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Hybrid NSE/EB technique for shear strengthening of reinforced concrete beams using FRCM: Experimental study

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HIGHLIGHTS

- NSE/EB pioneer FRCM systems were examined for shear strengthening of RC beams.
- Thirteen beams under three-point loading have been tested.
- Carbon-FRCM showed the highest increase in the load carrying capacity of 83%.
- PBO-FRCM showed the least increase in the load carrying capacity of 62%.
- Near surface embedding of FRCM mitigate deboning.

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ABSTRACT

The externally bonded (EB) fabric reinforced cementitious matrix (FRCM) has successfully been used as a structural strengthening for various applications including flexural and shear strengthening of reinforced concrete (RC) beams, flexural strengthening of RC slabs and column confinement. However, the EB-FRCM system is characterized by poor FRCM/concrete bond leading to premature debonding of FRCM off the concrete substrate, particularly for thicker FRCM. The present paper reports on an experimental study on the efficacy of a pioneer form of hybrid near surface embedded and externally bonded technique using FRCM composites (NSEEB-FRCM) for shear strengthening of RC beams. With such a technique, higher thickness of FRCM composites can be applied with less likelihood of debonding that is normally experienced when using the EB-FRCM system. Thirteen shear-deficient medium-scale RC beams were constructed, strengthened in shear and tested under three-point bending test. The test parameters were: (a) FRCM type (polyparaphenylene benzobisoxazole, carbon, and glass), (b) strengthening configuration (full versus intermittent strips), and (c) number of fabric layers.

The percentage enhancement in the shear capacity of the beams ranged from 43% to 114% indicating the successful implementation of the strengthening methods provided. An average enhancement in shear capacity of 83%, 72% and 62% were observed in carbon FRCM, glass FRCM and PBO-FRCM, respectively. The failure mode of the strengthened specimens was sensitive to the type and configuration of FRCM in addition to the number of FRCM layers. The strengthening systems also resulted in higher deflection at failure and energy absorption value of the strengthened beams with an average of 94% and 204% relative to the reference specimen, respectively.

1. Introduction

Retrofitting of deteriorated or deficient structures has become one of the main concern in the construction industry. The corrosion of steel bars is a major cause of deterioration that requires a remedy through the structural strengthening. Other factors causing structural deterioration include the increase in service loads caused by change in occupancy, deficiencies in design and/or construction, severe environmental conditions like hurricane and seismic events, and the lack of proper maintenance. A considerable amount of research has been carried out for developing strengthening systems that increase the load carrying capacity and ductility of the deteriorated structures; hence, extend their life span. In recent years, the development of fabric reinforced cementitious

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matrix (FRCM) composites is receiving popularity as a viable alternative strengthening materials that overcome the problems associated with the use of fiber reinforced polymer (FRP) composites [1–3]. FRP composites are incompatible with the concrete substrate usually leading to debonding [4]. Moreover, these composites are susceptible to failure at high-temperatures and are also problematic to apply on wet surfaces [4,5]. The replacement of epoxy with cement based matrix in FRCM composites, on the other hand, reduces the chance of debonding attributed to its' compatibility with the concrete substrate. FRCM composites possess good resistance to fire and elevated temperature [6,7] and can also be applied at a temperature as low as 0 °c [3].

Existing literature revealed effective uses of FRCM techniques for the structural strengthening of a variety of applications; e.g., including column confinement [8–10], flexural strengthening of RC beams [11–14], shear strengthening of RC beams [15–19], and flexural strengthening of RC slab [20]. FRCM composites can also be used to increase the ductility of the strengthened members [18,19,21]. In some cases, the application of FRCM strengthening systems changed the brittle shear failure into ductile flexural failure due to the large increase in the shear resistance of the strengthened beams [4]. Different techniques of FRP application have been developed through time among which the externally bonded (EB) [22–25], near surface mounted (NSM) [26–33], mechanically fastened [34], hybrid externally bonded and mechanically fastened [35,36] were commonly reported. The research work on FRCM systems; however, focused mainly on the use of externally bonded FRCM systems with anchorage [17,37] or without anchorage [2,5,18,21,38,39].

The efficacy of FRCM for the strengthening of shear-deficient RC beams is influenced by various factors including the number of fabric layers or FRCM thickness [4,5,16–18,39–42], wrapping scheme [4,16,38,43], internal shear reinforcement [39], geometric configuration [19,41,44], presence of end anchorage [2,17,37,42], fabric orientation [5], and fabric type [7,40,45]. With regard to the fabric type, the majority of the research work has focused on the use of a single fabric type; namely, carbon [4,16,39,40,42,46], glass [37], PBO [2,18,19], or basalt [5]. There is very few literature available on the comparison of the efficacy among different types of FRCM techniques for shear strengthening of RC beams [45]. A comparison between two FRCM types; namely, carbon FRCM and glass FRCM, was conducted for the shear strengthening of RC beams [17,38]. A comparison was also made among the PBO, carbon, and glass FRCM techniques, for the shear strengthening of RC beams [21,45].

