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Effect of combined pre-cracking and corrosion on the method of repair of concrete beams

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HIGHLIGHTS

- Effects of combined pre-cracking and corrosion on repair methods were studied.
- Two different methods were used to repair the damaged concrete beams.
- The properties of the repaired concretes were based on those of the strengthen system.
- The method of repair influenced considerably the results of the reinforced beams.
- Combining pre-cracking and corrosion influences the properties of the repaired beams.

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ABSTRACT

This study investigated the combined effect of pre-cracking and corrosion on repair methods of reinforced concrete beams. The experimental program consisted of prismatic pre-cracked reinforced concrete beam specimens, exposed to accelerated corrosion. The corrosion rate varied from 5% to 15% and the pre-cracking was achieved by preloading the beams up to 60% of their ultimate loads. Two different methods were used to repair the specimens. Carbon Fiber Reinforced Polymers plates (CFRP) were used to strengthen the bottom portion of the specimens in the first method, and sheets containing carbon fibers were added to the bottom portion, left and right sides of the specimens, in the second method. The test results revealed that, the harmful effect of combined corrosion and pre-cracking was notable especially at 15% corrosion rate. The two methods of repair used can be considered as convenient. The ultimate strengths of the repaired beams were equivalent or significantly higher than those of the control specimens, although reduced deflection capacities were registered after repair.

1. Introduction

The corrosion of steel reinforcements can be considered as the primary cause of damage and early failure in concrete structures. Indeed, it results in significant technical and financial problems in terms of maintenance and/or rehabilitation applications and re-construction or replacement of existing structures. For instance, it is estimated that it costs around 1.8 trillion US$ to repair corroded structures around the world annually [1].

In normal conditions, the reinforcement steel is protected from corrosion because of the high alkalinity of concrete. When carbonation occurs, or when the concentration of chloride ions near the steel reinforcement increases, the alkalinity of concrete is reduced. As a result, the passive layer that protects the steel reinforcement from corrosion gets destroyed [2]. Therefore, the embedded steel reinforcement corrodes, which leads to the reduction in the cross-sectional area of the reinforcing steel [3], cracking, delamination and spalling of the concrete cover [4], and thus deteriorating the bond at steel-concrete interface [5,6].

The repair and rehabilitation of reinforced concrete structures is only successful if the new material interact efficiently with the old concrete and form a durable barrier against the ingress of carbon dioxide and chlorides. A variety of methods have been developed to repair the corrosion damage of reinforced concrete (RC) beams, and strengthen them using plates and steel sheets, or by projecting the damaged area with concrete containing fibers [7]. However, there are many disadvantages to these methods, including the durability of the projected concrete as well as the heavy weight and corrosion of the steel plates. In order to overcome these disadvantages, fiber reinforced polymers (FRP) have been used in recent years to repair or strengthen the RC elements [8–11]. Among the

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common FRP techniques used to strengthen/repair the damaged RC beams, externally bonded reinforcement (EBR) and near-surface mounted (NSM) have gained great interest and use [12–15]. The EBR system involves the use of FRP sheets bonded in the external part of the element with an epoxy resin. While, in the NSM technique, FRP laminates are inserted into precut grooves in the concrete cover of the beams. Although, the use of FRP techniques has been investigated by several researchers, and proved to be of high level of strengthening efficacy [16,17], it's important to note that the damage in the RC elements used in these studies was limited to corrosion or pre-cracking.

Recently, limited studies have been completed about the effect of the combination of two simultaneous factors on the repair method of concrete beams. Wu (2010) [18], experimentally and theoretically investigated the combined effect of pre-cracking and cyclic loading on reinforced concrete short beams. The results revealed that the influence of repair under combined pre-cracking and cyclic loading was insignificant. The effects of coupled corrosion and progressive loading on the FRP repair of reinforced concrete beams, were considered by Ali (2012) [19], through Monte-Carlo simulation technique, which is based on Neural Networks and finite element method. The results of this study clearly showed that the coupling of two variables has a particular significance, which requires an extensive attention. In addition, regarding the real field observations, that usually showed two or more internal or external combined actions, the study of simultaneous degradation factors on the mechanical and durability properties of concrete beams repair can be considered as more accurate than that of dealing with a single factor.

