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NUMERICAL STUDY ON SHEAR BEHAVIOURS OF ECC BEAMS REINFORCED WITH FRP BARS

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Abstract: Fiber-reinforced polymer (FRP) bars have been widely used as novel concrete reinforcement due to its high tensile strength, good fatigue performance, and inherent corrosion resistance. However, the large deflection and crack width, as well as the low shear capacity and ductility of FRP reinforced concrete members always limit its application. Engineered cementitious composite (ECC) is a class of high performance cementitious composites with pseudo-strain-hardening behaviour and excellent crack control. Substitution of concrete with ECC can avoid the cracking and durability problems associated with brittleness of concrete. In this research, experimental work as well as nonlinear finite element analysis is conducted to study the shear behaviours of FRP reinforced ECC and concrete/ECC composite beams based on the software of ATENA. An appropriate constitutive model were applied in this simulation and the validity of the model was verified with the experimental results. According to the simulation result, substituting concrete with ECC partially in the tension zone of beam can effectively restrict the development of inclined cracks in concrete layer, and hence exhibits significant improvement in terms of shear carrying capacity, stiffness and deformation ability. To achieve a satisfactory cost efficient solution, an ECC layer in tension zone with thickness of 30% height of the beam is recommended for the design of FRP reinforced ECC/concrete composite beam.

1 INTRODUCTION

Substituting steel reinforcement with fiber-reinforced polymer (FRP) bars seems a promising solution to the durability concerns of reinforced concrete structures due to its inherent corrosion resistance. However, since FRP bars have a relatively lower modulus of elasticity compared with that of steel, FRP reinforced concrete members with the same reinforcement ratio will always exhibit larger deflections, crack widths and depths. Thus, the design of FRP-RC members is usually governed by serviceability performance [1]. Besides, deficiency of crack control capacity, and relatively low dowel action of FRP bars also decrease the shear capacity of concrete members reinforced with FRP bars [2].

Meanwhile, the absence of yielding plateau for FRP bars could always cause brittle failure with very limited ductility.

To enhance the shear capacity and ductility of FRP reinforced members, engineered cementitious composites (ECC) is proposed to replace the concrete partially or totally. Different from conventional concrete, ECC can exhibit a strain hardening and multiple cracking behavior under uniaxial tensile stress, with excellent crack control up to tensile strain of 3–5%. Flexural members can hence exhibit significant increases in ductility, load carrying capacity, and damage tolerance if concrete is replaced by ECC material [3-4]. In this paper, one FRP reinforced concrete beam, one FRP reinforced ECC beam, and two FRP reinforced concrete/ECC composite beams were tested to evaluate their shear behavior under four-point bending. Basalt fiber-reinforced polymer (BFRP) was used as the tensile reinforcement for all beam specimens. The influence of different parameters (including composite modes and substitution ratio) on the ultimate strength, deformation capacity, and ductility are evaluated based on the finite element analysis.

2 EXPERIMENTAL PROGRAM

2.1 Material properties

The matrix of ECC consisted of cement, water, fine sand, fly ash, and superplasticizer. The ratio of water to binder is 0.28. The fiber used for reinforcing the matrix was polyvinyl alcohol (PVA) short fiber. The fiber fraction was 2% in volume. The basic parameters of fiber included diameter d of 39 μm, length l of 12 mm, tensile strength f_t of 1,620 MPa, and tensile elastic modulus E of 42.8 GPa. A number of 150 mm cubic specimens were prepared with concrete and ECC, and tested in compression. The compressive strength of ECC and concrete are 25.05 MPa and 23.35 MPa, respectively. BFRP bars with diameters of 18 mm were used as tensile reinforcement for the FRP-reinforced beams. The elastic modulus and yield strength of BFRP bars are 40.5 GPa and 980 MPa, respectively. Steel bars with diameters of 8 mm were used as stirrups, the yield strength obtained through uniaxial tension tests were 463 MPa. Steel bars with diameters of 20 mm were used as compressive reinforcement, with the yield strength of 470 MPa. Fig. 1 shows the uniaxial tensile stress–strain curves of ECC, obtained from the uniaxial tensile test of dumbbell-shaped specimens.

