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Structural behaviour of Reinforced Concrete (RC) columns under fire

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Abstract. The paper presents a numerical study on the response of RC columns under fire. The numerical studies deal with both: during fire (fire rating) scenario and after fire (residual) scenario. The results highlight the importance of Load-Induced-Thermal-Strains (LITS) for predicting the Fire Rating (FR) of RC columns. The predicted temperature variation across the cross-section and axial deformation of column with time are in good agreement with the experimental measurements available in literature. The importance of considering cooling phase of fire for evaluating the behaviour of RC columns has been emphasized. Because of the peak temperatures occurring during the cooling phase and the additional damage due to cooling, the column may also fail during cooling period. The effect of exposure duration on the residual axial load carrying capacity of RC columns has also been discussed. The presented numerical studies using 3D fully-coupled thermo-mechanical model for simulating the behaviour of axially loaded RC columns during the complete fire hazard situation, shows its capabilities to realistically account for different strain components and damage components occurring during different phases of fire hazard (viz. heating-phase, cooling-phase & residual-state). The model uses temperature dependent microplane model for concrete and classical von-Mises plasticity models for reinforcing steel.

1. Introduction

Fire is one of the most common hazards to which a Reinforced Concrete (RC) structure may be exposed to during its design life. There are two different aspects associated with structural fire safety. First the structure should with-stand fire for the stipulate fire duration and the second aspect deals with the reusability of the structure after fire exposure. The paper presents the application of a 3D fully-coupled thermo-mechanical model for both the aspects mentioned above. The model uses temperature dependent microplane model & classical von-Mises plasticity models as material models for concrete and reinforcing steel, respectively.

The behaviour of Reinforced Concrete (RC) structures at elevated temperatures is a complex problem to simulate. This is due to the dependency of various material properties (thermal/mechanical) on temperature and the damage caused due to thermal cracking. At elevated temperature the total concrete strain consists of instantaneous stress related strain, Free-Thermal-Strains (FTS) and Load-Induced-Thermal-Strains (LITS). The most complex and least understood strain component which has most uncertainties associated with it, is the LITS [1]. This strain component basically accounts for strains due to chemical changes, moisture loss, transient creep, shrinkage etc. A detailed review of various strain

components that develop in concrete under transient thermal conditions was made by Torelli et al., 2016 [2]; outlining the physical origins of LITS based on the existing experimental studies.

The importance of considering LITS for predicting the fire rating of structural members has been highlighted time and again by different researchers [3-5]. But, as there exists in literature different formulations for LITS, it is also important to investigate how sensitivity is the numerical model to the used LITS model. It is also important to explicitly consider the LITS strain components as they are irreversible strains and do not recover during the cooling phase. Thus, influencing not only the response of RC columns during fire but also its response after fire. Hence, the first half of the paper presents the sensitivity of the predicted response of RC columns during fire, on 5 different LITS models.

The second half of the paper presents the numerical study investigating the residual axial load carrying capacity of RC columns after exposure to design fire (i.e., heating followed by cooling phase). The predicted variation of temperature and the column axial deformations are in good agreement with the experimental results available in literature. The results emphasize on the importance of considering cooling phase of fire for evaluating the behaviour of RC columns. As the peak temperatures are obtained during the cooling phase and the concrete properties further degrades during the cooling phase, the column may also fail during cooling period. The paper also discusses the effect of exposure duration on the residual axial load carrying capacity of RC columns.

2. Thermo-mechanical model

The 3D thermo-mechanical model used for the presented study is a sequentially coupled model i.e., the stress fields are dependent on temperature fields, but the temperature fields are independent of the stress fields. The following sections describes the model briefly.

2.1. Transient heat transfer analysis

As the first step of coupling between material properties and temperature, temperature distribution over a solid structure of volume Ω, for given thermal boundary conditions at time t has to be calculated. In each point of continuum, which is defined by the Cartesian coordinates *(x, y, z)*, the conservation of energy given by equation (1) has to be fulfilled. The surface boundary condition that has to be satisfied is given by equation (2).

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

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

Where, T = temperature, λ = conductivity, c = heat capacity, ρ = density, Δ = Laplace-Operator, n = normal to the boundary surface Γ, α = equivalent heat transfer coefficient and T_M = temperature of the media in which surface Γ of the solid Ω is exposed to (for present study it is the temperature of hot air/gasses).

