Composites Part B 133 (2018) 101–111

Contents lists available at ScienceDirect

Composites Part B

journal homepage: www.elsevier.com/locate/compositesb

Effect of patch repair and strengthening with EBR and NSM CFRP laminates for RC beams with low, medium and heavy corrosion

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ARTICLE INFO

Article history:
Received 15 July 2017
Received in revised form
14 September 2017
Accepted 15 September 2017
Available online 18 September 2017

Keywords:
Corrosion
Polymer-matrix composites (PMCs)
Laminates
Mechanical testing
Patch repair

ABSTRACT

The experimental results on the effectiveness of patch repair and FRP bonded laminates to retrofit reinforced concrete beams with corrosion damage are discussed in this paper. The uncovering of the damaged concrete cover provides a more accurate assessment of the corrosion degree, as the actual mass loss of reinforcement can be better calibrated. The mass loss of the tensile reinforcement varied at approximately 7.5%–24%. The necessity of the removal of the cracked concrete substrate, treatment of corroded reinforcement and repair by patching with a polymer modified mortar is highlighted. Two different strengthening techniques are implemented, of externally bonded EBR or NSM Carbon FRP laminates, having equivalent axial rigidity. CFRP wraps were also applied for shear strengthening to replace corroded stirrups. The load-deflection curves showed that the effect of corrosion on load bearing capacity and bond between the concrete and steel was detrimental for high mass losses. A satisfactory force transfer through the old and patch repaired concrete and through repair mortar and CFRP reinforcement interface was noted. The shear strengthening not only prevented the debonding of the EB laminate at the end but also improved the bond performance between the laminate and concrete, especially for the high corroded beam.

1. Introduction

The main issue associated with the deterioration of reinforced concrete (RC) structures due to corrosion of steel reinforcement is the reduction of the cross-sectional area and the mechanical properties of steel bars [1]. Furthermore, the corrosion products occupy much larger volume according to the composite hydrate rust than the original rebar and generate larger radial stress on the surrounding concrete at the interface between the rebar and the concrete which leads to cracking and spalling of the concrete cover [2]. The composite action between the steel and concrete is also lessened because of the deterioration of the bond at the steel-concrete interface caused by cracking of the concrete. Considerable research has been conducted on the flexural capacity and the bond strength of beams affected by corrosion [3–5]. For most existing structures, repair and strengthening of insufficient reinforced concrete members are of imperative need. Fiber Reinforced Polymers (FRP) have been successfully used in recent years in retrofitting and improving the structural performance of RC members ([6–18] among else).

In corroded RC beams, the majority of the studies involve strengthening with externally bonded reinforcement (EBR), where FRP sheets or laminates are bonded in the external tensile bottom with an epoxy resin, but often excluding the patch repair process of the damaged concrete substrate. The transverse laminate adequately confined corrosion cracking up to 6% corrosion, but extensive cracking and CFRP laminate delamination occurred beyond this level [19]. Confining corroded RC beams with CFRP-U wraps reduced the corrosion expansion as well as the corrosion mass loss [20]. In terms of the load-bearing capacity, El Maaddawy and Soudki [21] and Al-Saidy et al. [22] have shown that FRP strengthening of RC structures damaged by corrosion without replacing the cracked concrete cover is still able to improve the load capacity at all levels of corrosion damage, but reduces the deflection capacity. Al-Saidy et al. [22] also used transverse CFRP wraps anchoring the flexural CFRP, which were more effective in beams with higher corrosion rate. On the other hand, Ray et al. [23] tried to assess efficient concrete substrate repair methods for deteriorated concrete beams, strengthened with flexural CFRP sheets and then subjected to second corrosion cycle. Repair with polymer modified

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http://dx.doi.org/10.1016/j.compositesb.2017.09.029
1359-8368/

concrete resulted in better load capacity and ductile failure, enhancing the long-term durability performance. Davalos et al. [24] mentioned that more anchorage with FRP systems could be beneficial for long term durability, as the concrete substrate and FRP-concrete bond will deteriorate over time. Xie and Hu [25] developed three different retrofit methods and found better load carrying capacity and flexural stiffness for corroded beams with more than 15% mass loss of tensile steel after replacing V-notch of substrate concrete with polymer mortar. Al-Saidy and Al-Jabri [26] also removed the damaged concrete and cleaned the rusted bars. The test outcomes indicated that the patch repaired beams when coupled with FRP sheets could produce 13% higher loads compared to the corresponding beams without patch repair.

Near Surface Mounted (NSM) strengthening technique offers an advanced level of strengthening that is less prone to premature failure, more effective against fire, reveals better durability and stress sharing mechanisms and can strongly exploit the tensile strength of the FRP material [27,28]. Notwithstanding, the efficiency of EBR or NSM strengthening depends on the bond behavior, which is influenced by the concrete surface roughness, the dimensions of grooves, the mechanical properties of FRP and the type of adhesive material. Not enough research has been conducted on repairing and strengthening with NSM systems RC beams with corroded steel reinforcement. Kreit et al. [29] and Almassri et al. [30,31] applied a CFRP NSM rod directly on the cracked tensile face of naturally corroded RC beams. Despite the fact that the reinforcement was heavily corroded, the bearing capacity of the strengthened beam was similar to that of the uncorroded one. However, the failure mode was separation of the concrete cover due to corrosion induced cracks, as no patch repairing of the damaged substrate preceded.

