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Experimental and Numerical Study on Flexural Strength of ECC –Steel Composite Beams

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Concrete brittleness pave way for crushing of concrete slab before the yielding of steel section. An innovative solution to this problem is the replacement of normal concrete with Engineered Cementitious Composite (ECC) which has a higher compressive strain than concrete. Steel-concrete composite beams are structural elements in which concrete slab is connected to a steel beam with shear connectors. A numerical study was conducted on ECC-Steel composite beam using Finite Element (FE) software, ABAQUS. The beam was found to fail in a sequence, involving crushing of ECC slab in the bending region followed by yielding of bottom flange of beam. An experimental programme (four-point bending test) was conducted to validate the numerical results. The model satisfactorily predicted the experimental results and thus the validity of the model was justified. Also, the flexural behavior of conventional Steel- Concrete composite beam of M30 grade was compared with ECC- Steel composite beam. The load carrying capacity of ECC-Steel composite beam of M30 grade was 3.7 % more than that of its normal concrete counterpart.

1. Introduction

Steel-Concrete Composite beams are worldwide used structural elements in which concrete slab is connected to a steel beam with shear connectors. Composite construction combines the advantages of both non-composite steel frames and reinforced concrete frame systems (Stüssi,1947; Aziz, 1986; Bradford and Gilbert, 1992; Fu, 2008 Faella et al., 2010; Cui et al., 2018, Zhang et al., 2019). The advantage of prefabrication is retained, and the steel and concrete are utilised efficiently. The strength and stiffness of the steel beam is considerably increased by virtue of composite action. Moreover, due to the composite action the local and lateral torsional buckling and crippling of the steel beam is reduced and due to this the application of composite beam in longer spans has also increased. For the same span and loading conditions, composite construction provides a more economical steel section (in terms of depth and weight) when compared with the conventional non composite construction. Since the beam depth is reduced with the implementation of composite approach, enhanced headroom is possible in structures.

The class of highly ductile fibre reinforced cementitious composites known as Engineered

Cementitious Composites, or ECCs, was first developed at the University of Michigan in the early 1990s (Li et al.,1993). High ductility in the 3–7% range, a tight crack width of around 60 μm, and a comparatively low fibre content of 2% or less by volume are the characteristics of this class of materials (Weimann and Li, 2003). ECC is a cement based composite material containing discontinuous short polymeric fibres performing strain hardening behaviour and high ductility (Zhou et al.,2019). ECC generally consists of cement, supplementary cementitious materials like fly ash, fine aggregate, water, admixture and discontinuous short polymeric fibres (Zhang et al., 2019). ECC exhibits strain hardening behaviour and high ductility at relatively lower fibre volume fractions when compared with other High Performance Fibre Reinforced Cementitious Composites (HPFRCC) (Zhu et al., 2012). The minimum compressive strain of ECC is 0.5 % which makes it a suitable substitute for normal concrete having a compressive strain in the range of 0.23-0.35 % (Zhang et al., 2015). With less than 2% fibre volume fraction, ECC has high tensile ductility and toughness with tensile strain capacity typically ranging from 3% to 12% under uniaxial tension (Costa et al.,2015). The special composition of ECC makes it costlier than the conventional concrete. Most of the researches used micro silica sand as the fine aggregate in ECC mix which is expensive even though it is able to achieve a tensile strain capacity of 4 %. Suitable replacement of fine aggregate with locally available materials is one of the easiest ways to reduce the cost as well as density of the engineered cementitious composite mix (Costa et al., 2019).

