DESIGN OF COLD-FORMED STEEL COLUMNS AT ELEVATED TEMPERATURES SUBJECT TO FLEXURAL-TORSIONAL BUCKLING

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INTRODUCTION

Cold-formed steel members are becoming increasingly popular in the construction industry due to their superior strength to weight ratio and ease of fabrication as opposed to hot-rolled steel members. These thin-walled members can be subject to various types of buckling modes, including flexural-torsional buckling when they are subjected to axial compression loads. Many design standards provide guidelines for columns subject to flexural-torsional buckling at ambient temperature. However, there are no specific design guidelines for cold-formed steel members at elevated temperatures. Hence extensive research efforts have gone into the many investigations addressing the buckling behaviour of cold-formed steel columns at ambient and elevated temperatures [1-7]. In order to investigate the flexural-torsional buckling behaviour of cold-formed steel columns, an experimental study was carried out on lipped channel sections at ambient and uniform elevated temperatures by Bandula Heva and Mahendran [5].

In this research, nonlinear finite element analyses of cold-formed steel columns subject to flexural-torsional buckling were undertaken using ABAQUS. Reduced mechanical properties [8,9] were used with appropriate boundary conditions. The results of finite element analyses were compared and validated with test results reported in Bandula Heva and Mahendran [5] for fixed ended cold-formed steel columns. The overall aim of this research is to investigate the accuracy of current ambient temperature design rules in determining the strengths of concentrically loaded cold-formed steel columns with both fixed and pinned ends at elevated temperatures subject to flexural-torsional buckling using the validated finite element model. Hence a detailed parametric study was then carried out to understand the effects of different parameters that affect the flexural-torsional buckling behaviour of cold-formed steel compression members at ambient and uniform elevated temperatures. Three different steel grades and thicknesses were considered in this numerical study to investigate the effect of using low and high grade steels. Three different section sizes were also considered in this study with varying column lengths. The accuracy of using the current ambient temperature design rules in Australia/New Zealand, North American and European cold-formed steel standards [10-12] in the fire design of cold-formed steel compression members subject to flexural-torsional buckling was assessed by employing appropriately reduced mechanical properties. The results obtained from this study were compared with the predicted ultimate loads from the current cold-formed steel design standards, based on which the accuracy of current design rules for pinned and fixed ended cold-formed steel compression members subject to flexural-torsional buckling at elevated temperatures was investigated. This paper presents the details of this research study and the results.

1 EXPERIMENTAL STUDY

Bandula Heva and Mahendran [5] investigated the behaviour and strength of cold-formed steel lipped channel columns at both ambient and elevated temperatures. *Table 1* shows the details of test specimens and the mechanical properties at ambient temperature. Tests of 1800 mm and 2800 mm long columns were conducted at ambient and elevated temperatures up to 700 ^{o}C (20 ^{o}C, 200 to 700 ^{o}C at 100 ^{o}C intervals). Both ambient and elevated temperature tests of long columns were carried out with fixed-end supports, inside an electric furnace (*Fig. 1(a)*). *Fig. 1(b)* shows a test column located inside the electric furnace. Two segments of the furnace were used for shorter columns while three segments were used for longer columns. Once the specimen temperature reached the target temperature, the specimen was allowed another 10 minutes to ensure a uniform temperature in the column before loading. During the heating phase, special care was taken to monitor the load applied to the specimen due to thermal expansion effects. Once a steady state was reached, load was applied slowly using the hydraulic jack until failure. As expected, all the specimens failed in flexural-torsional buckling except the G550-1800-300 specimen, which showed interaction of flexural-torsional buckling and local buckling. Axial shortening and lateral deflections at mid-height were also measured with ultimate failure load.

Table 1. Details of test specimens

steel grade	f_y (MPa)	E (MPa)	nominal thickness (mm)	measured BMT (mm)	section dimensions (mm)			length of specimens (mm)	
					Web	Flange	Lip	Series 1	Series 2
G550	615	205000	0.95	0.95	55	35	9	1800	2800
G250	271	188000	1.95	1.95	75	50	15	1800	2800
G450	515	206000	1.90	1.88	75	50	15	1800	2800

