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Fire Temperature Distribution in Earthquake-Damaged RC Elements

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ABSTRACT

Post-earthquake fire hazards result in significant structural loss that, in some cases, exceed the initial damage due to earthquake itself. Although few research studies have addressed this topic, the fire performance of seismically-damaged Reinforced Concrete (RC) structures is not well understood. In addition, current building codes allow structural elements to undergo large plastic deformations and experience partial damage. This might increase the heat penetration inside the damaged cross-sections and leads to a fast-progressive collapse of the building. This paper utilizes a numerical approach to evaluate heat distribution in a seismically-cracked RC section. A cantilever-beam damaged under lateral cyclic load is chosen from the literature to be used as a case study. The strength and serviceability of the seismically-damaged beam are found to be highly affected by fire.

Keywords: Post-earthquake Fire, Heat Distribution, Seismically-Cracked section, Reinforced Concrete

INTRODUCTION

Severe seismic hazards can lead to major losses and significant damage. Generally, earthquakes are followed by various events, such as liquefaction, landslides, fire, and tsunami. In crowded residential areas, Post-Earthquake Fire (PEF) events are the dominant hazard [1] that may cause more losses and damage than the earthquake event itself [2]. To guarantee the building safety during PEF, seismically-damaged structural elements should withstand the effect of fire. Consequently, the thermal behavior of the damaged cross-sections, e.g. thermal conductivity, heat distribution, needs to be understood along with their influence on the overall building resilience during fire [3]. Few research studies addressed this topic, and much work is needed before reaching solid conclusions [4-6].

Several experimental and numerical research studies have been conducted to assess the heat transfer in cracked RC sections. Wu et al. [4], Ervine et al. [5], and Vejmelková et al. [7] concluded that cracks have a negligible effect on the heat transfer. Based on experimental and numerical study of nine pre-cracked plain concrete specimens, Wu et al. [4] concluded that cracks less than 3 mm width have a small effect on the heat transfer. Ervine et al. [5] experimentally evaluated the thermal propagation through tensile cracks for eight RC beams. The results indicated that there is a minor change in the heat propagation in cracked beams up to a crack width of 5 mm. Vejmelková et al. [7] suggested that the thermal conductivity of cracked concrete elements reduces due to the increase in the material porosity and proposed that the air within a crack works as an insulator, obstructing the heat flow within the body. On the other hand, Ba et al. [6], Shi et al. [8], Miao et al [9], Miao and Liu [10], and Shah et al. [11] showed that the cracks have a significant influence on the heat distribution. Shi et al. [8] performed an experimental test on six RC beams with various concrete cover thicknesses. The differences between the experimental results and the numerical predictions were attributed to the tensile cracks. Miao et al [9] conducted a fire test on two RC frames with various crack width sizes and concluded that cracks increased the thermal conductivity of RC sections. Miao and Liu [10] investigated the influence of corrosion cracks in marine environment on the fire endurance of beams. After fire exposure, the beams were loaded to collapse. The temperature within the corroded beams was found to be higher than the uncorroded beams. Shah et al. [11] conducted a PEF experimental test on a non-ductile frame. The frame was first loaded by a quasi-cyclic lateral load, representing the seismic loading. Later, the damaged frame was exposed to fire. The temperature inside the cracked sections were higher than the undamaged sections. Ba et al. [6], also, performed fire tests on seven beams, four columns, and two portal frames. In addition, a numerical model was constructed to predict the heat propagation inside cracked sections. They concluded that cracks have a substantial effect on the heat distribution inside RC sections. Further, they pointed out that the crack width increases with temperature.

Due to this drastic contrast among researchers, heat distribution inside seismically-damaged sections should be carefully explored. This paper aims at providing an accurate representation of the heat distribution inside seismically-damaged RC sections.

NUMERICAL MODEL

Wu et al. [4] developed a simplified model to simulate the heat propagation inside cracked concrete sections. Based on their test results, cracks have negligible effect on the heat distribution. The thermal conductivity of concrete was assumed to decrease at crack regions. An expression for calculating the conductivity reduction factor was also proposed. The convection heat transfer coefficient and thermal emissivity of concrete were taken as 25 W/m^2.K and 0.70, respectively. The heat convection and radiation within the cracks were ignored assuming that the air velocity, inside the crack, is almost zero and crack edges provides shelter from the furnace radiation [4]. Although their model has a good agreement with their experimental results, the assumption of only reducing the heat conductivity contradicts with many other experimental studies [6, 8-11].

