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## Design of Aluminum Alloy Channel Section Beams

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**Abstract:** Aluminum alloy members of channel sections are widely used in lightweight structures, especially as pillars of curtain wall systems, and brace and chord members in roof trusses. This paper presents both experimental and numerical studies on the behavior of aluminum alloy channel section beams. In this study, a series of four-point bending tests under minor-axis and major-axis bending was carried out. The test specimens included plain and lipped channel sections of both 6063-T5 and 6061-T6 aluminum alloys. A finite element (FE) model of the channel section beam was developed by using the FE package ABAQUS. The ultimate bending resistances and failure modes of the FE model were compared with the results from the bending tests. The validated model was employed for the parametric study to generate numerical simulation results. A total of 55 new experimental and numerical beam results were compared with the predictions from existing aluminum alloy design specifications from America, Australia/New Zealand, Europe and China. Additionally, two commonly used design approaches - the Continuous Strength Method (CSM) and the Direct Strength Method (DSM) - were also applied to predict the bending capacities for comparisons. A modified DSM approach for aluminum alloy channel section beams is proposed herein. Finally, reliability analyses were conducted to evaluate the aforementioned design methods. The results show that in comparison with other considered design

methods, the CSM provides more accurate and consistent results for aluminum alloy plain and lipped channel section beams.

**Keywords:** Aluminum alloy; Beam; Channel section; Continuous Strength Method; Direct Strength Method; Testing; Numerical investigation

## **Introduction**

Aluminum alloys have many desirable characteristics, such as great durability, high strength to weight ratios, and favorable corrosion resistance. Based on these advantages, aluminum alloys are commonly employed in long-span roof systems and in damp and corrosive environments. In the applications of aluminum alloy structures, closed sections, such as square and rectangular hollow sections (SHS and RHS) are common cross-section shapes. In addition, open sections are also popular to use in engineering structures because they are easy to connect. Therefore, the local buckling behavior and ultimate bending resistance of channel section beams were investigated by the experiments and numerical simulation in this paper.

There have been many previous studies on aluminum alloy beams performed by many researchers. Moen et al. (1999a; 1999b) investigated the behavior and failure modes of the RHS and I-section beams under moment gradient loading. This study showed the effect of strain hardening on the rotational performances of aluminum alloy flexural members and improved the classification of the section in the specifications. Zhu and Young (2009) carried out both experimental and numerical simulation studies on flexural members of SHS and compared the experimental results with the aluminum alloy codes from American, Australia/New Zealand and Europe. In addition, the study proposed design formulas for SHS flexural members based on the Direct Strength Method (DSM). Su et al. (2014; 2016a) compared the bending strengths predicted by specifications and by the Continuous Strength Method (CSM) and concluded that the compression and bending strengths

calculated using the specifications are conservative. Guo et al. (2015) presented an investigation on flexural-torsional buckling of T and I section beams and proposed fitting formulas to estimate the buckling capacities. Wang et al. (2016) presented an investigation on the local buckling of I-section beams under concentrated loads and found that intermediate stiffeners and a thick web are helpful to increase the bearing capacity of I-section beams. Feng et al. (2017) studied SHS/RHS beams with circular holes and compared the experimental results with the design results; the results found that the DSM approach provided relatively accurate predictions. These studies have focused to a large extent on the design of extruded aluminum alloy beams, but there are few studies on channel section beams.

Though there are limited studies on aluminum alloy channel section beams, a great number of studies on steel channel section members have been carried out in recent years. For example, Young and Rasmussen (1998a; 1998b) presented compression tests on fixed-ended plain channel steel columns and evaluated the specifications using test results; design recommendations of channel steel compression members were also proposed. Lee et al. (2005) found an optimum cross-section of a cold-formed channel steel beam using a micro Genetic Algorithm and presented the optimum design curves for various load levels. Maduliat et al. (2012) conducted a series of bending tests on the inelastic bending behavior of cold-formed channels (with or without stiffeners) and provided design rules considering such behavior. Wang and Young (2014) investigated steel channel beams experimentally and numerically to improve the DSM approach. Ye et al. (2016) optimized cold-formed steel channel beams to enhance their bending capacities for practical applications. Zhao et al. (2019) presented tests on cold-formed steel channel flexural members with holes in the webs and proposed a corresponding DSM accordingly. Zhao et al. (2018) proposed the CSM approach for the stainless-steel beams with singly symmetric section, such as angles, channels and T-sections. To summarize, the present study has

been developed based on key findings reported in the aforementioned literature.

