Evaluation of Current Standards in Designing Cold-rolled Aluminium Channel Beams

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Abstract. Cold-rolled aluminium alloy sections have been well known as new products of BlueScope Permalite, and have been produced by utilising the existing rolling system for cold-formed steel sections to successfully roll-form Channel and Zed sections in Australian market. The roll-forming approach is proven to be faster and more cost-effective as compared to the conventional extrusion method. This method has attracted the attention from the manufacturers and users as well as researchers which resulted in the ARC Linkage Research Project-LP140100863 grant funded by the Australian Research Council and BlueScope Permalite to perform research on these types of cold-rolled aluminium sections. One of the objects in this project is to evaluate the application of current design standards in designing cold-rolled aluminium alloy members which are necessary to propose modifications in Aluminium design standards. This paper presents the applicability of current Aluminium design standards including Australian Standard, American Specification and Euro code in designing cold-rolled Aluminium Alloy Channel Beams by using reliability analysis.

1. Introduction

Aluminium alloy members have been progressively applied in structural applications due to their light weight and their excellent corrosion resistance [1]. Extrusion is commonly used around the world to produce aluminium sections, while roll-forming is a new method recently introduced by BlueScope Permalite in Australia [2]. The drivers for BlueScope Permalite to start roll-forming aluminum sections are their competitive advantages as follows: 1) Cold-forming is substantially faster and far less energy demanding than extrusion; 2) Existing roll-formers for steel sections can be used without further inventory investment; 3) Extruded aluminium sections have been made by overseas manufacturers, while on-shore cold-rolling plants allow the BlueScope to control its priorities, business plans, and reduction of time manufacturing from six weeks to one week; 4) Cold-forming process can enhance material properties. Cold-rolled aluminium alloy structures have been used in Australia as conveyors for mining from inland to coast, carports, and commercial one story buildings [2].

Currently, there are no design guidelines for cold-rolled aluminium alloy sections in any standard. Many aspects of current design standards are based on comprehensive research into extruded aluminium structures. Hence, the ARC Linkage Research Project-LP140100863 grant funded by the
Australian Research Council and BlueScope Permalite was successfully awarded to perform the research on strength and behavior of cold-rolled aluminium structures. The design guidelines for this structure subsequently are proposed on the basis of evaluating the applicability of current aluminium standards. This paper presents evaluations of current aluminium design standards including AS/NZS 1664.1 [3], American Specification [4] and Eurocode [5] in designing cold-rolled aluminium alloy Channel beams as an outcome of this Linkage Research Project. This evaluation is conducted on the basis of experimental and numerical results reported in previous papers ([6], [7]) and the probability-based load and resistance factor design (LRFD) method in reliability analysis presented in this paper.

2. Experimental Study of cold-rolled Aluminium Channel beams
A series of four-point bending tests were conducted to investigate the member buckling of cold-rolled aluminium alloy 5052 Channel beams. Material properties were determined at both flat and corner areas using coupon tests thoroughly investigated in Huynh et al [8] as shown in Figure 1. The average material properties for both flat and corner portions are summarised in Table 1. The yield stresses and ultimate strengths of the corner portions were found to be higher approximately 10% as compared to those of flat portions due to the cold-rolling process.

The selection of cross-sections and specimen lengths are reported in Pham et al [9], as presented in Table 2. Geometric imperfections of each specimen were measured prior to testing by using laser scanner method. Details of the laser scanner method were fully reported in Pham et al [10].

The specimens were tested in the four-point bending configuration as shown in Figure 2. The mechanism of this configuration as shown in Figure 3 was developed by Niu and Rasmussen [11]. Applied load was pulled up by the vertical actuator through the shear centre of Channel beams. As flexural-torsional buckling occurred, the lateral displacement signals from a Linear Variable Displacement Transducer (LVDT) attached to the Channel web were sent to the controller. The lateral actuator would instantly adjust the lateral position of vertical actuator to ensure that the applied load always acted vertically. Flexural-torsional buckling or combined modes between lateral torsional or sectional buckling were observed during testing, as seen in Figure 4. Details of test set-up and test behavior are reported in Pham et al [6].

