# SHEAR AND FLEXURAL BENDING STRENGTH OF MASONRY WALL RETROFITTED USING PP-BAND MESH

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**ABSTRACT**

One of the main causes of casualties in major earthquakes around the world is the collapse of low earthquake resistant masonry structures. Retrofitting of these types of structures is the key issue for earthquake disaster mitigation in developing countries, because it is the only way to reduce significantly casualties in future earthquakes. This paper presents an innovative retrofitting method for masonry houses, which consists of polypropylene bands (PP-band) arranged in a mesh fashion. The PP-band technology aims to prevent or, at least, put off wall collapse by providing both sides with the mesh made of a cheap packthread and keeping the integrity of the walls. In order to verify the suitability of the proposed method, a series of masonry wallettes, with and without retrofitting, was tested under in-plane and out-of-plane loads. Although the retrofitted wall peak strength was almost the same as that of the bare wall, its post-peak strength was larger and sustained for lateral drifts. In order to investigate the proposed retrofitting features for different material properties and mesh configurations, tests on a number of masonry wallettes were performed.

*Keywords*: unreinforced masonry; PP-band; retrofitting; diagonal shear test; residual strength

**REZUMAT**

Una dintre principalele cauze ale producerii de victime în urma cutremurelor majore din lume este prăbuşirea structurilor de zidărie cu rezistenţă scăzută la seism. Consolidarea acestor tipuri de structuri este aspectul esenţial pentru reducerea dezastrelor produse de cutremure în ţările în curs de dezvoltare, deoarece este unicul mod de a reduce semnificativ numărul de victime la seismele viitoare. Articolul prezintă o metodă inovativă de reabilitare a caselor din zidărie, constând din benzi de polipropilenă (PP-band) dispuse sub formă de reţea. Tehnologia PP-band este destinată prevenirii sau, cel puţin, întârzierii prăbuşirii pereţilor, prin prevederea acestora, pe ambele feţe, cu o reţea realizată din sfoară ieftină şi păstrând, astfel, integritatea pereţilor. Pentru a verifica adecvarea metodei propuse, o serie de specimene de zidărie, cu şi fără consolidare, au fost testate la încărcări în plan şi în afara planului. Deşi capacitatea maximă a peretelui consolidat a fost aproape aceeaşi cu cea a peretelui neconsolidat, capacitatea remanentă a fost mai mare şi s-a susţinut la deplasări relative orizontale. În scopul investigării procedeului de consolidare propus pentru diferite proprietăţi ale materialului şi configuraţii ale reţelei, au fost executate încercări pe un număr de specimene de zidărie.

*Cuvinte cheie*: zidărie nearmată, benzi de polipropilenă, consolidare, încercare la forfecare diagonală, rezistenţă reziduală

## 1. INTRODUCTION

Unreinforced masonry is one of the most popular construction materials in the world. It is also unfortunate, the most vulnerable against earthquakes. In the event of an earthquake, apart from the existing gravity loads, horizontal racking loads are imposed on walls. The unreinforced masonry is a brittle material. Hence if the stress state within the wall exceeds masonry strength, brittle failure occurs, followed by possible collapse of the wall and the building. The major types of masonry failure modes have been identified as: in-plane diagonal cracking, out-of-plane wall collapse, separation of adjacent walls, and cracking due to stress concentrations around openings.

Human casualties due to earthquake in the 20th century are mostly due to structural damage and most of which are from low earthquake resistant masonry buildings (1). The only way to change this situation is to improve seismic performance of the existing low earthquake resistant masonry structures. A suitable retrofitting technique for low earthquake resistant masonry structures in developing countries should guarantee not only its efficiency in terms of improvement of the seismic resistant characteristics of the structure, it should also be considered that; the used material is economical and locally available and the required labor skill is low (2). Considering these issues, PP-band retrofitting technique has been developed, and many different aspects have been studied by Meguro Laboratory, Institute of Industrial Science, The University of Tokyo. (3).

PP-band retrofitting is a simple and low-cost method that consists of confining all adobe walls with a mesh of PP-bands. PP-bands are an inexpensive, durable, strong, and widely available material, commonly used for packing. A main objective of this technique is to hold the disintegrated elements together thus preventing the collapse. PP-meshing was first formally proposed in 2003 (4), is still under active research and currently has application in Nepal, Pakistan and China (5)-(6).