Ba et al. [6] used ANSYS [12] finite element software to develop a technique that captures the heat distribution inside cracked RC sections. Similar to Wu et al. [4], Ba et al. [6] assumed there is neither convection nor radiation heat transfer inside concrete cracks. However, they assumed that the air inside the crack has the same temperature as the fire. Cracks were modeled as a material having the thermal properties of air. This material transfers the fire heat to the inner concrete surface by conduction. The boundary condition of this material was set to equal the fire temperature. Eurocode2 [13] thermal properties were assumed. The convection heat transfer coefficient for the exposed and unexposed surfaces were taken as 25 and 4 W/m^2.K, respectively. The thermal emissivity of the concrete was 0.80. Results of the numerical analysis were in good agreement with the experimental work. However, the numerical simulation showed that the crack region was heated faster than the concrete surface. Unless the cracks are big enough to allow convection heat transfer inside the concrete mass, these results are not valid as propagation of the fire temperature in the concrete should be faster than the air. The relatively high thermal conductivity of concrete is the reason for such expectation.

In this paper, it is proposed to simulate heat propagation inside cracked sections using a modified Ba et al.'s model [6]. The modification relates to application of the fire temperature to the cracked area. Instead of setting the fire temperature as a boundary condition for the air within the crack, it was calculated using convection. Since thermal convection depends on the exposed area, small cracks would work as insulation systems, whereas, large cracks would transfer more heat toward the concrete core. Figure 1 shows the proposed model.

MODEL VALIDATION

The pre-cracked plain concrete beam (C-W3L160A0) analyzed by Wu et al. [4] is utilized for the model validation. The cross-section dimensions of the beam are 200 mm by 300 mm and its length is 800 mm, Figure 2a. The pre-fire crack is 3 mm wide and 160 mm deep. The crack width is assumed constant along its depth. The concrete mix consists of portland blast furnace slag cement, natural crushed limestone coarse aggregate, and river sand. The cube compressive strengths of concrete was 37.5 MPa. The fire in the furnace was applied at the four sides of the beam for 90 minutes following ISO 834 standard fire curve. The maximum fire temperature was 987℃. The temperature within the concrete beam was measured and recorded during the test using thermocouples at different locations, Figure 2b. Figure 3 Shows a snapshot from the Abaqus Model used in this validation.

Figure 4 shows the predicted elevated temperature at different locations inside the beam. A good agreement is found between the predicted temperatures and the experimental test except at thermocouple P(1). This can be due to neglecting the energy loss due to concrete water evaporation at 100℃, i.e. at 15 min fire exposure. Figure 5 shows the temperature gradient at 90 min fire exposure along the section depth. A good agreement is found between both the experimental and the numerical results.

