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Thermal fields of cracked concrete members in fire

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ABSTRACT

Ten concrete specimens (nine with pre-made cracks and one without crack) have been tested in fire to investigate the effect of cracks on temperature distributions of concrete members subjected to post-earthquake fire. After that, a simplified numerical method based on ABAQUS is proposed to determine the thermal fields of the cracked specimens. Three parameters considered in this study include the width, projected length, and inclination angle of the crack. From experimental and numerical investigations, it is found that (a) the measured temperatures on the surface of the pre-made crack for the cracked specimens are generally lower than those on the central cross section of the non-cracked control specimen; (b) when the crack is less than 3 mm wide, the influence of the crack width on the temperature distributions is negligible, and slightly higher temperatures are generally obtained with an increasing of the crack's projected length; (c) temperatures on the surface of the pre-made crack for the specimens with inclined cracks are marginally higher than those for the specimens with perpendicular cracks on the whole; and (d) the simplified numerical method is proven to determine the thermal fields of the cracked specimens rationally.

1. Introduction

Due to the high thermal inertia of concrete, fire resistance of concrete members is often considered to be satisfactory in an ordinary fire disaster. Although thermal properties of concrete material are generally independent of its mechanical properties, the mechanical phenomena of a seismic damaged concrete member, such as tensile cracking and loss of concrete cover, may give rise to a more rapid heat penetration into the damaged member as compared with that into an intact member, resulting in faster deterioration of the damaged member in post-earthquake fire and less fire resistance. Some past earthquakes (e.g., the 1906 San Francisco, 1923 Tokyo, 1971 San Fernando, 1994 Northridge, and 1995 Kobe earthquakes) witnessed secondary fires which brought about great loss [1].

Generally, major cracks and crushed concrete cover are often observed in severely seismic damaged concrete members. To calculate the thermal profiles of the damaged members under post-earthquake fire, the crushed concrete may be removed completely and then the inner of the members is exposed to fire directly. But in the preliminary studies on fire performances of seismic damaged concrete structures or members subjected to post-earthquake fire carried out by Ervine et al. [2], Mariyana et al. [3], and Wu and Xiong [4], the influence of the cracks on temperature distributions in the concrete structures or members was ignored or not mentioned.

To the authors' knowledge, the effect of the cracks on thermal profiles of the concrete members has not been sufficiently studied. Test results provided by Vejmelková et al. [5] indicated that the thermal conductivity of cracked concrete in dry state decreased up to 40% as compared with that of non-cracked concrete, and the change of the thermal conductivity was sensitive to the moisture. But it should be noted that the cracks in the specimens were made by heating the specimens up to 600 °C in an oven; the thermally induced cracks were quite different from the conceptual tensile cracks, so the applicability of the test results to the seismic damaged members is unclear now and further investigation is required. Ervine et al. [6] tested eight concrete beams to determine the thermal propagation through the tensile cracks, and a small decrease in the thermal propagation was observed. They attributed the phenomenon to the small geometric, mechanical and concrete compositional differences. In these tests, thermocouples were arranged during the casting of the specimens and their actual locations were confirmed by breaking the specimens after experiments. Obviously, it was difficult to get temperatures on the surface of the crack because the location of the crack could not be exactly predicted in advance. Through testing of five simply-supported concrete beams strengthened with carbon fiber sheet in fire, Liu et al. [7] concluded that the effect of the flexural cracks at the mid-span on the temperatures of the longitudinal tensile reinforcements was very limited.

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Contrary to the test results mentioned above, Miao et al. [8] carried out the fire tests of three concrete frames with different crack widths or without crack. It was concluded that the thermal conductivity of the concrete with cracks tended to increase resulting in higher temperatures inside the member. Similarly, Shi et al. [9] conducted the fire tests of six beams with different concrete cover thicknesses, and concluded that the cracking had a significant effect on the temperature distributions of the flexural members.

Since contradictory results were obtained by former scholars, the objective of this study is to understand the effect of the cracks on the thermal profiles of the concrete members more clearly through both experimental and numerical studies. Ten concrete specimens (nine with pre-made cracks and one without crack) were exposed to the ISO834 standard fire [10] for 90 min. The main parameters considered in the fire tests included the width, projected length, and inclination angle of the crack. During the casting of the specimens, thermocouples were exactly located on the surface of the pre-made crack, so the temperature distributions on this surface could be measured. Then, a simplified numerical method based on ABAQUS was proposed to predict the thermal fields of the cracked specimens, and the calculated results have been compared with the test results. Based on the experimental and numerical investigations, some interesting conclusions have been drawn.

