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Buckling analysis of cold-formed steel channel-section beams at elevated temperatures

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ABSTRACT

This paper presents a numerical investigation on the buckling behaviour of plasterboard protected CFS channel-section beams subjected to uniformly distributed loads when exposed to fire on its one side. The work involves three phases, namely heat transfer analysis, pre-buckling analysis and buckling analysis. The heat transfer analysis is accomplished using two-dimensional finite element analysis methods, from which the temperature fields of the channel-section beams are obtained. The pre-buckling analysis is completed using the Bernoulli bending theory of beams 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 there are significant temperature variations in web, fire exposed flange and lip. Also, it is found that the buckling behaviour of the beam with temperature variation in its section is quite different from that of the beam with a constant uniform temperature in its section.

1. Introduction

Thin-walled, cold-formed steel (CFS) members are traditionally used as purlins, the intermediate members in a roof system to support the corrugated roof or wall sheeting and transmit the force to the main structural frame. In recent years CFS has been also 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 because of the reduced mechanical properties at elevated temperatures [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 internal walls and/or floor panels when CFS members are exposed to fire on one side, the temperature-dependent material properties vary within the member. This makes the analysis of structures 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, for example [3–5]. However, limited studies could be found on the buckling behaviour of CFS beams in fire. The lateral-torsional buckling behaviour of CFS beams under uniform temperatures has been studied by Kankanamge and Mahendran [6] based on their experimentally obtained mechanical properties [7]. The comparison of their results with the design code recommended in EN1993-1-2 [8] showed that the design method presented in EN1993-1-2 is over-conservative for most members except that the members are very slender. It was also recognized that the moment capacity data were scattered in the intermediate slenderness range and therefore separate buckling curves are needed for different elevated temperatures in order to give accurate design prediction. Furthermore, the temperature limit of 350 °C for CFS recommended in EN1993-1-2 was found over conservative for CFS beams in fire [6,9]. Recently, Laím *et al.* have carried out an experimental study on the buckling resistance of CFS beams in fire [10]. Channel section and compounded lipped I-, R- and 2R-section beams were tested under various boundary conditions. It was found that the critical temperature of all simply supported beams went up to about 700 °C. Therefore a demand of an accurate design guideline has been raised to extend the use of CFS.

Direct Strength Method (DSM) [11] has been 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. Since the buckling resistance could be directly determined by using DSM based on the elastic buckling loads and the squash load, an accurate calculation of member elastic buckling load is essential. The eigenvalue analysis software CUFSM [12] based on the Finite Strip Method (FSM) has been widely adopted typically to get the elastic buckling loads. However, since CUFSM was developed under ambient temperature,

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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 the code. The present study is therefore to further explore the application of FSM to the buckling analysis of CFS members at elevated temperatures by considering non-uniform temperature distribution in the members.

2. Heat transfer

CFS sections utilised in buildings are usually protected by plasterboards or other fire resistant materials in order to increase their fire resistance. Thus, when they are exposed to a fire environment the temperature in CFS members will be much less than the fire temperature. Depending on how the member is protected, the temperature in a CFS member may be treated as time-dependent or both time- and position-dependent. The former means that the temperature is uniformly distributed within the member although it may vary with time, while the latter means that the temperature within the member varies with both time and position. Analytical approaches have been developed for calculating the uniform temperature in fire protected members using the concept of energy conservation [2]. For members with non-uniform temperature distribution numerical methods of heat transfer are normally used, in which the protected member and protection material are treated as a system for which the heat transfer analysis is conducted.

Consider a channel-section beam that is protected by plasterboard on its one side, as is shown in Fig. 1. When a fire occurs underneath the plasterboard heat will transfer from the fire to the beam through the plasterboard. The actual temperature distribution in the beam can be calculated using the theory of heat transfer as follows,

$$\rho c \frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) \tag{1}$$

where ρ is the density, c is the specific heat, T is the temperature, t is the time, λ is the thermal conductivity. For the case where the fire is uniform along the beam length, the heat transfer can be treated as a two-dimensional plane problem within the cross-section of the beam. The boundary conditions of Eq. (1) can be expressed as follows,

On the fire exposed surface:

$$\lambda \frac{\partial T}{\partial n} = \alpha_g \left(T_g - T\right) + \varepsilon_g \sigma \left[\left(T_g + 273\right)^4 - (T + 273)^4\right] \tag{2}$$

