OUT OF PLANE BEHAVIOR OF COMPOSITE RETROFITTED MASONRY WALL SYSTEMS

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ABSTRACT: The present study deals with the earthquake disaster reduction by the development of new composite material to mitigate the collapse of unreinforced masonry structures (URM) in urban and rural areas in developing countries. Collapse of unreinforced masonry walls causes a large number of human causalities due to a strong ground motion. Masonry walls are relatively strong for in-plane shear and much weaker in out of plane direction resulting collapse of masonry structure. Being highly expensive, FRP is a strong material and can significantly increase the out of plane bending strength of masonry walls. Being an expensive material, FRP exhibits a highly catastrophic brittle failure under extreme loading leaving no warning and evacuation time for residents. On the contrary, polypropylene band (PP-band) is a cheap material with much larger ductility and holding capacity to avoid sudden failure, caused by the breaking of wall into small fragments which has been found as a major cause of causalities. In this study, an attempt has been made to find a composite material by using FRP and PP-band to increase the shear capacity and to avoid the catastrophic brittle failure of masonry walls under strong ground shaking. In order to achieve required objectives, out of plane load tests have been carried out using six masonry wallets consisting of three non-retrofitted masonry wallets, PP-band retrofitted masonry wallet, FRP retrofitted masonry wallet and FRP+PP-band retrofitted masonry wallet. Behavior of wallets has been carefully observed in terms of peak strength, deflection and deformation capacity. It has been found that retrofitting of masonry walls using FRP and PP-band is much viable solution as compared to conventional retrofitting techniques because FRP+PP-band reduced the overall cost of retrofitting due to confining and holding effect of PP-band which is a very low cost material.

Key Words: Retrofitted, Composite, Polypropylene, Fiber reinforced polymer

INTRODUCTION

Masonry is one of most popular and oldest construction material. Because of its low cost and local availability, its significance as a construction material has become more relevant. Better aesthetics, good heat and sound insulation, high fire rating and economical construction are some of additional inherent advantages of masonry construction. Masonry contributes a large number of structures in world's inventory of non-engineered construction and almost all of the construction is composed of unreinforced masonry (URM). Seismic vulnerability of URM is highly questionable in the region of high seismic activity. According to Coburn and Spence [Coburn and Spence, 1992], collapse of URM masonry houses is the biggest cause of human causalities in under developed parts of world during earthquake hazards. Understanding and realizing the shortcomings of URM masonry, many researches worldwide started efforts to strengthen and retrofitting of existing masonry construction. In this regards many retrofitting techniques have been developed such as adding concrete frames, masonry jacketing, ferocement coatings, applying near surface mounting sheets or members using wire mesh. Most of these methods are expensive, aesthetically not good and add mass to the masonry wall system.

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Masonry walls are strong enough in in-plane direction of seismic force. On the other side, out of plane failure of masonry wall system is hazardous and explosive causing almost complete collapse of masonry structure [Bruneau, 1994]. There is no doubt to say that URM is more vulnerable when seismic force is acting in out of plane or perpendicular to longitudinal axis of wall. It is the idea of many researches that behavior of masonry walls in out of plane direction requires more experimental and theoretical investigation. [Flagan et al 1993, Drysdale et al 1994].

(a): Canterbury, New Zealand　　(b): Gedikbulak, Turkey

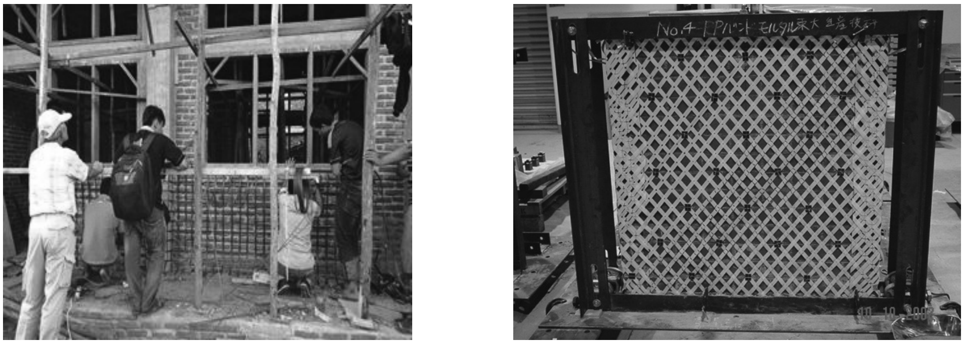
Figure 1. Typical out-of-plane failure of an unreinforced masonry