Increasing the number of fabric layers of FRCM results in an increase in its thickness. Strengthening with larger number of fabric layers is associated with debonding of EB-FRCM off the concrete substrate; thus, decreasing the utilization of FRCM strengthening material [16,18,47]. The NSE-FRCM strengthening system is believed to prevent or reduce the premature debonding failure. However, the NSE technique is limited to a certain number of fabric layers that can be embedded within the concrete cover. As a solution to such an issue, the authors have developed a pioneer utilization of the hybrid form of NSE and EB technique called NSEEB-FRCM as will be referred to in this paper. This new form of the NSEEB-FRCM utilized two layers of fabrics in constituting the near surface embedded FRCM part and additional two layers of fabrics for the EB-FRCM part with different FRCM configurations, resulting in a total of four layers of fabrics in the FRCM system.

In light of the aforementioned gaps, the present study; therefore, aims at introducing a new form of NSEEB-FRCM system for the shear strengthening of RC beams using three commercially available FRCM systems; namely, PBO-, carbon-, and glass-FRCM. For this purpose, experimental tests have been carried out on thirteen (13) medium-scale RC beams. To avoid long sentences in this paper, FRCM layers will refer to the number of fabrics used inside the FRCM. In addition, specimens strengthened using FRCM system will be referred to as FRCM specimens.

2. Testing program

2.1. Materials

2.1.1. Reinforced concrete

The specimens were cast using ready-mixed concrete of the same batch. The concrete mix comprised 800 kg of fine aggregate, 1100 kg of course aggregate, 371 kg of ordinary Portland cement, and 168 kg of water, for each cubic meter of concrete. The concrete characteristic compressive strength was obtained by testing standard concrete cylinders with dimensions of 150 mm in diameter and 300 mm in height according to ASTM C39/C39M [48]. The test results showed an average 28-day cylindrical compressive strength of 30 ± 1.65 MPa.

The reinforcement involved 16 mm diameter bars (used as tensile reinforcement) and 8 mm diameter bars (used as compressive reinforcement and shear link) with an average yield stress of 594 MPa and 536 MPa, respectively. Table 1 summarizes the results of the average mechanical properties of the reinforcement bars based on tested samples at the laboratory.

2.1.2. Fabric-reinforced cementitious matrix

Three commercially available fabric types were utilized in this study with their producer-recommended associated mortars to form three FRCM systems; namely, carbon (C)-FRCM [49], PBO-FRCM [50] and glass (G)-FRCM [51]. Table 2 summarizes the geometric and mechanical characteristics of each fabric type along with the corresponding mortar strength as provided by the manufacturers. Moreover, the geometry of the fabric is shown in Fig. 1a through c for carbon, glass and PBO fabrics, respectively. The center to center stitch spacing in glass fabric was 18 × 14 mm while it was 10 × 10 mm and 10 × 17 mm for carbon and PBO fabrics, respectively.

2.2. Specimens and test matrix

The construction of the test specimens involved a total of thirteen (13) medium-scale RC rectangular beams of dimensions 150 mm in width, 330 mm in depth and 2100 mm in length. Fig. 2a shows the longitudinal section of the beams. A constant value of 34 mm of concrete cover was provided, yielding a typical beam effective depth of 280 mm. The specimens were tested under three-point loading as simply supported with a clear span of 1.9 m between the supports. One specimen was un-strengthened to act as a benchmark, while the remaining twelve specimens were strengthened for shear using FRCM systems. Nine of the strengthened specimens used NSEEB-FRCM system while the other three specimens were strengthened using NSE-FRCM counterpart for the purpose of comparison. Fig. 2b and c show the cross-sectional details for the NSE-FRCM and NSEEB-FRCM strengthened specimens, respectively. The NSEEB-FRCM involved two layers of near surface embedded FRCM and two more layers of EB-FRCM with different configurations, resulting in a total of 4 layers of FRCM, while the NSE-FRCM utilized two layers of fabric applied in the prepared groove with its' associated mortar.

The experimental test matrix is provided in Table 3. The specimen designation follows two key parameters, namely; fabric type and FRCM configuration for both near surface embedded and EB-FRCM system. For NSEEB-FRCM system, the specimen designation is labelled using "A-B-D" format as shown in Table 3. "A" denotes the fabric type (C- for carbon, P- for PBO, and G- for glass); "B" and "D" denotes the strengthening configuration ("I"-represent inter-