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Structural behaviors of cold-formed steel channel members at elevated temperatures

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ABSTRACT

This paper presents an analytical study of the buckling behaviour of a simply supported cold-formed steel channel beam/column at elevated temperatures. An equation is derived to formulate the reduction of the critical buckling load at arbitrary elevated temperatures. Numerical models of a one-side protected ceiling beam are carried out in this study, which demonstrate that the temperature distribution on a one-side protected ceiling element with the bottom surface exposed to fire presents a non-uniform temperature field. Both simplified linear temperature fields proposed in this paper show good agreements on the reduction ratio of the critical buckling load with that by the simulated non-uniform temperature field (with a difference within 1%). However, the assumption of a uniform temperature on the cross-section for the ceiling member is not recommended as it gives an over conservative prediction of the critical buckling load (with a difference within 6.3%).

1. INTRODUCTION

The popularity of the cold-formed steel sections has dramatically increased in recent years due to the advantages such as high strength-to-weight ratios, ease of fabrication, lightness and the flexibility of the sectional profiles which can result in cost-effective designs and waste reduction. However, the thin thickness and high thermal conductivity of cold-formed steel lead to rapid steel temperature rise during fire, which makes the mechanical properties of cold-formed steels deteriorate rapidly, and result in the loss of load bearing capacity accordingly. Therefore a good understanding of fire resistance of cold-formed steel is of great significance. The mechanical properties of cold-formed steel at elevated temperatures were studied (Kankanamge and Mahendran, 2011; Ranawaka and Mahendran, 2009). These studies have made it possible for predicting the critical buckling loads of cold-formed steel sections suffered in fire. A considerable amount of work on the global buckling behaviours of cold-formed steel at elevated temperatures has been carried out recently (Kaitila, 2002; Feng and Wang, 2005; Shahbazian and Wang, 2011). An imperfection sensitivity analysis (Kaitila, 2002) was carried out on cold-formed lipped channel columns to evaluate the flexural buckling strength and ultimate strength of the sections. Experiments conducted by Feng and Wang (2005) on the full-scale cold-formed steel structural panels at ambient and elevated temperatures showed that the main failure mode of cold-formed channel steels under fire was overall flexural-torsional buckling, while the failure was local buckling at ambient temperature. Shahbazian and Wang (2011) modified Direct Strength Method (DSM) to calculate the global buckling ultimate strength of cold-formed steel lipped channel sections under uniform and non-uniform elevated temperatures, and concluded that the DSM global buckling column curve is applicable for uniform temperatures but a modification is required for non-uniform temperatures. However, since the FEA numerical studies could not cover all specific dimensional or thermal cases, it is necessary to conduct an analytical study on the critical buckling load of a cold-formed steel member at elevated temperatures.

2. CRITICAL BUCKLING EQUATIONS OF COLD-FORMED STEELS AT ELEVATED TEMPERATURES

This section is to deduce the buckling equations of simply supported cold-formed steel members endured elevated temperatures. Based on the assumptions of Bernolli beam theory, the axial strain at any coordinate point of the cross-section could be expressed by a membrane strain and a bending strain along the main axis as follows:

$$\varepsilon = \varepsilon_0 - yw'' \tag{1}$$

where ε_0 is the membrane strain, and w'' is the curvature of the beam in the xy- plane. On the other hand, the total strain can be decomposed by (Li and Purkiss, 2005)

$$\varepsilon = \varepsilon_\sigma + \varepsilon_{th} \tag{2}$$

where ε_σ is the stress-induced strain which is related to stress and temperature, and ε_{th} is the thermal strain which is the function of temperature. Substituting Eq. (1) into Eq. (2) yields,

$$\varepsilon_\sigma = \varepsilon_0 - yw'' - \varepsilon_{th} \tag{3}$$

and the mechanical stress can be expressed in terms of the secant form of stress-strain relation as follows,

$$\sigma_\sigma = E_T\varepsilon_0 - E_T yw'' - E_T\varepsilon_{th} \tag{4}$$

in which E_T is the secant elastic modulus at elevated temperature *T*.

