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Performance enhancement effect of unreinforced masonry walls using sprayable ECC

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ABSTRACT: In order to performing remodeling or change the usage of building, URM walls which used commonly in apartment as non-structural element need to have reliable performance of buildings because removal of this types of wall could make more wastes in construction site and removal procedure may cause delay of construction. Using normal shotcrete, as retrofitting method, cannot improve ductility and may cause brittle failure of structure. However, recent study for new materials, such as ECC or UHPC, can solve these problems increasing ductility and toughness of retrofitting materials. In this study, we used sprayed ECCs for retrofitting URM wall. ECCs can be designed to work in conjunction with existing walls to increase both strength and ductility for in-plane behavior of the URM wall. And this may change non-structural masonry wall to structural wall. To ensure that this technique will perform its intended purpose, in-plane lateral loading test was performed. The results of lateral load test of two retrofitted URM compared to non-retrofitted one. Retrofitted walls are consisted of just sprayed and anchored to wall base, RTM-ECC and have wire-mesh, same detail of others, RTM-ECC-WM. Retrofitted specimens show significant increase of strength, ductility and energy dissipation capacity compared to URM. RTM-ECC show stiff strength degradation however, RTM-ECC-WM show slow degradation of strength because of the load transferring effect of wire-mesh.

1 INTRODUCTION

Remodeling is an environmentally-friendly approach that reduces the amount of wastes in construction site. During performing remodeling project, some structural elements or non-structural elements would be destructed partly or totally. In many cases of apartment structure have not enough lateral resistance elements in longitudinal direction. In order to prevent the collapse of structure after remodeling project, many retrofitting methods were applied to deteriorated structural elements or in the some other cases, engineers construct new structural elements such as reinforced concrete walls. However, many resources were needed to construct new structural elements. To solve this problem we suggest the change of retrofitting objectives to non-structural elements, unreinforced masonry walls which were located between two households through longitudinal axis of structure. This would reduce more construction waste in remodeling site and keeps structural safety after remodeling of old structures. Numerous conventional techniques such as shotcrete, grout injection, external reinforcement are available for retrofitting or masonry structure. However, this methods or materials have not enough ductility enhancement effect but only have strength. Structures subjected to earthquake actions have great amount of ductility and conventional retrofitting methods cannot improve this type of performance. Therefore we suggested that using new retrofitting material, ECC, which have ductile property for tension and shear.

2 LITERATURE REVIEW

Many types of retrofitting materials are available for retrofitting of masonry structure and many researchers studied this objective and FEMA suggested many methods. Elgawady studied the retrofitting method using FRP Sheet against the diagonal shear failure of masonry wall. Jabarov suggested the retrofitting method for damaged unreinforced masonry wall which used the steel reinforcement and mortar.

Most of test results showed the strength enhancement, however retrofitting materials that was used in those studies failed in brittle manner. In this study, ductility enhancement is more important than strength, because objective building of retrofitting have insufficient reinforcement for ductile behavior of total structure against the earthquake.

Therefore, we use the Sprayable ECC (Engineered Cimentitious Composite) which has strain capacity 100 to 200 times the normal concrete.

2.1 *Capacity of Unreinforced Masonry*

In order to obtain accurate and economical value of retrofitting level, we first predict the capacity of unreinforced masonry wall. The behavior of unreinforced masonry wall under in-plane loads can generally be divided two categories, shear and flexure. The types of behavior influence with aspect ratio of wall. In this study we planned to retrofit the separation wall between rooms in one house hold and it has the aspect ratio of 1 approximately. And this wall is not designed to structural element so that axial load would not be induced to the wall. Therefore this unreinforced masonry wall should fail due to the rocking and toe crushing. Therefore we expect the wall shear strength using the equations below:

$$
\begin{aligned}
Q_{CE} &= V_r = 0.9\alpha P_E\left(\frac{L}{h_{eff}}\right) \\
Q_{CE} &= V_t = \alpha P_E\left(\frac{L}{h_{eff}}\right)\left(1-\frac{f_a}{0.7 f_m^{'}}\right)
\end{aligned}
\tag{1}
$$

where, P_E is expected axial force which is induced to the wall, h_{eff} is effective height of wall, L means length of wall and f_a is axial compressive stress due to gravity loads.

