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Experimental study on rehabilitation of corrosion-damaged reinforced concrete beams with carbon fiber reinforced polymer

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HIGHLIGHTS

- ▶ A modified retrofit method is developed for the corrosion-damaged RC beams.
- ▶ This method provides better load carrying capacity for the corroded beams.
- ▶ Optimizing CFRP amount to balance strength recovery with control of failure mode.

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ABSTRACT

The repair and rehabilitation of reinforced concrete (RC) structures in coastal areas is a challenging engineering problem. In order to retrofit the degraded RC structures, numerous studies have been devoted to the method of non-corroded RC components retrofitted with carbon fiber reinforced polymer (CFRP). There is, however, less research available on corroded, patched and CFRP-repaired RC specimens. The purpose of this paper is to investigate rehabilitation of corrosion-damaged RC beams with CFRP, which focus on the effectiveness of CFRP-repaired methods and the effects of CFRP amount on flexural behavior of the beams. In this study, a modified retrofit method based on substrate repairs was developed, which is bonding CFRP after replacing V-notch of substrate concrete with polymer mortar. To compare the modified method with two common retrofit methods, which are respectively bonding directly CFRP and bonding CFRP after replacing damaged concrete, four-point bending experiments were conducted on a series of corrosion-damaged RC beams with CFRP. Important factors were considered in the experimental study, including the number of CFRP layers and corrosion level denoted by the mass loss rate of tensile steel. There were totally 32 RC beams (250 mm × 150 mm × 1400 mm) constructed in these experiments, 27 of which were corroded by an accelerated aging approach. The results show that the modified retrofit method could provide better load carrying capacity for the beams having more than 15% mass loss of tensile steel. In addition, to improve the short-term performance, the simple method of directly bonding CFRP was suitable for the beams having less than 15% mass loss of tensile steel. It is noted that bonded CFRP could not work for the damaged beams which undertaken more than 50% mass loss of tensile steel. In particular, it is indicated that by optimizing the amount of CFRP, it is possible to balance strength recovery with control of failure mode.

1. Introduction

Concrete highway bridges in coastal areas are continuously exposed to chloride corrosion and dry-wet cyclic attack, which lead to degradation of the concrete and the reinforcing steel. Corrosion of reinforcing steel leads to a reduction in the cross-sectional area, and produces corrosion products with higher volume than the original steel resulting in cracking of the concrete surrounding the bars. These deleterious environmental factors interacted with loads would aggravate the deterioration processes, leading to the reduction of the load carrying capacity and the safety of the structure. Nowadays, reinforced concrete (RC) structures deterioration has motivated the development of new and innovative materials and methods for structural rehabilitation, as replacement of structures would be very costly and nearly prohibitive.

Traditionally, corroded RC structures such as bridges and marine structures have been repaired with steel plates. However, steel

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plates are prone to corrosion, and special equipments are needed to install these heavy plates. In recent years, carbon fiber reinforced polymer (CFRP) materials in the form of fabrics and laminates have been motivated to use for retrofitting these corrosion-damaged RC components. CFRP materials are lightweight, noncorrosive, and exhibit high tensile strength [1]. Additionally, they can be easily bonded to the concrete surface on-site, without the use of extensive scaffolding and jacks, requiring minimum amount of support equipment [2]. CFRP systems can also be used in areas with limited access where traditional techniques would be difficult to implement. Therefore, CFRP-repair technique not only increases the ease of the retrofitting, but also is more cost-efficient.

The advantages of retrofit technology of using CFRP externally bonded on concrete attracted the attentions of numerous researchers. Some researches have been conducted on the durability of CFRP-repaired concrete beams. In these studies, some researchers used natural corrosion methods to account for deteriorate material properties, either obtained directly from the field [3] or conditioned in the laboratory [1,4,5]. Although natural corrosion methods could closely simulate field conditions, they require a long time to achieve the desired corrosion level. To accelerate the aging process, others researchers used the application of induced electrical current [2,6–15]. By using the accelerated corrosion methods, Wang et al. [2], Bonacci and Maalej [7], Masoud and Soudki [10] experimentally studied the short-term performance of corrosion-damaged RC beams retrofitted with CFRP, Masoud and Soudki [11], Al-Hammoud et al. [13] investigated the fatigue behavior of corroded RC beams with CFRP, and Al-Hammoud et al. [14] focused on the durability of CFRP-concrete interface. However, these researchers did not investigate the effects of concrete patching before bonding CFRP. In fact, substrate repairs are often carried out on corroded RC structures to replace the damaged concrete and to restore the bond between steel and concrete. During a substrate repair, some measures such as application of corrosion inhibitors, cathodic protection and chloride extraction could be undertaken to prevent further steel corrosion [6,15].

