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Nonlinear fire analysis of steel structure using equivalent thermal load procedure for thermal geometrical change

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ABSTRACT

When a steel structure is subjected to fire attack, the thermal material degradation of the steel members can incur the premature material yielding, and also the thermal axial expansion and bowing on a steel structure can change its structural geometry. These thermal effects lead to the material and geometric nonlinearities of a structure, which therefore defy the accurate behavioural prediction by the general methods of analysis, and thereby impair the structural safety of a steel structure under fire. Unfortunately, the fire load is highly uncertain, which in turn undermine the cost effectiveness and reliability of the fire safety design of a whole structure when using the prescriptive-based fire safety design. To this end, this paper presents the nonlinear fire analysis, in which the geometric and material nonlinearities are with recourse to the higher-order element stiffness formulation and the refined plastic hinge approach, respectively. Specifically, the equivalent thermal load procedure is introduced to determine the thermal expansion effect prior to the fire analysis, which can be then incorporated into the higher-order element formulation. Therefore, the present nonlinear fire analysis can replicate the realistic behaviour, including thermal effects, geometric and material nonlinear effects, of an entire steel structure complying with a realistic fire scenario in the efficacious manner using least number of element(s).

1. Introduction

The prescriptive-based fire safety design, such as Eurocode 3 Part 1.2 [1], is based on some design parameters (i.e. limiting member resistance, critical temperature, fire protection, minimum time, etc.) to regulate the structural fire safety of a member basically. It inevitably and conservatively involves a high construction cost for the structural fire design when the realistic behaviour and beneficial contribution of a whole steel structure under fire cannot be accounted for. An alternative performance-based fire safety design approach is to grasp a thorough understanding of the realistic behaviour of an entire steel structure under the realistic fire scenarios, which gives adequate information to an engineer to adopt a more reliable and cost effective performance-based design solution of a structure at the fire attack.

The fire safety concern was significantly raised at about 1980 s. A number of researchers (i.e. Jeanes [2]; Dotreppe et al. [3]; the ARBED Research Center [4]) studied the structural behaviour of beams, columns and frames under fire by the finite element method. Later, Franssen [5] presented a fire analysis which considers non-uniform temperature distribution, material yielding and geometric nonlinearity. Further, Franssen et al. [6] developed a user-friendly computer program SAFIR, of which a fine grid of finite elements is required over each cross-section. Terro [7] studied the structural behaviour of the general three-dimensional building structures under fire, in which material and geometric nonlinearities are also taken into account. Meanwhile, Saab and Nethercot [8] presented the nonlinear fire analysis for evaluating the structural behaviour of a two-dimensional frame under fire. With recourse to the similar formulation, Najjar and Burgess [9] incorporated three-dimensional behaviour of the unprotected steel members, including the warping effect. Furthermore, Bailey [10] extended this work to develop the computer program 3DFIRE, which allows for the semi-rigid connections, lateral-torsional buckling, continuous floor slabs and strain reversal. However, their approaches accounting for the material nonlinearities at high temperature are reliant on the time and computational demanding plastic zone method. Although the merit of using the plastic zone method is the accurate evaluation of the material effects along an element technically, none of the above approaches can attain the research objective of using least number of element(s) or even one element for the accurate solutions of a member.

In contrast, Liew et al. [11] presented a fire analysis to compute a realistic representation of the material and geometrical nonlinearities of an overall steel frame using least number of element(s), in which a plastic hinge may be inserted along a member by divided into at least

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two elements while material nonlinear effect is sought along the span. Iu and Chan [12] developed the nonlinear pre-fire analysis of a steel frame, which is reliant on the plastic hinge method to simulate the residual strength of an element after its yield stress at high temperature. This residual strength was captured by the strain-hardening coefficient, which was firstly introduced in the framework of the plastic hinge approach. Iu et al. [13] first developed the post-fire analysis by virtue of the plastic hinge approach to investigate the cooling effect for the sake of the whole range fire safety concern (i.e. heating and cooling phases) of an entire steel frame. Further, Iu et al. [14] investigated the effect of restraints generated from the redundancy of an indeterminate steel framed structure under fire by making use of both axial and bending springs. Landesmann [15] presented the fire analysis of a composite structure by using the refined plastic hinge model. Unfortunately, the element discretisation for a member in the above fire analyses was still unavoidable and indispensable when being formulated by the lower-order finite element or under some circumstances. In the context of the higher-order element, Izzuddin [16] presented second-order elastic fire analysis of a steel frame. Recently Kassimali and Garcilazo [17] relied on the stability function to develop the second-order elastic analysis of a steel plane frame using least number of element(s). Unfortunately, both of them are restrictive to an elastic structure at fire.

In order to strike a subtle balance among the competent modelling capacity, numerical efficiency, using least number of element(s), the nonlinear fire analysis is presented in the context of the higher-order element formulation with the refined plastic hinge attached at both ends of an element, which can evaluate the thermal effects (i.e. thermal expansion, thermal bowing and material degradation), geometric nonlinearities (i.e. thermal buckling, large deformation behaviour, P-δ and P-Δ effects, etc.) as well as material nonlinearities (i.e. gradual and full yielding with interaction effect, residual strength after full plasticity at high temperature, etc.). Eventually, this nonlinear fire analysis can attain the competent modelling capacity of a whole steel structure at fire using the least number of element(s) in the efficacious manner. Unfortunately, as aforementioned, the ultimate error-proof fire analysis in terms of the accurate behavioural evaluation without element discretisation is not yet to materialise. It heralds the accurate solution by virtue of most of the fire analyses in the literature relies on the element discretisation to some certain extent. To this end, this paper also presents the understandable overview numerical algorithm including element formulation and solution procedure for the corresponding behaviour of a structure at fire, such that the practitioners can manipulate the general method of fire analyses to replicate the realistic behaviour of a whole steel structure under a realistic fire scenario as the performance-based fire safety design approach.