In addition, there are a number of design specifications for aluminum alloy structures published by different countries, including the Aluminum Design Manual (AA, 2015), Australia/New Zealand Standard (AS/NZS, 1997), Eurocode 9 (EC9, 2007) and Chinese code (CN, 2007). Furthermore, the Direct Strength Method (DSM) and the Continuous Strength Method (CSM) are two widely used approaches for aluminum alloy member design. The DSM was initially proposed by Schafer and Peköz (1998) for cold-formed carbon steel structures, and it is included in the North American Specification (ASIS, 2016). Afterwards, Zhu and Young (2008, 2009) modified the DSM for aluminum alloy SHS/RHS beams (Zhu and Young, 2009) and circular hollow section (CHS) columns (Zhu and Young, 2008). The CSM was first developed by Gardner and Nethercot (2004) for stainless steel hollow members. It employs a base curve to determine the relationship between cross section slenderness and deformation capacities. Later, Su et al. (2016b) modified the CSM for aluminum alloy columns, simply supported beams and continuous beams.

This study investigates the buckling behavior of channel section beams experimentally and numerically. A total of ten four-point beam tests including 6063-T5 and 6061-T6 alloys were tested. A non-linear finite element (FE) model for the channel section beams was developed using the ABAQUS program (2014). The FE model was validated against the experimental results. Upon validation, a parametric study was conducted to generate 45 numerical results. The combined data pool from the experimental program and parametric study was compared with the design strengths predicted by the American Aluminum Design Manual (AA, 2015), Australian/New Zealand Standard (AS/NZS, 1997), Eurocode 9 (EC9, 2007), Chinese Code (CN, 2007), the CSM (Zhao and Gardner, 2018)) and the DSM (NAS, 2016). The DSM approach was also further modified for the aluminum alloy channel section beams in this study. Additionally, reliability analyses were presented to

assess the reliability level of all the existing and new design methods.

## Experimental study

### Specimens

A total of ten four-point bending tests were carried out. The experimental program included minor-axis and major-axis bending (see Fig. 1). Two types of cross-sections were considered, namely, plain and lipped channel sections. The specimens were extruded using 6063-T5 and 6061-T6 aluminum alloys. The geometries and material properties of the specimens are shown in Table 1, where  $H$ ,  $B$ ,  $B_l$ ,  $t$ ,  $E$ ,  $f_y$ ,  $f_u$ , and  $\varepsilon_f$  are the section depth, section width, length of stiffener, cross section thickness, Young's modulus, 0.2% yield stress, ultimate stress, and tensile strain at fracture, respectively. The beams were labelled to identify the type of alloy, type of cross section and bending conditions. For example, the label "P-T5-minor-A-R" defines the following specimen:

- ◆ The first letter signifies the cross section, where "P" means the plain channel section, and "L" refers to the lipped channel section.
- ◆ The next part of the label shows the type of alloy, where "T5" indicates the aluminum alloy 6063-T5, and "T6" indicates the aluminum alloy 6061-T6.
- ◆ The third part means the bending condition, where "minor" means the minor-axis bending test, and "major" refers to the major-axis bending test.
- ◆ The next part of the label is used to distinguish the dimensions of cross section. "A", "B" and "C" represent three different cross sections as shown in Table 1.
- ◆ The last part of the label "R" indicates that the test is repeated.

### **Four-point bending tests**

The test configuration is shown in Fig. 2. For specimens “P-T5-minor-A” and “P-T5-minor-A-R”, the length of the whole beam was 990 mm and the pure bending section was 300 mm, as shown in Fig. 2 (a). For the rest of the specimens, the distance between the loading points was 500 mm and the length of the whole beam was 3040 mm, as shown in Fig. 2 (b). Both minor-axis and major-axis bending tests were carried out, as shown in Fig. 3. At loading and support points, a wooden block was placed inside the plain channel section and steel plates were placed at the two outer sides to prevent local buckling of the flanges and web due to load concentration. For the beams bent about their major axis, two channel section beams were bolted together at the loading and supporting positions through T-shape steel blocks, as shown in Fig. 3 (b). The beam was loaded symmetrically by a spreader beam. A data acquisition system was used to record the applied load and the readings of the displacement transducers at regular intervals during the tests. For each specimen, five transducers were installed to measure the vertical deflection within the moment span as well as at the loading points and supports of the beam. Three linear variable differential transformers (LVDT) were used to measure the vertical deflections and curvature of the specimens in the constant moment region as shown in Fig. 2. One 100 mm LVDT and two 50 mm LVDTs were used to measure the vertical deflection at the mid-span and at the loading points, respectively, in order to obtain the mid-span deflection and curvature in the constant moment region. Two 25 mm LVDTs were placed at each end of the beams to measure the end rotations.

