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Nonlinear behavior of steel structures considering the cooling phase of a fire

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ABSTRACT

The nonlinear behavior of steel structures considering the heating and the cooling phases of a fire is investigated by the Vector Form Intrinsic Finite Element (VFIFE) method. The temperature dependent constitutive relations of steel which include strain reversal effects are adopted. The numerical model is first verified by comparing the results with the published analytical and experimental results for steel structures in the cooling phase. Several numerical examples are then fully studied to investigate the cooling behavior of steel structures. The proposed numerical model can effectively predict the nonlinear behavior of the steel structure in both the heating and cooling phases.

1. Introduction

Steel structures have been widely used in high-rise buildings, although their temperature sensitivity is a weakness. Since the properties of steel, such as the Young's modulus and yielding strength, drop rapidly with increasing temperature, the loading capacity of such structures in fires will reduce dramatically. The large deformation induced by the thermal strain will result in structural damage or collapse. A number of researchers [1–7] adopted the conventional finite element method to investigate the fire response of steel structures, studying the inelastic large deformations of beams, columns and frames due to the degradation of strength and thermal expansion. There are many experimental results that have been adopted as design codes, such as ECCS [8], Eurocode 3 [9], BS 5950-8 [10] and AISC [11]. However, these studies focused on the structural behavior during the heating phase, and ignoring the cooling process.

The previous researches predicted the maximum allowable temperature of the structure under constant loading, and these results are important in preventing the collapse of buildings in a fire, as well as ensuring the safety of rescue workers in such situations. However, it is also important to evaluate structural damage after the fire and to draw up adequate repair plans. Steel structures that experience a high temperature and then cool after the fire will lose their original structural performance due to residual stress and strain in some elements. A numerical model for more accurate assessment is thus required to investigate the structural behavior in the cooling phase.

The famous British Cardington test provides much experimental information about composite steel frames during the cooling phase, such as the frame configuration, temperature distribution, and structural behavior [12–16]. In addition, Cong et al. [17] and Li et al. [18] provided time histories of the cooling temperatures and structural behaviors for steel beams and steel columns in fire resistant experiments, respectively. More recently, Li and Guo [19] performed experiments that examined the fire resistance of restrained steel beams during the heating and cooling phases. With respect to the numerical analysis, because strain reversal happens during the cooling phase, cooling can be treated as an unloading behavior when considering thermal effects as the equivalent loading. El-Rimawi et al. [20], Bailey et al. [21], Bailey [22], Iu et al. [23], Li and Guo [24], and Guo and Li [25] studied the cooling behavior on the basis of the model proposed by Franssen [26], which assumed that the plastic strain of the material is irrelevant to step-wise temperature change.

The analysis of the fire response of steel structures frequently requires the modeling of progressive failure and collapse, which needs the consideration of large rigid body motions, large deformations, and unbalanced applied forces. If the continuum is subjected to a set of non-equilibrium external forces, the rigid body motion is not zero and global equilibrium cannot be reached. In

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addition, if the order of magnitude of the rigid body component is much larger than the deformation, errors in the calculation of the internal forces may lead to numerical instability. There are fundamental difficulties in using conventional finite elements to treat large rigid body motion. Recently, Ting et al. [27,28] and Shih et al. [29] proposed a vector form intrinsic finite element (VFIFE) procedure. This procedure is designed to calculate the motions of a system of rigid and deformable bodies, which may include large rigid body motions and large geometrical changes.

This study adopts the VFIFE method to investigate the nonlinear behavior of steel structures during the cooling as well as the heating phases of fire. A two-dimensional frame element is employed. The numerical model is first verified by comparing the results with the published analytical and experimental results of the steel structure during the cooling phase. Several numerical examples are then fully studied to investigate the cooling behavior of steel structures.

2. Fundamentals of Vector Form Intrinsic Finite Element (VFIFE)

The VFIFE is a vector mechanics based mathematical calculation method for structures with a large deformation. It is based on an intrinsic finite element modeling approach, an explicit algorithm, and a co-rotational formulation of kinematics [27–30]. The VFIFE maintains the intrinsic nature of the finite element method and makes a strong form of equilibrium at the connection nodes of members. All the forces balanced at each node are obtained from the principle of virtual work. The VFIFE method adopts an explicit solution procedure to avoid the difficulties that are caused by iterations of material non-linearity and an incremental theory. All the material properties, stress distribution, particle velocities and geometry are defined from the calculation results of the previous time step. The primary objective of this method is to handle the motion and deformation of a system of multiple continuous bodies and their interactions.

The VFIFE approach introduces a general description of particle motion to handle large rigid body motion by incorporating an adaptive convected material frame in the basic definition of the displacement vector and strain tensor. The convected material frame is a modification of the co-rotational approach. The conventional co-rotational approach provides a simple kinematic description. Its constitutive equation is expressed by total stress and total strain, and it is well-suited to considering intermediate large rotation [5,29,30]. For the large displacement study of frame structures, small deformations superposed on large rotations are commonly assumed.

