Experimental study of aluminium lipped channel sections subjected to web crippling under two flange load cases

Mr Husam Alsanat

School of Engineering and Built Environment, Griffith University
Gold Coast, Australia. husam.alsanat@griffithuni.edu.au

Dr Shanmuganathan Gunalan

School of Engineering and Built Environment, Griffith University
Nathan, Australia. s.gunalan@griffith.edu.au

Professor Hong Guan

School of Engineering and Built Environment, Griffith University
Gold Coast, Australia. h.guan@griffith.edu.au

Dr Poologanathan Keerthan

Faculty of Engineering & Environment, Northumbria University
Newcastle, UK. keerthan.poologanathan@northumbria.ac.uk

Professor John Bull

Faculty of Engineering & Environment, Northumbria University
Newcastle, UK. john.w.bull@northumbria.ac.uk

Abstract

The application of aluminium alloy members in building construction has considerably increased in recent years due to their appealing advantages such as corrosion resistance and high strength-to-weight ratio. However, the elastic modulus of aluminium is only one third of that of steel, making aluminium members being susceptible to various buckling modes including web crippling. To date, only a limited amount of research study has been conducted to investigate the web crippling failure phenomenon in aluminium structural members, and no research has been carried out on the web crippling behaviour of roll-formed aluminium lipped channel sections. Hence, an experimental study was conducted to assess the web crippling behaviour and capacities of unfastened aluminium lipped channel sections under two flange load cases (End-Two-Flange (ETF) and Interior-Two-Flange (ITF)). Forty tests were performed with different bearing lengths, web heights and thicknesses. The results obtained from this study were then compared with the nominal web crippling strengths predicted using the design rules provided by the Australian, European and American Standards. The comparison showed that the current design equations are potentially unsafe and unreliable to estimate the capacity for aluminium lipped channel sections under both ETF and ITF load cases. Hence, suitable modifications were proposed to the available design equations based on the experimental results to accurately predict the web crippling capacities of aluminium lipped channel sections. Generally, it is shown that the web crippling results acquired from the modified equations agreed well with the test results.

Key words: aluminium lipped channel sections; web crippling; two flange load cases; experimental study; design rules

Nomenclature

b_f	flange width
C	web crippling coefficient
C_f	yield stress coefficient
C_h	web slenderness coefficient
C_n	correction factor depending on the number of tests
C_N	bearing length coefficient
C_R	inside corner radius coefficient
d	web (total) height
d_w	web height between flange mid-lines
E	Young's modulus of elasticity
F_m	mean value of fabrication factor
f_y	yield stress
h	web (flat) height
k_y	the yield strength factor
L	specimen length
l_b	lip length
M_m	mean value of material factor
n	number of tests
N	load bearing length
P_{AS1664}	ultimate load obtained from Eqs. (1 and 2)
$P_{AS1664(prop.)}$	ultimate load obtained from Eqs. (8 and 9)
P_{AS4600}	ultimate load obtained from Eq. (4a)
P_{EC3}	ultimate load obtained from Eqs. (5 and 6)
$P_{EC3(Prop.)}$	ultimate load obtained from Eqs. (10 and 11)
P_{EC9}	ultimate load obtained from Eq. (3)
$P_{Exp.}$	ultimate load obtained from experimental test
P_{LAVAN}	ultimate load obtained from Eq. (4b)
P_m	mean value of tested-to-predicted load ratio
$P_{Predicted}$	ultimate load obtained from equation
$P_{prop.}$	ultimate load obtained from Eq. (7)
r_i	inside corner radius
t	thickness
V_F	coefficient of variation of fabrication factor
V_m	coefficient of variation of material factor
V_P	coefficient of variation of tested-to-predicted load ratio
V_Q	coefficient of variation of load effect
α	coefficient for various local loads and support categories
β_0	reliability index
ε_u	elongation (tensile strain) at fracture
σ_u	static ultimate tensile strength
$\sigma_{0.2}$	static 0.2% proof stress
θ	angle between the plane of web and the plane of bearing surface
ϕ_w	resistance (capacity) factor
γ_{M1}	partial safety factor

1. Introduction

During recent decades, the use of aluminium alloys in construction industries has prominently increased due to the growing demand for sustainable structural performance. Possessing properties like high strength-to-weight ratio, corrosion resistance, recyclability, and low maintenance make aluminium structures cost and energy efficient. Moreover, aluminium proves to be more favourable than other materials in their entire life

cycle, regardless of high energy consumption and cost during production [1-3]. From design perspective, aluminium alloys can be made available with high strength, within the range of steel. However, the relatively low elastic modulus of aluminium material makes aluminium members more susceptible to various kinds of instabilities including web crippling.

In construction, aluminium as a load carrying element is becoming increasingly popular in a wide range of structural applications, from conventional structural applications including joists, rafters, purlins and columns [4] to innovative applications such as passive energy dissipation devices for seismic protection in framed buildings [5]. Figure 1 (a) shows the structural application of aluminium lipped channel members as purlins in the Caloundra potable water reservoir, Australia, while Figure 1 (b) shows the lipped channel section profile. Similar to cold-formed steel members, unstiffened roll-formed aluminium joists and bearers may experience localised web crippling failure due to high transverse concentrated forces applied over a short length of the beam. The web crippling failure modes of a beam can be different according to the loading locations such as end columns, interior columns and joists supported by bearers. For example when an aluminium rafter supported by columns from the bottom and highly loaded by a purlin from the top may induce web crippling failure. Depends on the locations of the loads and supports, four failure scenarios can be potentially occurred according to the AISI Standard test method [6], namely End-One-Flange (EOF), Interior-One-Flange (IOF), End-Two-Flange (ETF), and Interior-Two-Flange (ITF) load cases.

