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Repair of fire-damaged RC slabs with basalt fabric-reinforced shotcrete

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HIGHLIGHTS

- An innovative basalt fabric-reinforced shotcrete system was proposed.
- This system was implemented for strengthening fire-damaged RC slabs for the first time.
- The strengthened RC slabs exhibited excellent cracking, stiffness and strength behavior.
- Engineering cementitious composites performed better than polymer modified mortar as the matrix of the fabric.

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ABSTRACT

In this paper, an innovative basalt fabric-reinforced shotcrete system is proposed for the flexural strengthening of fire-damaged RC slabs for the first time. An extensive experimental program was conducted to validate this new fabric-reinforced cementitious matrix system. Parameters investigated in the tests included the duration of heating for the fire-damaged RC slabs, the types of the cementitious matrix (strain-hardening engineered cementitious composites (ECC) versus polymer-modified mortar (PMM)) and the layers of basalt fabrics that are used for the strengthening systems. A total of nine one-way slabs were constructed and tested in this paper. One slab served as the control specimen and was tested at ambient temperature, while the other eight slabs were initially exposed to the furnace fire following the ISO 834 standard temperature-time curve. After fire exposure, five slabs were strengthened using two or three layers of the strengthening systems. Test results indicated that the flexural capacity of the fire-damaged RC slabs strengthened with the basalt fabric-reinforced shotcrete systems was increased by 68.9–193.4% compared to their un-strengthened fire-damaged counterparts. The use of ECC as a cementitious matrix was found to be an attractive solution as the slabs strengthened using ECC achieved better results in terms of the cracking control and ultimate load, ductility performance as well as energy dissipation capacity.

1. Introduction

Fire is one of the most severe hazards which reinforced concrete (RC) buildings may be encountered during their service lives. Exposure of an RC structure to high temperatures during a fire leads to material property degradations and concrete cracking (possibly spalling), potentially resulting in significant losses in load-bearing and deformation capacities of the associated structural members. However, survey data of real fire events have indicated that the disastrous collapse of RC structures rarely occurs in fire or during the cooling stage after fire [1,2]. Demolishing the entire RC structure after fire exposure is not an advisable choice as the new reconstruction would be exorbitantly expensive. Therefore, most of the fire-damaged RC members need proper restorations to satisfy their structural requirements by efficient repair and strengthening solutions [3,4].

The most traditional techniques applied for the strengthening of fire-damaged RC members include the cross-sectional enlargement using concrete or mortar overlays and external bonding or bolting with steel plates (e.g., [5–8]). For the sectional enlargement strengthening technique, a new layer of reinforcing steel is usually needed to offset the mechanical property degradations of the

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original materials after fire exposure. Meanwhile, enough thick concrete or mortar cover is necessary to protect the new steel reinforcement against the electrochemical corrosion, resulting in a significant increase in deadweight to the RC structure and its supports. For the strengthening technique using steel plates, it also adds extra dead load to the structure and needs corrosion protection.

Recent years have seen a viable strengthening solution for fire-damaged RC members by replacing steel plates with fiber-reinforced polymer (FRP) composites (e.g., [4,9–12]). The primary advantages of FRP composites comprise the high strength-to-weight ratio, excellent corrosion resistance, ease and rapid installation, and the minimal change in dimensions of the strengthened member. The strengthening FRP system also has a few drawbacks, including the low vapor permeability [13], low glass transition temperature [14], poor performance in fire and high temperatures [15,16] and the inability to apply on wet surfaces [17,18]. Also, the thermal incompatibility of FRP and concrete may produce substantial thermal stresses at the bond interface when the strengthened member suffers from significant environmental temperature changes, resulting in the acceleration of the interfacial debonding failure [19,20]. The drawbacks as mentioned earlier are mainly attributable to the epoxy resins used for bonding FRP composites. In an attempt to remedy such drawbacks, a new strengthening technique for deficient concrete and masonry structures has recently been introduced that uses textile-reinforced mortar (TRM) systems or fabric-reinforced cementitious matrix (FRCM) systems by replacing the epoxy bonding adhesives with inorganic cement-based matrices [21,22]. Unlike the epoxy resins, the cement-based matrices are compatible with the original concrete substrate, allow vapor permeability, and have superior resistance to fire and high temperatures (at least they are not flammable in a fire). It should be noted that the textile reinforcement used in TRM systems usually consists of open-weave fiber fabrics (i.e., pre-impregnated with resin) whereas non-woven fiber rovings are typically applied for FRCM systems [23].

