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Reinforced concrete columns exposed to standard fire: Comparison among different constitutive models for concrete at high temperature

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ABSTRACT

Concrete behaviour at high temperature was investigated in depth since the 1970s, in order to highlight the main issues linked to its mechanical performance in hot conditions, such as chemical processes, kinematic behaviour (transient and creep strains) and evolution of the physico-mechanical properties. Thanks to these studies, a few constitutive models have been proposed in the literature for concrete at high temperature, with the aim of modelling reinforced concrete structural behaviour during heating. Within this context, a Beam Finite Element code for thermo-mechanical analyses has been developed by using a Fortran solver and GID as pre- and post-processor. A number of well-documented full-scale tests on reinforced concrete columns exposed to Standard Fire (without cooling) was simulated numerically, by implementing four different constitutive models proposed in the literature for concrete at high temperature. The main goals are: to highlight the role of some critical aspects regarding reinforced concrete members in hot conditions, in particular second-order effects, transient and creep strains (a), and to make a systematic comparison between numerical and experimental results in order to assess the reliability of both 1D numerical modelling (b) and the adopted constitutive models for concrete (c). The results confirm that 1D numerical modelling is generally consistent with the experimental evidence if transient and creep strains, as well as second-order effects are carefully taken into account. Moreover, the differences among the four investigated models for concrete behaviour in compression are quite limited.

1. Introduction

Since the early studies on heat-exposed concrete in the past century, reinforced concrete (R/C) structures showed good performance in fire thanks to some typical features of cement-based materials such as incombustibility and low thermal diffusivity.This latter property allows the external heat-damaged layers to protect the inner core from attaining too high temperature, even in the case of long fire durations. On the other hand, however, concrete mechanical properties are significantly influenced by high temperature (mainly above 400–500 °C). In particular, deformability is affected by both the thermal damage and the presence of further components of the load-induced deformation, namely the time-dependant creep strain and the temperature-induced transient strain. These two latter contributions of deformation proved to be of primary importance in modelling concrete at high temperature [1–4], being the cause of both a reduction of concrete apparent stiffness, with the ensuing enhancement of second-order effects, and a relaxation of the thermal stresses. This is one of the reasons why axially-restrained heated specimens do not collapse because of the thermal stresses induced by restrained thermal dilation. Clearly, to accurately evaluate the structural behaviour of any given heat-exposed R/C member, all the aforementioned strain components must be suitably taken into account: in redundant structures, because deformations and displacements influence the internal forces; in slender columns subjected to an eccentric axial force [5], because of the role played by second-order effects.

Within this context, a few constitutive models have been proposed in the past, taking into account creep and transient strains both explicitly or implicitly (by defining a single total load-induced strain component, which lumps instantaneous load-induced strain, creep and transient strains). Among the different formulations proposed in the literature, the four models investigated in the present paper are those by Anderberg and Thelandersson [6], Khoury and Terro [7], Schneider et al. [8] as well as the stress–strain law included in Eurocode 2 – Fire Design (EC2) [9]. The former three models define explicit transient and creep strain components, while the latter is an implicit formulation.

The present study aims at numerically simulating a number of well-documented full-scale tests on R/C columns exposed to Standard Fire, with three main objectives: (a) to assess the relevance of critical issues such as creep and transient strains, and

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second-order effects, (b) to verify the reliability of a Beam Finite Element analysis to numerically simulate the structural response of R/C members in fire, and (c) to make a systematic comparison among the abovementioned constitutive models. To this end, an ad hoc Beam Finite Element (FE) code has been developed by using a Fortran solver and GID as pre- and post-processor. A preliminary study on the same topics was already performed in 2010 [10]. It is worth underlining that, because of their typical loading conditions (prevailing axial force), columns are best-suited to highlight critical aspects related to concrete behaviour in compression.

Generally speaking, the simulation of heat-exposed R/C structures in fire would require the solution of an hygro-thermo-mechanical problem. If spalling is neglected, however, the hygral framework can be disregarded and only the thermo-mechanical problem can be dealt with. This can be performed by using either 3D FE [2,7,11] or 1D FE models [12–15]. In the present study, since spalling is not considered, the thermo-mechanical problem only is taken into account and a Beam FE code is preferred, because of the simplicity in implementing and the convenience for structural design (where a simple and time-saving approach is surely preferable). As a matter of fact, in the literature also simplified analytical models for the evaluation of the time to failure of slender R/C members have been proposed for simple loading and restraint conditions [16,17].

2. Concrete behaviour in compression during heating

2.1. Concrete kinematics in hot conditions

The kinematics of concrete during heating is characterized by the presence of four contributions, namely: thermal strain $\varepsilon_{th}(T)$, instantaneous stress-related strain $\varepsilon_{\sigma}(\sigma,T)$, transient strain $\varepsilon_{tr}(\sigma,T)$, and creep strain $\varepsilon_{cr}(\sigma,T,t)$. Hence, the load-induced strain $\varepsilon_{\sigma,tr,cr}(\sigma, T, t)$ is the sum of three contributions: $\varepsilon_{\sigma}(\sigma,T)$, $\varepsilon_{tr}(\sigma,T)$, and $\varepsilon_{cr}(\sigma,T,t)$.