2. Interpolation displacement function of a higher-order element

The displacements comprise the deformations u in the x direction, v in the y direction, w in the z direction and the twist ϕ about the x-axis. The displacement functions of axial deformation u and twist ϕ are assumed linear. The dependent variables of transverse deflections v and w are replaced by nodal rotations as θ_z and θ_y, about z- and y-axis, respectively, such as $\mathbf{u}=\{e, \theta_y, \theta_z, \phi\}^{\mathrm{T}}$. These rotations are the dependent variables in turn which define the transverse deflections in the element stiffness formulation.

External lateral loads acting on an element are able to generate the nonlinear elastic deflections. This element load effects can also result in the second-order distribution of bending moment and shear force along an element, in which the equivalent mid-span moment M_O and shear force S_O, in Eqs. (3) and (4) respectively, is introduced without loss of generality as illustrated in Fig. 1. Therefore, for the sake of taking the element load effect within an element into account, the higher-order transverse displacement interpolation function of an element with element load effect satisfies not only the compatibility conditions in Eqs. (1) and (2), but also the force equilibrium equations in Eqs. (6) and (7). Further, the higher-order element formulation complies with the elastic material law in alignment with the plastic hinge approach. This approach was founded on the works of Chan and Zhou [18]. Compatibility conditions of the transverse deflection v in the y direction are,

$$v = 0 \text{ and } \frac{\partial v}{\partial x} = \theta_1 \text{ at } \zeta = 0 \tag{1}$$

$$v = 0 \text{ and } \frac{\partial v}{\partial x} = \theta_2 \text{ at } \zeta = 1, \tag{2}$$

while the equilibrium equation of bending moment and shear force given by,

$$EI\frac{\partial^2 v}{\partial x^2} = Pv - M_1(1-\zeta) + M_2\zeta + M_0 \tag{3}$$

$$EI\frac{\partial^3 v}{\partial x^3} = P\frac{\partial v}{\partial x} + \frac{M_1 + M_2}{L} + S_0 \tag{4}$$

where

$$\zeta = \frac{x}{L}. \tag{5}$$

$$EI\frac{\partial^2 v}{\partial x^2} = Pv + \frac{M_2 - M_1}{2} + M_0 \text{ at } \zeta = ½ \tag{6}$$

$$EI\frac{\partial^3 v}{\partial x^3} = P\frac{\partial v}{\partial x} + \frac{M_1 + M_2}{L} + S_0 \text{ at } \zeta = ½ \tag{7}$$

and eventually leads to the transverse deflection,

$$\begin{aligned} v = &\left\{\left[\zeta - \frac{\frac{1}{2}(48+5q)}{48+q}\zeta^2 + \frac{4q}{48+q}\zeta^3 - \frac{2q}{48+q}\zeta^4\right]\right. \\ &\left.+\left[-\frac{\frac{1}{2}(240+7q)}{80+q}\zeta^2 + \frac{80+9q}{80+q}\zeta^3 - \frac{10q}{80+q}\zeta^4 + \frac{4q}{80+q}\zeta^5\right]\right\}L\theta_{z1} \\ &+\left\{\left[\frac{\frac{1}{2}(48+5q)}{48+q}\zeta^2 - \frac{4q}{48+q}\zeta^3 + \frac{2q}{48+q}\zeta^4\right]\right. \\ &\left.+\left[-\frac{\frac{1}{2}(240+7q)}{80+q}\zeta^2 + \frac{80+9q}{80+q}\zeta^3 - \frac{10q}{80+q}\zeta^4 + \frac{4q}{80+q}\zeta^5\right]\right\}L\theta_{z2} \\ &-\frac{\overline{M}_0 L}{48+q}[\zeta^2 - 2\zeta^3 + \zeta^4] + \frac{\overline{S}_0 L^2}{80+q}[\zeta^2 - 4\zeta^3 + 5\zeta^4 - 2\zeta^5] \end{aligned} \tag{8}$$

or

$$v = N_1 L\theta_{z1} + N_2 L\theta_{z2} - N_m L\overline{M}_0 + N_s L^2\overline{S}_0, \tag{9}$$

in which axial load parameter is given as,

$$q = \frac{PL^2}{EI}. \tag{10}$$

The transverse deflection w in the z direction is in a similar fashion for brevity. N_1, N_2, N_m and N_s are displacement functions with respect to rotations at first and second node, and element load contributed from moment and shear force components, respectively; the equivalent mid-span moment $\overline{M}_0$ and shear force $\overline{S}_0$ under the different sorts of element load scenarios are given in Iu and Bradford [19] and Iu [20]. These terms can account for the second-order elastic element displacement and force solutions with the element load effects along an element, which is termed as the generalised element load method to compensate the accurate element solutions that is ignored by both lumping and consistent load methods.

In view of the thermal expansion effect, the thermal strains subjected to the redundancies in a whole indeterminate structure can be determined by the equivalent thermal load analysis prior to the fire analysis as elaborated in the Section 3, which can then be incorporated

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