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Influence of Non-uniform Elevated Temperature on the Structural Stability and Strength of Gypsum-Sheathed Cold-Formed Steel Beam Channel Members

Elias Ali[1], Kermelos Woldeyes[2] and Girum Urgessa[3]

1. Department of Civil and Environmental Engineering, The University of Alabama in Huntsville, Huntsville, AL 35805, USA

2. Department of Civil, Architectural and Environmental Engineering, Drexel University, Philadelphia, PA 19104, USA

3. Department of Civil, Environmental and Infrastructural Engineering, George Mason University, Fairfax, VA 22030, USA

Abstract: The objective of this paper is to computationally explore the structural stability and strength of gypsum-protected CFS (cold-formed steel) beam channel sections under non-uniform elevated temperatures when exposed to standard fire on one side of the panel and subjected to pure bending. When a CFS member is subjected to fire (or thermal gradients) its material properties change—but this change happens around the cross-section and along the length creating a member which is potentially non-uniform and unsymmetrical in its response even if the apparent geometry is uniform and symmetric. Computational finite element models were analyzed in ABAQUS to establish steady-state thermal gradients of interest. Existing test data were utilized to develop the temperature dependence of the stress-strain response. The time-dependent temperature distribution on the cross-sections obtained from heat transfer analysis was later used in the stability and collapse analyses. The stability of the models was explored to characterize how local, distortional, and global buckling of the member evolves under both uniform and non-uniform temperature distributions. Finally, collapse simulations were performed to characterize the strength under pure bending and explore directly the evolution of strength under the influence of non-uniform temperature.

Key words: CFS, non-uniform temperature distribution, stability, collapse moment.

1. Introduction

The investigation of fire safety and responses of structures under elevated temperature has gained increased research interest in the last two decades due to the increased incidents of major fires and fire accidents in buildings, building compartments, and infrastructure. Recently, CFS (cold-formed steel) is extensively used from low to medium raised structures, namely for residential, industrial, and commercial buildings as the framing, partition walls, and exterior walls and even as a load-bearing structural component system on the floor and ceilings. This growing interest in thin-walled structural members in general and CFS, in particular, is due to their unique advantage of high strength to weight ratio. During fire accidents, steel would quickly heat up and results in a rapid reduction in its mechanical properties, particularly the yield strength and stiffness. These reductions in mechanical properties have been investigated by researchers such as Keerthan and Mahendran [1], Kankanamge [2], and Cheng et al. [3] both experimentally and numerically. It was found that the reductions in strength and stiffness are even more significant in CFSs. Therefore, CFS members are commonly used in structural wall and floor systems protected with gypsum board, with or without insulation, on both sides for fire protection.

Past researchers such as Kankanamge [2], Alfawakhiri and Farid [4], Shahbazian and Wang [5] have investigated the buckling behavior and resistance of CFS members at elevated temperatures. Yin and

Corresponding author: Elias Ali, Ph.D., lecturer, research fields: fire and blast safety of structures, composite materials.

Wang [6] investigated the effect of non-uniform temperature distribution on lateral-torsional buckling resistance of steel I-beams using parametric study. Alfawakhiri and Sultan [7] studied the fire resistance of load-bearing LSF (light gauge steel frame) assemblies using analytical thermo-structural model procedures to simulate lateral deformation histories and predict structural failure time. They considered the gypsum board and three different types of insulations (glass, rock, and cellulose) to determine the temperature profiles on the LSF steel stud and the failure time of the wall. Sultan et al. [8] provided a model for predicting heat transfer through insulated steel-stud wall assemblies exposed to fire on one side of the panel. To verify their model, they performed tests on four full-scale wall assemblies with insulation in the wall cavity. They considered two cases of gypsum board (single layer and two layers of gypsum at both ends). Kontogeorgos et al. [9] developed a model to simulate the temperature distribution in the wall assembly of the gypsum board using the ISO834 fire curve. Kukuck [10] studied heat and mass transfer through gypsum partition subjected to fire exposure. The developed model incorporates the mass transport effects of water in both liquid and vapor form and found that this mass transport plays a significant role in the thermal response of gypsum wallboard when subjected to fire. The application of a new composite material called functionally graded material for thermal sheathing in thin-walled structures was investigated by Ali and Bayleyegn [11]. Analytical and numerical buckling analysis of composite plates made of metal and ceramic plates was also studied by Ali and Bayleyegn [12] for extreme loading application.