Figure 1(a) shows typical out-of-plane failure of an unreinforced masonry wall on the second level of 146 Kilmore Street in Canterbury New Zealand [EERI, 2012]. The light blue concrete column, hanging from the second floor, has no reinforcement. Figure 1(b) shows the out of failure of masonry house during Van, Turkey Earthquake of October 23, 2011 [EERI, 2012].

Literature Review

Among some of recent retrofitting methods Fiber Reinforced Polymers (FRP) has become very popular because of its less retrofitting time, better aesthetics, high strength and ease in application over the masonry surface. On the other hand, FRP can increase the initial shear strength and out of plane bending strength to the great extent.

Meguro and Mayorca [Meguro and Mayorca, 2003] have developed polypropylene band (PP-band) retrofitting method considering economic affordability, local acceptability, material availability and technological applicability required for retrofitting. PP-band is a very cheap material with fairly large deformation capacity. Main objective of PP-band retrofitting is to hold the masonry components into a single unit and to prevent the collapse of masonry structure. After carrying out a series of experiments ranging from small-scale model to full-scale masonry house, it was found that PP-band retrofitted walls can withstand much stronger input ground motion without collapse [Meguro et al, 2005].



(a) PP-band retrofitting of a masonry house in Indonesia

(b) PP-band retrofitted wall in laboratory

Figure 2. Retrofitting of masonry wall using PP-band in the field and laboratory

FRP and PP-band Composite Retrofitting Technique

In this research we proposed a new retrofitting material which is a composite of Polypropylene band and Carbon Fiber Reinforced Polymer (CFRP). Both of these materials are applied on masonry wall system as a composite material and this composite not only increases initial shear strength but also serve satisfactory to keep integral the structural system by providing sufficient deformation and energy dissipation capacity. FRP is a brittle material and has ultimate tensile strain ranging from 2 to 4% [V. Turco and S. Secondin, 2005]. Whereas, PP-band cannot increase significantly initial strength of non-retrofitted masonry, it can enhance the structural deformation capacity up to 50 times larger than that of non-retrofitted one [Meguro et al, 2005]. FRP can serve satisfactory if it is applied completely or fully wrapped to hold the brick units which can increase tremendously the retrofitting cost and still do not allow the structural system a reasonable deformability, while PP-band is not only a fairly ductile and deformable but can also be wrapped completely to the wall system because of very low retrofitting cost.

In order to achieve the required objectives, a series of out of plane load tests are carried out using different wallet schemes. A total of six masonry wallets are tested, three non-retrofitted and three are retrofitted. Among retrofitted masonry wallets, one is PP-band retrofitted masonry wallet, one is CFRP retrofitted masonry wallet and one is CFRP+PP-band retrofitted masonry wallet. The main objective of this study was to investigate the effect of PP-band and CFRP composite on increasing bending strength and deformation and energy dissipation capacity in the out of plane direction of masonry walls.

EXPERIMENTAL PROGRAM

Properties of masonry

Compression, Shear and bond tests are carried out in order to determine the properties of brick, mortar, and masonry. Table 1 shows the properties of different materials used for construction of masonry wallets. Bricks compressive strength is determined according to ASTM C-67. Three samples of burnt brick were tested under direct compression. Three mortar cubes of 50mm×50mm×50mm containing a weight mixed proportion of cement, lime and sand (250g: 1,000g: 2,800g) were tested with 0.25 water/cement ratios according to ASTM C-109. Three samples of brick triplets, each triplet consisting of three bricks joined together by 5 mm mortar thickness were prepared to evaluate the shear strength of masonry units. Three masonry prisms each consisting of five bricks were tested according to ASTM C-1314.

