In Plane Behavior of Polypropylene and FRP Retrofitted Brick Masonry Wallets under Diagonal Compression Test

Saleem M. Umair
PhD Student,Civil Engineering Department,The University of Tokyo Japan

Muneyoshi Numada
Research Associate, Institute of Industrial Science, The University of Tokyo Japan

Kimiro Meguro
Professor, Institute of Industrial Science, The University of Tokyo Japan

SUMMARY:
Unreinforced masonry structures are highly vulnerable and have contributed a significant number of causalities during past earthquake disasters. Therefore, improvement of seismic capacity of unreinforced masonry structures is essentially important to reduce causalities due to future earthquakes. In order to improve seismic capacity of unreinforced masonry structures, we have proposed a new composite material which can increase shear strength and deformation capacity of masonry walls. To investigate properties of newly proposed composite materials which are ductile, cost effective and strong enough with large energy dissipation capacity, we have carried out experimental studies. Fiber reinforced polymer (FRP) is a very strong but costly material. It can significantly increase the shear capacity of unreinforced masonry but exhibits catastrophic and brittle failure due to its low ductility. While polypropylene (PP) band is very cheap material but has large deformation capacity. In this study, an attempt has been made to utilize the large deformation capacity of PP-band and an increase in strength with minimal use of FRP. A comparative study has been carried out by in-plane diagonal compression test using different types of masonry wallets, such as non-retrofitted ones, carbon fiber reinforced polymer (CFRP) retrofitted ones, PP-band retrofitted ones and a composite of CFRP and PP-band retrofitted ones.

Keywords: Polypropylene band, Retrofitting, Composite material, Fiber reinforced polymer, Diagonal compression, Unreinforced masonry,

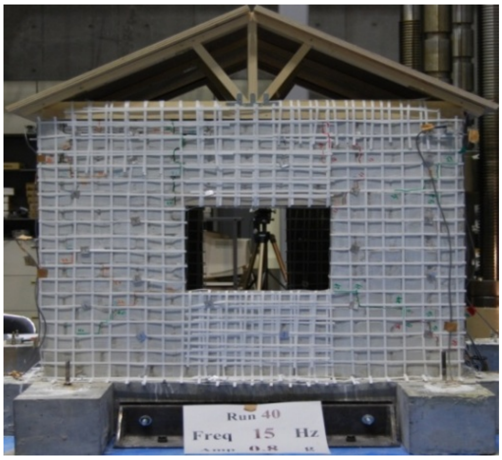
1. INTRODUCTION

A significant number of historical and traditional buildings and houses in the world are constructed by masonry. Being a locally available and low cost material, masonry still encourages lots of new constructions in many parts of the world especially in developing countries. Fire resistance, heat and sound insulation, and appealing aesthetics are some of inherent advantages of masonry residential structures[Y. Zhuge, 2010]. On the other hand, from structural safety point of view, masonry is a brittle material and unreinforced masonry can cause severe damage of life and property. Recently many earthquakes have highlighted the vulnerability of masonry structures against strong ground excitations. The 1997 Umbria-Marche, Italy,1999 Bhuj, India,2003 Bam, Iran, 2005 Kashmir, Pakistan and 2008 Wenchuan, China earthquakes have shown the collapse of larger number of masonry structures especially in concentrating areas of poorly designed and constructed. It is seen in past earthquakes that unreinforced masonry buildings are the largest cause of casualties during earthquakes. Human casualties due to earthquakes in the 20th century are mostly due to structural damage, most of which was assigned to unreinforced masonry buildings (Coburn and Spence, 2002).Therefore, retrofitting of low earthquake-resistant masonry structures is the key issue for earthquake disaster mitigation and significant reduction of causalities [Kimiro Meguro and Mayorca, 2005]. Seismic retrofitting reduces not only the damage to buildings during earthquakes, but also the costs of rescue and first aid activities, rubble removal, temporary shelter preparation and permanent residential reconstruction to re-establish normal daily life [Yoshimura and Meguro, 2004].

In order to encounter above problems, lots of retrofitting methods have been proposed by many researchers worldwide. Some of proposed retrofitting methods include use of cement grout injection, shotcreting, ferrocement coatings, external steel bars application and FRP external bars applications. These retrofitting methods reported not only restoration of original capacity of damaged masonry structures but also an increase in seismic capacity of undamaged masonry structures. For the last two decades, FRP has become a very popular retrofitting material not only for concrete but to a large extent for masonry as well. FRP has some well known advantages over conventional retrofitting techniques such as high strength, ease of application, corrosion resistance and high strength to weight ratio. FRP retrofitting methods can increase the structural strength but make failure brittle. Therefore, FRP retrofitted walls collapses suddenly unless the whole masonry wall is fully wrapped by FRP whose cost may become sometimes larger than that of masonry construction.