In nonlinear static analysis procedure, the rotation capacity is limited according to the acceptance criteria that IO is 0.1%, LS is 0.3 h_{eff}/L% and CP is 0.4 h_{eff}/L %. However, for the safety of total structure, this value can be neglected compared with capacity of other structural element.

2.2 *Retrofitting Effect*

Many types of retrofitting method for masonry were tested and analyzed. ElGawady summarized numerous conventional techniques such as shotcrete, grout injection, external reinforcement. The disadvantage of these techniques are long construction time, reducing the available space of building, affecting the aesthetics of the existing wall and adding additional mass of building. In order to solve these types of problem, ElGawady et al proposed and studied the other retrofitting materials, FRP(fiber reinforced plastic). Although FRP show good performance in strength enhancement, it showed several critical problems such as anchorage failure, limited energy dissipation and brittle mode of failure. Therefore, they suggested again the other retrofitting method, shotcrete overlay. Shotcrete overlays are sprayed onto the surface of a masonry wall over a wire-mesh. It is very convenient method in construction compared with conventional techniques and less costly than in-situ jacket retrofitting method.

Basically, shotcrete layer thickness is dependent on the seismic demand and it can be determined considering overlay as reinforced concrete shearwall. In general the overlay thickness is at least 60mm. the shotcrete overlay is typically reinforced with a minimum steel reinforcement ratio of shear wall in the shape of wire-mesh in order to crack control.

Retrofitting using shotcrete significantly increases the ultimate capacity of the retrofitted walls. In the diagonal tension test, shotcrete layer significantly increase the capacity of retrofitted wall. Although in diagonal tension test the improvement in the cracking load was very high, in a static cyclic test the increment in the cracking load was insignificant.

Other problem of applying shotcrete layer is quantification. There is no exactly mentioned rule for retrofitting area or thickness. It only constructed according to the construction availability and referring to the shear wall design.

3 EXPERIMENTAL PROGRAM

The experimental program was planned to verify the retrofitting performance of Sprayable ECC in reversed cyclic loading. The present study include following tests, URM-0.92, reference test specimen that is the unreinforced masonry wall, RTM-ECC which is the retrofitted with Sprayable ECC and anchor for preventing overturning and RTM-ECC-WM which is the specimen that anchor of RTM-ECC specimen connected directly to wire-mesh.

3.1 *Test Plan*

The reference test specimen, URM-0.92 represented the masonry wall that is constructed directed to the longitudinal axis of building which is built in 1970s in Korea. The test specimen constructed in full scale in order to preventing scale effect of brick elements. The test specimens had an effective moment/shear ratio of 0.92. All test specimens were constructed on a precast concrete footing. After brick element construction, upper part of wall was mortared in order to setup the steel loading beam.

Table 1. Properties of Test Specimens.

Specimen	H[mm]	L[mm]	Aspect Ratio	tECC [mm]	Wire-mesh Spacing	Shear Dowel Spacing	Brick Element
URM-0.92				-	-	-	
RTM-ECC	2380	2400	0.92	30	-	600	190x90x57
RTM-ECC-WM				30	300	600	

3.2 *Bricks, mortar and reinforcement*

In order to neglect the scale effect of material, specimens are constructed using 190x90x57 mm cement brick elements which are the standard form of Korea. Strength of brick elements are tested by the KS F 4004. Mean value of compressive strength for tested brick element is 15.7MPa. Mortar which is used to construct the test specimen commercially used mortar in Korea. Mean value of compressive test of cube test specimen is 8.45MPa.

