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EXPERIMENTAL STUDY ON DYNAMIC BEHAVIOR OF TIMBER ROOF MASONRY HOUSE MODELS RETROFITTED BY PP-BAND MESHES

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ABSTRACT

The collapse of non-engineering masonry is one of the major causes of human casualties during recent earthquakes in developing countries. Therefore, retrofitting of low earthquake-resistant masonry structures is the key issue for earthquake disaster mitigation in developing countries to reduce the casualties significantly. When we propose the retrofitting in developing countries, retrofitting 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 points, PP-band (polypropylene bands, which is worldwide available and cheap material, 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.

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. In this experimental program, ¼ scale single box shape room structure with wooden roof models were used. Addition to that, effect of surface plaster on PP-band retrofitted house model also studied.

From the experimental results, it was found that a scaled dwelling model with PP-band mesh retrofitting was able to withstand larger and more repeatable shaking than that without PP band retrofitting, which all verified to reconfirm high earthquake resistant performance. When surface finishing applied above house model, due to improve bond connection between PP-band and brick wall, surface plaster kept well with wall.

Introduction

In this research, by shaking table test, we will test the model’s dynamic characteristics and earthquake responses under different working stages; observe and record failure modes and failure characteristic under all intensities; evaluate seismic performance of the scale model building.

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Design and constructing the model

Designing of models

According to the shaking table size and allowable loading condition, the model scaling factor is 1:4 as shown in Fig.1. The model material, we use the unburnt bricks as masonry units and cement, lime and sand (1:2.8:8.5) mixture as mortar with cement/water ratio of 33%, to simulated to the replica of adobe masonry buildings in developing countries.

All the building models dimensions were 933mmx933mmx720mm with 50mm thick walls. The sizes of door and window in opposite walls were 243x485mm^2 and 325x245mm^2 respectively.

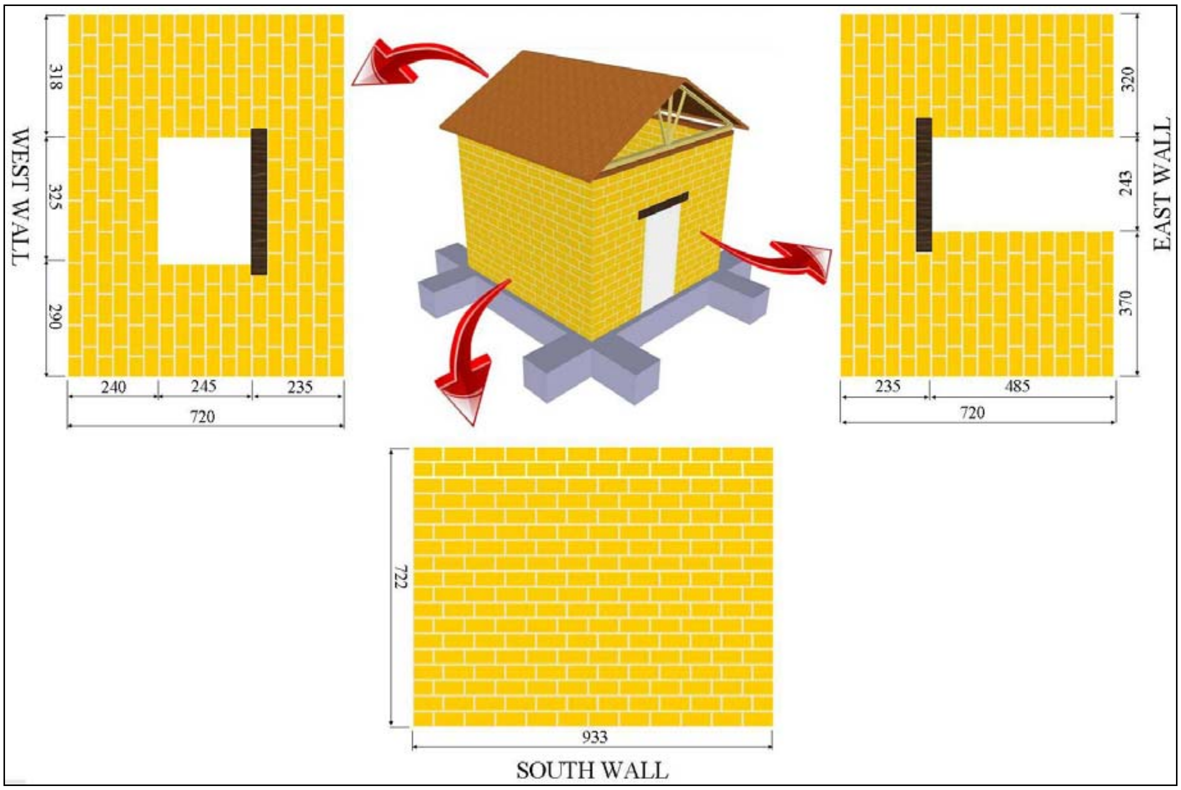

Figure 1. Model Dimension (in mm)

