Effect of Layer Thickness and FRP Reinforcement Ratio on the Load Carrying Capacity of ECC Composite Beams

Preethy Mary Arulanandam, Madappa V. R. Sivasubramanian, and Shamsher Bahadur Singh

Abstract In recent years, Fibre-Reinforced Polymer (FRP) bars have been used as reinforcement in concrete beams. However, the ductility of the beams is highly dependent on the properties of concrete since the failure mode of concrete is due to crushing. Substitution of concrete with Engineered Cementitious Composite (ECC) can avoid the ductility and durability problems associated with the concrete. In this paper, the flexural behaviour of FRP reinforced ECC-Concrete composite beams is numerically investigated through the Finite Element (FE) platform. To verify the robustness of the FE model of the composite beams, the simulation results were compared against the experimental results available in the literature and good agreements were achieved. An extensive parametric study was then conducted to examine the effect of the FRP reinforcement ratio against ECC layer thickness. It was observed that the load-carrying capacity of the composite beams is improved with the increase in ECC height replacement and Basalt Fibre Reinforced Polymer (BFRP) reinforcement ratios. In addition, composite beams show enhanced load-carrying capacity of 40% and 2%, of ECC layer thickness and FRP reinforcement ratio, respectively.

Keywords ECC · FRP · Layer thickness · Reinforcement ratio

1 Introduction

Reinforced concrete (RC) structures exposed to corrosive environments, such as de-icing salts, chemical treatment plants, structures built in or close to seawater, etc., are suitable to be reinforced with Fiber-Reinforced Polymer (FRP) bars to eliminate durability problems [1]. Over the past two decades, FRP materials have been used

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as an alternative for steel reinforcement in concrete structures [2, 3]. However, FRP reinforcement has low elastic modulus and linear deformation properties, leading to large deflections and crack widths which leads to brittle failure, which has prevented FRP structures from being widely used [4].

Engineered Cementitious Composite (ECC) is a cement-based composite material exhibiting superior ductility (typically >3%, 300 times that of normal concrete or FRC), tight crack width (less than 80 μm), and relatively low fiber content (2% or less of short randomly oriented fibers) [5, 6]. ECC's ultimate tensile strength and tensile strain capacities are 5–8 MPa and 3–5%, respectively. ECC's compressive strength and compressive strain capacity range from 30 to 90 MPa and 0.45–0.65%, respectively [7]. ECC exhibits superior tensile strain hardening and multiple cracking behaviors by systematically tailoring the fiber, matrix, and interface properties, guided by micromechanics principles [8].

In order to enhance both the ductility and durability of structures, researchers proposed FRP reinforced ECC-Concrete composite beams. The excellent crack control ability and durability of ECC materials have encouraged the use of ECCs in the tensile zone around longitudinal steel reinforcement [9, 10]. The results showed that the flexural capacity and deformation ability slightly improve, but the crack width before yielding of steel reinforcement significantly decreases to just 20% of that in conventional RC beams [11, 12]. ECC-concrete composite beams reinforced with FRP bars were also to solve cracking and deflection problems associated with the brittleness of FRP-reinforced beams [13, 14].

