.008\left(\frac{N}{t}\right)\right) \le 1 \quad (3)$$

**Table 3:** Accuracy data for the proposed ETF web bearing capacity reduction factor

| Specimen | $P_{Exp.}$ | $R$ | $R_{prop.}$ | $R/R_{prop.}$ |
|---|---|---|---|---|
| U-ETF-250-3-A0(a) | 5.1 | 1.00 | 1.00 | 1.00 |
| U-ETF-250-3-A0(b) | 5.0 | 0.98 | 1.00 | 0.98 |
| U-ETF-250-3-A0.2(a) | 4.8 | 0.94 | 0.89 | 1.06 |
| U-ETF-250-3-A0.2(b) | 4.7 | 0.92 | 0.89 | 1.04 |
| U-ETF -250-3-A0.5 | 3.9 | 0.76 | 0.73 | 1.05 |
| U-ETF -250-3-A0.8(a) | 3.0 | 0.59 | 0.58 | 1.02 |
| U-ETF -250-3-A0.8(b) | 3.1 | 0.61 | 0.58 | 1.05 |
| U-ETF -250-2.5-A0 | 3.8 | 1.00 | 0.98 | 1.02 |
| U-ETF -250-2.5-A0.2 | 3.1 | 0.82 | 0.88 | 0.94 |
| U-ETF -250-2.5-A0.5 | 2.4 | 0.64 | 0.73 | 0.88 |
| U-ETF -250-2.5-A0.8 | 2.0 | 0.53 | 0.57 | 0.93 |
| F-ETF -250-3-A0 | 8.1 | 1.00 | 1.00 | 1.00 |
| F-ETF -250-3-A0.2 | 7.6 | 0.94 | 0.89 | 1.06 |
| F-ETF -250-3-A0.5 | 6.5 | 0.80 | 0.73 | 1.10 |
| F-ETF -250-3-A0.8 | 4.4 | 0.54 | 0.57 | 0.95 |
| Mean | | | | 1.01 |
| COV | | | | 0.06 |

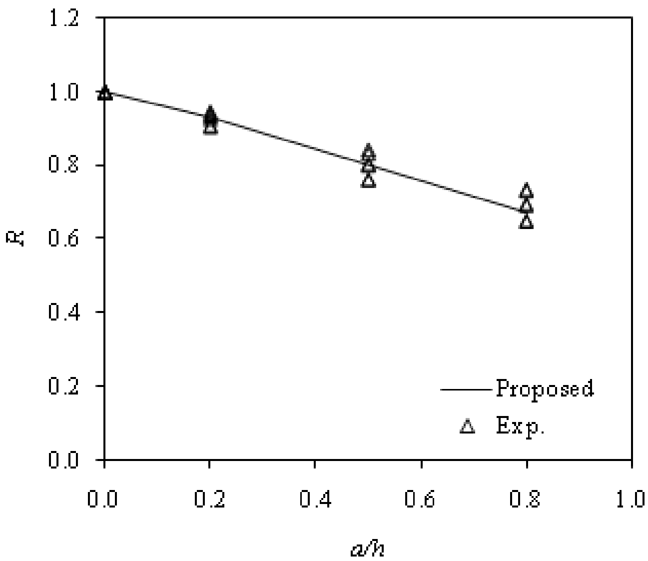



**Figure 5:** Variation in reduction factors with a/h

The web crippling reduction values ($R_{prop.}$) predicted by Equation (3) agree well with the experimental web crippling reduction values ($R$) of ALC sections under the ETF load case, as evidenced in Table 3. The mean value of $R/R_{prop.}$ of the sections is 1.01 with a COV of 0.06. Figure5 compares the experimental reduction results of the ALC sections with the predictions using the proposed Equation (3) under the ETF load case; from which the suitability of the proposed equation is confirmed.

## 4. Conclusions

This paper presents an experimental web crippling study of roll-formed aluminium lipped channel sections with/without web holes under end-two-flange load case. Both unfastened and fastened scenarios were considered. Fifteen specimens were tested and the influence of web hole-to-section depth ratio was investigated. The reduction in the web crippling capacity can reach up to 43% of specimens without web holes. Based on the experimental data, web crippling strength reduction factor equation was proposed for the Unfastened/fastened ETF load case. The comparison between the experimental and proposed reduction factor confirms the accuracy and reliability of the proposed equation.

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