Kabir et al. (2019) studied the flexural and bond slip behaviour of ECC encased steel composite beams when PVA fibres were used with different ECC-LWC (Light Weight Concrete) configurations. A four-point bending test was conducted on four composite beams of different ECC-LWC configurations and it was observed that the flexural resistance of the composite beams increased with increase in the yield strength of the steel section. It was observed that there was no significant improvement in flexural strength with increase in ECC thickness or compressive strength of LWC. Some significant flexural improvements were noticed with increase in ECC strength and HSS section web thickness. Nguyen et al. (2021) studied the flexural behaviour of ECC-HSS composite beams when Hybrid Polyethylene Steel Fibres were incorporated in ECC mix. Shear connection was ensured with headed shear studs and normal profiled steel sheeting (PSS). Four composite beams were subjected to four-point bending test. A control specimen with normal concrete slab and three ECC slabs were used for the experiment. The experimental results were complemented with a finite element model in ABAQUS. The flexural capacity of the tested ECC-HSS composite beam only showed a slight increase when compared with its NSC counterpart. However, all HSS-ECC composite beams showed high ductility and softening behaviours after passing the peak load when compared with the NSC-HSS composite beams.

The main objective of the paper is to study the flexural strength and behaviour of ECC- Steel composite beam both experimentally and numerically. The flexural strength and failure pattern was determined numerically by conducting finite element analysis in ABAQUS software. The ECC – Steel composite beam was designed and detailed according to the codal provisions of AISC 360-16, IS 800-2007 and IS 11384-1985 respectively and guidelines of INSDAG teaching resource for structural design.

2. Material Properties

Selection and proportioning of the constituent materials of ECC is to be carried out so as to produce a composite which are mainly characterized by its fine pore micro structure. The main ingredients used in the study are Ordinary Portland Cement of 53 grade, fly ash, silica fume, river sand passing through IS 600-micron sieve, polypropylene fibre, steel fibre and water. After an extensive trial and error, the ECC mix with a 28-day compressive strength of 30 MPa was achieved. The various weights of component materials in ECC mix are given in Table 1.

Table 1. ECC Mix Design

Material	Weight (kg/m^3)
Cement	400
Fly Ash	320
Silica Fume	80
River Sand	320
Water	248
Steel Fibre	78.5
Polypropylene Fibre	9.2
Water cement ratio	0.31

The composite beam used for the study consisted of steel I section fabricated by welding steel plates, profiled steel sheeting obtained by sheet pressing technique, headed shear stud connectors and steel reinforcements. To determine the stress-strain characteristics of the steel elements in tension, tensile coupons were conducted on these test specimens. Two different diameters of reinforcements were used for the construction of ECC-Steel composite beam. The steel beam of the composite structure is an I section which is fabricated by welding steel plates of 10 mm thickness (flange) with steel plate of 6 mm thickness (web). The PSS (Profiled steel sheeting) was manufactured by pressing steel sheet of 4 mm thickness.

Table 2. Material Properties of Steel

Sl.No	Material	Yield Strength (MPa)	Yield strain (mm/mm)	Ultimate strength (MPa)
1	Bar 8 mm φ	443.02	0.0022	556.22
2	Bar 6 mm φ	537.78	0.0027	608.91
3	Flange 10 mm thick	367.88	0.0018	436.05
4	Web 6 mm thick	359.7	0.0018	479.46
5	PSS 4 mm thick	330.68	0.0016	447.58

3. Design and detailing of ECC-Steel Composite Beam

The design of steel concrete composite beam was carried out as per IS 800: 2007 and IS 11384: 1985. Since, there is no mention of profiled steel sheeting in the Indian code; AISC 360-16 was used to fix the design of profiled steel sheeting. Also, the guidelines provided by INSDAG were followed for the design. Figure 1 shows the geometric properties of ECC Steel Composite

Beam.

