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Engineered cementitious composites for effective FRP-strengthening of RC beams

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Abstract

This paper presents the results of an experimental program designed to evaluate the performance of FRP-strengthened RC beams incorporating engineered cementitious composites (ECC) as a ductile layer around the main flexural reinforcement (ECC layered beams). The load-carrying and deflection capacities as well as the maximum FRP strain at failure are used as criteria to evaluate the performance. Further, 2-D numerical simulation is performed to verify the experimental results. The results have shown that ECC can indeed be used to delay debonding of the FRP resulting in effective use of the FRP material. These positive results warrant further studies on the use of ECC in combination with FRP to repair and strengthen deteriorating RC structures, particularly those where deteriorated concrete has to be replaced with a new repair material.

Keywords: A. Carbon fibres; A. Short-fibre composites; B. Debonding; B. Interface; C. Stress concentration

1. Introduction

The applications of fibre reinforced polymer (FRP) composites to concrete structures have been studied intensively over the past few years in view of the many advantages that FRPs possess [1,2]. While FRP has been shown to be effective in strengthening RC beams, strength increases have generally been associated with reductions in the beam deflection capacity due to premature debonding [3,4]. Debonding failure modes occur mainly due to interfacial shear and normal stress concentrations at FRP-cut off points and at flexural cracks along the RC beam.

In the present study, it is suggested that if the quasi-brittle concrete material which surrounds the main flexural reinforcement is replaced with a ductile engineered cementitious composite (ECC), then it would be possible to delay the debonding failure mode and hence increase the deflection capacity of the strengthened beam. ECC is a cement-based material designed to exhibit tensile strain-hardening by adding to the cement-based matrix a specific amount of short randomly distributed fibres of proper type and property [5]. ECCs are characterized by their high tensile strain capacity, fracture energy and notch insensitivity [6]. Under uniaxial tension, sequentially developed parallel cracks contribute to the inelastic strain at increasing stress level. The ultimate tensile strength and strain capacity can be as high as 5 MPa and 4%, respectively. The latter is two orders of magnitude higher than that of normal or ordinary fibre reinforced concrete.

When ECC is introduced in a RC member, more but thinner cracks are expected to form on the beam tensile face rather than fewer but wider cracks in the case of an ordinary concrete beam [7]. More frequent but finer cracks are expected to reduce crack-induced stress concentration and result in a more efficient stress distribu-

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Notation

c	cohesion
d	effective beam depth
DR	deflection ratio
E_a	elastic modulus of adhesive
E_c	elastic modulus of concrete
$E_{elastic}$	elastic energy (area under the linear-elastic potion of the load–deflection curve)
E_p	elastic modulus of CFRP sheet
E_s	elastic modulus of steel
E_{tot}	total energy up to ultimate load (area under the load–deflection curve)
f'_c	compressive strength of concrete/ECC
f_{ct}	tensile strength of concrete/ECC
f_p^t	CFRP sheet tensile rupture strength
f_y	yield stress of tension steel reinforcement
G_a	shear modulus of adhesive
P_u	beam ultimate load
SR	strengthening ratio
t_a	thickness of the adhesive layer
t_p	thickness of one layer of CFRP sheet
Δ_u	midspan beam deflection at ultimate load
Δ_y	midspan deflection at yielding of tension steel reinforcement
β	shear retention
ε_{ct}	concrete peak tensile strain ($=f_{ct}/E_c$)
ε_p^t	CFRP sheet tensile rupture strain
ε_s	maximum tensile strain at which concrete tensile stress is equal to zero
ϕ	friction angle
μ_e	energy ductility index
μ_Δ	deflection ductility index
ψ	dilatation angle

tion in the FRP layer. The objective of the present paper is therefore to establish both experimentally and numerically the structural performance of FRP-strengthened RC beams incorporating a ductile ECC layer around the main flexural reinforcement. The load-carrying and deflection capacities as well as the maximum FRP strain at failure are used as criteria to evaluate the performance.

2. Experimental investigation

2.1. Experimental program

Two series of RC beams were included in the experimental program. One series consisted of two ordinary RC beams (beam A1 and A2) and another series consisted of two ECC layered beams (ECC-1 and ECC-2). In each series, one specimen was strengthened using externally bonded CFRP while the second was kept as a control in order to compare its load–deflection behaviour under third-point loading with the strengthened specimen. For all beams, the longitudinal reinforcements consisted of 3–10 mm diameter deformed bars in the tension zone and 2–10 mm diameter deformed bars in the compression zone, corresponding to reinforcement ratios of 1.71% tensile and 1.14% compressive. Shear reinforcement consisted of 6mm plane bar stirrups spaced at 60 mm c/c in the shear span and a clear cover of 15 mm was used throughout.

The ECC layer was about one third of the total depth of the beam as shown in Fig. 1 and only one layer of CFRP sheet was used to strengthen the beam. The specimen dimensions and reinforcement details of the ECC layered beams were similar to those of the ordinary RC beams (A1 and A2), except that for beam ECC-2,

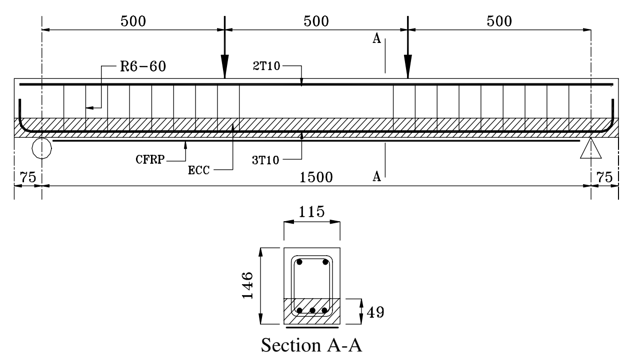

Fig. 1. Specimen geometry and reinforcement details.

the distance between the support and the CFRP cut-off point was increased from 25 to 100 mm to intentionally increase the peeling stresses in the region around the CFRP cut-off point.

The ECC material used in this investigation was reinforced with both high modulus (steel) and relatively low modulus (polyethylene) fibres with respective volume fractions of 0.5% and 1.5%. The properties of both fibres are given in Table 1. In addition, Type I portland cement, silica fume and superplasticizer were used to form the cement paste matrix. Further details on the mix constituents of the ECC and the concrete are given in Table 2. The material properties for the CFRP and those for the ECC and concrete at 28 days are shown in Tables 3 and 4, respectively. Tensile stress–strain curves obtained from ECC coupon specimens measuring $300 \times 75 \times 15$ mm are shown in Fig. 2. Further details regarding the ECC material and its properties can be found in Maalej et al. [8].

To measure the tensile strain distribution in the CFRP, the CFRP sheet in each strengthened beam