Experimental investigation of engineered cementitious composites (ECC) retrofitted masonry structures

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Abstract

Earthquake has proven the most damaging natural hazard in the world. So, structures in the earthquake-prone areas are need to be retrofitted prior and post of the calamity. It has been observed that most of the research solutions available focus upon reinforced concrete and steel constructions. Engineered cementitious composites (ECC) developed for economical utilization of fibres in retrofitting of masonry structures have been focused herein. The performance of beam-like masonry specimens subjected to their out-of-plane forces are experimentally and numerically investigated in this paper. Twelve beam-like specimens were cast and retrofitted with polyvinyl alcohol engineered cementitious composites (PVA-ECC) for the purpose. The casting of the retrofitting layer was done by varying percentages of PVA fibres that are 1%, 1.5% and 2% addition by the total volume of mortar. The performance of out-of-plane direction is investigated through static two-point loading. The specimens were tested at a constant load increment of 0.1 mm per second. Work was conducted to simulate the ultimate cracking loads, maximum tension/deflection and load to deflection relationships of retrofitted and non-retrofitted specimens. Preliminary experimental data were used for numerically modelling the specimens in finite element package. Numerical results for deflection and strength were finally compared with experimental results. Experimental results revealed that the maximum load-carrying capacity with retrofitted samples increased by 11.8, 10.15 and 11.13% for 1%, 1.5% and 2% fibre addition, respectively. Simultaneously, deflection before complete collapse increases 5, 8 and 10% for 1%, 1.5% and 2% fibre additions. It can be finally said that utilization PVA-ECC as retrofitting material is an economical and easy method available.

Keywords Engineered cementitious composites · Economical · Retrofitting · Masonry · Out of the plane · Fibres

1 Introduction

There are numerous old structures worldwide which carry some importance and many of such within them preserve histories. A general observation states that most of those old structures were constructed with unreinforced masonry (URM) technique. Among the different construction materials available, construction with stone and masonry has seen a major boost in the early 90s worldwide [1, 2]. These URM buildings carry an advantage of easy construction technique and easy availability of materials.

Contrarily, it is also noted that these types of construction technique are highly susceptible to out-of-plane loadings like seismic activities and heavy wind forces [3]. Considering these aspects, both pre- and post-retrofitting strengthening techniques for the earthquake-affected structures need equal importance [4].

Numerous researches have been carried out focusing on various aspects of retrofitting among which technique of addition of steel bracings for existing or new RC and steel buildings can be a proving technique in subsequent improvement in structural performance as well as damage

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control level of the structures [5]. Damage-resistant and inter-storey drift boost with the addition of viscous damping was also noted for seismic retrofit [6, 7]. The effective technique of addition of extra steel plates of subsequent thickness for the existing building was one more in the list [8]. Results of retrofitting of the structures with X-Bracings proved to be an effective technique for retrofitting low-rise structures. In addition to the bracings, including prior jacketing was seen of great importance for the X bracing systems [9].

Working on the same line, the various different options in retrofitting, like steel jacketing, use of carbon fibre-reinforced polymers (CFRPs), concrete jacketing, the introduction of polypropylene fibre ropes (PPFRs), application of high-performance fibre-reinforced composites, were discussed by researchers [10]. The experimental results with the effective utilization of steel jacketing, carbon fibre-reinforced polymer wrapping, concrete jacketing non-shrinkage mortar and amorphous metallic fibre-reinforced concrete were also studied. Research also tried discussing different methods based on such retrofitting techniques in varying field applications [2, 11, 12]. Observations state that the retrofitting techniques like surface treating which includes the use of bamboo-bank retrofitting, shotcreting, application of fibre-reinforced polymer layers, post-tensioning methods, external confinements, centre core method, external injections, etc., are few other strengthening techniques that can be adopted. One of the applications of FRC's was seen by developing a composite of glass fibre tubes to advance the axial behaviour of concrete structures [13]. Mitigating the hazards and strengthening the existing structural elements were tried to investigate using FRP laminates and were also tried to investigate by researchers. Those FRP composite laminates proved in hiking the load-carrying capacities of the structures and also to protract the failure modes and patterns' and to maintain the structural integrity [14].

New researches now tilt in introducing cementitious composites to compete with fibrous composites, which reduce reinforcing percentages and reduce the percentages of fibre additions [15]. Research has also been carried out to validate the experimented and analytical results of using different techniques for retrofitting purposes [16]. The clear difference between fibrous composites and engineered cementitious composites (ECC) can be said as ECC's are part of ultra-ductile composites families, which sustain higher load capabilities, tensile capabilities deflection capabilities with very low volume addition of fibres.