The thermal properties (specific heat and conductivity) for concrete, as function of temperature were taken from Eurocode2 [6] based on the sensitivity studies conducted by Lakhani, et al., 2013 [7]. (Lower bound thermal conductivity and specific heat for dry concrete were used for the presented numerical study)

2.2. Constitutive laws

Equation (3) gives the total strain tensor for concrete, which has three components: mechanical strain (ε_{ij}^{m}), free thermal strain (ε_{ij}^{ft}) and load induced thermal strain (ε_{ij}^{lits}). The mechanical strain component is further composed of elastic, plastic and damage part. In the present model temperature dependent microplane model is used as constitutive law to calculate the mechanical strain component. In the microplane model the material is characterised by the relation between the stress and strain components on planes of various orientations. These planes may be imagined representing the damage planes or

weak planes in the microstructure, such as those that exist at the contact between aggregate and the cement matrix. The microplane model used in the present paper was proposed by Ožbolt, et al., 2001; 2005 [8, 9].

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

The mechanical properties of concrete viz., compressive strength, tensile strength and fracture energy were temperature dependent. For further details readers may refer to Ožbolt et al., 2005 [9] and Periskic, 2009 [10]. The model considers that the strength degradation of mechanical properties of concrete is irrecoverable during cooling.

Steel is modeled using classical plasticity model (von-Mises). Figure 1 shows the variation of Young's modulus, yield stress and ultimate stress with temperature for reinforcing steel, used in the model. The strength recovery after cooling was considered based on the experimental observations of Takeuchi et al., (1993) [11], i.e., steel strength is completely recovered up to a temperature of 500°C and 80% recovered at 800 °C.

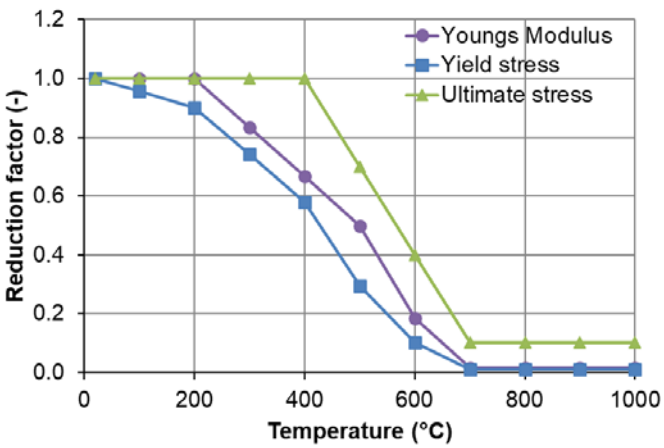

Figure 1. Degradation of mechanical properties of reinforcing steel as function of temperature (Hot state).

3. Numerical study

The 3D thermo-mechanical model, described in the previous section, was used for numerically investigating the response of RC columns during fire and after fire. The extensive experimental study to investigate the fire rating of RC columns conducted by Lie and Woollerton (1988) [12], provides a good data base for validating numerical models. For the numerical studies dealing with during fire scenario in this paper, 3 columns from Series-I (Columns nos: 3, 9 & 10) tested by Lie and Woollerton (1988) were selected. Details about the aggregate type, concrete compressive strength and load during fire, for these columns, are given in table 1. In these studies, the column was first loaded and then exposed to standard fire until failure.

Table 1. Properties for RC columns simulated during fire

Column No.*	Aggregate Type	$f_c^{'}$ (MPa)	Load level (kN)
3	Siliceous	34.2	800
9	Siliceous	38.3	1333
10	Carbonate	40.9	800

*-Column number as per Lie and Woollerton (1988) [12], test Series-I

The experiments performed by Lie et al., 1986 [13] on RC columns were selected for validating the model for simulating RC columns exposed to fire followed by cooling. Lie et al (1986) tested 2 full scale RC columns to evaluate their residual capacity after exposure to design fire, Col-A is simulated to validate the model. Column, Col-A was loaded with a load level corresponding to 25% (992 kN) of its

ultimate axial ultimate capacity and exposed to 60 minutes standard fire followed by linear cooling at 625 °C/hr. The cylinder compressive strength of the concrete on the day of testing was reported as 38.9 MPa.

The geometric details of the columns used by Lie et al., 1986 [13] were same as those for Lie and Woollerton (1988) [12]. The columns had a total length of 3.81m with a fire exposed length of 3.04m. Columns had a cross-section of 305 × 305 mm, with 4 -25 dia (#8) longitudinal reinforcement and 9 dia (#3) stirrups spaced at 305mm c/c along the column length. The longitudinal reinforcement had a clear cover of 48 mm. Preload was applied on the columns before fire exposure and was maintained constant during the heating phase or the heating & cooling phase. The column was fixed at the bottom end and the top end was fixed in plane but was free to have axial translation. The yield stress of the main reinforcement bars was 444 MPa and that of the stirrups was 427 MPa.

