Numerical study of reinforced concrete slabs under extreme loading conditions: Impact and fire

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Abstract. In the present paper, the influence of thermally induced damage of reinforced concrete (RC) slabs on their impact properties are numerically investigated. The RC slabs are first pre-damaged through fire load and then loaded by the impact of hammer. Transient 3D finite element (FE) thermo-mechanical analysis is performed. Subsequently, impact simulation is conducted based on the explicit multi-body dynamic analysis and contact algorithm with adaptive element deletion technique. As a constitutive law for concrete rate and temperature, dependent microplane model is employed. The co-rotational Cauchy stress tensor and Green-Lagrange strain tensor are used in the framework of total Lagrange FE formulation. The numerical results are discussed and compared with those obtained experimentally. It is shown that pre-damage of RC slab through fire reduces the impact resistance of the slabs, and that the simulation is able to realistically replicate the experimental tests.

1. Introduction

In recent years the exposure of RC structures under extreme loading conditions such as fire, impact, blast, earthquake, industrial accidents or their combination is becoming more relevant. These types of events, characterized by high loading rates, very often are accompanied by fire outbreak, exposing structures to extremely hard conditions. Coupling of the two extreme loading may cause severe and fast degradation of mechanical and physical material properties, as well as failure of structural elements. In order to minimize the effect of such events, it is important to understand the behavior of materials and structures exposed to such extreme conditions.

The behavior of RC structures under thermal exposure and subsequent dynamic loading is still an intensely discussed topic in the field of civil engineering. In the literature, a large number of studies can be found for concrete loaded under a relatively high range of loading rates at ambient temperature, and even more on thermal effects on concrete structural elements. However, there are only a few investigations for the coupled loading scenarios, e.g. impact after fire [1-4]. When concrete is heated up to several hundred degrees, its behaviour changes significantly. Its mechanical properties, such as strength and modulus of elasticity, decrease. In the event of a fire, temperature gradients occur, which lead to internal stresses. The boundaries of the RC structure can also hinder deformation due to thermal strains, resulting in restraining forces and damage. Effects such as creep and relaxation, which are increased by high temperatures, also play an essential role [5-10]. Furthermore, non-explosive or explosive concrete spalling can occur during fire exposure, which can lead to a decrease in the load-bearing capacity of RC structures.
The resistance, failure mode, crack pattern and crack velocity in concrete are strongly influenced by loading rate [11-13]. The rate-dependent response of concrete is controlled through different effects: (i) through the rate dependency of the growing micro-cracks (influence of inertia at the micro level); (ii) through the viscous behavior of the bulk material between the cracks (viscosity due to the water content) and (iii) through the influence of inertia, which comes from different sources [12-14]. If the concrete is first pre-damaged through thermal loading (fire), there is a strong degradation of mechanical properties, and at the structural level, there is an additional damage of concrete due to the thermally induced stresses. It has recently been shown that a thermally pre-damaged concrete is more brittle with the consequence that it becomes less sensitive in the influence of high strain rates [15]. Therefore, the dynamic response of RC structures that are thermally pre-damage can change significantly.

In the present paper, the impact properties of RC slabs after fire exposure are investigated numerically. The slabs are first exposed to elevated temperature (fire) and subsequently loaded by the impact of a falling stiff hummer. The numerical results are compared with the experimental tests that have recently been carried out at Bhabha Atomic Research Center (BARC), Mumbai, India [16].

2. Finite element analysis and constitutive law
The finite element analysis consists of two parts: (i) Transient thermo-mechanical analysis and (ii) Multi body dynamic analysis. The spatial discretization is performed using standard 3D solid finite elements. Thermal analysis is performed using direct integration scheme of implicit type [14]. The mechanical part is implicit and based on the Newton-Rhapson iteration scheme. After finishing thermo-mechanical analysis, multibody explicit dynamic finite element analysis with the contact algorithm is conducted. The analysis is performed in the framework of total Lagrange formulation and removal of damaged finite elements [14]. To account for large displacements and finite strains, as a strain measure, Green-Lagrange strain tensor together with co-rotational Cauchy stress tensor is used. To get analysis objective with respect of the size of finite elements, regularization scheme based on the crack band method is employed [17].