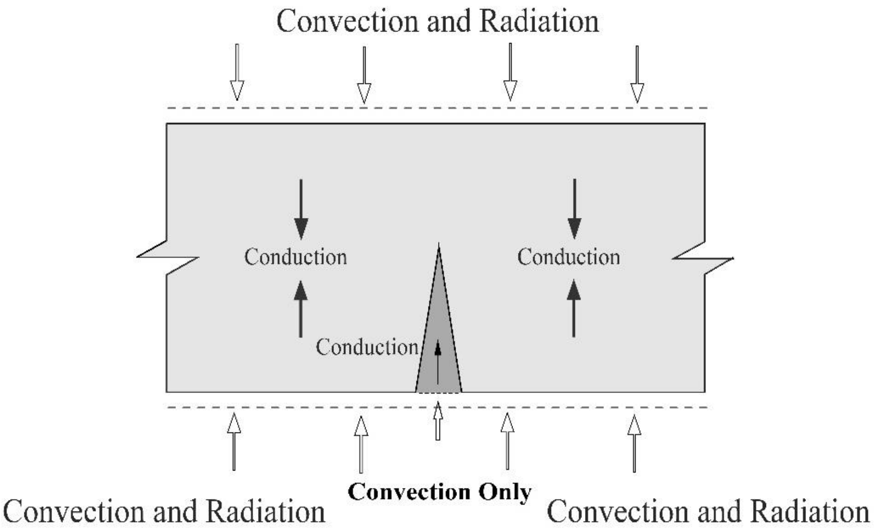
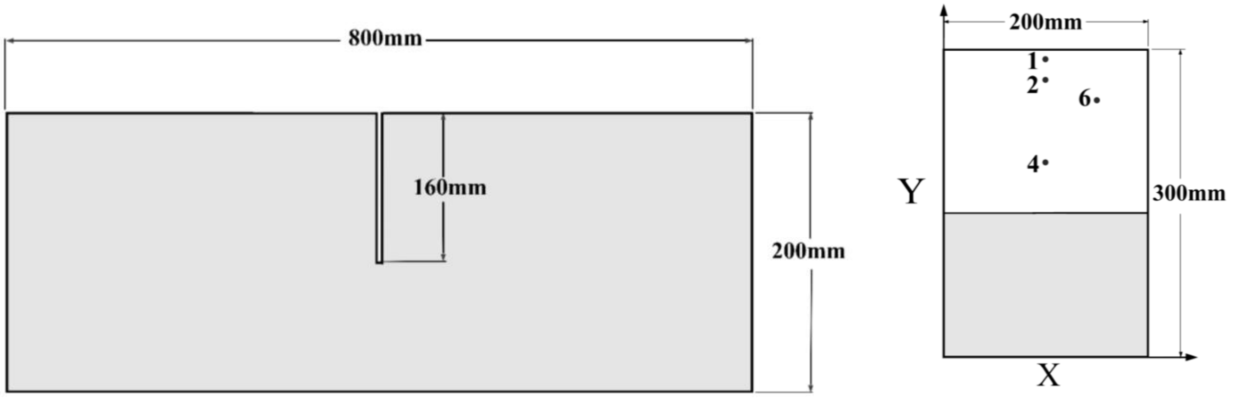


Figure 1. Heat propagation through cracks



(a) dimensions of the beam

(b) location of the thermocouples

Figure 2. Validation beam [4]

