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Review

Advanced inelastic analysis of steel structures at elevated temperatures by SCM/RPHM coupling

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ABSTRACT

When exposed to high temperatures, the structural members and frames have their bearing capacity compromised because the physical characteristics and material resistance used in the structures deteriorate during exposure to fire, resulting in a considerable loss of strength and stiffness. In this context, the present work carries out a whole thermomechanical analysis of steel members and frames using the Finite Element Method (FEM) inelastic formulation based on the Refined Plastic Hinge Method (RPHM) coupled with the Strain Compatibility Method (SCM). The use of SCM allows for a more realistic analysis against the design codes prescriptions. So even under high temperatures, SCM is used for both evaluation of bearing capacity and stiffness parameters. To do this, the steel behavior used in the structure numerical modeling must be described in a consistent manner through its constitutive relationship. A comparison of the results obtained here with the numerical and experimental results available in the literature suggest the effectiveness of coupling SCM/RPHM and that such a methodology can provide reliable analyses of steel members and frames subjected to high temperatures.

Contents

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1. Introduction

From the beginning, fire has always been present in man's daily life. Primitive man knew the fire only in forest, considering it a secret of the gods. It was an uncontrollable phenomenon, that causing injury and destruction. Gradually, the man discovered the usefulness of the fire to illuminate, to cook, to frighten animals and the cold. Thus, from the earliest days of civilization, there was a need to control it [1].

That control, however, is not complete and total. The human losses and material damages caused by out-of-control fires have underscored the importance of considering fire safety in civil engineering designs. The building stability in a fire situation involves engineers having a firm understanding of the elevated temperatures consequences in structures. Such an understanding has been achieved through laboratory experimentation and the use of increasingly sophisticated numerical models that afford researchers a better knowledge of the structural behavior in a fire situation. It is known, for example, that the high temperature in fire conditions causes changes in the materials physical and mechanical characteristics. In both steel and concrete, these characteristics deteriorate during fire exposure considerably reducing the strength and stiffness of the structural elements.

To mitigate the losses and damages caused by a fire, design codes have been developed that aim at enhancing the fire safety of buildings structural elements. ABNT has thus recently issued a series of codes and revision projects, including the following: NBR 14432 [2], NBR 14323 [3] and NBR 15200 [4]. These standards and procedures represent the researches consequences in the fire safety engineering area and are also based on international codes such as Eurocodes [5,6]. Several works deal with fire safety aspects [7–10].

Researchers have carried out important experimental, numerical, and analytical studies on steel structures behavior under high temperatures. These studies have enabled the development of increasingly sophisticated structural safety assessments, guaranteeing more realistic analyses of the structures performance under fire conditions.

Advanced models for heat transfer problems usually refer to computational models. In most structural engineering problems in a fire situation, thermal analysis is transient, with time-dependent boundary conditions and temperature-dependent material properties. This gives such analysis a considerably nonlinear character. These advanced models, for the most part, are developed based on the Finite Element Method (FEM). Some of these studies regarding the thermal analysis of steel structures stand out. Ribeiro [11] developed a FEM-based program for three-dimensional transient nonlinear thermal analysis. The author compared the results of the numerical analysis with the procedures prescribed by the Brazilian [3] and the European [5,6] codes. The THERSYS program, developed in Ribeiro's work, was validated through comparisons with already established programs. Following this same line, but for two-dimensional structures, Pierin et al. [12] presented a program that performed thermal analysis using linear finite elements of 3 and 4 nodal points for the cross-section discretization. Within this context, several works may be cited [1,8,9,13].

Still in relation to the advanced models of numerical analysis, however, in the thermo-structural analysis context, Wang and Moore [14] developed a FEM-based computational program for 2D and 3D analysis of steel and concrete structures in a fire situation. In their analyses, the authors considered second-order effects, semi-rigid connections, residual stresses in steel, and initial imperfections. To consider the effects of material nonlinearity under high temperatures, the authors implemented three constitutive relationships, based on the works of [15–17].

Iu [18], in his dissertation thesis, presented a FEM-based formulation for steel structures analysis in a fire situation via Plastic Hinge Method (PHM). In his analyses were considered the geometric and physical nonlinearities effects, as well as steel hardening. The steel constitutive relationship was adopted based on European [6] and British [19] codes. It is important to note that the developed software is capable of performing analyses in the cooling phase of the structure. Further research developed on PHM-based methodology can be observed in [7,8,20].

In the context of the FEM-based computational structural analysis, the CS-ASA program, Computational System for Advanced Structural Analysis [21], has been developed over the last years, aiming at the study of several sources of nonlinearity, both in the static and dynamic steel structures analysis. More recently, the system was expanded by Lemes [22,28] in order to enable the advanced analysis of reinforced concrete and steel-concrete composite structures. Thus, this program provides an ideal computational basis for the development of modules capable of conducting a thermal analysis of steel cross sections, as well as a thermomechanical steel structures analysis under fire conditions.

In this work, the goal is to perform the thermomechanical analysis of steel structural systems, submitted to high temperatures, using the Strain Compatibility Method (SCM) associated to the Refined Plastic Hinge Method (RPHM). For this, two computational modules were developed that are coupled to the CS-ASA program [21]. The first, called CS-ASA/FA (Fire analysis) [23–24] is able to determine the temperature field in the cross-section of the structural elements through thermal analysis via FEM in permanent and transient regimes. The second module, CS-ASA/FSA (Fire Structural Analysis) [25], was developed with the purpose of performing a second-order inelastic structural analysis under high temperatures. Thus, a SCM based approach [26–28] is proposed for the evaluation of both cross-section bearing capacity and stiffness parameters of steel structures under high temperatures [25]. The construction of the moment-curvature relationship becomes essential for such an evaluation. Once considering the tangent to the moment-curvature relationship, the stiffnesses depend only on the materials modulus of elasticity, draw from the respective constitutive relationships. It is intended, therefore, the coupling of this methodology to the RPHM, in which the plasticity is evaluated in nodal terms through the generalized stiffness parameters.

The products of the whole computational framework developed are: a complete sectional analysis, i.e., the knowledge of the temperature field of cross-section for any or all faces under fire exposition as well as the bearing capacity (interaction diagrams) of cross-section for any or all faces under fire exposition; a complete thermo-structural analysis, i.e., the obtaining of the structural members and system displacements and internal forces variation with the temperature increase. Therefore, the numerical assessment of some steel members and frames fire situation is proposed, for which experimental and other computational responses are available in the literature.

The present work is organized in 6 sections. The basic concepts for the understanding of the thermo-structural problem will be presented in Section 2. In Section 3, the FE formulation will be presented to obtain the temperature distribution at the element cross-section level, as well as the strategies for solving the transient heat transfer problem in the CS-ASA/FA. The formulation considering the geometric and material nonlinear effects for the thermo-structural problem solution, as well as the procedures for obtaining the normal force-bending moment interaction diagrams for structures in a fire situation, will be presented