Effect of loss in concrete cover during fire on the predicted temperature distribution

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Abstract. The paper presents a numerical study conducted using in-house code for 2D transient heat-transfer analysis. The code solves the governing differential equations for transient heat-transfer using finite difference scheme and iterative solver. The code takes the information related to loss of concrete cover as an input and update the thermal boundary conditions (moving BCs). The validation of the code against experimental results available in literature has been presented. The paper also presents a parametric study to investigate the effect of corner spalling on predicted reinforcement temperatures for a beam. The parameters investigated include: depth of lost concrete cover, time at which the cover is lost and fire exposure (ISO-834 and design fire). As expected, higher reinforcement temperatures were observed for higher loss of corner concrete corner cover but the effect of smaller cover loss (28% diagonal cover) was negligible. It was also observed that for longer fire exposures, depth of lost cover is more important than the time at which it is lost. In case of design fire exposure, it was observed that; large cover lost during heating-phase results in a higher temperature, which still occur during the cooling-phase but earlier as compared to the reference case.

1. Introduction

The present prescriptive design approach [1, 2] for designing Reinforced Concrete (RC) structures against fire rely mainly on the insulation provided by concrete cover to reinforcement. In real life, the concrete cover may be lost due to sequential hazard situation (e.g. fire-blast etc.) or due to thermal spalling. To answer the question about, how loss in concrete cover affects the response/resistance of RC structural member or sub-assembly or structure under fire, the first important step is to be able to compute realistic temperature distribution across the member cross-section considering the partial/complete loss of concrete cover.

The effect of loss of concrete cover is twofold: first, it reduces the cross-section of the member and second, it leads to higher temperature ingress into the member. Both these effects have negative impact on the fire rating of the member. At the same time, it should also be understood that the severity of these negative effects on the response of a structure/member, would be dependent on large number of factors. For example, on the location along the member length & cross-section where the cover is lost, the amount of cover that is lost and the time at which the cover is lost during fire. Thus, there is a need of advanced numerical tools to study the effect of loss of concrete cover on response of reinforced concrete structures/members under fire.

The paper discusses an advanced 2D transient heat transfer analysis, capable of accounting for the effect of loss of concrete cover in terms of amount, location and time. The model accounts for moving
thermal Boundary Conditions (BCs) to comply with the changing member cross-section. The validation of the in-house code and the numerical model has been presented in this paper. The paper also presents a parametric study, using the validated model, to investigate the effect of loss of corner concrete cover on the predicted reinforcement temperatures for beam (3-side exposure).

2. Numerical model
In order to carry out the thermal analysis the cross-section of the member (beam/column) is divided into $m \times n$ segments along its width and depth. This 2D discretized cross-section forms the computational domain, where each segment $S_i$, as shown in figure 1 is identified by its centroidal location $(x_i, y_i)$, which also serves as the computational points. Based on the assumption of lumped system [3], each segment is considered to have a uniform temperature and thermal properties lumped at the centre of the segment.

![Figure 1. Nomenclature for the segments used for section discretization.](image)

The governing differential equation for 2D transient heat conduction problem is given by equation (1). This equation is solved using Finite Difference Method (FDM). The equation (1) is formulated using implicit central difference scheme, which takes the form of equation (2) for a uniform grid. Equation (2) can be further rearranged to yield a simpler forms, given by equations (3) and (4) in terms of coefficients $(a_P, a_E, a_W, a_N, a_S, b)$ and temperatures of the segments $(T_{SP}, T_{SE}, T_{SW}, T_{SN}, T_{SS})$.

Equation (4) is then solved iteratively to obtain the spatial and temporal distribution of temperature, $T(x, y, t)$. The radiative and convective boundary conditions which are used for modelling the heat transfer from the hot gases to the member surface is given by equation (5). The model at every time step checks if some segments/elements are deleted/lost/spalled (based on the user input) and modifies the computational domain and updates the thermal BC’s to the new domain boundaries corresponding to the current time step.

\[
k \rho c \left[ \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right] = \frac{\partial T}{\partial t}
\]

\[
\alpha \left[ \frac{T_{SE}^i - 2T_{SP}^i + T_{SW}^i}{(Ax)^2} + \frac{T_{SN}^i - 2T_{SP}^i + T_{SS}^i}{(Ay)^2} \right] = \frac{T_{SP}^i - T_{SP}^{i-1}}{\Delta t} - \frac{T_{SP}^i}{\Delta t} - \frac{T_{SP}^{i-1}}{\Delta t} - \frac{T_{SP}^{i-2}}{\Delta t}
\]