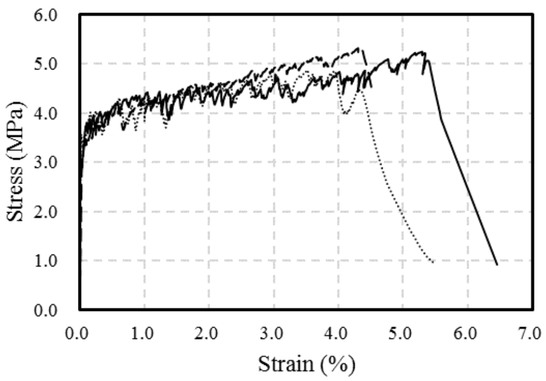


Figure 1: Stress-strain behavior of ECC under unixial tension

2.2 Specimen Preparation

Four BFRP reinforced beams were constructed and tested up to failure in total, including two ECC/concrete composite beams, one concrete beam and one ECC beam. All tested beams had the same size of cross section, with 210 mm in width and 300 mm in depth. The shear span was 650 mm for all beams, which corresponded to a shear span to effective depth ratio of 2.45. A stirrup ratio of 0.32% was designed in this test. Fig. 2 exhibits the configuration of tested beams. The reinforcement details of all specimens are summarized in Table 1. BRC means the BFRP reinforced concrete beam, BRE represents BFRP reinforced ECC beam, BREC-T means the BFRP reinforced ECC/concrete composite beam with an ECC layer of 90 mm from the bottom surface in the tension zone, and BREC-C stands for the BFRP-reinforced ECC/concrete composite beam with an ECC layer of 90 mm from the top surface in the compressive zone.

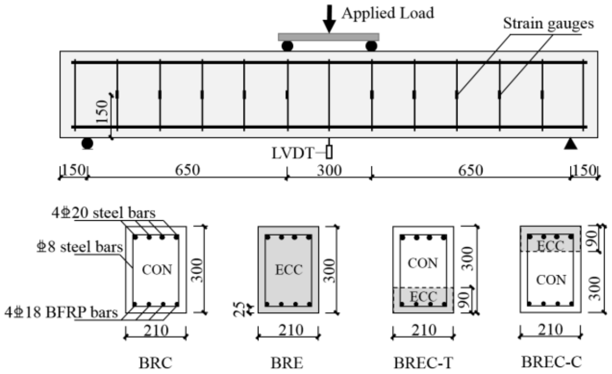


Figure 2: Schematic illustration of test setup and specimen details (mm)

Table 1. Summary of specimen information

Specimen	Main Bar		Stirrup
	Compression	Tension	
BRC	4Φ20	4Φ18	Φ8@150
BRE	4Φ20	4Φ18	Φ8@150
BREC-T	4Φ20	4Φ18	Φ8@150
BREC-C	4Φ20	4Φ18	Φ8@150

2.3 Experimental results

The load-deflection curves for all tested beams are shown in Fig. 5. It was found that the BFRP reinforced ECC beam increased shear capacity by about 10% and ultimate deformation by about 40% compared with the concrete counterpart beam. For concrete/ECC composite beams, BREC-T and BREC-B showed similar shear capacity. But substitution with ECC in tension zone showed much higher ductility as well as stiffness than substitution in compression zone, which brought about 54% increase of the ductility index. This was mainly because that substitution of concrete with ECC in tension zone could limit the formation and extension of shear cracks well.

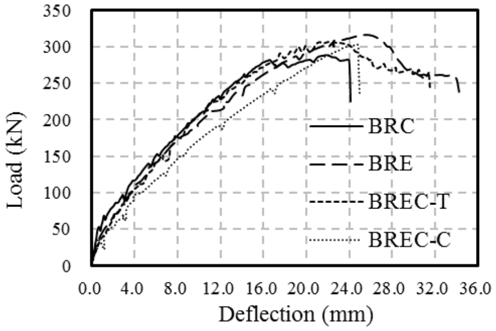


Figure 3: Load-deflection curves of tested beams

The final crack patterns for all specimens at ultimate failure are exhibited in Fig. 4.