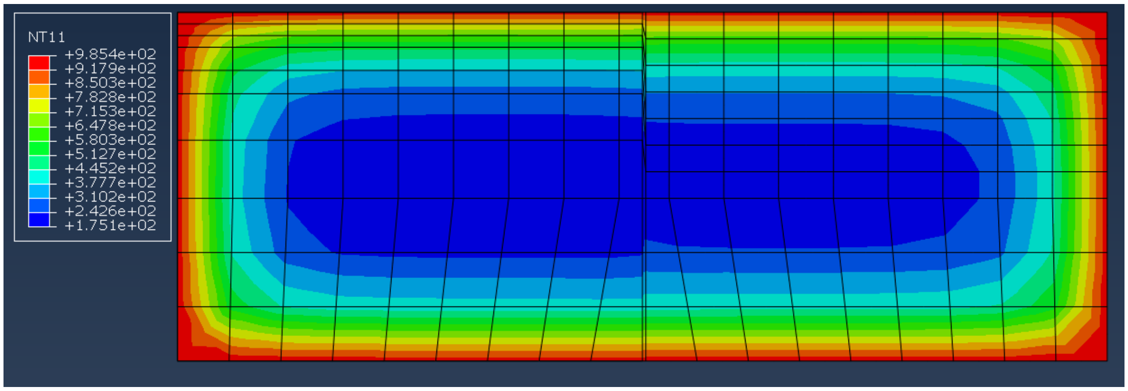


Figure 3. Abaqus heat transfer model

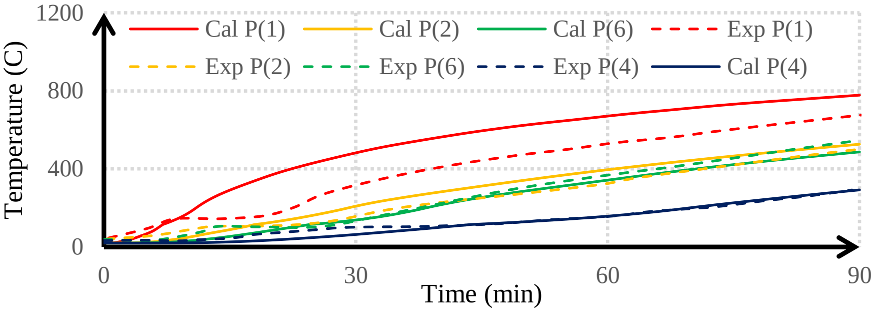


Figure 4. Elevated temperatures at points 1, 2, 4, and 6

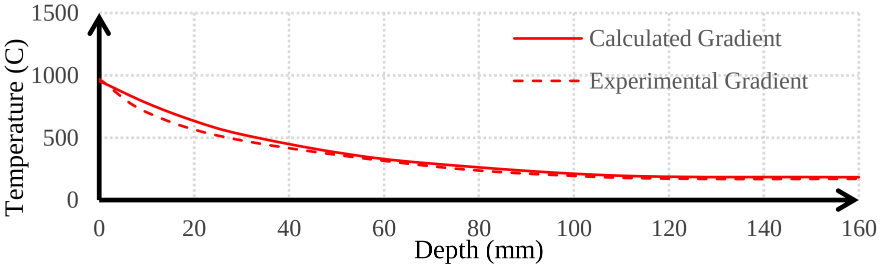


Figure 5.Temperature gradient across the section width at 90 min

SEISMICALLY-DAMAGED RC SECTIONS DURING FIRE

The damaged RC beam (B22S) reported by Chen et al [14] is considered to investigate the effect of seismic damage on the internal heat distribution inside RC sections. The cross-section dimensions of the beam are 200 mm by 400 mm and its length is 2120 mm, as shown in Figure 6. The concrete cube compressive strength and steel yield strength are 30 MPa and 350 MPa, respectively. The beam is reinforced with 2-22M at its top, 2-16M at its bottom, and 8M stirrups spaced at 100 mm. Under a lateral quasi-cyclic load, Chen et al. [14] reported the damage as concrete cover spalling for a length of 310 mm length and a residual crack width of 4 mm, as shown in Figure 7a.

ABAQUS finite element software [15] is used to investigate the heat distribution inside the beam. In this model, the Eurocode2 [13] thermal properties are followed. The convection heat transfer coefficient and the thermal emissivity of the concrete are assumed 32 W/m^2.K and 0.90, respectively. The fire in the furnace is applied at the three sides of the beam for 2.3 hrs following the ISO 834 standard fire curve. The influence of cracks on the heat propagation inside the RC section is modeled considering 4 potential cases: an intact section without damage (REF), concrete cover spalling with no crack (SP), concrete cover spalling along with 4 mm crack (SP4), and concrete cover spalling along with 10 mm crack. Figure 7b shows a longitudinal section of the examined beam.

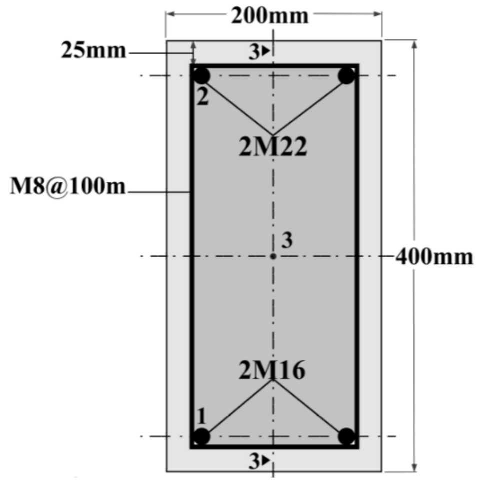
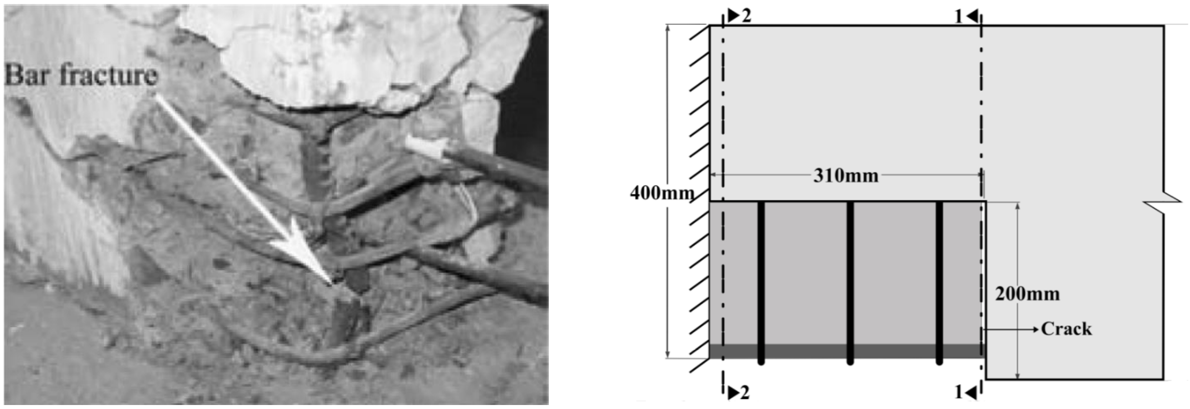


