NUMERICAL SIMULATION OF CONCRETE EXPOSED TO HIGH TEMPERATURE – DAMAGE AND EXPLOSIVE SPALLING

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Abstract
In the present paper a fully coupled three-dimensional thermo-hygro-mechanical model for concrete is discussed and used in the numerical studies. The model is formulated in the framework of continuum mechanics based on the principles of irreversible thermodynamics. Distribution of moisture, pore pressure, temperature, stresses and strains are calculated by employing a three-dimensional transient finite element analysis of implicit type. The mechanical strain, which is due to loading, temperature induced stresses and pore pressure, is calculated by using temperature dependent microplane model for concrete. The application of the model is demonstrated on three numerical examples. In the first degradation of bending resistance of plain concrete beams is studied as a function of temperature, the second demonstrates the influence of high temperature on bending resistance of reinforced concrete beams. It is shown that the model realistically predicts degradation of concrete resistance. Finally, due to the fact that explosive spalling is a local failure phenomenon, the influence of different kind of inhomogeneities is discussed. The local instead global (average) properties govern the explosive spalling. This explains the reason for relative large scatter of experimental results that are related to explosive spalling. The influence of inhomogeneities is illustrated on several numerical examples.

1. INTRODUCTION
Although the behaviour of concrete at high temperature is in the literature well documented [1,2], further experimental and theoretical studies are needed to clarify the interaction between hygro-thermal and mechanical properties, such as for instance explosive spalling of concrete cover. The main problem in the experimental investigations is that such experiments are rather demanding, i.e. one has to perform loading and measurement at extremely high temperatures. To better understand the behaviour of concrete at high temperature and to support the experiments, numerical analysis can be useful. However, one needs models, which can realistically predict behaviour of concrete at high temperature. Consequently, in the last two decades significant advancement has been achieved in the modelling of behaviour of concrete at high temperature [2,3,4,5].

In the present paper a three-dimensional (3D) single phase phenomenological model, which is based on the thermo-hygro-mechanical coupling between thermal (temperature), hygral (moisture and pore pressure) and mechanical properties of concrete is briefly discussed. The temperature dependent microplane model is used as a constitutive law for
concrete. The model is implemented into a 3D finite element (FE) code. The FE code is used to study the resistance of plain and reinforced concrete beams exposed to high temperature. Finally, the problem of explosive spalling of concrete cover at high temperature is investigated.

2. THERMO-HYGRO-MECHANICAL (THM) MODEL

The here presented single phase phenomenological model for concrete is a thermo-hygro-mechanical. It is formulated in the framework of continuum mechanics under the assumption of validity of irreversible thermodynamics [5]. The response of the model is controlled by the following state variables: temperature, pore pressure (moisture), stresses and strains. In the numerical model temperature, moisture and pore pressure are coupled with stresses and strains, i.e. thermo-hygro part of the model depends on damage of concrete. Moreover, the relevant macroscopic mechanical properties of concrete (Young’s modulus, tensile strength, compressive strength and fracture energy) are temperature dependent.

2.1 Coupled heat and moisture in concrete

The general approach for the solution of the problem of coupled heat and mass transfer in a porous solid, such as concrete, is within the framework of irreversible thermodynamics well known. However, there are a number of complex details, therefore, for the practical applications the model must be simplified. After introducing simplifications and assuming for a moment that the moisture flux ($J$) and heat flux ($q$) in concrete are independent of the stress and strain, the following is valid [6]:

$$\nabla J = -\frac{a_p}{g} \nabla p$$  

with $p = $ pore pressure, $T = $ temperature, $b =$ heat conductivity, $a = a_p/g = $ permeability, which is in the present model taken as a function of temperature according to the proposal of Bažant and Thonguthai [6], with $g =$ gravity constant.