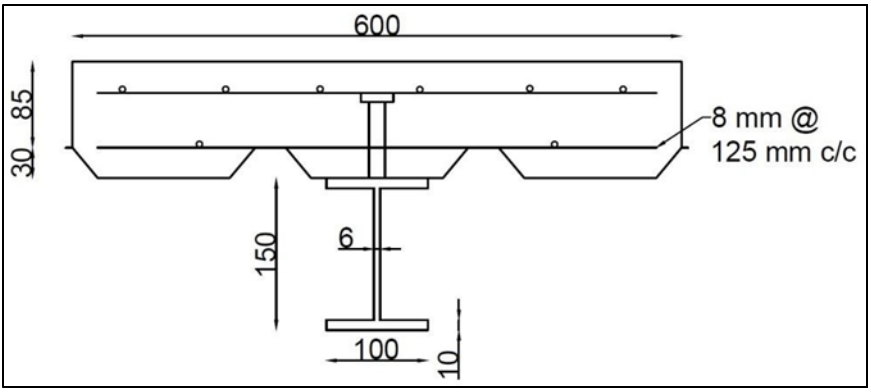

Figure 1 Geometric Properties of ECC Steel Composite Beam

4. Finite Element Modelling

Experimental research on the flexural behaviour of ECC-Steel composite beams consisting of steel I section beams connected to ECC slab with shear headed studs is expensive, time consuming and requires strong labour force. Hence, it is preferable to propose a numerical finite element model with constitutive material models and a reliable finite element modelling technique to simulate the nonlinear behaviour of ECC-Steel composite beams. A numerical study using FE method was conducted to understand the flexural behaviour of ECC-Steel composite beams. In this numerical study, a 3D nonlinear FE modelling procedure was first developed by using the general-purpose FE package ABAQUS. The material properties of steel and concrete for this purpose were determined experimentally. The influence of different contact interactions was observed and a suitable contact between concrete and steel was identified to get a proper model. Both geometric and material nonlinearities were considered in the FE model. The peak load, failure modes and load-deflection behaviour were observed in this study.

For the analysis of structural member, ABAQUS has been chosen for the purpose of modelling and analysing composite beams due to its flexibility in creating geometry and material modelling. This modelling procedure employed appropriate material constitutive models to define the stress–strain relationships of different components (ECC, PSS, Stud, Steel Section and reinforcement mesh) of the composite beams. In addition, suitable contact interactions and boundary conditions corresponding to the four-point bending tests were specified in the models. Non-linear analysis was carried out in the FE analysis.

Steel I section, profiled steel sheeting, shear headed studs, ECC, longitudinal and transverse reinforcements are the materials required to construct ECC-Steel composite beam. The FE model takes into account the nonlinear behaviour of these materials. The specimen comprised of ECC slab of thickness 115 mm supported by a formwork of profiled steel sheeting. The slab was connected to flange of steel I section of dimensions 100 mm × 10 mm with headed shear studs of shank diameter 16 mm. The length of the beam was 1.5 m. The cross section of the composite beam is shown in Figure 2.