Figure 6. Shows the beam cross section [14]



(a) the reported damages of B22S [14]

(b) the modeled beam

Figure 7. RC beam damage after earthquake loads

RESULTS AND DISCUSSION

The elevated temperatures are predicted at points 1 (Bottom Steel) and 3 (Mid-Section) for the mentioned models (REF, SP, SP4, SP10) at section 1-1 (S1) and section 2-2 (S2), Figures 6 and 7b. The heat gradient along the length of the beam is also determined at points 1 and 3. To demonstrate the effect of the post-earthquake fire (PEF) on the moment capacity, the moment-curvature response of the intact beam section at ambient temperature and during fire exposure are compared against the moment curvature response of the damaged beam section (SP4) under PEF.

Figure 8 presents the temperature at point 1 (P1) for all models at section 1-1 (S1) and section 2-2 (S2). As shown in the figure, seismically-damaged sections experience considerably higher temperature comparing to the temperature inside the intact section (REF). The concrete cover spalling has a crucial impact on the heat penetration inside the RC section whereas cracks have a minor effect on the heat propagation. Small cracks appear to act as insulators within the concrete body; for instance, the temperature at point 1 in SP4 is less than temperatures for both SP and SP10 at section 1-1. Furthermore, all models displayed higher temperatures at point 1 of section 2-2 (support section) as compared to point 1 of section 1-1 (section at the crack location).

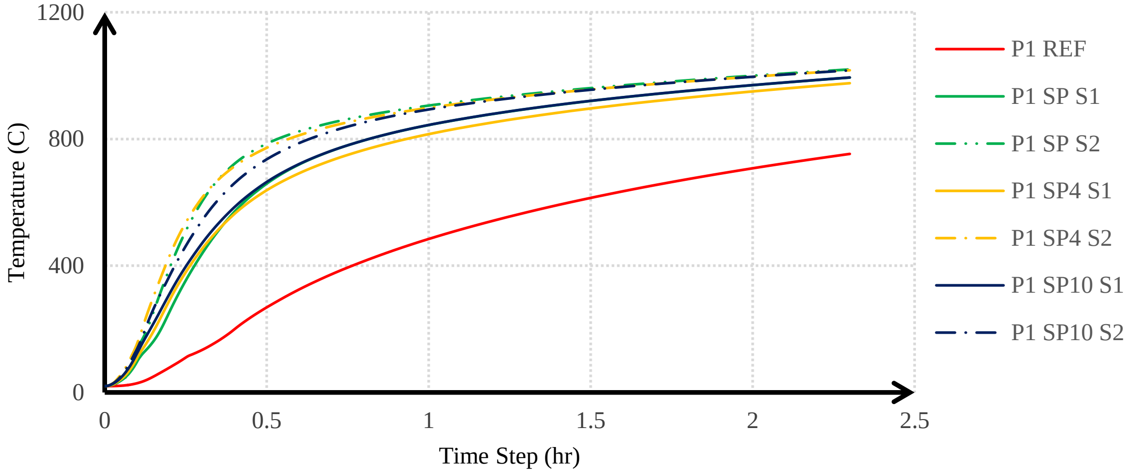


Figure 8. Temperature at point 1 at sections 1-1 and 2-2

Figure 9 exhibits the temperature at point 3 at sections 1-1 (S1) and 2-2 (S2). Similar to the results at point 1, the outcomes confirm that temperature is higher in the seismically-damaged sections as compared to the intact section (REF). The concrete cover has a significant effect on the heat distribution inside the RC section. On the other hand, the cracks have a small influence on the heat distribution. Despite their small influence, the 10 mm crack appears to have a notable increase on the heat flow toward the concrete core compared to the 4 mm crack. The results show that the temperature at section 2-2 is more than the temperature at section 1-1. It is worth mentioning that the temperature for point 2 (top steel) was the same for all models as no damage has occurred at the upper part of the section.