Along with above retrofitted methods, Meguro and Mayorca [Meguro and Mayorca, 2005] 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 [Sakthi and Meguro, 2008]. Figures 1 (a) and (b) show the non-retrofitted and PP-band retrofitted scaled models under shake table test.

a) Shake table test of 1/4-scale non-retrofitted masonry house



(b) Shake table test of 1/4-scale PP-band retrofitted masonry house

Figure1. Shake table test of 1/4 scaled non-retrofitted and PP-band retrofitted masonry houses [Sakthi and Meguro, 2008]

In this study, we have proposed a new composite masonry retrofitted by Carbon Fiber Reinforced Polymer (CFRP) and PP-band. An attempt has been made in order to find a composite material using CFRP and PP-band which can increase the structural strength and serve satisfactory to hold the structural system by providing sufficient deformation capacity. For this purpose, CFRP is used to increase shear strength up to 325% of non-retrofitted wallet [Hamid Mahmood and Jason M. Ingham,2011]. However failure mechanism of FRP is brittle since it has ultimate tensile strain ranging from 2 to 4% [V. Turco and S. Secondin, 2005]. On the contrary, 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 [Sakthi and Meguro,2008].

FRP can act in efficient way if fully wrapped but it increases a lot the retrofitting cost as FRP is an expensive material. On the other hand, PP-band is very cheap material. Therefore, we can use small amount of FRP to increase strength and PP-band to increase ductility to reduce drastically the overall cost of retrofitting. In order to achieve aforementioned targets, diagonal compression tests using retrofitted and non-retrofitted wallets have been carried. The main objective of this study was to investigate the effect of PP-band and FRP composite on increasing strength and deformation capacity. Six masonry wallets have been tested by the application of diagonal displacement to determine the effect of PP-band and FRP. A series of material experiments were also carried out to examine the properties of materials used for masonry wallets.

2. EXPERIMENTAL PROGRAM

Experimental program consists of two main parts: material testing and masonry wallets testing. Same brick and mortar mixed proportion were used for material testing and diagonal compression testing. All materials are carefully prepared for construction of wallets in order to produce the similar conditions but still variability in the final results was observed.

2.1 Material testing

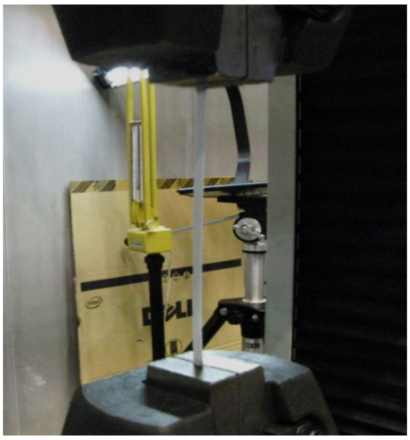
Material testing results are summarized in the Table 1**.** Construction procedure was kept same for all specimens of a testing material.

2.1.1 Axial Tensile test on Polypropylene (PP) Band

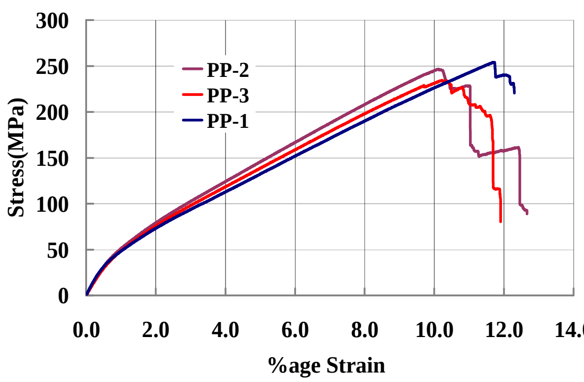
In order to obtain the deformational properties and strength of PP-band, axial tensile tests are carried out using three samples. Dimension of all three samples was 6mm×0.6mm in nominal area of cross section and 150mm in gauge length. Tests were carried out under displacement control system as shown in Fig. 2(a) and results are shown in Table 1 and Fig. 2(b). Figure 2 (b) shows stress-strain curve of PP-band. PP-band has shown a biaxial type of behavior with average initial modulus of elasticity of 6.92 MPa up to strain level of 0.8% and 1.98 MPa average modulus of elasticity up to failure.