According to the research work carried till date, the idea of ECC is clear that careful design strategies using these composites can play a vital role in many different fields. ECC has proved the capability to increase the service life of the deteriorating portion of the structures. This property

named as trapping mechanism not only helps to achieve the service integrity but also can prevent common failures and large deflections of structures [17]. Researches aiming towards high performances in tensile capabilities and multiple cracking properties to reduce seismic response and damage of the structures were also seen satisfying using ECC [18]. Replacement of virgin ECC with locally available wastes also performed well in increasing ductility of the structures (3–7%), tight cracking (60 μ m) and relatively low fibre content (2%). This replacement of partial coupling contents by limestone and blast furnace slag helps to reduce the CO₂ emission and increasing workability and durability of the materials [19].

Considering the availability, reliability and economical aspects, types of fibres need to be chosen. The different options of fibres available are steel fibres, polypropylene fibres, polyethylene fibres, polyvinyl fibres, carbon fibres, etc. [20–22]. Selection of the fibres according to the required properties plays a vital role; researchers also proved that not only one type but utilizing hybrid fibres properties also can help improve the properties of the structures. For example, utilizing hybrid of steel and polyethylene fibres resulted in 22 times increased load carrying, 16 times the original ductility and 286 times the energy absorption capacity in strengthening the masonry walls [23].

As per the early discussions, the earthquake has proven the most damaging natural hazard, and when talking about masonry structures, they tend to fail inwards to the construction. It has also been observed that most of the research solutions available focus upon reinforced concrete and steel constructions [24]. Aiming to consider the drawbacks of the structures and utilizing properties of ECC, work herein utilizes and suggests polyvinyl alcohol fibres with a nominal addition of fibres that is by 2% of the total volume of mortar for retrofitting of old masonry structures. The experimental outputs are then validated by nonlinear finite analysing the beams on the software package of ANSYS 14.5. The study clearly states that ECC's can be effectively used to improve out-of-the-plane performance of heritage structures.

2 Materials and methodology

2.1 Materials

Different materials based on their characteristics and scope of work have been chosen and utilized in this study. All the materials and their specifications are as mentioned below.

Bricks: class B Engineered solid clay bricks classified per IS: 1077: 1992 [25] with dimensions 220 × 100 × 65 mm

Table 1 Characteristics of PVA fibres

Parameters	Details
Type	Monofilament
Density	1.29 g/cm ³
Formula	(CH ₂ CHOH) <i>n</i>
Length	12 mm
Diameter	39 µm
Modulus of elasticity	40 GPa
Tensile strength	1600 MPa

were used. Class B bricks were selected based on compressive strength and water absorption to practically go closer with actual heritage, retrofit needed structures. Three individual brick units were tested for compression under the computerized universal testing machine (TUE-C-1000 KN capacity) manufactured in India. Loading was applied at a constant load increment of 0.1 mm/s, and the average compressive strength observed was 12.22 MPa. Water absorption for the bricks was found out to be 25%.

Cement: 53Grade Ordinary Portland cement with compositions according to IS: 12269-1987 [26] has been utilized in the preparation of mortar. Same cement was used in the preparation of the bonding material (low-strength mortar LSM) for construction of masonry beams and also in preparation of paste for ECC retrofit.

Artificial sand passing from 500 microns and retained on 90 microns Indian standard sieves confirming IS 460(Part-1)_1985 [27] was used for both low-strength motor and cementitious mix. Sand selected was on the basis to utilize economical and easily available materials in the development of composites (Ref. IS 650:1991) [28]. For the same purpose utilization of fly ash and additives were neglected. Performance for the same was observed as per the work conducted to study the performance of fibre-reinforced polymers without admixtures [21].

Polyvinyl alcohol fibres (PVA) used for the preparation of ECC matrix were buoyed from "The Yarn Guru India Inc". Rajasthan of bunchy Monofilament type. Table 1 describes detailed characteristics of PVA fibres used.

2.2 Casting methodology

During the entire casting procedure cement to sand and water to cement ratio was kept constant, which were 1:3 and 0.6 respectively. The mix proportion utilized in the study were in accordance with the studied literature [29]. Table 2 includes the mix proportions and characteristics of prepared composites.

Initial parametric testing of materials used includes uniaxial compression testing of composites. Samples were prepared with varying percentages of fibres concerning the total volume of mortar that is 0%, 1%, 1.5% and 2%.

