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Seismic Retrofitting of URM Structures by Engineered Cementitious Composites - An Experimental Study on Triplet and Prism Specimens

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2. 構造－11. 壁式構造・組積造　　建築構造
無補強組積造，ECC，HPFRCC，耐震補強，要素実験

1. Introduction

Unreinforced masonry (URM) structures have shown low lateral resistance and ductility during earthquake events and should be seismically retrofitted.

High Performance Fiber Reinforced Cement Composites (HPFRCC) or Engineered Cementitious Composites (ECC) with multiple fine cracks is a cement-based composite material with a strain-hardening tensile behavior and an excellent capability to control the width of crack [1),2)].

Kyriakides and Billington studied ECC retrofitting for steel frame-infill masonry walls [3)]. The effect of ECC mixture ingredients on its retrofit functionality for masonry walls was studied by Bruedern et al [4)]. Maalej et al studied the ECC retrofitting for URM walls under impact loading [5)].

Also Lin et al conducted some in-plane and out-of-plane tests on retrofitted masonry specimens and examined a two-story URM building shotcreted with ECC in New Zealand [6)] In this paper, due to the high tensile strength and strain-hardening behavior of ECC and low tensile strength and strain softening behavior of masonry on the other hand, the efficiency of this retrofitting method for URM walls was evaluated through an experimental study.

2. Outline of Experiments

2.1. Objective of Experiments

In order to evaluate the retrofit capability of ECC on URM structures, uniaxial compression and shear triplet tests were conducted on the wall specimens. The results of such an experimental study are necessary for analyzing and evaluating the behavior of the whole retrofitted structure.

2.2. Test Specimens

The specimen types which the tests were conducted on are shown in Table 1 and Figure 1. Three series of masonry specimens were constructed such as unit brick, triplet and prism. Each series was consisted of both unretrofitted and retrofitted specimens. The brick used for the construction of specimens was a rectangular parallelepiped one without holes and with approximate dimensions of 210 mm x 110 mm x 60 mm with a compressive strength of 0.65 N/mm^2. In order to obtain more realistic and applicable results of these tests, bed joint mortar was prepared with a 28 days compressive strength close to the one being used in common masonry construction in many earthquake-prone regions. Bed joint mortar constitutes of cement, sand, Lightweight silica powder and methyl cellulose which were blended with

Table 1. Specimen types

Type	Name	Dimensions (mm)			ECC Thickness (mm)	Age (day)
		Width (W)	Depth (D)	Height (H)		
Brick	1UBH	209.90	99.06	59.83	0	
	2UBH	209.00	98.42	59.14	0	
	3UBH	210.50	99.69	59.86	0	
	1RBH	209.80	112.80	59.21	10	49
	2RBH	210.60	120.20	59.17	10	49
	3RBH	210.10	114.70	58.60	10	49
Triplet	1UT	191.30	210.60	98.49	0	42
	1RT	191.60	212.20	119.60	10	42
	2RT	191.80	213.20	136.00	20	42
Prism	1UP	210.30	100.20	340.50	0	42
	1RP	210.40	121.70	338.20	10	42
	2RP	210.90	138.40	341.00	20	42

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- An Experimental Study on Triplet and Prism Specimens
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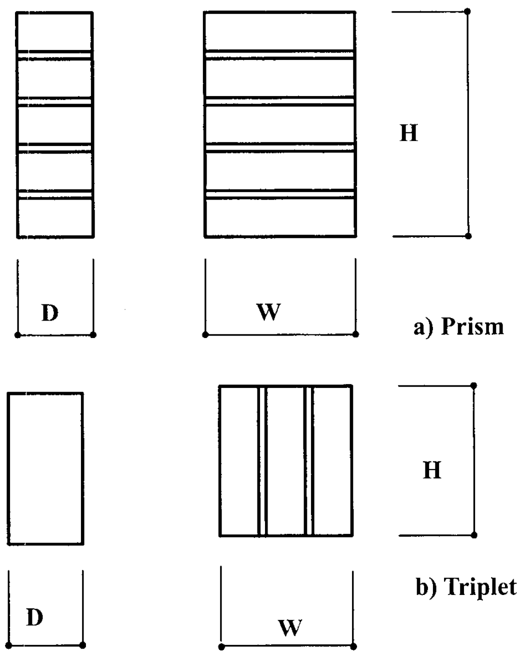


