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3D numerical analysis of reinforced concrete beams exposed to elevated temperature

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ABSTRACT

Numerical results of the behaviour of reinforced concrete (RC) beams subjected to elevated temperatures followed by mechanical loading are discussed. The model used in the study is a transient three-dimensional thermo-mechanical model that was implemented into a three-dimensional (3D) finite element (FE) code. The mechanical constitutive law for concrete is the temperature dependent microplane model. The experimental details of the investigated RC beams are taken from the literature and the same loading scenarios are numerically simulated. The beams are analysed for the case of four-point bending with no fire load and for the post fire cases with three different exposure times. The numerically predicted load–deflection curves, temperature fields, strains and stresses and crack patterns (damage) of the beams exposed to high temperature and mechanical load are analysed and compared with the experimental results. It is shown that the employed numerical modeling technique can successfully predict the behaviour of the RC beams under mechanical load, fire and fire followed by mechanical load. Therefore, the used 3D thermo-mechanical model is useful numerical tool for the realistic prediction of the behaviour of concrete and RC structures exposed to high temperature.

1. Introduction

Behaviour of reinforced concrete (RC) under fire or elevated temperatures is one of the major topics of research today, worldwide. Most of the codes provide certain simplified guidelines for the design of RC structures to withstand fire [1,2]. In case of fire or high temperatures, concrete exhibits relatively good behaviour compared to other building materials. Nevertheless, during and after fire exposure, its original properties are adversely affected. Mechanical strength, elasticity modulus and fracture energy get reduced depending on the duration and the intensity of the fire as well as on the properties of the virgin concrete itself. Moreover, when exposed to high temperatures, concrete cracks. The surface exposed to high temperature gets heated quickly, whereas inner parts of the cross-section have significantly lower temperatures. These temperature gradients induce restrained stresses and cause the concrete to crack.

Concrete is a three phase material consisting of cement paste, aggregates and free water. This free water changes its aggregate state as it evaporates (begins at approximately 105 °C), thus increasing the porosity and permeability of concrete. At approximately 500 °C, around 70% of the dehydration reaction is complete and the CSH gel has been completely destroyed at approx. 850–900 °C [3]. The aggregates also lose their evaporable water and, depending on the type, are subjected to physical changes. Aggregates expand at high temperatures whereas the degree of expansion depends on the aggregate type.

In reinforced concrete, there is an additional effect due to the difference between the thermal dilation of the reinforcement bars and of the concrete. Although, approximately up to 400 °C the thermal expansion of reinforcing steel and concrete is similar, the difference becomes significant at higher temperatures. Moreover, with increasing temperature steel resistance decreases, however in contrary to concrete, after cooling the steel resistance gets almost fully recovered.

Many researchers have performed tests under elevated temperatures or fire to investigate their effect on structural properties and behaviour of concrete. Considering the difficulties in measurement at high temperatures, most of the mechanical strength tests are done after cooling, that is, residual properties are investigated [3–5]. The list is only exemplary and not exhaustive. These experiments have clearly demonstrated the degradation of mechanical properties such as compressive and tensile strength, Young's modulus, and flexural toughness due to elevated temperatures and fire.

Kumar and Kumar [6] have performed experiments on reinforced concrete beams subjected to fire loads following ISO 834 curve for the duration of 1 h, 1.5 h and 2 h, all beams experiencing three sided heating. Specimens were subsequently cooled to room temperature and loaded in four point bending test

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up to failure. One specimen was tested as a reference to measure the beam resistance without influence of high temperatures. The load–deflection curves for all the loading scenarios were reported.

In the present work, the aforementioned experiments were numerically simulated using a 3D FE code.

The constitutive law considered for concrete is the temperature dependent microplane model developed within the framework of the irreversible thermodynamics. Numerically obtained residual load carrying capacities, temperature profiles and failure modes are reported. It has been shown that the formulations, as discussed in the paper, can successfully predict the mechanical as well thermal behaviour of reinforced concrete beams, alone or coupled.

2. Research significance

Understanding the behaviour of reinforced concrete under fire and mechanical loads and realistic prediction of the ultimate fire resistance is essential to have adequate design provisions. Existing codes provide simplified guidelines for the design of RC structures to withstand fire mostly as cover as well as member thickness and corresponding time of fire resistance. Many researchers tried to investigate the effect of high temperature on residual load carrying capacity experimentally and certain guidelines are now available to analytically predict the mechanical behaviour of reinforced concrete subjected to high temperatures [7]. Such models require estimating the temperature inside the reinforced concrete section due to external temperature and empirically reducing the constitutive laws of materials. The equilibrium conditions are then satisfied to obtain the residual load carrying capacity of the members.