**Fig. 1**. PP-band retrofitting method

Fig. 1 shows the retrofitting procedure during the retrofitting of the full-scale house model. The advantages of the PP-band mesh retrofitting method compared to the other earthquake strengthening technology are as follows:

- The method can be used for both new construction and existing structure.
- The method is simple and inexpensive.
- The method does not require high skills.
- The method does not change the local life style.
- The material needed for the method is cheap, world wide available, light and can be easily carried in the mountainous region and so on.
- Because of the PP-band is water proof and chemically stable (6), it is possible to use mud, which is abundant in the region and commonly used by the local people in accordance with their custom and culture.

In order to verify the effects of PP-band mesh retrofit method, a number of experimental and numerical studies have been done on 3-dimensional miniature and real scaled structures with static and dynamic loading conditions (Fig. 2) (7)-(9).

**Fig. 2**. Shaking table testing on non-retrofitted and retrofitted scale house model.

In this paper, we report on an experimental study comparing the effect of retrofitting by means of varying parameters of the PP - band on masonry wallette subjected to static loads. The experimental testing program consisted of two parts: testing on PP-bands, diagonal compression testing and out-of-plane testing. The first one concentrated on the evaluation of the PP-band parameters, i.e. tensile strength and modulus of elasticity. The later part consisted of diagonal compression test and out-of-plane test for both non-retrofitted and retrofitted masonry wallettes, to evaluate the beneficial effects of proposed PP-band mesh retrofitting method.

## 2. TESTS ON POLYPROPYLENE BANDS

In order to obtain the deformation properties and strength of the PP - band, preliminary testing of the PP-bands available in Japan were carried out. To determine the modulus of elasticity and ultimate strain, three bands were tested using a uniaxial tensile test. The test was carried out under displacement control. Dimension of all three PP-bands was 15.5mm×0.6mm in nominal area of cross section and 150mm in gauge length.

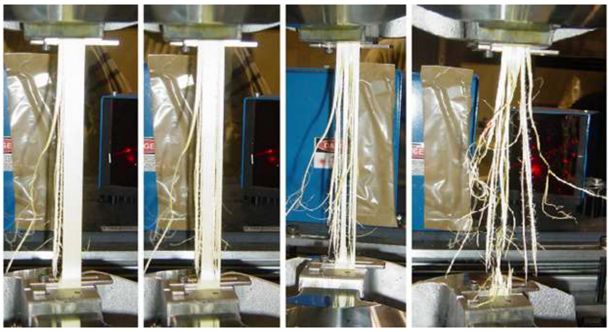

**Fig. 3**. Failure pattern of PP-band under tensile force

All the bands exhibited a large deformation capacity, with more than 14% axial strain and average tensile strength of 171 MPa. The stress-strain curve is fairly bilinear, with an initial and residual modulus of elasticity of 3.2 GPa and 1.0 GPa, respectively. Given its large deformation capacity, it is expected that the PP-band mesh will improve the ductility of the retrofitted structures (10). Also progressive failure was observed after the PP - band reached its peak strength. This behavior was due to the individual failure of PP-band fibers as shown in Fig. 3.

In case of long term use of the PP-band mesh method of construction, the confirmation of the strength variation of the PP-band under the temperature change in the extended period becomes important. The relationship between the temperature and tensile strength of the PP-band was shown in Table 1. Base upon the test results, it was found that the tensile strength of the PP-band was decreasing while the applied temperature was increasing or inversely proportional to the applied temperature.

**Table 1. PP-band performance under different temperature**

| Temp (°C) | Cut-off Strain (%) | Maximum tensile stress (MPa) | Residual modulus of elasticity (GPa) |
|---|---|---|---|
| -20 | 13.8 | 182 | 1.14 |
| -10 | 15.4 | 195 | 1.13 |
| 0 | 15.6 | 186 | 1.07 |
| 10 | 19.4 | 194 | 0.93 |
| 20 | 20.7 | 187 | 0.87 |
| 30 | 22.2 | 174 | 0.76 |
| 40 | 27.4 | 164 | 0.61 |
| 50 | 26.0 | 157 | 0.58 |

The main benefit of attaching PP-band on masonry, it can resist large deformation after the cracking of the structure caused by the external load. Also, this test was measuring about the extension of the band at the broken point during the tensile test, and the big extension of the band when the breakage occurs under higher temperature.

PP-bands properties vary from country to country; therefore tensile testing of the PP-bands from different countries was carried out and was shown in Table 2.