Figure 1. Specimen forms

proportion of 1:6.5:1:0.01, respectively. In order to measure the material constants of bed joint and ECC mortar such as compressive and tensile strength, compressive and three-point bending tests were conducted on the cylindrical and prism samples, respectively. Specific weight and compressive strength of bed joint mortar was measured as 1.96 g/cm3 and 10.0 N/mm^2, respectively. Also for ECC mortar, specific weight and compressive strength was measured as 1.64 g/cm^3 and 24.6 N/mm^2, respectively.

Mechanical properties of bed joint and ECC mortar are shown in Table 2.

Six unit brick specimens were provided which three of them were retrofitted in both sides and the other three ones left bare.

Nine triplet specimens were constructed to obtain the shear effect of ECC retrofit and three of them were retrofitted by ECC mortar in both sides with thickness of 10 mm and the other three ones were retrofitted in a similar way but with thickness of 20 mm. Three specimens were left unretrofitted as control ones.

Also nine masonry prism specimens were constructed to find out the compressive effect of ECC treatment. Three of specimens were retrofitted by ECC mortar in both sides with thickness of 10 mm and other three ones were retrofitted with thickness of 20 mm. Also three specimens were left bare. All of the bare specimens were built and cured, then they were retrofitted in both sides and cured again.

2.3. Testing Method

The displacement and strain on unit brick, triplet and prism specimens were measured using the displacement transducers and strain gauges.

Arrangement of these tools which were pasted up on the both sides of specimens is shown in Figure 2.

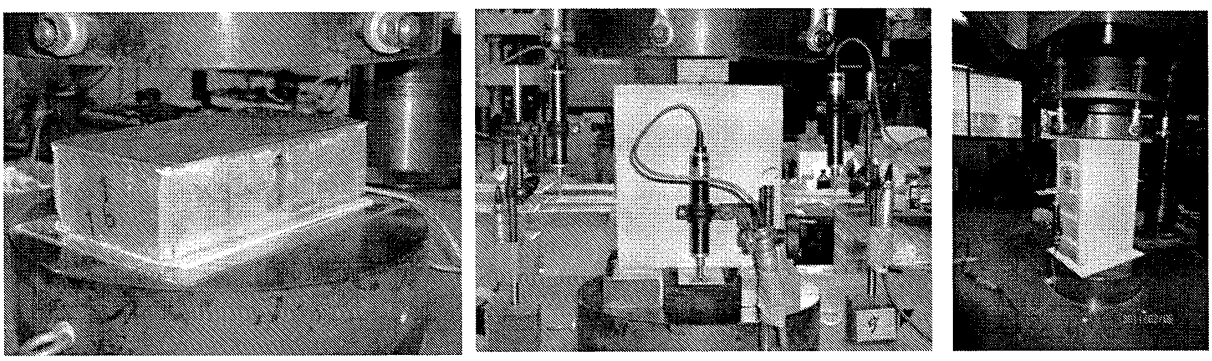
3. Results of Experiments and Discussion

3.1. Unit brick Tests

Both bare and retrofitted unit brick specimens were failed in

Table 2. Mortar specifications

Material	Elastic Modulus	Poisson's Ratio	Compressive Strength
Bed Joint Mortar	12.3 GPa	0.158	10.0 MPa
ECC Mortar	15.8 GPa	0.203	24.6 MPa



(a) Retrofitted unit brick **(b) Retrofitted triplet** **(c) Retrofitted prism**

Figure 2. Compressive and shear loading tests on specimens

a vertical side splitting mode together with the buckling of ECC overlay in retrofitted ones. However the buckling of ECC overlay was occurred prior to brick failure.