The aims of this research are to investigate the web crippling strengths and behaviour of aluminium lipped channel sections under the ETF and ITF load cases, and evaluate the accuracy and the reliability of the current design rules. Test setup and specimen lengths were selected according to the AISI Standard test method [6]. The web crippling strengths acquired from the tests were compared with the predicted web crippling capacities using the currently available design rules including AS/NZS 1664.1 [7], AA Specification [8], AS/NZS 4600 [9] and AISI S100 [10] and Eurocode 3 [11]. Subsequently, suitable amendments were made to improve the accuracy of these equations and to produce accurate predictions of the web crippling capacity for aluminium lipped channel sections. It should be noted that the design rules for aluminium structures in AS/NZS 1664.1 [7] are identical to those in AA Specification [8], and hence only AS/NZS 1664.1 [7] is discussed in this paper. Similarly the design rules for cold-formed steel structures in AS/NZS 4600 [9] are identical to those in AISI S100 [10], and hence only AS/NZS 4600 [10] is discussed in this paper.

2. Previous studies on web crippling

Literature review shows that a considerable amount of experimental research has been conducted to investigate the web crippling failure phenomenon in structural members. Most of these studies were focused on cold-formed steel members with only few of them being performed using aluminium members.

2.1. Cold-formed steel sections

Since 1940s, extensive testing of different cold-formed steel sections such as Z-, C- and hat sections as well as built up sections has been undertaken in order to develop empirical design rules to predict the web crippling capacity. The web crippling capacities of cold-formed steel sections under different load cases were investigated in the past [12-23] using different section types, material strengths and bearing lengths.

Recently Gunalan and Mahendran [24] investigated the web crippling capacities of DuraGal sections (unlipped channel) subjected to two flange (ETF and ITF) load cases using unfastened bearing plates. The results were compared with the currently available design rules to investigate their suitability and new equations were proposed to predict the web crippling capacities of channel sections. Sundararajah et al. [25, 26] conducted a series of tests of lipped channel beams (LCBs) under two flange load cases and proposed an improved equation to determine the web crippling capacities of LCBs. The equation uses the same technique as of AS/NZS 4600 [9] with introduction of a new factor accounting for the effect of yield stress. Furthermore, Sundararajah et al. [27] performed experimental study on innovative SupaCee sections with longitudinal web stiffeners under two flange load cases. New coefficients were proposed with the web crippling design rule in the AS/NZS 4600 [9] standard to predict their capacities.

Keerthan et al. [28], and Steau et al. [29, 30] investigated the web crippling behaviour and capacity of hollow flange channel beams under ETF and ITF load cases. The test results showed that the predictions from the current design equation in AS/NZS 4600 [9] are either over-conservative or unconservative and hence new proposed equations were presented to estimate the web crippling capacity of hollow flange channel beams.

2.2. Aluminium sections

Tryland et al. [31] conducted web crippling tests using aluminium beams with three different extruded sections (two square hollow sections with different wall thicknesses and a double T section) fabricated by AA6082-T6 aluminium alloy. However, the minimum lengths as specified in the AISI Standard test method [6] were not considered in this study.

Zhou and Young [32] and Young and Zhou [33] performed a series of tests using square and rectangular hollow sections subjected to web crippling under the ETF and ITF load cases. The sections were fabricated using 6061-T6 and 6063-T5 heat-treated aluminium alloys. The results were compared with the current design rules given by AS/NZS 1664.1 [7], Eurocode 9 [34] and AS/NZS 4600 [9]. This study found that the design strengths predicted by the aforementioned specifications were either over-conservative or unconservative, and the predictions were in general unreliable. Thus, two unified web crippling equations for aluminium square and rectangular hollow sections were proposed under ETF and ITF load cases. Zhou and Young [35] also conducted a series of tests under end and interior one flange load cases using high-strength extruded hollow

sections fabricated by 6061-T6 aluminium alloy. The support condition of the specimens closely resembled that of the joist members seated on a solid foundation in the floor system.

Recently, Chen et al. [36] carried out an investigation on web crippling failure of extruded aluminium tubular sections to propose improved design rules. Specimens with different boundary conditions, section heights and bearing lengths were tested. They also investigated the effects of these variables on the web crippling ultimate capacity and the ductility of aluminium square hollow sections. Su and Young [37] performed experimental and numerical web crippling investigations on relatively stocky hollow sections under the four load cases. The specimens were extruded using 6063-T5 and 6061-T6 heat treated aluminium alloys. The acquired results were used to assess the currently available design rules and new equations were proposed with the consideration of strain hardening effects.

It should be mentioned that majority of the existing experimental studies on aluminium members were focused on extruded sections, particularly rectangular hollow sections. However, the design guidelines resulted from these studies may not be applicable to roll-formed aluminium sections including channel sections. This is due to the nature of roll-forming fabrication, which involves continuous bending to a strip of sheet metal to achieve the desired shape, and consequently leads to a remarkable change to the material properties. Another reason is that hollow sections (SHS/RHS) are considered as multi-web symmetrical sections, and the design guidelines given in the current specifications, including the AISI Standard test method [6] and Eurocodes [11,38], explicitly distinguish between single web sections (channel sections) and multi-web sections. Hence, the present experimental study is carried out to investigate the web crippling behaviour of roll-formed aluminium lipped channel sections.

3. Current design rules

The nominal web crippling capacities of cold formed lipped channel sections under the ETF and ITF load cases could be predicted using AS/NZS 1664.1 [7] and Eurocode 9 [38] for aluminium structural members, and AS/NZS 4600 [9] as well as Eurocode 3 [11] for cold-formed steel structural members.

