On The Expected Location of Fire-Induced Concrete Spalling

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ABSTRACT: The occurrence of fire-induced spalling in concrete structures and shotcrete elements (aka sprayed concrete) is influenced by various factors including the type of heat and applied fire curves, temperature gradient, sample size, and quality and mixture of the concrete. Predicting the location of spalling can significantly assist with developing fire resistance tests to allow for the correct placement of instrumentation and monitoring equipment such as temperature and pressure sensors, high-speed cameras, and 3D/2D Digital Image Correlation imaging, among others, in optimal positions to be able to closely monitor the spalling process. This study examines the data from tests previously carried out to generate a model for predicting the location of fire-induced spalling in concrete samples, and then compares it experimentally to validate the proposed model. The results indicate good compatibility between the data from literature and the performed experiments.

Keywords: Fire-induced Spalling, Spalling Positions, Pressure, Temperature.

1 INTRODUCTION

There has been a surge in research related to fire-induced spalling in concrete and shotcrete structures in recent years due to the danger it poses and the uncertainties this phenomenon involves (Hua et al., 2022; Kodur & Banerji, 2021; Maluk et al., 2021; Saha et al., 2022; Serati et al., 2022). Spalling is an event where flakes and surface layers of concrete or shotcrete are violently and spontaneously ejected from the surface when exposed to high-temperature gradients, e.g., in the case of a tunnel fire. The damage due to spalling is often very severe and can readily turn into a catastrophic situation depending on the intensity of the fire. Spalling in the lining of tunnels can be stress-driven (e.g., due to the formation of unwanted tensile cracks in deep mines) or fire-induced (mainly due to excess vapour pressure generation). The key parameters in fire-induced concrete spalling are the applied heating rate, reinforcement, external loading, material parameters (cement, aggregate, moisture content, compressive strength etc.), and boundary conditions as well as geometric parameters such as size, shape, and concrete thickness (Kodur, 2014; Le et al., 2019; Malik et al., 2022; Saha et al., 2023; Serati et al., 2016; Serati et al., 2018).

To understand better the nature of spalling, full-scale furnace tests are carried out. Such tests are very costly and often not practical in most scenarios. An alternative method includes the use of a Heat-Transfer Rate Inducing System (or so-called H-TRIS test) by adopting radiant heat panels which are much more economical although limited in scale (Breunese et al., 2008; Maluk et al., 2019). Regardless of the test method, however, the process of fire-induced testing of concrete/shotcrete samples consists of batching concrete mixtures, curing samples, and preparing and conducting fire tests at different thermal and mechanical stresses. These procedures are very lengthy and often take up to 3 to 4 months to complete. The preparation of concrete mixes, experimental set-up, and testing must therefore be carried out with extreme care and according to standard recommendations to ensure accurate and valid results in a timely manner (EFNARC, 2006).

Temperature, vapour pressure, the extent of spalling, spalling depth and shape, and time to spall are typical parameters measured during a fire-induced spalling test (Choe et al., 2019; Kalifa et al., 2000; Le et al., 2018). To measure these parameters, thermocouples and thermistors, strain gauges and displacement sensors, pressure gauges, humidity sensors, and high-speed and infrared thermal cameras are commonly used. While the selection of sensor combinations in designing a fire test depends on the specific research or regulatory requirements as well as the characteristics of the material being tested, the correct placement and positioning of these sensors are also of critical importance to guarantee the quality of the data obtained. For instance, the position of temperature sensors (typically embedded at various depths within the material during batching) is crucial in accurately capturing the temperature profile of concrete during heating. The temperature profile can then provide valuable information on the thermal behaviour of the material and its susceptibility to spalling. If the temperature sensors are positioned incorrectly or inaccurately the data obtained may be unreliable, leading to incorrect conclusions about the material's behaviour. It should be noted that the location of spalling can vary significantly depending on the heat flux, type of concrete, curing conditions, structural design, section geometry, section size, the load-bearing capacity of the concrete element, location of heat, heating method, and orientation of the sample. While it is believed that spalling occurs primarily in the centre of a heated concrete sample (Felicetti et al., 2017; Li et al., 2021; Mindeguia et al., 2010), there are many published examples in the literature that prove otherwise. Access to a model that predicts spalling location based on the sample size, fire curve, and mixture design could be therefore of extreme benefit to optimizing the sensor arrangements and instrumentation costs in designing a fire-induced spalling test. This study aims to propose a model for the prediction of the spalling location by conducting a series of tests complemented by a comprehensive literature review.