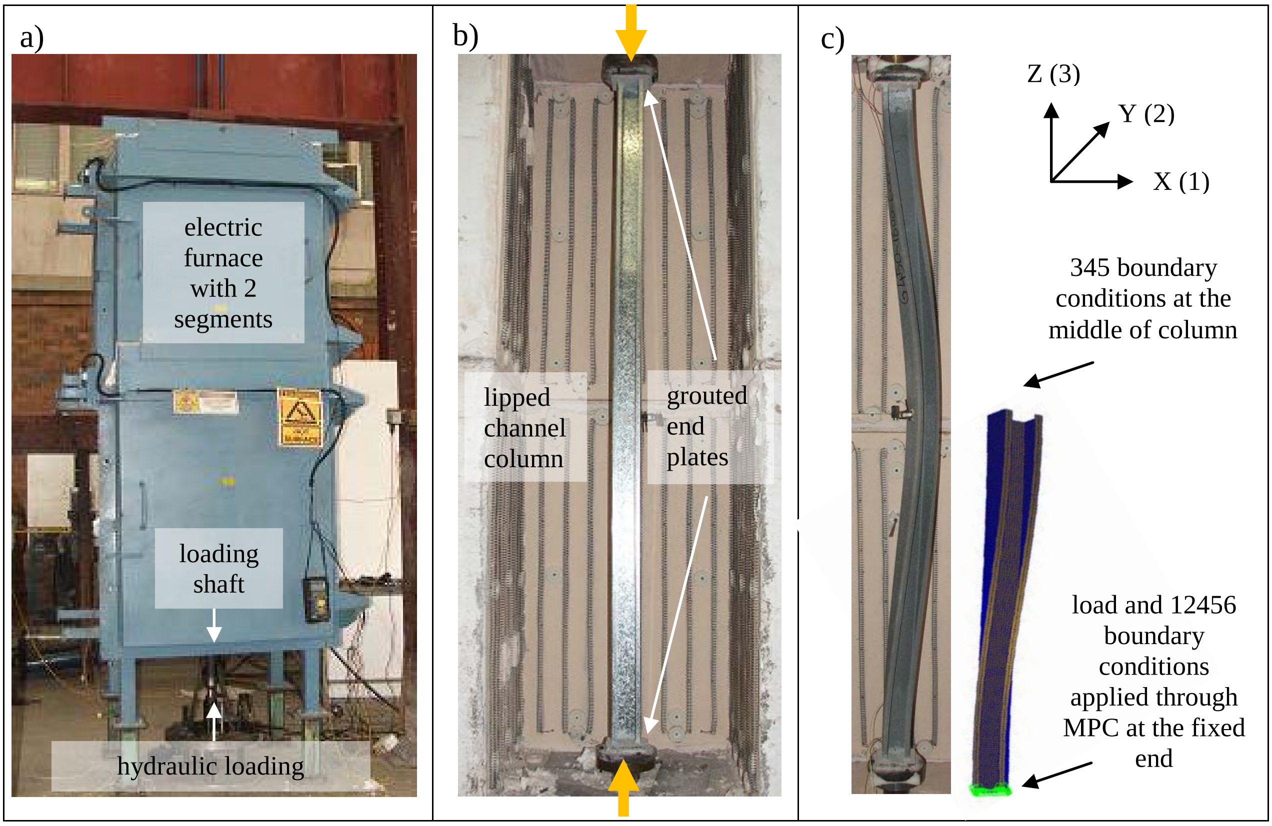

Fig. 1. a) Furnace and loading set-up; b) Test specimen; c) Failure modes from test and FEA

2 FINITE ELEMENT MODELLING

In this research ABAQUS was used in the finite element analyses (FEA) of cold-formed steel columns subject to axial compression loads. The measured dimensions of test specimens including their base metal thicknesses were used in the analyses. Suitable element type (S4) and size (5 mm x 5 mm) were selected considering the accuracy and economy of simulations. The measured stress-strain curves of the cold-formed steel showed significant nonlinearities at elevated temperatures. Therefore a strain hardening model was used in the simulations. Appropriate mechanical properties and Ramberg Osgood stress-strain model for the selected cold-formed steels were obtained from [8,9]. Elastic-perfect plastic model was used in the FEA of low strength cold-formed steel columns at lower temperatures up to and including 300^{o}C as suggested in [5].

Due to the symmetry conditions of the test specimen and loading, only one half of the column length was simulated with appropriate boundary conditions as shown in *Fig. 1(c)*. Axial translation was allowed at the bottom end. These boundary conditions were applied to the independent node of the rigid fixed MPC (Multi Point Constraint) located at the bottom end of the model. In this model, the independent node was located at the geometric centre of the cross-section. At the middle of the model, out of plane displacements were allowed while restricting the axial displacement. In addition, axial rotation was allowed at the middle of the model. The measured global geometric imperfections reported in [5] were used with the lowest eigen mode from the bifurcation buckling analyses. The residual stresses for lipped channel sections without rounded corners proposed in [13] were used in the finite element of model at ambient temperature. The reduced residual stresses were used in the analyses at elevated temperatures as was done in [13]. Nonlinear analyses were undertaken using the modified Riks method to find the ultimate compression load.