**Table 2. PP-band properties comparison**

| Specimen | Cut-off Strain (%) | Maximum tensile stress (MPa) |
|---|---|---|
| Japan | 14.0 | 171 |
| India | 10.2 | 167 |
| Pakistan | 13.4 | 123 |
| Iran | 14.1 | 142 |
| Peru | 22.7 | 113 |
| Indonesia | 18.5 | 167 |

## 3. DIAGONAL SHEAR TEST

To evaluate the beneficial effects of proposed PP-band mesh retrofitting method, diagonal compression tests were carried out on masonry wallettes with and without retrofitting by the PP-band mesh. Average measured mechanical properties of the masonry at the time of testing are shown in Table 3. Direct compression, direct shear and bond tests were carried out to obtain these properties.

**Table 3. Mechanical properties of masonry**

| | Burned Brick | Unburned brick |
|---|---|---|
| Compressive strength (MPa) | 21.78 | 4.45 |
| Shear strength MPa) | 0.075 | 0.006 |
| Bond strength (MPa) | 0.055 | 0.006 |

### *3.1. Test setup*

The wallette dimensions were 275×275×50 mm$^3$ and consisted of 7 bricks rows of 3.5 bricks each (Fig. 4). The mortar joint thickness was 5mm. The mortar with the mixture ratio of cement, lime and sand=1: 7.9: 20 and the Cement / Water ratio equal to 0.14% was used for masonry. In order to prevent the wires from cutting the PP-band mesh, a plastic piece or any other stiff element is placed between the band and the wire.

The specimens were tested 28 days after construction under displacement control. The loading rate was 0.3mm/min for first 10mm and 2mm/min for remaining loading. The retrofitted wallettes were applied 50mm vertical displacement.

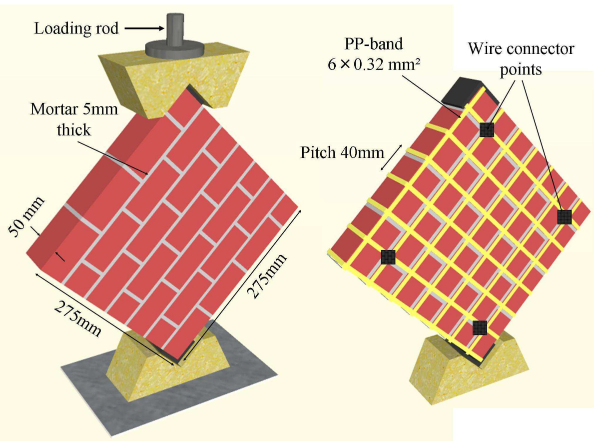


**Fig. 4**. Diagonal shear test setup

### *3.2. Behavior of burned brick specimens*

Fig. 5 shows the non-retrofitted and retrofitted specimens at the end of the test, which corresponded to vertical deformations equal to 0.71mm and 50mm, respectively. In the non-retrofitted case, the specimens split in two pieces after the first diagonal crack occurred and no residual strength was left. In the retrofitted case, on the other hand, diagonal cracks appear progressively, each new crack followed by a strength drop. Although the PP-band mesh influence was not observed before the first cracking, after it, each strength drop was quickly regained due to the PP-band mesh effect. Although at the end of the test almost all the mortar joints were cracked, the retrofitted wallettes did not lose stability.

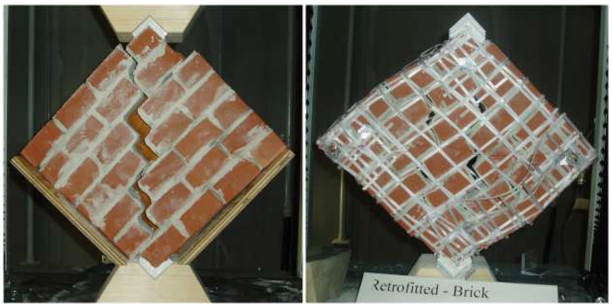


**Fig. 5**. Failure patterns of burned brick masonry wallettes (left) without retrofitting (right) with retrofitting (10)