2 EXPERIMENTAL PROGRAM

A total of 8 samples were cast and tested to investigate the location of spalling. Four of these samples were cured for 28 days and the other four left uncured, to also assess the effect of moisture content on spalling results. Details of the mixed portion and testing conditions are presented elsewhere by Emami. et al (2023). Samples were placed in front of the HTRIS unit with nine radiant sources of heat which are programmed to follow the Hydrocarbon fire curve (Figure 1). All samples have been spalled and the spalling parameters for each test are summarised in Table 1.

Table 1. Spalling parameters for the 8 tests conducted at UQ Civil laboratories. All tests were performed under the Hydrocarbon fire curve.

Sample ID	Time to Spall (min)	Heat Flux at Spalling (kW/m^2)	Surface temperature immediately after Spalling (°C)
H1	2.54	138.23	215
H2	2.21	135.18	205
H4	2.19	134.94	220
H5C	1.67	128.32	210
H6C	1.66	126.73	210
H7	2.29	136.03	235
H9C	1.76	129.42	220
H10C	2.56	138.38	210

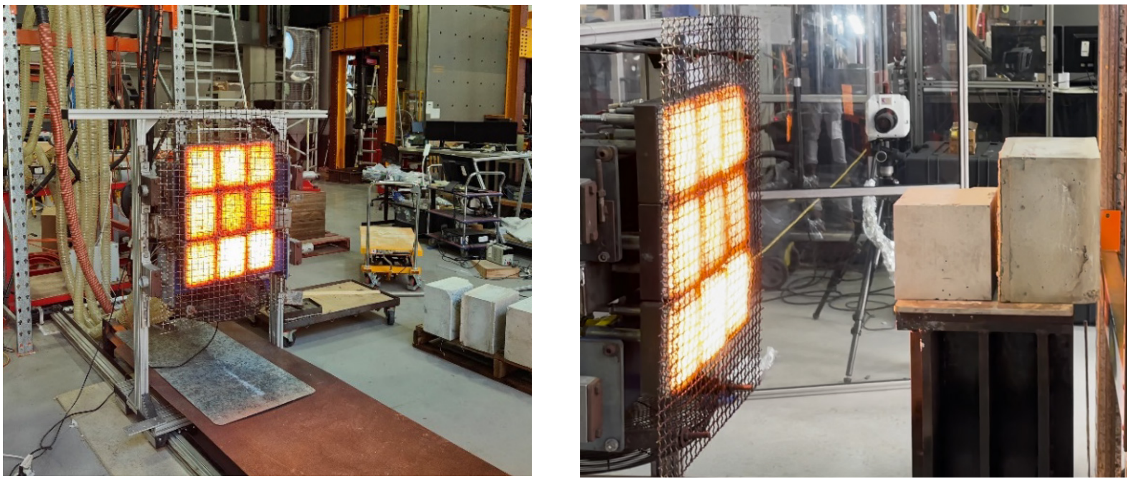


Figure 1. Experimental set-up using the Heat-Transfer Rate Inducing System (H-TRIS).

The temperature at the specimen's surface was recorded using a handheld thermometer immediately after spalling. To investigate the location of spalling, results from the eight experiments above together with 80 more test results from the literature were carefully collected and examined. The following pseudocode was then prepared in the R programming platform to generate a model for predicting the spalling location based on the collected datasets.

Table 2. Flow chart to calculate the probability of spalling in different locations.

Step 1: Data Preparation	Step 2: Data Analysis	Step 3: Descriptive and Inferential Statistics
Extracting spalling boundary points in different samples	Checking if points fall inside the 2D polygons	Preparing descriptive statics
Normalizing the boundary points based on the sample size	Counting points inside all polygons	Visualization data in 2D contour plots
Creating 2D polygons from boundary points	Locating the number of points in each grid for all polygons	
Creating a grid over polygons	Aggregating data into a single store data frame	
Generating points data frame using the center of the grid		

3 RESULTS AND DISCUSSIONS

The available 80 test results from the literature were collected and reviewed using the procedure described above to predict the probability of spalling at different locations on the sample surface. To confirm and extend the results of this analysis, as described above, eight samples both cured and uncured, were exposed in front of the HTRIS heat panel (see also Figure 1) under the hydrocarbon curve.