\[
\left[ I + \frac{2\alpha}{(Ax)^2} + \frac{2\alpha}{(Ay)^2} \right] \Delta t T_{SP}^i = \frac{\alpha \Delta t}{(Ax)^2} T_{SE}^i + \frac{\alpha \Delta t}{(Ay)^2} T_{SW}^i + \frac{\alpha \Delta t}{(Ay)^2} T_{SN}^i + \frac{\alpha \Delta t}{(Ay)^2} T_{SS}^i + \frac{\alpha \Delta t}{(Ay)^2} T_{SS}^i + \frac{\alpha \Delta t}{(Ay)^2} T_{SS}^i + a_P T_{SP}^i + a_E T_{SE}^i + a_W T_{SW}^i + a_N T_{SN}^i + a_S T_{SS}^i + b
\]

\[
-k \frac{\partial T}{\partial n} = h \left[ T_g - T_S \right] + \epsilon \sigma \left[ (T_g + 273)^4 - (T_S + 273)^4 \right]
\]
Where, $k$ is the thermal conductivity (W/m °C), $\rho$ is the mass density (kg/m$^3$), $c$ is the specific heat (J/kg °C), $h$ is convective heat transfer coefficient (W/m$^2$ °C), $\varepsilon$ is Stephen Boltzmann constant ($5.667 \times 10^{-8}$ W/m$^2$ °K$^4$), $\sigma$ is surface emissivity (-), $T_g$ is gas temperature (°C) and $T_S$ is surface temperature (°C).

Reinforcing steel has not been modelled explicitly for the heat transfer analysis. The temperature of reinforcing steel is assumed to be same as that of concrete at corresponding centroidal location of the respective reinforcement bars. Several proposals for the variation of thermal properties (specific heat and conductivity) of concrete with temperature can be found in literature. The presented model uses thermal properties of concrete as given in Eurocode2 (2004) [2] (lower limit conductivity and specific heat modified for 3% moisture content). The selection of these thermal properties is based on the parametric study and validation done by Lakhani et al (2013) [4]. The model also assumes that the thermal properties are irreversible, i.e., with cooling the thermal properties do not recover.

3. Validation

The numerical model for the transient heat transfer analysis, discussed in previous section has been implemented in an in-house code. The validation of the in-house code against the beam H5 tested by Choi & Shin (2011) [5] and column, Col-A tested by Lie et al., (1986) [6] is presented in this section.

3.1. Beam H5 exposed to ISO834 fire

Beam H5 was selected out of the four beams tested by Choi & Shin (2011) [5], as the spalled profile for this beam was reported in detail by the authors. The beam was made of high strength concrete (55 MPa) and has a cross-section of 250 x 400 mm. The beam had 3-22ϕ rebar as tension reinforcement and 2-22ϕ rebar as compression reinforcement. The clear cover to the 10ϕ stirrup was 50mm on all sides. During the fire test the top face of the beam was insulated and the other three faces were exposed to ISO834 standard fire [7].

![Assumed spalled sections](image1)

*Figure 2. Assumed spalled sections [8]. (All dimensions are in mm) (Fire exposed faces are indicated by red lines)*

![Comparison between predicted and measured temperature](image2)

*Figure 3. Comparison between the predicted and measured temperature at various locations for beam H5 [8].*
Based on the reported spalling profiles and spalling time, the beam cross-section was assumed to change at 15 minutes to cross-section:2 and at 40 minutes to cross-section:3, as shown in figure 2. The comparison between the computed temperatures at various thermocouple locations are shown in figure 3. It can be seen from figure 3 that the predicted temperatures are in good agreement with the experimental values.

3.2. Column: Col-A exposed to design fire
To validate the ability of the discussed model and the in-house code, to predict the temperatures across sections exposed to design fires i.e., fires with cooling phase, column Col-A tested by Lie et. al., (1986) [6] was selected. The column had a cross-section of 305x305mm, with 4-25ϕ rebars as main reinforcement and stirrup of 9ϕ @ 305 c/c. The column was exposed from all sides to design fire which had a heating phase of 60 minutes as per standard fire followed by linear cooling phase at a rate of 500 °C/hr. The column was made of normal strength concrete (38.9 MPa). The comparison between the measured and predicted temperatures at 25mm and 64 mm from the exposed column face in the middle of the exposed face is shown in figure 4. The model is able to predict not only the peak temperatures with good accuracy but also the time at which the peak temperatures were observed.

4. Parametric Study
The parametric study was conducted on beam H5 (from Choi &Shin (2011)). The thermal properties for concrete were kept the same as used for validation case i.e., lower bound conductivity and specific heat modified for 3% moisture as per Eurocode 2. The configurations with loss of corner cover was selected for the parametric study, as this configuration is presumed to be more severe than others. Two different depths: 40mm (designated as CS40) & 80 mm (designated as CS80), of lost corner cover as shown in figure 5 were investigated.
4.1. Investigations with standard fire exposure

The parameters investigated included the two configurations CS40 & CS80 (see figure 5) and two different time at which the cover is lost viz., 10 minutes (designated as t10) & 30 minutes (designated as t30). The times for cover loss were so selected, as to simulate the effect of thermal spalling.