3.1. Aluminium structures design rules

3.1.1. AS/NZS 1664.1 [7]

The web crippling design rules for flat webs subjected to a concentrated transverse load are specified in Section 4.7.7 in the AS/NZS 1664 Standard [7] Part 1 for aluminium structures. The nominal web crippling capacity (P_{AS1664}) is calculated based on Equations (1) and (2) for the ETF (where the concentrated load is applied at a distance from the member end which is less than $d/2$) and ITF (where the concentrated load is applied at a distance from the member end that equals or exceeds $d/2$) load cases, respectively.

$$P_{AS1664} = \frac{1.2t^2 \sin \theta (0.46f_y + 0.02\sqrt{Ef_y})(N + C_{w2})}{C_{w3} + r_i(1 - \cos \theta)} \quad (\text{ETF}) \quad (1)$$

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

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

3.1.2. Eurocode 9 [38]

The Eurocode 9 Standard [38] Part 1.4, Section 6.1.7.2 provides Equation (3) to estimate the web crippling strength of unstiffened webs in cold-formed aluminium members.

$$P_{EC9} = \alpha t^2 \sqrt{f_y E} \left(2.4 + \left(\frac{\theta}{90} \right)^2 \right) \left(1 - 0.1 \sqrt{\frac{r_i}{t}} \right) \left(0.5 + \sqrt{\frac{0.02N}{t}} \right) \quad (3)$$

where α is the coefficient for various local loads and support categories for cross-sections with two or more webs.

This equation is only limited to aluminium structural sheeting (members with two or more webs) and do not have the ability to estimate the web crippling capacity of single-web sections including aluminium lipped channel sections under ETF and ITF load cases. It should be noted that Eurocode 9 [38] and AS/NZS 4600 [9], as discussed in the next section, follow the same technique in predicting the web crippling capacities of cold-formed aluminium and steel sections, respectively.

3.2. Cold formed steel design rules

3.2.1. AS/NZS 4600 [9]

3.2.1.1. Current design rule

The specified web crippling strength (P_{AS4600}) according to the AS/NZS 4600 Standard [9] is calculated according to Equation (4a) for C-Sections.

$$P_{AS4600} = Ct^2 f_y \sin \theta \left(1 - C_R \sqrt{\frac{r_i}{t}} \right) \left(1 + C_N \sqrt{\frac{N}{t}} \right) \left(1 - C_h \sqrt{\frac{h}{t}} \right) \quad (4a)$$

where h is the flat portion of the web (mm); C is the 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 shown in Table 1. Note that in Equation (4a), the following conditions $h/t \leq 200$, $N/t \leq 210$, $r_i/t \leq 3$, $N/h \leq 2$, and $\theta = 90^\circ$ must be satisfied.

3.2.1.2. Sundarajah et al. [25].

After conducting an extensive parametric study on web crippling failure of cold-formed lipped channel beams (LCBs), Sundarajah et al. [25] proposed an improved unified web crippling design Equation (4b) for both ETF and ITF load cases with new coefficients as shown in Table 1. This equation has an additional factor to determine the effect of yield stress on web crippling capacity.

$$P_{LAVAN} = Ct^2 \sin \theta (f_y + C_f \sqrt{250f_y}) \left(1 - C_R \sqrt{\frac{r_i}{t}}\right) \left(1 + C_N \sqrt{\frac{N}{t}}\right) \left(1 - C_h \sqrt{\frac{h}{t}}\right) \quad (4b)$$

where C_f is the coefficient of yield stress.

3.2.2. Eurocodes 3 [11]

The Eurocode 3 [11] Part 1.3 for cold-formed steel structures provides several equations derived based on past experimental studies to predict the web crippling capacity for cold-formed steel sections. Equations (5) and (6) show the design formulae given in the Eurocode 3 [11] for cross sections with an unstiffened single web under ETF and ITF load cases, respectively. These equations are limited for cold-formed steel sections with $r_i/t \leq 6$ and $d_w/t \leq 200$.

$$P_{EC3} = \frac{k_1 k_2 k_3 f_y t^2}{\gamma_{M1}} \left[6.66 - \frac{d_w}{64t}\right] \left[1 + 0.01 \frac{N}{t}\right] \quad (5)$$

$$P_{EC3} = \frac{k_3 k_4 k_5 f_y t^2}{\gamma_{M1}} \left[21 - \frac{d_w}{16.3t}\right] \left[1 + 0.0013 \frac{N}{t}\right] \quad (6)$$

where:

$$k_1 = 1.33 - \frac{f_y}{690.9};$$

$$k_2 = 1.15 - 0.15 \frac{r_i}{t} \quad (0.5 \leq k_5 \leq 1.0);$$

$$k_3 = 0.7 + 0.3 \left(\frac{\theta}{90}\right)^2;$$

$$k_4 = 1.22 - \frac{f_y}{1036.4};$$

$$k_5 = 1.06 - 0.06 \frac{r_i}{t} \quad (k_5 \leq 1.0);$$

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.

4. Experimental study

4.1. Test specimens

Two series of web crippling tests including 40 test specimens of aluminium lipped channel sections were conducted. The sections were roll-formed from a well proven marine grade structural aluminium alloy 5052

H36. Five different sectional sizes (with each having two nominal thicknesses (t) of 2.5 and 3 mm) which are commonly used in aluminium structural applications were tested as shown in Tables 2 and 3. The section depth (d) ranged from 100 to 250 mm while the nominal flange widths (b_f) ranged from 60.5 to 75 mm. The specimens were cut to specific length (L) according to the AISI Standard test method [6]. The specimen lengths (L) should be at least equal to three and five times the flat portion of the clear web height (h) for the ETF and ITF load cases, respectively. All of the above mentioned dimensions were accurately measured at three points on each sample using a vernier calliper, micrometre and tap meter. The average values of these measured dimensions are presented in Tables 2 and 3 as specimen details.

Bearing plates were used as a means to apply the load or reaction forces on the specimens. They were fabricated using 450 MPa high-strength steel. Four different bearing lengths (25, 50, 100 and 150 mm) were used in both the ETF and ITF load cases in order to investigate the effect of bearing length on the web crippling capacity. During the test, the flanges of lipped channel section specimens were unfastened (not attached) to the bearing plates.

The specimens were labelled in a way that the load case, web height, thickness, as well as, the length of bearing plate could be easily identified from the label. For example, the label “ITF-10030-N50 (a)” is designated as:

- The first three letters indicate the load case (ETF or ITF).
- 10030 indicates the web height of 100 mm and the web thickness of 3.0 mm.
- N50 indicates the bearing length of 50 mm.
- If a test was repeated, then “(a)” indicates the first test and “(b)” indicates the second test.

