MODELING OF STEEL STRUCTURES IN FIRE CONDITIONS USING IAEM

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1. Introduction

The paper presents the methodology of a new approach for thermal analysis of the large deflection behavior of steel structures at elevated temperatures. The Improved Applied Element Method (IAEM), which was originally developed as an effective analysis technique of large-scale structures up to complete failure under different hazardous loads[1)], has been developed to cover both geometric and material nonlinearities, including the changes to material properties as temperatures increase. Rigorous treatments of thermal analysis in plane frame steel structures are illustrated. The effectiveness and validation of the proposed approach are demonstrated.

2. Improved Applied Element Method (IAEM)

IAEM is a newly developed method for structural analysis of large scale structures. It can follow total behavior of structures up to complete failure stage with high accuracy in reasonable CPU. In IAEM, each structural member is divided into a proper number of elements connected by pairs of normal and shear springs uniformly distributed on the boundary line between elements. The value of normal and shear stiffness for each pair of springs can be determined as:

$$K_n^i = \frac{E \times d \times T_n^i}{a} \quad \text{and} \quad K_s^i = \frac{E \times d \times T_s^i}{a} \qquad (1)$$

where: d is the distance between each spring; a is the length of the representative area; E and G are Young's and shear modules, respectively; T_n^i and T_s^i are the thickness represented by the pair of springs "i" for normal and shear cases, respectively.

3. Constitutive Model of steel under fire

For heated and loaded steel, the constitutive model is described by assuming that the change in $\Delta\varepsilon$ is expressed as the sum of two components, as described in **Eq. (2)**:

$$\Delta\varepsilon = \varepsilon_t - \varepsilon_{\text{int}} = \Delta\varepsilon_{th}(t) + \Delta\varepsilon_\sigma(\sigma, T) \qquad (2)$$

where $\varepsilon_{th}(T)$ is the thermal strain being a function only of temperature "T" and $\varepsilon_\sigma(\sigma,T)$ is the stress-related strain, being a function of both the applied stress "σ" and the temperature "T"

A simplified uniaxial bilinear stress-strain model with strain hardening is adapted for representing the normal stiffness component of structural steel. In this model, the plastic range remains constant throughout the various loading stages. Although, this is not an entirely realistic representation of the material behavior, it allows for the hardening to be included using very simple formulations.

4. THERMAL ANALYSIS BY USING IAEM

A step-by-step time integration procedure has been adopted to follow the response of the structure subjected to elevated temperature. For convenience of analysis, the following hypotheses are employed:

1. Update the temperature profile through a given structure. The temperature $\{T_i\}$ at time t_i is calculated at each spring location according to the selected fire scenario.
2. Calculate the thermal elongation (ε_{th}) due to the temperature increment.
3. Update the material properties (Young's modulus (E), initial yield strength (σ_y) and strain hardening parameter (μ)) of all springs when the temperature of the structure is increased from $\{T_{i-1}\}$ to $\{T_i\}$.
4. Create the new stiffness matrix of the structure considering the variation of material parameters at each spring due to the rising of temperature.
5. Calculate the thermal load vector of each element $\{F_{Ti}\}$ due to the temperature increment. For each spring, the thermal load is calculated according to **Eq. (3)** and applied as a compression force to the elements' boundary.

$$F_n^i = K_n^i(\varepsilon_{th}(T_i) - \varepsilon_{th}(T_{i-1})) \qquad (3)$$

where K_n^i is the normal stiffness of spring i.

6. The general equation of motion in case of thermal analysis is changed to be:

$$[M][\Delta\ddot{U}] + [C][\Delta\dot{U}] + [K][\Delta U] = \Delta f(t) + R_m + R_G + \Delta F(T) \qquad (4)$$

where: $[M]$ is mass matrix; $[C]$ is the damping matrix; $[K]$ is the nonlinear stiffness matrix; $\Delta F(T)$ is the incremental applied thermal load vector; $\{\Delta\ddot{U}\},\{\Delta\dot{U}\}$ and $\{\Delta U\}$ are the incremental acceleration, velocity and displacement vectors.

7. The value of the geometrical residuals around each element (R_G) in case of dynamic load condition is calculated according to **Eq. (5)**.

$$R_G = \Delta F(T) - [M][\ddot{U}] - [C][\dot{U}] - F_m \qquad (5)$$

where F_m is the element force vector from the surrounding springs of each element.

8. Solve the equation of motion. Calculate the incremental and total displacement vectors and obtain the total strain at each spring.
9. Subtract thermally induced strains (ε_{th}) from total strains (ε_t) to obtain the mechanical strains (ε_m) at each spring.
10. Assuming the stress-induced incremental strain is elastic, calculate the current stress.

$$\sigma = E(\varepsilon_t - \varepsilon_{th} - \varepsilon_{p0}) \qquad (6)$$

11. If the stress obtained in the above step exceeds the tensile or the compressive yield strength then recalculate the stress according to the inelastic rule given by:

$$\sigma = \mu E(\varepsilon_t - \varepsilon_{th}) \pm (1-\mu)\sigma_y \qquad (7)$$

12. Calculate the geometrical residuals around each element from the equation below.
13. Apply again a new time increment and repeat the whole procedure.

The most important feature in this technique is that it allows evaluated temperature analysis beyond instability. Moreover, it takes into account the dynamic

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effects, which can either add to destabilizing forces or delay them or both.