During a fire, the temperature distribution along the CFS section is usually assumed to be uniform, for analytical simplicity, both across the section and along the member length. Thus, buckling behavior is analyzed based on uniform reduced material properties. However, in a real fire scenario, the temperature distribution in a CFS section is generally not uniform. This is especially true when the CFS structural member is exposed to fire only on one side. This phenomenon would make buckling behavior and analysis more complicated than the commonly practiced analysis approach.

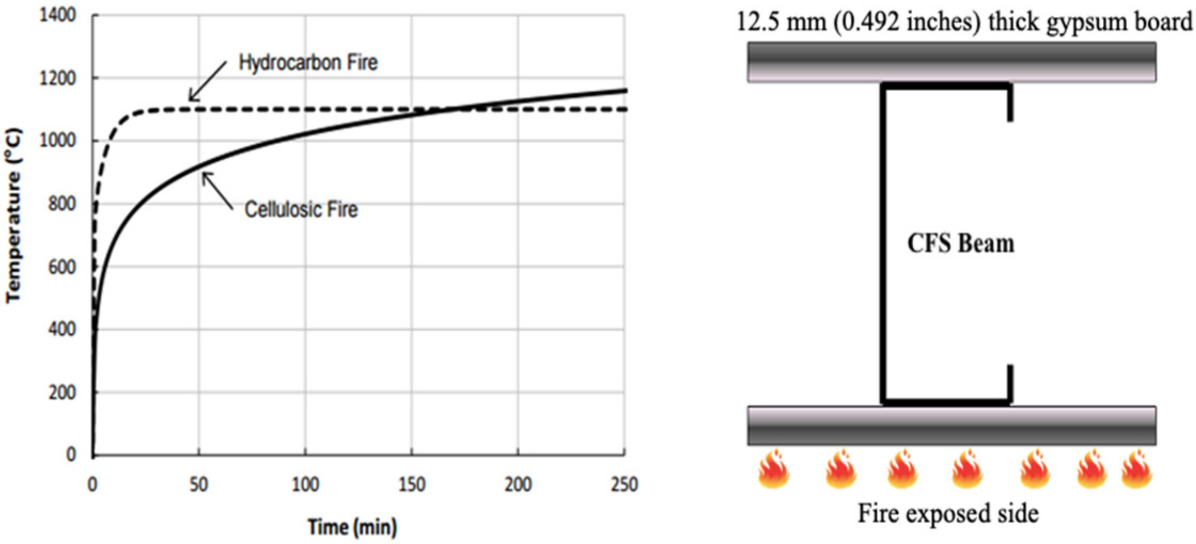
Thus, this paper presents the analysis that adds to the state-of-the-art in understanding the effect of non-uniform elevated temperature distributions on the structural buckling behavior and responses of a CFS beam under pure bending due to fire on one side of the panel.

2. Modeling Approach and Thermal Analysis

Evaluating the non-uniform temperature distribution in the CFS channel cross-section, which is protected by the gypsum board, requires heat transfer analysis. Commonly, these temperature distributions are performed using finite element analysis. However, this approach would consume time and high storage capacity when there is a need to perform a parametric study. Thus, three separate input scripts for 2-D time-dependent heat transfer analysis, elastic buckling analysis, and non-linear collapse analysis were developed using a MATLAB program, which is then coupled with a finite element package ABAQUS. The fire temperature used in the heat transfer analysis was defined using the ISO834 (International Organization for Standardization 834) standard fire curve given by Eq. (1), where T_a = 20 °C is the ambient temperature and t is time in seconds.

$$T = T_a + 345\log(8t/60+1) \quad (1)$$

Fig. 1 shows the ISO standard fire curve used in the study, the configuration of the CFS, and a 12.5 mm gypsum board on both exposed and unexposed sides of the structural member. Material properties used in the heat transfer were density, thermal conductivity, and specific heat for both steel and gypsum boards.



