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FRCM/internal transverse shear reinforcement interaction in shear strengthened RC beams

Tadesse G. Wakjira, Usama Ebead*

Department of Civil and Architectural Engineering, College of Engineering, Qatar University, P.O. Box 2713, Doha, Qatar,

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ABSTRACT

This paper presents a study on the efficacy of a shear strengthening technique utilizing fabric reinforced cementitious matrix (FRCM) systems for beams with and without internal transverse shear reinforcement (ITSR) within the critical shear span (CSS). The paper focuses on the FRCM/ITSR interaction, experimentally and analytically. Three different FRCM fabric types were used; namely, glass, carbon and polyparaphenylene benzobisoxazole (PBO). The test matrix consisted of fourteen medium-scale RC beams prepared and tested to fail in shear. The test results indicated a clear influence of the ITSR within the CSS on the gain in the ultimate load carrying capacity (P_u) of the beams. The FRCM strengthening system has enhanced the shear strength of the beams. With regard to the FRCM fabric type, carbon FRCM was the most effective of all in terms of the gain in P_u of the strengthened beams. Moreover, the beams strengthened with continuous strengthening configuration intuitively performed better than those strengthened with discontinuous configuration. A simplified compression field theory (SCFT) model was used for predicting the ultimate load carrying capacity of the beams. This model features two important contributions; namely, considering the effect of FRCM strengthening and accounting for the critical shear span to depth ratio.

1. Introduction

Shear failure in reinforced concrete (RC) elements is brittle in nature with no adequate warning because diagonal shear cracks form considerably faster and wider than flexural cracks [1]. Flexural RC members are designed to behave in a ductile manner under loading conditions. To guarantee such ductility, the members should be designed with adequate shear capacity. However, due to structural deterioration caused by different factors, an RC beam, as a common flexural member, may become shear-deficient. The development of strengthening systems for shear-deficient beams to increase their shear capacities; hence, extend their life span has been the focus of several studies [2–8].

Different strengthening materials and methods have been developed and presented in several research contributions including steel plates [9], ferrocement [10,11], and fiber reinforced polymer (FRP) [12,13]. The latter had gained popularity, over the last decades, as a viable strengthening solution due to its favorable properties over those of the traditional strengthening solutions. However, the FRP composites possess some drawbacks owing to the reliance on epoxy adhesives. Some of these drawbacks include the incompatibility with the concrete [14], susceptibility to failure at high temperatures [15,16], and inability to apply on wet surfaces [14,17]. In order to partially alleviate these problems, fabric reinforced cementitious matrix (FRCM) strengthening system has been introduced as an alternative to the FRP counterpart [18–21]. Existing literature have shown a successful utilization of the externally bonded (EB) FRCM as a strengthening system for various applications including flexural [18,21–25] and shear [2–5] strengthening of beams and flexural strengthening of slabs [26]. FRCM composites may be regarded as more advantageous when compared to the FRP composite materials [3,4,27] due to their compatibility with the concrete substrate. In addition, FRCM composites possess good resistance to elevated temperatures and fire [15,16], while being able to be applied at a temperature as low as 0 °C [20]. The eco-friendly FRCM composites accommodate recycled cementitious materials as part of the matrix composition [18]. It is believed that the existence of the internal transverse shear reinforcement (ITSR) influence the strengthening efficacy of the FRCM system. Literature available on the effect of ITSR on the efficacy of FRCM system has been rather limited [5,8] and has focused on the use of a single type of EB-FRCM system, i.e., carbon FRCM.

In a recent study, Younis and Ebead [28] have shown that the FRCM system is successful in enhancing the shear behavior of the strengthened beams when externally bonded to the sides of the beams [28]. As reported, FRCM/concrete debonding governed the mode of failure of

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* Corresponding author.
E-mail addresses: twakjira@qu.edu.qa (T.G. Wakjira), uebead@qu.edu.qa (U. Ebead).

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the EB-FRCM system that limited the effectiveness of the strengthening system [28]. Increasing the number of fabric layers and hence the thickness of the EB-FRCM layer also leads to the susceptibility to debonding [4,28–30]. To enable the use of a higher number of fabric layers, i.e., 4 layers, the authors used the near surface embedded (NSE) concept to insert two layers of fabrics within the concrete cover and add two additional layers of fabrics in an externally bonded FRCM part [31]. This was referred to as hybrid NSE/EB strengthening technique, which has shown to effectively decrease and/or prevent the debonding of FRCM from the concrete substrate [31]. The results also showed that the NSE technique led to a better utilization of the FRCM by virtue of the improved FRCM/concrete interaction. Moreover, the grooves in the NSE are rough enough to reduce/eliminate the need for sandblasting of concrete surfaces.

This paper features an innovative research on the interaction between the FRCM and the ITSR while examining the efficacy of the NSE-FRCM system in the context of enhancing the shear strength and deformational characteristics. The NSE is a new way of applying the FRCM to concrete surfaces with inherited roughened surface and proved FRCM/concrete bond enhancement [31]. The failure characteristics of the strengthened beams will also be emphasized. The work also includes analytical assessment of the simplified compression field theory (SCFT) as a predicting tool for the ultimate load carrying capacity of the beams. The ultimate load carrying capacity of the beam will be referred to as ultimate capacity throughout this paper.