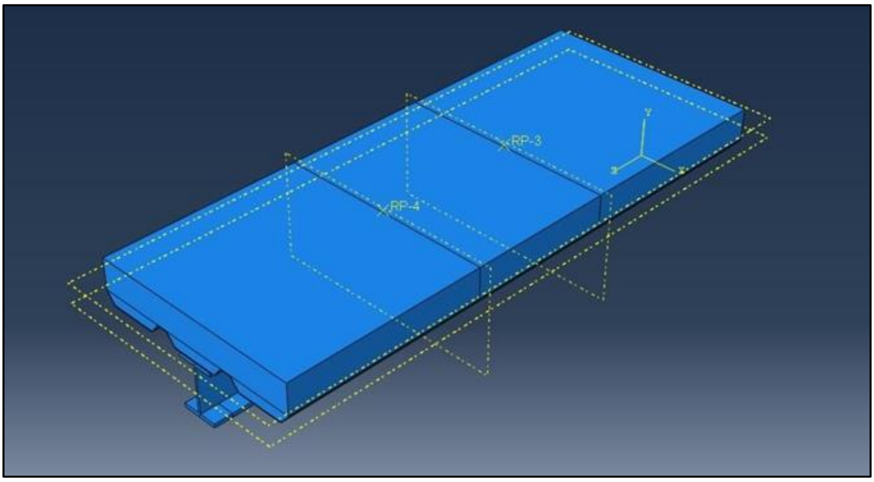

Figure 2. Assembled model of specimen

M30 Grade ECC was used for the modelling. To incorporate the material nonlinearity in ECC specimen to carry out nonlinear analysis, concrete damaged plasticity model in ABAQUS was adopted to define ECC material. The modulus of Elasticity of ECC in the study was calculated from the expression E = 1.5 × $(f_C)^{0.638}$, where f_C is the compressive strength of ECC, as shown in Figure 3. The stress strain curve of ECC adopted for the study is shown in Figure 4. The material property and behaviour for the flange and web of steel section, PSS, stud and reinforcement are different from each other. The flange and web of steel section were modelled using the bilinear stress strain relations. The model for steel reinforcement is similar to that of structural steel. However, for steel reinforcement, initial modulus of elasticity at the onset of strain hardening should be taken as 0.03 times initial modulus of elasticity. The elastic-perfectly plastic model was used to reflect the behaviour of PSS.

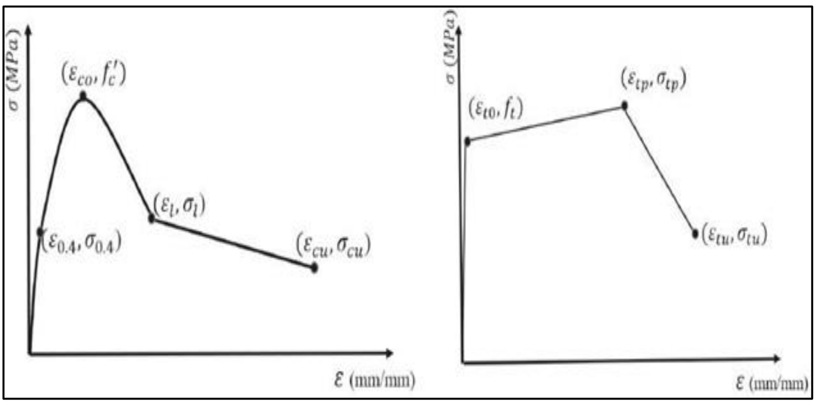

Figure 3. Compressive and Tensile Stress Strain Curves for ECC (Nguyen and Lee, 2021)

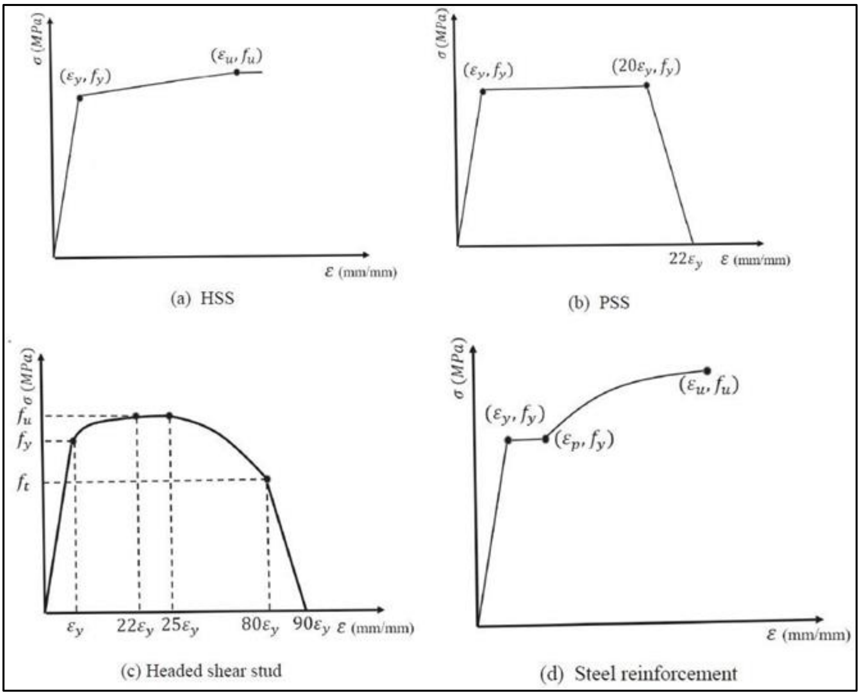

Figure 4. Stress Strain models for materials (Nguyen and Lee, 2021)