(a) (b)

Fig. 1 (a) ISO834 standard fire and (b) CFS channel section protected by gypsum board and fire on one side.

Table 1 Material properties used in the heat transfer analysis.

Material	Density (kg/m^3)	Thermal conductivity (W/m·°C)	Specific heat (J/kg·°C)
Steel	7,850	$\lambda = 54 - 3.33 \times 10^{-2}(T)$ (20 °C ≤ T < 800 °C) $\lambda = 27.3$ (800 °C ≤ T ≤ 1,200 °C)	$c = 425 + 7.73 \times 10^{-1}(T) - 1.69 \times 10^{-3}(T^2) + 2.22 \times 10^{-6}(T^3)$ (20 °C ≤ T < 600 °C) $c = 600 + \frac{13,002}{738 - T}$ (600 °C ≤ T < 735 °C) $c = 545 + \frac{17,820}{T - 731}$ (735 °C ≤ T ≤ 900 °C)
Gypsum board	727	0.2 at 10 °C 0.218 at 150 °C 0.103 at 155 °C 0.3195 at 1,200 °C	925.04 at 10 °C 941.5 at 95 °C 24,572.32 at 125 °C 953.14 at 155 °C 1,097.5 at 900 °C

These values vary with temperatures and a range of values were suggested by several researchers. In this paper, the values obtained from Feng et al. [13] were used as shown in Table 1.

Heat transfer analysis and structural behavior investigation were carried out for three CFS sections (362S200-54, 400S200-54, and 600S200-54). The thermal boundary conditions considered during the heat transfer analysis were convection and radiation for both fire exposed sides and ambient sides. These interaction properties were defined by convection surface film coefficient of 25 $W/m^2 \cdot K$ and 10 $W/m^2 \cdot K$ for the exposed side and ambient side respectively. Radiation film coefficient of 25 $W/m^2 \cdot K$ for fire exposed side, and emissivity of 0.3 and 0.8 for fire exposed and ambient sides were used respectively.

Fig. 2 shows the temperature profile for CFS beam channel section 400S200-54 (web height = 4 inches, flange width = 2 inches, and design thickness = 0.0556 inches) sheathed with a single-layer gypsum board after 60 min of fire. It was observed that the temperature in the web elements of the CFS section is not uniform with the highest temperature at parts closer to the fire exposed side and gradually tends to