3.3 *Sprayable ECC*

In present study use the Sprayable ECC which was developed by Kim as a retrofitting material. Sprayable ECC shows better bond strength between ECC and main structural element and shows tensile strength and deformation characteristics of conventional ECC. Figure 1 shows the deformation characteristics of Sprayable ECC which was used in this study. It has the approximately 0.02 of strain in tension and 4MPa of tensile strength with strain hardening.

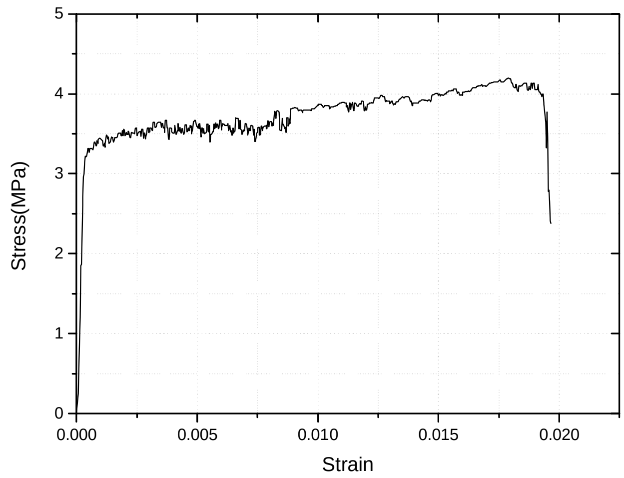


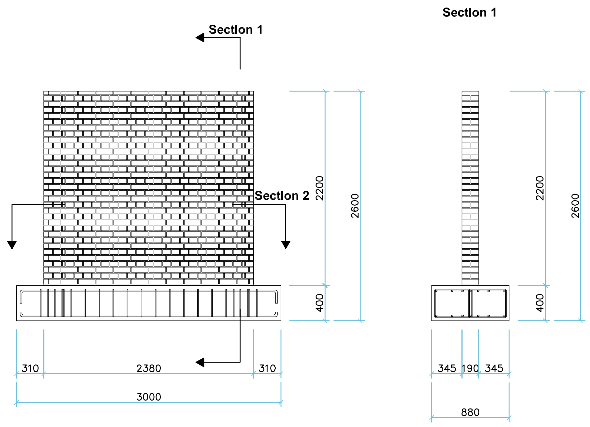
Figure 1. Stress-Strain Relation in tension of Sprayable ECC.

In order to specify the retrofitting layer thickness, we referred the literature that Sprayable ECC was used as retrofitting material for perforated reinforced concrete shear wall which was performed by Choi.[11] The results show that effective shear strength that was evaluated is the same amount of direct tensile strength of ECC. Using this vale in reinforced concrete shear strength equation proposed by ACI or other researchers we decided that thickness of retrofitting layer is 30mm for both side of masonry wall for present seismic demand proposed in KBC-S. The equation that was used in this study showed below

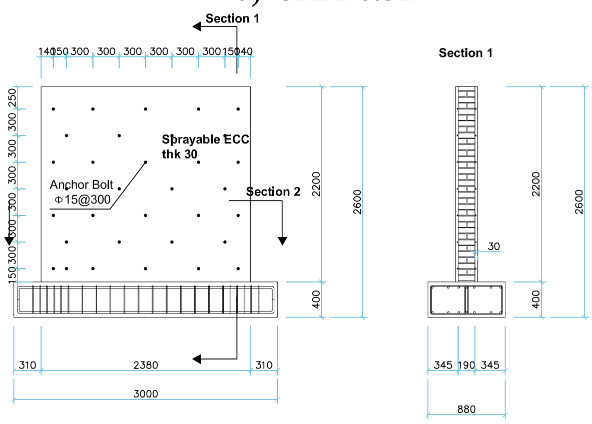
$$V_c = 0.27\sqrt{f_c^{'}}hd \qquad (2)$$