Table 1: Characteristics of materials used in experiments

Test / Specimen	Compressive strength of brick (MPa)	Compressive strength of mortar cube (MPa)	Compressive strength of masonry prism (MPa)	Shear strength of mortar (MPa)	Bond strength of mortar (MPa)
1	25.10	1.08	15.95	0.24	0.0040
2	26.60	1.07	11.60	0.15	0.0050
3	26.70	1.34	13.25	0.21	0.0040
Average	26.10	1.16	13.60	0.20	0.0043

Axial tensile test on polypropylene (PP) band

Three sample of PP-band with 6mm×0.6mm in nominal area of cross section and 150mm in gauge length are tested under uniaxial tensile loading using displacement control universal testing machines (UTM). Table 2.0 shows the tension test results of PP-band.

Table 2: Polypropylene band tension test results

Specimen	Maximum Axial Stress (MPa)	Initial Modulus (GPa)	Residual Modulus (GPa)	Failure Strain (%)
PP-1	254.20	7.38	1.91	12.30
PP-2	246.50	6.95	2.06	12.67
PP-3	234.40	6.42	1.96	11.91
Average	245.03	6.92	1.98	12.29

Properties of CFRP and epoxy

Properties of CFRP and epoxy are provided by the supplier of these materials. Bi directional type of fiber layout is used in CFRP. Thickness of CFRP sheet is 0.5mm. Bond E-250 epoxy is used to apply CFRP over the brick surface. Table 3 and Table 4 show the properties of CFRP and epoxy. All epoxy strength parameters are examined at temperature of 20±1^{o}C after curing time of 7 days.

Table 3: Material properties of CFRP

Material	Tensile modulus (GPa)	Bending strength (MPa)	Bending modulus (GPa)	Compressive strength (MPa)	Ultimate Elongation (%)
CFRP	120	130	90	900	2

Table 4: Material properties of Epoxy

Material	Tensile strength (MPa)	Tensile shear bond strength (MPa)	Bending strength (MPa)	Compressive strength (MPa)	Compressive shear bond strength (MPa)
Epoxy	20	9.6	45	50	21

MAOSNRY WALLETS TESTING SCHEME

Masonry wallets testing and experimental setup

Four types of masonry wallets are shown in the Fig 3. Size of masonry wallet is 475mm x 238mm x 50mm. All of these wallets are constructed using 75mm x 37mm x 50mm burnt brick units. Cement lime mortar with a weight mixed proportion of cement, lime and sand (250g: 1,000g: 2,800g) is made with 0.25 water/cement ratios. Masonry wallets are constructed, cured and tested under similar conditions. In case of CFRP and CFRP+PP-band retrofitted masonry wallets, CFRP is pasted on wallet surface with the help of strong epoxy and cured for 24 hours whereas PP-band and CFRP+PP-band retrofitted, PP-band is applied on both faces with the help of ultrasonic welder and also connected in out of plane direction.