Although numerous studies have been devoted to the performance of non-corroded RC specimens retrofitted with CFRP, not much information is available on corroded and CFRP-repaired flexural RC components, especially on the effects of combining substrate repair and CFRP repair. To get better understanding of the performance of corroded RC structures with CFRP, an extensive experimental program was conducted by the authors to evaluate the post-repair structural behavior of corrosion-damaged beams repaired with three retrofit methods. In this study, a modified retrofit method was developed based on substrate repairs, which is bonding CFRP after replacing V-notch of substrate concrete with polymer mortar. To compare the modified method with two common retrofit methods, which are respectively bonding directly CFRP and bonding CFRP after replacing damaged concrete, four-point bending experiments were conducted on a series of corrosion-damaged RC beams with CFRP. Additionally, important factors were considered in the experimental study, including the number of CFRP layers and corrosion level which was denoted by the mass loss rate of tensile steel. The focus in this paper is on the effectiveness of CFRP-repaired methods and the effects of CFRP amount on flexural behavior of corroded RC beams.

2. Experimental program

2.1. Material properties

There were totally 32 RC beams (250 mm × 150 mm × 1400 mm) constructed in this study. The typical geometry and reinforcement of the beams are shown in Fig. 1. The specimens were fabricated from ordinary Portland cement. The cube compressive strength and elastic modulus of concrete were 33.3 MPa and 30 GPa, respectively. The internal reinforcement was made of smooth bars, and the main tensile steel exhibited a yield strength of 310 MPa and an elastic modulus of 206 GPa. The elastic modulus of CFRP sheets was 205 MPa, with an ultimate tensile strength of 3500 MPa, and one layer of CFRP sheets had a nominal thickness of 0.11 mm.

2.2. Accelerated corrosion

Since the objective of this research is to evaluate the effectiveness of applying CFRP to retrofit corrosion-damaged RC beams, 27 RC beams were firstly corroded by an accelerated corrosion system, and 5 specimens were un-corroded as the control beams. In this corrosion system, the bottom surface of beam was coated with a copper mesh, and then the beams were respectively connected by copper mesh to the cathode and by steel bar to the anode of the DC power supply, as shown in Fig. 2. In order to accelerate the corrosion process, the beams were placed in a corrosion pool which contained industrial salt solution of 3% concentration, and then subjected to wet-dry cycles (1 day wet and 2 days dry).

To evaluate the corrosion level, the mass loss rate of tensile steel was regarded as corrosion rate, which can be easily calculated based on the assumption that the corrosion state is uniformly distributed within the steel material. In order to achieve the desired mass loss of tensile steel, the corrosion time was estimated using Faraday's law, which is expressed by the following equation:

$$m = \frac{atI}{nF} \tag{1}$$

where m = mass loss; I = corrosion current; t = time of the corrosion process; a = atomic mass of iron (55.85 g); n = valence of the reacting electrode for the material ($n_{\text{steel}} = 2$); F = Faraday's constant (96500 C/mol).

Additionally, the maximum width of corrosion cracks as another index of the corrosion level was measured by crack width detector. In this study, according to the mass loss rate of tensile steel r and corrosion crack width w, the test beams were divided into five groups as listed below:

(1) Group A, in which the beams had no corrosion damages.
(2) Group B ($0 < r \leqslant 5\%$ and $0 < w \leqslant 0.3$ mm).
(3) Group C ($5 < r \leqslant 15\%$ and $0.3\text{ mm} < w \leqslant 1.0$ mm).
(4) Group D ($15 < r \leqslant 50\%$ and $1.0\text{ mm} < w \leqslant 3.0$ mm).
(5) Group E ($50\% < r$ and $3.0\text{ mm} < w$).

2.3. Retrofit methods

Traditionally, there are two common CFRP-retrofit methods for the corrosion-damaged RC members, which are directly bonding CFRP (retrofit method 1) and bonding CFRP after replacing corrosion-damaged concrete with polymer mortar (retrofit method 2), respectively. Comparing with method 2, retrofit method 1 is easier to handle, but does not prevent further steel corrosion. On the other hand, though retrofit method 2 could protect steel, it does not only increase the difficulty of retrofitting, but also is more costly. In addition, the interface between old concrete and new mortar is prone to crack. Thus, retrofit method 2 is usually just used for the beams undertaken high corrosion level. To overcome the main shortcomings of the above two methods, as described below, a modified retrofit method based on substrate repairs was developed in this study.

Retrofit method 1 – Directly bonding CFRP (Fig. 3). For retrofit method 1, none of the old deteriorated concrete was removed prior to CFRP repair, CFRP were directly bonded on the tensile surface of the corrosion-damaged beams. During the retrofit

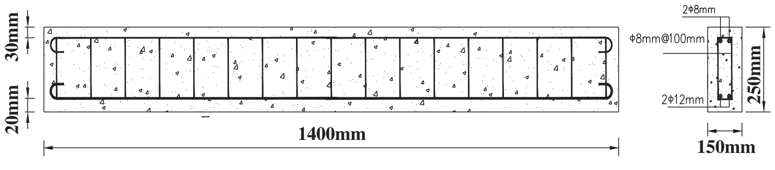

Fig. 1. Concrete beam-geometry and reinforcement details.