$$0.27\sqrt{f_c^{'}} \rightarrow 3.2MPa\text{(Direct Tensile Strength)}$$

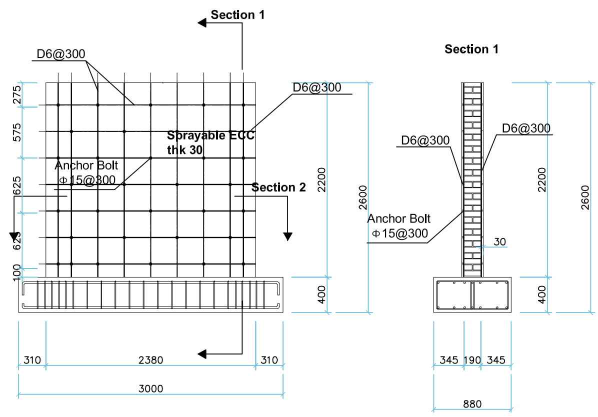
where, h = wall thickness and d = wall length.



a) URM-0.92



b) RTM-ECC



c) RTM-ECC-WM

Figure 2. Test Specimens.

Retrofitting test of perforated reinforced concrete shear wall showed the out of plane exclusion of retrofitting layers in compression process of loading history. In order to prevent the exclusion of ECC overlay, shear dowels which have 10mm diameters were constructed.

Wire-mesh was constructed in order to improve the bond strength of retrofitting materials and control the crack of ECC overlays. High strength reinforcement was used for wire-mesh which have 745MPa of yield strength.

Table 2. Characteristics of Materials.

Compressive Strength of Brick Element [MPa]	Compressive Strength of Mortar [MPa]	Compressive Strength of ECC [MPa]	Tensile Strength of ECC [MPa]	Tensile Strain of ECC [MPa]
15.7	8.4	41	4.18	0.018
Yield Strength of Wire-mesh [MPa]		Tensile Strength of Wire-mesh [MPa]		
745		800		

3.4 *Test Set-up*

The general arrangement of the experimental setup is shown in Figure 3. The test specimens were constructed on a precast RC footing which post-tensioned to the strong frame in laboratory. Only self weight of specimens and loading frame is applied as gravity load. The horizontal load was applied to the steel head beam, which in turn distributed the force to the wall panel. The load was applied using 1000kN actuator. In order to prevent out of plane buckling of wall during loading process additional frames were installed. The typical cyclic loading, which was illustrated in Figure 4 was used. At each loading stage, each specimen was subjected to a complete cycle for three times. The increment in the displacement was accordance with the rotational angle of specimen.

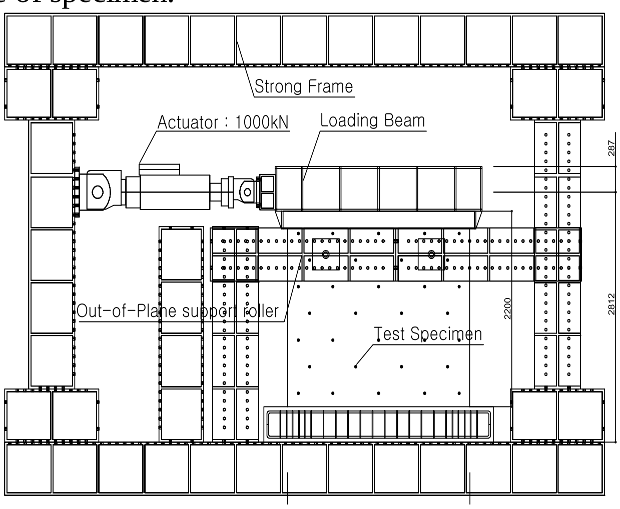


Figure 3. Test Setup.