Model types

All four models are represented one-storey box-like building with timber roof; two models are non-retrofitted and other two models are retrofitted with PP-band mesh after construction. In each case, one specimen; i.e. one non-retrofitted and one retrofitted, were applied by surface finishing. The mortar thickness covering the inside and outside of walls is 7.5mm. For surface finishing material mixing ratio as follows; Water: Cement: Sand: Lime = 1.00: 0.14: 2.80: 1.11. This simple geometry and boundary conditions were considered as the data generated will be used for numerical modeling in future. Physical characteristic of the models are showed in Table 1.

Table 1. Model types

Model no.	Model name	Brick unit	Roof condition	Retrofitted condition	Surface finishing
1	A-NR-X	Adobe	√		
2	A-RE-X	Adobe	√	√	
3	A-NR-P	Adobe	√		√
4	A-RE-P	Adobe	√	√	√

Making of Models

All specimens consisted of 18 rows of 44 bricks in each layer except openings. Construction process takes place in two days, first 11 rows in first day and remaining rows construct in following day. The geometry, construction materials and mix 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 retrofitted procedure presented below is illustrated with photos taken during the experimental program.

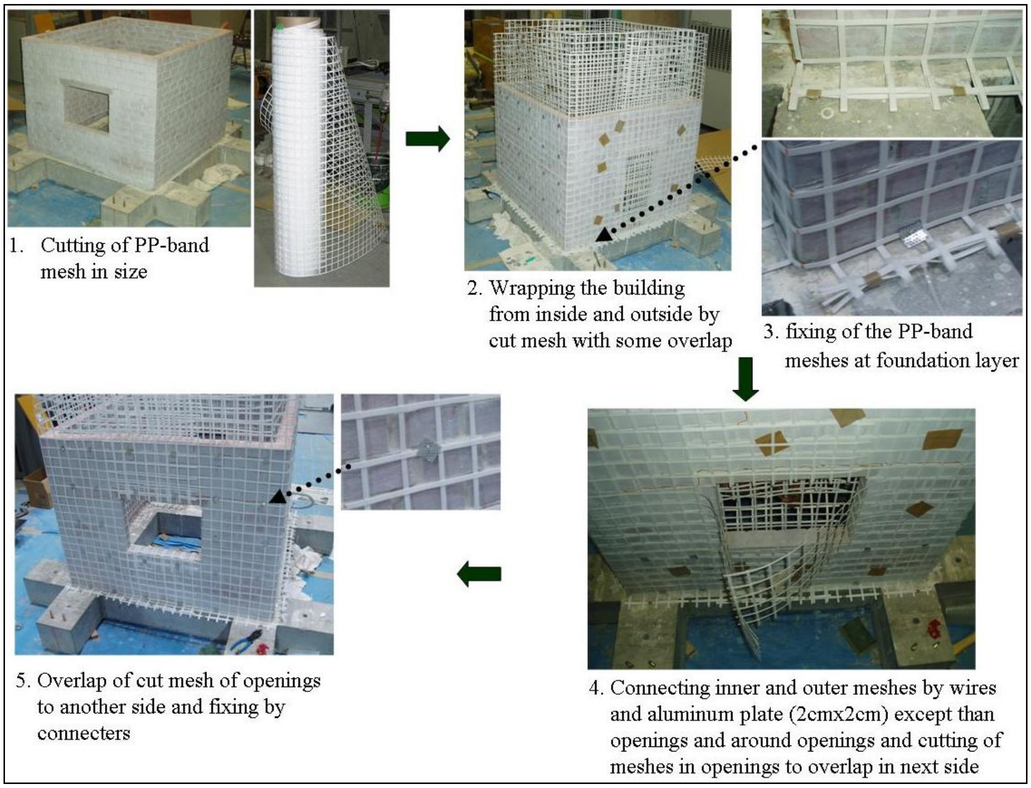

Figure 2. Retrofitting procedure

- 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 placed the straw in where we required a holes. Straw are placed at approximately 200mm pitch. In real case holes can be prepared by drilling through the wall).
- Meshes are wrapped 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. As much as possible, the bottom edge should be connected to the structure foundation for a better performance of the retrofitted structure. This step concludes the setting of the PP-band mesh.
- Fixed connectors around the openings after the mesh was cut and overlapped on the other side.

