SEISMIC STUDY OF 1/4 SCALE UNREINFORCED ADOBE MASONRY MODELS RETROFITTED WITH PP-BAND MESHES

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ABSTRACT: This paper introduces a technically feasible and economically affordable PP-band (polypropylene band) retrofitting for low earthquake resistant masonry structures in developing countries. Results of the shaking table tests on building models show that the PP-band retrofitting technique can enhance safety of both existing and new masonry buildings even in worst case scenario of earthquake ground motion like JMA7 seismic intensity. Therefore proposed method can be one of the optimum solutions for promoting safer building construction in developing countries and contribute earthquake disaster mitigation in future.

Key Words: adobe masonry, polypropylene band, shaking table test, arias intensity

INTRODUCTION

Masonry is the most universally available and economical construction material. Individual owner used it widely around the regions and it is a highly durable form of construction because the materials used are not much affected by the elements, but the quality of the mortar and the pattern of the brick units can strongly affect the quality of the overall masonry construction. The common materials of masonry construction are burned and unburned bricks called adobe, stones and concrete blocks. Adobe masonry made of unburned bricks is the most common type of masonry. Masonry structures are generally self-made because the construction practice is simple and does not require additional energy consumption. In addition to its low cost and simple construction technology, masonry has other advantages, such as excellent thermal and acoustic properties. In spite of this, the technological development of masonry in earthquake engineering has lagged behind compared to the other structural materials like concrete and steel. Therefore, earthquake prone regions in the world have suffered a large number of casualties due to the collapse of this type of structures. This is a serious problem for the societies. Apparently, its solution is straight forward: retrofitting the existing structures. When we propose the retrofitting method in developing countries, that method should respond to the structural demand on strength and/or deformability as well as to availability of material with low cost including manufacturing and delivery, practicability of construction method and durability in each region. Considering these issues on developing appropriate seismic retrofitting techniques for masonry buildings to reduce the possible number of casualties due to future earthquakes in developing countries, a technically feasible and economically affordable PP-band (polypropylene bands; PP-band is commonly used for packing.) retrofitting technique has been developed and many different aspects have been studied by Meguro Laboratory, Institute of Industrial Science, The University of Tokyo (Mayorca P. and Meguro K., 2004).

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A real scaled model test makes possible to obtain data similar to real structures. However, it requires large size testing facilities and large amount research funds, so it is difficult to execute parametric tests by using full scaled models. Therefore, in this study we performed scale model tests to understand the overall behavior of the system. In this research, in order to understand the dynamic response of masonry houses with and without PP-band mesh retrofitting, crack patterns, failure behavior, and overall effectiveness of the retrofitting technique, shaking table tests were carried out.

DESIGN AND CONSTRUCTING THE MODEL

Considering the shaking table size and allowable loading condition, the model scaling factor adopted was 1:4 as shown in **Figure 1**. Two models were used for shaking table test. The dimensions of both building models were 933mmx933mmx720mm with 50mm thick walls. The sizes of door and window in opposite walls were 243mmx485mm and 325mmx245mm, respectively. Both models were represented one-storey box-like building with timber roof; one model was non-retrofitted and other model was retrofitted with PP-band mesh after construction.