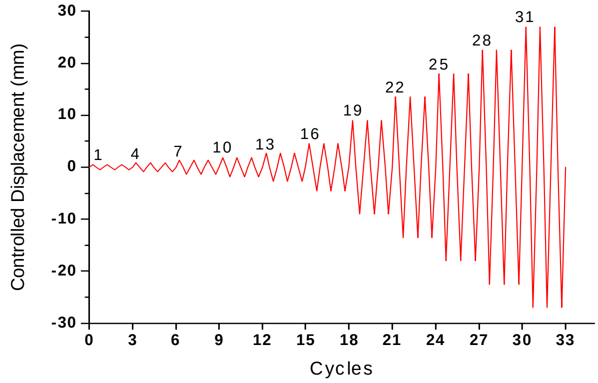


Figure 4. Loading History.

4 TEST RESULTS

The results of present study are presented here according to the test specimens.

4.1 *URM-0.92*

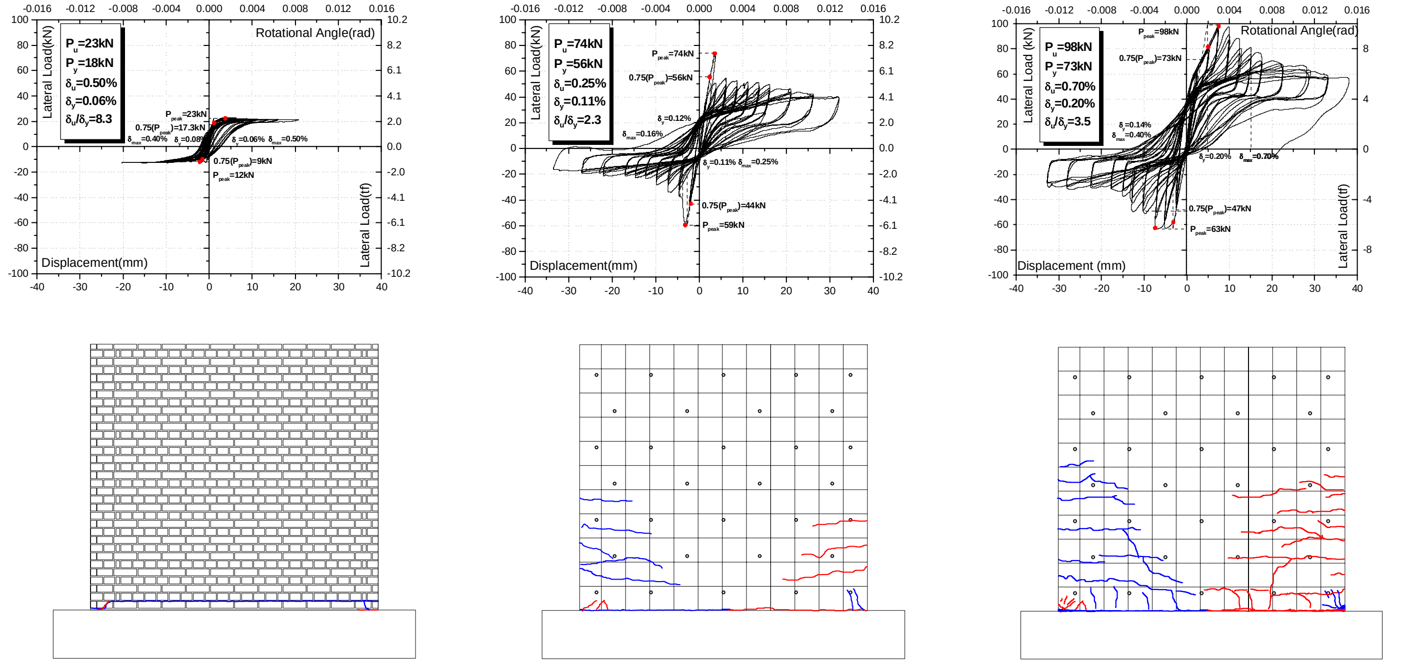
Specimen URM-0.92, a reference specimen, had an average lateral strength of 23kN. It had mixed modes of failure, namely rocking, sliding and toe crushing. At a drift of 0.01% and a lateral load of 18kN, a first flexural crack formed in the first bed joint and second bed joint in other direction of loading. Maximum lateral resistance was occurred at drift 0.1%. At drift 0.5% specimen was failed due to rocking at second bed joint and crushing was occurred.