Compressive strength of both bare and retrofitted bricks is shown in Figure 3 which shows an increase about 38% in the retrofitted bricks.

3.2. Triplet Tests

Bare triplet specimen was failed through splitting of brick and bed joint mortar at a very low displacement. It is because of weak bed joint mortar and low bond strength between brick and mortar interface. However in the retrofitted ones, symmetric developing cracks in failure mode were observed which showed that ECC retrofitting increases homogeneity in masonry as a composite element.

Also it decreased stress concentration or prevent unsymmetrical failure mode.

Shear stress-strain diagram of both bare and retrofitted specimens are shown in Figure 4.

It was found out that ECC retrofitting increased shear modulus of triplet significantly. The amount of shear modulus for bare specimen (1UT) (1.82 GPa) increased to 3.76 and 3.47 GPa for retrofitted ones with ECC overlay of thickness 10 mm (1RT) and 20 mm (2RT) respectively. Also shear strength of unretrofitted triplet (0.94 MPa) increased to 2.85 and 3.3 MPa for retrofitted ones with 10 and 20 mm ECC overlay, respectively which is shown in Figure 5. This shows a significant increase about 203% and 251% for shear strength.

3.2. Prism Tests

Failure mode in bare prism specimen was represented by vertical tensile cracks parallel to the loading direction which appeared mostly on the longer sides of prism. However in retrofitted specimens, due to confining effect of ECC overlay, failure condition was similar to buckling behavior. Moreover, it was observed that in the case of ECC overlay of 20 mm thickness, debonding of ECC overlay from brick surface was started before the above mentioned bending-buckling behavior.

Compressive stress-strain diagram of both type of specimens are shown in Figure 6. Compression behavior of bare prism can be divided to two zones with elastic modulus of 2.56 and 12.5 GPa. Retrofitted prisms showed elastic modulus as 11.4 and 17.4 for 10 mm and 20 mm ECC overlays which show an increase about 345% and 580%.

Also it was found out that retrofitting with 10 mm and 20 mm layers results in a decrease about 10% and 24% in compressive strength respectively. It can be explained by this fact that in the retrofitted prisms major part of compressive load is resisted by ECC overlay which buckled before the collapse of the whole specimen and resulted in lower compressive strength of the specimen.

