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Refined plastic-hinge model for analysis of steel-concrete structures exposed to fire

Alexandre Landesmann *

Civil Engineering Program, Federal University of Rio de Janeiro - COPPE/UFRJ, P.O. Box 68506 21945-970 Rio de Janeiro/RJ, Brazil

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A B S T R A C T

This paper is concerned with the application of a proposed approach, denoted as *SAAFE* Program (*System for Advanced Analysis for Fire Engineering*), developed to provide inelastic analysis of steel and composite (steel-concrete) 2D framed-structures exposed to fire. The method, although similar in concept to earlier plastic-hinge approaches, differs in relation to both numerical methodology and precision, allowing accurate description of the structural non-linear response with little computational effort, when compared to that of the general *FEM* formulation. The analysis is based on the *two-level approach*, in which the cross-section and member are continuously performing in an interactive way. The variation on member is performed by a transient heat-transfer analysis model, accounting for thermo-dependent properties of heated materials. A second-order plastic-hinge model is formulated in a succinct format considering yielding progress during fire and accurate identification of member instability. Obtained results for calibration examples are compared to those of the *FEM* approach, showing reasonable agreement. A proposed multi-storey composite framed structure is assessed by SAAFE, outlining the advantage of considering advanced analysis in the current fire-design practice of structures.

1. Introduction

The ideal combination of strengths – with concrete efficient in compression and steel in tension – can significantly enhance structural members by providing both strength and reduction of size. While steel can improve resistance and speed of construction concrete can provide corrosion protection and thermal insulation to steel at elevated temperatures. The extensive use of steel-concrete composite members, to increase fire resistance of steel frames, can be evidenced by the availability of several current simplified design methods, such as: part 1.2 of the EC4 [1], the Appendix 4 of the American recommendation (AISC/LRFD) [2] among others [3, 4]. Although the proposed design equations are very straightforward to be used, they possess many shortcomings in safe and economical design of structures subjected to fire, *e.g.* checking is performed for isolated members only and a uniform temperature is assumed for steel members. As a consequence, code equations are not able to describe the actual behaviour of structures subjected to fire, especially, when global deformations are large and nonlinear behaviour becomes relevant (*e.g.*, [5, 6]). By contrast, applications of sophisticated FEM-based (*Finite Element Method*) approaches have grown in importance over the last decade [7–13], and it has become possible to simulate a complete structural system, including both thermal and mechanical responses to design-basis fire. Nevertheless, the significantly large amount of produced data and the computational effort involved in the modelling process make it difficult to interpret the produced results. Alternative solution techniques are still needed that could provide a less time-consuming accurate response. As a matter of fact, results for isolated steel and steel-concrete composite members [13] indicated that typical savings in computing time is about 5 to nearly 8 times lower, when comparing plastic-hinge with the FE approach. In this context, the original *Advanced Analysis Concept* ([14], among others) has been extended to study the global performance of steel framed structures subjected to compartment fires [15–17]. Accordingly, this paper is concerned with the development of an inelastic hinge-based numerical tool, denoted as *SAAFE* Program (*System for Advanced Analysis for Fire Engineering*), able to perform material and geometric non-linearity analysis of 2D steel-concrete composite framed structures under fire conditions, in a simple and efficient manner [18–20]. The basis of the *two-level approach* [21] is considered by SAAFE, in which cross-section and member analyses are continuously connected over the computation process. The proposed plastic-hinge model, which has previously been implemented for steel frames [16,22,23], is adapted herein to assorted composite sections configurations under fire.

Because of its simple and efficient modelling, it can be extended to virtually any kind of material behaviour. In addition, SAAFE approach can integrally represent nonlinear material behaviour of an entire steel-concrete section in line and also, obtain a faster and better-controlled convergence than the plastic zone method [22]. The presented model is derived from inelastic moment–curvature-temperature-thrust response of composite elements under fire, representing a smooth transition from initial yield to full plastic domain under the interaction of axial

* Tel.: +5521 2562 8493; fax: +5521 2562 8484.
E-mail address: alandes@coc.ufrj.br.

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and bending effects [23, 24], which describes relationship between the load and displacement due to material non-linearity.

The boundary surface approach [20] is used by the SAAFE model, which is consistent with plastic-hinge formulations that appear in design codes *e.g.* EC4 part 1.2 [1]. The geometric non-linearity is included in accordance to an updated Lagrangian formulation, for which the geometry of the structure is continuously updated at each iteration.

In summary, Section 2 of this paper presents the general formulation of SAAFE model. Sub-section 2.1 starts by describing the cross-section level analysis methodology and the adopted nonlinear transient heat transfer analysis model. The constitutive law models of composite materials are also outlined in sub-section 2.1. The member analysis, *i.e.*, the second-order inelastic formulation for composite beam-column under fire is presented in sub-section 2.2. A set of calibration examples is selected and analysed by SAAFE as presented by Section 3. Obtained results are compared to those of the *FEM* approach, showing reasonable agreement. A composite 12-storey framed structure is investigated by SAAFE in order to illustrate the efficacy of the proposed procedure for solving more complex structures under fire. The main conclusions derived from the proposed implementations and results are presented in Section 4.

2. Thermo-mechanical model

The proposed SAAFE model adopts an analysis scheme based on the *two-level approach* [21], in which cross-section and member analyses are continuously performing in an interacted way. The main guidelines of each analysis level are presented in the following sections.

