Fire Safety Journal 71 (2015) 268–278

Contents lists available at ScienceDirect

Fire Safety Journal

journal homepage: www.elsevier.com/locate/firesaf

A plastic-damage model for concrete in fire: Applications in structural fire engineering

Thomas Gernay [a,*], Jean-Marc Franssen [b]

[a] The National Fund for Scientific Research F.R.S.-FNRS, Structural Engineering Department, University of Liege, Ch. Des Chevreuils 1, 4000 Liege, Belgium
[b] Structural Engineering Department, University of Liege, Ch. Des Chevreuils 1, 4000 Liege, Belgium

ARTICLE INFO

Article history:
Received 4 December 2013
Received in revised form
15 October 2014
Accepted 30 November 2014
Available online 16 December 2014

Keywords:
Concrete
Constitutive model
Structural analysis
Finite element analysis
Fire

ABSTRACT

The research aims at developing a new multiaxial constitutive model for concrete in the fire situation. In addition to validity at the material level, a crucial feature of a constitutive model is the applicability at the structural level; yet for concrete in fire there remains a serious lack of models combining reliability and robustness. The theoretical aspects and validation of the new model, which rely on a plastic-damage formulation, have been the subject of a former publication; they are briefly summarized here. This paper explores the capabilities of the concrete model for being used in a performance-based structural fire engineering framework. Several examples of numerical simulations by non-linear finite element method are discussed, with emphasis on practical applications that are demanding for the material model. In particular, it is shown that the simulations using the new concrete model succeed in capturing, at ambient temperature, the crack pattern in a plain concrete specimen and the influence of the loading path on reinforced concrete (RC) slabs. At high temperature, the presented applications include a RC slab subjected to furnace fire and a large-scale composite steel–concrete structure subjected to natural fire. In the numerical analyses, no parameter calibration was required on the particular concrete type, except for the uniaxial strengths and tensile crack energy which are to be defined case-by-case. The results illustrate the reliability and numerical robustness of the model. Also, they suggest that satisfactory prediction of structural behavior in fire can be obtained when no additional data is available on the specific properties of the particular concrete mix that is used in the project, as is often the case in practice, by using standard values of parameters.

1. Introduction

Advanced computational mechanics is a very powerful tool for investigating the behavior and the performance of structures subjected to fire. The last decades have seen significant advances in the development of these numerical methods. Owing to the increase in computing power and to the development of new concepts and theoretical tools, the capabilities of numerical methods have evolved from prescriptive evaluation of simple structural elements towards performance-based assessment of the fire behavior of complex structures. This evolution is necessary to improve understanding of the behavior of buildings in fires.

Since a few years, it has appeared that a significant new frontier in the development of the numerical methods lies in the proper modeling of the behavior of concrete material. Indeed, the numerical analysis of structures in fire requires reliable and robust temperature dependent constitutive models for the load-bearing materials used in the structure such as, for instance, steel and concrete. Despite the wide use of concrete material in civil engineering, modeling of concrete thermo-mechanical behavior remains a challenging issue for engineers. This is mainly due to the complexity of the concrete behavior characterization and to the severe requirements for material models raised by the development of performance-based design. Recurrent issues of concrete models are their lack of numerical robustness and their large number of parameters, both limiting the practical applicability of the models in real engineering projects.

Considering this situation, research efforts have been dedicated to the development of an advanced constitutive model for concrete in the fire situation which meets the requirements of structural fire engineers. At ambient temperature, research in computational mechanics has shown that the combination of continuum damage mechanics (CDM) with plasticity theory offers a very interesting theoretical framework for efficiently modeling

* Corresponding author. Fax. +32 43669534.
E-mail addresses: Thomas.Gernay@ulg.ac.be (T. Gernay), JM.Franssen@ulg.ac.be (J.-M. Franssen).

http://dx.doi.org/10.1016/j.firesaf.2014.11.028
0379-7112/

the mechanical behavior of concrete material [1–9]. Yet, the development of concrete plastic-damage models at high temperature has been hardly treated in the literature. Nechnech et al. [10] proposed an interesting contribution which highlighted the interest of plastic-damage models for concrete at high temperature, but their model was not applied to practical examples of structural fire engineering, except for the very simple case of simply supported reinforced concrete beams. In the present work, it was decided to adopt the plastic-damage approach to develop a new multiaxial constitutive model for concrete in the fire situation. The model includes a number of original contributions, in particular regarding the modeling of transient creep phenomenon, the combination of the theories of elastoplasticity and damage at high temperature, the implementation of temperature-dependent relationships for the material parameters and the numerical integration of the constitutive laws in a finite element code. It has been developed for normal strength concrete. As the aim of the model is not to capture spalling, it should be used carefully when this could be an issue such as, for example, with some high-strength concretes. Above all, the model has been designed for use in real applications of structural fire engineering; therefore, emphasis has been put on combining an advanced constitutive model with a robust numerical implementation. Also for enabling practical usefulness, the model has been based on a limited number of physical parameters. Incorporation of all these features in a model for concrete at high temperature contributes to fulfill the need for robust and reliable constitutive models in structural fire engineering.