4.2. Material properties

Tensile coupon tests were conducted to determine the material properties of the specimens including the yield stress, elastic modulus, ultimate strength and the stress strain-curve. Three coupons were taken from the centre, upper and bottom parts of the web plate in the longitudinal direction, similar to the roll-forming direction, for each section (10030, 15030, 20025, 20030 and 25025). The tensile coupons were prepared and tested according to the AS 1391 [39] and the American Society for Testing and Materials Standard ASTM [40] for the tensile testing of materials.

An Instron displacement controlled testing machine was used to test the coupons. The longitudinal strain was measured using a calibrated extensometer and two strain gauges (one on each side). A data acquisition system was used to record the load and strain at regular intervals during the tests. The material properties obtained from the tensile coupon tests are summarised in Table 4, which includes the average values of the elastic modulus (E_0), 0.2% tensile proof stress ($\sigma_{0.2}$), ultimate tensile strength (σ_u) and the strain at the fracture load (ϵ_u). Figure 2 shows the typical steel-strain curve of structural Aluminium alloy 5052 H36.

Figure 2 also shows a comparison between typical stress-strain curves for aluminium alloy 5052 H36 and mild steels. It can be observed from the comparison of both stress-strain curves that they behave linear elastically with a different slope of the $\sigma - \epsilon$ curve up to the elastic limit for the yield stress f_y for steel and $f_{0.2}$ for aluminium. Basically, this part of the curve covers the working range of structures. After the elastic range, aluminium alloys have a continuous strain-hardening behaviour, however; mild steel is preceded by a perfectly plastic branch corresponding to yielding plateau. The ultimate deformation for aluminium alloys 5052 H36 (around 6%) is lower than the one of mild steel (around 20%).

4.3. Test set-up and procedure

Two series of forty tests were conducted using a Materials Test System (MTS) machine to investigate the web crippling capacity and behaviour of the aluminium lipped channel sections. Figures 3 (a) and (b) 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.

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 measured load was initialised with zero value before commencing each test. A displacement-controlled system was used to move down the cross-head of the MTS machine at a constant rate of 2 mm/min for all test specimens until failure. The applied load as well as the vertical and horizontal displacements of the web were recorded during the tests. As shown in Figures 3 (a) and (b) three laser displacement transducers were used to measure the lateral displacement of the web in three different positions whereas one laser was used to measure the vertical displacement of the bottom flange.

4.4. Test results and discussion

Tables 2 and 3 present the experimental ultimate web crippling load ($P_{Exp.}$) from the two series of tests. 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 (1.1% for ETF-10030-N50 and 3.5% for, ITF-10030-N50), indicating that the test results are accurate and reliable.

Figures 4 (a) and (b) show the typical load versus deflection curves from the web crippling tests for specimens ETF-15030-N100 and ITF-15030-N150, respectively. As shown in Figure 5, web crippling is the only failure mode for the ETF specimens, however two failure modes were observed in the ITF load case. All the ITF specimens loaded by 50, 100 and 150 mm bearing lengths failed in web crippling failure mode (see Figure 6) while those with a small bearing plate (25 mm) failed in a combined flange crushing and web crippling failure as shown in Figure 7. Figure 8 (a) shows the plot of applied load versus vertical deflection for the ITF-25025-N25 specimen with 25 mm bearing length. From Point-A to Point-B, the plot shows an initial increase in load with a uniform gradient and the web crippled like an arc. After Point-B, web-flange juncture started to

deform under the bearing plates which leads to a significant reduction in the inside bent radius and therefore the section became more resistant to the bearing load and thus increased the web crippling capacity. A comparison of web crippling failure capacities as a function of bearing lengths is shown in Figure 8(b). The increased web bearing capacity of aluminium lipped channel section with small bearing plate (25 mm) was identified due to combined web crippling and flange crushing of the section. Gunalan and Mahendran [24] and Sundararajah et al. [25, 26] also observed similar kind of failures during their experimental work on cold-formed steel sections.

It was also observed during the experimental study that all specimens under ITF load case and with 100 mm and 150 mm bearing plates did not reach their maximum possible web crippling capacity as their edges started to deform before reaching the ultimate load (Figures 9 (a) and (b)). In other words, the length of the influence zone extended to more than the length of the specimens. This indicates that the specimen length (L) proposed by the AISI Standard test method [6] could be extended for aluminium lipped channel sections under the ITF load case. However, it should be noted that the ultimate loads obtained from this experimental study (using the test specimen lengths proposed by AISI Standard test method [6]) were conservatively compared with the current and proposed design rules.

4.5. Comparison with current design rules

The web crippling ultimate loads ($P_{Exp.}$) obtained from the tests were compared with the nominal web crippling strengths predicted ($P_{Predicted.}$) using the available design rules in AS/NZS 1664.1 [7], AS/NZS 4600 [9] Sundararajah et al. [25] and Eurocode 3 [11]. Tables 5 and 6 show the comparison of the test ultimate loads (P_{Exp}) with the design strengths for the ETF and ITF load cases, respectively. The design strengths were calculated using the measured cross-sectional dimensions and material properties of each specimen as detailed in Tables 2, 3 and 4.

The mean values of the test-to-predicted web crippling capacity ratio for the equations provided by AS/NZS 1664.1 [7] are 0.50 and 0.88, whereas the corresponding coefficient of variations (COV) values are 0.37 and 0.24 for the ETF and ITF load cases, respectively (see Tables 5 and 6). This indicates that the web crippling predictions using the AS/NZS 1664.1 [7] design equations is rather unconservative with unreliable COV values for aluminium lipped channel sections under both ETF and ITF load cases.

The design strengths predicted by AS/NZS 4600 [9] are also unconservative with low mean values (0.55 for ETF and 0.78 for ITF) but with reasonably well COV value of 0.06 for the ETF load case and a high COV value of 0.17 for ITF load case. The improved equation proposed by Sundarajah et al. [25] also overly predict the web crippling capacity of aluminium lipped channel sections with mean values 0.50 and 0.59, while the COV value is 0.08 for both ETF and ITF load cases, respectively.