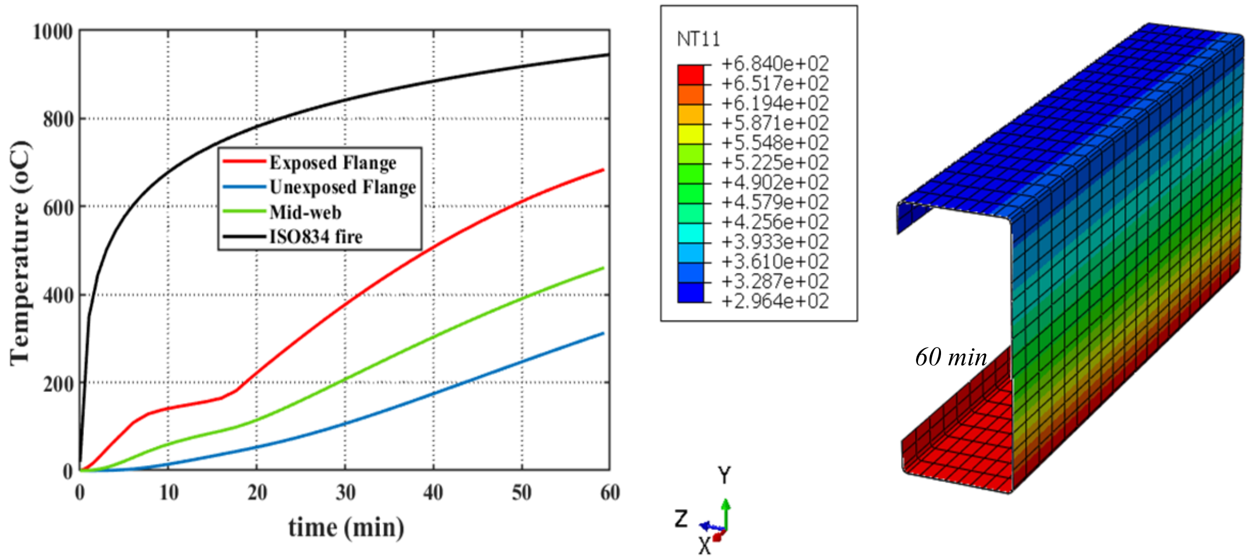


Fig. 2 Temperature distribution on 400S200-54 CFS section after 60 min of fire.

attain smaller temperature at the unexposed surface. The temperature in the unexposed flange and lip remains relatively low even after 60 min of fire exposure, compared to the fire exposed flange and lip.

3. Model Details and Assumptions

3.1 Mechanical Properties of CFS at Elevated Temperatures

When CFS structural members are exposed to fire or elevated temperature, there will be a rapid increase in temperature in the member which causes a significant reduction in mechanical properties, particularly its stiffness, yield strength, and coefficient of thermal expansion. These reductions would facilitate the collapse of the member or the entire structure at a critical temperature and loadings.

Many researchers carried out experimental tests on different steel sections and grades and developed equations for predicting the reduction in the mechanical properties of steel at elevated temperatures. Gerlich [14] derived an equation for yield strength and elastic modulus for a temperature range below 650 °C using several data from steady-state experimental tests. Chen and Young [15] investigated the mechanical properties of CFSs at elevated temperatures for both steady and transient tensile coupon tests for a temperature range of up to 1,000 °C for two steel grades of G550 and G500 with a plate thickness of 1.0 and 1.9 mm respectively. They proposed two mechanical properties reduction equations for yield strengths and elastic modulus, both normalized at ambient temperature properties.

This paper uses the recent experimental results from Kankanamge [2] who modified the previous results from Ranawaka and Mahendran [16] and proposed predictive equations for both high and low-grade steel types. The reduction factors in Table 2 were used for elastic buckling and collapse analyses.

3.2 Boundary Conditions and Loading in the Model

A simply supported CFS beam member subjected to pure bending was used in both elastic and non-linear collapse analysis. Four node S4R5 type shell elements were used in both elastic and non-linear collapse analysis of the CFS. This selection was based on the sensitivity study performed for different mesh types and sizes. At both ends of the beam, longitudinal (u_1) and transverse (u_3) deformations, and twisting in the minor axis (u_{R2}) were restrained in the analysis as shown in Fig. 3.

Table 2 Reduction factors of mechanical properties of CFS at elevated temperature.

Temperature (°C)	20	100	200	300	400	500	600	700	800
$k_{yT} = (f_{y,T}/f_{y,20})$	1	0.999	0.990	0.952	0.694	0.391	0.111	0.070	0.030
$k_{ET} = E_T/E_{20}$	1	0.933	0.849	0.715	0.580	0.445	0.310	0.175	0.040