Further research is necessary to assess the efficiency of patch repair and FRPs in retrofitting corroded RC structures. This paper reports the experimental results from the evaluation of the effectiveness of patch repair and of two different strengthening methods on corroded RC beams at three different levels of corrosion damage (low, medium, high). It follows the experimental procedure of beams at low level of corrosion exposure that referred to a characteristic limit state based on the serviceability requirements (SLS) for crack width (see Triantafyllou et al. [32]). After repairing the damaged substrate and treating the corroded reinforcement, carbon FRP laminates using EBR and NSM methods were provided as flexural strengthening. The longitudinal cracks induced by corrosion, the load bearing capacity and the developed strains of CFRP were assessed. It should be noted that the presented experiments involve 3 bottom longitudinal bars that are closer to real applications and lead to extensive cracking of the whole bottom concrete cover region.

2. Experimental procedure

2.1. Test specimens

The experiments included testing of 10 RC beams in the Reinforced Concrete Laboratory of D.U.Th. One beam named RC-N was neither corroded nor repaired to act as a reference, while the remaining nine beams were subjected under the same conditions of an accelerated corrosion process for different periods of times. Beams RC-COR1, RC-COR2 and RC-COR3 were the control specimens that were subjected to three different corrosion levels. The number describes the level of corrosion which corresponds to low (-COR1), medium (-COR2) and high (-COR3) level. Beams RC-COR1S1, RC-COR2S1 and RC-COR3S1 were corroded to three levels and then repaired and strengthened with EBR carbon FRP materials (attributed to S1), while beams RC-COR1S2, RC-COR2S2 and RC-COR3S2 with NSM (attributed to S2) carbon FRP systems. The specimens' description is summarized in Table 1.

All specimens had a rectangular cross section of 150 mm width and 300 mm depth, a length of 2300 mm and an effective span of 2100 mm. The longitudinal steel reinforcement consisted of three ribbed bars of 12 mm diameter in tension and two ribbed bars of 10 mm diameter in compression. To prevent shear failure of the beams, ribbed stirrups of 8 mm diameter were used and were spaced at 150 mm (with 50 mm spacing at the support), having a clear concrete cover of 20 mm on all sides of the beams. The typical geometry of the beams, the reinforcement schemes and the test set-up are shown in Fig. 1.

2.2. Materials

The 28-day average compressive strength of concrete and the average modulus of elasticity obtained according to the standard on three cylindrical specimens (150 mm diameter and 300 mm height) were 34.6 MPa and 32300 MPa respectively. The average tensile strength from splitting tests was 2.2 MPa. The nominal yield strength of steel reinforcement was 500 MPa. The average yield and ultimate tensile strength of 5 non-corroded steel coupons of 12 mm diameter measured equal to 552 MPa and 653 MPa respectively, while the minimum ultimate strain measured around 0.1.

Before replacing the damaged concrete of corroded beams with polymer mortar, the cracked substrate was removed and the corroded steel reinforcement was healed with the corrosion inhibitor *SikaFerroGard-903* + for reinforced concrete and the epoxy-cement and anti-corrosive bonding primer *SikaTopArmatec-110 EpoCem*. The polymer modified cementitious repair mortar with synthetic fibers *Sika MonoTop 627* having high compressive strength of 50 MPa and high flexural strength of 8 MPa at 28 days was used for patch repair.

For the EBR strengthening method the carbon CFRP laminate *Sika CarboDur S512* was used with 50 mm width and 1.2 mm thickness. For the NSM strengthening method the carbon CFRP strips *Sika CarboDur S1.030* were used with 10 mm width and 3 mm thickness. The ultimate tensile strength of the CFRP composites was 3100 MPa, the modulus of elasticity was 165 GPa and the elongation at break was equal to 1.7% according to the manufacturer's data. The bonding of the CFRP laminate was made using epoxy resin *Sikadur-30* having flexural strength of 90 MPa, tensile strength of 30 MPa and elastic modulus of 11200 MPa. Carbon FRP sheets *SikaWrap-300C* were also applied at shear spans, having ultimate strength equal to 3800 MPa, modulus of elasticity 242 GPa, elongation at break 1.43% and thickness equal to 0.171 mm. The bonding of the NSM CFRP strips and of the shear CFRP wraps was made using epoxy resin *Sikadur-330* with a tensile strength of 30 MPa and elastic modulus of 4500 MPa. All these materials are products of Sika Hellas S.A., Kryoneri Attikis, Greece.

2.3. Accelerated corrosion process

In order to accelerate the corrosion process, the beams were partially immersed inside a tank with 3% industrial salt solution and were subjected to a constant current density using power supplies. The tensile longitudinal steel bars were connected to the positive terminal of the power supply to act as an anode and a dummy external steel rod that was placed longitudinally along the corroded beams was connected to the negative terminal to act as a cathode. In conformity with Faraday's law, three different durations of impressed current were applied so as to achieve three different degrees of corrosion. The beams were then subjected to wet-dry cycles consisting of one week wet cycle followed by one week dry cycle, for physical representation of the natural corrosion