The governing equation for mass conservation is written in Eq. (3), where $w =$ water content, $t =$ time and $w_d =$ total mass of water released into the pore by dehydration. In the present model dehydration is not accounted for. The balance of heat is given by Eq. (4), where $C =$ mass density and isobaric heat capacity of concrete, $C_a =$ heat sorption of free water and $C_w =$ heat capacity of water, which is in the present model neglected.

$$\frac{\partial w}{\partial t} = -\nabla \cdot J + \frac{\partial w_d}{\partial t}$$  

$$C\rho \frac{\partial T}{\partial t} - C_a \frac{\partial w}{\partial t} - C_w \frac{\partial T}{\partial t} \nabla J \cdot T = -\nabla \cdot q$$

Boundary conditions at concrete surface can be defined as:

$$n \cdot J = \alpha_w(p_0 - p_E)$$  

$$n \cdot q = \alpha_G(T_0 - T_E)$$

where $\alpha_w =$ surface emissivity of water, $\alpha_G =$ surface emissivity of heat, $T_0$ and $p_0$ are temperature and pore pressure at concrete surface and $T_E$ and $p_E$ are temperature and pore pressure of environment.

The constitutive laws for $p$, $w$ and $T$ follow simplified suggestions proposed by Bažant and Thonguthai [6]. To describe the state of pore water in concrete, one has to distinguish between three different states: (i) non-saturated concrete, (ii) saturated concrete and (iii) transition from non-saturated to saturated concrete. For more detail see also Ozbolt et al. [4,5].
The model is implemented into a 3D FE code using direct integration scheme. To assure stability of the time integration, a backward difference method is used. Since the controlling parameters are coupled, the partial differential equations (3) and (4) have to be solved iteratively.

2.2 Thermo-hygro-mechanical coupling

To account for the influence of temperature on the strain development in concrete, the total strain tensor $\varepsilon$ for stressed concrete exposed to high temperature is decomposed as [5]:

$$\varepsilon = \varepsilon^m(T,\sigma) + \varepsilon^f(T) + \varepsilon^{\text{cm}}(T,\sigma) + \varepsilon^c(T,\sigma)$$

(7)

where $\varepsilon^m$ = mechanical strain tensor, $\varepsilon^f$ = free thermal strain tensor, $\varepsilon^{\text{cm}}$ = thermo-mechanical strain tensor and $\varepsilon^c$ are strains due to the temperature dependent creep of concrete. For more detail see [4,5]

The mechanical strain tensor $\varepsilon^m$, that comes into the 3D constitutive law for concrete (microplane model), is calculated as $\varepsilon^m = \varepsilon^m - (\varepsilon^f + \varepsilon^{\text{cm}} + \varepsilon^c)$. The mechanical strain is then used to calculate the effective stresses increments $\tilde{\sigma}$ (stress in solid phase of concrete matrix) and macroscopic stresses increments $\dot{\sigma}$ from the microplane constitutive law [4,5]:

$$\dot{\sigma} = D : \varepsilon^m + \sigma^p$$

(8)

in which $D$ = tangent material stiffness tensor obtained from the microplane model, $\varepsilon^m$ = increment of the mechanical strain tensor and $\sigma^p$ = increment of pore pressure, which is calculated from the increment of volumetric pore pressure $\sigma^v = n \cdot \dot{p}$, with $p$ = increment of pore pressure. Note that according to definition pore pressure $p$ is negative. The internal parameters of the microplane model are modified such that the macroscopic response of the model fits temperature dependent mechanical properties of concrete [4].

It is known that permeability and porosity of concrete are relevant parameters that control transport processes in concrete. On the other hand, both porosity and permeability are strongly influenced by damage, i.e. for higher level of damage, porosity and permeability increase. To account for this, permeability and porosity of concrete are assumed to be strain dependent [5].

To account for finite strains the co-rotational stress tensor together with Green-Lagrange finite strain tensor are used in the formulation of microplane model. The finite strain formulation is needed in order to investigate the influence of the geometrical instabilities (buckling) of a concrete layer on the explosive type of spalling of concrete cover. The objectivity of the mechanical part of the analysis with respect to size of the finite element is assured by the crack band method.

In the finite element analysis the mechanical and non-mechanical parts of the model are treated separately, however, in every time (load) step the relevant state variables that control model response are continuously updated. In this way the interaction between both parts of the model is implicitly accounted for.