![Figure 1. Flat and corner coupon tests [8].](image1)

![Figure 2. The nominal dimensions of the Channel section.](image2)
Table 1. Tensile material properties.

| Coupon     | Position | $\sigma_{0.2}$ (MPa) | $\sigma_{u}$ (MPa) | $E_0$ (GPa) | $\epsilon_f$ | $n$  |
|------------|----------|----------------------|-------------------|-------------|--------------|------|
| C10030     | flat     | 224                  | 277               | 69.3        | 5.6          | 12.4 |
| C25025     | flat     | 218                  | 267               | 69.7        | 9.0          | 12.1 |
| C40030     | flat     | 222                  | 271               | 69.6        | 10.0         | 11.9 |
| C10030     | corner   | 248                  | 290               | 70.4        | 5.2          | 12.5 |
| C25025     | corner   | 243                  | 291               | 70.5        | 6.4          | 12.6 |
| C40030     | corner   | 240                  | 279               | 70.5        | 5.3          | 12.5 |

Note: $\sigma_{0.2}$ is the 0.2% proof strength; $\sigma_u$ is the ultimate tensile strength; $E_0$ is the Young’s modulus; $\epsilon_f$ is the uniform elongation corresponding the total elongation after fracture; and ‘$n$’ is the Ramberg-Osgood index.

Table 2. Nominal cross-section dimensions and specimen lengths.

| Sections     | t (mm) | D (mm) | B (mm) | L (mm) | Specimen lengths (m) |
|--------------|--------|--------|--------|--------|----------------------|
| C10030       | 3.0    | 105    | 60.5   | 16.0   | 2.0; 3.0; 4.0         |
| C25025       | 2.5    | 255    | 76.0   | 25.5   | 2.5; 4.0; 5.0         |
| C40030       | 3.0    | 400    | 125.5  | 30.0   | 4.0; 5.0; 6.0         |

Figure 3. Mechanism of the bending test

Figure 4. Flexural-torsional buckling mode of a specimen
3. Numerical investigation of cold-rolled Aluminium Channel beams

Detailed nonlinear finite element (FE) models were developed using the software package ABAQUS [12] to investigate strength and behaviour of cold-rolled aluminium Channel beams. Material properties including nonlinear stress-strain behavior and enhanced corner properties based on coupon tests in Section 2 were used for FE modelling. Measured initial geometric imperfections were incorporated into the FE models fully presented in Pham et al [10], as shown in Figure 5 where local imperfections (d1) of the web, distortional imperfections (d2) of the flanges and initial twist (G3) at two end sections. The end boundary conditions includes shear centre shaft through three reference points at two end sections which were restrained in the x-axis and y-axis, and were free in z-axis, as illustrated in Figure 6. The FE results were subsequently calibrated against the experimental results as presented in Pham et al [7]. The FE results were generally in good agreement with the experimental results, as shown in Figure 7. A parametric study based on the reliable model was performed to extend the data range by varying cross-section dimensions and specimen lengths. More details of the FE model development, calibration and parametric study are fully reported in Pham et al [7]. The available data from experimental and numerical results will be utilised to evaluate the current aluminium standards/specifications in this paper by using LRFD method in reliability analysis.

![Figure 5. Geometric imperfections of a FE model](image1)

![Figure 6. Boundary conditions of the bending model](image2)

![a) Experimental result b) FE modelling result](image3)

**Figure 7.** The flexural-torsional buckling mode of specimen C25025-4.0m-2

4. Current design standards/specifications for Aluminium structures

4.1. Australian/New Zealand Standard AS/NZS 1664.1:1997

The AS/NZS 1664.1:1997 [3] provides design formulae for aluminium alloy beams in Clause 3.4.12. The design bending capacities are determined as the limit state design stress ($F_L$) multiplied by the elastic section modulus ($W_{el}$).

$$M_{AS/NZS} = F_L W_{el}$$

(1)
Fl is determined as follows:

For $\lambda \leq S_1^*$:

$$F_L = \varphi_L F_{cy}$$

(2)

For $S_1^* < \lambda < S_2^*$:

$$F_L = \varphi_L (B_c - D_c \lambda)$$

(3)