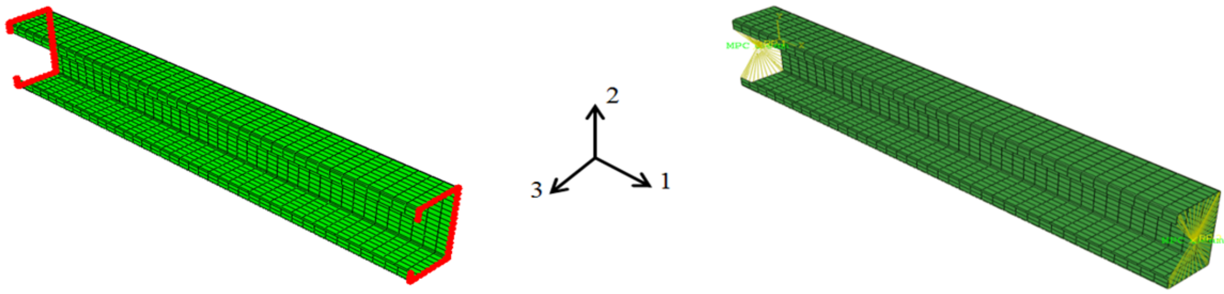


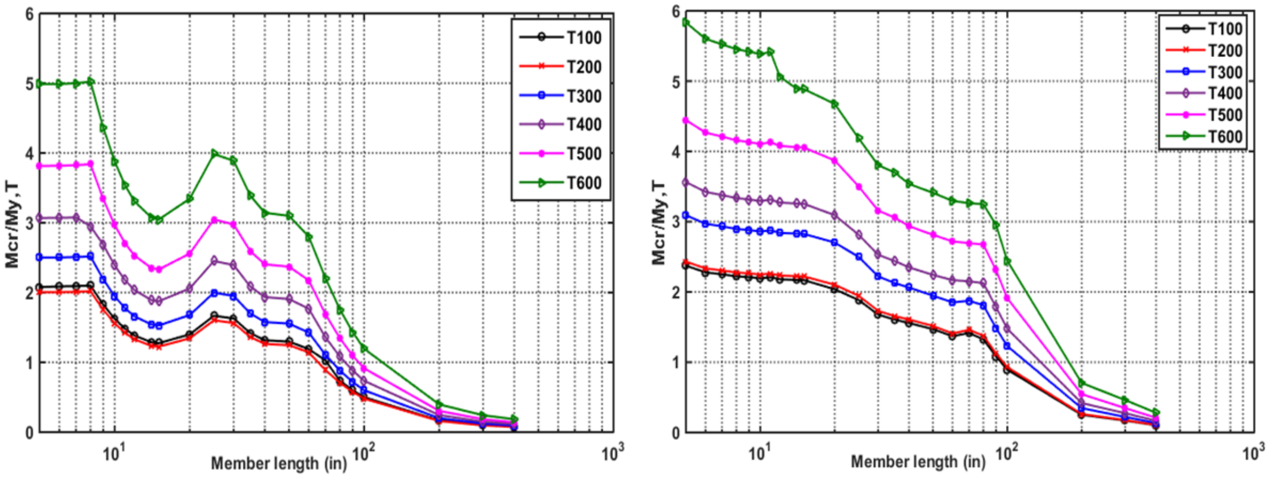
Fig. 3 Boundary condition on CFS beam.