A full range stress-strain curve was used to model shear headed studs. Values of the material parameters obtained from the coupon test such as yield strength, yield strain and ultimate strength are indicated in Table 2. Surface to surface contact interaction was provided between steel beam and PSS, PSS and slab. A frictional coefficient of 0.5 was adopted for tangential direction. Hard contact was provided for normal direction. Since, the studs are to be welded to the flange plate in actual practice, tie constraints were provided to connect them. The interaction between reinforcement meshes and ECC slab was ensured using the embedded region option in ABAQUS. Also, the studs were embedded into the slab using the embedded region option. In the FE model, the simply supported boundary conditions applied during four-point bending tests were reproduced by imposing the roller support boundary conditions at one end of the beam and the pin support boundary conditions at the other end. The load was applied to the structure using the MPC beam constraint option in ABAQUS. All components except PSS and reinforcements were modelled using eight-node hexahedral solid elements with reduced integration (C3D8R). The element size for both steel beam and slab were 60 mm. PSS was modelled using the four-node shell elements (S4R) of element size 60 mm. The reinforcement meshes were modelled using three-node truss elements (T3D2) of size 100 mm. The element size for studs was 10 mm.

The load deflection graph was obtained from the finite element analysis which is shown in Figure 5. The beam was found to fail under a sequence involving crushing of ECC slab in the bending region followed by yielding of bottom flange of beam. A peak load of 250.34 kN was reached when crushing of ECC occurred. The post peak behaviour indicated that the beam continued to show high ductility with gradual load reduction. Figure 6 shows the Damage and failure pattern of ECC-Steel composite beam

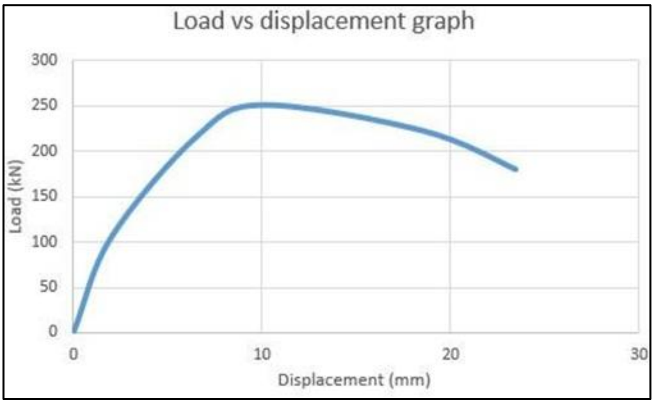

Figure 5. Load Displacement Curve for ECC-Steel Composite Beam

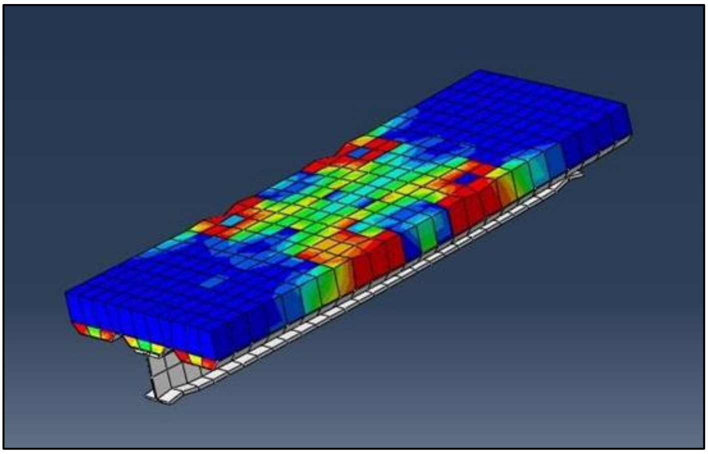

Figure 6. Damage and failure pattern of ECC-Steel composite beam

5. Experimental Programme

Experimental investigation was performed to validate the results of numerical modelling and to study the strength and behaviour of ECC-steel composite beams. A beam was cast, cured for 28 days and tested under four– point loading test using 500 kN hydraulic jack. The flexural load and deflection values and failure pattern for the specimen was observed.

