Engineering Structures 172 (2018) 172–186

Contents lists available at ScienceDirect

Engineering Structures

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

Experimental results and modelling of corrosion-damaged concrete beams strengthened with externally-bonded composites

Mohammed Elghazy[a], Ahmed El Refai[a,*], Usama Ebead[b], Antonio Nanni[c]

[a] Department of Civil and Water Engineering, Laval University, Quebec City, Quebec G1V 0A6, Canada
[b] Department of Civil and Architectural Engineering, College of Engineering, Qatar University, P.O. Box 2713, Doha, Qatar
[c] Department of Civil, Architectural & Environmental Engineering, University of Miami, FL, USA

ARTICLE INFO

Keywords:
Corrosion
Fabric-reinforced cementitious matrix
Fiber reinforced polymer
Finite element analysis
Flexure
Reinforced concrete
Repair
Strengthening

ABSTRACT

This paper presents the results of 3D finite element (FE) modelling of corrosion-damaged reinforced concrete (RC) beams strengthened in flexure with externally-bonded composites. The models were validated against the results of experimental tests conducted on ten unstrengthened and strengthened beams. The investigated parameters included the corrosion levels (10 and 20% mass loss of steel reinforcement), the type of composite (fabric-reinforced cementitious matrix (FRCM) and fiber-reinforced polymers (FRP)), and the number of composite layers (one, two, and four). The predicted results showed good agreement with those of the experimental tests. The FE models were able to capture the non-linear behavior of the strengthened beams. The interfacial bond stress-slip models at the fabric/matrix and composite/concrete interfaces and the number of composite layers had the most significant impact on the predicted response of the strengthened beams whereas the corrosion level, modeled as a reduction in the steel reinforcement cross-section, showed a slight effect on their performance. The validated models were used in a parametric study to investigate the effect of varying the compressive strength of the concrete substrate and the thickness of concrete cover on the flexural performance of the strengthened beams. It was observed that lowering the concrete compressive strength or increasing the concrete cover decreased the load-carrying capacities of the strengthened beams regardless of the strengthening system used (FRCM or FRP). Unlike the FRP-strengthened beams, the failure of FRCM-strengthened beams was independent of both parameters and was solely governed by the fabric slippage within the matrix.

1. Introduction and background

Strengthening corrosion-damaged reinforced concrete (RC) structures has become one of the most imperative activities in the construction industry. Corrosion impairs the structural integrity and the serviceability of the structures and can lead to unexpected collapses [1–3]. In the past decades, previous research has documented the effectiveness of fiber-reinforced polymers (FRP) as reliable strengthening materials for concrete structures [4–6]. More recently, cement mortars reinforced with fabrics made of carbon, glass, or polyparaphenylene benzobisoxazole (PBO), known as fabric-reinforced cementitious matrix (FRCM) or textile-reinforced mortar (TRM), have been introduced as promising, sustainable, and durable alternatives to FRP composites. FRCM systems own all the merits of FRPs in terms of corrosion resistivity, light weight, and ease of installation but with the use of inorganic cementitious matrices as bonding materials in lieu of the epoxy-bonding agents for FRPs to overcome the drawbacks associated with epoxies [7–11].

Previous researchers have used finite element packages to examine the structural performance of strengthened concrete beams and slabs [12–14] with the majority of the literature body focusing on modelling the behavior of beams strengthened using externally-bonded FRP sheets or plates. Bond between concrete and FRP have been examined through rigorous numerical modelling of concrete-FRP joints in direct shear tests, a basic application that provides insight into FRP-concrete interfacial behavior [15–16]. The motivation for such existing numerical work was the fact that, despite the large amount of experimental data available on FRP strengthening of concrete structures, a full understanding of the various load-deformation behaviors and debonding phenomenon was still lacking.

On the other hand, recent experimental studies involving FRCM systems have focused on strengthening undamaged RC members. Test results have demonstrated their efficiency in restoring the capacities and serviceability of the deficient members [17–20]. Elsanadedy et al. [21] developed a FE model to predict the flexural behavior of six beams strengthened with basalt FRCM (B-FRCM) and carbon-FRP systems (C-

* Corresponding author.
E-mail addresses: mohammed.elghazy.1@ulaval.ca (M. Elghazy), ahmed.elrefai@gci.ulaval.ca (A. El Refai), uebead@qu.edu.qa (U. Ebead), nanni@miami.edu (A. Nanni).

https://doi.org/10.1016/j.engstruct.2018.06.037
Received 11 January 2018; Received in revised form 26 May 2018; Accepted 9 June 2018
0141-0296/

FRP) using LS-DYNA software. Bond between FRCM and concrete was modeled through the tiebreak surface-to-surface contact definition of LS-DYNA to account for both normal and shear forces at the interface. A parametric study was also conducted by altering the type of mortar and the number of B-FRCM layers used. A bond-stiffness coefficient, defined as the ratio of the B-FRCM stiffness to its tensile bond strength, was introduced and recommended not to be less than 225 to avoid premature debonding failure.

Al-Salloum et al. [22] evaluated both experimentally and numerically the efficacy of B-FRCM system for shear strengthening of deficient concrete beams using long woven, knitted, or even unwoven fiber rovings in two orthogonal directions. A prefect bond between FRCM composites and concrete was assumed in the FE model. The number of textile layers and the orientation of the textile material were altered through a parametric study using FE models. The models were able to accurately capture the shear strengths of the strengthened beams.