The temperature variation for bottom corner rebar and middle rebar for various combinations of lost cover depths and time are shown in figure 6 (a) and figure 6 (b), respectively. It was observed that CS40 configuration did not had significant influence on the predicted temperature. But for CS80 configuration an increase of approx. 100°C was observed for both corner and middle reinforcement at 180 minutes, irrespective of the time at which the cover is lost. Insignificant influence from CS40 configuration on the corner reinforcement temperature can be attributed to the fact that the diagonal cover is reduced only by 28.3mm (see figure 5). Moreover, it can be seen from the temperature contours shown in figure 7, that due to the loss of triangular corner cover, the heat concentration in the corner (as seen in contour for NoSpall) changes to more uniformly distributed heating due to the chamfering of the corners. It can also be seen from figure 6 that sooner the cover is lost faster is the rate of increase in temperature. It was also observed that for longer fire exposures, depth of lost cover is more important than the time at which it is lost. As the temperature variation due to a later loss in cover tends to coincide with the temperature variation due to an early cover lost during long fires, for a given cover loss.

![Figure 6](image)

**Figure 6.** Predicted reinforcement temperatures for beam H5 under standard fire exposure (a) Corner reinforcement (b) Middle reinforcement.

![Figure 7](image)

**Figure 7.** Temperature contours for different corner cover loss configuration for beam H5 at 60 minutes of standard fire exposure.
4.2. Investigations with design fire exposure

The beam H5 was now exposed to design fire which had a 60 minutes heating phase as per ISO834, followed by a linear cooling phase at 500 °C/hr. The parameters investigated once again included the two CS40 & CS80 configurations. For the parameter of time two additional values of 60 & 120 minutes were studies for CS80 configuration, along with the 10 & 30 minutes for both CS40 & CS80 configurations. The smaller time values (10 & 30 minutes) were selected to simulate the effect of thermal spalling and the larger time values (60 & 120 minutes) represented the effect of cover falling off later during the fire due to thermal damage.

The temperature variation for bottom corner and middle reinforcement for various combinations of lost cover depths and time are shown in figures 8 (a) and (b), respectively. It can be seen from figure 8 that CS40 does not significantly influence the predicted temperature variation with time, due to the reasons explained in section 4.1. But CS80 significantly influenced the predicted temperature variation for both corner & middle reinforcement, not only in terms of peak temperatures but also in terms of the time at which the peak temperatures are observed. It was interesting to observe that if the cover is lost (spalling configurations considered) at any time during the heating phase (in present case up to 60 minutes) the temperature variation was significantly different during the heating phase (for CS80) but the peak temperatures were relatively same (similar values higher than the reference case). This can be attributed to the thermal inertia effect observed in concrete due to its low conductivity. It was also observed that if the cover is lost during the cooling phase (as in present case at 120 minutes), it results in quicker cooling and hence, lower peak temperatures. Thus, cover lost later during the cooling phase may have positive effect. This effect needs to be further investigated.

Figure 8. Predicted reinforcement temperatures for beam H5 under design fire exposure (a) Corner reinforcement (b) Middle reinforcement.

5. Concluding remarks

The paper presented a numerical model for transient heat transfer analysis, capable of considering the effect of loss of concrete cover. The model takes the information related to the lost cover as an input. This input consists of the location where the cover is lost, the amount of cover that is lost and the time at which the cover is lost. The loss of cover can also be simulated in steps i.e., varying lost depths with time. The heat transfer between the concrete surface and hot gases is modelled using radiative & convective Boundary Conditions (BCs), which are updated at every time step to the new boundaries generated due to lost concrete cover (moving BCs). The validation of the model and the in-house code, by comparing the predicted temperatures with the experiments from literature has been presented.

The validated in-house code was used to conduct a numerical parametric study for a beam section. The parameters investigated for corner spalling configuration includes: exposure scenarios (ISO-834 & design fire), depths of lost corner cover (40 & 50 mm) and the time at which the cover is lost (10 & 30 minutes for standard fire and 10, 30, 60 & 120 minutes for design fire). As expected, higher rebar
temperatures were observed for higher loss of concrete cover. It was also observed that smaller lost depth of corner concrete cover did not significantly change the rebar temperature for the beam geometry investigated. It was observed that for ISO 834 fire exposure, the predicted temperature variation with early cover loss acts as an envelope for those where the cover is lost later during fire. It was also observed that for longer fire exposures, depth of lost cover is more important than the time at which it is lost.

It was observed that in case of design fire, the loss of larger cover during heating phase also results in a higher peak temperature, although the peaks are still observed during the cooling phase. It was also observed that these peak temperatures occur earlier as compared to the reference case of no-spooling. However, if the cover is lost during cooling phase it led to relatively faster cooling. Thus, reducing the observed peak temperatures as compared to cover lost during heating phase.

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