2 Research Significance

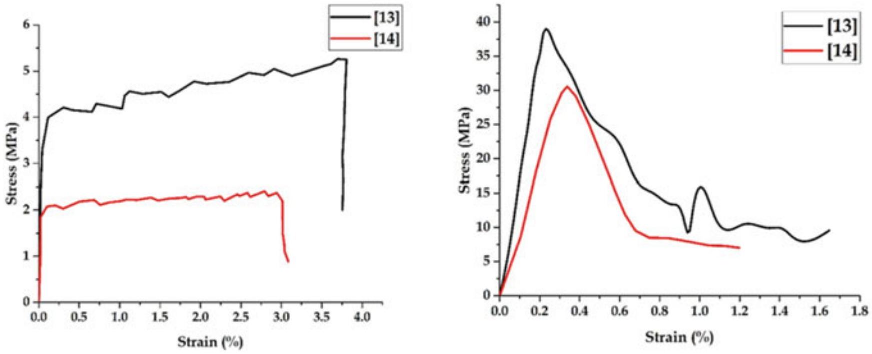
Strength and ductility are critical parameters in the design of concrete structures. It is anticipated that utilizing FRP bars and ECC at strategic locations in the RC beam elements will give promising results in high strength and ductility. However, the successful utilization of ECC requires robust analysis and design procedures. Studies available in the literature deal only with modelling and analysis of FRP reinforced composite beam against particular ECC layer thickness and FRP reinforcement ratio. Hence, in this study, the numerical analysis of FRP reinforced ECC-Concrete composite beams with different reinforcement ratios against ECC layer thickness are investigated and presented the effects on the flexural capacity of the composite beams.

3 Finite Element Analysis

This research study is conducted on the nonlinear analysis, and the response of FRP reinforced ECC-Concrete composite beams under monotonic loading through FE analysis on the ABAQUS platform. The numerical investigation for the response of FRP reinforced ECC-Concrete composite beams under monotonic loading was performed in ABAQUS finite element software. For this purpose, three Basalt Fibre Reinforced Polymer (BFRP) reinforced ECC-Concrete composite beams chosen from the literature [13, 14] were modelled and analysed. The numerical results are obtained in terms of load–deflection response and compared with the experimental results.

Constitutive Model and Plasticity Parameters

In the present study, ECC and concrete are modelled using the damage plasticity model available in the ABAQUS nonlinear program to define the damage and failure mechanisms [15]. Uniaxial tensile and compression stress–strain responses (Fig. 1) are employed to develop the constitutive behaviour of the materials. The input parameters needed to model the constitutive behaviour of composite beams is presented in Table 1.



(a) Tension

(b) Compression

Fig. 1 Stress–strain behaviour of ECC

Table 1 Input parameters required for FE analysis

Properties	ECC		BFRP	
	[13]	[14]	[13]	[14]
First cracking strength (MPa)	2.8	2.0	Not applicable	Not applicable
First cracking strain (%)	3.20×10^{-4}	0.023	Not applicable	Not applicable
Tensile strength* (MPa)	4.6	2.4	907	1250
Ultimate tensile strain	0.018	0.025	0.0196	0.026
Young's modulus (GPa)	15.50	16.15	46.2	50
Compressive strength# (MPa)	38.3	31.4	Not applicable	Not applicable

*Tensile test values are taken from the uniaxial test of ECC coupons and dogbone specimens
#Compressive test values are taken from the compression test of ECC cubes and cylinders

This model incorporates two main failure mechanisms in the form of tensile cracking and compressive crushing. Thus, damage parameters, strain hardening, and strain-softening rules for ECC and concrete materials are duly incorporated in this study. The compressive and tensile damage parameters (d_c and d_t) are calculated based on Eqs. (1), (2), respectively,

$$d_c = 1 - \frac{\sigma_c E_c^{-1}}{\varepsilon_c^{pl}(1/b_c - 1) + \sigma_c E_c^{-1}} \tag{1}$$

$$d_t = 1 - \frac{\sigma_t E_c^{-1}}{\varepsilon_t^{pl}(1/b_t - 1) + \sigma_t E_c^{-1}} \tag{2}$$

where σ_c and σ_t are compressive and tensile stresses, respectively, E_c is the modulus of elasticity, ε_c^{pl} and ε_t^{pl} are plastic strains corresponding to compressive and tensile strengths, respectively. $b_c = \frac{\varepsilon_c^{pl}}{\varepsilon_c^{in}}$, ε_c^{in}—compressive inelastic strain, $b_t = \frac{\varepsilon_t^{pl}}{\varepsilon_t^{cr}}$, ε_t^{cr}—tensile cracking strain. b_c and b_t are the constant parameters that can vary from 0 to 1, whereas 1 means no damage and 0 means total damage.