In this research, the ultimate failure load, load-deflection curves and deflected shape from FEA were compared with corresponding test results reported in Bandula Heva and Mahendran [5]. *Fig. 1(c)* shows the failure modes observed in test and compares it with corresponding failure mode from FEA. These figures show that the failure modes from FEA and test are similar, ie. flexural-torsional buckling mode. The developed finite element model was finally validated by comparing the ultimate loads obtained from tests and FEA for different steel grades, thickness and lengths. The mean value of Test/FEA ultimate load ratio is close to one (1.037) while the associated coefficient of variation is also small (0.131). Therefore the developed finite element model can be considered to accurately to simulate the behaviour of long cold-formed steel columns subject to flexural-torsional buckling effects at ambient and elevated temperatures.

3 PARAMETRIC STUDY OF LIPPED CHANNEL COLUMNS

In the parametric study, the validated finite element model described in the last section was used with appropriate changes to the geometric parameters and boundary conditions. Both pinned and fixed ended columns were considered at ambient and uniform elevated temperatures. *Fig. 1 (c)* shows the boundary conditions used in FEA for fixed ended columns. Pinned ended columns were simulated similarly with nodal loads and "1,2,6" boundary conditions at the column end. Instead of the measured thicknesses and imperfections, nominal thicknesses and geometric imperfection values (L/1000) were used. Reduced mechanical properties with corresponding stress-strain curves based on Ramberg-Osgood model at elevated temperatures were obtained from [8,9].

3.1 Flexural-torsional buckling behaviour of pinned ended columns

A series of analyses was undertaken for pinned ended columns with a lipped channel section of 55x35x9 mm. The comparisons showed that the current design rules based on AS/NZS 4600 can be used to predict the ultimate loads of pinned ended cold-formed steel columns subject to flexural-torsional buckling at both ambient and uniform elevated temperatures by using the appropriately reduced mechanical properties of steels at elevated temperatures. The mean values of the ratio of ultimate loads from FEA and AS/NZS 4600 are 1.076, 1.006 and 1.060 with smaller coefficients of variations of 0.025, 0.062 and 0.029, respectively for G250-0.95, G250-1.95 and G450-1.90 steel sections. In the case of Eurocode 3 Part 1.3, the mean values of the ratio of ultimate loads from FEA and design code are higher than those obtained for AS/NZS 4600 (1.096, 1.125 and 1.111, respectively). It was found that the buckling curve "a" is more appropriate to predict the flexural-torsional buckling capacity of pinned ended columns. However, buckling curve "b" provides safer lower bound predictions.

3.2 Flexural-torsional buckling behaviour of fixed ended columns

Three different steel grades and thicknesses (G450-1.90 mm, G250-1.95 mm and G550-0.95 mm) were selected in this parametric study to investigate the behaviour of fixed ended cold-formed steel columns at ambient and elevated temperatures subject to flexural-torsional buckling. Various lipped channel cross-sections were selected for each thickness to obtain a wide range of results. For each cross-section a range of member lengths (1500 to 4000 mm) was selected to obtain flexural-torsional buckling as the failure mode. Elevated temperatures for this study were selected as 100 ^{o}C to 700 ^{o}C at 100 ^{o}C intervals. For some of the shorter columns, the effective area calculated using AS/NZS 4600 effective width equations was slightly less than the gross area, implying the possible occurrence of local and global buckling interaction. Such columns were not included in the comparisons and discussions of this paper.

The ultimate loads of cold-formed steel compression members subject to flexural-torsional buckling at ambient and elevated temperatures were compared with the predictions of ambient and elevated temperature design standards using the reduced mechanical properties at elevated temperatures. Fixed-end supports provide restraints against major and minor axis rotations as well as twist rotations and warping. Hence fixed ended columns failing by overall buckling were designed as concentrically loaded compression members using their effective length as equal to half the column length. In this case, the effective lengths for major and minor axis flexural buckling as well as torsional buckling were assumed to be equal to one half of the column length.