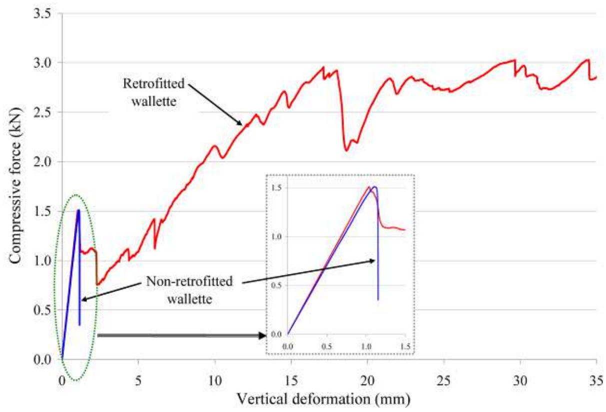


**Fig. 6**. Shear Strength vs. shear strain for burned brick masonry wallette

Fig. 6 shows the diagonal shear strength variation with shear strain for the non-retrofitted and retrofitted specimens. In the non-retrofitted case, the average initial strength was 1.51kN and there was no residual strength after the first crack. However, in the retrofitted case, although the initial cracking was followed by a sharp drop, at least 50% of the peak strength remained. Subsequent drops were associated with new cracks like the one observed at the deformation of 6mm. After this, the strength was regained by readjusting and packing by PP-band mesh. The final strength of the specimen was equal to 2.86kN relatively higher than initial strength.

### *3.3. Efficiency of mesh orientation*

Fig. 7 compares the diagonal shear strength of retrofitted masonry wallettes with different mesh orientation:

- Type 1 is a PP - band mesh oriented parallel to the masonry joints.
- Type 2 is a PP - band mesh oriented 45° from the masonry joints.

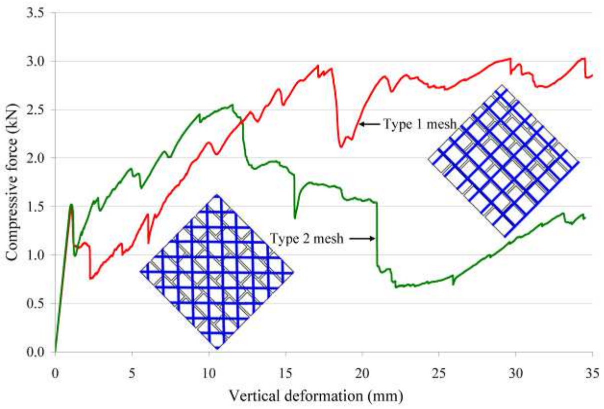


**Fig. 7**. Comparison between masonry wallettes retrofitted by different orientation meshes.

Generally Type 2 mesh provided larger strength than Type 1 mesh arrangement. This was expected because the confining effect on the masonry wall is larger in the former case. The cracks become gradually wider as the vertical deformation increased. In this condition, the reinforcement oriented perpendicular to the crack. i.e. Type 2 worked under optimum conditions. The results of Type 1 and Type 2 were compared; the maximum strength difference was 40% at a deformation of 5mm. Although the mesh Type 1 did not fully use the mesh capacity, it improved the wallette behavior to a degree which can be considered enough for the purpose of earthquake damage mitigation. In addition to this, the mesh Type 1 is easier to manufacture and install. Therefore, it was selected as the proper solution for retrofitting.

### *3.4. Effect of attachment condition between PP-band mesh and masonry wallette*

To easily compare the behavior of retrofitted masonry wallettes; the behavior idealized as shown in Fig. 8. Initial strength (Vo) and Initial stiffness (Ko) mainly depended on the masonry properties. Residual strength after the initial crack (Vr) and residual stiffness (Kr) mainly depend on PP-band properties and PP-band density.

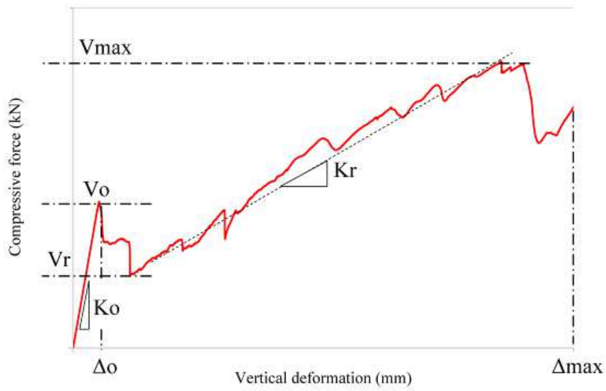


**Fig. 8**. Real and ideal behavior of PP-band mesh retrofitted wallette.

Fig. 9 shows the conditions of connecter fixing modes for bad and good performance of the structure. The left shows no slick in the PP - band and connecter was also strained while the right figure shows the conditions either slack in PP-band or connecter no strained. So, in order to get better performance of the structure, the connecter should be connected tightly.