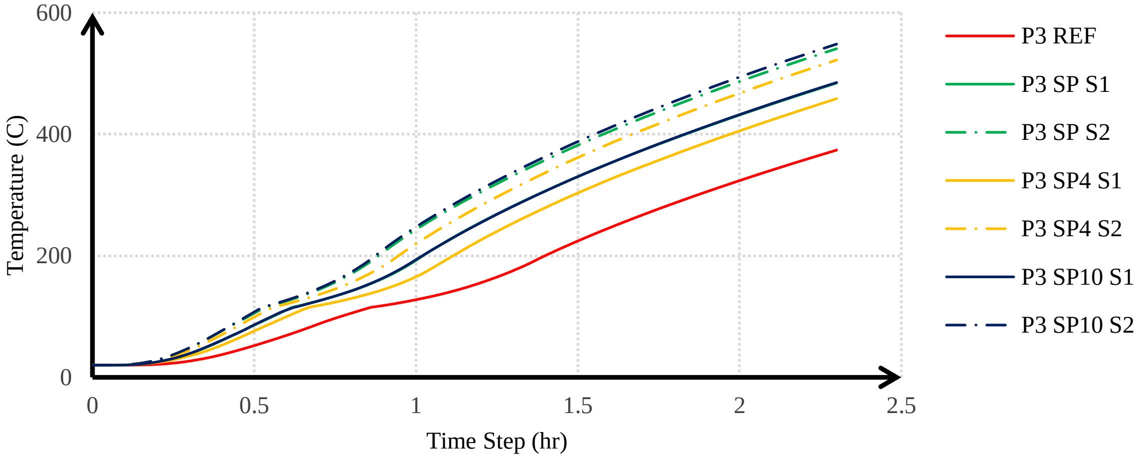


Figure 9. Elevated temperature at point 3 - sections 1-1 and 2-2

Figure 10 shows the heat gradient along the length of the beam at points 1 and 3; as well as a cross-section from ABAQUS demonstrating the full heat gradient along the beam. The figure explicitly shows the effect of seismic damage on the heat distribution inside the section. Specifically, the temperature rises about 260℃ at point 1 and about 175℃ at point 3. The results at point 3 indicate that the 10 mm crack allows far more heat penetration towards the core. Figure 11 displays the heat gradient along section 3-3 of SP4 and the heat gradient along the intact beam depth. It is obvious that the seismic damage has caused rapid heat flow towards the concrete core, as well as an increase in the temperature inside the section.

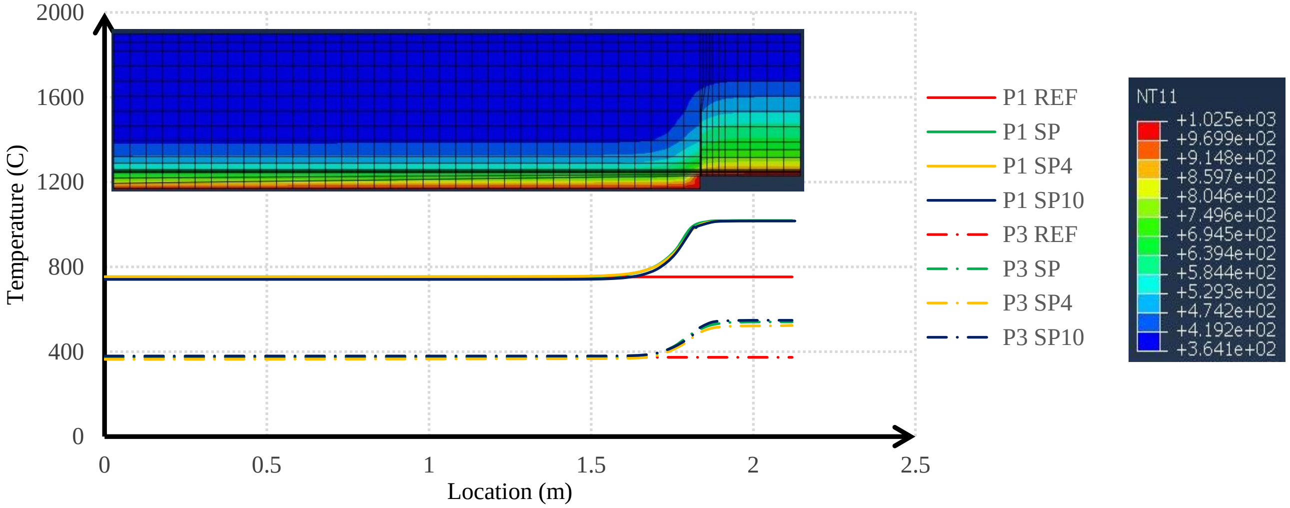


Figure 10. Effect of crack on elevated temperature distribution (points 1-5)