Fig. 2(a) shows the ultimate loads of fixed ended columns subjected to flexural-torsional buckling at ambient temperature, in the form of non-dimensionalised ultimate stress versus slenderness curves. Comparison of results showed that AS/NZS 4600, AISI S100 and DSM predictions are reasonable for shorter and intermediate columns (where λ_c is less than or equal to 1.5) subject to flexural-torsional buckling. However, for longer columns (second region where λ_c>1.5) their predictions were found to be too conservative. This behaviour was investigated in detail at ambient temperature by Gunalan and Mahendran [14]. It was found that the warping fixity provided by fixed ends enhance the ultimate capacity of cold-formed steel lipped channel columns subject to flexural-torsional buckling. Hence they investigated the second region for slender columns (where λ_c is greater than 1.5), and proposed a new set of equations (*Eqs. (1)* and *(2)*) for fixed ended columns with warping fixity when they are subjected to flexural-torsional buckling. The ultimate loads of these columns agreed well with the proposed equations compared to the design curve based on AS/NZS 4600 as shown in *Fig. 2(a)* (mean value is 1.005 and associated coefficient of variation is 0.05).

$$f_n = \left(0.69^{\lambda_c^2}\right) f_y \quad \text{for } \lambda_c \le 1.5 \tag{1}$$

$$f_n = \left(\frac{0.8}{\lambda_c^{1.5}}\right) f_y \quad \text{for } \lambda_c > 1.5 \tag{2}$$

where f_n is the critical stress and λ_c is the non-dimensional slenderness given by,

$$\lambda_c = \sqrt{\frac{f_y}{f_{oc}}} \tag{3}$$

where f_{oc} is the minimum of elastic buckling stresses f_{ox}, f_{oy}, f_{oz} and f_{oxz}, f_{ox} and f_{oy} are the elastic flexural buckling stresses about major and minor axes, respectively, f_{oz} and f_{oxz} are the elastic torsional and flexural-torsional buckling stresses, respectively.

In the current study it was observed that the ultimate loads of fixed ended columns at elevated temperatures agreed well with the proposed equations [14] compared to those in AS/NZS 4600 as shown in *Fig. 2(b)*. The stress-strain curve of low grade steels has a significant nonlinear region than in high grade steels. Nonlinear behaviour of low strength steels at lower elevated temperatures commences well before the yielding point. Usually flexural-torsional buckling failures occur in the elastic region. Since low strength steel loses their linear behaviour well below the 0.2% proof stress, failure occurs before it reaches the 0.2% proof stress. Therefore the axial compression load capacity is reduced at 400 ^{o}C and 500 ^{o}C for low grade steel columns.

Based on the current study it was found that the ambient temperature design equations proposed by Gunalan and Mahendran [14] can be used to predict the ultimate compression capacities of fixed ended columns at elevated temperatures reasonably well when they are subjected to flexural torsional buckling, by using the reduced mechanical properties. However, further research is needed into the effect of nonlinear stress-strain behaviour on the flexural-torsional buckling behaviour of cold-formed steel columns at elevated temperatures.

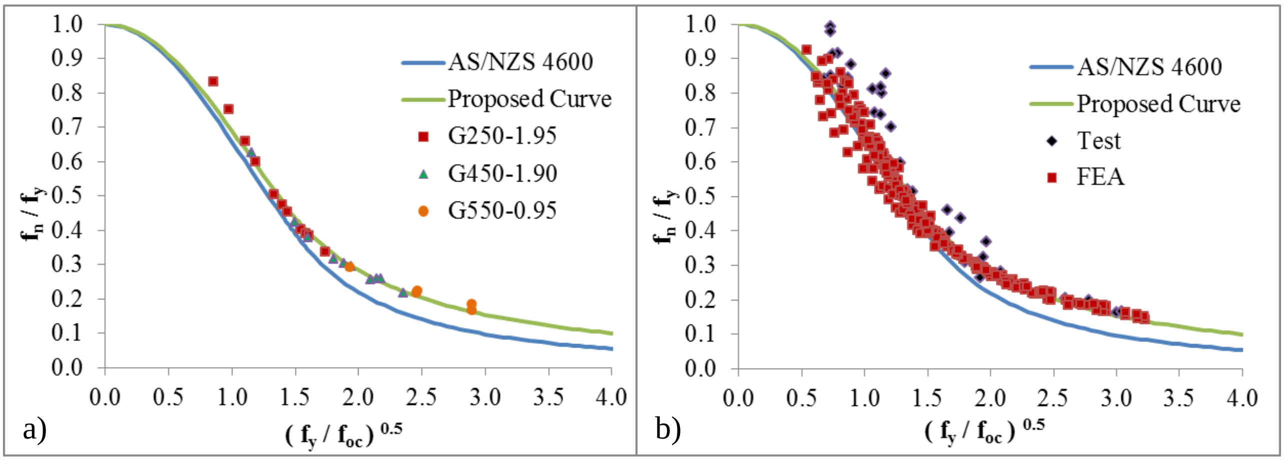

Fig. 2. Comparison of FEA results with AZ/NZS 4600 design rules for fixed ended columns at a) ambient temperature; b) elevated temperatures