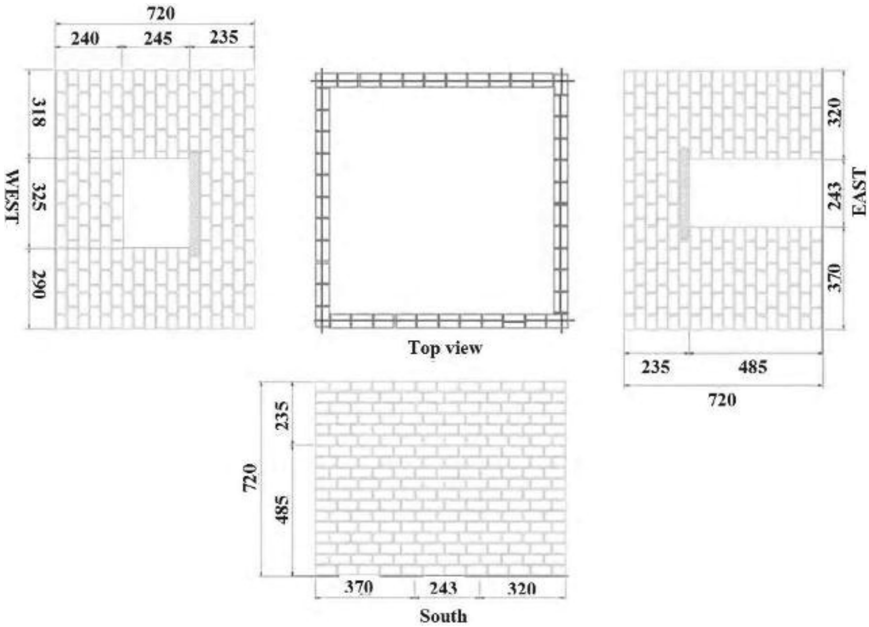

Figure 1. Model dimension (in mm)

Specimens are consisted of 18 rows of 44 bricks in each layer except openings. It took two days for construction of one specimen. The first 11 rows were constructed in first day and remaining rows were done in following day. The geometry, construction materials and mixture proportion, construction process and technique and other conditions that may affect the strength of the building models were kept identical for better comparison. The cross-section of the band used was 6mm×0.32mm and the pitch of the mesh was 40mm.

The mortar with the mixture ratio of cement, lime and sand=1:2.8:8.5 and Cement/Water ratio=0.33% was used for adobe unburned brick masonry to simulate adobe masonry buildings in developing countries. Average measured mechanical properties of the masonry at the time of testing are listed in **Table 1**.

Table 1. Mechanical property of masonry specimens

Strength	Non-retrofitted model (in MPa)	Retrofitted model (in MPa)
Compression	4.28	4.36
Shear	0.0057	0.0068
Bond	0.0046	0.0046
Diagonal shear	0.041	0.045

The retrofitted procedure explained below is shown in photos (**Figure 2**) taken during the preparation of experimental program.

- PP-bands are arranged in meshes and connected at their intersection points using a portable plastic welder.
- Structure walls are cleaned and any loose pieces of brick should be removed.
- Straw, which placed in holes are removed. (In this experiment, during construction of model house, we put the straw in the place at approximately 200mm pitch where we required holes.) In case of existing structures, holes can be prepared by drilling through the wall.
- Walls are wrapped by meshes around the corners and wall edges. The overlapping length should be long enough to accommodate sufficient wire connectors as these are the only system used to connect meshes to the structure.
- Wires are passed through wall holes and used to connect the meshes on both wall sides. In order to prevent the wires from cutting the PP-band meshes, a plastic piece or any other stiff element is placed between the band and the wire. It is desirable to have connectors as close as possible to the wall intersections and corners.
- The top/bottom mesh edges are connected with steel wires. The bottom edge should be connected to the structure foundation as much as possible.
- Fixed connectors around the openings after the mesh was cut and overlapped on the other side.

