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Buckling analysis of partially protected cold-formed steel channel-section columns at elevated temperatures

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ABSTRACT

This paper presents a numerical investigation on the buckling behaviour of plasterboard protected CFS channel-section columns subjected to axial loading when exposed to fire on its one side. The work involves temperature-dependent pre-buckling stress analysis and buckling analysis. Two non-uniform temperature distributions with linear and nonlinear temperatures along the web and constant temperatures in flanges and lips have been included in this paper. Bernoulli beam theory has been used in the pre-buckling stress analysis with considering the effects of temperature on strain and mechanical properties. The buckling analysis is performed using combined finite strip analysis and classical Fourier series solutions, in which the mechanical properties are considered to be temperature dependent. The results show that the temperature distributions have a significant influence on both the pre-buckling stress distribution and slenderness of CFS column members. It is also found that the thermal bowing effect improves the buckling performance of intermediate CFS members, but deteriorates that of long CFS members. This paper gives a better understanding of the effect of non-uniform temperatures on the buckling behaviour of CFS columns, and further extends the potential application of the finite strip method to the buckling analysis of CFS members at elevated temperatures.

1. Introduction

Thin-walled, cold-formed steel (CFS) members have been increasingly used as load-bearing components in low- and mid-rise buildings due to its advantages of high strength-to-weight ratio, ease of fabrication, and the flexibility of sectional profiles. However, the features such as thin thickness, open cross-section and great flexural rigidity difference about two cross-sectional axes, lead the buckling failure to be the main failure mode of CFS members [1]. When it is exposed to a fire, the rapid temperature rise in a CFS member makes the buckling behaviour even worse [2]. If the temperature distribution in a member is uniform, the buckling behaviour of the member can be analysed based on uniformly reduced material properties. However, if the temperature distribution in a member is not uniform, which usually happens in walls and/or floor panels when CFS members are exposed to fire on one side, the temperature-dependent material properties vary within the member. Together with the thermal bowing effect caused by various thermal expansions on the member, the analysis of structures could be much complicated, the problem of which is not fully addressed in the existing analysis of CFS members.

The buckling resistance of CFS columns at elevated temperatures has been investigated by many researchers. Mechanical properties of CFS have been investigated by Chen and Young [3] and Kankanamge and Mahendran [4], which showed a remarkable difference on the reductions of yield strength and elastic modulus when compared to hot-rolled steels. Feng and Wang [5] and Feng et al. [6] conducted experimental and numerical studies on the axial strength of CFS channel columns in wall panel systems exposed to fire on one side. It was found that the non-uniform temperature distributions have significant influence on the fire resistance of CFS wall panels. To better understand the fire performance of CFS wall panel systems, the effect of different insulation materials, insulation methods [7], and various fire protection wall panels [8] on the fire performance of the CFS wall systems has been studied recently.

Based on the available experimental and numerical studies of CFS members at elevated temperatures, many modifications have been proposed to the design methods in order to promote the potential applications of CFS. A modification to the design method recognised in EN1993-1-3 [9] was presented by Feng and Wang [10] to take into account the effect of the reduced mechanical properties and thermal bowing deflection at elevated temperatures. Shahbazian and Wang [11–13] presented a design method based on Direct Strength Method (DSM) to calculate the critical buckling load of CFS columns under high temperatures. Gunalan

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and Mahendran [14] proposed fire design rules based on the CFS design codes AS/NZS 4600 [15] and NAS [16] at room temperature.

Among all the design methods, DSM [17] has been increasingly adopted as an alternative design method to the Effective Width Method (EWM) due to the advantages of no need for tedious calculation of effective width. However, an accurate calculation of member elastic buckling load is essential when using DSM since the resistance of the member is directly determined by the elastic buckling loads and the squash load. The eigenvalue analysis of the Finite Strip Method (FSM) based software [18] has been widely applied to get the elastic buckling loads. However, since most existing FSM based software are developed under ambient temperature, the effect of thermal expansion on the stress distribution and the shift of neutral axis under non-uniform temperatures are not taken into account in these codes. Although the temperature effect has been considered by Shahbazian and Wang [11] in columns by using an "effective" squash load, this simplified method may not be able to reveal the actual non-uniform stress-distribution on the cross section and the corresponding effect on the buckling performance of CFS members. Furthermore, most existing FSM based codes are only available to the members subjected to uniform longitudinal stresses. Therefore it is not able to reveal the feature of the thermal bending moment which varies along the member length with a maximum value at the middle of the member and a zero value at support ends. The present study is therefore to further explore the application of the FSM to the buckling analysis of CFS members at elevated temperatures by considering both the reduced material properties and non-uniform stress distributions within the cross-section and along the member at elevated temperatures.

2. Pre-buckling stress analysis

If the channel section has a uniformly distributed temperature the reduction of material properties is identical everywhere in the section. The cross section will be subjected to uniform compression when the member is subjected to an axial load acted at the centroid of the cross section. However, if the temperature distribution is not uniform the stress distribution on the cross-section would be also not uniform, which is highly dependent on the temperature distribution due to the varying reduction of the mechanical properties within the cross-section and the bending moment caused by thermal bowing effect.