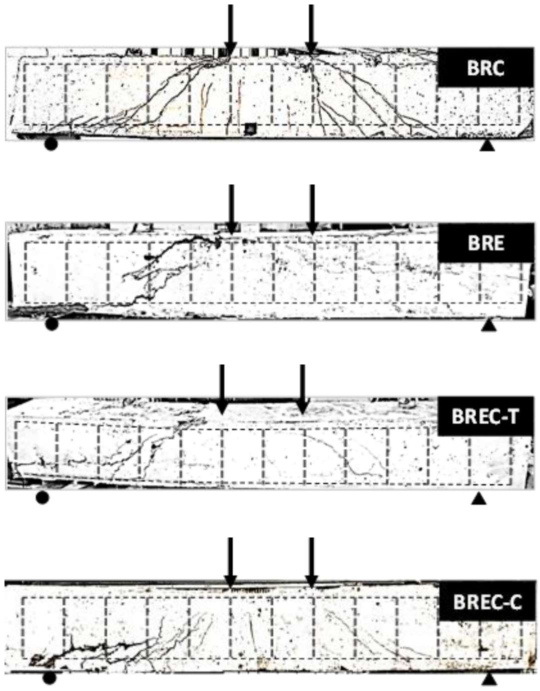


Figure 4: Failure modes of beam specimens

3 NUMERICAL STUDY

The shear behaviors of all tested beams are numerically modeled with the nonlinear finite element software ATENA.

3.1 Material model and bond–slip behavior

In this program, a fracture-plastic model named *Cementitious 2 SHCC* was specially developed for strain-hardening cementitious composites with a modified tensile behavior and shear retention. A simplified tri-linear stress-strain curve is adopted to model the tensile behavior of ECC material according to the aforementioned direct tensile tests, as shown in Fig. 5(a). The compressive stress-strain of ECC consists of initial elastic stage, elastic-plastic stage and a double-linear softening stage, which was proposed by Zhou et al. [5], as shown in Fig. 5(b). Material properties for ECC are listed in Table 2. The fracture-plastic model *NonLinCementitious2* provided by ATENA is used to simulate the quasi-brittle behavior of concrete. The steel bars are described by a bi-linear curve by considering its strain-hardening behavior, and the BFRP reinforcement is considered as linear elastic material.

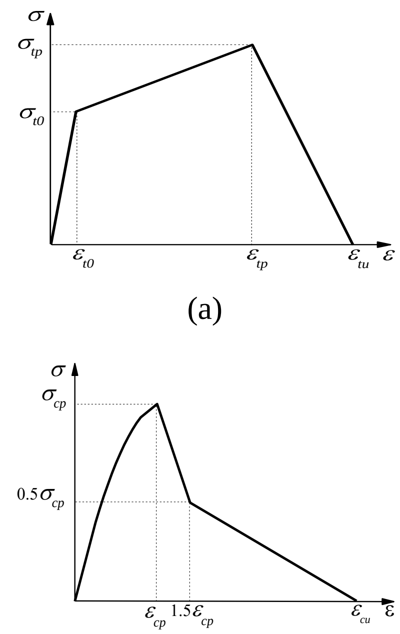


Figure 5: Stress-strain relationship of ECC: (a) under uniaxial tension; (b) Under uniaxial compression

Table 2. Material properties for ECC

ε_{t0}	0.00025
ε_{tp}	0.0415
ε_{tu}	0.0559
ε_{cp}	0.004
ε_{cu}	0.03
σ_{t0} (MPa)	3.49
σ_{tp} (MPa)	5.14
σ_{cp} (MPa)	25.05