Table 1. 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



(a) Test setup for PP-band



(b) Stress-strain curve for PP-band

Figure 2. Experimental setup and stress-strain curve obtained

2.1.2 Properties of CFRP and Epoxy

In order to increase original strength of walls, CFRP is used. CFRP carries a biaxial type of fiber layout with a fabric thickness of 0.5mm. Properties of CFRP provided by supplier are summarized in Table 2. Bond E-250 epoxy is used to apply CFRP over the brick surface. Properties of epoxy provided by supplier are presented in Table 3. All epoxy strength parameters are examined at temperature of 20±1^{o}C after curing time of 7 days.

Table 2. Material properties of CFRP

Material	**Specific gravity**	**Tensile strength** (MPa)	**Tensile modulus** (GPa)	**Bending strength** (MPa)	**Bending modulus** (GPa)	**Compressive strength** (MPa)	**Coefficient of thermal expansion** ($10^{-6}/C^{0}$)	**Ultimate Elongation** (%)
CFRP	1.5	1600	120	130	90	900	0.2	2

Table 3. Material properties of Epoxy

Material	**Specific gravity**	**Tensile strength** (MPa)	**Tensile shear bond strength** (MPa)	**Bending strength** (MPa)	**Compressive strength** (MPa)	**Compressive shear bond strength** (MPa)	**Compressive elasticity modulus** (GPa)
Epoxy	1.4	20	9.6	45	50	21	1.5

Note: + Sign indicates minimum value.

2.1.3 Properties of Masonry

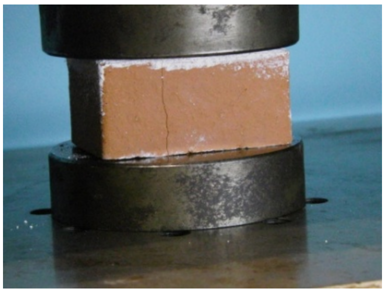
In order to examine the properties of brick, mortar, and masonry, a series of tests on compression, shear and bond using bricks, mortar cubes and masonry prisms were carried out. Material testing results are summarized in Table 4.

Clay burnt bricks were used for experiments. The scaled burnt brick dimensions are 75mm×37mm×50mm. Samples are tested according to ASTM C-67. Three samples of burnt brick were tested under direct compression. Test setup for brick compression test is shown in Fig 3.(a). All three brick samples have shown a very close agreement of compressive strength with an average value of 26.1 MPa. Table 4 shows the compressive strength of three brick samples. Three mortar cubes of 50mm×50mm×50mm containing a weight mixed proportion of cement, lime and sand (140g: 1,110g: 2,800g) were tested with 0.14 water/cement ratios. After curing period of 28 days, mortar strength is examined according to ASTM C-109. Figure 3 (b) shows the experimental setup for mortar cube test. Results for direct compression test of mortar cubes are presented in Table 4. A large variation in the test results has been observed. 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. Test setup is shown in Fig. 3 (c). Curing time for all three samples was 28 days. Figure 3 (d) shows the test setup of bond test. For bond test, specially cut steel plates were used and connected with opposite faces of brick by a strong epoxy. Two screwing steel rods are used to fix the sample in tension test machine. Samples were tested under constant rate deformation of 0.05 mm/min. Experimental results show a scatter of values which is a characteristic of bond strength. Test results for shear test and bond test are summarized in Table 4.

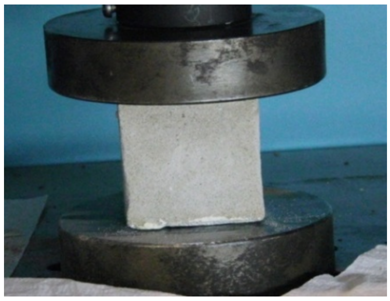
Three masonry prisms each consisting of 5 bricks joined together with 5mm mortar were prepared and cured under the same conditions for 28 days, in which the wallets were cured, i.e. water spray for 14 days after construction. These are the conditions according to ASTM C-1314. Figures 3 (e) and 3 (f) show the test setup and typical failure and crack patterns of masonry prisms. Average compressive strength of masonry prism is 13.42 MPa.