Table 2 Mix proportions and mechanical properties

	Fibre type	Fibre volume	Average compressive strength (MPa)
Regular mortar	N.A.	N.A.	9.79
PVA-ECC_01	PVA	1.00%	16.73
PVA-ECC_02	PVA	1.50%	17.88
PVA-ECC_03	PVA	2.00%	21.13

70.6 mm cubes were tested per IS 4031 (Part-6)-1988 [30], under the computerized universal testing machine. Loading applied was with a constant load increment of 0.1 mm per second. Cube moulds were oiled, compacted in three layers and vibrated simultaneously to achieve proper compaction. Three water cured specimens for each volume percentage were tested at the age of 7 days, 14 days and 28 days, respectively.

To check the effect of fibres on the shrinkage characteristics of composites, specimens of varying fibre volume percentages were cast for the test [31]. Dimensions of samples were kept 200 × 50 × 50 mm as per standard code IS 1199.1959 [32]. Shrinkage testing included repetitive drying and wetting procedure as mentioned in the specified code. For the sample preparation, wooden mould was prepared which were taped and then oiled before casting to prevent water loss. Samples were normally compacted in three layers and demoulded after 24 h. Immediately, the samples were carefully punched with metal balls at both top and bottom sides to facilitate proper testing. Initial wet measurements were noted and then the specimens were immersed in the water keeping one face just breaking the water level for 4 days. After removing from water, specimens were oven-dried for 48 h. Samples were then desiccated for an hour after removing from oven. Desiccated specimens were then observed for dry measurement. The same steps were repeated until the dry reading attains a constant value.

Test apparatus for the shrinkage measurement was cast in the house with identical assembly to that specified in the reference test specifications. Metal ball at the base stand was firmly welded at the centre of the base plate to keep the sample in position during the measurement. Figure 1 shows a detailed arrangement of testing apparatus, including base stand, support columns, dial arrangement and sample placing. The dial gauge for measuring the change in length was attached at the top of the apparatus. The least count of the gauge was 0.01 mm to measure the accurate deflection.

The flexural test was carried out on twelve prismatic masonry beam-like specimens. Beams were tested under two-point loading on UTM with transient loading of 0.1 mm per second. Beam specimens were constructed

Fig. 1 Details of shrinkage measurement apparatus

Fig. 2 Procedure for casting of brick beams **a** placing bricks one after another and allowed to strengthen for 3 days. **b** applying retrofitting layer by laying beam on the ground after 3 days curing

with seven bricks and six mortar joints. The casting was carried after keeping the clay bricks immersed in water for around 24 h. One after another bricks were laid in the mould and kept vertical for 72 h. So that the mortar joints attain its strength by self-weight of up laid bricks. Figure 2 shows the casting procedure of the beams [33].

Out of the 12 casted specimens, three were strengthened with a plain mortar and the other nine were retrofitted with approximately 15-mm-thick layer of PVA-ECC. The retrofitting layer was applied at the top of the beam, and beams were inverted during testing. Three samples of each 1%, 1.5% and 2% cementitious composite were cast. The casted beam specimens had their final dimensions as $515 \times 220 \times 115$ mm ($L \times B \times H$), where depth 115 mm includes 100-mm brick and 15-mm ECC retrofit layer. Figure 3 shows detailed dimensions of beam and fixed support locations for the flexural testing setup [2, 34].

PVA-ECC paste was prepared by first dry mixing of sand and cement. Half of the total water was then added, and the mixture was allowed to mix into the mechanical mixer for 5 min. The remaining water was added to the mix and again allowed to mix for the next 3 min. Properly hand-separated fibre samples were then mixed with the matrix. The mortar was allowed to mix for the next 5 min. So, the total ECC preparation time observed was approximately 18–20 min.

2.2.1 Retrofitting technique

The casted masonry beam specimens were cured and kept in the mould for 3 days. Beams were then laid on the plane ground as shown in Fig. 2b, and a thin layer of 15-mm PVA-ECC (retrofitting material) was applied to the surface. There are various methods available for applying retrofitting material. Among them, the method has been chosen to suggest engineers to simply plaster the masonry walls with retrofitting material. So that it can be beneficial in terms of time-saving and even in terms of cost.

2.3 Numerical analysis

2.3.1 About software package

ANSYS workbench majorly combines core solvers and management tool to focus upon stress, deflection and safety factors. Project in ANSYS workbench is driven by the schematic workflow. Native workspaces include project schematic, engineering data and design exploration (parameters and design points). Data-integrated applications include the mechanical APDL application (formerly ANSYS), ANSYS FLUENT, ANSYS CFX, the Mechanical application (formerly Simulation), etc. [34].