5.1. Specimen Details

An ECC-Steel composite beam with slab size 1500 mm × 600 mm × 115 mm and beam depth of 150 mm was cast in the laboratory. Cast specimens were subjected to water curing for 28 days. The steel plates were welded together to form the steel beam. The PSS with holes drilled was kept on top of the steel beam. Then, stud shear connectors were welded to the top flange of steel beam. The assembly was then moved to the plywood mould prepared for casting the slab. Before the placement of concrete, the steel reinforcement mesh was placed into the mould. For mixing of concrete, an electrically operated concrete mixer was used and the concrete was placed immediately after mixing. The plywood mould was removed after 24 hours of casting and the specimens were cured for 28 days.The specimen after casting is shown in Figure 7.

Figure 7 Specimen after casting

5.2. Test Setup

Figure 8 shows the experimental setup provided for the composite beam specimen under four-point loading condition where all dimensions are in mm. Two 10 mm LVDT's are provided at the interface of slab and PSS to check if there is any slip between them. A dial gauge of 25 mm was provided at bottom mid-point for obtaining the central deflection. Hydraulic jack of 500 kN capacity was used for loading the specimen.

5.3. Test Result

The load deflection curve of the test results obtained for the specimen is shown in Figure 9. The specimen failed by crushing of ECC slab in the bending region. The failure pattern for the specimen is shown in Figure 10. The peak load obtained for the specimen was 228 kN. The central deflection value obtained for the peak load was 8.57 mm. Since, the experiment was conducted in a load-controlled setup, the post behaviour was not determined.

Figure 8 Experimental setup

5.4. Validation

The results obtained from the experiment were compared with the results from FE model. The peak load in the experiment was 228 kN with a central deflection value of 8.57 mm. The peak load predicted by FE model was 250.34 kN with a central deflection value of 9.98 mm. The model satisfactorily predicts the experimental results and thus the validity of the model is justified, as shown in figure 11. Also, the post peak behaviour which was not obtained in the experiment shall be determined using the FE model.