Procedure of tests

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 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.

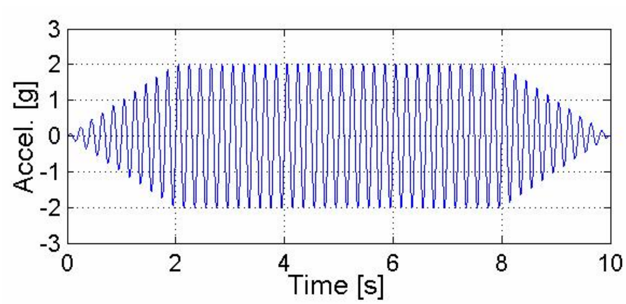

Figure 3. Typical Shape of Input Sinusoidal Motion

Loading was started with a sweep motion of amplitude 0.05g with all frequencies of 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							
	2Hz	5Hz	10Hz	15Hz	20Hz	25Hz	30Hz	35Hz
1.4g		50						
1.2g	54	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							

Process of shaking table tests

In case of models without surface finishing, due to shrinkage, some minor cracks were observed before the test. These cracks mainly appear closer to opening in horizontal direction.

For non-retrofitted model (A-NR-X) up to Run 21, no major crack was observed. Major cracks were observed closer to openings from Run 23. At run 28, crack was observed at one of the top corner of the door opening and it propagates up to top layer of the wall. After that, cracks widened with each successive run. At run 44, there were large amount cracks observed in walls in the direction of shaking. Exciting cracks widened and connection between adjacent walls was become weak. In case of walls perpendicular to shaking direction, top part of the east wall (part, above the door opening) was totally separated from the specimen. It was removed from specimen before next test run proceed. At run 45, all top part of the wall with opening was totally separated from the specimen. It was fallen from specimen. Now the roof only 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 4. Specimen A-NR-X after run 44 (left) and run 45 (right)

For retrofitted model (A-RE-X) up to run 21, no major crack was observed in this model. Major cracks were observed closer to openings from Run 25. After those new cracks appear in each run and cracks widened with each successive run, thus, extensive cracking was observed. Although the PP-band mesh kept the structure integral during the shaking, it allowed the sliding of the bricks along these cracks to some extent. In later stages, there was significant permanent deformation of the structure. At the final stage of the test, run 52, with 37.3mm base displacement, 6 times more than the input displacement applied in run 45 and 2.5 times more velocity, virtually all 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.

