NUMERICAL SIMULATION OF THE EFFECT OF HIGH TEMPERATURES ON FLEXURAL AND SPLITTING STRENGTH OF PLAIN CONCRETE

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ABSTRACT

In the present paper the deterioration of flexural and splitting strength of various grades of concrete due to exposure to elevated temperatures is numerically investigated. A 3D finite element study was performed on plain concrete beams and cylinders under thermal loading followed by mechanical loading. The experimental results are taken from the literature. To study the influence of high temperature on flexural strength retention characteristics, 100 x 100 x 500 mm plain concrete beams were considered. Concrete cylinders with a diameter of 150 mm and height of 300 mm were used to investigate the deterioration of splitting strength. In both cases concrete having standard 150 mm cube strength varying from 30 to 50 MPa (M20 to M40) was considered. The considered temperature ranges were between 100°C and 800°C in steps of 100°C. The relative strength retention is reported for different heating regimes and the results are compared with the experimental results. To investigate the effect of cooling, both residual and hot strength are reported. It is shown that the model is capable of predicting the loss in both flexural and splitting strength for different grades of concrete as well as for different heating regimes.

INTRODUCTION

The loss of moisture and pore pressure in concrete due to exposure to high temperature that leads to a loss of structural resistance of concrete structures is a matter of high concern in case of concrete reactor vessels, which may be subjected to very high temperatures under accident conditions. Even though behavior of concrete after exposure to elevated temperatures is better than that of most engineering materials, concrete also suffers deterioration due to high temperature. The mechanical properties such as Young’s modulus, compressive strength, tensile strength and fracture energy will be adversely affected when concrete is exposed to elevated temperatures. Depending on the initial mechanical and thermal conditions, the maximum temperature reached during the exposure, duration of exposure and type of cooling, the effect of elevated temperature on residual mechanical properties will be different.

One of the main constituents of concrete is water, which changes its aggregate state and evaporates during heating. Concrete aggregates also change their structure when exposed to high temperature. These changes are very much influenced by the type of aggregate. These two concrete constituents affect mostly the behaviour of concrete at elevated temperatures.

Though significant work is done in the past to evaluate the effect of high temperature loading on the mechanical properties of the concrete [1], the research is mostly limited to experiments and/or analysis using empirical or relatively simplified phenomenological models. Experimental studies usually report residual concrete properties under assumption that the properties of heated specimens are the same as those of specimens cooled down to room temperature. This is due to the fact that the mechanical loading at elevated temperatures is technically very challenging and therefore avoided in experiments. In a numerical analysis it is possible to gain insight into residual as well as into properties at elevated temperatures.

In the present paper the deterioration of flexural and splitting strength, two important strength parameters for concrete, due to exposure to elevated temperatures is numerically investigated. Results are reported for both hot and residual strength retention. A 3D finite element study was performed on plain concrete beams and cylinders under thermal loading followed by mechanical loading.

The model used in this study is a transient three-dimensional thermo-mechanical model developed at Institute for Construction Materials (IWB), University of Stuttgart. The thermo-mechanical model is implemented into a three-dimensional FE code. Constitutive law for concrete used in the model is a temperature dependent microplane model. In the following chapters the aforementioned model will be shortly discussed. For more detail see [2-5].
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 $\Omega$ 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:

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

where $T = \text{temperature [K]}$, $\lambda = \text{conductivity [W/mK]}$, $c = \text{heat capacity [J/kgK]}$, $\rho = \text{mass density [kg/m}^3\text{]}$ and $\Delta = \text{Laplace-Operator}$. The surface boundary condition that has to be satisfied reads:

$$n \frac{\partial T}{\partial n} = \alpha (T_M - T)$$

where $n = \text{normal to the boundary surface } \Gamma$, $\alpha = \text{transfer or radiation coefficient [W/(m}^2\text{K}]}$ and $T_M = \text{temperature of the media in which surface } \Gamma \text{ of the solid } \Omega \text{ is exposed to [K]}$ (for instance temperature of air).

To solve the problem by the finite element method the above equations (1) and (2) have to be written in weak (integral) form [3, 5].

DECOMPOSITION OF STRAIN

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

$$\varepsilon_{ij} = \varepsilon_{ij}^m(T,\sigma_{il}) + \varepsilon_{ij}^f(T) + \varepsilon_{ij}^{li}(T,\sigma_{il})$$

where $\varepsilon_{ij}^m = \text{mechanical strain tensor}$, $\varepsilon_{ij}^f = \text{free thermal strain tensor}$, $\varepsilon_{ij}^{li} = \text{load-induced thermal strain tensor}$ [4,5]. 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 concrete, 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 [6]. 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 [6]. 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 in a single strain tensor. The same method is used in the present model.