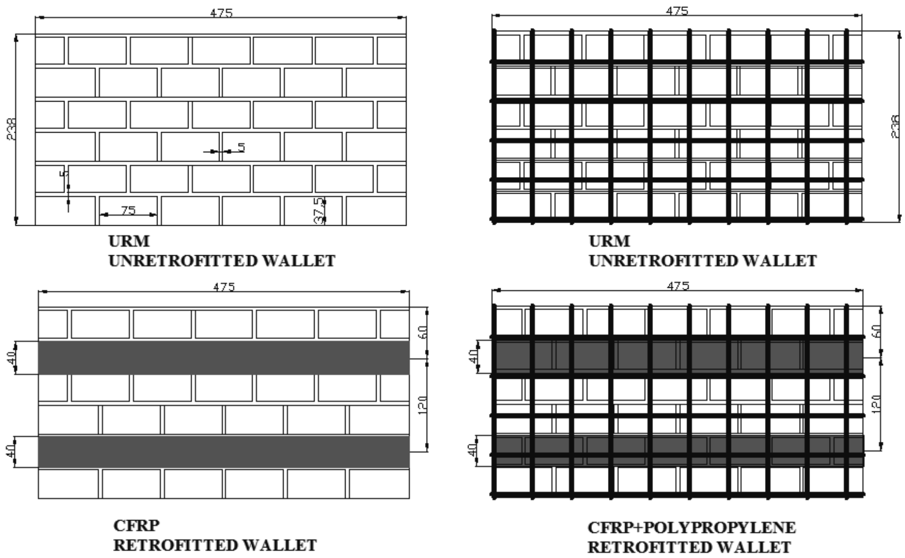
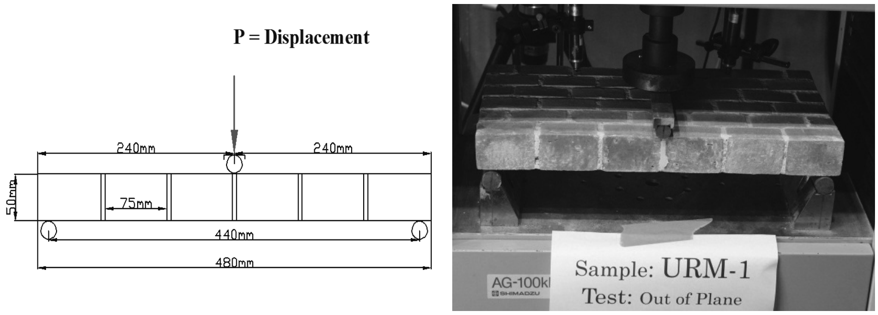


Figure 3. Masonry wallets retrofitting scheme for out of plane load test.

Three of the masonry wallets are retrofitted using different retrofitting schemes. One is PP-band retrofitted, one is CFRP retrofitted and one is CFRP+PP-band retrofitted. Two CFRP strips of dimension 475mm x 40mm x 0.5mm are used on both faces of CFRP and CFRP+PP-band retrofitted masonry wallets. PP- band mesh pitch of 50mm is used for PP-band retrofitted and CFRP+PP-band retrofitted masonry wallet.

Test Setup

Each of the wall specimen was tested like a simply support beam of center to center span of 440mm with one displacement at the center of span in the form of line load throughout the width of the masonry wallet as shown in Fig 4 (a) and (b). Total size of masonry wallet is 480mm from edge to edge of specimen. Vertical displacement is applied at center of the specimen at a loading rate of 0.1 mm/min. Two LDTV displacement transducers with 500×10^{-6}/mm sensitivity are used at quarter span to measure the deflection. Wall specimen is simply supported on two steel rollers and displacement is transferred from machine to specimen with the help of steel roller and a cap plate. A small initial displacement is applied to assure the full contact of the wallet and loading arrangement. Specimens were completely inspected in throughout the length of loading increments. Different displacement loading rates are selected depending upon the failure displacement and duration of test. All displacement and loading data is recorded in a computerized digital acquisition system.



(a) Schematic diagram (b) Experimental setup

Figure 4. Test setup of out of plane load test

TEST RESULTS

Non-retrofitted masonry wallet

One of the main focuses of experimental results was load-displacement curves of masonry wallets. Figure 5 shows the load displacement curve of non-retrofitted masonry wallets. All URM specimens are tested using same loading rate of 0.1mm/min. Although preparation, curing and testing conditions of masonry wallets were similar still the non-retrofitted wallets show a variety of peak strength with an average value of 0.7 kN with almost similar initial stiffness. Behaviour of wallets was almost linear up to the peak value. Sliding type of failure has been observed exhibiting a weak brick mortar joint at vertical displacement range from 0.6mm to 1.2mm as shown in Fig.5 (a).