2. Characteristics of the experiments

2.1. Specimens

Fourteen medium-scale RC rectangular beams of dimensions 2100 × 150 × 330 mm (length × width × height) were fabricated and divided into two groups, with and without ITSR within the critical shear span (CSS). Each group included an un-strengthened control beam. The ITSR within the CSS consisted of 6 mm diameter bars spaced at 215 mm. Fig. 1a and b show full longitudinal reinforcement details of typical beams without and with the ITSR, respectively. The beams were designed to fail in shear within the CSS; hence, adequate ITSR of 8 mm diameter bars spaced at 100 mm were provided outside the CSS. For the medium scale beams in this study, a side concrete cover of 25 mm was used on both sides of the beams, as shown in Fig. 1c. In full-scale RC beams, a higher concrete cover be should used as per ACI 318 [32].

Each strengthened beam utilized two layers of fabrics in the FRCM composites. Roughening of the concrete surface was substituted by using the near surface embedded concept [31]. The NSE roughening also kept the original shape of the beam unchanged as shown in the cross sections of un-strengthened and strengthened beams in Fig. 1c and d, respectively. Preliminary design of the strengthened beams substantiated the beam dimensions and strengthening configuration parameters, such as the spacing between the discontinuous FRCM strips and the strengthening zone width. Fig. 2a and b show schematic of the strengthening configuration details. A list of the beams is given in Table 1.

Three test variables were considered:

i. Presence of ITSR within the CSS: Beams without ITSR (Group-1) and with ITSR (Group-2) within the CSS as shown in Fig. 1a and b, respectively.
ii. Type of FRCM fabric: The strengthening system utilized three different types of fabric, i.e., polyparaphenylene benzobisoxazole (PBO), glass (G), and carbon (C).
iii. Strengthening configuration: Discontinuous (Fig. 2a) versus continuous (Fig. 2b) FRCM. The discontinuous FRCM strengthening system utilized 120 mm wide strips spaced at 95 mm within the CSS as shown in Fig. 2a.

For Group-1, the beam designation used “X-Y” nomenclature as listed in Table 1 in which “X” denotes the fabric type (G- for glass, P- for PBO and C- for carbon) and “Y” denotes the strengthening configuration (“I” represents intermittent or discontinuous strips, and “F” represents full or continuous FRCM plate). For Group-2, the beams were designated in a similar way as those of Group-1 beams with “S” added at the end to indicate the presence of ITSR within the CSS as listed in Table 1. Accordingly, C-I-S denotes a test beam strengthened with two layers of discontinuous strips of C-FRCM and internally reinforced with ITSR within the CSS, while P-F denotes a beam without ITSR within the CSS and strengthened with continuous strip of PBO-FRCM.

2.2. Materials

Ready-mixed concrete was used to cast the beams using the same batch to ensure consistency of concrete characteristics. Compression tests carried out on eight standard 150 × 300 mm concrete cylinders as per ASTM C39/C39M [33] showed an average 28-day cylindrical compressive strength of 30 MPa with a standard deviation of 1.6 MPa.

Reinforcement bars with diameters of 8 mm and 16 mm were used for compression and main tensile reinforcement, respectively. Bars with a diameter of 6 mm and 8 mm were used for the ITSR within and outside the CSS, respectively. The longitudinal tensile reinforcement bars had an average yield strength 595 MPa and elastic modulus of 224 GPa, while the compressive and transverse reinforcement bars had an average yield strength of 535 MPa and elastic modulus of 207 GPa. The yield strain was 0.266% for the tensile bars and 0.258% for the transverse and compressive reinforcement bars.

The three different types of fabrics used in the FRCM strengthening systems are shown in Fig. 3a through c. For the preparation of the FRCM composites, each fabric type was used along with its respective manufacturer-recommended type of mortar [34–36]. The mortar mix uses a water-to-cement ratio of 0.2 by weight of G-FRCM and 0.28 by weight of C- and PBO-FRCM. The geometrical and mechanical properties of each fabric type are listed in Table 2 in terms of the area per unit width in the warp ($A_{f,wp}$) and weft direction ($A_{f,wf}$), modulus of elasticity (E_f), tensile strength (f_f), ultimate strain (ε_{uf}), and average 28-day compressive strength of the associated mortar (f_{cm}) as provided by the manufacturer [34–36].

2.3. Preparation

The preparation of the beams and the strengthening procedure are summarized in Fig. 4a through d. The specimen preparation involved two main steps:

i) Creating the roughened grooves: Initially, grooves of 15 mm depth were cut using a slitting tool based on the configuration of the FRCM system as shown in Fig. 4a and b. Based on the experience of the authors, the labor cost of creating the roughened grooves can be considered as equivalent to roughening the surface using sandblasting for the externally bonded FRCM counterpart. Moreover, the preparation of the roughened grooves is not associated with any hazards unlike the sandblasting process that creates a high level of noise and dust that are hazardous to the workers unless proper safety precautions are taken. The cutting discs in the slitting tool are fully enclosed on all sides for maximum safety of the workers. Following the preparation of the grooves, the concrete surface was then dampened with water to a saturated surface dry (SSD) condition with no excess water.
ii) FRCM application: The FRCM composites were applied on each side of the beams by applying a first layer of mortar followed by slightly impregnating a first layer of fabrics in the mortar (Fig. 4c). Afterwards, a second mortar layer, a second layer of fabrics and then a finishing mortar layer were applied. The fabrics were installed by aligning the stronger fabric tows perpendicular to the longitudinal