Similarly, the equations provided by Eurocode 3 [11] for cold-formed steel structures are quite unconservative with reliable COV values under the both load cases. The mean value of the test-to-predicted load ratio is 0.49 with the corresponding COV of 0.06 for the ETF load case while these values are 0.60 and 0.07 for the ITF load case.

In general, The reduced values of COV for the equations provided by Eurocode 3 [11] and Sundarajah et al. [25] mean that they could comparatively predict the effect of different height to thickness ratio (h/t), bearing length to thickness ratio (N/t) and radius to thickness ratio (r/t) for the web crippling capacity for rolled-formed aluminium lipped channel sections under both ETF and ITF load cases. However they failed to predict the bearing capacity of aluminium lipped channel sections due to the difference in material properties as it was proposed for cold-formed steel members.

Figures 10 (a) and (b) present the test-to-predicted web crippling capacity ratios for the currently available design rules for both ETF and ITF load cases. Generally, the current design rules, as compared with the test results, failed to accurately and safely predict the web crippling capacities of aluminium lipped channel sections.

5. Proposed design rules

Since the current web crippling design rules based on AS/NZS 1664.1 [7], AS/NZS 4600 [9], Sundarajah et al. [25] and Eurocode 3 [11], were found to be unconservative for aluminium lipped channel sections, new design equations are proposed to predict the web crippling capacities based on the experimental results. This approach is similar to that used in the current design codes. It should be noted that the increased ultimate loads obtained from combined flange crushing and web crippling failure were not considered in this study in the development of the proposed design rules.

At present, the fabrication of roll-formed aluminium lipped channel sections in the industry is a new concept and is limited to 5052-H36 alloy. It is believed that the proposed equations based on the test results would be suitable for other aluminium alloys if their stress-strain behaviours are similar to the 5052-H36 alloy regardless of their mechanical properties values (E , f_y and f_u). The stress-strain curve behaviour of 5052-H36 aluminium alloy closely resembles the bilinear stress-strain curve (see Figure (2)) which is generally used to represent the cold-formed steel material behaviour [41]. Further FE analysis will be conducted to confirm the validity of the proposed equations for other alloys including highly rounded stress-strain curves for future applications.

5.1. Unified design rules for aluminium and cold-formed steel lipped channel sections

As discussed in Section 4.5, Eurocode 3 [11] and Sundarajah et al. [25] (improved AS/NZS 4600 [9] equation) are able to comparatively predict the effect of cross-section geometrical parameters (h , r_i , t , and N) on web crippling capacity of aluminium lipped channel sections under both ETF and ITF load cases. However they failed to predict the bearing capacity of aluminium lipped channel sections due to the difference in material

properties as they were proposed for cold-formed steel members. This section, therefore, investigates the effect of material properties (yield strength and elastic modulus) on the predicted web crippling capacity based on AS/NZS 4600 [9], Sundarajah et al. [25], Eurocode 3 [11] and the Eurocode 9 [38] design rules.

The yield strength factors (k_y) obtained from these design rules are summarised below.

- AS/NZS 4600 [9]: $k_y = f_y$
- Sundarajah et al. [25]: $k_y = f_y + C_f \sqrt{250 f_y}$
- Eurocode 3 [11]: $k_y = f_y \left(1.33 - \frac{f_y}{690.9} \right)$ (ETF)
 $k_y = f_y \left(1.22 - \frac{f_y}{1036.4} \right)$ (ITF)
- Eurocode 9 [38]: $k_y = \sqrt{f_y}$

Figures 11 (a) and (b) show the predicted web crippling capacity ratios (normalised based on Grade 250) with respect to yield strength for the aforementioned standards under both ETF and ITF load cases, respectively. According to the AS/NZS 4600 [9] design equations, the web crippling capacity proportionally increases with material yield strength. However, Sundarajah et al.'s [25] modification, based on extensive parametric study, has significantly reduced the effect of yield strength on the web crippling prediction compared to AS/NZS 4600 [9]. It can also be observed that the yield strength factors provided by Eurocode 3 [11], Eurocode 9 [38] and Sundarajah et al. [25] reasonably agreed well with each other as shown in Figures 11 (a) and (b).

Based on the above discussion, suitable modifications to the design rules given by AS/NZS 4600 were made. Following the same technique specified in the Eurocode 9 [38], the factor $\sqrt{E f_y}$ was introduced to Equation (7) to consider the effect of both yield strength (represent yield capacity) and elastic modulus (represent buckling capacity), as it plays an important role in the ultimate strength of the section. It should also be noted that this modification maintains the unit balance of the modified equation, and expand its application to the predict the web crippling capacity of both cold formed steel and rolled-formed aluminium lipped channel sections.

$$P_{prop.} = C t^2 \sqrt{E f_y} \sin \theta \left(1 - C_R \sqrt{\frac{r_i}{t}} \right) \left(1 + C_N \sqrt{\frac{N}{t}} \right) \left(1 - C_h \sqrt{\frac{h}{t}} \right) \quad (7)$$

where C_R , C_N and C_h are the coefficients proposed by Sundarajah et al. [25] (Table 1). The coefficient C is empirically modified to maintain the suitability of this equation to be used for both aluminium and cold formed steel lipped channel sections ($C = 0.273$ for ETF load case, and $C = 0.78$ for ITF load case).

The proposed Equation (7) can accurately predict the web crippling capacities of aluminium lipped channel sections under the ETF and ITF load cases. The mean value of the test-to-predicted load ratio is 1.00 with the corresponding COV value of 0.08, under the ETF load case, as shown in Table 5. For ITF load case, the mean value of test-to-predicted load ratio is 1.00 with the corresponding COV value of 0.05, as shown in Table 6.

Moreover, the web crippling test data for cold-formed lipped channels reported by Sundarajah et al. [25] was used in this study to validate the suitability of Equation (7) for cold-formed steel sections. Figures 12 (a) and (b) show a good agreement between the experimental and the predicted data for aluminium and cold-formed steel specimens.