4. Results and Discussion

4.1 Effect of Temperature Distribution on the Stability of CFS Beam

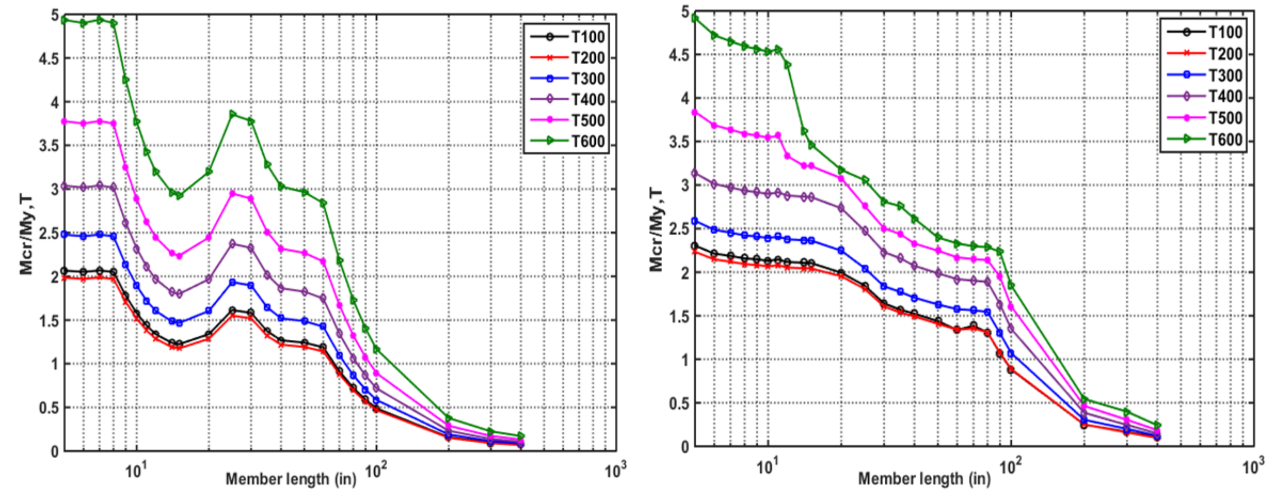
Both uniform and non-uniform temperature distributions were investigated for the three CFS sections. A uniform temperature in the CFS section means the whole cross-section was assumed to have the same temperature for each analysis step while for non-uniform temperature distribution cases predefined thermal gradient from the heat transfer outputs was used for each time step for the stability analysis of the CFS beams. Stress due to unit concentrated moment was then applied at the simply supported end to analyze the elastic buckling analysis. This process was repeated for all three sections with 11-time steps, which range from 37 °C to 600 °C and beam length from 5-400 inches, a total of 264 separate analyses for each beam. The critical buckling moment and normalized critical buckling moment results for the three CFS sections are presented in Figs. 4-7. The elastic critical buckling analyses for all the three sections in both uniform and non-uniform temperature distributions considered clearly show the reduction in critical buckling moments with increased fire temperature. These reductions also exhibit the same pattern for the reduction in material properties mainly the modulus of elasticity. It has a small or gradual reduction until the maximum flange temperature reaches 250 °C and follows with a step-change in capacity up to 600 °C, it then starts to exhibit a gradual change in moment capacity. These observed temperatures are consistent with the changes in mechanical properties listed in Table 2.

The critical moment for all three sections exhibits mainly two buckling modes for all temperature ranges: local buckling and distortional. The local buckling mode was predominant for the half wavelength of up to 5 inches where the minimum elastic critical moment was observed after the maximum elevated temperature on the exposed flange reaches 250 °C and beyond. The distortional buckling mode was predominant at a half wavelength of 12 inches and above. A combination of both local and distortional buckling modes was observed in the intermediate member lengths between 6-12 inches. It was also observed that using a non-uniform temperature distribution in the stability analysis significantly increases the section’s critical buckling moment compared to the uniform temperature cases. The reason for such behavior can also be explained by an increase in rigidity at both compressions flanges and lips, due to relatively lower temperature at the non-exposed side, which would directly affect the compression stresses at the flanges, resulting in a higher buckling moment. Also, an increase in section web would increase the critical buckling moment as shown in Fig. 7.



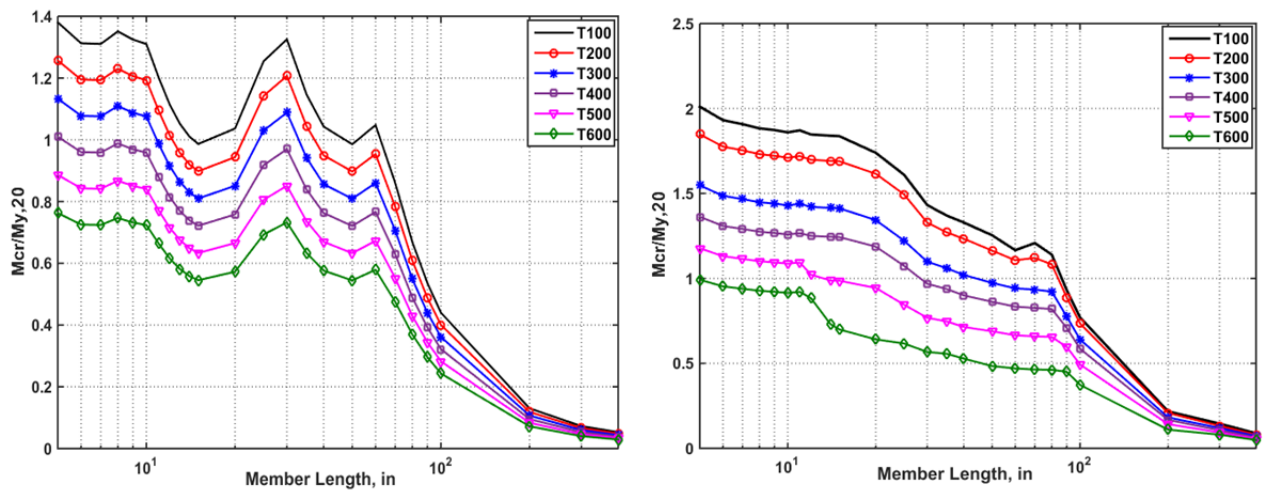
(a) (b)