4.2 *RTM-ECC*

RTM-ECC specimen showed great increase in ductility. The maximum load of 74kN applied at drift 0.15%. After applying maximum load, load was abruptly decreased to the level of yield strength of specimen and slightly decreased to failure of specimen due to crushing of compression side and rocking of specimen at drift of 1.2%. Showing this ductile behavior, flexural cracks were appeared at both side of the wall. To avoid anchorage failure of the wall panel and prevent shrinkage of retrofitting layer, wire-mesh was constructed at URM surfaces. Yielding strength, 73kN and maximum strength, 98kN, of test specimen were occurred at drift of 0.2% and 0.3%.

4.3 *RTM-ECC-WM*

Comparing RTM-ECC wire-mesh constructed test specimen show no abrupt decrease of strength. After showing maximum strength of specimen, applied load of specimen decrease slowly to the drift of 1.4% and more flexural cracks were appeared at both side of wall panel during failure of specimen due to rocking and toe crushing.



a) URM-0.92 b) RTM-ECC c) RTM-ECC-WM

Figure 5. Crack and Failure Pattern of Specimens.

5 RETROFITTING PERFORMANCE

5.1 *Retrofitting effect in strength and ductility*

Table 3 and figure 5 show the comparison of test results about positive and negative loading state. Strength enhancement of RTM-ECC is 3.2 times of URM-0.92 and RTM-ECC-WM is 4.3 times of URM-0.92.

Unreinforced masonry wall show consistence strength after peak load. However, in the unloading process, it showed very slow stiffness recovery during load reversal. However, retrofitted specimens, RTM-ECC and RTM-ECC-WM showed significant increase in strength and ductility. Firstly, RTM-ECC showed increased stiffness compared with non-retrofitted masonry wall test specimens. However, after peak load, load bearing capacity was reduced to the half of the peak load, approximately. This load was maintained to the ultimate failure which was occurred by the crushing of ECC layer.

RTM-ECC-WM show comparatively better behavior than RTM-ECC. Wire-mesh which was constructed due to the controlling of cracks affected structural performance after peak load and during the unloading process slowing stiffness decreasing.

Consequently, strength enhancements of retrofitting specimens are 3.2 and 4.3 times of non-retrofitted test specimens, respectively. And ductility enhancements of test specimens are 1.2 and 1.25 times, respectively. These phenomena were caused by the straining of ECC layer and anchors which is constructed in order to prevent the overturning of wall panel. Additionally, in the case of RTM-ECC-WM, deformation of wire-mesh affect to the effective stress distribution which was occurred by moment through wire-mesh to the wall panel.
Table 3 shows the test results briefly.

Table 3. Test Results.

Specimens		P_{cr} (kN)	P_y (kN)	P_u (kN)	δ_y (mm)	δ_u (mm)	$\delta_{\max}$ (mm)	θ_y (%)	θ_u (%)	$\theta_{\max}$ (%)	μ_u	$\mu_{\max}$	$\frac{P_{u,ret}}{P_{u,URM}}$
URM-0.92	Pos	19	18	23	1.5	12.6	12.6	0.06	0.5	0.5	8.3	8.3	-
	Neg	-10	-9	-12	-1.8	-9.8	-9.8	-0.08	-0.4	-0.4	5.4	5.4	-
RTM-ECC	Pos	38	56	74	2.6	6.1	26.4	0.11	0.25	1.3	2.3	10.1	3.2
	Neg	-22	-44	-59	-2.9	-3.7	-26.9	-0.12	0.16	-1.1	1.3	9.2	4.8
RTM-ECC-WM	Pos	44	73	98	3.39	15.1	33	0.13	0.7	1.34	3.5	10.3	4.3
	Neg	-32	-47	-69	-3.4	-10.1	-32	-0.14	-0.4	-1.3	2.9	9.4	5.8