Moreover, the axial membrane force N_x and the bending moment about the z-axis M_z can be expressed as

$$\begin{cases} N_x = \int_A \sigma_\sigma dA \\ M_z = -\int_A y\sigma_\sigma dA \end{cases} \tag{5}$$

Substituting Eq. (4) into Eq. (5) yields,

$$\begin{cases} N_x = k_{11}\varepsilon_0 + k_{12}w'' + F_1 \\ M_z = k_{12}\varepsilon_0 + k_{22}w'' + F_2 \end{cases} \tag{6}$$

in which

$$k_{11} = \int E_T dA,\ k_{12} = -\int E_T y dA,\ k_{22} = \int E_T y^2 dA,$$
$$F_1 = -\int E_T \varepsilon_{th} dA,\ F_2 = \int E_T \varepsilon_{th} y dA$$

For a simply supported member, the additional bending moment M_z induced due to the buckling deflection by the axial force can be expressed as $M_z = N_x \cdot w$, therefore Eq. (6) can be solved as

$$w = C_1 \sin kx + C_2 \cos kx + C \tag{7}$$

in which $k = \sqrt{\dfrac{N_x}{\dfrac{k_{12}{}^2}{k_{11}} - k_{22}}}$, $C = \dfrac{k_{12}(N_x - F_1) + F_2 \cdot k_{11}}{k_{11} \cdot N_x}$, and C_1 and C_2 are arbitrary constants. Substituting the boundary conditions of a simply supported member, $w_{x=0} = w_{x=l} = 0$, into Eq. (7), the deflection w could be given as

$$w = -C \tan\frac{kl}{2} \sin kx - C \cos kx + C \tag{8}$$

By evaluating Eq. (8) at $x = \dfrac{l}{2}$, the value of the deflection at the middle point of a simply supported member is obtained as

$$w_m = -C \frac{1 - \cos\dfrac{kl}{2}}{\cos\dfrac{kl}{2}} \tag{9}$$

which shows that the value of w_m goes infinite when $\cos\dfrac{kl}{2} = 0$. Therefore when $k = \dfrac{\pi}{l}$, the critical buckling load of a simply supported column yields,

$$N_{x,cr} = \frac{\pi^2}{l^2} \cdot \left(\frac{k_{12}{}^2}{k_{11}} - k_{22} \right) \tag{10}$$

Eq. (10) could be rewritten as

$$N_{x,cr} = P_{cr} \cdot f_T \tag{11}$$

in which $P_{cr} = \dfrac{\pi^2 E_{20} I}{l^2}$ is the Euler critical buckling load at an ambient temperature, f_T is treated as the reduction factor of critical buckling load at elevated temperatures and defined as

$$f_T = \frac{k_{22} - \frac{k_{12}^2}{k_{11}}}{E_{20}I} = \frac{1}{E_{20}I}\left(\int E_T y^2 dA - \frac{\left(\int E_T y dA\right)^2}{\int E_T dA}\right) \tag{12}$$

If the temperature distribution is uniform on the cross-section, the Young's Modulus across the section would be constant. Eq. (12) could be therefore simplified as

$$f_T = \frac{E_T}{E_{20}I}\left(\int y^2 dA - \frac{\left(\int y dA\right)^2}{A}\right) = \frac{E_T}{E_{20}} \tag{13}$$

which is very interesting to note that the reduction factor of the critical buckling load at a uniform elevated temperature coincidently equals the reduction factor of Young's Modulus at that elevated temperature accordingly.

Eqs. (11) and (12) give a general expression of the elastic critical buckling load of a simply supported cold-formed steel member at elevated temperatures. If the temperature distribution on a cross-section is known, the critical buckling load at an elevated temperature could be easily obtained from Eqs. (11) - (13).