In the numerical simulation, the rate and temperature dependent microplane model is used to model concrete [18-19]. Steel is modelled using thermo-mechanical model in the framework of classical rate theory of plasticity based on the von-Mises yield plasticity. Mechanical properties, i.e. Young’s modulus, yield stress and strength as well as thermal properties (free thermal strains, heat capacity and conductivity) are temperature dependent [10]. These properties are taken according to Eurocode 2 [20]. The total strain tensor is decomposed into mechanical, free-thermal strain and load induced thermal strains (concrete). Note that in contrary to concrete, the mechanical properties of steel are recovered after cooling down to the ambient temperature.

3. Numerical study
3.1. Geometry, FE discretization and material properties
Numerically are simulated three slabs that were previously experimentally tested at BARC (Mumbai, India) [16]. The experiments were carried out on RC slabs with dimension 1700 x 2000 mm (see figure 1). Slabs with different reinforcement ratios and thicknesses $D = 200$ and 150 mm were tested under different fire exposure and impact load (see figure 1 and table 1).

In the finite element analysis two bodies are involved, the RC slab and the steel impact hammer. In the first stage RC slab is exposed to thermal load, heating and subsequent cooling down to the ambient temperature. After thermo-mechanical analysis, dynamic analysis is performed (hammer impact). In the second stage, the problem to be solved is a typical impact problem with two bodies, reinforced concrete slab (master), and hammer (slave). In thermo-mechanical and dynamic analysis the mechanical boundary conditions where as shown in figure 1c, i.e. the top and the bottom nodes along the edge of the slab were fully constrained. In order to save CPU time for both, thermo-mechanical and dynamic, simulations double symmetry was utilized.
Figure 1. Reinforced concrete slabs [16]: (a) geometry and (b) reinforcement details and (c) boundary conditions (all in mm).

Table 1. Summary of geometry and loading for simulated RC slabs.

| Specimen | Thickness (mm) | Thermal load | Single drop | Impact Punch weight (kg) | Falling height (m) |
|----------|----------------|--------------|-------------|--------------------------|-------------------|
| Slab 1   | 200            | Bottom       | ✓           | 588                      | 5.0               |
| Slab 2   | 150            | Top          | ✓           | 588                      | 3.0               |
| Slab 6   | 150            | No           | ✓           | 588                      | 3.0               |

The concrete slab is discretized using 4-node constant strain finite elements (figure 2a). Finer mesh (element size approximately 10 mm) is used in the center of the slab (impact zone) and slightly coarser far from that zone, with the element size of approximately 25 mm. The steel reinforcement is discretized with the same finite elements and is modeled as rectangular welded bars (square cross-section) with dimension (section area) corresponding to the bar diameter of 8 mm ($D = 150$ mm) and 10 mm ($D = 200$ mm), respectively. The reinforcement spacing is the same as in the experimental tests and corresponds to 150 mm ($D = 150$ mm) and 200 mm ($D = 200$ mm), respectively. A perfect connection between concrete and reinforcement is assumed (no slip). Impacting hammer is modeled as a cylindrical body (diameter 170 mm and total length 420 mm) with a smooth spherical head (radius 191 mm) on the impact side.
The material properties employed in the numerical simulations are summarized in Table 2 and are based on Eurocode 2 [20], using the compressive strength measured on concrete cylindrical specimens at an ambient condition as the reference [16]. The steel hammer is assumed to be linear elastic with specific weight $\gamma_s = 7800$ kg/m³, Young’s modulus $E_s = 210$ GPa and Poisson’s ratio $\nu_s = 0.33$. Table 2 also summarizes the main thermal properties (for ambient temperature) of concrete and steel, which were used as the input parameters in the transient thermal analysis.

**Table 2. Summary of mechanical and non-mechanical properties of concrete and steel.**

| Property                 | Concrete Slab D = 150 mm | Concrete Slab D = 200 mm | Reinforcement |
|--------------------------|--------------------------|--------------------------|---------------|
| Density, $\rho$ (kg/m³)  | 2400                     | 2400                     | 7800          |
| Young’s mod., $E$ (GPa)  | 28.60                    | 26.30                    | 210           |
| Compr. strength, $f_c$ (MPa) | 24.00                    | 18.20                    | -             |
| Ten. strength, $f_t$ (MPa) | 1.90                     | 1.40                     | -             |
| Fracture ener., $G_F$ (J/m²) | 55.00                    | 46.00                    | -             |
| Poisson’s ratio, $\nu$   | 0.18                     | 0.18                     | 0.33          |
| Yield stress, $f_y$ (MPa) | -                       | -                        | 480           |
| Strength, $f_u$ (MPa)    | -                        | -                        | 550           |
| Conductivity, $\lambda$ (W/mK) | 1.36                    | 1.36                     | 43.0          |
| Heat capacity, $c_p$ (J/kgK) | 900.0                   | 900.0                    | 490.0         |