5.2 *Retrofitting effect in strength and ductility*

The overall force-deformation responses of test specimens were illustrated in Figure 5. The envelopes of the hysteresis loops of the tested specimens are shown in Figure 6. As shown in the figure retrofitting improved the strength and ductility significantly, comparing URM. Because of high tensile strength and stiffness of ECC, the initial stiffness of test specimens was higher than URM specimen. High strength reinforcement improved stiffness, strength and ductility of wall specimen. Especially, the gradual strength deterioration allow RTM-ECC-WM to develop up to 1.2% drift at a lateral resistance approximately four times the peak strength of the reference specimen. The cumulated energy dissipation of the specimens was calculated (Fig. 7). In this graph RTM-ECC-WM shows great significant performance enhancement. Deformation of wire-mesh was effectively occurred during load reversal and this phenomena increase the energy dissipation capacity significantly with deformation of retrofitting layer which was illustrated in Figure 7.

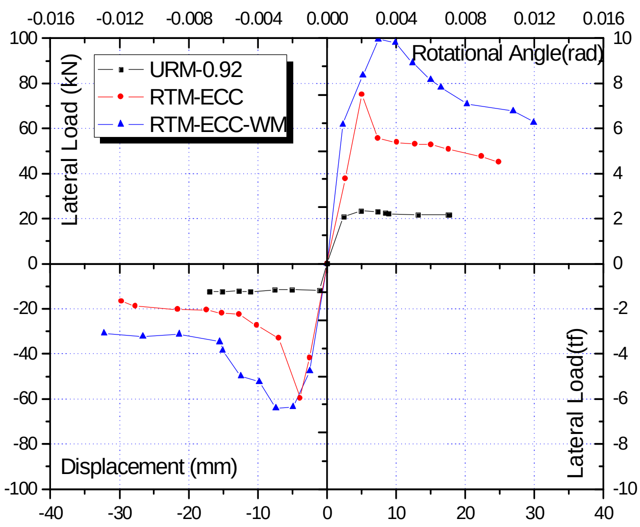


Figure 6. Backbone Curves for test specimens.

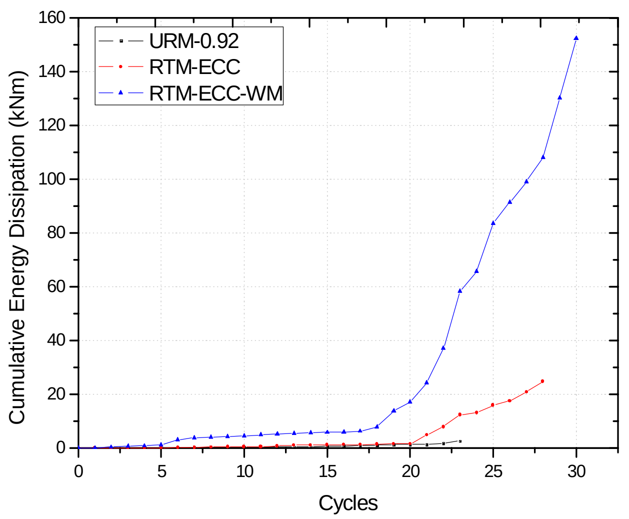


Figure 7. Acumulative Energy Disspation of test speimens.

6 CONCLUSION

In this study, unreinforced masonry and retrofitted wall specimens were tested under cyclic loading. Based on the test results described in this paper, the following conclusions can be shown.

1. All specimens were failed due to rocking and toe crushing in flexural mode.

2. Significant enhancement of strength and ductility was shown in retrofitting specimen RTM-ECC. Wire-mesh can increase the strength and ductility and prevent abrupt deterioration of strength.

3. ECC layer can improve the wall stiffness effectively but overturning effect of wall was significant and deformation of wall was not enough for high energy dissipation. Wire-mesh transfer stress more effectively in ECC layer and this improve energy dissipation capacity.

7 ACKNOWLEDGMENTS

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