In this research, the four-linear bond–slip model in ATENA was applied to simulate the bond–slip behavior between FRP and concrete, which is shown in Fig. 6 and illustrated as follow [6]:

$$\tau = \begin{cases} \tau_{max}(\frac{s}{s_1})^{0.4} & 0 \le s \le s_1 \\ \tau_{max} & s_1 < s \le s_2 \\ \tau_{max} - (\tau_{max} - \tau_f)\left(\frac{s-s_2}{s_3-s_2}\right) & s_2 < s \le s_3 \\ \tau_f & s_3 < s \end{cases} \quad (1)$$

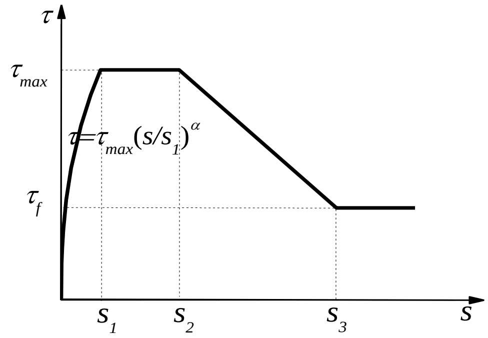


Figure 6: Bond-slip behavior between BFRP reinforcement and concrete

where $\tau_{max} = 2.5\sqrt{f_c}$, $f_c = 23.35$ MPa, $\tau_f = 0.4\tau_{max}$, $s_1 = 1.0$ mm, $s_2 = 3.0$ mm, and $s_3 = 7.0$ mm. A similar expression can be adopted to represent the bond behavior between BFRP bars and ECC matrix according to the experimental study conducted by Wang et al. [7], where $\tau_{max} = 3.0\sqrt{f_c}$, $f_c = 25.05$ MPa, $\tau_f = 0.7\tau_{max}$, $s_1 = 2.0$ mm, $s_2 = 4.0$ mm, and $s_3 = 11.0$ mm.

Three-dimensional finite element models were adopted to simulate the experimental beam specimens, and a half of the beam model was set up for numerical analysis according to the symmetry of the beam about its vertical axis.

3.2 Verification of numerical model

Fig. 7 exhibits the comparison of load-deflection curves between the simulation and test results. Generally, the simulation results are in good agreement with the experimental results. The simulated final crack patterns for all specimens at ultimate failure are exhibited in Fig. 8. Both of failure modes and crack patterns are similar to the experimental results, thus the validation of the proposed finite element model to study the shear performances of ECC and concrete beams reinforced with BFRP are verified.

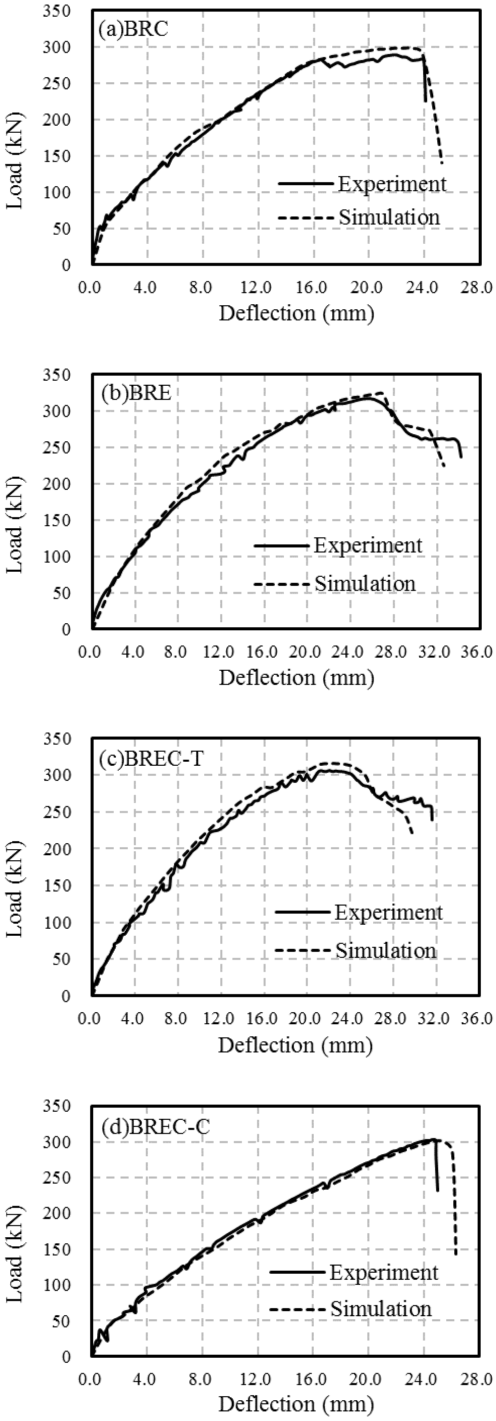
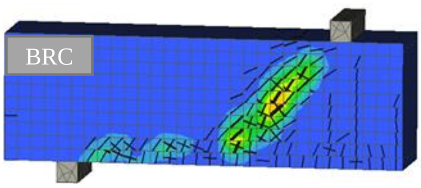