### 3.2. Loading scenario

As specified in Table 1, the simulations are three RC slabs that were previously tested experimentally. Slab 1 ($D = 200$ mm, fire at the bottom surface) and Slab 2 ($D = 150$ mm, fire at the top surface) were before hammer impact exposed to fire, whereas Slab 6 ($D = 150$ mm) was not pre-damaged by fire. The initial thermal conditions in thermo-mechanical analysis are given in terms of initial nodal temperature ($T_0 = 20°C$). To allow the heat transfer through the concrete slab surface, heat flux is applied on the heated surface of the slab. Principally, in the thermo-mechanical simulations, three different exposure stages were applied. In the first step, the heating of the environment is provided based on the ISO834 temperature-time history. After 60 minutes of heating ambient temperature of about 950°C is reached. In the second part, the cooling phase is applied by a linear decrease of ambient temperature over one hour. After that, ambient temperature is kept constant (20°C) for several hours to allow the complete cooling of the slab, the same as in the experiment. After thermal exposure, RC slabs were subjected to impact of hammer provided in the centre of the top slab surface. The impact load is generated by dropping a hammer of 588 kg mass from the height of 3 m (impact velocity 7.67 m/s, Slabs 2 and 6) and 5 m (impact velocity 9.75 m/s, Slab 1), respectively.

### 3.3. Results and discussion

The typical results obtained for the thermo-mechanical and dynamic simulations are shown for Slab 1. Figure 2 shows the distribution of temperature at different stages of the thermal analysis. As can be seen from the temperature distributions, the numerical profiles fit very well with those measured in experimental tests. The curves are plotted for mid of the slab. Location 1 corresponds to the section closest to the exposed surface, while location 5 to the opposite, non-exposed surface.

After Slab 1 was thermally pre-damaged at the bottom side, it was loaded by the hammer impact with an impact velocity of 9.75 m/s at the top side. Similar as in the experiment, there is a complete perforation of the slab. In principle, the hard hammer perforation process can be divided into an initial cratering phase, a subsequent tunneling phase and a final phase characterized by the spalling at the bottom surface of the slab. Due to the initial high impact velocity, the entrance crater is well defined with no evident spalling or cracking at the front face. The top reinforcement is catted in the first phase of the impact, while that at the bottom side, due to the high reduction of the hammer velocity during the penetration, is just pushed and spread around the hole.
Figure 2. Distribution of temperature for different heating stages (1/4 of the slab): (a) time history temperature profiles and (b) distribution of temperature over the slab (Slab 1).

Figure 3. Comparison between numerical (right) and experimental (left) [16] failure profiles for the Slab 1: (a) entrance crater and (b) exit crater (rear face scabbing).

Figure 3 shows the comparison between numerical and experimental results in terms of damage at the top and bottom of the slab. The numerical analysis can realistically reproduce the experimental test results, characterized by a clear entrance crater with a diameter almost coincident with the hammer diameter and by an exit crater with scabbing of concrete pieces ejected from the bottom face. Moreover, there is a clear cut of the top reinforcement layer already in the first penetration stage. Nevertheless, with the proceeding of hammer penetration loading waves propagate through the
specimen and reflected from the free surface of the slab, it will cause scabbing. In addition, it is important to note that the slab was thermally pre-damaged at the bottom surface up to approximately 950 °C. The thermal exposure yields to degradation of mechanical properties, which makes the concrete much weaker and more brittle, with the consequence that the scabbing area is getting larger in comparison with the same case without thermal pre-damage.

Figure 4 shows experimentally and numerically obtained history response of impact load and punching velocity of the hammer. The acceleration and velocity histories are obtained using high-speed photography and accelerometers mounted on the hammer. The impact force is calculated from the measured accelerations. As can be seen from Figure 5a, the numerically predicted impact force exhibits a higher peak and the curve is characterized by an initial very steep increase up to the peak load.

