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Innovative ECC jacketing for retrofitting shear-deficient RC members

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HIGHLIGHTS

- The ECC jacket improved the cyclic behavior of shear-deficient beams considerably.
- Using ECC to replace mortar in ferrocement reduced the crack width by two times.
- Cover spalling of regular ferrocement was improved by using ECC to replace mortar.
- The ECC jacket with a single layer of bar meshes was the best retrofitting scheme.

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ABSTRACT

Engineered Cementitious Composite (ECC) is distinguished from conventional fiber reinforced concrete by its ductile tensile strain-hardening behavior and crack width control ability. This study investigates the performance of ECC jacketing for retrofitting shear-deficient reinforced concrete (RC) members. Six RC cantilever structural beams are prepared, and five of them are retrofitted with jackets. The experimental parameters involve the properties of the jacket, i.e., (1) ECC or mortar as the matrix, (2) presence or absence of steel meshes, and (3) welded wire or bar meshes. The performance of the various schemes of ECC jacketing is evaluated using the test results of the cantilever beams under cyclic loading. In particular, this study explores whether the appealing properties of ECC shown on the material scale can translate into better performance of the ECC jacket on the structural scale. Multiple performance measures of the beams are employed, including damage patterns, hysteretic loops, energy dissipation capacities, rebar strain profiles, shear distortions, and failure modes. The test results show that the ECC jacket without steel meshes is able to improve the cyclic behavior of the original shear-deficient beam considerably. The behavior of the retrofitted beam at the performance level of the ultimate limit state can be further enhanced by reinforcing the ECC jacket with steel meshes. In addition, the multiple performance measures suggest that the ECC jacket with a single layer of bar meshes be the best retrofitting scheme. Based on the test results, both the advantages and disadvantages of the ECC jacketing technique are reported.

1. Introduction

RC jacketing is a popular method for retrofitting RC structural members. This is mainly because while it can effectively enhance the mechanical performance of structural members, it also has a set of other advantages when compared to steel or fiber reinforced polymer composite jackets, which include high durability, adequate fire and corrosion resistance, simple construction technique, and wide availability of construction materials [1–6].

Ferrocement jacketing is a special class of the RC jacketing technique. Ferrocement, which is a thin laminated cement based composite, is commonly made with a cement-based mortar reinforced with closely spaced layers of continuous steel meshes [7]. It is distinguished from regular reinforced concrete by its relatively small size reinforcement and the absence of large size aggregates in the matrix. Ferrocement has been used in numerous applications as a tough and strong protective shell element, such as in new terrestrial and marine structures and for the repair and rehabilitation of existing structures [8–11]. Kondraivendham and Pradhan [12] applied ferrocement as an external confinement to concrete members under compression. The effect of external ferrocement on the compressive behavior of the strengthened members, including the ultimate compressive strength and failure strain, was investigated. Mourad and Shannag [13] repaired and strengthened reinforced concrete square columns using ferrocement jackets containing two layers of welded wire meshes. The

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experimental variable was the magnitude of the preloading axial compression on the column specimens. Kumar et al. [14] studied the effectiveness of ferrocement jacketing for retrofitting, and the experimental variable was the angle of the steel wire mesh. The evaluation was conducted based on the results of four-point bending tests on the retrofitted beams. Anugeetha and Sheela [15] also investigated the performance of ferrocement jacketing for retrofitting beams using four-point bending tests, with the experimental variable being the number of layers of steel meshes. Shah [16] used ferrocement for strengthening unreinforced masonry columns. The effects of mesh spacing and water-to-cement ratio of the ferrocement on the compressive property of the strengthened masonry columns were investigated. Kaish et al. [17] used ferrocement jacketing for re-strengthening square RC short columns, with a focus on the performance of various schemes for enhancing the bond between the jacket and the original column.

When ferrocement is subjected to external loading, the contribution of the reinforcement becomes significant only after matrix cracking. The tensile property of the matrix is therefore a critical factor affecting the performance of ferrocement. Engineered Cementitious Composite (ECC) is a special class of high performance fiber reinforced cement-based composites (HPFRCCs) [18–22]. As illustrated in Fig. 1 [18,22], it is characterized by the ductile pseudo strain-hardening behavior under direct tension, with an ultimate strain capacity often reported to be greater than 2%. It has been widely shown in material tests that ECC possesses a favorable crack width control ability that restrains the average crack width of ECC to less than 60 μm until failure [18].

The objective of the present study is to investigate the performance of various ECC jacketing schemes for retrofitting shear-deficient RC members. The design variables of the jacket include: (1) mortar or ECC as the matrix, (2) presence or absence of steel mesh reinforcement, and (3) welded steel bar or wire meshes. Six cantilever beams are tested under displacement reversals to assess the feasibility of ECC jacketing. Multiple performance parameters of the beams are computed for evaluation purpose.