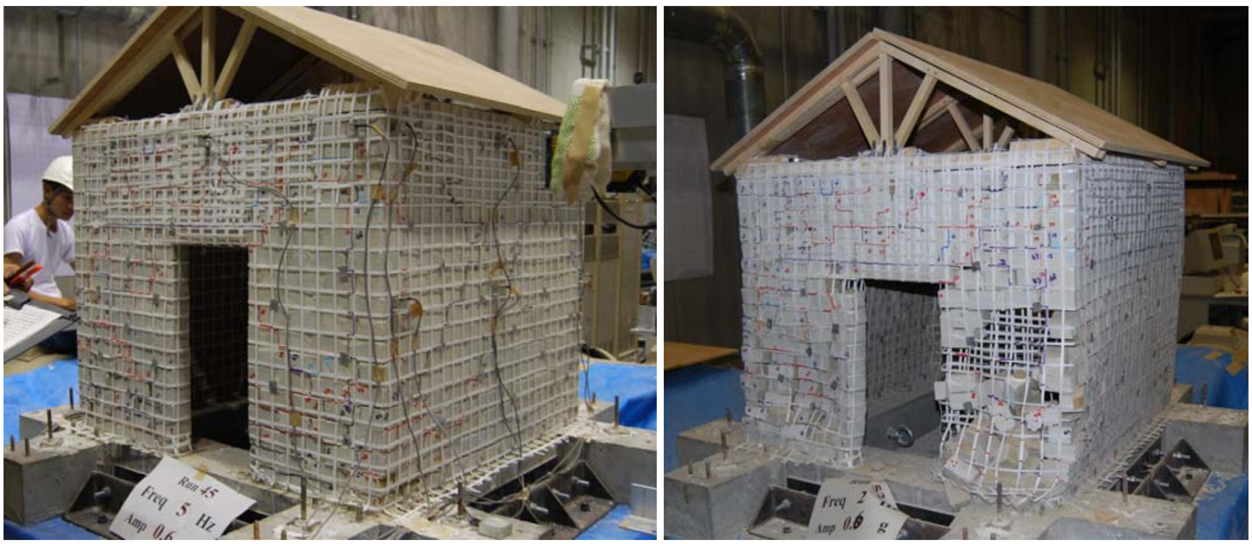

Figure 5. Specimen A-RE-X after run 45 (left) and run 52 (right)

For model A-NR-P, at run 26, major cracks were observed close to connection between roof and south wall. At run 43, lot of damage observed in the modal. Separation between east wall and its adjacent walls was observed. Also lot of surface finishing separated from the walls. At run 44, Top corner of the east wall and its adjacent walls was totally separated from specimen. At run 45, all the top part of the north and south walls was totally separated form specimen. Now roof only supported by two walls, which are in the perpendicular direction of shaking. This finally led to the structure collapse at run 47.

Figure 6. Specimen A-NR-P after run 45 (left) and run 47 (right)

In case of the retrofitted model A-RE-P, similar cracks as non-retrofitted building started from top corner of the south wall in the run 33. After that, the process of widening of the cracks occurred and propagation of new cracks continues until the run 50. Although at the end of 50th run almost cracks observed in entire walls, the specimen did not lose stability. Some bricks from bottom part of east wall were spilled out from PP-band mesh. Therefore some looseness was observed in bottom part of the wall. Even this very high input motion, most of the surface finishing still attached with walls. At the final stage of the test, run 54, with 74.6 mm base displacement, 9 times more than the input displacement applied in run 47 and 3.7 times more velocity, virtually all 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, PP-band retrofitting technique maintained 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.

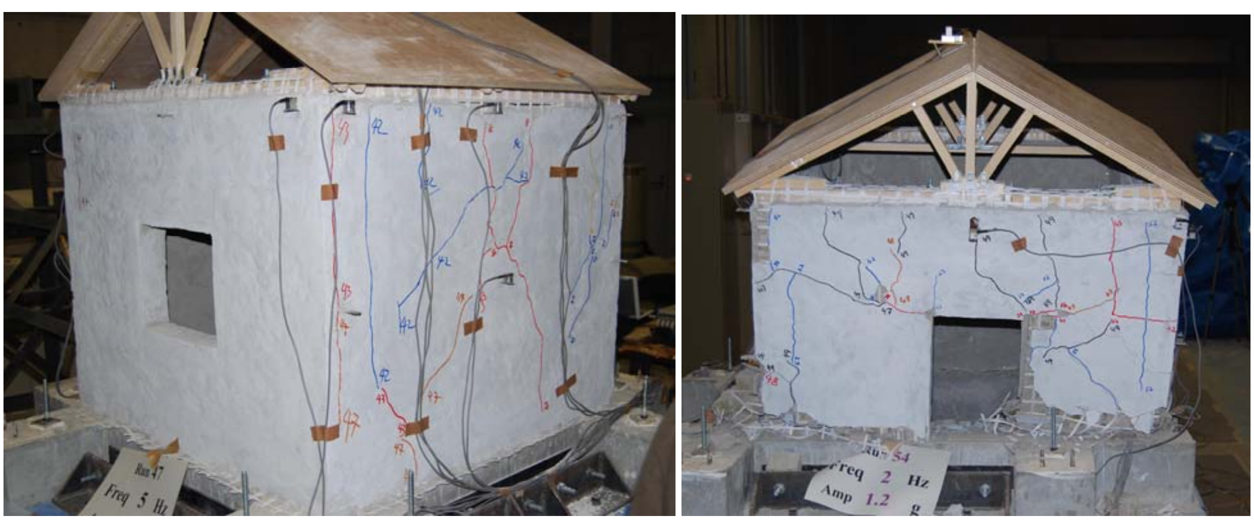

Figure 7. Specimen A-RE-P after run 47 (left) and run 54 (right)

When we applied the surface finishing to house model, due to improve bond connection between PP-band and brick wall, surface plaster kept well with wall. This is not observed in non-retrofitted model. Because of this, brick unit confined effect inside the PP-band mesh is improved and it improves the overall earthquake resistant performance.