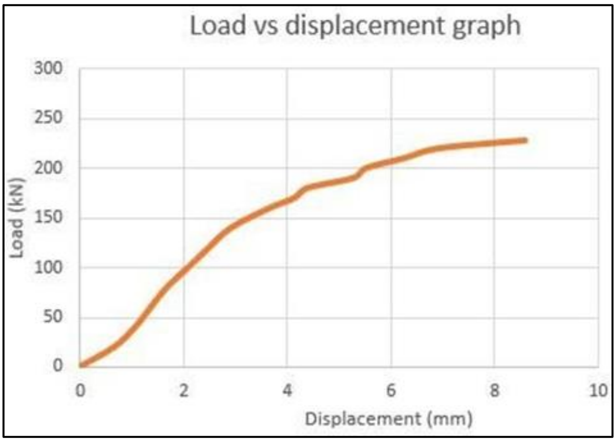

Figure 9 Load displacement curve of experiment

Figure 10 Flexural failure for specimen

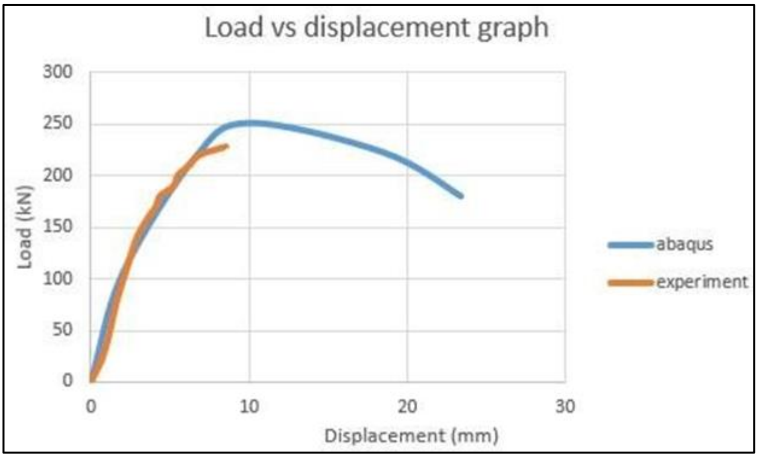

Figure 11 Validation of numerical model

6. Parametric study

With the developed FE model, the effect on the composite beam due to change in some parameters were explored. The parameter investigated in the study include replacement of ECC with conventional concrete. The composite beam under flexural loading reached a peak load of 240.96 kN with a mid-span displacement of 7.87 mm. The composite beam also failed by crushing of concrete slab followed by yielding of steel beam. The load deflection graph obtained for NCC-Steel concrete composite beam was similar to ECC-Steel composite beam. The peak load carrying capacity of NCC-Steel composite beam was slightly less than ECC-Steel composite beam of the same grade by 3.7 %. However, a vertical drop occurred in the load deflection curve in Figure 12 , after reaching the maximum load carrying capacity for NCC-Steel composite beam.

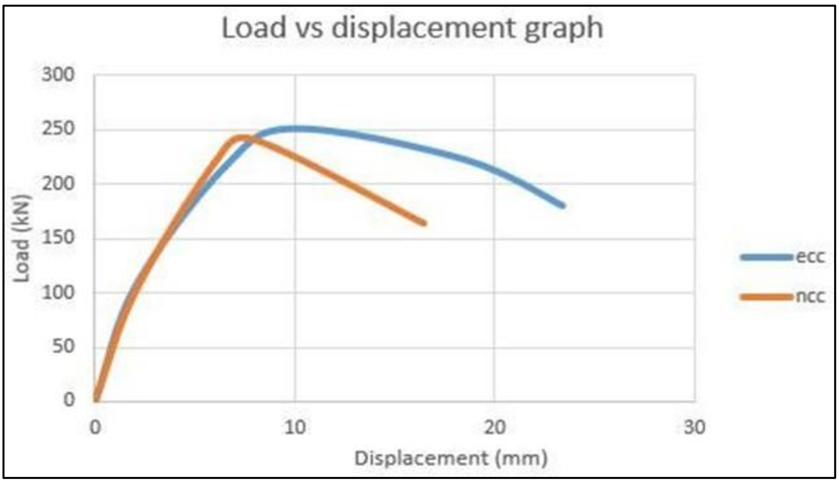

Figure 12 Comparison of load deflection curves after replacement of ECC with normal concrete

7. Conclusion

Flexural strength and behaviour of ECC-Steel composite beam was studied both experimentally and numerically. The flexural strength and failure pattern obtained using finite element analysis using ABAQUS software was almost same as that obtained from experimental programme. Hence, ABAQUS can be used as an effective tool for flexural strength and behaviour of ECC-Steel composite beams. The major conclusions obtained from the present study are;

1. It was observed from the finite element analysis that ECC-Steel composite beams have a slightly higher peak load carrying capacity than NCC-Steel composite beams. The load carrying capacity of ECC-Steel composite beam was 3.7 % more than that of its normal concrete counterpart.

2. As it is demonstrated that the flexural performance of composite beams is improved by use of ECC, this new form of composite beams could be employed to achieve efficient designs for long span structures under high loading conditions.

The behaviour of ECC-Steel composite beams with different diameter of shear headed studs, different thickness of slab and different orientation of profiled steel sheeting is not done yet. Hence, further studies can be performed for ECC-Steel composite beams to improve its flexural performance.