The plasticity parameters following the Drucker-Prager criteria are employed to define the failure of ECC and concrete materials, which are present in [16] (Table 2).

Details of the Experimental Study

The details of the composite beam specimens available in the literature, which are used in this study, are presented in Table 3. During the experimental study, all the beam specimens were tested under vertical monotonic loading and the mid-point load–deflection response was measured. The loading patterns of the beam specimens are shown in Fig. 2.

Modelling of Composite Beams

The modeling procedure for the selected composite beams in the ABAQUS platform is discussed in this section. ECC and concrete are modeled using 8-noded linear hexahedral solid elements with reduced integration (C3D8R). A 2-noded nonlinear truss element (T3D2) is used for steel reinforcement. The embedded

Table 2 Details of plasticity parameters

Parameter	Value	Description
ψ (°)	20 (ECC) 36 (Concrete)	Dilation angle
ε	0.1	Eccentricity
σ_{b0}/σ_{c0}	1.16	The ratio of biaxial compressive ultimate strength to uniaxial ultimate compressive strength
K_C	0.67	A ratio of the second stress invariant on the tensile meridian to that on the compressive meridian
μ	0.01	Viscosity parameter

Table 3 Details of beam specimens

S. No.	Beam ID	Dimensions ($b \times d \times l$)* (mm)	FRP type	Reinforcement ratio (%)	ECC layer thickness (mm)
1	EC-1 [13]	200 × 300 × 2350	BFRP	1.05	90
2	EC-2 [14]	150 × 200 × 1500	BFRP	0.57	50.75
3	EC-3 [14]	150 × 200 × 1500	BFRP	0.57	99.75

*(b = breadth, h = height, l = span)

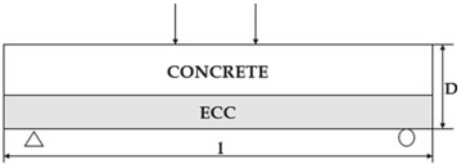


Fig. 2 Loading pattern of composite beams

method with the perfect bond between reinforcement and the surrounding material is adopted to simulate the reinforcement-material bonding interaction properly. In addition to this, for composite beams, a perfect bond was assumed between concrete and ECC since experimentally, no debonding was observed between the materials. Hence, tie constraint (surface-to-surface property) generates the composite action. The boundary (simply supported ends) and loading conditions (two-point loading) were specified in the analysis. The geometry, reinforcement, boundary conditions and loading pattern of the composite beam simulated are shown in Fig. 3. The meshing of the beam element is performed by employing fine mesh (i.e., 30 × 30 mm mesh size) to attain an accurate response with the experimental results. An incremental displacement-control program was adopted to analyze the selected FRP reinforced composite beams.