For $\lambda \geq S_2^*$:

$$F_L = \frac{\varphi_L}{\lambda^2} F_{cy}$$

(4)

where $S_1^*, S_2^*$ are the slenderness limits;

$L_b$ is the length of the beam between bracing points;

$r_y$ is the radius of gyration about an axis parallel to the web

$B_c, D_c$ are the buckling constant (Table 3.3 of the Standard)

Effect of local buckling is applied to member performance in Clause 4.7 [3]. This effect is applied when the local buckling stress is less than the global buckling stress. Member strength due to the effects of local buckling is determined as follows:

$$\phi F_{yb} = \phi_\lambda (F_{wc})^{1/3} (F_{cr})^{2/3}$$

(5)

where

$F_{ec}$ is elastic global buckling stress of beams;

$F_{cr}$ is local buckling stress given in Clause 4.7.1 [3];

$\phi, \phi_\lambda$ are capacity factors.

4.2. American Aluminum Design Manual AA 2015

Member strength of aluminium beams are presented in Chapter F of the Aluminum Design Manual 2015 [4]. The nominal flexural strength of an aluminium beam is least of available strengths including yielding, rupture, local buckling, lateral-torsional buckling and interaction of local and lateral-torsional buckling, as follows:

Yielding and rupture:

Yielding:

$$M_{yp} = \text{Min}(1.5S_{Fy}, 1.5S_{Fcy})$$

(6)

Rupture:

$$M_{wu} = \frac{ZF_{wu}}{k_y}$$

(7)

Local buckling:

Weighted average method:

$$M_{nb} = \frac{F_f I_f}{c_{cf}} + \frac{F_w I_w}{c_{cw}}$$

(8)

Direct strength method:

$$M_{nb} = F_b S_{ew}$$

(9)

Lateral-torsional buckling:

Inelastic buckling $\lambda < C_c$:

$$M_{mnb} = M_{yp} \left(1 - \frac{\lambda}{C_c}\right) + \frac{\pi^2 E \lambda S_{ew}}{C_c^3}$$

(10)

Elastic buckling $\lambda \geq C_c$:

$$M_{mnb} = \frac{\pi^2 E \lambda S_{ew}}{\lambda^2}$$

(11)

Interaction between local buckling and lateral-torsional buckling:
where
\( C_c \) is determined from Tables B.4.1 or B.4.2 of the Specification;
Z, \( S_t \), \( S_c \) are the plastic modulus and section modulus on tension and compression sides of the neutral axis respectively;
\( S_{xc} \) is the section modulus about the compression side of the \( x \)-axis;
\( F_b \) is determined in Section B.5.5.5 of the Specification [4];
\( F_c \) is the smallest elastic local buckling stress determined in Section B.5.6 [4].

4.3. European Code BS EN 1999: 2007

The European Code BS EN 1999: 2007 [5] provides design rules for calculating resistance of cross-sections in bending (Clauses 6.1.3 and 6.1.4) as follows:

\[
M_{c,\text{rd}} = \text{Min}(W_{\text{eff}}f_y, (W_{el} + (W_{pl} - W_{el})4(1 - \lambda / \lambda_{el})f_y, W_{pl}f_y)
\]

where
\( W_{el}, W_{pl} \) are elastic and plastic moduli of gross section;
\( W_{\text{eff}} \) is effective section modulus in bending.

The effect of local and distortional buckling is included in the determination of \( W_{\text{eff}} \) using the effective thickness method (ETM) (Clause 5.5 [5]). The buckling resistance of an aluminium beam is determined using a reduction factor on the resistance of the cross-section as follows:

\[
\phi_{LT} = \frac{1}{\phi_{LT}^2 + (\phi_{LT}^2 - \lambda_{LT}^2)^{1/2}} \leq 1
\]

\[
\phi_{LT} = 0.5(1 + \alpha_{LT}(\lambda_{LT} - \lambda_{0,LT}) + \lambda_{LT}^2)
\]

where
\( \chi_{LT} \) is the reduction factor for bending;
\( \alpha_{LT} \) is imperfection factor;
\( \lambda_{LT}, \lambda_{0,LT} \) are the relative slenderness and the limit of horizontal plateau, see Clause 6.2 [5].