5.2. Australian design rules for aluminium lipped channel sections

As Equations (1) and (2), recommended by AS/NZS 1664.1 [7], are unsafe for aluminium lipped channel sections, suitable modifications were proposed to improve their accuracy and limitation to predict the web crippling capacity for aluminium lipped channel sections under two flange load cases. Equations (8) and (9) are proposed herein incorporating modified web crippling coefficients, C_{w1} , C_{w2} and C_{w3} . It should be noted that Equations (1) and (2) do not consider the effect of web slenderness (h/t) in predicting the nominal web crippling capacity. As shown in Figure 13 (a), the test-to-predicted ultimate load ratio decreases when h/t increases for both the ETF and ITF load cases. Hence, the ratio h/t is introduced in Equations (8) and (9) to enhance the accuracy of these equations.

$$P_{AS1664(Prop)} = \frac{0.31t^2 \sin \theta (0.46f_y + 0.02\sqrt{Ef_y})(N + C_{w2})}{C_{w3} + r_i(1 - \cos \theta)} \left(1 - C_{h1} \sqrt{\frac{h}{t}} \right) \quad (\text{ETF}) \quad (8)$$

$$P_{AS1664(Prop)} = \frac{0.258t^2 \sin \theta (0.46f_y + 0.02\sqrt{Ef_y})(N + C_{w1})}{C_{w3} + r_i(1 - \cos \theta)} \left(1 - C_{h2} \sqrt{\frac{h}{t}} \right) \quad (\text{ITF}) \quad (9)$$

where $C_{w1} = 780 \text{ mm}$; $C_{w2} = 238 \text{ mm}$; $C_{w3} = 10 \text{ mm}$; $C_{h1} = 0.05 \text{ mm}$ and $C_{h2} = 0.025 \text{ mm}$.

The proposed Equations (8) and (9) are shown to be able to accurately predict the web crippling capacities of aluminium lipped channel sections under the ETF and ITF load cases, respectively. The mean value of the test-to-predicted load ratio is 1.00 with the corresponding COV of 0.05, for the ETF load case, as shown in Table 5. The mean and COV values are 1.00 and 0.06 for the ITF load case, respectively, as shown in Table 6. Figures 13 (b) and (c) present the test to predicted ultimate load ratios obtained from the proposed equation without and with considering the effect of h/t ratio, respectively.

5.3. Eurocode design rules for aluminium lipped channel sections

Eurocode 9 [38] and AS/NZS 4600 [9] follow the same technique in predicting the web crippling capacities of cold-formed aluminium and steel sections, respectively. Hence, the unified proposed Equation (7) can be considered as an improved equation based on Eurocode 9 [38] for aluminium single web sections. Alternatively, the design rules in the Eurocode 3 [11] is improved here and can also be employed in the Eurocode 9 for single web sections.

Similar to the technique followed in Section 5.1, the design rules in the Eurocode 3 (Equations (5) and (6)), were modified by introducing the factor $\sqrt{E f_y}$ in the proposed Equations (10) and (11), with maintaining all the factors (k_1, k_2, k_3, k_4, k_5 and k_6) as the same.

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

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

The prediction of Equations (10) and (11) agreed well with the experimental web crippling capacities of aluminium lipped channel sections with a mean value of 1.01 and corresponding COV value of 0.06, for the ETF load case as presented in Table 5. For the ITF load case, the mean value of test-to-predicted load ratio is 0.99 with the corresponding COV value of 0.07 as shown in Table 6.

Over all, the aforementioned proposed equations (Equations (7-11)) have the ability to accurately predict the web crippling capacity of aluminium and lipped channel sections under two flange load cases as shown in Figures 12 (a) and (b).

5.4. Capacity reduction factor (ϕ_w)

The North American Specification AISI S100 [10] recommends a statistical model to determine the capacity reduction factor. This model accounts for the variations in material, fabrication, and loading effects. The capacity reduction factor is given by Equation (12a).

$$\phi_w = 1.5M_mF_mP_me^{-\beta_0\sqrt{V_M^2+V_F^2+C_nV_P^2+V_Q^2}} \quad (12a)$$

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

Substitution of all the above values into Equation (12a) leads to the following equation.

$$\phi_w = 1.65P_me^{-2.5\sqrt{0.0502+C_nV_P^2}} \quad (12b)$$

Equation (12b) was used to determine the capacity reduction factors for the values obtained from the design codes as well as the proposed design rules. As shown in Tables 5 and 6, the capacity reduction factors (ϕ_w) according to the proposed equations range between 0.90 and 0.93. Therefore, it is recommended to use a ϕ_w factor of 0.90 for all the proposed equations to predict the web crippling strengths of aluminium lipped channel sections under ETF and ITF load cases.

6. Conclusions

An experimental investigation of the aluminium lipped channel sections subjected to web crippling under the ETF and ITF load cases is reported herein. Forty tests were conducted with different section heights, bearing lengths and thicknesses. This paper presents a full description of the web crippling behaviour including the ultimate loads, the failure modes and the load-deformation curves. All the ETF load case specimens failed in pure web crippling while two types of failures were observed for ITF load case specimens which are the web crippling failure for specimens with 50,100 and 150 mm bearing plates, and the combined flange crushing and web crippling failure for specimens with 25mm bearing plates. It is also found that the specimen lengths recommended by the AISI testing method [6] could be further extended for aluminium lipped channel sections under the ITF load case to achieve slightly higher capacities. The web crippling capacities of aluminium lipped channel sections obtained from the tests were then compared with the nominal strengths calculated using AS/NZS 1664.1 [7], AS/NZS 4600 [9], Sundarajah et al.'s [25] modifications, Eurocode 3 [11]. It was found that the design strengths predicted by the aforementioned specifications are quite unconservative and unsafe. Therefore, new equations were proposed based on the experimental results to accurately predict the web crippling capacities of aluminium lipped channel sections. Generally, these improved equations are capable to predict the ultimate strengths for aluminium lipped channel sections with good agreement with the experimental results.

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(a) Caloundra potable water reservoir, Australia

(b) Typical lipped channel cross section

Figure 1: Roll-formed aluminium members.