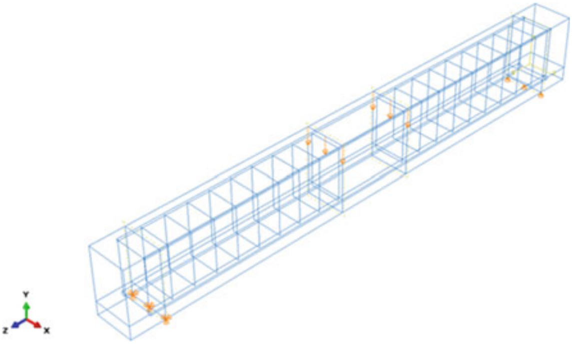


Fig. 3 Composite beam simulated in ABAQUS

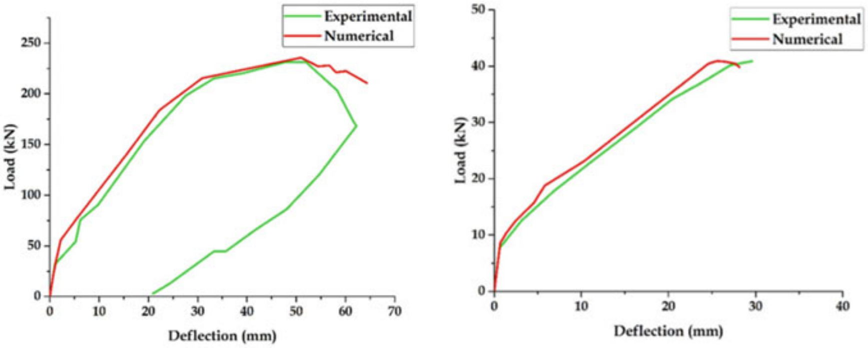
4 Verification of Numerical Models

In this section, the load–deflection response of all the composite beams has been evaluated numerically and compared against the experimental results. The verification and discussion of the obtained results were discussed as follows.

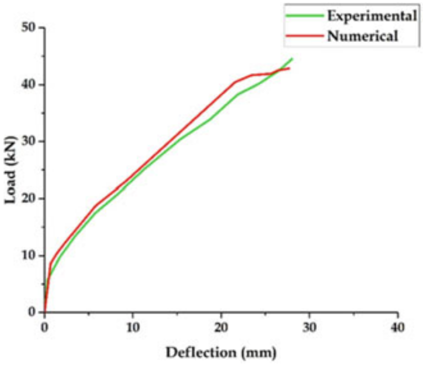
Load–Deflection Response

To understand the effectiveness of the procedure adopted for the numerical simulation, the load–deflection response of the composite beams obtained from the FE analysis were compared against the results from the experimental study (Fig. 4).

In general, from Fig. 4 it can be seen that the numerical response shows good agreement with the experimental response. From Table 4, it can be observed that the difference between the numerical and experimental responses of the composite beams is less than 5% for all composite beams. This shows the robustness of the numerical procedure adopted for the analysis of the FRP reinforced composite beams.



(a) EC-1 *(b) EC-2*



(c) EC-3

Fig. 4 Load–deflection response of composite beams

Table 4 Comparison of results

S. No.	Specimen ID	Ultimate deflection (mm)		Ultimate load (kN)		% difference in load
		Experimental	Numerical	Experimental	Numerical	
1	EC-1 [13]	51.9	50.9	231.2	235.7	1.93
2	EC-2 [14]	29.7	26.1	40.9	41.2	0.73
3	EC-3 [14]	28.1	27.6	44.5	42.8	3.82

5 Parametric Study

As is stated above, the numerical load–deflection behaviour agrees well with the experimental behaviour which shows the robustness of the employed numerical procedure. Hence, it is appropriate to adopt the same procedure for the parametric study. The parametric study includes:

- Effect of ECC layer thickness against various FRP reinforcement ratio
- Effect of FRP reinforcement ratio against various ECC layer thickness.

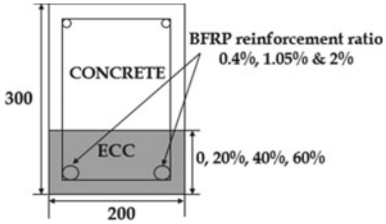
The parametric study is done to understand the effect of ECC layer thickness and BFRP reinforcement in the composite beam. For this purpose, a constant cross-section of the beam is used whereas the ECC layer thickness and BFRP reinforcement ratio are varied. The cross-section of the composite beam along with ECC layer thickness and BFRP reinforcement ratio is shown in Fig. 5.

Effect of ECC layer thickness against various FRP reinforcement ratio

In this section, the selected FRP reinforcement ratios are analysed for five different ECC layer thicknesses (i.e., 0, 20, 40 and 60% of the beam depth) to investigate the effect of various ECC layer thickness against each reinforcement ratio in composite beams.