Figure 2 shows some of the events of concrete spalling observed in different experiments. It is clear that concrete spalling can take different forms of chipping, cracking, or large flaking due to various reasons such as concrete mix strength, fire curve, and moisture content.

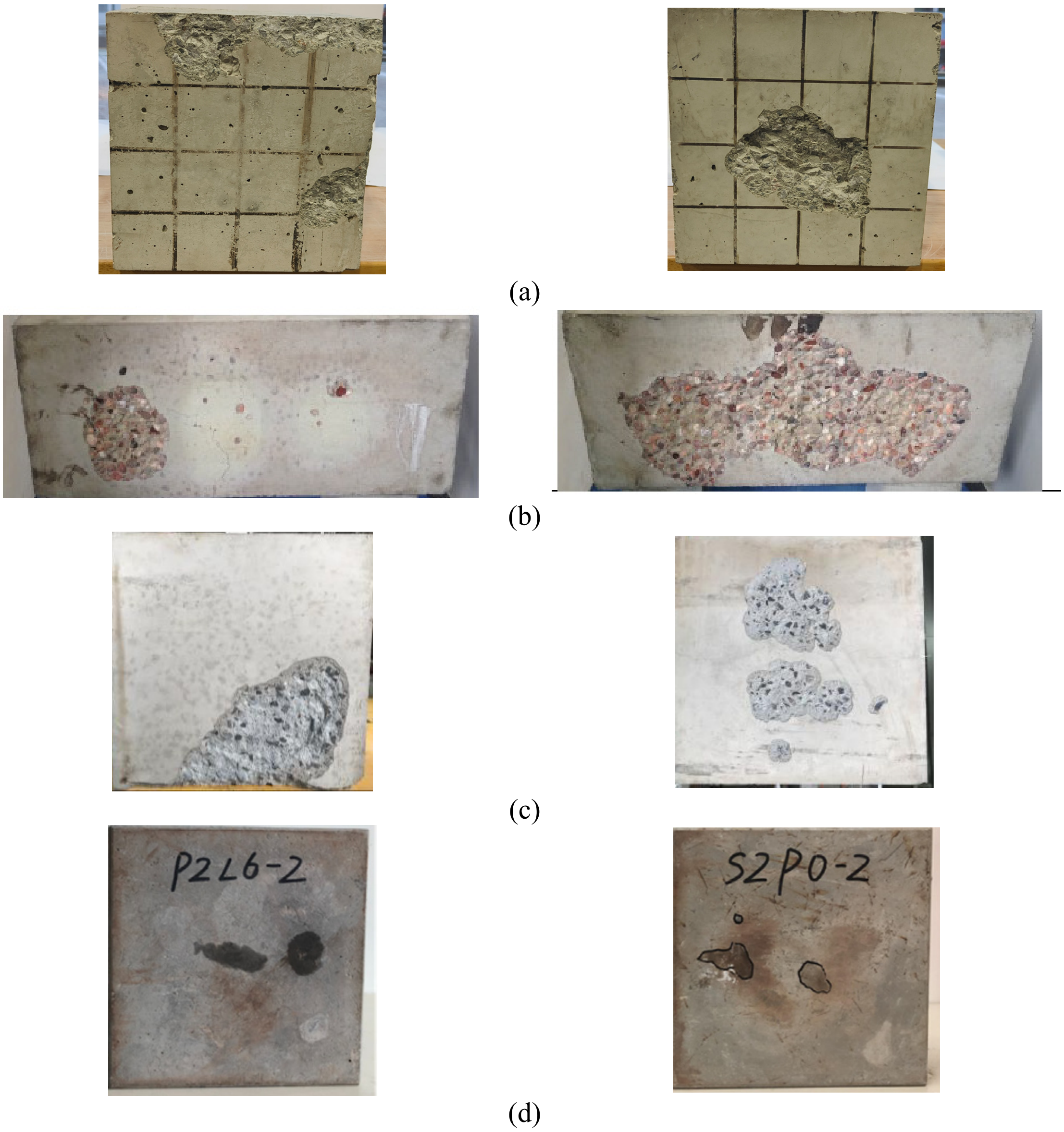
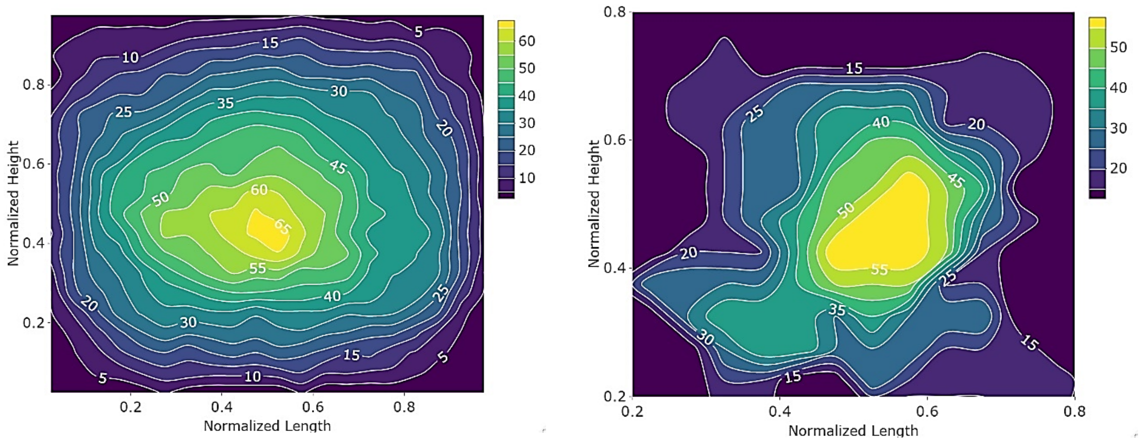