Table 4. Characteristics of materials used in experiments

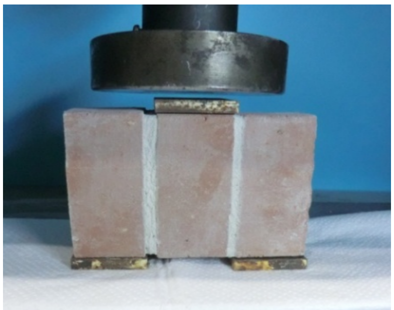
Test	**Compressive strength of brick**	**Compressive strength of mortar cube**	**Compressive strength of masonry prism**	**Shear strength of mortar**	**Bond strength of mortar**
Specimen	(MPa)	(MPa)	(MPa)	(MPa)	(MPa)
1	25.10	0.57	18.95	0.020	0.0027
2	26.60	0.42	10.70	0.016	0.0041
3	26.70	2.10	10.60	0.032	0.0029
Average	26.10	1.03	13.42	0.023	0.0032



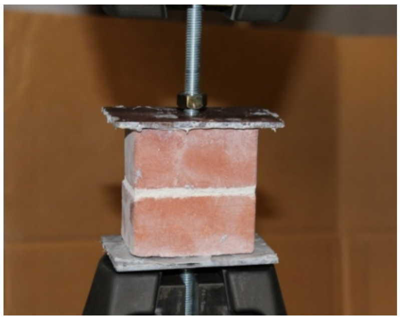
(a) Setup of brick compression test



(b) Setup of mortar cube compression test



(c) Setup of direct shear test



(d) Setup of bond test

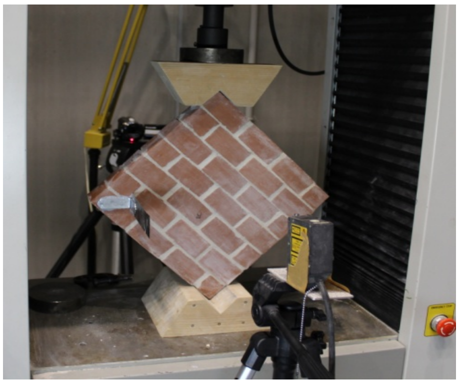
(e) Setup of compression test of masonry of prism

(f) Crack patterns of masonry prisms

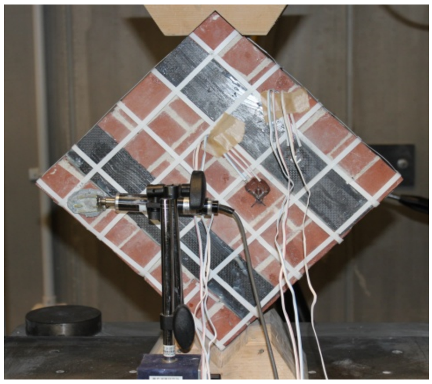
Figure 3. Test setup of different types of initial tests

2.2 Test setup and instrumentation

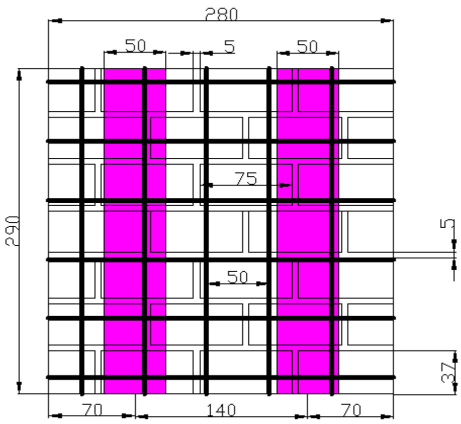
A schematic test setup ofdiagonal compression test is shown in Figs. 4 (a) and (b). All test wallets were built under same constituent and cured for 28 days under same environmental conditions. Two specially made strong wooden wedges are used to apply diagonal force over the corners of masonry wallets. Wooden wedges are connected with 100 KN Shimadzu UTM top and bottom platens. Loading rate over different test specimens are given in Table 5. For displacement response measurement, two different type of test setup are used. Two high power lasers are used for in plane horizontal deformation and out of plane bulging for non-retrofitted and PP-band retrofitted masonry wallets. Horizontal displacement using laser is monitored by attaching a stiff target with epoxy to the wallet as shown in the Fig. 4 (a). While LDTV displacement transducer with 500×10^{-6}/mm sensitivity are used for CFRP retrofitted and CFRP+PP-band retrofitted wallet. Six strain gauges are also used on each CFRP and CFRP+PP-band retrofitted wallet. Three strain gauges at an angle of 45^{o} from each other are pasted using CN bond after application of PS bond over the brick surface where as 3 strain gauges are directly applied over the CFRP surface using CN bond after rubbing the CFRP surface using a sand paper. Different displacement loading rates are selected depending upon the failure displacement and duration of test. In order to connect the PP-band, sufficient lap is provided between bands and ultrasonic welding device is used to connect PP-bands with each other. In case of PP-band retrofitting bands on two faces of wallets are connected by provision of small hole at spacing of 40 mm from each corner at four points connected by ultrasonic welding device as shown in Fig. 4 (d). CFRP and PP-band is applied on the both faces of wallet.