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Disclosure Statement

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References

1. Abdel Aziz, K. (1986). Modèlisation et étude expérimentale de poutres mixtes acier- béton à connexion partielle ou espacé. Ph.D. thesis, Département de Génie Civil et Urbain, Institut National des Sciences Appliquées des Rennes.
2. Bradford, M. A., and R. I. Gilbert. (1992). Composite beams with partial interaction under sustained loads. J. Struct. Eng. 118 (7): 1871–1883. https://doi.org/10.1061/(ASCE)0733-9445(1992)118:7(1871).
3. Cong-Luyen Nguyen and Chi-King Lee (2021). Flexural behaviours of Engineered Cementitious Composites – High strength steel composite beams, Engineering Structures, Vol. 249.
4. Cui, C., Q. Zhang, Y. Luo, H. Hao, and J. Li. (2018). Fatigue reliability evaluation of deck-to-rib welded joints in OSD considering stochastic traffic load and welding residual stress. Int. J. Fatigue 111 (Jun): 151–160. https://doi.org/10.1016/j.ijfatigue.2018.02.021.
5. F.B.P. da Costa, D.P. Righi, A.G. Graeff and L.C.P. da Silva Filho (2019). Experimental study of some durability properties of ECC with a more environmentally sustainable rice husk ash and high tenacity polypropylene fibers, Construction and Building Materials, Vol. 213, April 2019.
6. F.B.P. da Costa, D.P. Righi, A.G. Graeff and L.C.P. da Silva Filho (2015). Mechanical performance of ECC with high-volume fly ash after sub-elevated temperatures, Construction and Building Materials, Vol. 99, September 2015.

7. Faella, C., E. Martinelli, and E. Nigro. (2010). Steel-concrete composite beams in partial interaction: Closed-form exact expression of the stiffness matrix and the vector of equivalent nodal forces. Eng. Struct. 32 (9): 2744–2754.https://doi.org/10.1016/j.engstruct.2010.04.044.
8. Fu, G. (2008). Experiments and theoretic research on steel-concrete composite beams considering interface slip and uplift. [In Chinese.] Ph.D. thesis, School of Civil Engineering, Xi'an Univ. of Architecture and Technology.
9. Li VC (1993). From micromechanics to structural engineering the design of cementitious composites for civil engineering applications. JSCE J Struct Mech Earthq Eng 10(2):37–48.
10. Li VC, Leung CKY (1992). Theory of steady state and multiple cracking of random discontinuous fiber reinforced brittle matrix composites. J Eng Mech 118(11):2246– 2264.
11. Rui Zhang, Koji Matsumoto, Takayoshi Hirata, Yoshikazu Ishizeki and Junichiro Niwa (2015). Application of PP-ECC in beam–column joint connections of rigid-framed railway bridges to reduce transverse reinforcements, Engineering Structures, Vol. 86, January 2015.
12. Stüssi, F. (1947). Zusammengesetzte Vollwandträger." [In German.] IABSE Publ. 8: 249–269.
13. Weimann MB, Li VC (2003). Hygral behavior of engineered cementitious composite (ECC). Int J Restor Build Monum 9(5):513–534.
14. Yang EH, Wang S, Yang Y, Li VC (2008). Fiber-bridging constitutive law of engineered cementitious composites. J Adv Concr Tech 6(1):181–193.
15. Yingwu Zhou, Bin Xi, Lili Sui, Shuyue Zheng, Feng Xing and L. Li (2019) Development of high strain-hardening lightweight engineered cementitious composites: Design and performance, Cement and Concrete Composites, Vol. 104, November 2019.
16. Yu Zhu, Yingzi Yang and Yan Yao (2012). Use of slag to improve mechanical properties of engineered cementitious composites (ECCs) with high volumes of fly ash, Construction and Building Materials, Vol. 36, June 2012.
17. Zhigang Zhang, Ananya Yuvaraj, Jin Di and Shunzhi Qian (2019). Matrix design of light weight, high strength, high ductility ECC, Construction and Building Materials, Vol. 210, June 2019, pp. 188-197.