Figure 2. The occurrence of various forms (and sizes) of concrete spalling observed in (a) uncured and cured samples in this study during the hydrocarbon curve test conditions, (b) concrete samples with recycled steel and polymer fibres during the hydrocarbon curve test (Figueiredo et al., 2019), (c) concrete samples with micro polypropylene fibres during the "short-hot" fire curve test (Zhu et al., 2019), (D) hybrid steel and polypropylene fibre-reinforced concrete samples during the ISO 834 fire curve test (Shen et al., 2023).

Figure 2 illustrates that spalling can occur in various locations, which could be attributed to a range of factors including the intensity of heating or fire, the composition of the concrete, the conditions during curing, the design of the structure, the geometry and size of the section, the load-bearing capacity of the concrete element, the location and method of heat application, and the orientation of the sample. This can be seen more clearly by the proposed models' outcomes presented as 2D contour plots using the flowchart described in Table 2. These plots interestingly show that only about 60% of spalling events occur within the 0.4–0.6 range of the normalized sample size grid while in nearly 40% of the spalling tests, the location of spalled fragments was recorded outside the central zone (Figure 3). Consequently, while the centre of the sample is a common location for spalling, it is evident that predicting the spalling position at the centre alone may not be an accurate assessment.



(a) (b)

Figure 3. The probability of spalling at different locations from (a) the published results in the literature, and (b) test results from this study.

4 CONCLUSION

A fire-induced spalling test involves a sample of concrete or shotcrete structure exposed to controlled heating conditions, i.e., a target fire curve, to understand its behaviour under high-temperature gradients. The results of fire tests provide valuable information for designing resilient concrete structures against fire and are critical for ensuring the desired level of fire resistance and structural safety. It is, therefore, necessary to be able to predict where spalling could occur when designing a fire test to place instrumentation devices and sensors during the tests and to guarantee the quality of the data obtained. This study proposes a model that predicts the location of fire-induced spalling as a function of sample size based on the results from a series of spalling tests complemented by a comprehensive literature review. Further improvement of the model is recommended to account for the effect of the fire curve, mixture design, and applied loading conditions on the spalling location.

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