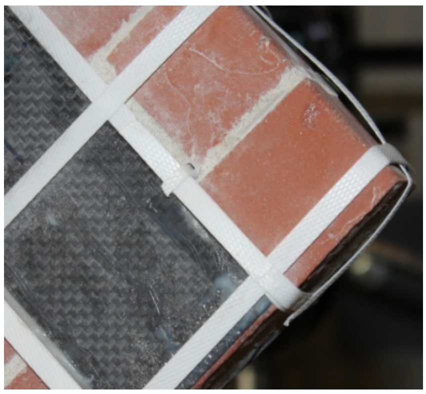
(a) Test setup of non-retrofitted wallet of diagonal compression test



(b) Test setup of CFRP+PP-band retrofitted wallet of diagonal compression test



(c) Details of CFRP+PP-band retrofitted wallet



(d) Out of plane connectivity of PP-band

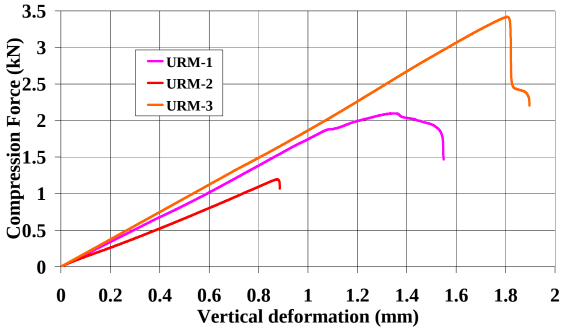
Figure 4. Test setup of in-plane diagonal compression test of non-retrofitted, PP-band, CFRP retrofitted and CFRP+PP-band retrofitted wallets

Table 5. Loading conditions of experiments

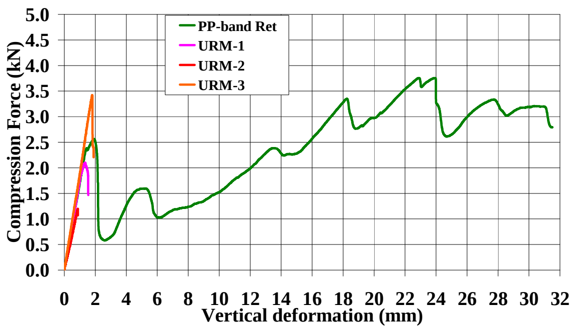
Specimen	No. of Specimens	Description	Loading Rate
URM	3	Non-retrofitted masonry wallet	0.15mm/min
PP	1	Only PP-band retrofitted wallet	0.25mm/min
CFRP	1	Only CFRP retrofitted wallet	0.25mm/min
CFRP+PP	1	Both CFRP and PP-band retrofitted	0.50mm/min