2. ECC materials

The mixed proportions of the ECC material employed in this study are summarized in Table 1. The components of ECC include Type I ordinary Portland cement (specific gravity = 3.15), Class F fly ash (moisture content = 7% and loss of ignition = 2.6%), silica sand (specific gravity = 2.65, AFS = 75, water absorption = 3%, and particle sizes ranging between 0.15 and 0.2 mm), polycarboxylate-based superplasticizer admixture, water, and polyvinyl alcohol (PVA) fibers. No coarse aggregate is used in ECC. The water-to-binder ratio is 0.35. A 2% volume fraction of PVA fibers is used in the ECC. The length and diameter of the PVA fibers are 12 mm and 39 μm, respectively. The fibers have a tensile strength of 1600 MPa, a density of 1300 kg/m^3, an elastic modulus of 41 GPa, and a maximum elongation ratio of 6%.

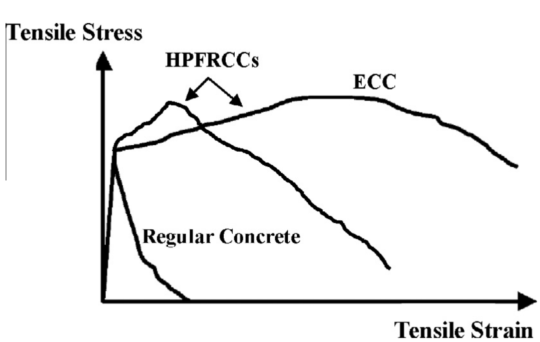


Fig. 1. Tensile stress and strain relationships for HPFRCCs.

Table 1
Mixed proportions of ECC (kg/m^3).

Type I Portland cement	Fly ash	Silica sand	Water	HRWR[a]	PVA fiber
548	658	548	397.5	24.6	28.6

[a] High-range water reducers.

The tensile characteristics of the ECC material are determined using uniaxial tensile testing. Fig. 2 shows the test setup, configuration, and dimensions of the tensile specimen. The deformation of the specimen is measured using two linear variable displacement transducers (LVDTs) mounted on the two sides of the specimen, with a gauge length of 80 mm. The magnitude of the applied tensile force is measured using a load cell attached to the actuator. The tensile test is terminated when the applied force drops to 70% of the maximum force. The compressive strengths of the used cementitious materials are obtained via compressive tests of standard cylinder specimens (100 mm × 200 mm). Both the tensile and compressive tests are carried out using displacement control with a loading rate of 0.5 mm/min to simulate the quasi-static loading condition.

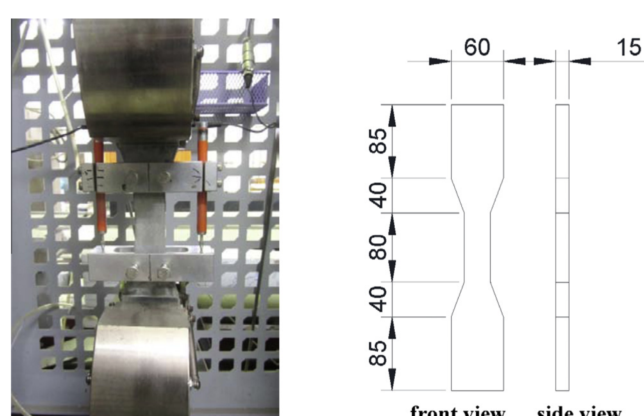
3. Experimental program

Six identical shear-deficient RC structural members are prepared. The design details of the prototype specimen are shown in Fig. 3. The specimen is composed of a beam element connected to an RC stub. The cross-sectional dimensions of the beam element are 250 mm in width, 350 mm in height, and 1200 mm in length. The beam element is intended to represent a beam cantilevered from the RC stub. The test setup for the specimens is shown in Fig. 4. In order to sufficiently restrain the RC stub in all degrees of freedom, the stub is clamped by a top steel plate and a precast RC foundation through ten steel rods. The steel rods are fixed to the strong floor with a total prestressed force of 1250 kN. Vertical displacement reversals are imposed on the free-end of the beam element.

3.1. Specimen designs and test setup

The reinforcement details of the prototype shear-deficient beam are shown in Fig. 3. The beam specimen is flexurally reinforced with 4-#8(D25) steel bars. In the transverse direction, #3(D10) steel stirrups with a loose spacing of 300 mm are used. The names and details of the six beam specimens are summarized in Table 2.

B-CONT, which is employed as the control specimen, is the original specimen without retrofitting. The five other specimens are retrofitted using U-shape, i.e., three-sided, jacketing with a uniform thickness of 40 mm, as shown in Fig. 3c. Before the beams are retrofitted, the concrete cover is chipped, and the surface is roughened to increase the bond strength between the original and the new parts. The experimental variables of the five retrofitted specimens are associated with the materials of the jacket, i.e., (1) mortar or ECC as the matrix, (2) presence or absence of steel reinforcement, and (3) welded steel bar or wire meshes as the reinforcement. Both the steel bar mesh and the steel wire mesh have square mesh openings. The steel bar mesh has a bar diameter of 6 mm and a bar spacing of



(a) test setup (b) dimensions of tensile specimen (unit: mm)

Fig. 2. Uniaxial tensile testing on ECC materials.