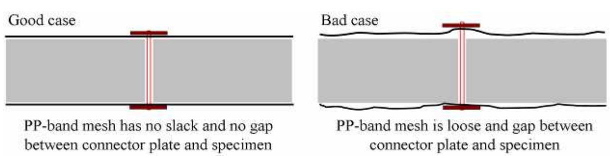


**Fig. 9**. Detail of Connecter Fixing Modes

To verify the effect of looseness of the retrofitting attachment on retrofitted specimen, 0mm (fully fixed), 3mm and 6mm of gap between PP-band mesh and wallette were provided. Fig. 10 shows the residual strength/initial strength (Vr/Vo) variation with looseness of attachment between PP-band mesh and masonry wallettes.

The result shows that; when there is looseness, it does dramatically reduce the residual strength of the masonry wallettes after initial crack. When we applied the surface finishing above the masonry wallette, because of surface paste fill the gap between PP-band mesh and masonry wallette; even after the initial crack, at least 80% of the initial strength remained.

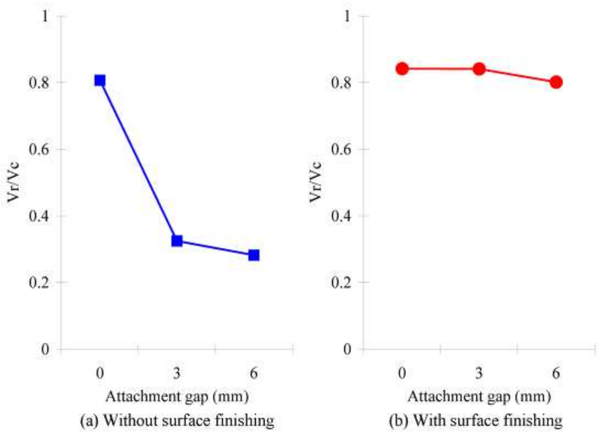


**Fig. 10**. Effect of attachment condition

The surface finishing also protects the mesh against UV radiation and severe temperature variations, as well as providing a smooth finish on the retrofitted structure.

### *3.5. Effect of PP-band mesh pitch*

For retrofitted specimen, four cases varying PP-band mesh pitches of 33mm, 40mm, 50mm, 66mm were used for retrofitting keeping other parameters same; such as attachment of PP-band mesh on retrofitted specimen was fully fixed. Fig. 11 shows the residual strength/initial strength (Vr/Vo) and residual stiffness/initial stiffness (Kr/Ko) variation with PP-band mesh pitch of the masonry wallette. From the experiment it was found that there is a significant role of PP-band pitch in the behavior of masonry wallettes.

In general, residual strength after crack initiation and residual stiffness of masonry walls with PP-band mesh retrofitting are directly proportional to PP-band density up to some value.

But when it exceeds the optimum value, improvement ratio of residual strength after crack initiation and residual stiffness are not increasing with the amount of the PP-band density.

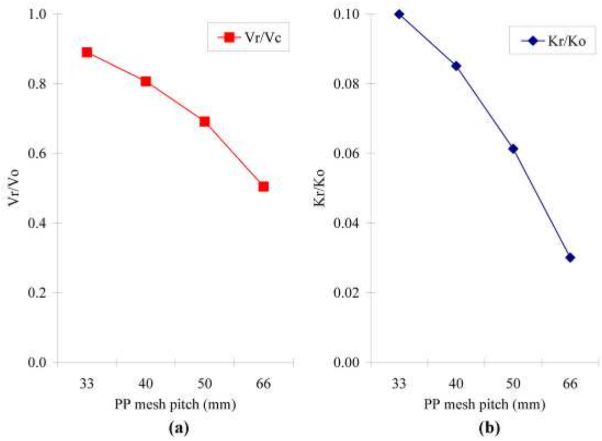


**Fig. 11**. Effect of PP-band density

### *3.6. Wire connector alternative*

Test results show PP-band meshes with steel wire connectors can effectively increase the seismic capacity of masonry wallette. Although this technique has proved to be effective in increasing strength and ductility of masonry wallette, steel wire has the disadvantages of being susceptible to corrosion and relatively difficult to install. PP-string with their inherent properties, which include high specific tensile strength, no corrosion problem, no need additional steel plate and ease of use, make them an attractive alternative to steel wire connector with steel plates in the retrofitting of masonry wallette.