3. APPLICATIONS OF THE MODEL

The application of the above discussed model is demonstrated on three numerical examples. In the first, the degradation of bending resistance of a plain concrete beams is studied as a function of temperature. The second example shows the influence of high temperature on the bending resistance of reinforced concrete beams. To investigate the failure mechanism of explosive spalling, the third example deals with problem of different kind of inhomogeneities that are related to explosive spalling of high strength concrete. In the first two examples only thermo-mechanical (TM) part of the model is exploited, i.e. pore pressure is not considered.
3.1 Bending resistance of plain concrete beams

In the example the loss of flexural strength of concrete due to exposure to elevated temperatures is investigated using the above discussed model. The numerical results are compared with experimentally measured data [7]. Relatively small simply supported beams (500x100x100 mm) are used as test specimens. The concrete of different qualities is used with 150 mm average cube strength ranging from 30 to 50 MPa (C25 to C45). Heating regime included uniform heating with temperature ranges between 100°C and 600°C in steps of 100°C. Flexural strength for each temperature range is investigated on both hot specimens (“hot” strength) and specimens cooled down to room temperature (“residual” strength). For every concrete grade one control specimen, which underwent no heating, is loaded in flexure. The spatial discretization using eight-node solid finite elements is shown in Fig. 1. The mechanical load is applied by displacement control.

The decrease of flexural strength as a function of temperature for two concrete qualities is summarized in Fig. 2. Shown are numerical results obtained for “residual” and “hot” strength as well as experimental results (“residual” strength). It can be seen that for all concrete qualities there is almost linear decrease of flexural strength with increasing temperature. Flexural strength reduces to zero at temperatures between 500 and 600°C. As expected, for all concrete types the “residual” strength is slightly lower than the “hot” strength. The reason is the damage induced by cooling of the beams. The numerical prediction is in good agreement with experimental data.

Fig. 1 Geometry of the test specimen and finite element discretization

Fig. 2 Temperature dependent resistance of concrete beams: (a) C25 and (b) C45

3.2 Reinforced concrete beams

The experiments performed by Kumar and Kumar [8] on simply supported RC beams are numerically simulated. The test setup of the investigated beams, geometry and loading are shown in Fig. 3. The concrete properties are: elasticity module 19600 MPa, cylinder compressive strength 17.13 MPa, tensile strength 2.0 MPa, fracture energy 0.10 N/mm,
specific heat 850 J/kgK and thermal conductivity 1.75 W/mK. The reinforcement yield stress and strength are 480 MPa and 550 MPa, respectively. Fire tests are performed on the beams by subjecting them to three sided temperature loads according to the ISO 834 curve. The upper face of the beam is not directly exposed to the heat. To investigate the behavior of beams after different fire exposures, different specimens are tested after 1 hour, 1.5 hours and 2 hours. To have reference values, one specimen is submitted to load test without imposing temperature. The heated specimens are cooled and four point bending tests are performed.

Fig. 3 Geometry of the test specimen, finite element discretization and heating condition

Fig. 4 Degradation of resistance and failure modes – at normal temperature and after 120 min. heating

The 3D FE analysis is performed using the above discussed model for concrete. The degradation of steel strength as a function of temperature is also accounted for. The bond between reinforcement and concrete is not modeled, i.e. stiff connection is assumed. The spatial discretization of concrete and reinforcement is shown in Fig. 3.

The numerically predicted and experimentally obtained failure of RC beams is due to diagonal shear failure. This is the case for failure at normal and elevated temperatures. The typical crack patterns at normal temperature and after 2 hours of heating are shown in Fig. 4. It can be seen that in case of failure of heated beam there is damage in the reinforcement-concrete interface, which significantly reduces shear capacity of the beam. The ultimate load reduction as a function of duration of fire exposure is shown in Fig. 4. There is good agreement between numerical prediction and experimentally measured resistance. The beam shear capacity after exposure of 2 hours is reduced by approximately 40%.
3.3 Explosive spalling of high strength concrete (HSC)

In the framework of DFG research project [9] the experimental and numerical studies of explosive spalling of HSC are carried out. Concrete with and without polypropylene is investigated. In the experiments, among other techniques, non-destructive method based on the acoustic emission is employed. The main objective of the project is to better understand mechanism of explosive spalling, to calibrate and improve the above presented numerical model, to develop a new technique for measuring of concrete permeability in hot state and to verify the acoustic emission technique as a useful non-destructive measuring method. The research is still in progress and currently only preliminary results are available.