### **Test results**

The moment-curvature relationships derived from the tests are shown in Fig. 4 and the ultimate moment are shown in Table 2. Beams in minor axis bending failed by local buckling with compression in the web. For major-axis bending tests, local buckling failure was observed in the plain channel section beam tests, whereas

interaction of local and distortional buckling was found in the lipped channel section beam tests. Local buckling can be obviously observed when the test member reaches the ultimate state. At the end of the test, local buckling followed by some form of plasticity can be observed in the member.

## **Numerical simulations**

The numerical model developed by the ABAQUS program (2014) was validated against the results obtained from the four-point bending tests. Upon validation, the FE model was used for the parametric study.

### **Model development**

The numerical program ABAQUS (2014) was employed to establish the finite element model of aluminum alloy channel section beams subjected to minor-axis and major-axis bending. A four-node shell element with reduced integration (S4R) was adopted, which has been commonly used in the modelling of metallic structures (Chen and Young, 2019a, 2019b). The mesh size for the plain channel section beam is  $10 \times 10$  mm, and that for the lipped channel section is  $5 \times 5$  mm. When simulating the major-axis bending tests, two beams were connected by four trapezoidal solid elements, and the mesh size of the solid element was the same as the specimen. The FE model adopted the same loading configuration as that used in the experiment, and all simulations were displacement controlled. The material properties of the specimens were obtained from tensile coupon tests, as shown in Table 1. To ensure the beams failed in the pure bending span in the simulation, the thickness of the section elements in the pure bending span was taken as the measured thickness, while that in the shear spans were taken as double the measured thickness. The bearing steel plates at the supports and loading points were simulated as rigid bodies.

### **Model validation**

The numerical ultimate resistances are compared with the experimental results in Table 2. The average ultimate



moment ratio  $M_{EXP} / M_{FE}$  between the test and the FE results is 1.01, and the corresponding coefficient of variation (CoV) is 0.045, which shows that the predictions of the bending moments by the FE model are accurate and consistent. The moment-deflection curves obtained from the numerical simulations are also close to those obtained from bending tests, as shown in Fig. 4. The typical comparisons of failure mode between the tests and numerical modelling are shown in Fig. 5. The failure mode of the lipped channel section beams under major-axis bending was interaction of local and distortional buckling, while the rest of specimens failed by local buckling, as shown in Fig. 6. To summarize, the results show that the FE model is reliable and can accurately simulate the behavior of aluminum alloy channel section beams.

### **Parametric study**

The parametric study generated 45 numerical results for aluminum alloy channel-section beams, including 25 minor-axis and 20 major-axis simulated bending tests. Normal and high strength aluminum alloys (6063-T5 and 6061-T6, respectively) were employed for the parametric study and the properties of these two alloys can be found in Table 1. Both plain and lipped channel sections were included with five different section dimensions for each, as shown in Table 3. Depth-to-thickness ratios ( $H/t$ ) ranging from 20 to 100 were considered. The ultimate bending strengths obtained from the parametric study are presented in Tables 4-5.

## **Existing design approaches**

### **American Aluminum Design Manual (AA)**

According to the American Aluminum Design Manual (AA, 2015), the available flexural strengths of the beams are equal to the minimum of the yield strength ( $M_{np}$ ), local buckling strength ( $M_{nlb}$ ) and lateral-torsional buckling strength ( $M_{nmb}$ ). It is noted that lateral-torsional buckling is not taken into account

when calculating the minor axis bending strength. The flexural resistances ( $M_{AA}$ ) of the channel-section beams can be calculated as follows, according to the AA design formulas:

$$M_{AA} = \min(M_{np}, M_{nlb}, M_{nmb}) \quad (1)$$

The yield strength  $M_{np}$  is given by:

$$M_{np} = \min(W_{pl}f_y, 1.5S_t f_t, 1.5S_c f_y) \quad (2)$$

The strength of local buckling  $M_{nlb}$  is determined from:

$$M_{nlb} = f_c I_f / c_{cf} + f_b I_w / c_{cw} \quad (3)$$

The strength of lateral-torsional buckling  $M_{nmb}$  is calculated by:

$$M_{nmb} = \begin{cases} M_{np} \left(1 - \frac{\lambda}{C_c}\right) + \frac{\pi^2 E \lambda S_{xc}}{C_c^3} & \lambda < C_c \\ \frac{\pi^2 E S_{xc}}{\lambda^2} & \lambda \geq C_c \end{cases} \quad (4)$$