However, this approach is inadequate in predicting the overall response of structural elements subjected to fire and mechanical loads e.g. this approach gives no or little information about thermally induced strains and stresses or about crack patterns due to fire alone or coupled with mechanical loads. Also, this approach is too simplistic and cannot be used to correctly predict the behaviour of complex sub-assemblies or structural members. Keeping the above-mentioned points in mind, a new approach has been followed to investigate the coupled thermal-mechanical behaviour of reinforced concrete structural members. The approach aims at providing the following information: (1) temperature profiles inside the RC sections; (2) state of stresses and strains due to external temperatures; (3) crack patterns developed due to thermal and/or mechanical loads; (4) change in failure modes, if any due to thermal loads; and (5) load–deflection behaviour of the structural members subjected to thermal loads, at high temperatures or after cooling.

The approach is equally applicable to determine the behaviour of structural members such as beams, columns, slabs or of sub-assemblages, such as beam–column joints. Also, the approach has been shown to work very well in predicting the behaviour of concrete under thermal loads in combination with complex state of stresses such as anchors under fire loads and tensile loading [8].

3. Numerical modeling of concrete exposed to high temperature

The realistic modeling of concrete under fire is a relatively new topic of research being pursued since last three decades. The models can be broadly divided into two groups: (i) thermo-mechanical models [9–11] and (ii) thermo-hygro-mechanical models [3,12,13]. In the models of the first group the mechanical properties of concrete are temperature dependent whereas the mechanical properties of concrete do not influence the temperature distribution. These models are adequate to realistically predict an overall response of structural elements exposed to elevated temperatures and mechanical loads.

In the thermo-hygro-mechanical models, the physical processes taking place in the concrete are fully coupled, i.e. interaction between mechanical properties, temperature and moisture is accounted for. Thus these models are physically more realistic and therefore more suitable to capture moisture-dependent phenomena such as explosive spalling. However, due to lack of sufficient experimental data, certain assumptions are required which make the model vulnerable [10].

In the present paper a thermo-mechanical model [10] has been used to simulate the mechanical response of RC beams after fire exposure. The constitutive law for concrete is the temperature-dependent microplane model. The parameters of the model are formulated as temperature dependent and implemented into a 3D FE code.

4. Transient thermal analysis

As the first step of coupling between mechanical properties of concrete and temperature, the temperature distribution over a solid structure of volume Ω at time t is calculated. In each point of continuum, which is defined in Cartesian coordinate system (x, y, z), the conservation of energy has to be fulfilled. This can be expressed by the following equation:

$$\lambda \Delta T(x,y,z,t) - c\rho \frac{\partial T}{\partial t}(x,y,z,t) = 0 \tag{1}$$

where T = temperature (K), λ = conductivity (W/mK), c = heat capacity (J/kg K), ρ = mass density (kg/m^3) and Δ = Laplace-Operator. The surface boundary condition that has to be satisfied reads:

$$\lambda \frac{\partial T}{\partial \mathbf{n}} = \alpha (T_M - T) \tag{2}$$

where $\mathbf{n}$ = normal to the boundary surface Γ, α = transfer or radiation coefficient (W/(m^2 K)) and T_M = temperature of the media in which surface Γ of the solid Ω is exposed to (K) (for instance temperature of air). To solve the problem by the finite element method the above Eqs. (1) and (2) have to be written in weak (integral) form. For more detail see [10,14].

4.1. Decomposition of strain tensor

In the present model the total strain tensor ε_{ij} (indicial notation) for stressed concrete exposed to high temperature can be decomposed as:

$$\varepsilon_{ij} = \varepsilon_{ij}^{m}(T, \sigma_{kl}) + \varepsilon_{ij}^{ft}(T) + \varepsilon_{ij}^{lits}(T, \sigma_{kl}) \tag{3}$$

where ε_{ij}^{m} = mechanical strain tensor, ε_{ij}^{ft} = free thermal strain tensor, ε_{ij}^{lits} = load-induced thermal strain tensor [14–16]. In general, the mechanical strain component can be decomposed into elastic, plastic and damage part. In the present model these strain components are obtained from the constitutive law. The free thermal strain is stress independent and is experimentally obtained by measurements on the load-free specimen. In such experiments it is not possible to isolate shrinkage of cement paste, therefore the temperature dependent shrinkage is contained in the free thermal strain. The load-induced thermal strain is stress and temperature dependent. It appears only during the first heating and not during subsequent cooling and heating cycles [17]. This strain is irrecoverable and can cause severe tensile stresses during cooling in concrete structures. It generally comprises several components including transient strain (consisting of transitional thermal creep and drying creep), time-dependant creep and changes in elastic strain that occur during heating under load [17]. Due to the fact that these components have similar properties – they are all irrecoverable – and are hard to be individually identified in an experiment, it is common praxis to model them mutually