The concrete and the reinforcing steel were discretization spatially using 4 noded tetrahedron and the 8 noded hexahedron solid elements, respectively.

3.1. RC columns during fire: Standard fire

For the accurate/realistic finite element analysis of RC columns exposed to fire, LITS is a crucial parameter, as it is not only a function of temperature but also the stress level. Also, there are different LITS formulations available in literature, having different level of complexity depending on the various factors accounted. Hence, there is a need to study the suitability/sensitivity of using these formulations for numerically predicting the fire rating of RC columns. The various LITS formulations studied includes Anderberg & Thelanderson model [14], Schneider's model [15], Diederich's model [16, 17], Terro's model [18] and Preiskic's model [10].

Figure 2 shows the predicted response of Column 9, in form of deformation time curves, using different LITS formulation. It can be observed that the predicted FR for the RC column are very sensitive to LITS. The predicted response using Schneider's model was closest to the experimental results. To further validate the suitability of Schneider's model for concrete made of different aggregate types (Siliceous & Calcareous), column 3 (Siliceous aggregates) and column 10 (carbonate aggregates) were also simulated. The comparison between predicted and experimental deformation-time curves for columns 3 & 10 are shown in figure 3. The predicted maximum axial expansion, complete deformation-time response and failure time (fire rating) are in good agreement with the experimental results.

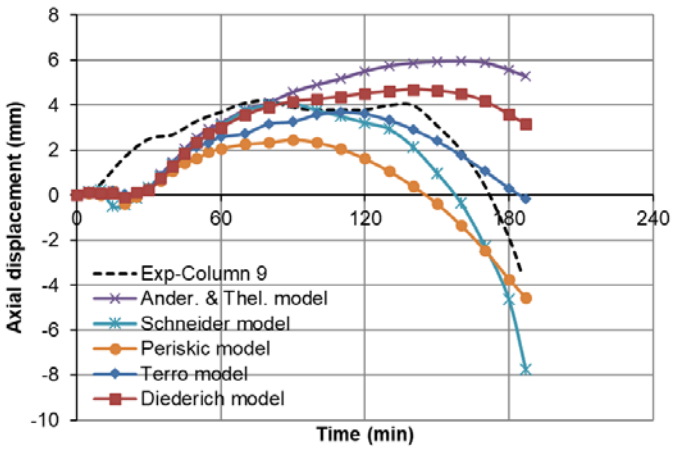

Figure 2. Predicted response of column 9 using different LITS models.

3.2. RC columns during fire: Design fire

Salient features and assumptions for modelling RC columns under design fire are mentioned below:

1. The thermal conductivity of concrete is known to decrease with increasing temperature. This reduction in conductivity is assumed to be irreversible.
2. The mechanical properties of concrete do not recover during the cooling phase.

3. The mechanical properties of reinforcing steel are assumed to recover during the cooling phase.
4. LITS have been treated explicitly in the model.

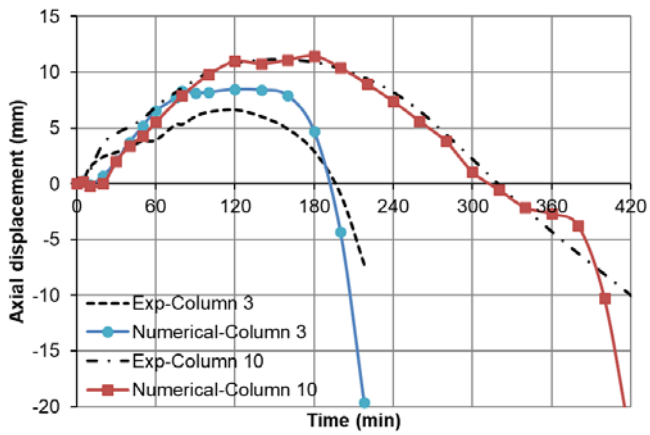

Figure 3. Predicted response of columns made of different aggregates using Schneider's model for LITS.
Note: Column 3-Siliceous; Column 10-Carbonate.

The comparison between the predicted and measured temperature variation with exposure time, at 3 different locations across the column cross-section are shown in figure 4. The locations correspond to a depth of 25 mm, 64 mm and 152 mm from the exposed face, along the centre-line of the cross-section. The predicted peak temperatures and the corresponding time matched very well with the experimental observations. It can also be seen from figure 4 that the maximum temperatures are observed during the cooling phase due to the effect of thermal inertia. This effect becomes stronger as the point of observation move deeper into the member, this is seen as the shift in the temperature peak on the time scale. Since, the temperatures are still rising in the core of the member, during the cooling phase, the column may also fail during the cooling phase.