3. NUMERICAL STUDY ON THE BUCKLING ANALYSIS OF COLD-FORMED STEEL IN FIRE

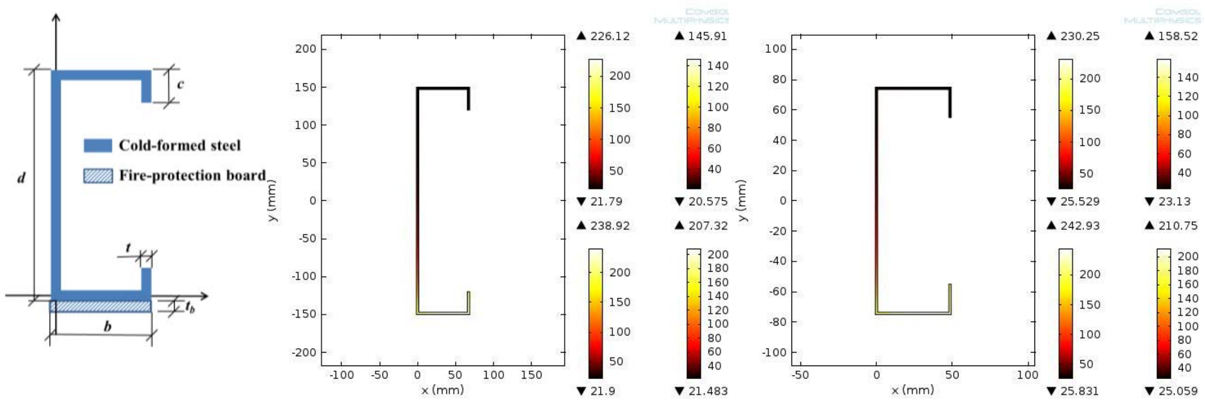
This section is to give an example of the application of the analytical equations of the critical buckling load presented in Eqs. (11) and (12). The thermal performance of cold-formed steel channel section members with one side protection to reveal the case of ceiling elements was conducted using a FEA commercial software called Comsol Multiphysics. Fig. 1(a) shows the nominal dimensions of the model. The model is geometrically carried out by two section scales, 300x70x30x3.0 mm and 150x50x20x1.5 mm, indicating the depth of the web, the width of the flange, the length of the lip, and the thickness throughout the cross-section from front to back. The fire protection board was chosen as the commonly used Gypsum plasterboard with a thickness of 12.5mm. The boundaries exposed to fire or ambient was considered by the heat flux expressed as the combination of convection and radiation, while the vertical boundaries of the protection boards were treated as the thermal insulated surface. The thermal properties of cold-formed steel were taken as those of carbon steel for whose data are provided in EN1993-1-2 (2005). The material properties of Gypsum plasterboard were taken from Kontogeorgos et al. (2012).

3.1 Thermal performance of cold-formed steel members

By conducting transient numerical studies of heat transfer, the evolution of a temperature field could be predicted specifying to different protection measures as well as different dimensional scales. Fig. 1 shows the temperature distributions on the cross-sections at elevated temperatures, in which the increase of temperature is revealed observably slow. The temperature scales on the right side represent temperatures at 30 minutes, 60 minutes, 90 minutes and 120 minutes respectively in the order of top right, bottom right, top left and bottom left. The highest temperatures on the cross-sections after 2 hours exposed in fire are exhibited as 238.92 °C for the large scale cross-section and 242.93 °C for the small scale cross-sections respectively. The interesting fact to emerge from these two figures is that the temperature on the fire unexposed flange keeps nearly ambient, which is presented as 21.9 °C for the large scale cross-section and 25.8 °C for the small scale cross-section after exposing in a standard fire for 2 hours.

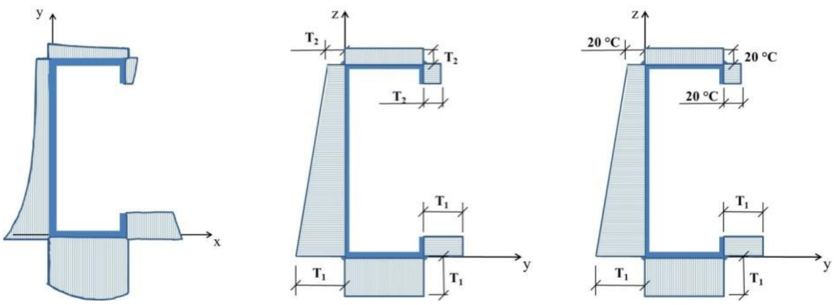
3.2. Buckling performance of cold-formed steel members

It is already known from Fig. 1 that the temperature distribution field is non-uniform on the cross-section of a cold-formed channel steel ceiling element, as shown in Fig. 2(a). In order to make the critical buckling load equations conducted in this study easily used in general, two simplified linear temperature fields have been performed as shown in Fig. 2(b) and Fig. 2(c), where T_1 and T_2 are the temperatures at the fire exposed/unexposed flange-web joints carried out in Section 3.1. In addition, a uniform temperature distribution, taken as T_1, is also assumed here in order to evaluate the influence of the non-uniform temperature on the critical buckling load.