The interface of workbench displays toolbox allowing users to go with the type of structure to be modelled and analysed. Selecting approximate analysis pops up to select

Fig. 3 Detailed specifications of the flexural test sample and loading arrangement (dimensions in mm)

different cells. Cells displayed are engineering data (allows to upload material type and property), geometry (to create/upload mechanical model), model (allows meshing, detailing, loading of mechanical model), solution (runs approximate finite simulations to solve the system) and results (to display and allow reporting of final solver).

2.3.2 Adopted design specifications and modelling

Modelling started with a step file created considering constraints on mechanical bases software package of CATIA. Detailed dimensions and loading specifications for both experimental and numerical analysis are shown in Fig. 3. The adopted material properties were adopted as per the reference by authors [35] and based on the laboratory tested results of the materials, which were uploaded at the initial cell of engineering data as shown in Table 3. Material properties are then assigned to the respective parts.

Fine Meshing of the model was done using ANSYS Automechanical mesh tools. Going closer to experimental approximations loads were applied at the top face of the brick element. Fixed supports were assigned considering steel roller supports at the locations as shown in Fig. 3. The load applied was the maximum load at failure obtained

from experimentation work. The maximum load can be divided into 10 steps assigned in the current solver system.

Model, after loading and constraining with required additions, was allowed to run for solver interface. This solver interface resulted in deflection characterization and maximum stresses.

3 Test results and discussions

Failure modes: The exact definition of fibre bridging effect [10] was clear from the behaviour of compression test specimens when subjected to static loading. Specimens with plane mortar under compression testing showed complete dispersion of its constituents. On the contrary, the specimen cast with PVA fibres shows a bonded layer of materials as shown in Fig. 4. The same effect of crack stitching or fibre bridging was seen in specimens tested for flexural testing.

During the testing procedure for flexural strength, it was observed that the non-retrofitted masonry specimens (reference specimens) failed immediately after a day of casting. Failure pattern of the plane specimen is shown in Fig. 5. Reason for the same was due to brittle

Table 3 Engineering properties of materials used in numerical modelling

Specifications	Brick units	Low-strength mortar (LSM)	1.0_PVA-ECC	1.5_PVA-ECC	2.0_PVA-ECC
Elastic modulus (Pa)	2.5E+07	3.0E+07	3.5E+07	3.5E+07	3.5E+07
Compressive strength (Pa)	3.5E+07	2.0E+07	3.5E+07	3.5E+07	3.5E+07
Tensile strength (Pa)	2.0E+06	2.2E+06	6.0E+06	1.1E+07	2.2E+07
Poisson's ratio	0.2	0.2	0.2	0.2	0.2
Density (kg/m ³)	1600	1800	2100	2100	2100

Fig. 4 Observed fibre bridging effect under compression loading

Fig. 5 Destroyed beam specimen with a plane mortar layer

behaviour of bricks and plain mortar layer at the tension face. And hence specimen cannot undergo any tensile capability. The same may be the reason for the destruction of non-reinforced old age masonry structures which when subjected to very low amount loading in their out-of-the-plane direction. On the other hand, beams retrofitted with PVA-ECC layer showed good load-carrying capacity.

It was observed that crack first appears at the tension face of the beam and then transforms inward. The observed developed crack then widens and propagates either into brick or towards the brick–mortar interface. This propagated crack allows either brick or the bonded interface to fail completely. Failure modes of 1%, 1.5% and 2.0% PVA-ECC are shown in Fig. 6.

Compression test results: Specimens as the discussed methodology was tested in order to study the effect of fibre addition on compression behaviour of the matrix. For the same purpose, the average of three samples with each fibre volume per cent is tabulated in Table 4. Standard deviation for all the results was noted within the range of 0.3–1.0.

It was clearly observed that there was very little increase in compression behaviour of the composite sample in comparison with the reference specimen. Observations also states decrease in the compressive strength in the initial days. This can be due to the replacement of cement with the fibres, which takes time to properly combine with the cementitious constituents to facilitate proper bonding. Considering applying retrofitting layer of ECC to masonry specimen, compression results will depend upon the strength of brick. This is because ECC will play no role in implementing compressive strength. Compressive strength of brick units individually will reflect the compressive capacity of the structure.

Flexural test results: Flexural test on brick beam specimens to know the tensile, as well as flexural behaviour of specimens, was conducted. The stress-to-strain behaviour of each sample was clearly observed. Observations stated that the reference beam cracked and shown an instant brittle behaviour under a universal testing apparatus. Figure 8 shows the destroyed reference specimen. The same observation was noted by researchers [16]. Graph for the beam with 0% fibre addition or the reference beam is not shown in Fig. 7, due to the same reason.