It is well known that steel has large thermal conductivity coefficient and thus for most cases the temperature in the steel can be approximately treated to be uniform. However, in the CFS sections, if the heat is transferred only from its one side and all of other sides are exposed in a cooling air environment, then the temperature variation within the cross-section will be remarkable owing to the thin thickness of the CFS sections. This happens in the external walls where the inner layer uses CFS sections protected by plasterboard. When there is a room fire the heat is transferred from the plasterboard to the CFS sections. In this case the CFS section is subjected to elevated temperatures on its one side and exposed to ambient on all of other sides (see Fig. 1(a)).

The heat transfer can be analysed using finite element analysis packages such as ANSYS. Since the longitudinal dimension is much greater than the cross-section dimensions, the heat transfer analysis can be carried out by using a 2-dimensional geometric model as shown in Fig. 1(a). A CFS channel section with a web depth of 200 mm, flange width of 75 mm, lip length of 20 mm and thickness of 2 mm is analysed, and a single layer of plasterboard with a thickness of 12.5 mm is used. All material properties such as density, specific heat, and thermal conductivity for CFS and plasterboard are assumed to be temperature-dependent, which are provided in [19,20]. The initial temperatures in both the CFS and plasterboard are assumed to be ambient. The combined convection and radiation boundary conditions are applied to all boundaries. However, the environmental temperatures surrounding the section are different. For the fire exposed surface (one side of the plasterboard) the environmental temperature is the fire temperature, which is calculated based on the standard fire curve; whereas for the fire unexposed surfaces the environmental temperature is the room temperature (20 °C). The convective coefficients employed in the fire exposed and fire unexposed surfaces are 25 and 9 W/m^2 K, respectively.

Fig. 1(b) shows the temperature distribution obtained from the finite element analysis. It can be seen from the figure that the temperature exhibits highly nonlinear on the flange, lip and web near to the plasterboard exposed to the fire. In order to examine the effect of nonlinear distribution of temperature on the buckling behaviour of the CFS section members, two simplified temperature distributions shown in Fig. 1(c) and (d) are proposed for the pre-buckling stress analysis. In Fig. 1(c) the temperature is assumed to be constants in flanges. Along the web the temperature decreases parabolically from fire exposed side to the geometrical centroid

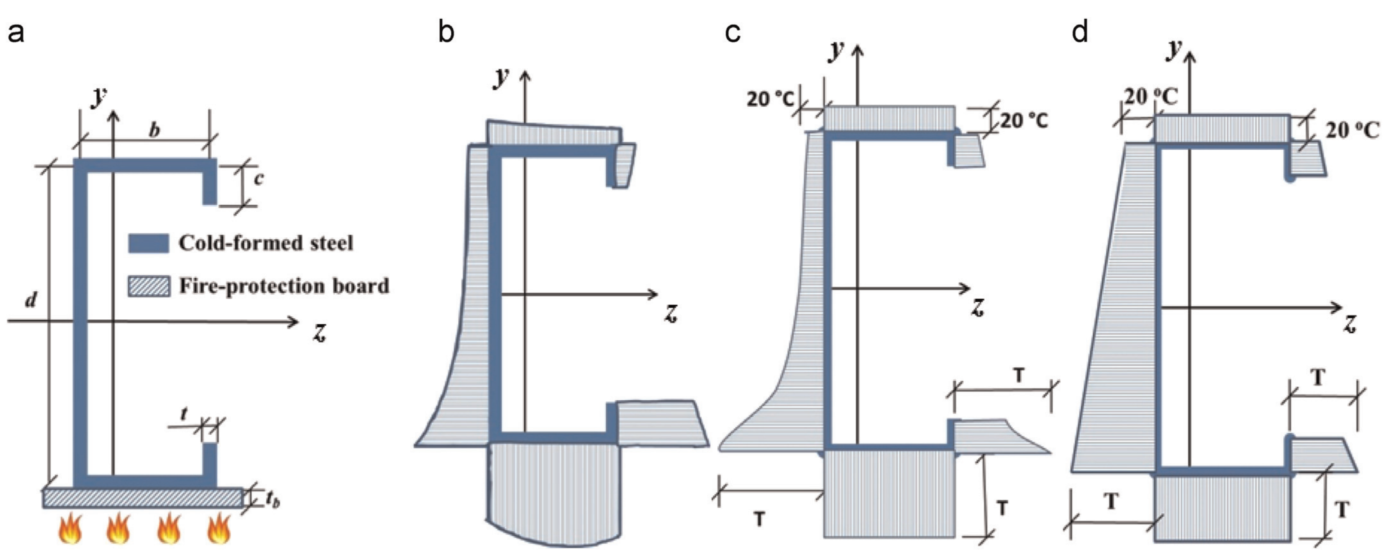

Fig. 1. Temperature distributions of CFS channel-section columns in fire: (a) CFS sketch (d=200 mm, b=75 mm, c=20 mm, t=2 mm, t_b=12.5 mm); (b) temperature distribution calculated from FEA; (c) assumed nonlinear temperature distribution and (d) assumed linear temperature distribution.