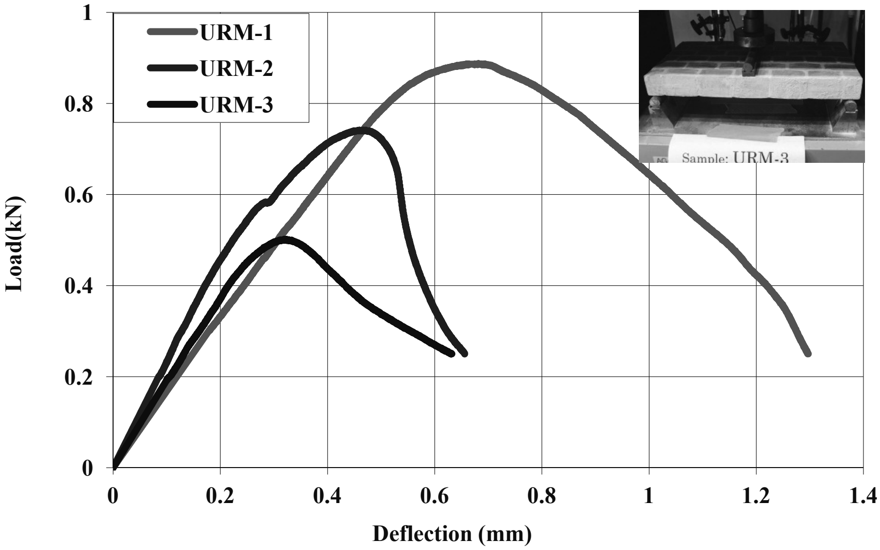


Figure 5. Load-displacement curves of non- retrofitted masonry wallets

PP-band retrofitted masonry wallet

Figure 6 shows the load displacement curve of PP-band retrofitted masonry wallet. It has shown almost similar initial stiffness and peak strength of 0.79 kN which is almost same as that of non-retrofitted masonry wallet. Up to initial peak loading rate of 0.1mm/min is used and after that the test was continued at a loading rate of 2.0 mm/min. In case of PP-band retrofitted masonry wallet after the displacement of 1.2 mm/min the sample again started taking load with some reduced stiffness, even it has gone up to a displacement of 57.7 mm with a load value of 0.88 kN. PP-band retrofitted masonry wallet has shown a fairly long deflection and deformation as compared to URM masonry wallets

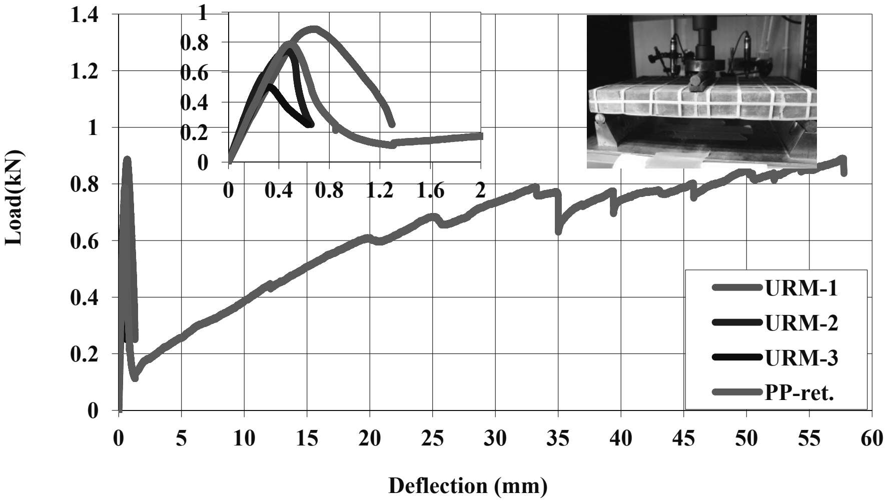


Figure 6. Load-displacement curves of non- retrofitted masonry wallets and PP-band retrofitted masonry wallet

CFRP retrofitted masonry wallet

Figure 7 shows the load displacement curve of non-retrofitted masonry wallet, PP-band retrofitted and CFRP retrofitted masonry wallet. CFRP retrofitted masonry wallet is tested at a loading rate of 0.25mm/min and use of CFRP has increased initial peak strength of no-retrofitted masonry wallet from 0.8kN to 8kN. CFRP retrofitted masonry wallet has shown a high initial stiffness as compared to URM and PP-band retrofitted masonry wallets. Use of CFRP has also increased the mid span deflection from 1.2 to 5.0mm but it is far less than PP-band retrofitted case. PP-band retrofitted masonry wallet has increased the displacement from 1.2mm to 58 mm. It can also be seen from figure 7 that CFRP retrofitted wallet has shown a sudden drop in strength from 1.6kN to 1.0kN at a displacement of 0.65mm. This sudden drop was due to detachment and falling of one layer of brick at the inner edge of masonry wallet. After that it again started taking load and reached to peak strength of 8.0kN. CFRP was acting just like tension reinforcement on tension face of a simply supported beam and bricks were taking care of compression just like a simply supported beam having reinforcement on both of the faces.