(a) geometrical model (b) 300x70x30x3 (c) 150x50x20x1.5

Fig. 1 Temperature distribution on the one-side protected cold-formed steel cross-sections



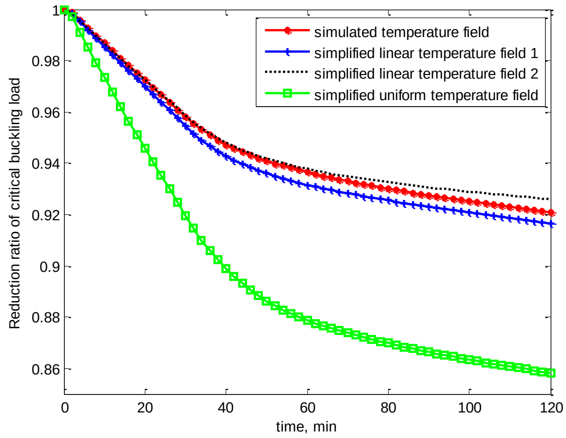
(a) (b) (c)

Fig. 2 Temperature fields. (a) simulated temperature field; (b) simplified linear temperature 1; (c) simplified linear temperature 2

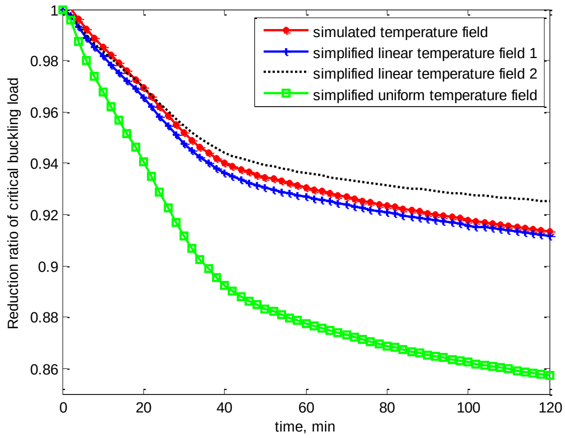
Fig. 3 shows the details of the predictions of the critical buckling loads given by the simplified temperature fields and the simulated temperature field, in which the reduction factors of Young's Modulus of the cold-formed steel at elevated temperatures are taken from Kankanamge and Mahendran (2011). Both simplified linear temperature fields give good agreements on the reduction ratio of the critical buckling load with that given by the simulated non-uniform temperature field (with a maximum difference of 0.5% for the big scale section, and 1% for the small scale section). However, although the uniform temperature field is commonly used by other researchers when calculating the critical buckling loads, it appears to be over conservative since the ratio of the critical buckling load is reduced almost as twice as that by the simulated non-uniform temperature field (with a maximum difference of 6.3% for the big scale section and 5.6% for the small scale section).

4. CONCLUSIONS

A detailed description of the derivation of the critical buckling load gives an invaluable insight into the buckling behaviours of cold-formed steel members at elevated temperatures. A reduction factor of the critical buckling load at an arbitrary temperature distribution has been given in this study, which is easily carried out when an elevated temperature field is given. The numerical thermal analyses carried out in this study have highlighted the non-uniform temperature distribution on the web of a cold-formed steel ceiling member with one-side protection, while it is acceptable to assume the temperature distribution linear when calculating the critical buckling load. However, the assumption of a uniform temperature on the cross-section for the ceiling member is not recommended as it gives an over conservative prediction of the critical buckling load.



(a)



(b)

Fig. 3 Comparison of the reduction ratio, $P_{cr,T}/P_{cr,20}$, of a one side protected channel section. (a) 300x70x30x3; (b) 150x50x20x1.5

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