Figure 7: Load-deflection curves for both experiments and finite element analysis



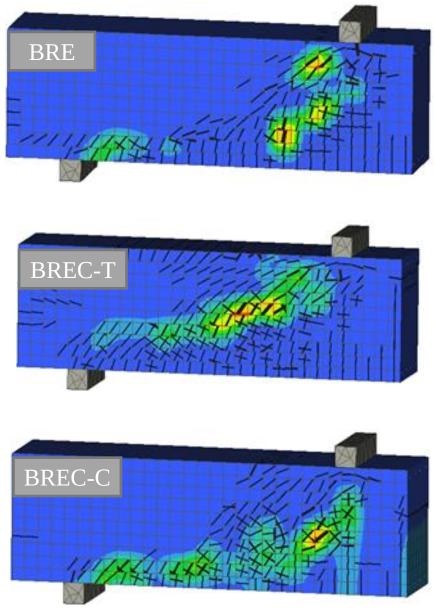


Figure 7: Load-deflection curves for both experiments and finite element analysis

3.3 Parametric analysis

Since the cost of ECC is much higher than conventional concrete, parametric analysis can be conducted to study the influence of ECC thickness and position on the shear behaviour of BFRP reinforced beams for achieving a satisfactory performance/cost ratio.

Table 2. Summary of simulated specimens

ECC position	ECC thickness (mm)	Ultimate shear force (kN)
---	0	146.6
Full-height	300	161.5
Tension zone	30	151.8
	60	154.5
	90	157.9
	120	158.8
	150	159.1
Compression zone	30	148.6
	60	151.7
	90	152.1
	120	153.6
	150	155.2

Table 2 exhibits the effect of ECC position and thickness on shear carrying capacity of ECC/concrete composite beams. In general, with the identical ECC thickness, substituting concrete with ECC in tension zone of the beam specimen can obtain higher shear carrying capacity than in compression zone, since the strategic use of ECC in tension zone can restrict the development of flexure-shear crack in concrete effectively. On the whole, an evident increase of ultimate shear carrying capacity can be observed for the composite beam with ECC layer in tension zone at the substitute ratio of 0.3, indicating that substituting concrete with ECC in tension zone with a depth ratio of 0.3 would be a proper parameter for designing FRP reinforced ECC/concrete composite beam.

4 CONCLUSIONS

In this paper, the shear behavior of BFRP reinforced ECC/concrete composite beams are investigated. An appropriate constitutive model were applied in the simulation work and the validity of the model was verified with the experimental results. According to the experiment as well as simulation result, substituting concrete with ECC in tension zone can effectively restrict the development of inclined cracks in concrete layer, and hence exhibits significant improvement in terms of shear carrying capacity, stiffness and deformation ability. To achieve a satisfactory cost efficient solution, an ECC layer in tension zone with thickness of 30% height of the beam is recommended for the design of FRP reinforced ECC/concrete composite beam.

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