The *thermal strain* ε_{th} represents the variation of the specific length induced by heating; it is a function of temperature only and is mainly influenced by the aggregate type. The thermal strain is usually measured on heat-exposed unstressed specimens.

The *instantaneous stress-related strain* ε_{σ} occurs instantaneously in heated concrete at a given temperature upon the application of an external load (= *instantaneous load-induced strain*). It is usually worked out by means of simple compression tests on specimens heated at a reference temperature *T*.

The *transient strain* ε_{tr} is an additional contribution to the strain induced by load and seems to be related mainly to the properties of the cement paste. As such, it could be reduced by increasing the quantity of aggregates [18]. The transient strain plays a very important role during heating, because it represents the largest contribution to the load-induced strain. The most important features of the transient strain include: (a) occurrence only during first heating [19]; (b) irreversibility; and (c) stress-, time- and temperature-dependency (though time-dependency becomes negligible for temperatures above 100 °C [1]). It is generally evaluated via compression tests performed on specimens heated up to collapse under a constant sustained level of stress σ.

The *creep strain* ε_{cr} has basically the same features of creep at ambient temperature, but with higher values, due to the effect on the rate of bond breakages of both temperature and water micro-diffusion between capillary and gel pores [20]. It can be determined by means of compression tests on specimens heated to a reference temperature *T* and subjected to a given stress σ maintained for a time duration *t*.

As confirmed by experimental evidence [2], the principle of superposition can be assumed; then, the total strain ε_{tot} can be expressed by Eq.(1):

$$\varepsilon_{tot}(\sigma, T, t) = \varepsilon_{th}(T) + \varepsilon_{\sigma}(\sigma, T) + \varepsilon_{tr}(\sigma, T) + \varepsilon_{cr}(\sigma, T, t) \tag{1}$$

Both transient and creep strains bring in a significant increase of the load-induced strain, thus making concrete apparent stiffness lower: as already mentioned, this effect has both pros (lower sensitivity to restrained thermal dilation thanks to the relaxation of thermal stresses [4]) and cons (higher sensitivity to second-order effects [4,5]). Whether the former or the latter prevails is something that cannot be foretold, due to the several variables involved in the problem, such as geometry, structural layout, boundary restraints, etc. For common values of fire duration, however, the creep strain plays a minor role compared to the transient strain, and is often either neglected or lumped into the transient strain [21].

The models (that implicitly or explicitly include transient and creep phenomena) considered in this paper will be indicated as follows:

Model 1: Anderberg and Thelandersson's model [6];
Model 2: Khoury et al.'s model, developed at the beginning of the 80s, and later refined by Terro [7] for structural applications;
Model 3: Schneider, Schneider and Franssen's model [8];
Model 4: EC2's model [9].

The main features of the aforementioned models will be now briefly recalled.

2.1.1. Model 1: Anderberg and Thelandersson

Anderberg and Thelandersson [6] defined transient and creep strains separately, as expressed in Eqs. (2) and (3):

$$\varepsilon_{tr}(\sigma, T) = k_{tr}\frac{\sigma(\varepsilon_{\sigma})}{f_c^{20}}\varepsilon_{th} \tag{2}$$

$$\varepsilon_{cr}(\sigma, T, t) = 5.3\cdot10^{-4}\cdot\frac{\sigma(\varepsilon_{\sigma})}{f_c^{20}}\cdot\sqrt{\frac{t}{3}}\,e^{3.04\cdot10^{-3}\cdot(T-20)} \tag{3}$$

being k_{tr} a constant ranging from 1.80 to 2.35 for ordinary concrete, depending mostly on aggregate type (for siliceous aggregates the recommended value is k_{tr}=2.35), f_c^{20} the cylindrical compressive strength at 20 °C, f_c^{T} the cylindrical compressive strength at temperature *T*, and *t* the time expressed in hours.

It is worth noting that the transient strain depends on the temperature only, through the thermal strain ε_{th}. On the other hand, the creep strain depends on both time and temperature. Considering, however, that according to Eqs. (2) and (3) the creep strain attains significantly smaller values than the other strain components, generally, the dependency of the load-induced strain on time is limited.

2.1.2. Model 2: Khoury and Terro

Khoury introduced the concept of *load-induced thermal strain (LITS)* as the contribution to the load-induced strain caused by heating in addition to the purely elastic strain occurring at room temperature. LITS was evaluated starting from the analysis of several experimental results obtained at high temperature (up to 600 °C, [1,2,7]) and can be expressed by means of Eq. (4) [7]:

$$\mathrm{LITS}(\sigma, T) = \varepsilon_{\sigma}(\sigma, T) + \varepsilon_{tr}(\sigma, T) + \varepsilon_{cr}(\sigma, T) - \frac{\sigma}{E_0} = \varepsilon_{tot}(\sigma, T) - \varepsilon_{th}(T) - \frac{\sigma}{E_0} = \varepsilon_{\sigma,tr,cr}(\sigma, T) - \frac{\sigma}{E_0} \tag{4}$$

where E_0 is the initial tangent modulus of concrete in virgin conditions.