Cracks in RC elements may be expected, even under normal service conditions that include tensile strength of concrete, humidity, temperature, shrinkage, and creep effects [20]. In addition, concrete cracking can be subject to development during the entire service life of RC members due to the extreme exposure environments caused by either the overloading or the ingression of chemical gases and liquids [21]. Although, cracks in RC elements do not certainly cause the failure of concrete structures, the presence of cracking can cause an excessive carbonation and chlorides ingress, which aggravates and accelerates the corrosion and the damage of concrete cover. When the cracking of the concrete cover occurs due to steel corrosion, the repair of RC members is essential to maintain or restore the serviceability of structure [22,23]. Despite the importance of studying the repair of RC elements subjected to the combined effects of cracking and corrosion, no investigation into this subject has so far been carried out. Hence, this study investigated the effect of combined pre-cracking and corrosion on the method of repair of RC beams. In order to examine the effect of these simultaneous factors on the structural behavior of pre-cracked RC beams, corrosion rates varying from 5% to 15% were used. These corrosion percentages represent the loss in the cross-sectional area of the steel reinforcement on the tension side. Two methods were used to repair the damaged reinforced concrete corroded beams. For the first method, Carbon Fiber Reinforced Polymers (CFRP) were used to strengthen the bottom portion of the specimens. And for the second method, sheets containing carbon fibers were added to the bottom portion, left and right sides of the specimens.

2. Materials and methods

2.1. Specimens details

A total of 15 RC beams were tested in this study as summarized in Table 1. The test beams were categorized into four series, according to the corrosion rate (0%, 5%, 10% and 15%). The specimens were 960 mm long, 150 mm wide, and 150 mm high, as illustrated in Fig. 1. All of the beams were reinforced with four 10 mm bottom bars (tensile reinforcement), two 10 mm top bars (compression), and 6 mm stirrups spaced at 100 mm. The concrete cover was 20 mm. Each bottom steel reinforcement was fitted with an electric connection in order to facilitate the corrosion process, as illustrated in Fig. 1.

Table 1
Experimental parameters of tested beams.

Beam	Pre-cracking	Corrosion %	Mode of repair
PC0T1	No	0	No
PC0T2	No	0	No
PC0T3	No	0	No
PC5	No	5	No
PC5P	Yes	5	No
PC5P-M1	Yes	5	M1
PC5P-M2	Yes	5	M2
PC10	No	10	No
PC10P	Yes	10	No
PC10P-M1	Yes	10	M1
PC10P-M2	Yes	10	M2
PC15	No	15	No
PC15P	Yes	15	No
PC15P-M1	Yes	15	M1
PC15P-M2	Yes	15	M2

Beams PC0T (0%) were control beams with no corrosion or pre-cracking, while beams PC5, PC10, and PC15 were corroded at a 5%, 10%, and 15% corrosion rate, respectively, with no pre-cracking. Beams PC5P, PC10P, and PC15P were pre-cracked to 60% of the ultimate load of the control beams at a 5%, 10%, and 15% corrosion rate, respectively. Beams PC5P-M1, PC10P-M1, and PC15P-M1 were pre-cracked and corroded at a 5%, 10%, and 15% corrosion rate respectively, then repaired by external bonding of CFRP sheets to the bottom of the beams. Beams PC5P-M2, PC10P-M2, and PC15P-M2 were pre-cracked and corroded at 5%, 10%, and 15% corrosion rates respectively, then repaired by external bonding of CFRP sheets to the bottom part, and carbon fibers tissue sheets in the bottom, left and right sides of the beams.

2.2. Material properties

The concrete mixture used in this study was composed of water to cement (W/C) ratio of 0.63, according to the Dreux Gorisse method [24], in order to get slump of 7 cm and 28-day compressive strength around 40 MPa. Ordinary Portland cement complying with ASTM C150 Type I cement [25] was used as part of the cementitious materials. Its principal properties provided by the manufacturer indicated: C_3S and C_3A contents of 60% and 7.5% respectively, specific gravity of 3.13, Blaine fineness of 380 m^2/kg and 28-day compressive strength of 42.5 MPa. Siliceous round sand and crushed silico-calcareous rocks with maximum grain sizes of 3 mm and 12.5 mm were used as fine and coarse aggregate in the production of the concrete. The yield strength of the reinforce-

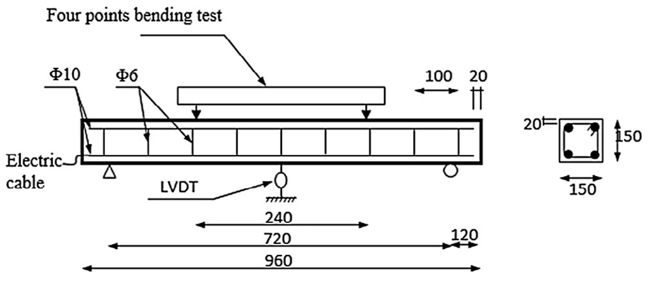

Fig. 1. Geometry of beams specimens.