5. Reliability basis of design

Reliability analysis is conducted using the probability-based load and resistance factor design (LRFD) method, detailed in the American Aluminum Design Manual [4]. The LRFD approach is underpinned by AS/NZS 4600, AS/NZS 4673 ([13], [14]) and has been successfully applied to the design of stainless steel [11] and aluminum alloys [15]. The first-order second moment reliability analysis, used to develop the LRFD criteria [16], requires only the first two parameters (mean and coefficient of variation) to calculate the reliability index. Details of the first-order second moment reliability analysis were presented in the text book by Nowak and Collins [17].

Probability of failure is determined on the basis of the reliability index (\( \beta \)). As this index grows, the structure member would be safer. The reliability index of 2.5 is taken for structural members [4]. Resistance factor (\( \phi \)) is determined from Equations (16) to (18) depending on the Standards/Specifications due to the differences of load combinations.

In the AS/NZS 1664.1:1997 [3]: Load combination [1.2G+1.5Q]

\[
\phi = \frac{1.438M_{m}F_{m}P_{m}}{\exp(\beta\sqrt{V_{d}^2 + V_{s}^2})}
\]
In the Aluminum Design Manual AA2015 [4]: Load combination \([1.2G+1.6Q]\]

\[
\phi = \frac{1.5M_wF_mP_m}{\exp(\beta \sqrt{V_R^2 + V_S^2})}
\]  

(17)

In the BS EN 1997:2007 [5]: Load combination \([1.35G+1.5Q]\]

\[
\phi = \frac{1.462M_wF_mP_m}{\exp(\beta \sqrt{V_R^2 + V_S^2})}
\]  

(18)

where \((V_R, V_S)\) are coefficients of variations of the resistance and load effects, respectively.

Reliability analysis is based on the American Aluminum Design Manual [4] with the following statistical data:
- The ratio of dead and live load \((G_n/Q_n)\) is 0.2;
- The material factor: the mean and coefficient of variation \((M_m, V_M)\) are \((1.10, 0.06)\);
- The fabrication factor: the mean and coefficient of variation \((F_m, V_F)\) are \((1.0, 0.05)\);
- The coefficient of variation of dead \((V_D)\) and live load \((V_L)\) are 0.1 and 0.25, respectively;
- The professional factor: mean \((P_m)\) is the ratio of actual to predicted strength and is determined using means of ratios of test to numerical strengths and numerical to prediction strengths (see Equation (20)). Member capacities are significantly impacted by global imperfections, and consequently, an imperfection factor is considered in the reliability analysis, using mean values and coefficients of variation \((G_m, V_G)\). Therefore, the coefficient of variation of professional factor includes three components: i) \(V_{\text{mod}}\) is the coefficient of variation of test to numerical results, ii) \(V_{\text{pre}}\) is the coefficient of variation of numerical to prediction results, and iii) \(V_G\) is the coefficient of variation of member strengths to global imperfections.

\[
P_m = \frac{P_{\text{test}}}{P_{\text{FE}}} \times \frac{P_{\text{FE}}}{P_{\text{prediction}}} \times G_m
\]  

(19)

The mean \((G_m)\) is taken as unity, whereas the coefficient of variation \(V_G\) for bending members is taken as 0.030, presented in [18]. Finally, the coefficients of variation of resistance \(V_R\) and load effects \(V_S\) are determined as follows:

\[
V_R = \left[V_M^2 + V_F^2 + C_n(V_{\text{pre}}^2 + V_G^2 + V_{\text{mod}}^2)\right]^{1/2}
\]  

(20)

\[
V_S = \left[\frac{1.05 G_n}{Q_n} V_G^2 + V_L^2\right]^{1/2}
\]  

(21)

where \(C_n\) is a correction factor depending on the number of tests.

6. Evaluation of current design standards/specifications in designing cold-rolled Aluminium alloy Channel beams

The predicted and numerical FE results for Channel beams are fully reported in Pham [18]. The failure modes were observed as lateral-torsional and distortional-global interaction buckling. The numerical FE results are used to evaluate current aluminium alloy standards.