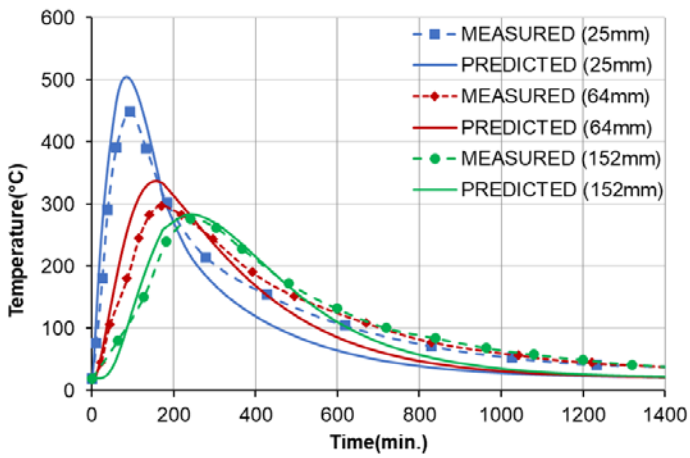

Figure 4. Temperature variation at various locations for Col-A [19].

The structural response of column Col-A is shown in figure 5. A good match is observed between the predicted and experimentally observed response. The deformed state due to the initial loading was taken as the reference and hence, the curve starts from zero. It may be noted that the column contracts back to its reference position at approx. 300 minutes while the temperatures are still between 150 – 275 °C and the column continues to contract further during the cooling phase.

3.3. RC columns after fire: Residual capacity

After validating the numerical model by simulating Col-A, parametric study was performed to investigate the effect of duration of heating phase on the residual capacity of column Col-A after exposure to design fire. For parametric study the load level during fire was kept as 25% (992 kN) of the

ultimate axial load carrying capacity of the column and the duration of the heating phase was varied as 60 minutes, 90 minutes and 120 minutes followed by the cooling phase. The results of the parametric study are shown in figure 6. It can be observed, that for the given geometric and loading conditions (for Col-A), a linear trend for residual capacity with increasing heating phase is predicted.

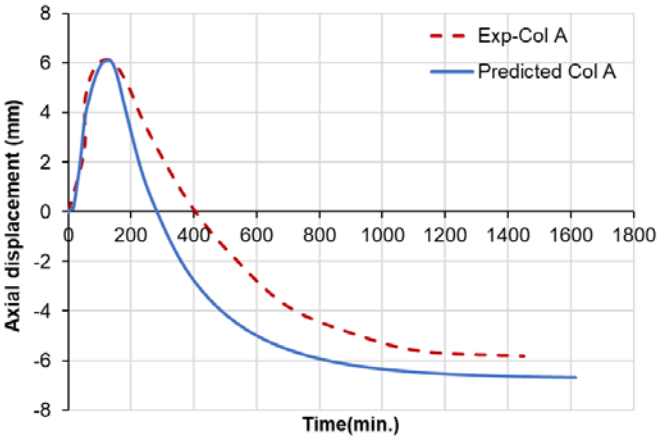

Figure 5. Comparison between the predicted and experimental structural response of Col-A [19].

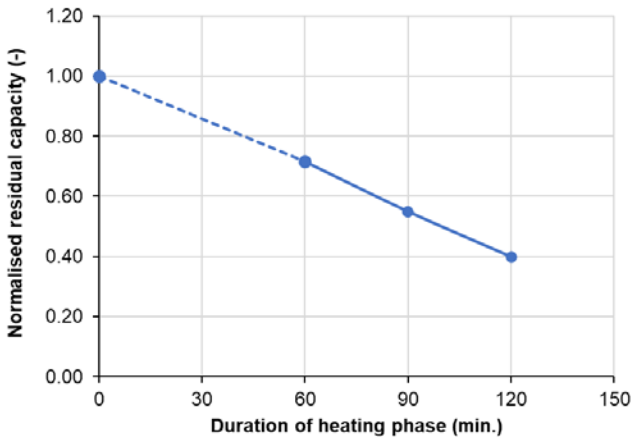

Figure 6. Effect of heating phase duration on the residual capacity of Col-A.

4. Concluding remarks

In the present paper a transient 3D thermo-mechanical model has been used to simulate the behaviour of RC columns during all sequential event (phases) that occur during a fire hazard i.e., during heating phase, cooling phase and post fire phase. The predicted thermal and the structural response of concentrically loaded RC columns exposed to standard fire and design fires, are in good agreement with the experimental results available in literature.