3. EXPERIMENTAL RESULTS AND DISCUSSION.

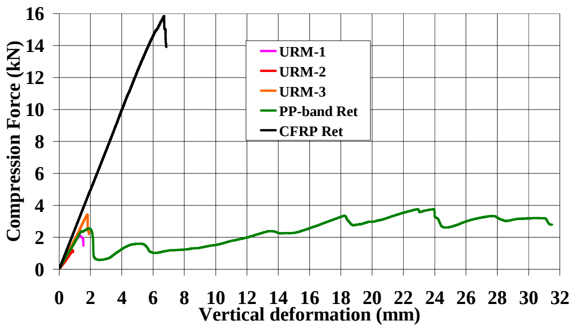
Load versus displacement of all specimens are plotted in Fig. 5. Non-retrofitted wallets show a variety of peak strength with an average value of 2.23 kN. Sliding type of failure has been observed exhibiting a weak brick mortar joint at vertical displacement range from 0.9mm to 1.8mm as shown in Fig.5 (a). From Fig. 5(b), PP-band retrofitted wallet shows the peak strength of 2.5 kN. Sudden drop of load occurred due to failure of brick masonry inside PP-band but with the further increase of vertical displacement, it again started taking load with a residual effect due to inter locking effects of cracked masonry and confining effect of PP-band. Even after the displacement range of 16mm, PP-band confining effect become more prominent and system showed a loading capacity even greater than initial peak strength of masonry. Beyond 24mm of vertical displacement, crushing of bricks started. Figure 5 (c) demonstrates the load-displacement curves of non-retrofitted wallets, PP-band retrofitted wallet and CFRP retrofitted wallet. CFRP has increased the peak strength of URM from 3.4 kN to 15.7 KN. The initial failure displacement of non-retrofitted wallet also increased from 1.7mm to 6.7mm. But final failure of CFRP retrofitted was sudden and highly brittle. Initial stiffness of URM-1, URM-2, URM-3 and PP-band retrofitted were not exactly similar but within a close range to each other where as CFRP retrofitted wallet has shown higher initial stiffness and peak strength. Figure 5 (d) shows the load-displacement curves for all specimens including CFRP and CFRP+PP-band retrofitted wallet. Peak strength of CFRP+PP-band retrofitted was significantly higher then non-retrofitted wallets and only PP-band retrofitted wallet but less than only CFRP retrofitted wallet. Increased rate of loading has been used for CFRP+PP-band retrofitted wallet to avoid long test durations. After the initial failure of CFRP+PP-band retrofitted wallet, a sudden drop in load carrying capacity was observed, even peak strength of 11.45 kN reduced to 4.6 kN. But after that system again become stable and started taking load. At displacement of 16mm, the load carrying capacity of damaged wallet was 7.55 kN which is even 3 times bigger than that of the non-retrofitted wallet. System has shown a good residual load carrying capacity after the initial damage. Because in case of CFRP+PP-band retrofitted wallet, CFRP is not completely separated due to holding effect of PP-band. CFRP and PP-band composite system has shown not only a fairly long deformation capacity as compared to non-retrofitted and CFRP retrofitted wallet but also a significant increase in peak strength of non-retrofitted and only PP-band retrofitted wallet. Figures 5 (e) and (f) have shown the strain distribution of FRP and brick at their respective locations. Strains are recorded by digital dynamic strain meter (DDSM). FRP strain gauge-1(St-1), strain gauge-2(St-2) and strain gauge-3 (St-3) have shown a low initial increase up to the loading value of 4 KN for CFRP retrofitted wallet and up to 2 kN for CFRP+PP-band retrofitted wallet. After these values, the strain rate increased and reached their maximum values close to peak and then again reduced due to debonding and cracking after the peak strength. Peak strain of 0.002 is recorded in the CFRP which is in fair agreement of values provided by different effective strain based models like AC 125 model ICC Evaluation Service, Inc (2007). In CFRP and CFRP+PP-band, no damage was observed on the surface of CFRP. Strain gauges for CFRP+PP-band retrofitted were removed after initial drop in peak strength. All wallets exhibited almost a linear behaviour about 75-90% of peak load. Variation of experimentally obtained brick and CFRP strains was in consistent with the peak load. Very low strains were recorded for brick element because the location of strain measurement for brick element was inside straining action of CFRP and major share of load was carried by CFRP resulting low strain values over the inside brick surrounded by CFRP as shown in Fig. 4 (b).



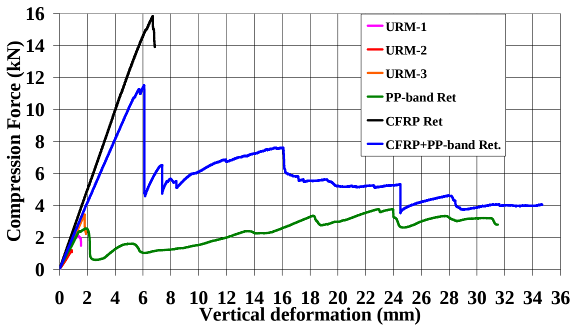
(a) Load-displacement curves of non-retrofitted wallets