Fig. 4 Normalized critical buckling moment for section 362S200-54 (a) uniform and (b) non-uniform.



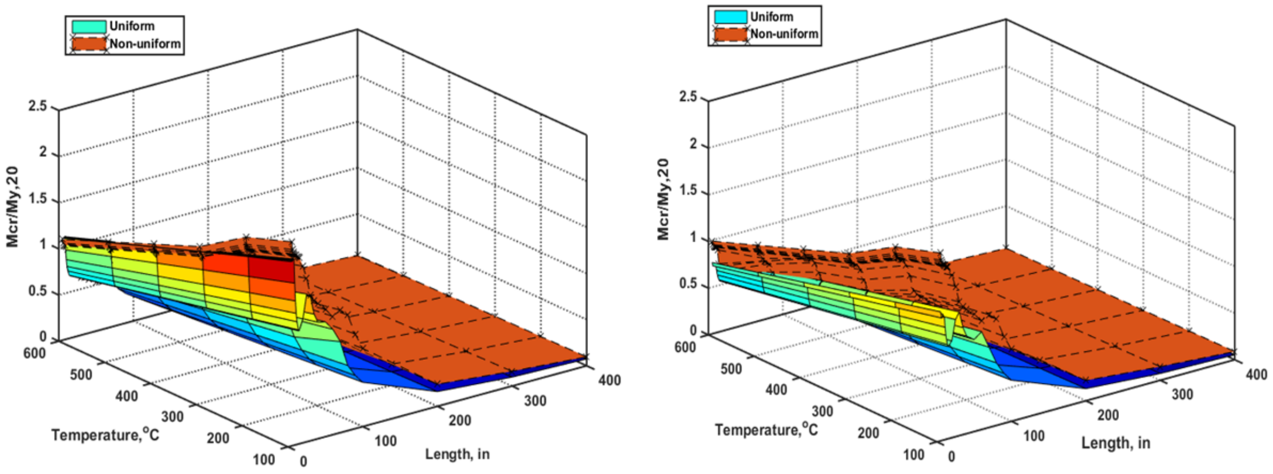
(a) (b)

Fig. 5 Normalized critical buckling moment for section 400S200-54 (a) uniform and (b) non-uniform.



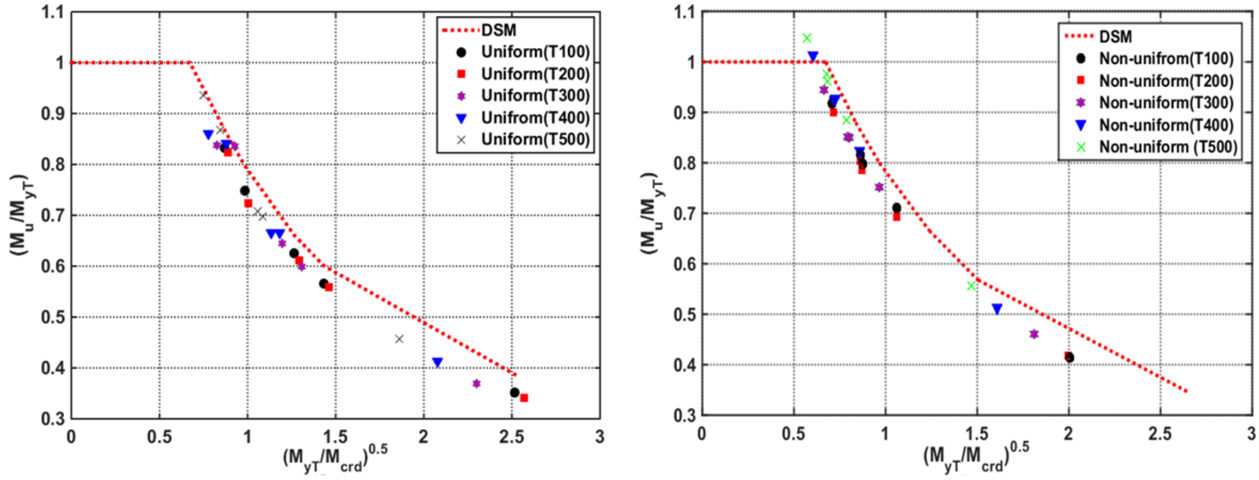
(a) (b)