### Australian/New Zealand Standard (AS/NZS)

The Australian and New Zealand Standards (AS/NZS, 1997) adopt the limit state design (LSD) method to calculate the strengths of aluminum alloy structures. The bending resistance equals to the product of the bending stress and the elastic section modulus of each component. All reduction factors are taken as 1.0 in the calculation. The design bending strengths ( $M_{AS/NZS}$ ) can be determined from the AS/NZS as follows:

$$M_{AS/NZS} = F_L W_{el} \quad (5)$$

$$\text{For } \frac{L_b Z_c}{0.5 \sqrt{I_y J}} < S_1, \quad F_L = f_y \quad (6)$$

$$\text{For } S_1 \leq \frac{L_b Z_c}{0.5 \sqrt{I_y J}} < S_2, \quad F_L = B_c - 1.6 D_c \sqrt{\frac{L_b Z_c}{0.5 \sqrt{I_y J}}} \quad (7)$$

$$\text{For } \frac{L_b Z_c}{0.5\sqrt{I_y J}} \geq S_2, \quad F_L = \frac{\pi^2 E}{2.56 \left( \frac{L_b Z_c}{0.5\sqrt{I_y J}} \right)} \quad (8)$$

where

$$S_1 = (B_c - f_y) / 1.6D_c; \quad S_2 = (C_c / 1.6)^2$$

### Eurocode 9 (EC9)

In EC9 (2007), the cross section is divided into four classes according to the yield strength and slenderness ratio of each element. When calculating the bending resistance of flexural members, different section classes will adopt a corresponding shape factor, which is related to the plastic, elastic or effective modulus of the section. For minor-axis bending, the bending moment resistance ( $M_{EC9}$ ) is calculated by Eq. (10). For major-axis flexural members, the bending moment resistance ( $M_{EC9}$ ) is taken as the smaller value of the yield resistance ( $M_{c,Rd}$ ) and buckling resistance ( $M_{b,Rd}$ ), and the calculation is carried out using Eq. (9).

$$M_{EC9} = \min(M_{c,Rd}, M_{b,Rd}) \quad (9)$$

$$M_{c,Rd} = \alpha_{EC9} W_{el} f_y / \gamma_{M1} \quad (10)$$

$$M_{b,Rd} = \chi_{LT} \alpha W_{el,y} f_y / \gamma_{M1} \quad (11)$$

### Chinese Code (CN)

The design rules from the Chinese Code (CN, 2007) consider both the flexural strength ( $M_{CN1}$ ) and stability bending capacity ( $M_{CN2}$ ) of the flexural member. For minor-axis bending members, the bending moment resistance  $M_{CN}$  equals  $M_{CN1}$  because there will be no instability failure, while for major-axis bending members, the value for the bending resistance  $M_{CN}$  is the lower value of  $M_{CN1}$  and  $M_{CN2}$ .

The flexural strength  $M_{CN1}$  is given by:

$$M_{CN1} = \gamma_{CN} f_y W_{en} \quad (12)$$

The stability capacity  $M_{CN2}$  is calculated by:

$$M_{CN2} = f_y \phi_b W_{ec} \quad (13)$$

### Continuous Strength Method (CSM)

The Continuous Strength Method could be used for the design of aluminum alloy members, which was originally developed by Gardner and Nethercot (2004) for stainless-steel structures. Later, Su et al. (2016b) modified the CSM for aluminum alloy stub columns, simply supported beams and continuous beams with doubly symmetric cross-sections. Recently, Zhao and Gardner (2018) proposed the CSM for stainless steel beams with mono-symmetric and asymmetric cross-sections, such as the channel section, angle section and T-section. Therefore, in this study, the CSM approach proposed by Zhao and Gardner (2018) is employed. The design bending moment capacity ( $M_{CSM}$ ) is given by Eq. (14); the key design parameters are obtained according to Eqs. (15) - (19).