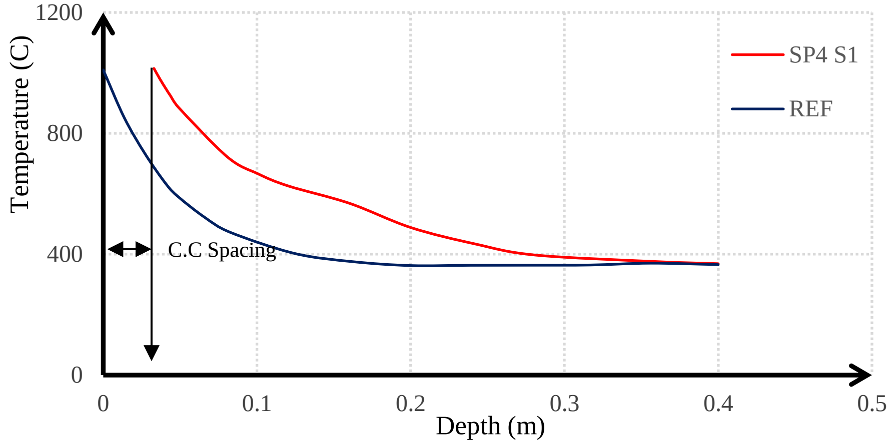


Figure 11. Temperature gradient along the section depth of SP4 (B22S)

Figure 12 shows a comparison between the moment-curvature of the intact section at ambient temperature, the moment curvature of the REF section under fire, and the moment curvature of SP4 under PEF. The PEF is shown to have a major effect on the capacity of the RC structural element. The figure suggests that the section capacity during fire exposure is reduced by 50 % from the ambient, while during PEF exposure the section capacity is reduced by 90 %. This significant capacity reduction may result in a structural collapse under gravity loads alone. Furthermore, Figure 12 demonstrates that SP4 under PEF becomes extensively ductile when compared to the REF section under fire and the intact section under ambient temperature. This could potentially result in serviceability issues if failure did not occur.

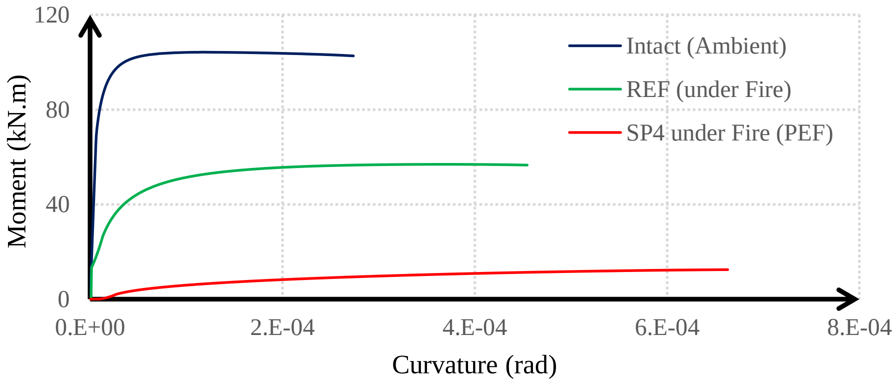


Figure 12. Effect of Post-Earthquake fire on moment-curvature of damaged RC beams

CONCLUSION

The effect of earthquake damage, i.e. wide cracks and concrete spalling, on the fire resistance of RC beams is discussed in this paper. The obtained results show that spalling of concrete cover has a significant impact on the heat distribution inside an RC section. Cracks have a minor influence on the heat flow within the concrete mass. Small cracks appear to act as insulators whereas large cracks can transfer heat towards the core of the RC section. In general, seismic damage lead to rapid heat propagation towards the concrete core and the reinforcing steel. This can substantially alter the moment-curvature behavior by considerably minimizing the moment capacity and increasing the section ductility. Therefore, post-earthquake structural failure or serviceability problems are more susceptible to occur. In addition, the rapid heat transfer generates internal thermal forces between the concrete core and the concrete cover, which accelerate the spalling of concrete cover and increases the crack propagation during fire. More experimental work is needed to deduce the crack width threshold, at which cracks can be effective in the heat distribution, as well as to determine the crack width threshold at which heat is transferred by convection within the crack itself.

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