Figure 2: Measured tensile stress-strain plot of structural aluminium alloy 5052 H36.

(a) ETF load case.

(b) ITF load case

Figure 3: Web crippling test setups.

(a) ETF-15030-N100

(b) ITF-15030-N150

Figure 4: Typical load versus deflection curves.

(a) ETF-20025-N50

(b) ETF-10025-N25

(c) ETF-20025-N25

(d) ETF-25025-N150

Figure 5: Web crippling failure modes for ETF load case.

(a) ITF-10030-N50

(b) ITF-25025-N50

Figure 6: Web crippling failure modes for ITF load case.

Figure 7: Combined flange crushing and web crippling failure for ITF-15030-N25.

(a) Applied load versus vertical deflection

(b) Failure load versus bearing length

Figure 8: Flange crushing failure mechanism of ITF-25025-N25.

(a) Applied load versus vertical deflection curve

Stage - A (Initial)

Stage - B (Section ends started to deform)

Stage - C (Failure)

(b) Failure modes in different stages during the test

Figure 9: Test results for ITF-25025-N100.

(a) ETF load case

(b) ITF load case

Figure 10: Web crippling capacities from tests and current design rules.

(a) ETF load case

(b) ITF load case

Figure 11: Effect of material yield strength on web crippling capacity.

(a) ETF load case

(b) ITF load case

Figure 12: Web crippling capacities from tests (current study and Sundarajah [25]) and proposed design rules.

(a) Current design rule

(b) Proposed design rule - without considering the effect of h/t

(c) Proposed design rule - with considering the effect of h/t

Figure 13: Comparison of test-to-predicted capacity ratios for current and proposed design rules.

Table 1: AS/NZS 4600 [9] and Sundarajah et al. [225] coefficients for lipped channel sections.

Equation	Load case	C	C_R	C_N	C_h	C_f	LRFD ϕ_w
AS/NZS 4600 [9]	ETF	13	0.32	0.05	0.04	-	0.90
	ITF	24	0.52	0.15	0.001	-	0.80
Sundarajah et al. [25]	ETF	1.03	0.21	0.16	0.06	6.85	0.85
	ITF	1.24	0.17	0.04	0.03	16.90	0.88

Table 2: Test specimen details and results for ETF load case.

Specimen	Depth d (mm)	Flange b_f (mm)	Lip l_b (mm)	Thickness t (mm)	Radius r_i (mm)	Length L (mm)	Load $P_{Exp.}$ (kN)
ETF-10030-N25	107.3	60.4	14.9	2.95	4.9	316	6.19
ETF-10030-N50(a)	106.5	58.4	16.1	2.95	5.0	317	6.23
ETF-10030-N50(b)	107.1	59.7	15.1	2.97	4.9	317	6.30
ETF-10030-N100	107.3	59.4	15.0	2.95	4.8	316	7.41
ETF-15030-N25	156.7	62.8	22.9	2.93	4.9	466	5.23
ETF-15030-N50	157.5	63.3	22.4	2.93	5.0	465	5.50
ETF-15030-N100	158.3	63.5	21.7	2.92	5.1	465	6.37
ETF-15030-N150	155.5	63.5	22.9	2.92	4.9	467	7.25
ETF-20025-N25	208.1	74.6	25.5	2.42	5.1	617	3.33
ETF-20025-N50	208.1	74.2	25.4	2.43	4.9	615	3.61
ETF-20025-N100	207.3	74.3	25.7	2.43	5.0	615	3.92
ETF-20025-N150	204.0	75.8	26.5	2.43	4.8	615	4.23
ETF-20030-N25	204.6	74.9	27.4	2.9	4.6	611	4.95
ETF-20030-N50	208.4	73.0	27.5	2.9	5.0	615	5.07
ETF-20030-N100	204.5	75.4	27.7	2.89	4.6	613	5.82
ETF-20030-N150	208.3	73.5	27.1	2.89	5.0	615	6.06
ETF-25025-N25	259.8	80.8	23.4	2.43	4.4	765	2.95
ETF-25025-N50	259.9	76.1	23.7	2.44	4.9	765	3.09
ETF-25025-N100	262.1	76.2	22.7	2.44	4.8	765	3.76
ETF-25025-N150	260.3	76.3	23.4	2.45	4.6	765	4.15

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

Table 3: Test specimen details and results for ITF load case.

Specimen	Depth d (mm)	Flange b_f (mm)	Lip l_b (mm)	Thickness t (mm)	Radius r_i (mm)	Length L (mm)	Load $P_{Exp.}$ (kN)
ITF-10030-N25	106.9	59.3	14.3	2.94	4.8	527	21.40
ITF-10030-N50(a)	106.4	59.4	14.8	2.95	4.9	525	18.90
ITF-10030-N50(b)	106.9	59.0	14.4	2.94	4.9	521	18.23
ITF-10030-N100	106.1	59.6	14.4	2.94	4.8	523.5	18.29
ITF-15030-N25	156.5	62.6	22.6	2.93	4.8	774	18.71
ITF-15030-N50	156.7	62.4	22.7	2.92	4.9	775	18.29
ITF-15030-N100	156.2	62.1	22.7	2.92	4.8	776	18.00
ITF-15030-N150	156.6	62.5	22.8	2.93	4.9	774	18.30
ITF-20025-N25	206.2	74.0	26.3	2.43	4.6	1028	12.82
ITF-20025-N50	207.2	73.3	26.0	2.44	4.9	1022	12.23
ITF-20025-N100	207.3	73.9	26.3	2.43	5.0	1019	12.19
ITF-20025-N150	207.4	73.4	26.9	2.44	4.6	1021	12.27
ITF-20030-N25	205.6	74.5	31.6	2.9	4.4	1022	18.12
ITF-20030-N50	206.6	75.3	27.4	2.93	4.8	102	18.00
ITF-20030-N100	206.5	74.4	26.7	2.9	4.8	1021	17.59
ITF-20030-N150	206.5	74.5	26.7	2.89	4.6	1022	17.62
ITF-25025-N25	259.9	76.1	22.1	2.43	4.4	1273	12.08
ITF-25025-N50	260.0	76.0	22.4	2.42	4.5	1274	11.79
ITF-25025-N100	259.8	76.3	22.5	2.43	4.5	1269	11.77
ITF-25025-N150	259.9	76.2	22.2	2.43	4.5	1275	11.91