$$M_{CSM} = \begin{cases} \frac{\varepsilon_{csm}}{\varepsilon_y} W_{el} f_y & \frac{\varepsilon_{csm}}{\varepsilon_y} < 1 \\ W_{el} f_y \left[ 1 + \frac{E_{sh}}{E} \frac{W_{el}}{W_{pl}} \left( \frac{\varepsilon_{csm}}{\varepsilon_y} - 1 \right) - \left( 1 - \frac{W_{el}}{W_{pl}} \right) / \left( \frac{\varepsilon_{csm}}{\varepsilon_y} \right)^\alpha \right] & \frac{\varepsilon_{csm}}{\varepsilon_y} \geq 1 \end{cases} \quad (14)$$

(1) The cross-section slenderness is given by:

$$\bar{\lambda}_p = \sqrt{f_y / \sigma_{cr}} \quad (15)$$

where  $\sigma_{cr}$  is the elastic buckling stress, which can be determined by using the CUFSM software (Seif and Schafer, 2010).

(2) The deformation capacity of the cross section is determined from:

$$\frac{\varepsilon_{csm,c}}{\varepsilon_y} = \begin{cases} \frac{0.25}{\bar{\lambda}_p^{3.6}} \leq \min(15, \frac{0.5\varepsilon_u}{\varepsilon_y}) & \bar{\lambda}_p \leq 0.68 \\ \frac{1}{\bar{\lambda}_p^{1.05}} (1 - \frac{0.222}{\bar{\lambda}_p^{1.05}}) & \bar{\lambda}_p > 0.68 \end{cases} \quad (16)$$

$$\frac{\varepsilon_{csm,t}}{\varepsilon_y} = \frac{\varepsilon_{csm,c}}{\varepsilon_y} \frac{(h - y_c)}{y_c} \quad (17)$$

$$\frac{\varepsilon_{csm}}{\varepsilon_y} = \max(\frac{\varepsilon_{csm,c}}{\varepsilon_y}, \frac{\varepsilon_{csm,t}}{\varepsilon_y}) \quad (18)$$

(3) The strain hardening modulus is calculated by:

$$E_{sh} = \frac{f_u - f_y}{0.5\varepsilon_u - \varepsilon_y} \quad (19)$$

### Direct Strength Method (DSM)

The DSM approach considering the flexural strength up to the first yield, codified in the F2.1, F3.2.1 and F4.1 of the North American Specification (2016), is adopted to calculate the capacities of the channel-section beams ( $M_{DSM}$ ). This method considers three failure modes: lateral-torsional buckling, local buckling and distortional buckling. The calculation procedure is shown as follows:

$$M_{DSM} = \min(M_{ne}, M_{nl}, M_{nd}) \quad (20)$$

The flexural strength  $M_{ne}$  for the lateral-torsional buckling is given from:

$$M_{ne} = \begin{cases} M_{cre} & M_{cre} < 0.56M_y \\ \frac{10}{9}M_y (1 - \frac{10M_y}{36M_{cre}}) & 2.78M_y \geq M_{cre} \geq 0.56M_y \\ M_y & M_{cre} > 2.78M_y \end{cases} \quad (21)$$

The flexural strength  $M_{nl}$  for the local buckling is calculated by:

$$M_{nl} = \begin{cases} M_{ne} & \lambda_l \leq 0.776 \\ \left[ 1 - 0.15 \left( \frac{M_{crl}}{M_{ne}} \right)^{0.4} \right] \left( \frac{M_{crl}}{M_{ne}} \right)^{0.4} M_{ne} & \lambda_l > 0.776 \end{cases} \quad (22)$$

The flexural strength  $M_{nd}$  for the distortional buckling is determined according to:

$$M_{nd} = \begin{cases} M_y & \lambda_d \leq 0.673 \\ \left[ 1 - 0.22 \left( \frac{M_{crd}}{M_y} \right)^{0.5} \right] \left( \frac{M_{crd}}{M_y} \right)^{0.5} M_y & \lambda_d > 0.673 \end{cases} \quad (23)$$

### Result comparisons

The design bending moments of the aluminum alloy channel section beams were calculated by the AA, AS/NZS, EC9, CN design specifications as well as the CSM, and DSM design approaches. All partial safety factors in this study were set to unity. All the design bending moment resistances were compared with the results obtained from bending tests and numerical simulations in this paper. The results of the comparisons are shown in Tables 4-5 and summarized in Fig. 7. In the following discussion, the mean value of the ratio of experimental or simulated results to the design strengths is abbreviated as ‘Mean’ and the coefficient of variation is abbreviated as ‘CoV’.