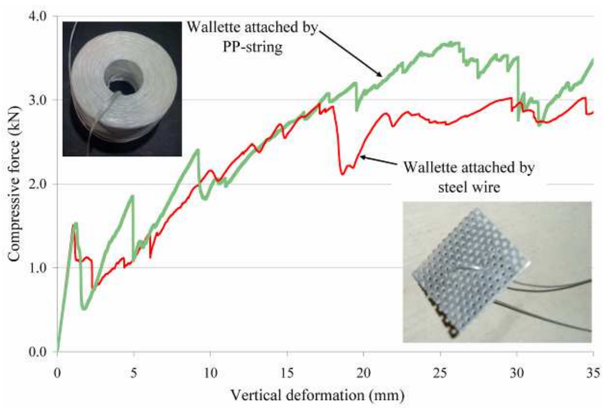


Fig. 12. Comparison between masonry PP-band retrofitted wallettes connected by steel wire and PP-string.

Fig. 12 shows the diagonal shear strength variation with shear strain for the PP-band retrofitted wallette connected by steel wire and PP-string. Generally steel wire connector provided lesser strength reduction after initial strength than the PP - string connector. After initial crack, the behavior of both specimens was almost similar and at later strength PP-string connector shows better performance.

**Table 4. Comparison of (Vr/Vo) ratio for different connectors**

| | Steel wire connector | PP-string connector |
|---|---|---|
| Without surface finishing | 0.52 | 0.34 |
| With surface finishing | 0.84 | 0.86 |

Table 4 shows the Vr/Vo ratio for the different connector condition for the wallette with surface finishing and without surface finishing. When we applied the surface finishing above the masonry wallette, in both cases, even after the initial crack, at least 84% of the initial strength remained.

### *3.7. Behavior of unburned brick specimens*

Fig. 13 shows the non-retrofitted and retrofitted specimens at the end of the test, which corresponded to vertical deformations equal to 1mm and 50mm, respectively. In the non-retrofitted case, the specimens split in two pieces after the first diagonal crack occurred and no residual strength was left while in the retrofitted case, diagonal cracks appear progressively, each new crack followed by a strength drop.

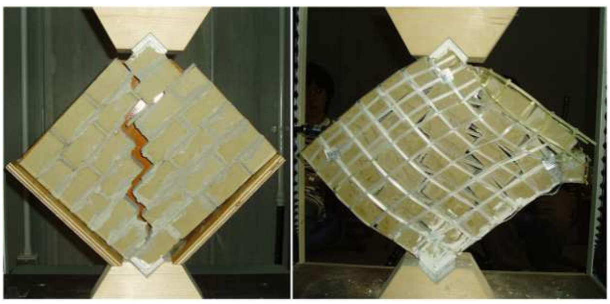

Fig. 13. Failure patterns of unburned brick masonry wallettes (left) with retrofitting (right) without retrofitting (11)

Although the PP-band mesh influence was not obvious before the first cracking, after it, each strength drop was quickly regained due to the PP-band mesh effect. Although at the end of the test, almost all the mortar joints were cracked, the retrofitted wallettes did not lose stability.

In the non-retrofitted case, the initial strength was 0.89kN and there was no residual strength after the first crack. In the retrofitted case, although the initial cracking was followed by a sharp drop, at least 70 % of the peak strength remained (Fig .14). As expected, the initial strength of unburned brick specimens was relatively lower than that of the burned brick one.