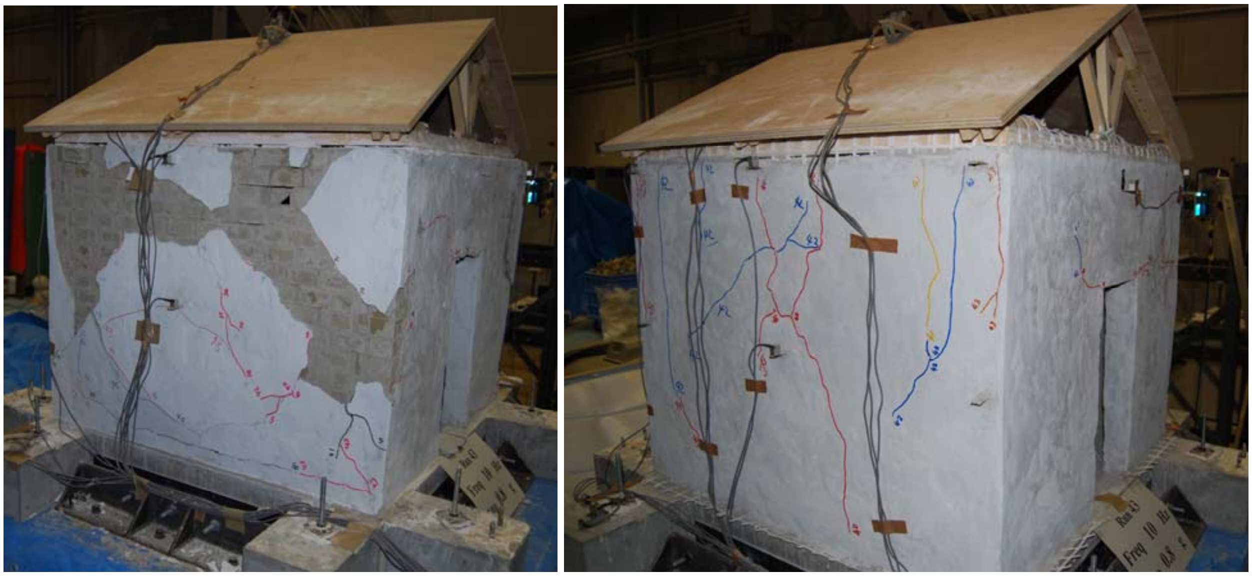

Figure 8. Specimen A-NR-P (left) and A-RE-P (right) after run 43

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 structure resistance capacity has not been reduce noticeably.
D2: Moderate structural damage	Small cracks in masonry walls, falling of plaster block. The structure resistance capacity is partially reduced.
D3: Heavy structural damage	Large and deep cracks in masonry walls. Some bricks are fall down. Failure in connection between two walls.
D4: Partially collapse	Serious failure of walls. Partial structural failure of roofs. The building is in dangerous condition
D5: Collapse	Total or near collapse

The Japan Meteorological Agency seismic intensity scale (JMA) is a measure used in Japan to indicate the strength of earthquakes. Unlike the Richter magnitude scale (which measures the total magnitude of the earthquake, and represents the size of the earthquake with a single number) the JMA scale describes the degree of shaking at a point on the Earth's surface.

Fig. 9 shows the performances of model houses with different JMA intensities. In case of house model without surface finishing (A-NR-X & A-RE-X), partial collapse of the non-retrofitted building was occurred at the 44th run at intensity JMA 5-. The retrofitted building performed moderate structural damage level at 45th run at which the non-retrofitted building was partially collapsed. Moreover, moderate structural damage level of performance was maintained until 50th run, leading to intensity JMA 6-. As the model was already considerably deformed beyond the limit of measurement system, test was stopped after the 52nd run. It should be noted again that this model survived 7 more shakings in which many runs were with higher intensities than JMA 5- at which the non-retrofitted building was collapsed before reaching to the final stage at the 52nd run.