For the minor-axis bending members, the design bending moments predicted by existing specifications are generally conservative. The design results calculated by the AS/NZS are the most conservative ( $M_u / M_{AS/NZS}$ : Mean=1.80, CoV=0.141). The design bending moments from the AA are slightly better, but they are still conservative ( $M_u / M_{AA}$ : Mean=1.37, CoV=0.275). The results of EC9 and CN are close to each other ( $M_u / M_{EC9}$ : Mean=1.21, CoV=0.245;  $M_u / M_{CN}$ : Mean=1.32, CoV=0.230). Departing from other design methods, the predictions using the existing DSM approach are the least conservative ( $M_u / M_{DSM}$ : Mean=1.07, CoV=0.244). The bending strengths predicted by the CSM are the most consistent ( $M_u / M_{CSM}$ : Mean=1.13, CoV=0.106).

Regarding the major-axis bending beams, the design bending strengths from EC9 are the most conservative, though they are rather consistent ( $M_u / M_{EC9}$ : Mean=3.99, CoV=0.078). The design results from the CN are also found to be conservative ( $M_u / M_{CN}$ : Mean=2.80, CoV=0.090). In comparison, the results from the AA and the AS/NZS are more accurate ( $M_u / M_{AA}$ : Mean=1.04, CoV=0.219;  $M_u / M_{AS/NZS}$ : Mean=1.10, CoV=0.127). Similar to the predictions for the minor-axis bending, the performance of the CSM and DSM are fairly good compared to other design methods ( $M_u / M_{CSM}$ : Mean=1.10, CoV=0.09;  $M_u / M_{DSM}$ : Mean=1.01, CoV=0.110).

## Modified DSM approach

### Modified DSM

In this study, a modification is proposed to the existing DSM approach in order to improve its appropriateness for aluminum alloy structures. The modified DSM approach is denoted as  $M_{DSM-1}$ . Based on the available data pool and a regression analysis, a modification is proposed for the design curve of local buckling strength  $M_{nl}$ , as shown in Eq. (25). The boundary limit of the non-dimensional slenderness  $\lambda_l$  changes to 0.648.

$$M_{DSM-1} = \min(M_{ne}, M_{nl}, M_{nd}) \quad (24)$$

$M_{ne}$  and  $M_{nd}$  are consistent with the Eqs. (21) and (23), and

$$M_{nl} = \begin{cases} M_{ne} & \lambda_l \leq 0.648 \\ \left[ 1 - 0.28 \left( \frac{M_{crl}}{M_{ne}} \right)^{0.76} \right] \left( \frac{M_{crl}}{M_{ne}} \right)^{0.76} M_{ne} & \lambda_l > 0.648 \end{cases} \quad (25)$$

### Result comparisons

The design bending moments of the aluminum alloy channel section beams were calculated by the modified DSM design approaches. The results of the comparisons are shown in Tables 4-5 and summarized in Fig. 7.

For the minor-axis bending members, the predictions made by the modified DSM are more consistent after modifications ( $M_u / M_{DSM-1}$ : Mean=1.16, CoV=0.191). Regarding the major-axis bending beams, after modifications to the existing DSM, the design results become more conservative with similar scatter level ( $M_u / M_{DSM-1}$ : Mean=1.17, CoV=0.114).

## Reliability analyses

The reliability of design methods for aluminum alloy channel beams is evaluated by reliability analyses according to the clause 1.3.2 of Appendix 1, Part I in the American Aluminum Design Manual (AA, 2015). The reliability index ( $\beta$ ) is a parameter used to measure the reliability level of design methods, with the target value of 2.5 for aluminum alloy beams, as recommended in Appendix 1, Part I of the AA (2015). If the reliability index is greater than or equal to 2.5, the design method is deemed to be reliable. The resistance factor ( $\phi$ ) depends on the structural scenario being addressed and the design specification under consideration, as given in Eqs. 27-30. Please note that the load combinations of 1.2D+1.6L, 1.25D+1.5L, 1.35D+1.5L and 1.2D+1.4L are employed for the AA, AS/NZS, EC9 and CN specifications, respectively. Thus, as for aluminium alloy beams, the resistance factor ( $\phi$ ) is assumed as 0.90, 0.85, 0.91, 0.83 for AA (2010), AS/NZS (1997), EC9 (2007) and CN (2007), respectively. The load combination case and resistance factor for both CSM and DSM approaches refer to the AA standard (see Tables 4-5).