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_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

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

Specimen	h/t	$P_{Exp.}$ (kN)	Ultimate load ratios (Test/Prediction)						
			P_{AS1664}	P_{AS4600}	$P_{Sundararajah}$	P_{EC3}	P (Prop.)	P_{AS1664} (Prop.)	P_{EC3} (Prop.)
ETF-10030-N25	31.1	6.19	0.89	0.50	0.54	0.55	0.99	1.06	1.12
ETF-10030-N50	30.7	6.27	0.64	0.48	0.49	0.52	0.89	0.98	1.06
ETF-10030-N100	31.1	7.41	0.46	0.52	0.49	0.53	0.90	0.97	1.08
ETF-15030-N25	48.1	5.23	0.78	0.47	0.54	0.50	0.99	1.02	1.02
ETF-15030-N50	48.4	5.50	0.58	0.47	0.50	0.49	0.92	0.99	1.00
ETF-15030-N100	48.7	6.37	0.42	0.52	0.51	0.51	0.93	0.99	1.03
ETF-15030-N150	47.9	7.25	0.34	0.55	0.51	0.50	0.94	0.96	1.02
ETF-20025-N25	79.8	3.33	0.72	0.51	0.63	0.53	1.15	1.11	1.10
ETF-20025-N50	79.6	3.61	0.53	0.51	0.59	0.51	1.07	1.07	1.06
ETF-20025-N100	79.2	3.92	0.36	0.52	0.54	0.48	1.00	0.99	0.99
ETF-20025-N150	78.0	4.23	0.28	0.52	0.52	0.44	0.95	0.91	0.91
ETF-20030-N25	65.3	4.95	0.72	0.46	0.57	0.49	1.05	1.04	1.01
ETF-20030-N50	66.4	5.07	0.53	0.46	0.53	0.48	0.97	1.00	0.98
ETF-20030-N100	65.6	5.82	0.37	0.49	0.52	0.47	0.94	0.95	0.97
ETF-20030-N150	66.6	6.06	0.29	0.50	0.50	0.45	0.91	0.89	0.92
ETF-25025-N25	101.3	2.95	0.59	0.45	0.62	0.47	1.14	1.02	0.97
ETF-25025-N50	100.5	3.09	0.45	0.46	0.58	0.46	1.06	1.00	0.95
ETF-25025-N100	101.5	3.76	0.34	0.52	0.60	0.48	1.10	1.03	0.98
ETF-25025-N150	100.4	4.15	0.26	0.53	0.58	0.45	1.06	0.97	0.93
Mean			0.50	0.50	0.55	0.49	1.00	1.00	1.01
COV			0.37	0.06	0.08	0.06	0.08	0.05	0.06
ϕ_w			0.27	0.46	0.49	0.45	0.90	0.92	0.93

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

Specimen	h/t	P_{Exp} (kN)	Ultimate load ratios (Test/Prediction)						
			P_{AS1664}	P_{AS4600}	$P_{Sundararajah}$	P_{EC3}	P (Prop.)	P_{AS1664} (Prop.)	P_{EC3} (Prop.)
ITF-10030-N25	31.1	21.40*	1.30	1.01	0.67	0.63	NA	NA	NA
ITF-10030-N50	30.8	18.57	0.98	0.79	0.56	0.54	0.98	1.01	0.90
ITF-10030-N100	30.9	18.29 [#]	0.76	0.66	0.52	0.52	0.91	0.94	0.87
ITF-15030-N25	48.2	18.71*	1.17	0.91	0.63	0.60	NA	NA	NA
ITF-15030-N50	48.3	18.29	1.01	0.82	0.59	0.58	1.06	1.08	0.98
ITF-15030-N100	48.2	18.00 [#]	0.78	0.68	0.55	0.56	0.98	0.99	0.94
ITF-15030-N150	48.1	18.30 [#]	0.65	0.64	0.54	0.56	0.95	0.96	0.93
ITF-20025-N25	79.0	12.82*	1.12	1.02	0.67	0.66	NA	NA	NA
ITF-20025-N50	78.9	12.23	0.93	0.91	0.61	0.62	1.08	1.06	1.05
ITF-20025-N100	79.2	12.19 [#]	0.75	0.81	0.58	0.61	1.03	1.02	1.04
ITF-20025-N150	79.2	12.27 [#]	0.60	0.66	0.55	0.59	0.97	0.94	1.00
ITF-20030-N25	65.9	18.12*	1.10	0.82	0.63	0.61	NA	NA	NA
ITF-20030-N50	65.3	18.00	0.95	0.76	0.60	0.59	1.05	1.06	1.00
ITF-20030-N100	65.9	17.59 [#]	0.75	0.66	0.56	0.58	1.00	1.00	0.98
ITF-20030-N150	66.3	17.62 [#]	0.62	0.59	0.54	0.57	0.96	0.94	0.97
ITF-25025-N25	101.3	12.08*	1.03	0.89	0.66	0.67	NA	NA	NA
ITF-25025-N50	101.7	11.79	0.88	0.80	0.62	0.65	1.09	1.05	1.11
ITF-25025-N100	101.2	11.77 [#]	0.69	0.68	0.58	0.63	1.02	0.98	1.07
ITF-25025-N150	101.3	11.91 [#]	0.58	0.62	0.56	0.62	0.98	0.94	1.06
Mean			0.88	0.78	0.59	0.60	1.00	1.00	0.99
COV			0.24	0.17	0.08	0.07	0.05	0.06	0.07
ϕ_w			0.61	0.62	0.53	0.57	0.93	0.92	0.91

* The specimen failed in combined web crippling and flange crushing.

[#] The ends of specimen started to deform before reaching the ultimate load.