Figure 4. Experimental [16] vs. numerical results: (a) load-time history and (b) penetration velocity-time history (Slab 1).

Figure 4b, instead, shows the comparison in terms of hammer velocity histories (node at the punch tip is monitored). Numerical and experimental curves match very well. Moreover, from the analysis of the curves, the different penetration phases can be observed. At the beginning of the impact, velocity exhibits a very steep initial slope. This first part corresponds to the cratering phase, in which the hammer has a large amount of kinetic energy and it can easily penetrate the concrete slab. At about 0.01 second, the hammer impacts against the first reinforcement layer leading to a strong immediate reduction of the velocity. After this point, the hammer penetration is progressively slowing down and continues to penetrate between the two reinforcement layers. When the hammer made impacts against the second reinforcement layer, almost all the impact energy was dissipated, i.e. the hammer penetration velocity gets low and not enough energy is available to cut the second reinforcement layer.

In the numerically predicted velocity history, three strong oscillations can be observed at about 0.01, 0.025 and 0.045 seconds. These instabilities correspond to the steps in which the hammer impacts against the reinforcement: (i) impact to the top reinforcement layer, (ii) cutting of the top reinforcement layer and (iii) impact to the bottom reinforcement layer. Taking into consideration the complexity of the problem and of the performed thermo-mechanical-impact coupling, the numerical analysis shows good agreement with the experiments in terms of hammer velocity history, impact forces and failure mode.

The above presented numerical results for Slab 1 (D = 200 mm) are typical also for Slabs 2 and 6 (D = 150 mm). In the case of Slabs 1 and 2, which were pre-damaged by thermal loading, the hammer penetrated through the entire slab, i.e. up to the bottom reinforcement layer. However, for thermally not pre-damaged Slab 6, which is the same as Slab 2, the hammer did not completely penetrate. This
clearly shows that 60 min of standard fire load (ISO834) significantly contributes to the degradation of impact properties of the slab, and that the numerical simulation which combines both loading scenarios (thermo-mechanical loading and impact), is able to realistically replicate experimental tests.

In figure 5 the time history of hammer velocity is shown for all three slabs. The velocity degradation is normalized for each case concerning the initial impact velocity. The plot clearly shows the effect of fire exposure on the slab response (compare Slab 2 and 6).

![Figure 5. Punching velocity reduction histories for all three simulated slabs.](image)

The behaviour observed for Slab 1 seems to be between the two above discussed observations. The initial slope, the tunnelling behaviour and its duration, exhibit an average trend with higher magnitudes compared to Slab 2, but lower than observed for Slab 6. Same behaviour is observed in the tunnelling phase, which takes place between 0.030 and 0.055 seconds. The reason for this kind of “average trend” can be addressed is the fact that for this type of impact, the thermal exposure was provided at the bottom slab surface, while the impact on the top. Moreover, the thickness of the slab \(D = 200 \text{ mm}\) is thicker than for two other slabs. Therefore, the thermal damage and the material degradation are lower than for the Slab 2.

4. Conclusions

In this paper, 3D finite element impact simulation of thermally pre-damaged RC slabs is carried out. Based on the results of numerical simulations, the following points can be concluded. (i) The results of 3D FE thermo-mechanical simulation show that 60 min of heating and subsequent cooling to the ambient temperature leads to significant thermally induced damage of RC slabs; (ii) The comparison between experimental and numerical results shows that numerical transient analysis based on the temperature-dependent microplane model is able to realistically replicate experimental tests. This is valid for both, temperature induced damage and temperature distribution, Furthermore, the multi-body 3D dynamic finite element analysis, based on the rate-dependent microplane model, contact algorithm, and finite element erosion technique, is able to realistically predict response and failure mechanism of RC slabs that were previously pre-damaged through fire load; (iii) Typical impact failure mechanism consists of three stages: initial cratering phase with sharp input crater, subsequent tunneling phase with cutting of the top reinforcement, and a final phase characterized by the spalling of the bottom face of the slab; (iv) As expected, the numerical and experimental results clearly show that 60 min of fire according to ISO834 heating curve and subsequent cooling to the ambient temperature significantly reduce impact resistance of RC slabs. However, the typical failure mechanism is not much influenced by the thermal pre-damage; (v) Further, numerical parameter studies would be useful to systematically investigate the influence of different loading scenarios, material properties, and geometries on the impact properties of the RC slabs.
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