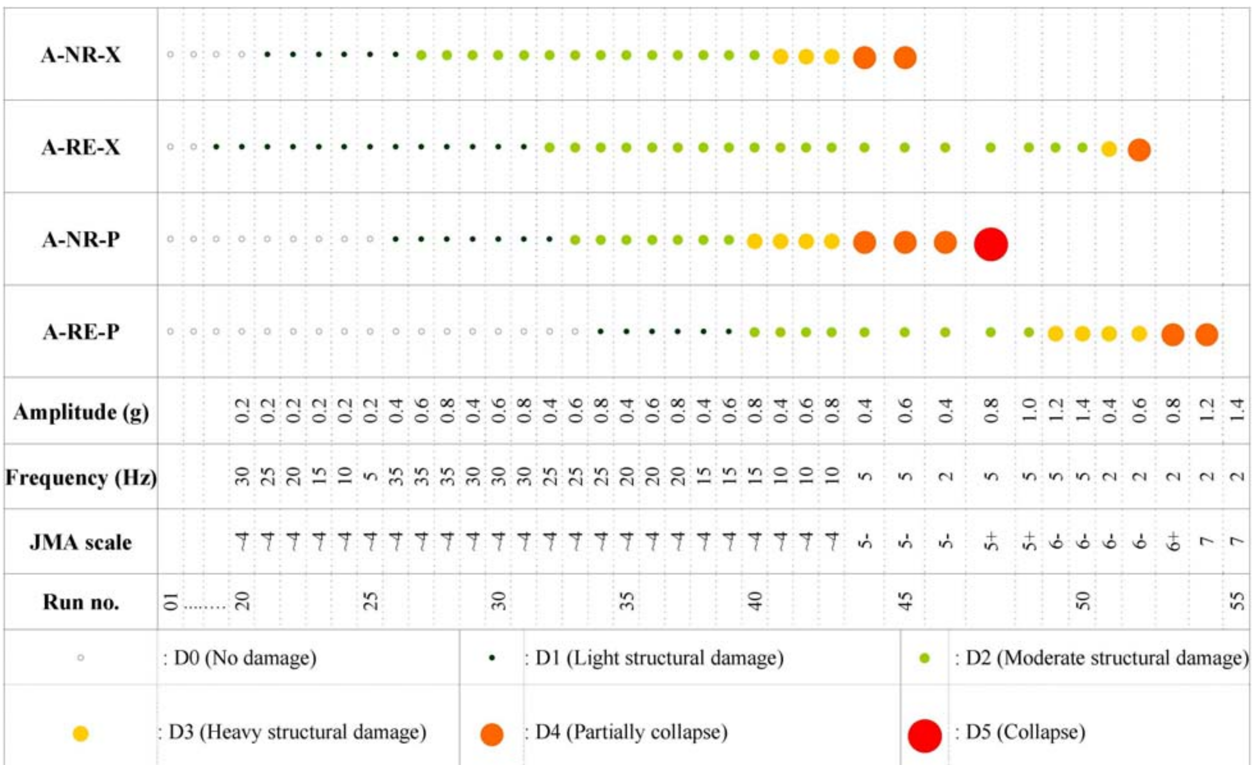

Figure 9. Performance evaluation analysis

In case of house model with surface finishing (A-NR-P & A-RE-P), total collapse of the non-retrofitted building was occurred at the 47th run at intensity JMA 5+. The retrofitted building performed moderate structural damage level at 47th run at which the non-retrofitted building was totally collapsed. Moreover, moderate structural damage level of performance was maintained until 48th run. It should be noted again that this model survived 7 more shakings in which many runs were with higher intensities than JMA 5+ at which the non-retrofitted building was collapsed before reaching to the final stage at the 54th run.

Conclusion

Four adobe masonry building models, identical in terms of masonry strength and geometry were constructed and two models were retrofitted with an easy-to-install and economic retrofitting technique. Models were tested on shaking table by applying similar input motions. Dynamic behaviors of the models were studied. Cracks patterns were analyzed and failure behavior and performances were evaluated.

- Shaking table test showed that; a scaled dwelling model with PP-band mesh retrofitting is able to withstand larger and more repeatable shaking than that without PP band retrofitting, which all verified to reconfirm high earthquake resistant performance.
- When we applied the surface finishing to house model, due to improve bond connection between PP-band and brick wall, surface plaster kept well with wall. This is not observed in non-retrofitted model. Because of this, brick unit confined effect inside the PP-band mesh is improved and it improves the overall earthquake resistant performance.

From the experimental results, it was found that this retrofitting technique can enhance safety of both existing and new masonry buildings even in 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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