On the ambient exposed surface:

$$\lambda \frac{\partial T}{\partial n} = \alpha_a (T_a - T) + \varepsilon_a \sigma \left[(T_a + 273)^4 - (T + 273)^4\right] \tag{3}$$

On the symmetric plane:

$$\lambda \frac{\partial T}{\partial n} = 0 \tag{4}$$

where n is the surface normal, $\alpha_g = 25$ W/m^{2}K is the coefficient of heat transfer by convection on the fire exposed surface, $\alpha_a = 9$ W/m^{2}K is the coefficient of heat transfer by convection on the ambient exposed surface, T_g is the fire temperature in the vicinity of the fire exposed surface, T_a is the air temperature in the vicinity of the ambient exposed surface, $\varepsilon_g = 0.7$ is the surface emissivity on the fire exposed surface, $\varepsilon_a = 1$ is the surface emissivity on the ambient exposed surface, and $\sigma = 5.67\text{x}10^{-8}$ W/m^{2}K^4 is the Stephan Boltzmann constant.

For the present problem Eq. (1) is applied to the fire exposed surface of the plasterboard, Eq. (4) is applied to the two vertical sides of the plasterboard because of the periodically symmetrical boundary condition, and Eq. (3) is applied to all exposed surfaces of the channel section. Solving Eq. (1) with the boundary conditions defined by Eqs. (2)-(4) using finite element methods the temperature distribution in the channel section can be obtained. The material properties used in the heat transfer analysis are given in [13] for the plasterboard and [8] for the CFS. Fig. 2 plots the temperature distributions in the channel section at three different times, in which the fire temperature is defined using a standard fire curve, i.e. $T_g = T_a + 345\log(8\,t/60 + 1)$ and the air temperature is defined as a constant, i.e. $T_a = 20$ °C. As is to be expected, the temperature in the channel section is found to be higher at a point that is closer to the fire exposed surface. It can be seen from Fig. 2 that the variation of temperature in the fire exposed flange, fire exposed lip and web is quite significant, indicating that the temperature is not uniformly distributed in these elements. Compared to the temperature in the fire exposed elements, the temperature in the fire unexposed flange and lip remains low even after an hour of the fire exposure. Note that the highest temperature in the channel section is much lower than the fire temperature because of the use of 12.5 mm thick plasterboard protection. For example, after an hour fire exposure, the highest temperature in the two channel sections is 250 °C, while the fire temperature at the same time is about 945 °C.

3. Pre-buckling analysis

The channel section is not symmetric about the principal axis parallel to its web line. Its shear centre is also not at the centroid. However, when they are used in buildings to support the loading on the floor or ceiling, several channel-section beams are usually used together (see Fig. 1). In this case the transverse loading on the channel-section beam can be assumed to act at the shear centre of the section.

If the channel section has a uniformly distributed temperature then the mechanical properties of the section are also symmetric about its geometrically symmetric axis. However, if the temperature is not uniform in

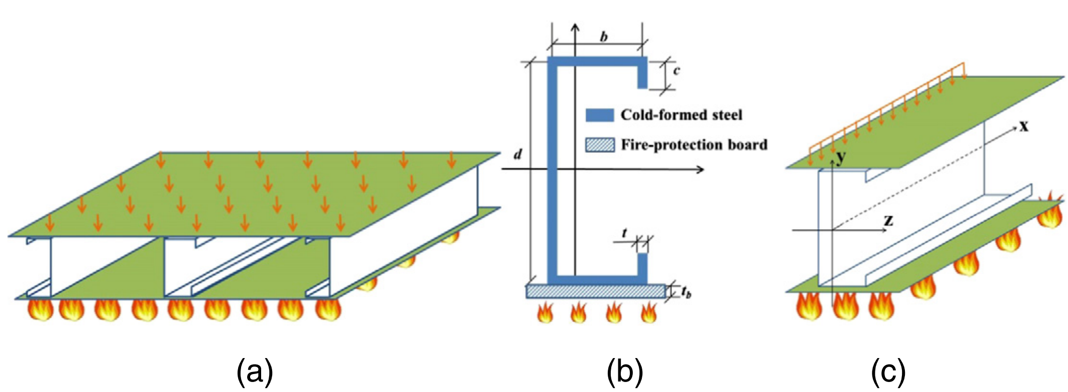

Fig. 1. CFS channel-section beams subjected to transverse loading in fire. (a) Beam-sheet in system. (b) Boundary conditions used in heat transfer analysis. (c) Model used in pre-buckling stress analysis.