2. Experimental program

2.1. Test specimens

Ten concrete specimens (nine specimens with pre-made cracks and one reference specimen without crack) with dimensions of 200 mm × 300 mm × 800 mm were prepared. The assumption that the temperature distribution of the specimen in fire is independent of the loading pattern is adopted in this study, so for simplicity all the specimens were not loaded during the heating process. The specimens were made from one batch of ready-mix concrete. The concrete was made of Portland blast furnace-slag cement (P.S.A 32.5), natural crushed limestone (coarse aggregate) with a maximum size of about 20 mm, and local river sand (fine aggregate, 0–4 mm). Table 1 shows the concrete mixture proportion. The 28-day and test-day cubic compressive strengths of the concrete were, respectively, 34.1 MPa and 37.5 MPa.

Table 1
Concrete mixture proportion.

Water (kg/m^3)	Cement (kg/m^3)	Coarse aggregate (kg/m^3)	Fine aggregate (kg/m^3)	Fly ash (kg/m^3)	Water reducer (kg/m^3)
173	376	1133	738	30	3

Except for the control specimen without crack, each of the other nine specimens was pre-made with a perpendicular or inclined crack. Fig. 1 shows the schematic diagrams of the specimens with cracks. Three parameters were employed to describe the crack: (a) nominal crack width ω; (b) crack's projected length from the specimen's top surface (i.e., L in Fig. 1); and (c) crack's inclination angle measured at the crack tip (i.e., θ in Fig. 1(b)). The specimens are identified by the notation — C-*W*#*L*#*A*#, where "C" stands for the concrete material, "*W*" indicates the nominal crack width (*W*1/2 = 0.5 mm, *W*1 = 1 mm, *W*2 = 2 mm, and *W*3 = 3 mm), "*L*" gives the crack's projected length (*L*100 = 100 mm, *L*130 = 130 mm, and *L*160 = 160 mm), and "*A*" refers to the crack's inclination angle (*A*0 = 0°, *A*10 = 10°, and *A*30 = 30°). For instance, C-*W*1*L*100*A*10 indicates a concrete specimen with a nominal crack width of 1 mm, a crack's projected length of 100 mm, and a crack's inclination angle of 10°. It should be noted that the nominal crack width was constant along the crack's projected length in this study. Table 2 illustrates details of all 10 specimens. In this table, C-*W*0*L*0*A*0 denotes the reference specimen without crack.

Fig. 2(a) displays a schematic diagram of the specimen's plywood mold with an inserted steel plate. Two notches were pre-cut on the side boards of the mold, and the length and inclination angle of the notches were equal to those of the intended concrete crack of the specimen. Then a steel plate with a nominal thickness equal to the nominal crack width was inserted in the notches. The measured thickness of the inserted steel plate is also listed in Table 2. It can be seen from this table that the measured thickness is less than the nominal thickness due to the manufacturing tolerance. Several steel bars, at least 50 mm far from the inserted steel plate, pierced through the side boards of the mold and acted as retainers of the thermocouples (see Fig. 2(b)). During the casting of the specimen's concrete, the thermocouples were firmly tied to these steel bars, so the tips of the thermocouples could be exactly located at different intended positions. The concrete near the thermocouples was poured very slowly and carefully, and during this process the thermocouples were held by hand to prevent them from bending and moving. Since the minimum distance between the steel bars and the tips of the thermocouples was larger than 50 mm, the influence of the steel bars on the temperature distributions close to the concrete crack was negligible. Before pouring the concrete, oil was greased on the steel plate to facilitate the removal of the plate after the final setting of the concrete. Pictures of four specimens with cracks are shown in Fig. 3.

All the specimens were cured in air for more than half a year at room temperature. The specimens' crack widths were measured just before the fire tests, and the measured results are listed in Table 2. It can be seen that the measured widths are generally larger than the actual thicknesses of the inserted steel plates due to the shrinkage of the concrete.

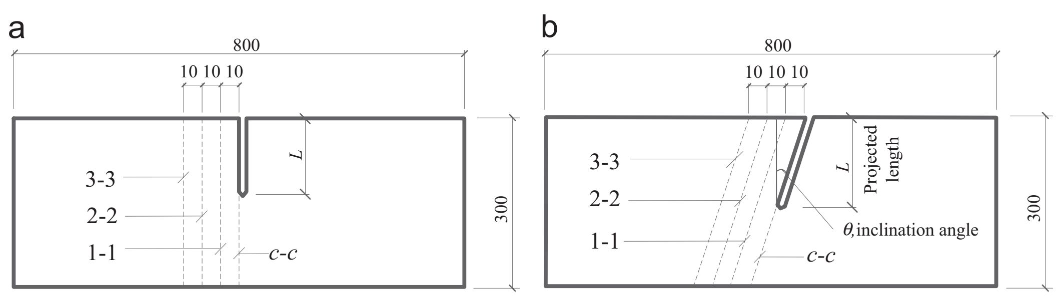

Fig. 1. Schematic diagrams of specimens with pre-made cracks (unit: mm). (a) Specimen with perpendicular crack and (b) Specimen with inclined crack.