It was observed that most of the previous studies have reported that debonding of FRCM composites governs the failure of the flexural strengthened RC members [23–25], which highlights the significance of examining bond of FRCM to the concrete substrate. Debonding of FRCM usually occurs at the fabric/matrix interface rather than the matrix/concrete interface unlike what is typically reported for FRPs, in which debonding occurs at the epoxy/concrete interface [15,26,27]. D'Ambrisi et al. [28] developed bond-slip models to describe bond between FRCM fabric and the surrounding matrix. The models were then calibrated with data obtained from experimental tests in which RC elements were strengthened with PBO-FRCM layers. This model will be described later in the FE model developed in this study. Ombers [29] proposed another bond-slip relationship for PBO-FRCM composites bonded to concrete. However, Ombres' model was reported to be more conservative than that introduced by D'Ambrisi et al. [28].

The available literature shows that little attention has been devoted to investigating the feasibility of using FRCM composites in strengthening corrosion-damaged RC members. Corroded structures are characterized by the deterioration of concrete and the loss of structural integrity as a result of expansive corrosion products. Using cement-based mortars in repair might be a challenge from the practical and technical points of view. To the authors' knowledge, only two studies [30–31] have documented the potential of using FRCM composites to restore the ultimate capacities and the serviceability of corrosion-damaged beams. However, many parameters that might affect the performance of FRCM-strengthening have not been fully documented and yet need to be thoroughly investigated.

The aim of the current study is twofold, namely:

(a) expand our understanding of the flexural behavior of corrosion-damaged RC elements strengthened with FRCM composites by investigating various parameters that were not included in previous studies [30–31] and comparing their performance with that of FRP-strengthened elements;
(b) validate newly-developed FE models that utilize the bond stress-slip model proposed by D'Ambrisi et al. [28] to describe the bond behavior between PBO-FRCM and concrete.

Details about the test specimens, the test setup, and the test results of the strengthened specimens have been reported in [31] and are summarized here for convenience. The FE models were then extended in a parametric study to examine the effect of varying the compressive strength of the concrete substrate and the thickness of the concrete cover on the flexural enhancement of the strengthened specimens.

2. Experimental investigation

2.1. Test matrix

The test matrix of the experimental program is given in Table 1. The beam specimens were subdivided into two groups A and B and were subjected to accelerated corrosion process to obtain theoretical mass losses of 10 and 20%, respectively, in the middle third of their tensile steel reinforcement. Details about the accelerated corrosion process can be found in [31]. At the end of the corrosion process, one beam in each group was not strengthened (beams CU-A and CU-B) and were used as benchmarks, while other beams were strengthened with the designated externally-bonded composite system. In addition, two virgin beams (i.e., not corroded nor strengthened: beams UU_a and UU_b) were used as controls. The test parameters included the level of corrosion damage (10 and 20%), the type of the externally-bonded composite system (FRCM and FRP), and the volume fraction of the fabric used in the FRCM-strengthened beams (1, 2, or 4 layers).

2.2. Test specimen

The geometry and details of reinforcement of the test specimen are shown in Fig. 1. The beams were 2.8 m long with a cross section of 150 × 250 mm and a clear span of 2.4 m. The bottom and top reinforcement consisted of two 15 M (diameter 15 mm) and 8 M (diameter 8 mm) deformed bars, respectively, placed at a clear cover of 25 mm. Steel stirrups of 10 mm diameter were provided along the shear spans to avoid shear failure. After testing the beams, the corroded steel bars were extracted from the beams and the actual mass loss of the corroded bars were determined according to ASTM G1-03 provisions [32]. Table 1 lists the actual average steel mass loss for each beam.

The cylinder compressive strength of concrete was 41.8 MPa with standard deviation of 4.8 MPa. The splitting tensile strength of concrete was 3 MPa with standard deviation of 0.3 MPa. The yield strength of the longitudinal reinforcing steel bars of diameters 15 and 8 mm were 466 MPa (standard deviation of 4.2 MPa) and 573 MPa (standard deviation of 17.7 MPa) as determined by the authors.

2.3. Externally-bonded composite systems

Two types of externally-bonded composites were used to strengthen the beams namely, the P-FRCM and the C-FRP composites. The P-FRCM composite consisted of a fabric made of polyparaphenylene benzobisoxazole (PBO) fibers impregnated and bonded to the concrete surface by a polymer-modified cementitious matrix having compressive and flexural strengths of 43.9 and 3 MPa (standard deviations of 0.4 and 0.3 MPa), respectively, as determined by the authors. The PBO fabric consisted of an unbalanced net of spaced fiber bundles organized along two orthogonal directions as shown in Fig. 2a. The fabric openings were 5 and 15 mm wide in the primary and the secondary directions, respectively. The bundles were 5 and 2.5 mm wide with thicknesses of 0.046 and 0.011 mm in the main and secondary directions, respectively. The tensile tests conducted by D'Antino et al. [33] on the same fabric indicated a tensile modulus of 206 GPa, a tensile strength of 3014 MPa, and an ultimate elongation of 1.45%. The P-FRCM composite had a cracked tensile modulus of 121 GPa, a tensile strength of 1550 MPa, and an ultimate elongation of 1.4% as determined by Ebead et al. [20].

On the other hand, the C-FRP composite consisted of flexible unidirectional carbon fiber sheet (Fig. 2b) impregnated and bonded to concrete with an epoxy resin having a tensile modulus of 3.8 GPa and a tensile strength of 30 MPa according to the manufacturer's data sheet. The dry carbon fiber sheet had a tensile modulus of 230 GPa, a tensile strength of 3.22 GPa, an ultimate elongation of 1.45%, and a nominal thickness of 0.13 mm. The cured laminate had a tensile modulus of 65.4 GPa, a tensile strength of 0.894 GPa, an ultimate elongation of 1.33%, and a nominal thickness of 0.38 mm, as reported in the manufacturer's data sheet.

To compare between the two strengthening systems, the equivalent axial stiffness, K_f, for each composite system was determined based on their tensile modulus, E_f, and the cross-sectional area of the fibers