In this study, the proposed method models the structure as a system of discrete mass points, and these positions of mass points characterize the shape and motion of the structure. The motion of each mass point satisfies Newton's laws. The internal forces induced by deformation and the external load are applied at each mass point. The internal forces of the elements are then calculated by using the convected material reference frame and fictitious reversed rigid body motion [31]. A simple central difference scheme is adopted to solve a set of equations of motions for each particle. The rigid body motion and deformation displacement are decoupled for each increment. By assuming a lumped mass matrix of diagonal form, the explicit finite element analysis involves only vector assemblage and vector storage.

Fig. 1 shows the schematic configuration of deformation of the frame elements. The initial position of an element at time t_0 is assumed to be $(1^0, 2^0)$, the position at time $t_a = t - \tau$ is $(1, 2)$, and the current position of an element at time t is $(1', 2')$. The displacement increment vectors $\Delta\mathbf{d}_1$ and $\Delta\mathbf{d}_2$ can be calculated from the equations of motion with a reference coordinate at $(1, 2)$.

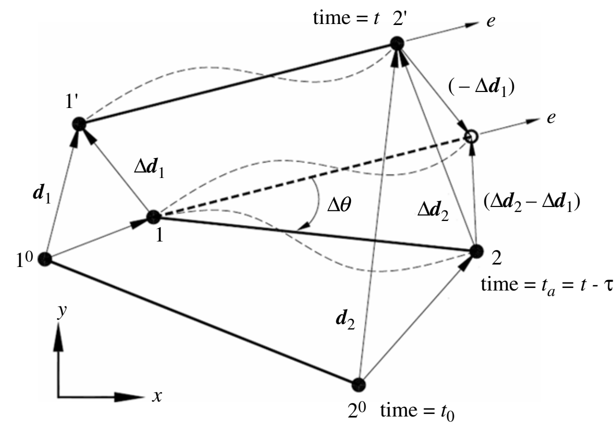

Fig. 1. Schematic configuration of deformation of the frame elements.

The component of rigid body motion is decomposed from the displacement increment vectors by the fictitious reverse rigid body motion. First, the element $(1', 2')$ translates to make points 1 and $1'$ coincide, and then rotates an angle $\Delta\theta$ to the direction of element $(1, 2)$. The deformation displacement increment vector $\Delta\mathbf{d}^d$ is thus expressed as

$$\Delta\mathbf{d}^d = \Delta\mathbf{d} - \Delta\mathbf{d}^r \tag{1}$$

where $\Delta\mathbf{d}$ and $\Delta\mathbf{d}^r$ are the total displacement increment vector and displacement increment vector induced by rigid body motion, respectively. A two-node plane frame element has only three independent variables of deformation displacement, and it is expressed as

$$\mathbf{d}_e^{\mathrm{T}} = \begin{bmatrix} \Delta_e & \theta_1 & \theta_2 \end{bmatrix} \tag{2}$$

where Δ_e is the axial deformation increment, and θ_1 and θ_2 are the changes of slopes of the nodes. The displacement field of the Bernoulli–Euler frame element can be written as

$$u^d = s\Delta_e - [(1 - 4s + 3s^2)\theta_1 + (-2s + 3s^2)\theta_2]y \tag{3a}$$

$$v^d = (s - 2s^2 + s^3)l\theta_1 + (-s^2 + s^3)l\theta_2 \tag{3b}$$

where $s = x/l$, and l is the element length. The axial strain increment in the frame element is

$$\Delta\varepsilon = \mathbf{B}\mathbf{d}_e = \frac{1}{l}[1 \quad (4 - 6s)y \quad (2 - 6s)y] \begin{Bmatrix} \Delta_e \\ \theta_1 \\ \theta_2 \end{Bmatrix}. \tag{4}$$

With regard to the thermal effect, the axial strain increment is written as

$$\Delta\varepsilon = \Delta\varepsilon_\sigma + \Delta\varepsilon_{th} \tag{5}$$

where $\Delta\varepsilon_\sigma$ is the strain increment induced by stress, and $\Delta\varepsilon_{th}$ is thermal strain increment.

$$\Delta\varepsilon_{th} = \alpha(T_t - T_a) \tag{6}$$

where $\alpha = \alpha(T)$ is the thermal expansion coefficient, and $T_t = T_t\,(s, y)$ and $T_a = T_a\,(s, y)$ represent the temperature distribution at time t and t_a, respectively.

The virtual internal energy increment of the planar frame is

$$\delta U_e = \int_V \delta(\Delta\varepsilon)^{\mathrm{T}}\sigma\,\mathrm{d}V = \delta(\mathbf{d}_e)^{\mathrm{T}}\mathbf{f}_e^{\mathrm{int}} \tag{7}$$

where σ and $\mathbf{f}_e^{\mathrm{int}}$ are the total stresses at time t and the internal force of the element. The incremental internal force $\Delta\mathbf{f}_e^{\mathrm{int}}$ in each time increment is written as

$$\Delta\mathbf{f}_e^{\mathrm{int}} = \int \mathbf{B}^{\mathrm{T}}\Delta\sigma\,\mathrm{d}V = \int \mathbf{B}^{\mathrm{T}}E\Delta\varepsilon_\sigma\,\mathrm{d}V = \int \mathbf{B}^{\mathrm{T}}E(\Delta\varepsilon - \Delta\varepsilon_{th})\mathrm{d}V \tag{8}$$