2.1. Cross-section analysis level

In the first level, the member cross-section is divided into a number of small sub-areas of predefined shapes and materials. The equations for the cross-section analysis are derived by considering an arbitrary cross-section that comprises n_E sub-areas of various shapes and sizes, as illustrated by Fig. 1a. Each sub-area is defined by its surface A_i and the coordinates of its centroid (y_i, z_i), in which the subscript i denotes the sub-area number (*i.e.*, $i = 1, 2, \ldots, n_E$). It is assumed that the temperature, stress and strain associated with each sub-area are uniform, allowing the action and deformation to be calculated at its centroid. In addition, no separation between sub-areas is allowed, so that they have a same curvature.

2.1.1. Heat transfer analysis model

The temperature response of members exposed to fire is simulated by means of a 2D nonlinear transient heat transfer analysis modulus of SAAFE, applied to cross-section mesh geometry discretization (Fig. 1a). The thermal temperature-dependent properties of materials, such as: (*i*) thermal conductivity, (*ii*) specific heat and (*iii*) density are considered in the proposed procedure, regarding part 1.2 of EC4 [1]. A direct time integration scheme, known as the generalized trapezoidal rule [25], is used to determine the temperature variation (θ) as a function of the fire elapsed-time $(t+1)$. The transient behaviour is expressed with respect to a predefined time-step (Δt), as follows (Eq. 1):

$$\left(\frac{1}{\Delta t}[\mathrm{M}] + \omega[\mathrm{C}+\mathrm{H}]\right)\{\theta\}_{t+1} = \left(\frac{1}{\Delta t}[\mathrm{M}] - (1-\omega)[\mathrm{C}+\mathrm{H}]\right)\left\{\dot{\theta}\right\}_t + (1-\omega)\{\mathrm{R}\}_t + \omega\{\mathrm{R}\}_{t+1} \tag{1}$$

where the following terms are give [25]: temporal integration factor ω (assumed as 2/3), the lumped mass matrix [M] and the conductivity and heat capacity matrixes [C + H]. Convective and radiative heat fluxes boundary (vectors {R}) are also accounted for, being assumed 25 W/°Cm² as the convective heat transfer coefficient and the resultant emissivity as 0.5 and 0.7, respectively for steel and concrete surfaces [1]. Although the proposed model is able to account for any time–temperature curve, the standard EC1 part 1.2 [26] has been adopted as the design-basis fire in the present analysis. Results in temperature domain have been previously compared with the FEM analysis [7], and a good agreement could be observed [18, 19].

2.1.2. Material model representation

SAAFE model is able to account for any given material constitutive law, in which idealised multi-linear stress–strain-temperature relationships are applied. In this paper, only three materials are considered for the analysis of steel-concrete composite elements under fire: (*i*) structural steel, (*ii*) normal concrete — in terms of strength and weight, and (*iii*) steel reinforcement bars. For these, the constitutive relation with the temperature is assumed to follow the model prescribed in EC4 part 1.2 [1]. The temperature dependence is invariably taken into account by means of reduction factors applicable to the steel Young's modulus and ultimate stress. Since the stress is determined from strain, the uncertainty and ambiguity that often arise when determining strain from stress are eliminated [21]. Tensile strength of concrete and strain hardening range of steel has not been considered in the present approach.

2.1.3. Inelastic axial and flexional cross-sectional behaviour

The total strain $\varepsilon_T(y,z)$ of each sub-area centroid, as given by Fig. 1a, is calculated from the cross-section deformation and can be divided into 2 components: (*i*) a constant related to axial parcel ε_N and (*ii*) a second one for pure bending action $\varepsilon_M(y,z)$, as follows:

$$\varepsilon_T(y,z) = \varepsilon_M(y,z) + \varepsilon_N.$$

The axial stiffness $(EA)_{eq}$ and ultimate axial strength (P_U) of the composite section are obtained by an implemented simplified numerical-incremental procedure [19,20]. In this, a constant infinitesimal strain $d\varepsilon_N$ is continuously imposed on the cross-section model, until material strain limits are reached [1]. This process is repeated for tension $(\varepsilon_N>0)$ and compression$(\varepsilon_N<0)$ strains, where the correspondent axial force P_R are performed, accounting for each sub-area stress–strain-temperature $\sigma(\varepsilon_N, \theta)_i$ relationship, as given by Eq. (2):

$$P_R = \int \sigma \cdot dA = \sum_{i=1}^{n_E} \sigma(\varepsilon_N, \theta)_i \cdot A_i \tag{2}$$

Since all obtained points (P_R, ε_N) are collected, and used to trace the equivalent axial stiffness, the P_R-ε_N relationship can be derived at the

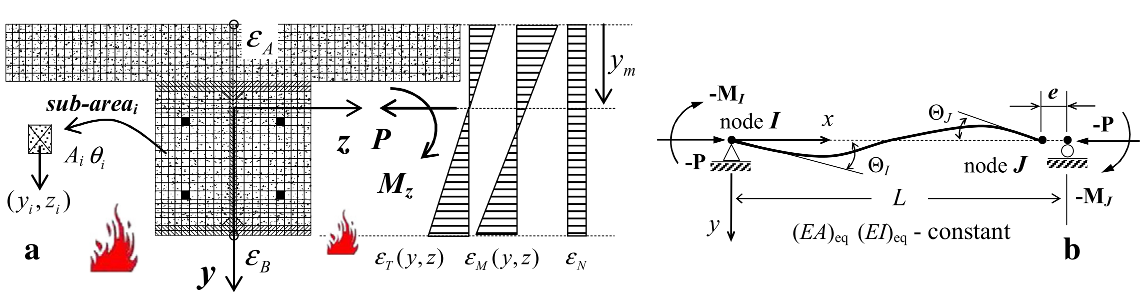

Fig. 1. Element representation adopted by SAAFE: (a) cross-section sub-area refinement, and (b) beam-column element subject to end moments and axial force.