$$\phi = (1.673P_m) \exp(-2.5\sqrt{0.0491 + C_n V_p^2}) \text{ for the AA, CSM and DSM} \quad (26)$$

$$\phi = (1.582P_m) \exp(-2.5\sqrt{0.0491 + C_n V_p^2}) \text{ for the AS/NZS} \quad (27)$$

$$\phi = (1.609P_m) \exp(-2.5\sqrt{0.0491 + C_n V_p^2}) \text{ for EC9} \quad (28)$$

$$\phi = (1.491P_m) \exp(-2.5\sqrt{0.0491 + C_n V_p^2}) \text{ for the CN} \quad (29)$$



where  $P_m, V_p$  are ratios of the mean value of test and FE results to predictions and their corresponding CoV for design strengths.  $C_n$  is correction factor,  $=(n^2 - 1) / (n^2 - 3n)$ , where  $n$  is the number of specimens.

The reliability indices  $\beta$  of all the design methods are summarized in Tables 4-5 for both the minor-axis and major-axis bending beams, respectively. For the minor-axis bending members, the  $\beta$  of the AA, AS/NZS, EC9, CN, CSM and modified DSM are 2.95, 5.12, 2.50, 3.36, 3.17 and 2.50, respectively, which are all greater than or equal to 2.50 and considered as reliable for minor-axis bending channel beams. Nevertheless, the reliability index ( $\beta$ ) of the DSM is 2.16, which is lower than 2.50; it is mainly due to the overestimation of the DSM local buckling design curve for some plain channel section beams under minor-axis bending, thus leading to scatter predictions (CoV= 0.244). For the major-axis bending channel beams, the reliability indices ( $\beta$ ) of all the design methods are found to be greater than or marginally lower than 2.50.

## Conclusions

This study focuses on the aluminum alloy flexural members of channel sections. Four-point bending tests were carried out on both plain and lipped channel section beams under minor-axis and major-axis bending. According to the test results, the failure modes of local buckling and distortional buckling were observed for lipped channel section beams bent about their major axes. For the rest of the specimens, the failure mode was found to be local buckling. A finite element model of the channel section beams was established and validated with the bending test results (bending strengths and failure modes). The comparisons of the tests and numerical simulations show that the two series of results are in good agreement. Afterwards, the validated FE model was employed for parametric analyses and generated 45 numerical results. Both the test and numerical bending resistances were compared with the predictions from the American Aluminum Design Manual, the

Australian/New Zealand Standard, the Eurocode 9 Standard, the Chinese Code, the Continuous Strength Method and the Direct Strength Method. The DSM was modified for the minor-axis and major-axis flexural members. It was shown that the bending strengths calculated by the specifications are quite conservative. The results show that the CSM provided more accurate and consistent predictions. Finally, the reliability levels of all design methods were evaluated. All design methods were found to be reliable for aluminum alloy channel section beams, except for the existing DSM approach. It is suggested that the CSM be employed and the modified DSM be used for the design of aluminum alloy channel section beams

## Data Availability

Some or all data, models, or code generated or used during the study are available from the corresponding author by request.

## Notation

The following symbols are used in this paper:

$B$  = section width

$B_c$  = buckling constant intercept for member buckling

$B_l$  = length of stiffener

$C_c$  = buckling constant intersection for member buckling

$C_n$  = correction factor,  $=(n^2 - 1)/(n^2 - 3n)$

CoV = coefficient of variation

$C_{cf}$  = distance from the centerline of a uniform compression element to the cross section's neutral axis

$C_{cw}$  = distance from a flexural compression element's extreme compression fiber to the cross section's

neutral axis

$D_c$  = buckling constant slope for member buckling

$E$  = Young's modulus

$E_{sh}$  = strain hardening modulus

$f_b$  = stress corresponding to the strength of an element in flexural compression determined using

Sections B.5.5.1 through B.5.5.4 in the AA (AA, 2015)

$f_c$  = stress corresponding to the strength of an element in uniform compression determined using

Sections B.5.4.1 through B.5.4.5 in the AA (AA, 2015)

$f_t$  = tensile yield strength

$f_u$  = ultimate stress

$f_y$  = compressive yield strength

$H$  = section depth

$h$  = overall height of the section in the bending direction

$I_f$  = moment of inertia of the uniform stress elements about the cross section's neutral axis

$I_w$  = moment of inertia of the flexural compression elements about the cross section's neutral axis