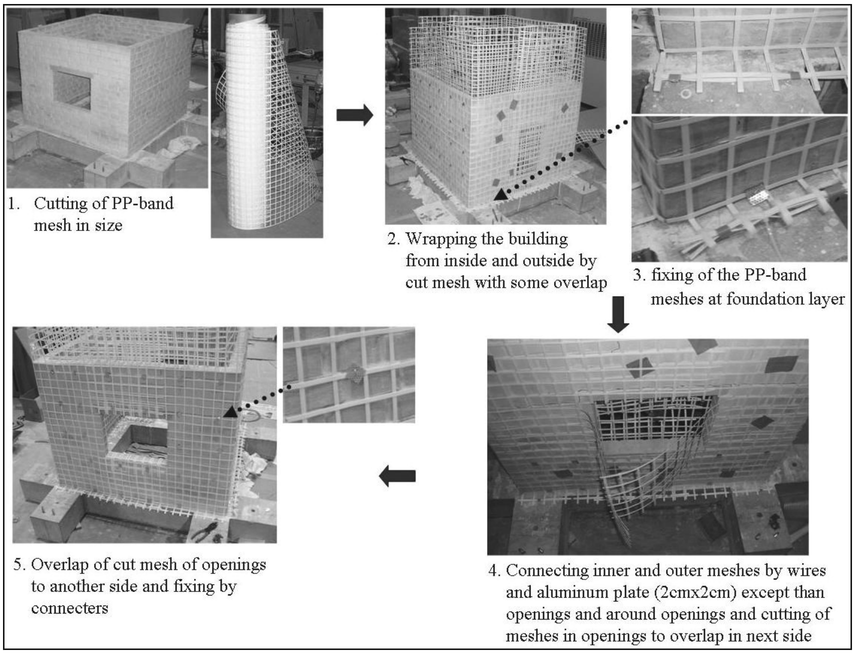

Figure 2. Retrofitting procedure

INPUT MOTION

Simple easy-to-use sinusoidal motions of frequencies ranging from 2Hz to 35 Hz and amplitudes ranging from 0.05g to 1.4g were applied to the specimens to obtain the dynamic response of both retrofitted and non-retrofitted structures. This simple input motion was applied because of its adequacy for later use in the numerical modeling. **Figure 3** shows the typical shape of the applied sinusoidal wave input motion.

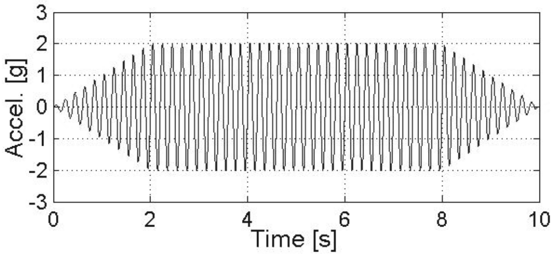

Figure 3. Typical Shape of Input Sinusoidal Motion

Loading was started with a sweep motion of amplitude 0.05g with all frequencies from 2Hz to 35Hz for identifying the dynamic properties of the models. The numbers in **Table 2** indicate the run numbers. General trend of loading was from high frequency to low frequency and from lower amplitude to higher amplitude. Higher frequencies motions were skipped towards the end of the runs.

Table 2. Loading Sequence

Amplitude	Frequency							
	2	5	10	15	20	25	30	35
1.4g		50						
1.2g		49						
1.0g		48						
0.8g	53	47	43	40	37	34	31	28
0.6g	52	45	42	39	36	33	30	27
0.4g	51	44	41	38	35	32	29	26
0.2g	46	25	24	23	22	21	20	19
0.1g	18	17	16	15	14	13	12	11
0.05g	10	09	08	07	06	05	04	03
Sweep	01,02							

To assess the global and local behavior, specimens were instrumented to measure accelerations and displacements. During the tests, twenty four accelerometers, eighteen on house and six on roof were installed at the location shown in **Figure 4**. The number of accelerometers was 16, 4 and 4 in the exciting, transverse and vertical direction respectively.

Five lasers, in N-S direction were used to measure displacements. The locations of laser measuring instruments are shown in **Figure 4**. L1, L2, L3 aimed at obtaining the wall deformation at top level in the direction of shaking. Laser L4 recorded the facade wall deformation at centre. Laser L5 recorded the deformation at base. The measured data were recorded continuously throughout the tests. The sampling rate was 1/500 sec in the all runs.