Fig. 6 Normalized critical buckling moment for section 600S200-54 (a) uniform and (b) non-uniform.



(a) (b)

Fig. 7 Critical moment comparison under uniform and non-uniform temperature distribution for section (a) 362S200-54 and (b) 600S200-54.



(a) (b)

Fig. 8 Moment capacity prediction of section (a) 362S200-54 and (b) 600S200-54 under non-uniform elevated temperature.

4.2 Collapse Behaviour of CFS Beams under Non-uniform Temperature Distribution

The results obtained from elastic buckling analysis mostly predicted a higher critical buckling moment than the actual resisting capacity of the sections. This is true as the material property in such analysis uses the entirely elastic property, even if the material reaches its yield point. Thus, to observe the true buckling behavior, the material property has to be modeled with its yield stress specified during the analysis using an appropriate temperature-dependent stress-strain model. There are two ways to model material properties. One is the elastic-perfect plastic-type which assumes the yield stress on the material remains unchanged with an increase in plastic strain while the second modeling is an isotropic strain hardening, which allows the stress to increase with the plastic strain. Based on the experimental result by Kankanamge [2], higher grade CFS shows isotropic hardening behavior at both ambient and elevated temperatures whereas, low-grade CFS shows a well-defined yield point at a temperature range below 500 °C. The stress-strain model at the elevated temperature used was based on the Ramberg-Osgood stress-strain model modified by Kankanamge and

Mahendran [17]. The non-linear buckling analysis was then performed using the RIKS ON algorithm which provided LPF (load proportionality factor) versus Arch length. The predefined non-uniform temperature distribution was first imported from the heat transfer output files and the first Eigen-moment from the elastic analysis was then applied at the simply supported end for each time step. This operation is repeated for all sections. The finite element (FE) simulation moment capacity was then validated with the Direct Strength Method developed by Schafer [18].

Fig. 8 shows that the FE collapse analyses using uniform temperature distribution and direct strength method (DSM) for distortional section capacity are in good agreement for all temperature ranges considered in the collapse analysis. Up to 6.5% difference is observed for beam length 200 inches at a temperature of 400 °C. This difference is caused due to a combination of distortional buckling and lateral distortional buckling modes at such beam length. In all the temperature ranges, the DSM equation gives lower (conservative) section capacity than the FE collapse analysis especially for beam slenderness value ranging from 1 to 2.5.

5. Conclusions

This paper presented the results of a numerical simulation of the influence of uniform and non-uniform temperature distributions on the stability and moment capacity of the CFS channel beam section under pure bending and elevated temperature for three CFS channel sections. The following conclusions may be drawn:

- Non-uniform temperature distributions on the CFS channel beam resulted in a higher critical buckling and strength compared to uniform temperature distributions.
- Increasing the CFS section thickness and flange widths resulted in higher critical buckling moments for each temperature distribution.
- The critical moment for all the three sections exhibits mainly two buckling modes for all temperature ranges depending on member lengths. These buckling modes are local buckling and distortional.
- Even though the DSM equation for distortional buckling mode resulted in conservative section capacity, it can still be used without modification for uniform temperature distribution but might need further study to modify for the non-uniform temperature distribution cases.

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