In contrary, the retrofitted specimens at tensile face by PVA-ECC showed good performance under application of loading. Stress-to-strain curves show a quasi-brittle behaviour of beams. Beams continued to sustain loading even after first cracking stress. It was also observed that the presence of fibres show a great impact on the first crack load and maximum deflection that occurred at the centre of the beam. Combined load to deflection relationship for 1, 1.5 and 2% fibre addition are shown in Fig. 7.

The average of first crack loads of retrofitted samples with 1%, 1.5% and 2% fibres observed was 11.8, 10.15 and 11.13 KN, respectively, which in comparison with reference specimens shows increment by 11.8, 10.15 and 11.13%, respectively. Similar were the results observed by Pourfalah et al. [36].

The maximum deflection of crosshead observed at the centre of the beam was 4.8, 8.01 and 9.75 mm which shows an increment by 5, 8 and 10%, respectively.

Shrinkage testing: Repetitive wetting and drying testing of plain mortar and mortar with 1 and 2% fibres were

Fig. 6 Failure and crack propagation under two-point loading for **a** 1.0%, **b** 1.5%, and **c** 2.0% PVA-ECC retrofit

Table 4 Average compressive strengths for different curing days and different fibre %

Average	7 days strength (N/mm ²)	14 days strength (N/mm ²)	28 days strength (N/mm ²)
0	5.59	6.79	9.79
1	11.34	15.29	16.73
1.5	10.83	16.52	17.88
2	10.6	17.39	21.13

carried out as discussed above. Reduction in the load-carrying capacity of 1.5% PVA-ECC retrofitted specimens leads to study of the shrinkage behaviour for rest of the specified materials. The test purely shows the effect of fibres on the shrinkage characteristic. The study showed that in comparison with that of reference specimens, a substantial deduction of 29.03 and 46.24% was observed in shrinkage characteristics, which was due to the capability of fibres

Fig. 7 Load to deflection relationship for different fibre volume %

to bond the cracks and allow time in the development of microcracks.

It was also observed that shrinkage of specimens repetitively varies with respect to time. At the initial stage, shrinkage attains a higher level and then continues to be constant.

Fig. 8 Shrinkage behaviour of the retrofitted and non-retrofitted specimen

Graphical representation of the change in drying shrinkage with respect to time is shown in Fig. 8.

3.1 Numerical solutions and observations

Numerical validating results obtained from ANSYS software which is a finite element-based analysing software are plotted below. Table 5 shows the comparative results obtained experimentally and numerically.

Images of obtained results in software package are shown in Figs. 9, 10 and 11.

4 Conclusion

Preserving old age structures have seen great importance in the current scenario for which this paper suggests an easy and economical retrofitting technique. It suggests the application of a thin layer of PVA-ECC to the unreinforced masonry elements. The retrofitting technique shows a significant increase in flexural behaviour of the masonry structure. The following were observed and plotted:

- 1 Flexural behaviour was greatly influenced as the peak load of non-retrofitted and retrofitted specimens

Table 5 Comparative experimental and numerical observations

Sample ID	Experimental observations		Numerical observations		% Variations in deflection
	Maximum load (kN)	Deflection (mm)	Maximum load (kN)	Deflection (mm)	
1.0_PVA-ECC	11.8	4.8	12	6.06	20.79
1.5_PVA-ECC	10.15	8.01	10	7.72	3.62
2.0_PVA-ECC	11.3	9.75	11	10.627	8.25

Fig. 9 Total deformation result for 1.0_PVA-ECC retrofitted beams

Fig. 10 Total deformation result for 1.5_PVA-ECC retrofitted beams

Fig. 11 Total deformation result for 2.0_PVA-ECC retrofitted beams

shows an increment of 11.8, 10.15 and 11.13 KN for 1.0, 1.5 and 2.0%, respectively.

- 2 Crack healing approach of fibres shows its influence in reducing the shrinkage of concrete by 29.03 and 46.24% for 1.0 and 2.0% fibre addition, respectively.
- 3 There was very little effect of fibre addition on compression test results, and hence it can be said that compressive strength of brick itself plays a vital role in imparting compressive strength.
- 4 Work suggests the addition of 2% fibres by total mortar volume in the wide retrofitting area. The results for 2% fibre addition are well-acceptable and further addition of fibres can result in lumps formation which can reduce the tensile as well as flexural performance.
- 5 Numerical modelling to realistically predict behaviour and deflection capabilities of retrofitted and non-retrofitted samples gave acceptable results.

- 6 Observations clearly state that failure of the specimens occurred at the tension side of the specimens and failure propagated upward towards the neutral axis.
- 7 Deflection results for applied loads showed variation by 20.79, 3.62 and 8.25% variations for 1, 1.5 and 2% PVA-ECC retrofitted specimens.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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