The sensitivity of the model to five different LITS formulations viz. Anderberg & Thelanderson model, Diederich's model, Schneider's model, Terro's model and Periskic's model has been presented. It has been shown with the help of numerical study that the LITS have a significant influence on the predicted fire rating of RC columns. In view of the presented results it was concluded that the Schneider's model for LITS was most suitable for predicting the response of RC columns during fire. The 3D thermo-mechanical model along with Schneider's model for LITS is also able to account for the effect of different aggregates on the predicted response of RC columns during fire.

The model was further validated for design fire exposures. The predicted maximum temperatures and the corresponding time are in good agreement with the measured values. It was observed that due to thermal inertia effect the peak temperatures across the column cross-section were observed during the cooling phase. Hence, the column may fail during cooling phase for certain load levels. This needs

to be further investigated. Moreover, it was also observed that the peak axial expansions occur during the cooling phase, thus emphasising on the importance of considering a fire scenario with cooling phase.

Furthermore, a parametric study to investigate the effect of heating phase duration for a given geometry and load level has been presented. It was observed that the axial load capacity of column reduces to 70% after exposure to design fire (heating + linear cooling phase with 625 °C/hr) with 60 minutes heating phase and reduces linearly with increasing duration of heating phase, to 40% corresponding to 120 minutes of heating phase. The presented results are preliminary and further investigations with different load levels & column geometries are necessary to identify the main governing factors.

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References

[1] Ellingwood B and Shaver J R 1979 Analysis of reinforced concrete beams subjected to fire *NBS Building Science Series 76 National Bureau of Standard* US Department of Commerce
[2] Torelli G, Mandal P, Gillie M and Tran V X 2016 Concrete strains under transient thermal conditions: A state of the art review *Engineering Structures* **127** 172-188
[3] Bratina S, Saje M and Planinc I 2007 The effect of different strain contributions on the response of RC beams in fire *Engineering Structures* **29** 418-430
[4] Gernay T and Franssen J M 2012 A formulation of the Eurocode2 concrete model at elevated temperature that includes an explicit term for transient creep *Fire Safety J.* **51** 1-9
[5] Kodur V K R and Alogla S M 2017 Effect of high temperature transient creep on response of reinforced concrete columns in fire *Materials and Structures* **50**
[6] Eurocode2 2004 *Design of concrete structures - Part 1-2: General rules - Structural fire design* (Brussels: European Committee for Standardization)
[7] Lakhani H, Kamath P, Bhargava P, Sharma U K and Reddy G R 2013 Thermal analysis of reinforced concrete structural elements *J. of Structural Fire Engineering* **4**(4) 227-243
[8] Ožbolt J, Li Y and Kožar I 2001 Microplane model for concrete with relaxed kinematic constraint *Int. J. of Solids and Structures* **38** 2683-2711
[9] Ožbolt J, Kožar I, Eligehausen R and Periskic G 2005 Three-dimensional FE analysis of headed stud anchors exposed to fire *Computers and Concrete* **2**(4) 249-266
[10] Periskic G 2009 *Development of a 3D thermo-hygro-mechanical model for concrete under fire and application to fastenings loaded in tension* Dissertation Institute of Constuction Materials (German: University of Stuttgart)
[11] Takeuchi M, Hiramoto M, Kumagai N, Yamazaki N and Kodaira A 1993 Material properties of concrete and steel bars at elevated temperatures *SMiRT - 12* H04/4
[12] Lie T T and Woollerton J L 1988 *Fire resistance of reinforced concrete columns: Test results* Internal Report No. 569 Institute for Research in Construction, National Research Council Canada
[13] Lie T, Rowe T and Lin T 1986 Residual strength of fire exposed reinforced concrete columns *ACI SP* **92**(9) 153-174
[14] Anderberg Y and Thelandersson S 1976 *Stress and deformation characteristics of concrete at high temperature, 2: Experimental investigation and material behaviour model* Bulletin 54 (Sweden: Lund Institute of Technology, Lund)
[15] Schneider U 1988 Concrete at high temperatures: A general review *Fire Safety J.***13** 55-68
[16] Li L and Purkiss J A 2005 Stress strain constitutive equations of concrete material at elevated temperatures *Fire Safety J.* **40** 669 - 686
[17] Youssef M A and Moftah M 2007 General stress-strain relationship for concrete at elevated

temperatures *Engineering Structures* **29** 2618-2634
[18] Terro M J 1998 Numerical modeling of behaviour of concrete structures in fire *ACI Structural J.* **95**(2) 183 – 193
[19] Lakhani H, Vučko H, Ožbolt J and Harapin A 2019 Behavior of concentrically loaded reinforced concrete columns under design fire *Proc. Fib symposium-innovations in materials design and structures* Krakow May 27-29, 2019