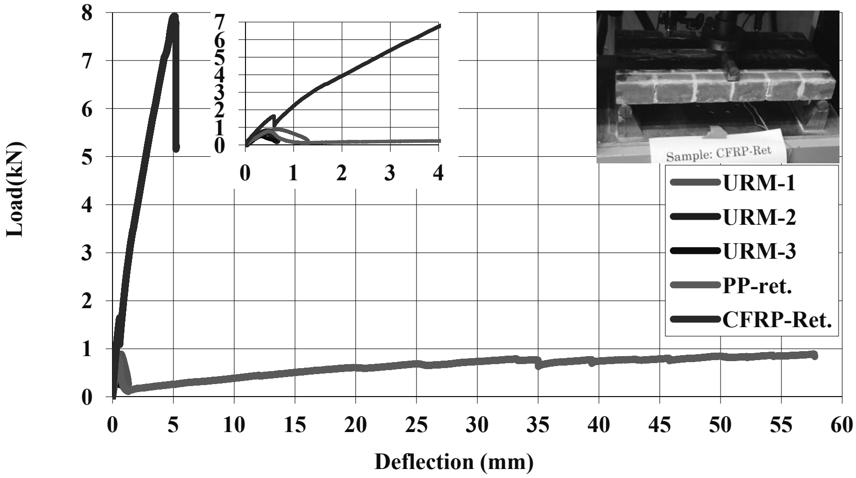


Figure 7. Load-displacement curves of non- retrofitted masonry wallets, PP-band retrofitted and CFRP retrofitted masonry wallet

CFRP+PP-band retrofitted masonry wallet

Figure 8 shows the load-displacement curve for URM, PP-band retrofitted and CFRP+PP-band retrofitted. In case of CFRP+PP-band retrofitted masonry wallet initial strength of URM is increase from 0.8kN to 5.5kN and displacement carrying capacity is also increased from 1.2mm to 62mm. After the peak strength of 5.5kN, there is a sudden drop but still CFRP+PP-band retrofitted masonry wallet has shown a good residual strength up to the final failure of wallet. Proposed composite material has increased intial strength, deformation capacity, and residual strength of non-retrofitted masonry wallet.

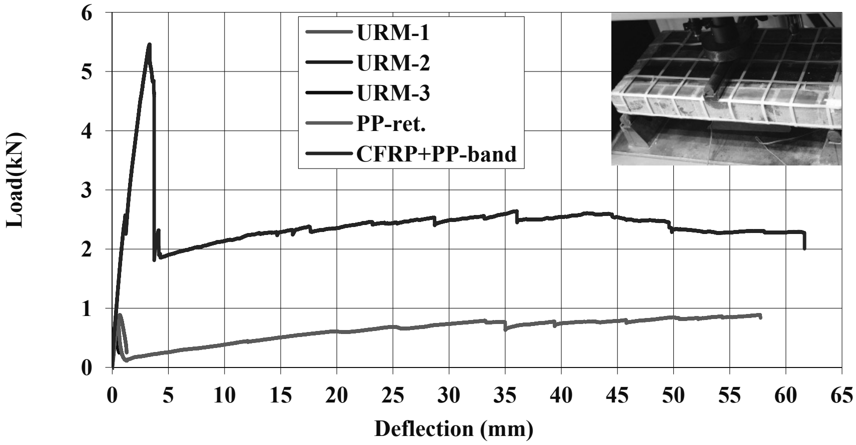
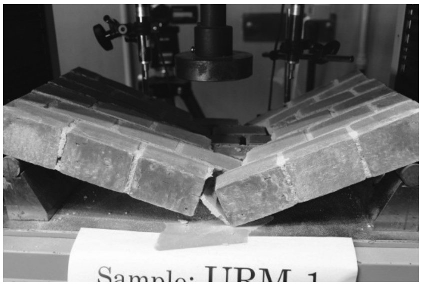