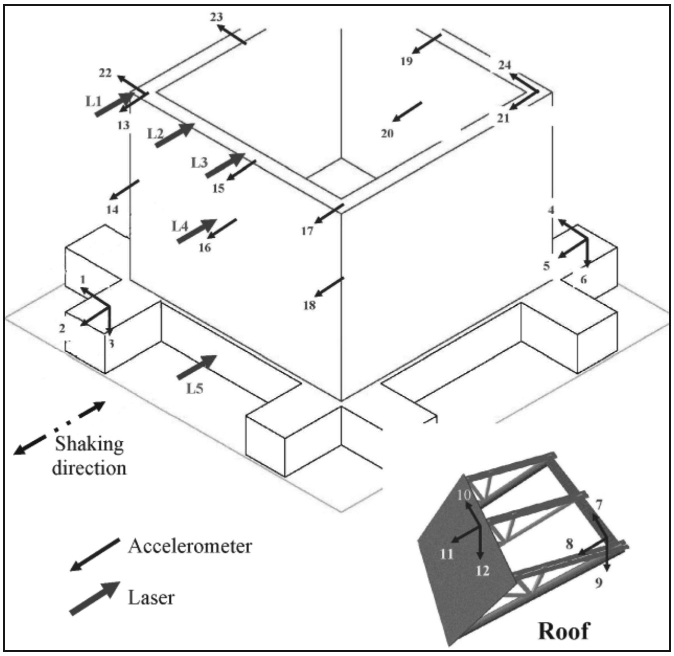

Figure 4. Location of accelerometers and lasers

CRACK PROPAGATION

In both specimens, due to shrinkage, some minor cracks were observed before the test. These cracks mainly appear closer to opening in horizontal direction. Up to the Run 21, no major crack was observed in both models.

Non-retrofitted model

Observed responses during test runs for non-retrofitted model were given as follows;

- Run 22 - Cracks were observed from corners of the window opening and they propagated up to top and bottom layer of the wall. Still there were no major cracks observed in walls, which are in the direction of Shaking (**Figure 5**).
- Run 28 - Cracks were observed at one of the top corners of the door opening and they propagated up to top layer of the wall.
- Run 34 - Cracks propagated from openings to corners were more widen up. Cracks at bottom of the east wall and top of the north and south walls were observed.
- Run 37 - Cracks appeared at the top of the north and south walls and propagated through out the whole wall. More cracks were observed in the part above the openings.
- Run 45 - All top part of the wall with opening was totally separated from the specimen and fallen from specimen. The roof was just supported by two walls, which were in the direction of shaking. Therefore, due to walls subjected to out-of-plane load; they were bursts outwards in shaking direction. This finally led to the structure collapse.

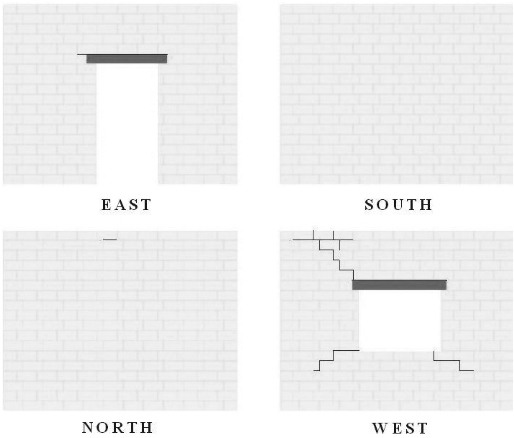

Figure 5. Crack patterns observed on non-retrofitted model after Run 22

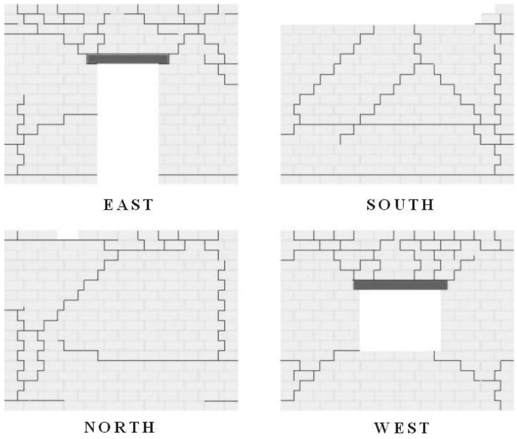

Figure 6. Crack patterns observed on for non-retrofitted model after Run 44

Figure 7. Non-retrofitted model after Run 45

Retrofitted model

Observed responses during test runs for retrofitted model were given as follows;