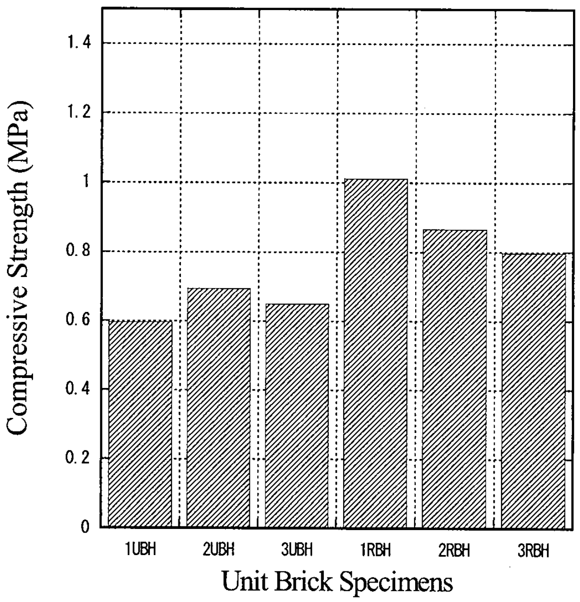


Figure 3. Compressive strength of unit bricks

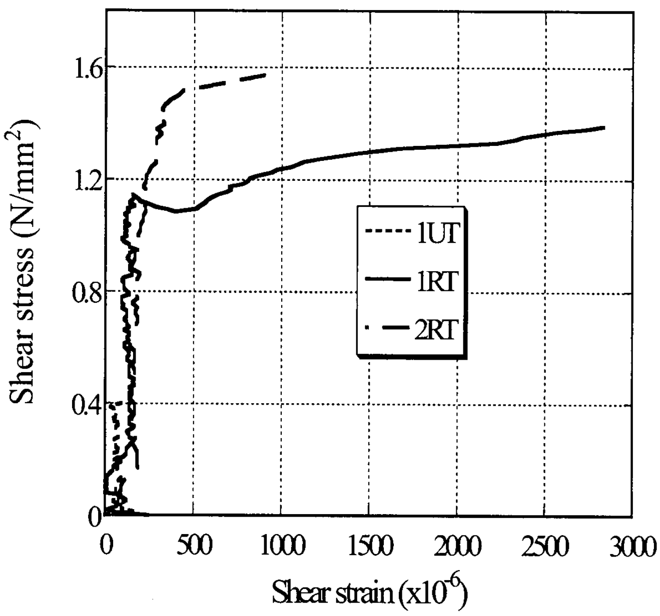


Figure 4. Shear stress-strain diagram of triplet specimens

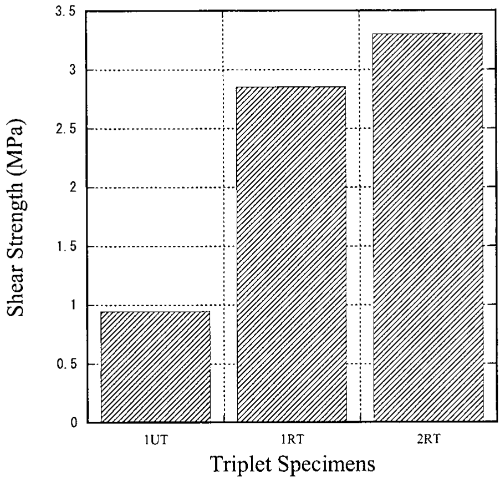


Figure 5. Shear strength of triplet specimens

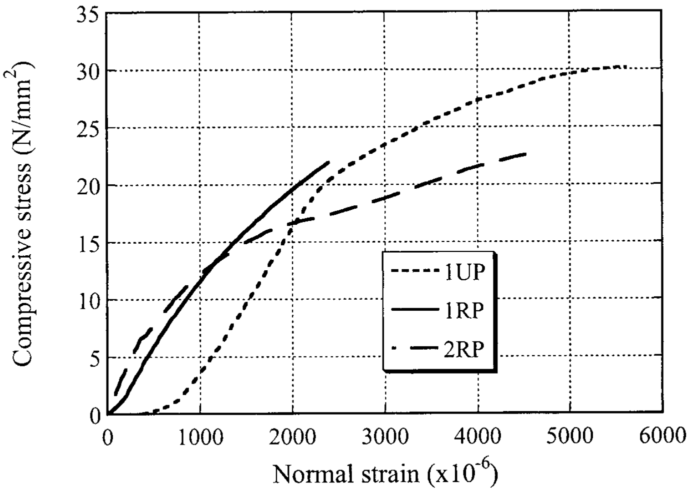


Figure 6. Compressive stress-strain diagram of prism specimens

Conclusion

By comparing the compressive and shear test results of unretrofitted and retrofitted specimens, following conclusion remarks were found out:

(1) Shear resistance and ductility of triplet specimens were increased significantly. For Shear strength, the increase was about 203% and 251% for ECC retrofit overlays of thickness 10 mm and 20 mm, respectively.

(2) Shear modulus of triplet showed an increase about 106% and 91% for ECC overlays of thickness 10 mm and 20 mm, respectively.

(3) ECC retrofitting changed the brittle failure mode of the URM to a ductile and developing failure which means better energy dissipation behavior and deformability.

(4) Symmetric developing cracks in the failure mode of shear triplet test showed that ECC retrofitting increases the homogeneity in URM as a composite material. Also it decreased stress concentration and makes it easy to predict the possible failure pattern of masonry.

(5) Elastic modulus of masonry prism increased about 345% and 580% for ECC overlays of thickness 10 mm and 20 mm, respectively.

Due to significant improving effect of ECC on shear behavior of specimens, it can be considered as a suitable retrofitting method for URM walls.

Acknowledgement

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