Mechanical strain

The mechanical strain components are obtained from the constitutive law of concrete. In the present model temperature dependent (isothermal) microplane model is used as constitutive law [3]. In the microplane model the material is characterized by a relation between the stress and strain components on planes of various orientations. These planes may be imagined to represent the damage planes or weak planes in the microstructure, such as those that exist at the contact between aggregate and the cement matrix. In the model the tensorial invariance restrictions do not need to be directly enforced. Superimposing the responses from all microplanes in a suitable manner automatically satisfies them. The microplane model used in the present paper was proposed by Özbolt et al. [3]. The temperature dependency of the microplane model is adopted such that the macroscopic properties of concrete (Young’s modulus, compressive and tensile strength and fracture energy) are made temperature dependent, according to the available experimental data [1].
Free thermal strain

The experimental evidence [1] indicates that the free thermal strains in concrete specimen mainly depend on the type and amount of the aggregate. Although the experiments indicate that the free thermal strain depends on the rate of the temperature, in the present model it is assumed that this strain depends only on temperature. Moreover, it is assumed that in the case of a stress free specimen, the thermal strains are equal in all three mutually perpendicular directions (isotropic thermal strains). The temperature dependency of the free thermal strain, as adopted in the present model, reads:

\[
\dot{\varepsilon}_{ij}^{H} = \alpha T \delta_{ij} \\
\alpha = \begin{cases} 
6.0 \cdot 10^{-5}, & \text{for } 0 \leq \theta \leq 6 \\
7.0 - \theta, & \text{for } \theta > 6 
\end{cases} \\
\text{with } \theta = (T - T_0)/100^\circ C
\]  

(4)

Load-induced thermal strain

When a concrete specimen is first loaded and subsequently exposed to high temperature, the resulting thermal strain is different than for the case of an unloaded specimen [6]. The difference can be obtained if the free thermal strain is subtracted from the resulting thermal strain, which results in the so called load-induced thermal strain. It is relatively insensitive to aggregate type and cement paste since it originates in a common gel or C-S-H structure. Due to its similarity for different concrete types, a common ‘master’ LITS cure is taken to exist up to temperatures of about 450°C [6]. In the present model the bi-parabolic function is used for representing load induced thermal strain [7], which reads:

\[
\dot{\varepsilon}^{lm}(T, \sigma) = \frac{\sigma}{f_c} \beta T \\
\beta = 0.01 \begin{cases} 
2 \cdot A \cdot \theta + B, & \text{for } 0 \leq \theta \leq \theta^* = 4.5 \\
2 \cdot C \cdot (\theta - \theta^*) + 2 \cdot A \cdot \theta^* + B, & \text{for } \theta > \theta^*
\end{cases}
\]  

(6)

where \( \theta^* \) is a dimensionless transition temperature between the two expressions (470°C) and \( \theta \) according to Eq.(5). The above two expressions are introduced to account for abrupt change in behavior detected in the experiments. \( A, B \) and \( C \) are experimentally obtained constants that are in the present model set as: \( A = 0.0005, B = 0.00125 \) and \( C = 0.0085 \).

EXPERIMENTAL DETAILS

The above described model was implemented into a three-dimensional FE code and used to simulate the retention of flexural and splitting strength of concrete after exposure to elevated temperatures. The numerical results were then compared to the experiments performed by Yaragal et al. [8]. Concrete used in these tests ranged from grade M20 to grade M40. Specimens were heated in an electrical oven with a rate of 2°C/min up to 800°C in steps of 100°C. Before performing residual strength test the specimens were cooled down to room temperature with a rate of 2°C/min. Residual flexural tensile strength was measured on beam specimens with dimensions 500 x 100 x 100 mm according to IS code IS:516-1959. In the second example the cylinders with a diameter of 150 mm and height of 300 mm were used to test the residual splitting tensile strength. Both test setups are shown in Fig. 1.
Finite Element Analysis – Retention of Flexural and Splitting Strength

Geometry, finite element mesh and boundary conditions

Flexural strength was analyzed on small beam specimens (500 x 100 x 100 mm), which were first heated and consequently loaded in four point bending. For determination of the splitting strength after exposure to high temperatures Brazilian splitting test was performed on cylinders (D=150 mm, H=300 mm). For both geometries one reference specimen was mechanically loaded without prior exposure to elevated temperatures.

The geometry and boundary conditions for both test types are same as in the experiment. Fig. 2. shows the 3D finite element mesh and boundary conditions for both flexural and splitting test specimens. Concrete was in both cases modeled using hexagonal solid finite elements. It was necessary to introduce plates at the supports and in the loading points to prevent localization of damage in these points. These plates were also modeled as hexagonal finite elements. The mechanical loading in both experiments was performed in displacement control regime.

Material properties

The retention of flexural and splitting strength was analyzed for concrete grades M20, M30 and M40. The summary of all concrete properties used in the finite element study is given in the Table 1. Tensile and compressive strength were obtained from the experiments and the other material properties were estimated.