- Run 22 - Cracks were observed from top corner of the door opening and they propagated up to top layer of the wall. Additional cracks propagated horizontally from top and bottom of the door opening **(Figure 8**).
- Run 31 - Cracks were observed from one side top corner of the window opening and they propagated up to top layer of the wall.
- Run 34 - Cracks were observed from all corners of the window opening and they propagated to corners of the wall.
- Run 40 - A long horizontal crack at the top part and couple of vertical cracks were observed in south wall. Cracks appeared in the bottom layer of the east wall propagated through to whole wall.
- Run 43 - much more cracks were observed in the above part of the openings. Even though cracks propagated more wider at this level compared with non-retrofitted model, there was no brick fallen down from the wall observed.

- Run 49 - Although almost all the mortar joints were cracked at the end of this run, the specimen did not lose stability.
- Run 53 - Even some local failure was observed closer to door opening, the specimen did not lose stability. This input motion was 1.3 times larger acceleration and 2.7 times larger displacement than the input motion was applied in the Run 45. Another important point to mention was that the retrofitted model could sustain 8 more runs with higher input energy before this run.

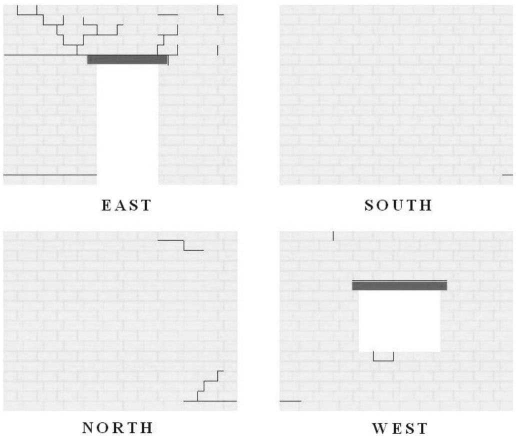

Figure 8. Crack patterns observed on retrofitted model after Run 22

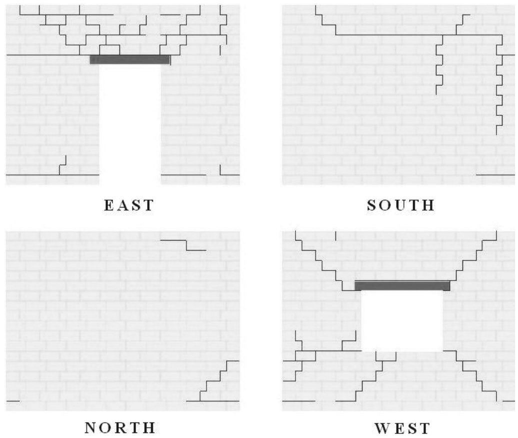

Figure 9. Crack patterns observed on for retrofitted model after Run 40

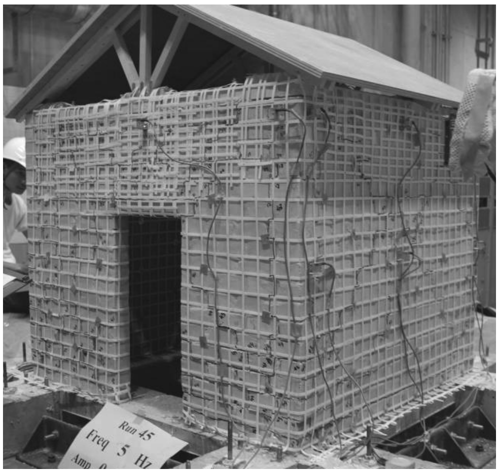

Figure 10. Retrofitted model after Run 45

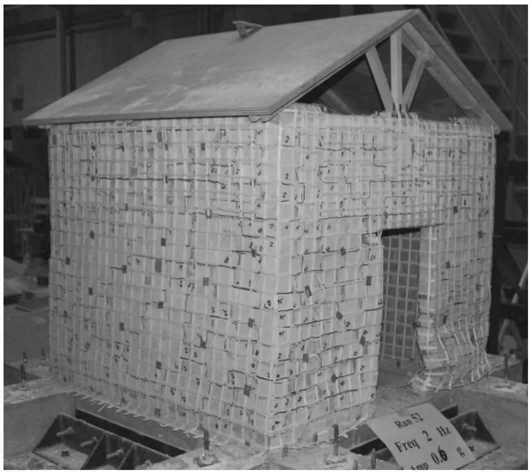

Figure 11. Retrofitted model after Run 53

At the final stage of the test, Run 53, with 50.6 mm base displacement, 8 times larger input displacement and 2.7 times larger input velocity than the Run 45 was applied. At this stage, most of the brick joints were cracked and the building had substantial permanent deformations. However, building did not loose the overall integrity as well as stability and collapse was prevented in such a high intensity of shaking. Thus, we could say that, PP-band retrofitting technique could maintain the integrity of the structural elements. Further, the retrofitted model showed the better energy dissipation mechanism as many new cracks were propagated without loosing the overall integrity and stability of the structure.