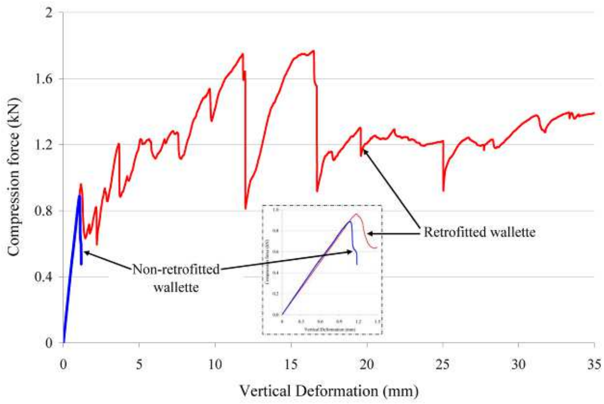


Fig. 14. Shear Strength vs. shear strain for unburned brick masonry wallette

## 4. OUT-OF-PLANE TEST

Out-of-plane tests were carried out, in order to investigate the PP-band mesh effectiveness in walls exhibiting arching action. The nominal dimensions of these walls were 475mm by 235mm and consisted of 6 bricks row of 6 bricks each. The mortar joint thickness was 5mm. Six wire connectors were used to attach the meshes with masonry wallettes. Considering the stability of the specimens, for mortar joint following mixing ratio was used; Water: Cement: Sand: Lime equal to 1.00: 0.25: 2.80: 1.00.

Bond tests were performed to characterize the engineering properties of the material used in the investigation. The average tensile strength of burned brick and unburned brick masonry obtained from bond test were 0.162MPa and 0.006MPa, respectively.

### 4.1. Test setup

The specimens were tested 28 days after construction under displacement control. The wallettes were simply supported with a 440mm span. Steel rods were used to support the wallettes at the two ends. The masonry wallettes were tested under a line load which was applied by a 20mm diameter steel rod at the mid-span of the wallettes. The loading rate was 0.05mm/min for the non-retrofitted case. For the retrofitted case, it was also 0.05mm/min for the first 30mm vertical deflection, and then it was increased to 2mm/min for the remaining test period. The retrofitted wallettes were applied up to 60mm vertical displacement. The test setup is shown in Fig. 15.

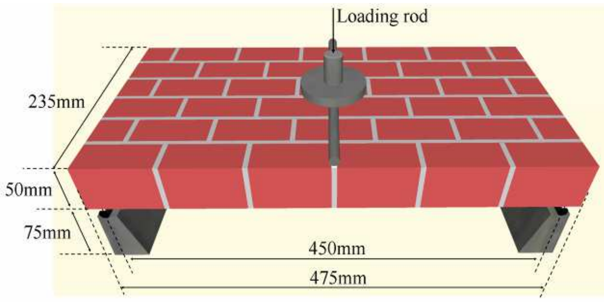


Fig. 15. Out-of-plane test setup

### 4.2. Behavior of burned brick specimens

Fig. 16 shows the non-retrofitted and retrofitted masonry wallettes at the end of the test, which corresponded to a mid-span net deformation equal to 2.8mm and 60.0mm, respectively. In the non-retrofitted case, the specimens split in two pieces just after the first crack occurred at mid-span, and no residual strength was left. In the retrofitted case, on the other hand, although PP-band mesh influence was not observed before the first cracking, after it, strength was regained progressively due to the PP-band mesh effect.

Fig. 17 shows the out-of-plane load variation in terms of net vertical deformation of the non-retrofitted and retrofitted wallettes in the mid-span. For burned brick, in the non-retrofitted case, the initial strength was 0.63 kN and there was some residual strength remaining for further small amount of deformation after the first crack. This behavior was observed due to interlocking between bricks and also the application of load under displacement control method. In the retrofitted case, although the initial cracking was followed by a sharp drop, at least 45% of the peak strength remained.

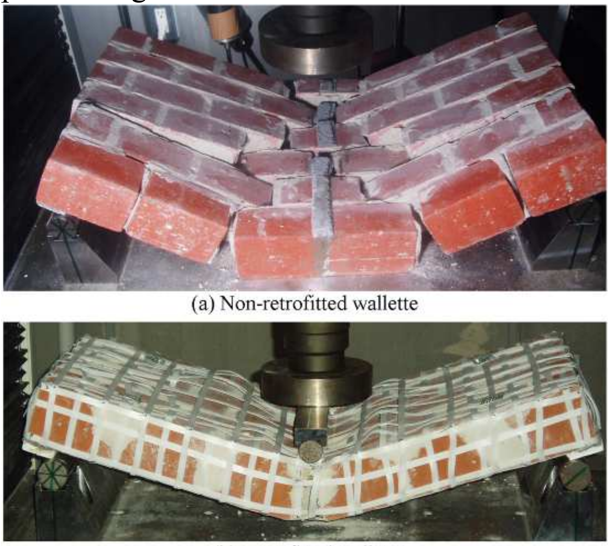


Fig. 16. Failure patterns of brick masonry wallettes with and without retrofitting by PP-band mesh.