6.1. Australian Standard AS/NZS 1664.1:1997

The numerical FE and predicted strengths are plotted on the graphs for lateral-torsional and interaction buckling, respectively (see Figure 8). If a point lies above the diagonal line, the numerical strength at
that point would be less than the prediction strength, and vice versa. Resistance factors ($\phi$) are given in Table 3. The AS/NZS 1664.1:1997 [3] gives good predictions for lateral-torsional buckling strengths, but gives un-conservative predictions for interaction buckling strengths. Resistance factor ($\phi$) of 0.780 is used for the application according to this Standard in overall case (including all modes) for the design of cold-rolled aluminium Channel beams.

6.2. American Specification AA 2015
Comparisons are presented in Figure 9 for member and interaction buckling strengths using diagonal graphs, respectively. Distortional-global interaction buckling is not considered in this Specification [4]. Table 4 shows resistance factors ($\phi$) for lateral-torsional buckling and interaction buckling. This specification gives good predictions for lateral-torsional buckling, but gives un-conservative predictions for interaction buckling.

6.3. European Code BS EN 1999:2007
Comparisons are shown in Figure 10 for member and interaction buckling modes, respectively. Resistance factors ($\phi$) are presented in Table 5. Predictions are in good agreement for lateral-torsional buckling, but are un-conservative for interaction buckling. Resistance factor ($\phi$) is taken as 0.724 for the application of this code for the design of the cold-rolled aluminium alloy Channel beams including all modes (Overall).

### Table 3. Resistance factors for Channel beams in the AS/NZS 1664.1:1997 [3]

|                      | Global buckling mode | Interaction buckling mode | Overall (All modes) |
|----------------------|----------------------|---------------------------|---------------------|
| $M_{num}/M_{pred}$   | Mean: 1.065          | 0.969                     | 0.987               |
|                      | CoV: 0.139           | 0.221                     | 0.181               |
| $\phi$               | 0.898                | 0.697                     | 0.780               |

a) Lateral-torsional buckling

**Figure 8.** Comparison of numerical and predicted results in the AS/NZS 1664.1:1997

b) Distortional-global interaction buckling

### Table 4. Resistance factors for Channel beams in the AA: 2015 [4]

|                      | Member buckling mode | Interaction buckling mode | Overall (All modes) |
|----------------------|----------------------|---------------------------|---------------------|
| $M_{num}/M_{pred}$   | Mean: 1.232          | 0.756                     | 1.093               |
|                      | CoV: 0.234           | 0.161                     | 0.306               |
| $\phi$               | 0.900                | 0.621                     | 0.691               |
7. Conclusion
The paper presents the evaluation of the current aluminium standards/specifications in designing cold-rolled aluminium alloy 5052 Channel beams. This evaluation is based on the experimental and numerical strengths of Channel beams as presented in Pham et al ([6], [7]). Lateral-torsional and distortional-global interaction buckling modes were observed. This evaluation is conducted by using LRFD method currently regulated in American Aluminum Design Manual [4] in reliability analysis. This LRFD method is subsequently used to determine the resistance factors in AS/NZS 1664.1: 1997 [3] and BS EN 1999:2007 [5] with the differences of load combinations. Also, the effect of geometric imperfections to the professional factor is investigated and included in the reliability analysis, as fully reported in [18]. In general, the Standards/Specifications provide good predictions for lateral-torsional
buckling strengths of Channel beams with approximate 0.9 of the resistance factor. They give unconservative predictions for distortional-global interaction buckling strengths with smaller than 0.7 of the resistance factor. The reason for this fact is that the Standards/Specifications were calibrated on the basis of extruded aluminium sections where interaction buckling modes were unclear. Research on the development of design formulae for designing cold-rolled aluminium alloy 5052 Channel beams is ongoing at the University of Sydney.

Acknowledgement
Funding provided by the Australian Research Council Linkage Research Grant LP140100863 between BlueScope Permalite and the University of Sydney has been used to perform this research. The authors would like to thank Permalite Aluminium Building Solutions Pty Ltd for the supply of test specimens and financial support for the project. The first author was sponsored by the scholarship from Australian Awards Scholarships (AAS) scheme by Australian Government.

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