5. Illustrative Examples

To evaluate the capability of IAEM in modeling a steel structure under fire, a comparison was conducted between the numerical model and the results obtained experimental works. A 5.50 m span beam of 305 x 165 UB 40 kg m^{-1} cross-section and Grade 43 steel was loaded equally at the quarter points, as shown in **Fig. 1**. Firstly, the beam was loaded with R = 0.6 where R is the load ratios defined as the maximum bending moment of a simply supported beam to the plastic bending moment capacity of the beam at ambient temperature according to BS5950: Part 8[3]. After fully applying the vertical loads, the beam is uniformly heated. Two support conditions had been considered in the analysis as shown in **Fig. 1**: Case 1: Pin–Roller support conditions and Case 2: Fixed–Slide support conditions.

To model the steel properties at elevated temperatures, the bilinear material model is employed with reduction factors shown in **Fig. 2**. These factors are chosen as a best fit to the steel moment-rotation-temperature relationship[2].

The mid span deflections, plotted against temperature, are shown in **Fig. 3** for the two cases, together with the results illustrated by Bailey (1998). It can be seen from the figure the well agreement between the analytical modeling using IAEM and test results. The high capability of IAEM for evaluating the critical temperature and for following the total behavior of the beam is demonstrated. **Figure 4** shows the failure mechanisms and the formation of the plastic zones for the heated beams. From the figure, in case of Pin–Roller support beam since the beam was free expand, the bending moment along the beam was only due to the imposed load and no axial load had been generated. The beam failed due to the formation of one plastic hinge at the mid-span. The figure shows the spread yielding sequences illustrated by the dark color. When the plastic zones develop, the beam has lost most of its strength and the deflection increases greatly, pulling the roller support closer to the pin support. This mode of failure is known as a runaway failure mode. Alternatively, in case of Fixed–Slide support case, the supports of the beam started to yield first. Subsequently, a third plastic hinge is formed at the mid span of the beam due to increase of deflection caused by formation of plastic hinges at the beam supports. Moreover, the critical temperature that produces failure of the beam is higher than that in pin-roller support case.

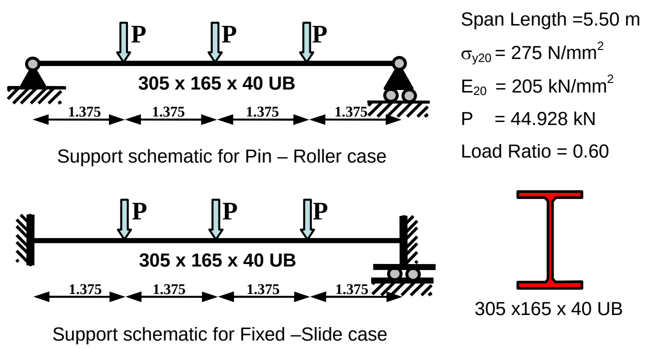

Fig. 1: Beams configuration and loading

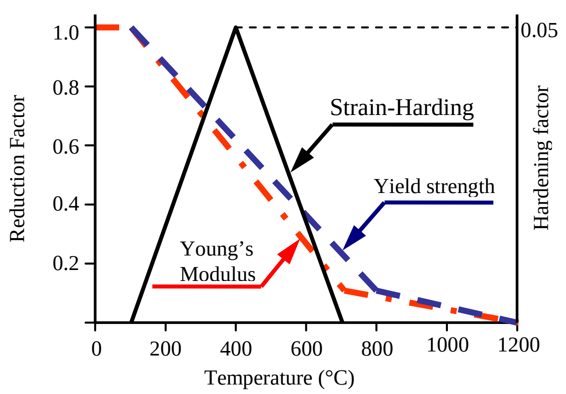

Fig. 2: Material properties at elevated temperatures

6. Conclusions

The paper presents the methodology and basic formulations of a new approach for thermal analysis to discuss the large deflection behavior of steel structures at elevated temperatures which can be considered a pioneering attempt to implement the thermal analysis in the filed of Discreet Element based approaches. IAEM has been progressively developed to carry out simulation of the behavior of plane frame steel structures under fire.

References

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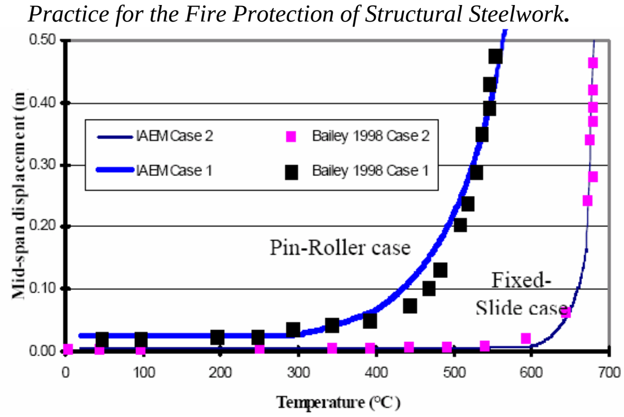

Fig.3: Behavior of heated beams

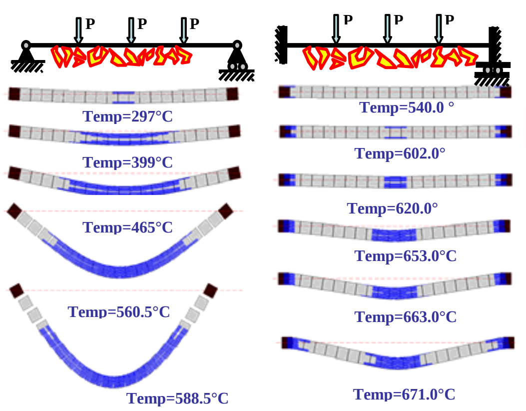

Fig.4: Failure mechanism of the heated beams