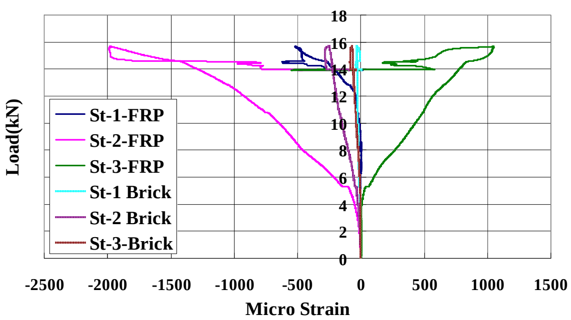
(b) Load-displacement curves of non-retrofitted and PP-band retrofitted wallets



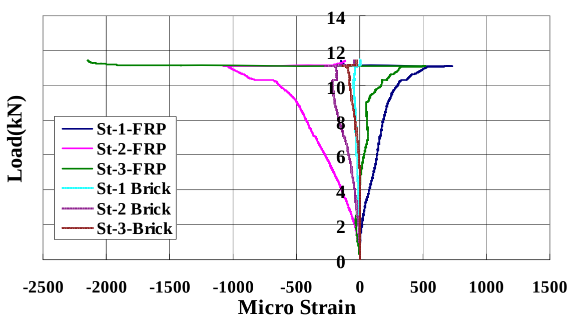
(c) Load-displacement curves of non-retrofitted, PP-band retrofitted and CFRP retrofitted wallets



(d) Load-displacement curves of non-retrofitted, PP-band retrofitted, CFRP retrofitted and CFRP+PP-band retrofitted wallets



(e) Strain distribution of CFRP retrofitted wallet

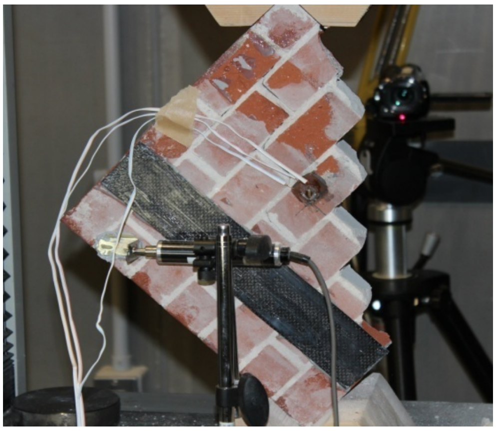


(f) Strain distribution of CFRP+PP-band retrofitted wallet

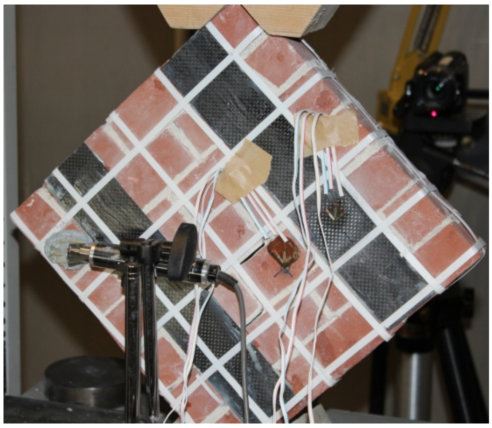
Figure 5. Diagonal compression test results of non-retrofitted, PP-band retrofitted, CFRP retrofitted and CFRP+PP-band retrofitted wallets

4. FAILURE MODES

The strength of non-retrofitted wallets depends upon the governing failure mode. In all non-retrofitted and only PP-band retrofitted wallets, a shear sliding type of failure was observed exhibiting a weak brick to mortar cohesion and weak mortar. Where as in case of CFRP retrofitted wallet, the failure mode was changed from shear sliding to diagonal tension cracking as shown in Fig. 6 (a). Furthermore, failure was first initiated in CFRP retrofitted wallet by CFRP debonding over the brick surface and then completely separation and debonding. There could be three possible failure mode of FRP retrofitted wallets, 1) epoxy debonding, 2) brick surface tension failure, 3) FRP rupture. Mostly epoxy debonding and brick surface tension failure are observed. Figure 6 (c) shows a close view of brick surface tension failure which assures a good bond between CFRP and epoxy. In case of CFRP+PP-band retrofitted wallet, the failure was initiated by brick surface debonding but it was gradual and diagonal crack passes through the brick and reaches up to the other CFRP strip as shown in Fig. 6 (b). But there was no full separation and structural system of wallet was still stable for residual strength. Figure 6 (d) shows the crack opening and brick crushing of CFRP+PP-band retrofitted after a significant amount of deformation and still this wallet was acting as single body due to holding effect of PP-band. PP-band has played an important role and changed the sudden brittle failure of only CFRP retrofitted wallet to a ductile type of gradual failure with sufficient warning.