The TRM and FRCM systems have been successfully applied for repairing and strengthening of deficient concrete structures in existing research studies. In particular, they are used for the strength and ductility enhancements of RC columns [18,24], flexural and shear strengthening of RC beams [25–28], flexural strengthening of RC slabs [29], and the seismic strengthening of RC members and joints [30]. However, the majority of the cited work efforts involved the applications of the strengthening systems by hand troweling, and thus the repair procedure was time-consuming as the scaffolding works might be required in practice. An innovative installation method, such as spraying the cementitious matrix using a shotcrete machine, is therefore needed to reduce the construction time for repair. Also, to the best of the authors' knowledge, no research has yet been reported on the use of FRCM systems to strengthen fire-damaged RC members. Based on the existing research studies on strengthened RC as mentioned earlier, FRCM is an attractive candidate for the rehabilitation and strengthening of fire-damaged RC members.

The experimental study presented in this paper is a part of a comprehensive research project, actually in progress, aimed at exploiting an innovative FRCM composite for the flexural strengthening of fire-damaged RC members. Within this context, a new type of fabrics consisting of basalt fibers is applied as the reinforcement of this FRCM system. The main reason for selecting the basalt fibers is that they possess good resistance to alkaline and other aggressive environments [31], combined with superior resistance to humidity [32,33]; these two characteristics are necessary for the durability design of the FRCM system. Besides, the basalt fibers have the higher tensile strength and elastic modulus than those of the glass fibers and are much cheaper than carbon fibers, and they are therefore considered as promising alternatives to conventional fibers (e.g., carbon and glass fibers) for future strengthening applications of deficient RC members [34]. In this project, polymer-modified mortar (PMM) and engineered cementitious composite (ECC) are employed as the cementitious matrices of the FRCM composites to investigate their impacts on the strengthening efficiency of fire-damaged RC members. The PMM or ECC matrix is sprayed on the surface of the fire-damaged RC member to develop a basalt fabric-reinforced shotcrete (BFRS) strengthening system, which reduces the labor of forming and stripping and enables a rapid strengthening process. Furthermore, the BFRS strengthening system is inherently noncombustible and can be applied without fire protection, which may reduce the material and installation costs with an enhanced architectural aesthetics when compared to the FRP strengthening system protected with a fire-insulation layer in indoor applications (e.g., in buildings) [35–37].

The present experimental study consists of a total of nine one-way RC slabs tested under four-point bending up to failure. One slab serves as the control specimen and is tested at room temperature without any fire damage, whereas the other slabs are initially exposed to the furnace fire according to ISO 834 standard temperature-time curve. Amongst the fire-damaged slabs, two specimens are tested without any strengthening procedure while the other six ones are designed to be strengthened with the BFRS systems before the flexural bending tests. The test variables of this study comprise: (a) the type of cementitious matrix (PMM versus ECC), (b) the number of fabric layers (two or three layers of basalt fabrics), and (c) the level of heat-induced damage after 60-min or 90-min fire exposure. During the bending tests, the displacement fields and crack patterns of BFRS-strengthened fire-damaged slabs are also monitored by a digital image correlation (DIC) system. The experimental results in terms of the temperature profiles over the slab depth during the fire tests (except the control specimen), and the failure modes, load-deflection curves, ductility performance, and the strain measurements during the flexural bending tests, are examined and compared. The experimental study aims at filling the research gap as mentioned earlier and providing insights into the flexural performance of fire-damaged RC slabs strengthened with FRCM systems. It represents the first research work and provides unique experimental data on the use of FRCM as an innovative solution for repair of fire-damaged RC slabs.

2. Experimental program

2.1. Details of test specimens

A total of nine one-way RC slabs were constructed and tested in this paper. Of these slabs, one slab served as a control specimen tested at ambient temperature, whereas the remaining eight slabs, divided into two main series (Series I and Series II), were subjected to ISO 834 standard fire with heating periods of 60 min and 90 min, respectively. The two heating periods were selected as they represented the moderate and relatively high fire-resistance ratings specified by current design guidelines [38,39]. Five of the fire-damaged slabs were strengthened with different BFRS strengthening systems. Table 1 illustrates the terminology used for the slab specimens and the test variables considered in this experimental program.

The geometrical dimensions and the steel reinforcement are all the same for the tested specimens. Each slab had a total length of 3600 mm and a rectangular cross-section of 100 mm thickness × 1000 mm width (Fig. 1). Such dimensions were chosen based on the sizes of the floor furnace in the State Key Laboratory of Tongji University, which has a chamber of 4500 mm long and a 3000 mm width that can test four slabs simultaneously (see Fig. 2 for more details). Each slab was reinforced with a single layer of steel mesh at the bottom, and the detailed positions of the longitudinal and transverse steel bars are illustrated in Fig. 1. The longitudinal reinforcement consisted of six HRB 335 steel bars with a nominal diameter of 10 mm spaced at 190 mm along the span direction, while HPB 300 steel bars with a nominal diameter of 8 mm spaced at 200 mm were used as the transverse reinforcement. The clear concrete cover to the longitudinal steel rebars was set at 15 mm.

Before the concrete casting, each slab was instrumented with Type-K chromel-alumel thermocouples (with a diameter of 2 mm) to measure the temperature distributions over the slab thickness. After finishing the concrete casting, all specimens