ANALYSIS ON TEST RESULTS

The performances of the models were assessed based on the damage level of the buildings at different levels of shaking. Performances were evaluated in reference to five levels of performances: light structural damage, moderate structural damage, heavy structural damage, partially collapse, and collapse.

Table 3. Damage categories

Category	Damage extension
D0: No damage	No damage to structure
D1: Light structural damage	Hair line cracks in very few walls. The structural resistance capacity did not decrease noticeably.
D2: Moderate structural damage	Small cracks were observed on masonry walls. The structure resistance capacity decreased partially.
D3: Heavy structural damage	Large and deep cracks were observed on masonry walls. Some bricks are fallen down. Failure in connection between two walls.
D4: Partially collapse	Serious failure and Partial structural failure were observed on walls and roofs, respectively. The building was in dangerous condition
D5: Collapse	Structure is totally or partially collapsed.

Based on JMA Scale

The Japan Meteorological Agency seismic intensity scale (JMA) is a measure used in Japan to indicate the strength of earthquake ground motions.

Figure 12 shows the performances of model houses with different JMA intensities. Collapse of the non-retrofitted building was observed at the 45th run at intensity JMA 5-. The retrofitted building performed moderate structural damage level at the 45th run at which the non-retrofitted building was collapsed. Moreover, moderate structural damage level of performance was maintained until the 50th run. It should be noted again that this model survived 8 more shakings in which many runs were with higher intensities than JMA 5- at which the non-retrofitted building was totally collapsed before reaching to the final stage at the 53rd run.