The above THM model was recently employed in several studies of explosive spalling of concrete [5]. It was concluded that the main reason for explosive spalling is high pore pressure in combination with thermally induced stresses and thermal degradation of mechanical properties of concrete. In the above mentioned research project the model is used to reproduce experimental investigations of spalling of HSC. The experiments are carried out on concrete specimens dimensions of 700 x 700 x 300 mm for concrete without and with 1% of polypropylene (in weight), respectively. The surface of the specimen is heated according to the ISO 834 curve. More detail related to the experimental investigations can be found in the companion paper. In the experiments the explosive spalling is obtained only for concrete without addition of polypropylene.

![Fig. 5 Spalling failure modes in terms of maximal principal strain](image)

In the framework of the aforementioned DFG project a number of numerical parametric studies related to explosive spalling are carried out. Numerical results confirm that HSC without polypropylene exhibits explosive spalling. Here are discussed only results related to the influence of different kind of inhomogenities on explosive spalling. It is important to note that explosive spalling of concrete is a local phenomena and therefore local material, geometrical and loading (heating) properties, i.e. their variation in space, must be relevant. For instance, due to the high inhomogeneity of concrete, its porosity can locally be quite different than its average value. Consequently, saturation, permeability and pore pressure at high temperature can locally vary for an order of magnitude, or even more. The large scatter of measured experimental results related to the explosive spalling is most probably due to the fact that the local properties control the problem. Because of these arguments it is important...
to investigate the influence of local variation of relevant parameters (material properties, loading and geometry) on the explosive spalling of concrete.

Here are elaborated results of the following cases: (a) homogeneity of the material and heating field; (b) homogeneity of the material and inhomogeneity of heating field; (c) inhomogeneity of the material which is modeled in discrete sense, i.e. discretized as cement paste (mortar), aggregate pieces and interface. Heating field at the surface of the specimen is assumed to be uniform; (d) Same as (c) accept with different distribution of aggregate pieces. In cases (a), (c) and (d) only one row 3D solid finite elements are used assuming plane strain condition. In case (b) four rows of 3D solid finite elements are used with plain strain condition, however, the surface of the specimen is not uniformly heated. In cases (c) and (d) mechanical properties of mortar and interface are the same as given for macroscopic properties of HSC except that the tensile strength of the interface is reduced to 0.5 MPa. The aggregate is assumed to be linear elastic. Thermal properties of all components are similar to macroscopic concrete properties except permeability of aggregate pieces which is assumed 100 times smaller than that of mortar. In the contrary to (a) and (b) in cases (c) and (d) stress induced thermal strains are not considered.

In Fig. 5 are shown spalling failure modes in terms of maximal principal strains. In case (a) splitting crack localizes over the entire heated surface of the specimen, what is not realistic. In case (b) the explosive spalling localizes only on the domain of the surface with slightly higher surface heating. In cases (c) and (d) spalling initiates on the aggregate-mortar interface. Obviously, the results indicate strong influence of local properties on explosive spalling.

4. CONCLUSIONS

- The presented THM model is fully coupled phenomenological model formulated in the framework of continuum mechanics and irreversible thermodynamics.
- It is demonstrated that the model is able to realistically predict degradation of resistance of concrete and reinforced concrete beams exposed to high temperature.
- The explosive spalling of concrete is a local phenomenon and therefore the variation of local material, geometrical and loading (heating) properties have significant effect on the explosive spalling.
- In reality it is possible that the permeability of concrete locally varies by one or even two orders of magnitude. Consequently, the average properties cannot govern explosive spalling.
- The effects of inhomogeneity should be in future investigated in more detail.

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REFERENCES