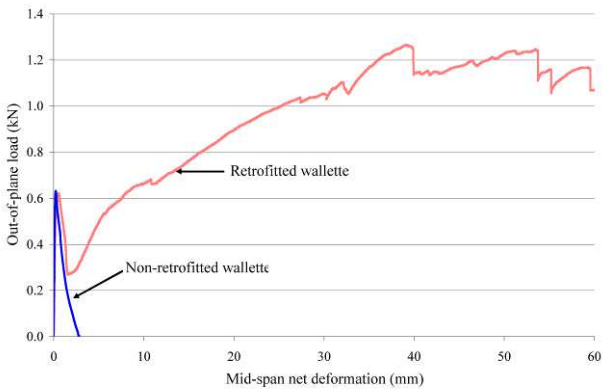


Fig. 17. Out-of-plane load variation in terms of net vertical deformation for burned brick wallette (10)

### 4.3. Behavior of unburned brick specimens

As expected, the initial strength of the burned brick was relatively higher than that of unburned brick (Fig. 18). Even higher cement/water ratio was used for unburned brick, the poor bonding between mortar and unburned brick led to separation along the brick and mortar. On the other hand, in the burned brick case, failure occurred within the mortar. This behavior highly influenced the initial strength of the specimens.

After the initial drop in strength, the mesh presence positively influenced the wallette behavior. Both types of retrofitted brick wallettes showed similar behavior in strength up to a vertical deformation equal to 8mm. At the point, brick crushing was observed in the unburned brick case. Due to that, the overall strength of the unburned brick wallettes was considerably smaller than that of burned brick wallettes. Thereafter, if two types of bricks are compared, almost 40% difference in strength was observed.

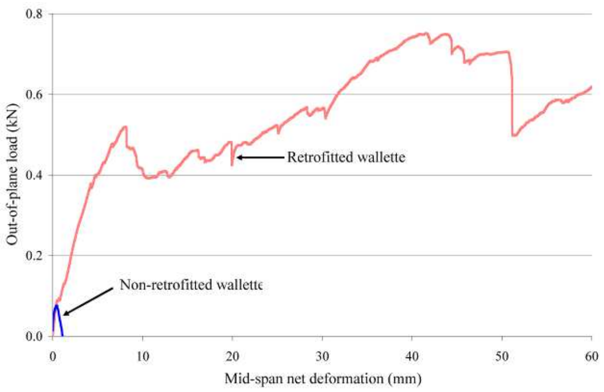


Fig. 18. Out-of-plane load variation in terms of net vertical deformation for unburned brick wallette

## 5. CONCLUSIONS

This paper discusses the results of a series of diagonal compression tests and out-of-plane tests that were carried out using non-retrofitted and retrofitted wallettes by PP-band meshes.

- The diagonal shear tests show that masonry wallette without PP-band mesh would loose the entire load bearing capacity immediately after initial cracks. Retrofitting masonry walls with polypropylene meshing were allowed specimens to continue to maintain load after the initial failure of the masonry and prevented the loss of debris, even after the failure of several straps. With the effect of the PP-band meshes, it could regain the load bearing capacity and recover immediately, and its strength and deformability improves.
- Residual strength after crack initiation and residual stiffness of masonry walls with PP-band mesh retrofitting are directly proportional to PP-band density up to some value. But when it exceeds the optimum value, improvement ratio of residual strength after crack initiation and residual stiffness are not increasing with the amount of the PP-band density.
- Looseness of the PP-band attachment with specimen reduces the residual strength after crack initiation of the specimen. Because of this, covering the mesh with mortar is very important to fill up any gaps between mesh and masonry thus improving the structural performance.
- PP-string with their inherent properties, which include high specific tensile strength, no corrosion problem, no need additional steel plate and ease of use, make them an attractive alternative to steel wire connector with steel plates in the retrofitting of masonry wallette.
- The out-of-plane tests showed that the mesh effect was not observed before the wall cracking. After cracking, the mesh presence positively influenced the wallette behavior. In case of burned brick, the retrofitted wallettes achieved strengths twice greater and deformations 60 times larger than the non-retrofitted wallettes strength. Despite the overall strength of burned retrofitted wallettes was higher than that of the unburned (adobe) ones, the ratio maximum strength/cracking strength in the latter was larger.

Given the low cost, high availability and relative simplicity of the PP-band retrofitting technique, this technology may potentially be used to prevent/delay brittle collapse of non-engineered structures under seismic loading.

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