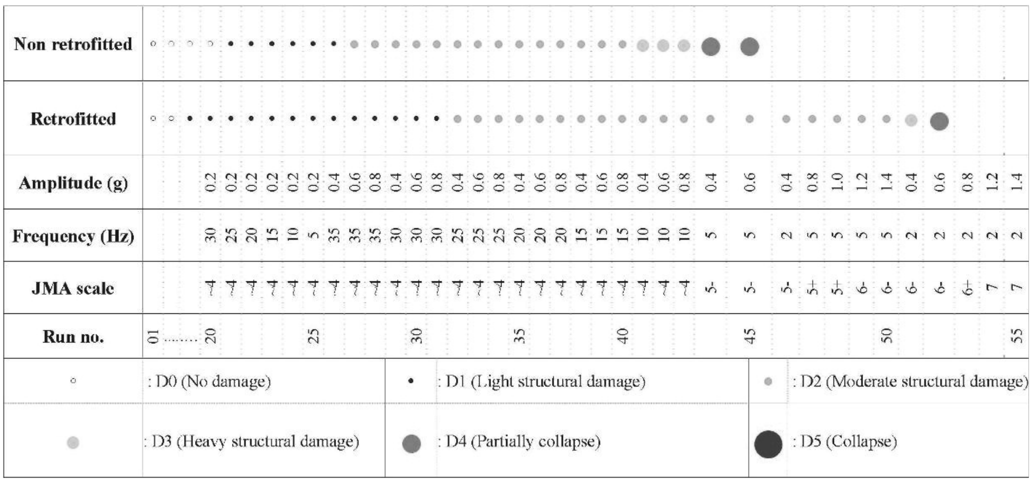

Figure 12. Performance evaluation based on input motion intensity by JMA scale

From these results it can be concluded that a structure retrofitted with PP-band meshes would be able to resist against strong aftershocks. Moreover, it proves that even though houses retrofitted with PP-band were cracked due to strong earthquake, it could be repaired and be expected to withstand subsequent strong shakes.

Based on Arias Intensity Scale

The Arias intensity was initially defined by Arias (Arias A., 1970) as

$$I_a = \frac{\pi}{2g}\int_0^t a^2(t)dt \tag{1}$$

and was called scalar intensity. It is directly quantifiable through the acceleration record a(t), integrating it over the total duration of the shaking. The arias intensity is claimed to be measure of the total seismic energy absorbed by the ground.

Figure 13 shows the performance levels of each specimen against dynamic motion based on arias intensity scale. Form the results, retrofitted model damage level performance was at least 3 times better than that of non-retrofitted model

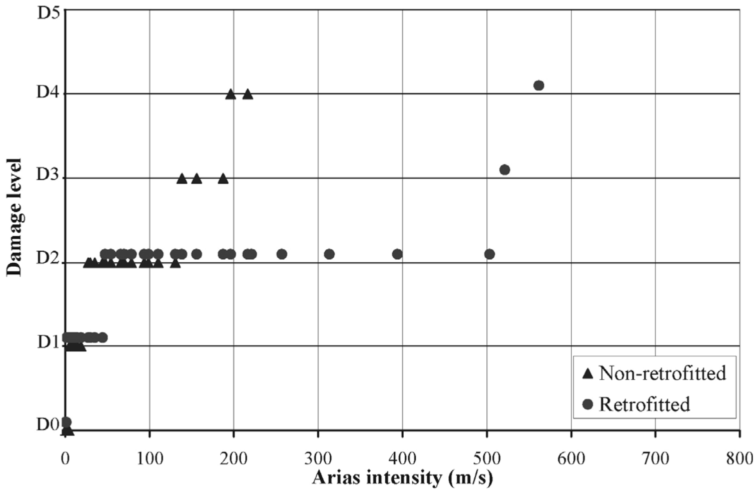

Figure 13. Performance evaluation based on arias intensity scale

CONCLUSION

This paper discusses the results of a shaking table tests that were carried out using non-retrofitted and retrofitted wallettes by PP-band meshes.

- The effect of the PP-band meshes was not observed before the appearance of initial cracking. However, after cracking, they effectively helped to increase the ductility of walls parallel to the shake direction, i.e. subjected to in-plane loading, to prevent the toppling of the walls perpendicular to the shake, i.e. subjected to out-of-plane loading, and to keep the integrity of the structure by limiting corner damage. With this mechanism, PP-band mesh could avoid the typical failure modes observed in masonry structures.
- A scaled dwelling model with PP-band mesh retrofitting was able to withstand larger and more repeatable shaking than that without PP band retrofitting.
- Considering the easiness of installation and inexpensiveness of PP-band mesh, it can be considered as one of the best solutions to overcome the quality deficit of existing building stock

in developing countries and therefore reduce the number of human fatalities in future seismic events.

From the experimental results, it was found that PP-band retrofitting technique proposed can enhance safety of both existing and new masonry buildings even in the worst case scenario of earthquake ground motion like JMA 7 intensity. Therefore proposed method can be one of the optimum solutions for promoting safer building construction in developing countries and can contribute earthquake disaster in future.

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