Eurocode 3 Part 1.3 appears to be too conservative in predicting the ultimate loads of fixed ended columns subjected to flexural-torsional buckling at ambient temperature. The mean value of FEA to code prediction ratio is 1.335. Eurocode 3 Part 1.3 recommends the buckling curve "b" for cold-formed steel lipped channel sections. However, comparison of FEA results with the different buckling curves in Eurocode 3 Part 1.3 shows that buckling curve "b" is too conservative. Instead it appears that the ultimate load results follow buckling curve "a_o". As observed in the case of AS/NZS 4600, the ratio of FEA to Eurocode 3 prediction increases with increasing slenderness due to the beneficial effect of warping restraint. However, it is not possible to propose any improvements to the design curves within Eurocode 3 Part 1.3 guidelines.
Eurocode 3 Part 1.3 predictions are conservative than AS/NZS 4600 in predicting the ultimate loads at elevated temperatures. Eurocode 3 Part 1.3 recommends the buckling curve "b" for channel sections. However, comparison of results showed that buckling curve "b" produces more conservative results than buckling curves "a_o" and "a", particularly for high strength steels. In the case of low strength steels at 400 ^oC and 500 ^oC, results are unconservative even for predictions with buckling curve "b" due to significant nonlinearity in the stress-strain curve before yielding. Considering the distribution of results, buckling curves given in *Table 2* are recommended for fixed ended lipped channel columns at elevated temperatures based on the steel grade and temperatures.
Eurocode 3 Part 1.2 [15] is the only available elevated temperature design standard which provides design rules for the fire design of cold-formed steel members. Its predictions for Class 3 sections are overly conservative because imperfection factors based on ambient temperature yield stress are higher than that of buckling curve "b" recommended by Eurocode 3 Part 1.3. Therefore considering the FEA results, Eurocode 3 Part 1.2 is not recommended for the fire design of cold-formed steel compression members since it provides overly conservative capacity predictions.

Table 2. Proposed buckling curves for fire design using Eurocode 3 Part 1.3

grade	low grade steel			high grade steel	
temperature ^oC	$20^oC \leq T \leq 300^oC$	$300^oC < T \leq 500^oC$	$500^oC < T \leq 700^oC$	$20^oC \leq T \leq 500^oC$	$500^oC < T \leq 700^oC$
buckling curve	a_o	c	b	a_o	a

4 SUMMARY

This paper has described a numerical study of the flexural-torsional buckling behaviour of cold-formed steel lipped channel columns at ambient and uniform elevated temperatures. Suitable finite element models were developed and validated using the results obtained from the experimental study conducted by the authors and used further in a parametric study. The ultimate load results were compared with the predictions from the ambient temperature cold-formed steel design standards using appropriately reduced mechanical properties. Elevated temperature capacity predictions of AS/NZS 4600, AISI S100, DSM and Eurocode 3 Part 1.3 using reduced mechanical properties showed a good agreement and a better consistency for pinned ended columns subjected to flexural-torsional buckling. However, they were too conservative for fixed ended slender columns subject to flexural-torsional buckling. This is due to the fact that these design rules ignore the beneficial effect of warping restraint provided by fixed ended columns. Hence it was concluded that the recently proposed equations within AS/NZS 4600 and AISI S100 design provisions should be used with appropriately reduced mechanical properties to accurately predict the flexural-torsional buckling capacity of cold-formed steel compression members at elevated temperatures. The comparative study of ultimate load results from finite element analyses and design codes showed that the capacity of low grade steel columns with intermediate slenderness was adversely affected by the increased nonlinearity in the elevated temperature stress-strain curves. Further research is required to include the effects of nonlinear stress-strain characteristics within the guidelines of AS/NZS 4600 and AISI S100. However, suitable buckling curves can be used for this purpose within Eurocode 3 Part 1.3 design provisions. In contrast, the current Eurocode 3 Part 1.2 design rules were found to be overly conservative.

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