<table>
<thead>
<tr>
<th>Concrete Property</th>
<th>M20</th>
<th>M30</th>
<th>M40</th>
</tr>
</thead>
<tbody>
<tr>
<td>f_{c, cube}</td>
<td>32.96</td>
<td>31.93</td>
<td>50.60</td>
</tr>
<tr>
<td>f_{c, cyl}</td>
<td>26.37</td>
<td>25.54</td>
<td>40.48</td>
</tr>
<tr>
<td>G_{t}</td>
<td>0.07</td>
<td>0.07</td>
<td>0.09</td>
</tr>
<tr>
<td>E</td>
<td>24391</td>
<td>24007</td>
<td>30221</td>
</tr>
<tr>
<td>f_{split}</td>
<td>2.78</td>
<td>3.25</td>
<td>4.38</td>
</tr>
<tr>
<td>f_{direct}</td>
<td>2.50</td>
<td>2.93</td>
<td>3.94</td>
</tr>
</tbody>
</table>
The material used for the loading and supporting plates was assumed to be linear elastic in order to avoid unrealistic local damage. The layer of the loading plate elements in contact with concrete elements (interface) was assumed to be extremely weak during heating. This allowed concrete to expand freely when heated as in the experiment. Otherwise the concrete would be constrained and unrealistic cracking of these contact areas would occur. After the heating phase the analysis was stopped and the material of the weak elements were replaced with initial linear elastic relatively stiff material. The analysis was then restarted and four point bending and splitting tests were performed. This was necessary to assure numerical stability in the analysis of hot and residual flexural and splitting strength.

Heating/cooling regime and consequent loading
The specimens were heated up to 800°C with temperature steps of 100°C. Heating rate was 2°C/min. After each step temperature was retained for 2 hours. Flexural and splitting strength were investigated on both heated (“hot strength”) and specimens cooled down to room temperature (“residual strength”). To investigate the hot strength the specimen was mechanically loaded upon end of the retention time at each of the target temperatures. Residual strength tests were performed on cooled specimens. After retention time of 2 hours at each temperature level the specimens were cooled to the 20°C at a cooling rate of 2°C/min.

Results - Flexural tensile strength
Fig. 3. shows the results of the numerical simulation as well as their experimental counterparts. The experimental results represent residual flexural strength, as the loading was performed on specimens cooled down to room temperature. 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°C and 600°C.

The retention of the hot strength is also given in Fig 3. It has no experimental counterparts as experiments on hot specimens are technically demanding and were not performed in this case. It is noticeable that the hot strength is in general somewhat greater than the residual strength. This can be explained by the additional cracking (damage), which concrete suffers during cooling. As the cooling rate was relatively slow (2°C/min), the cracking due to the cooling is not very severe. If, however, cooling rate would be somewhat higher most probably the difference between residual and hot strength would also increase. This can be a significant effect as most of the real fires are put down using water and decrease of temperature can be quite fast.

It can be concluded that the numerical prediction of residual strength is in good agreement with the experimental results.

Fig. 4. shows load-displacement curves obtained for concrete grade M30 for different temperature levels. The data given are numerically obtained residual flexural strengths. No experimental counterparts were provided in the literature. It is apparent that flexural strength drops with increasing temperature. The stiffness of the beams decreases and ductility increases with increasing temperature.
Results - Splitting tensile strength

The comparison of the numerical and experimental results is given in Fig. 5. The experimental results represent residual splitting strength. The loss of splitting strength is almost a linear function of temperature. Beyond 700°C residual strength drops to almost zero. It can be seen that the numerical results are again in good agreement with their experimental counterparts.

In this case the difference between residual and hot strength is not as obvious as in the case of four point bending. Only at temperatures above 600°C hot strength exceeds the residual values. Inner portion of the concrete needs longer time to heat and therefore has probably not been exposed to the same temperature as the surface of the specimen. Cracking due to the cooling will also most severely affect the surface portion of concrete. In the splitting strength test the maximum tensile stresses are generated in the inner portions of the specimen, whereas in four-point bending maximum tensile stress is at the lower surface. Therefore the flexural strength will be more sensitive to cracking due to cooling than the splitting strength.

CONCLUSION

In the present paper the deterioration of flexural and splitting strength due to exposure to elevated temperatures is numerically investigated. Numerical results are compared with experimental results obtained from the literature [8]. The 3D finite element study was performed on plain concrete beams and cylinders under thermal loading followed by mechanical loading. The model used in the study is a transient three-dimensional thermo-mechanical model that was implemented into a 3D FE code. Constitutive law for concrete used in the model is the temperature dependent microplane model. It has been shown that the model is capable of predicting the retention of both flexural and splitting strength of concrete after exposure to elevated temperatures. It has also been demonstrated that the hot and residual strength after exposure to elevated temperatures are not the same. This indicates that there is an influence of cooling and most probably of cooling rate on the residual properties of concrete.
REFERENCES