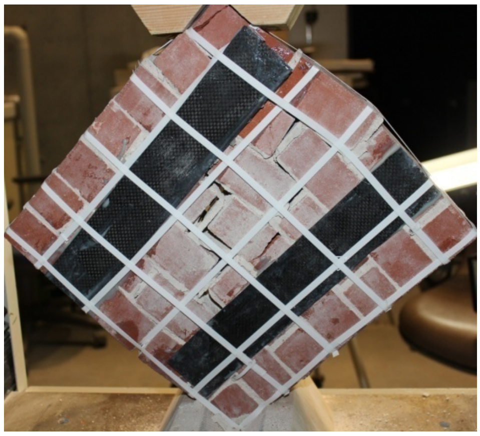


(a) Failure and crack patterns of CFRP retrofitted wallet under diagonal compression



(b) Failure and crack patterns of CFRP+PP retrofitted wallet under diagonal compression

(c) Debonding of CFRP from brick surface crack patterns of CFRP retrofitted wallet



(d) Debonding failure and crack patterns of CFRP+PP retrofitted wallet

Figure 6. Failure, debonding and crack patterns of CFRP and CFRP+PP-band retrofitted wallets under diagonal compression loading

5. CONCLUSIONS

PP-band is a cheap material as compared to FRP with a failure strain of 12% which is a high value as compared to failure strain of CFRP which is 2-4%. PP-band can increase the deformation capacity of structural system by releasing energy through crack propagation. It can hold well even for an intense shaking but can not increase the original shear capacity. While as FRP is an expensive material but can significantly increase and restore the shear capacity of a structural system but the final failure is highly brittle and energy is suddenly released by severe damage and cracking which may lead a quick collapse of structure. Failure mode of the non-retrofitted walls is changed by the application of CFRP and further controlled by the use of PP-band, as PP-band resisted the complete debonding of CFRP from brick surface, imparting more residual strength as compared to only PP-band retrofitted wallet. In case of FRP retrofitted wallets, failure is mostly governed by epoxy debonding or brick surface tensile failure. Full capacity of CFRP can not be efficiently utilized, so a high strength FRP material for the retrofitting of structural wall system is not advisable. Strong bricks with good tensile strength and strong adhesive can play significant role in increase in strength of wall system rather than a strong FRP material. A composite of FRP and PP-band can lead the development of a good material which can increase not only the strength of structural system but also the deformation capacity with reasonable cost.

REFERNCES

Y. Zhuge. (2010). FRP-Retrofitted URM Walls under in Plane Shear: Review and Assessment of Available Models. ASCE *Journal of Composites for Construction,* **14: 6**, 743-753.

K . Meguro, P . Mayorca, N . Sathiparan, R . Guragain, N . Nesheli. (2005). Shaking Table Tests of 1/4 Scaled Masonry Models Retrofitted with PP-band Meshes. *Proceedings of the Third International Symposium on NewTechnologies for Urban Safety of Mega Cities in Asia, Singapore.* **Vol1:** 9-18.

Coburn, A. and Spence, R. 2002.*Earthquake Protection.* West Sussex: John Wiley & Sons Ltd. ISBN 0-471-49614-6.

Yoshimura, M. and Meguro, K. (2004). Proposal of Retrofitting Promotion System for Low Earthquake-Resistant Structures in Earthquake Prone Countries. *Proceedings on 13th World Conference on Earthquake Engineering,*Vancouver,Canada. **Vol1**: Paper No. 927

NavaratnarajahSathiparan. (2008). Experimental study of PP-band mesh seismic retrofitting for low earthquake masonry resisting structures. *PhD Dissertation*, Department of Civil Engineering, University of Tokyo Japan.

Hamid Mehmood, Jason M Ingham. (2011). Diagonal Compression Testing of FRP Retrofitted Unreinforced Clay Burnt bricks masonry Wallets. *Journal of Composites for Construction.* **15:5**, 810-820.

V. Turco, S. Secondin, A. Morbin, M.R. Valluzzi, C. Modena. (2006). Flexural and shear strengthening of unreinforced masonry with FRP bars. *Composites Science and Technology.* **6:1**, 289–296.