It is noteworthy that advanced concrete models are needed for modeling of reinforced concrete structures in fire, both when these structures exhibit failure in concrete (e.g. cracking or crushing) or in other structural materials. Indeed, running a numerical analysis until failure may be demanding for the concrete material model whatever the structural failure mode. For instance, the development of tensile membrane action in composite slabs in fire has been extensively studied in the last years. Simulation of this behavior requires accommodating the several transitions between tension and compression in the concrete slab caused by thermal strains as well as by transition from a bending load transfer mode to a tensile membrane action mode. A robust and reliable concrete model is therefore needed, whether failure eventually occurs in the steel reinforcement, or by excess of compression in the concrete slab, which is a failure mode that is captured by the model.

The theoretical aspects of the model and its numerical implementation in finite element software are presented in another publication [11]; they are briefly summarized in Section 2. The former reference also includes the model validation based on experimental results on concrete samples at both ambient and elevated temperature. The present paper focuses on the model applicability at the structural level. The aim is to illustrate the capabilities of the concrete model in a performance-based framework; this is done by presenting numerical simulations of experimental tests on concrete structures, first at ambient temperatures then in the fire situation. Hence, Section 3 presents applications at ambient temperature and Section 4 addresses applications at high temperatures. These applications are used as a basis for discussing the model properties and capabilities. Demonstrating the practical applicability of a constitutive model developed at the material scale for structural analysis is an important step, although it is not so commonly addressed in the field. Many concrete models are developed with different objectives, for instance focusing on the proper modeling of the initiation and propagation of a single crack in a simple concrete member, or on the modeling of the hygro-thermo-mechanical mechanisms leading to spalling in heated concrete. Despite all their merits, these models are presently not intended to be used for more complex structures; or, at least, their usability to complex structures is not demonstrated. This usability requires specific properties in terms of numerical implementation and parameter identification. By addressing these issues, the present work has practical significance for researchers and for practitioners. It makes available a new model for concrete that is shown to be reliable and robust not only at the material scale, but also for the analysis of large structures in fire. It also gives essential information about the proper use of the material parameters for such applications as well as interpretation of the results. The model is available in finite element software and can be used for research and design projects.

2. Presentation of the model

2.1. Plastic-damage model

In the model, the total strain tensor $\underline{\underline{\varepsilon}}_{tot}$ is decomposed into elastic strain $\underline{\underline{\varepsilon}}_{el}$, plastic strain $\underline{\underline{\varepsilon}}_{p}$, free thermal strain $\underline{\underline{\varepsilon}}_{th}$ and transient creep strain $\underline{\underline{\varepsilon}}_{tr}$ according to Eq. (1) [10,12]. The sum of the elastic strain and the plastic strain is referred to as instantaneous stress-related strain $\underline{\underline{\varepsilon}}_{\sigma}$:

$$\underline{\underline{\varepsilon}}_{tot} = \underline{\underline{\varepsilon}}_{el} + \underline{\underline{\varepsilon}}_{p} + \underline{\underline{\varepsilon}}_{th} + \underline{\underline{\varepsilon}}_{tr} \quad (1)$$

Considering that the plastic behavior occurs in the undamaged material, the characterization of plastic response can be formulated in the effective stress space following the classical elastoplastic theory. The elastic strain tensor is related to the effective stress tensor $\underline{\underline{\bar{\sigma}}}$ by means of the fourth-order isotropic linear-elastic stiffness tensor $\underline{\underline{\underline{\underline{C}}}}_0$, see the following equation:

$$\underline{\underline{\bar{\sigma}}} = \underline{\underline{\underline{\underline{C}}}}_0 : \underline{\underline{\varepsilon}}_{el} = \underline{\underline{\underline{\underline{C}}}}_0 : (\underline{\underline{\varepsilon}}_{\sigma} - \underline{\underline{\varepsilon}}_{p}) \quad (2)$$

Concrete exhibits damage mechanisms which are different in tension and in compression. In this model, a tensile damage scalar d_t and a compressive damage scalar d_c are adopted to capture the phenomenological effects induced by microcracking in concrete under tension and compression, respectively. Based on the work by Wu et al. [6], these two damage scalars are applied to fourth-order projection tensors to lead to a fourth-order damage tensor $\underline{\underline{\underline{\underline{D}}}}$, which is employed to characterize the state of isotropic damage in concrete, see Eq. (3). This representation of the state of damage allows representing the effect of the tensile cracks closure on the material stiffness, when the stress state in the material changes from tension to compression (unilateral effect):

$$\underline{\underline{\sigma}} = \left(\underline{\underline{\underline{\underline{I}}}} - \underline{\underline{\underline{\underline{D}}}}\right) : \underline{\underline{\bar{\sigma}}} \quad (3)$$

A composite yield surface is used for capturing the concrete non-symmetrical behavior in tension and in compression; a Rankine yield criterion is used to limit the tensile stresses and a Drucker–Prager yield contour is used for compression. The equations of the composite yield surface are written in terms of effective stresses, see Eq. (4) where κ_t and κ_c are the tensile and compressive hardening parameters, respectively:

$$f_t(\underline{\underline{\bar{\sigma}}}, \kappa_t) \le 0; \quad f_c(\underline{\underline{\bar{\sigma}}}, \kappa_c) \le 0 \quad (4)$$

By assumption, damage mechanism is coupled to plasticity in the model. Consequently, there is no specific threshold for damage and the evolution laws for tensile and compressive damage are driven by the accumulated plastic strains (in tension and compression, respectively). From a computational point of view, once convergence has been obtained in the plastic return mapping algorithm, update of the damage variables is thus an explicit calculation.