The effect of the load-carrying capacity of the ECC-Concrete composite beams with different ECC layer thicknesses is shown in Fig. 6. It is observed that an increase in ECC layer thickness increases the load-carrying capacity of the beam, after a peak load is achieved, the load-carrying capacity decreases as an increase in ECC layer thickness. This behavior is observed in all composite beams employed in this study, irrespective of the reinforcement ratio. For a composite beam of a particular cross-section, 40% ECC layer thickness exhibits enhanced load carrying capacity

Fig. 5 Cross-section detail of composite beam



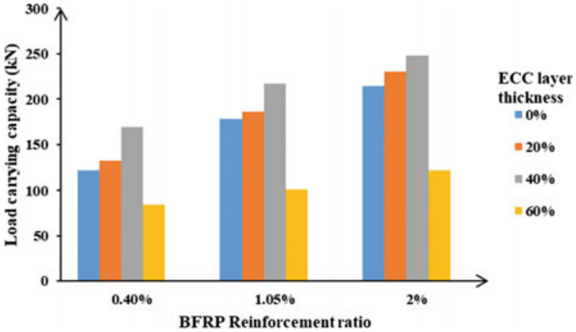


Fig. 6 Load versus FRP reinforcement ratio

for all reinforcement ratios used. However, with a further increase of the ECC layer thickness, the ultimate load carrying capacity of the composite beams were reduced to some extent. This was mainly because as the height of the ECC in the cross-section increased, and extent above the neutral axis where ECC materials are participated in the compressive zone. The incorporation of PVA fibres increases the porosity of the cement-based materials, which leads to internal structural damage, which in turn affects the compressive capacity of the beams. As the load increased, the overall load bearing capacity decreased. Therefore, there was an optimal range for cross-section replacement ratios. Hence, for this study the 40% ECC height replacement of the composite beams could obtain better mechanical properties and economic benefits.

Effect of FRP reinforcement ratio against various ECC layer thickness

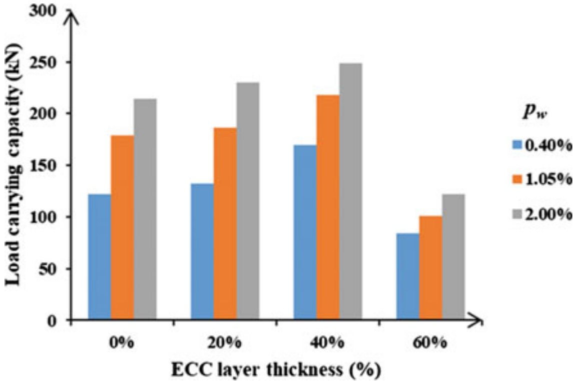
In this section, the selected ECC layer thickness is analyzed for various FRP reinforcement ratios (0.4, 1.05 and 2%) to investigate the effect of reinforcement ratio for each ECC layer thickness in composite beams.

The effect of the load-carrying capacity of the ECC-Concrete composite beams with different FRP reinforcement ratios is shown in Fig. 7. It is understood that an increase in FRP reinforcement ratio increases the load-carrying capacity of full concrete and for all ECC-Concrete composite beams irrespective of the ECC layer thickness. Further, it is observed that the highest reinforcement ratio of 2%, showed enhanced load carrying capacity for the composite beam with 40% ECC layer thickness.

6 Conclusion

This study is conducted on the numerical analysis of BFRP reinforced ECC-Concrete composite beams and the obtained results are verified against the experimental studies. Upon analysis, the load–deflection response was generated. Based on the numerical and experimental results, the following conclusions are drawn:

Fig. 7 Load versus ECC layer thickness



- The material constitutive model and plasticity parameters in the damage plasticity model are effectively used to define the behavior of ECC, concrete and FRP in the analysis.
- Close agreement between the numerical and experimental results is observed. In addition, the difference between the peak load of the numerical and experimental responses of all the reinforced beams is within the range of 5%, which shows the robustness of the procedure adopted for FE models.
- Generally, the load-carrying capacity of the composite beams is improved with the increase of the ECC height replacement and BFRP reinforcement ratios.
- Composite beams of a particular cross-section exhibit enhanced load carrying capacity of 40 and 2%, of ECC layer thickness and FRP reinforcement ratio, respectively.

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