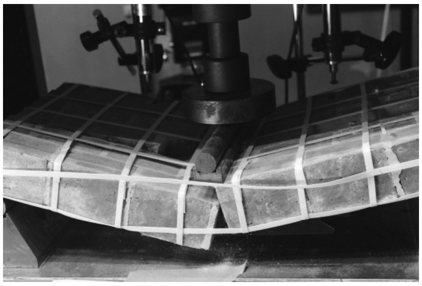
Figure 8. Load-displacement curves of non- retrofitted masonry wallets, PP-band retrofitted and CFRP+PP-band retrofitted masonry wallet

FAILURE MODES

Figure 9 shows that failure pattern of different type of masonry wallets under out of plane loading. Figure 9 (a) shows a pure bending type of failure with major central cracking with spalling of bricks in the central part of masonry wallets. There were no signs of shear failure near supports. Figure 9 (b) shows that PP-band retrofitted masonry wallet failure. It is almost same type of failure as that of URM but PP-band kept holds the masonry units. As PP-band is attached with the out of plane connectors, so it has not provided any increase in bending strength but after the peak, it kept the brick unit as single mass to further take load up to a displacement of 58 mm as shown in Fig 6. Figure 9 (c) shows the failure the failure of CFRP- retrofitted masonry wallet. CFRP- retrofitted masonry wallet has shown a step wise failure initiated with the fall of inner and outer brick layers. Failure of wallet was mainly due to detachment and debonding of CFRP from brick surface. CFRP+PP-band retrofired masonry wallet failure has shown in the Fig 9 (d). Use of PP-band along with the CFRP has changed the failure mode of only CFRP retrofitted masonry wallet as the step was failure is vanished. In CFRP retrofitted case the wallet was disintegrated into longitudinal strips but CFRP+PP-band retrofitted masonry wallet has avoided the delamination of brick layers form the wallet. It kept hold the entire brick mas into a single system even up to the final failure of masonry wallet.

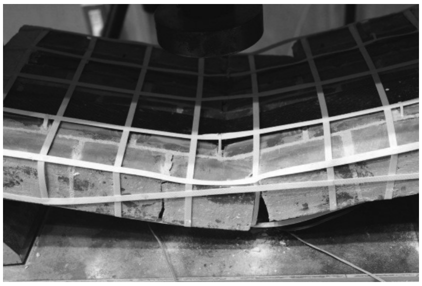


(a) Failure pattern of URM



(b) Failure pattern of PP-band retrofitted masonry wallet

(c) Failure pattern of CFRP-retrofitted masonry wallet



(d) Failure Pattern of CFRP+PP-band retrofitted masonry wallet

Figure 9. Failure pattern of different types of masonry wallets under out of plane loading

CONCLUSIONS

FRP is an expensive and has very high initial stiffness with a failure strain ranging from 2-4% whereas PP-band is a cheap material with very high failure strain ranging from 12-14%. Non retrofitted masonry wallet has shown very sudden failure breaking the wall into small pieces. PP-band has provided very high deformation and energy dissipation capacity but the release of energy through proper crack distribution on all over the masonry wall units. CFRP has increased the initial strength of masonry wall but it could not increase the deformation and energy dissipation capacity of masonry wallet exhibiting a very high brittle failure. Failure of CFRP was mainly due to debonding of CFRP strips from the brick surface. In order to further increase the performance of masonry wall units less thickness with more surface area with good brick surface conditions are recommended. CFRP+PP-band together have not only increased the initial strength, deformation capacity, energy dissipation capacity but also the residual strength of masonry wallet in post peak behaviour. This increase in residual strength is due to holding effect of PP-band provided to the bricks and CFRP and it reduces the chances of further detachment of CFRP from brick surface as wallet undergoes further displacements. CFRP+PP-band retrofitted has changed the mode of failure of CFRP retrofitted wallet from sudden brittle failure to gradual ductile failure. Use of both the materials has given a very high performance and cost effective technique for retrofitting of masonry structures which can save property and human life during a seismic hazard.

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