$I_y$  = moment of inertia of a beam about the axis parallel to the web

$J$  = torsion constant

$L_b$  = length of the beam between the bracing points

$M_{AA}$  = ultimate moment capacity predicted by the AA

$M_{AS/NZS}$  = ultimate moment capacity predicted by the AS/NZS

$M_{b,Rd}$  = buckling resistance predicted by the EC9

$M_{CN}$  = ultimate moment capacity predicted by the CN

$M_{CN1}$  = flexural strength predicted by the CN

$M_{CN2}$  = stability bending capacity predicted by the CN

$M_{CSM}$  = ultimate moment capacity predicted by the CSM

$M_{crd}$  = critical elastic distortional buckling moment

$M_{cre}$  = critical elastic lateral-torsional buckling moment

$M_{crl}$  = critical elastic local buckling moment

$M_{c,Rd}$  = yield resistance predicted by the EC9

$M_{DSM}$  = ultimate moment capacity predicted by the DSM

$M_{DSM-1}$  = ultimate moment capacity predicted by the modified DSM

$M_{EC9}$  = ultimate moment capacity predicted by the EC9

$M_{EXP}$  = experimental ultimate moment

$M_{FE}$  = ultimate moment obtained from FE models

$M_{nd}$  = nominal flexural strength for distortional buckling

$M_{ne}$  = nominal flexural strength for lateral-torsional buckling

$M_{nl}$  = nominal flexural strength for local buckling

$M_{nlb}$  = local buckling strength predicted by the AA

$M_{nmb}$  = lateral-torsional buckling strength predicted by the AA

$M_{np}$  = yield strength predicted by the AA

$M_u$  = ultimate moment obtained from either test or FE models

$M_y = S_y f_y$ , yield moment about the axis of bending

Mean = ratio of experimental or simulated results to the design strengths

$n$  = number of specimens

$P_m$  = ratio of the mean value of test and FE results to predictions

$S_c$  = section modulus on the compression side of the neutral axis

$S_t$  = section modulus on the tension side of the neutral axis

$S_{xc}$  = section modulus about the compression side of the x-axis

$S_y$  = gross section modulus referenced in the extreme fiber in first yield

$t$  = cross section thickness

$V_p$  = corresponding CoV of the mean value of test and FE results to predictions

$W_{ec}$  = effective section modulus for the compressed edge of the major-axis

$W_{eff}$  = the elastic modulus of the effective section

$W_{el}$  = elastic section modulus

$W_{el,y}$  = elastic modulus of the gross section without reduction for HAZ (Heat Affected Zone) softening,

local buckling or holes

$W_{en}$  = effective net section modulus of each axis, which is considered the local buckling

$W_{pl}$  = plastic section modulus

$y_c$  = distance from the neutral axis to the outer compressive fiber

$Z_c$  = section modulus of the bending members on the compression side

$\alpha$  = CSM bending coefficient, as shown in Table 5 of the reference paper (Zhao and Gardner 2018)

$\alpha_{EC9}$  = shape factor,  $\alpha_{EC9} = W_{pl} / W_{el}$  for class 1 and 2;  $\alpha_{EC9} = 1$  for class 3;  $\alpha_{EC9} = W_{eff} / W_{el}$  for class 4

$\beta$  = reliability index

$\gamma_{CN}$  = plastic adaption coefficient of cross section bending, for the plain channel section  $\gamma_{CN} = 1.0$ , and

for the lipped channel section,  $\gamma_{CN} = 1.25$

$\gamma_{M1}$  = partial factor for resistance of members to instability, assessed by member checks,  $\gamma_{M1} = 1.0$  for

the plain channel section and  $\gamma_{M1} = 1.25$  for the lipped channel section

$\varepsilon_f$  = tensile strain at fracture

$\varepsilon_u = 0.13 (1 - f_y / f_u) + 0.059$ , strain at the ultimate tensile stress

$\varepsilon_y = f_y / E$ , yield strain

$\lambda$  = lateral-torsional buckling slenderness using Sections F.4.2.1 through F.4.2.5 in the AA (AA, 2015)

$\lambda_d = \sqrt{M_y / M_{crd}}$ , the cross-section slenderness for the distortional buckling

$\lambda_l = \sqrt{M_{ne} / M_{crl}}$ , the cross-section slenderness for the local buckling

$\bar{\lambda}_p$  = cross-section slenderness

$\sigma_{cr}$  = elastic buckling stress

$\varphi_b$  = global stability coefficient of beams, given by Appendix C in the CN (CN 2007)

$\phi$  = resistance factor

$\chi_{LT}$  = reduction factor for lateral torsional buckling (see Chapter 6.3.2.2 in the EC9 (2007))

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