PP-BAND RETROFITTING TECHNIQUE: AFFORDABLE, ACCEPTABLE AND FEASIBLE METHOD FOR DEVELOPING COUNTRIES

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ABSTRACT

An economically affordable, culturally acceptable, technically feasible and easy-to-use PP-band retrofitting technique for masonry buildings is being developed at Meguro Laboratory, IIS. Two identical brick masonry building models were constructed and one was retrofitted. Both models were tested on a shaking table with similar input motions. It was found that the technique enhanced the seismic capacity of buildings to sustain large base displacements and velocities and could improve the safety of masonry buildings to survive JMA7 earthquakes. It is an optimum solution for developing countries.

Key Words: *Masonry Structures, Seismic Retrofitting, Affordable Technology, Developing Countries, PP-band Technique, Non-engineered Buildings*

INTRODUCTION

Human casualties due to earthquakes in the 20th century are mostly due to structural damage and most of which are from unreinforced masonry buildings (Coburn and Spence, 2002). This has also been seen in recent earthquakes in developing countries India, Iran and more recently in Pakistan. Therefore, retrofitting of low earthquake-resistant masonry structures is the key issue for earthquake disaster mitigation in developing countries to reduce the casualties significantly. Seismic retrofitting not only reduces the damage to buildings during earthquakes, but also the costs of rescue and first aid activities, rubble removal, temporary residence building, and permanent residence reconstruction to re-establish normal daily life (Yoshimura and Meguro, 2004).

An appropriate retrofitting technique for developing countries should consider not only its efficiency in terms of improvement of the seismic resistant characteristics of the structures but also economical affordability, cultural acceptability and material as well as technological availability. An appropriate seismic retrofitting technique, PP-band retrofitting technique for masonry buildings has been developed and different aspects are being researched in Meguro Laboratory, in the Institute of Industrial Science, The University of Tokyo for some years considering these issues (Mayorca and Meguro, 2004). This paper focuses on shaking table experiments which were carried out to understand the dynamic response of masonry buildings, crack propagation, failure behaviour, and overall effectiveness of the newly developed retrofitting technique.

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SPECIMENS CONSTRUCTION

For shaking table experiment, two models were built in the reduced scale of 1:4 using the burnt bricks as masonry units and cement, lime and sand (1:8:20) mixture as mortar with c/w ratio of 14%. Attention was paid to make the models as true replica of brick masonry buildings in developing countries in terms of masonry strength even though the construction materials used were those available in Japan. Both the models represented a one-storey box-like building without roof. This simple geometry and boundary conditions were considered as the data generated will be used for numerical modelling in future. Both the buildings dimensions were 950mmx950mmx720mm with 50mm thick walls. The sizes of door and window in opposite walls were 243x485mm^2 and 325x245mm^2 respectively.

One of the buildings was retrofitted with PP-band mesh after construction. 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 6x0.24mm^2 and the mesh pitch was 40mm. The retrofitting procedure is described in next section of this paper. In this paper, the non-retrofitted model is named as "N-B-40" and the retrofitted one "R-B-40". The mechanical properties of masonry in terms of compressive, shear and bond strength were similar in both the cases and are given in Table 1.

Table 1: Mechanical Properties of Masonry

Properties	Model N-B-40 (MPa)	Model R-B-40 (MPa)
Compressive strength	20.96	20.30
Shear strength	0.074	0.075
Bond strength	0.085	0.074
Diagonal compression strength	0.173	0.181

RETROFITTING PROCESS

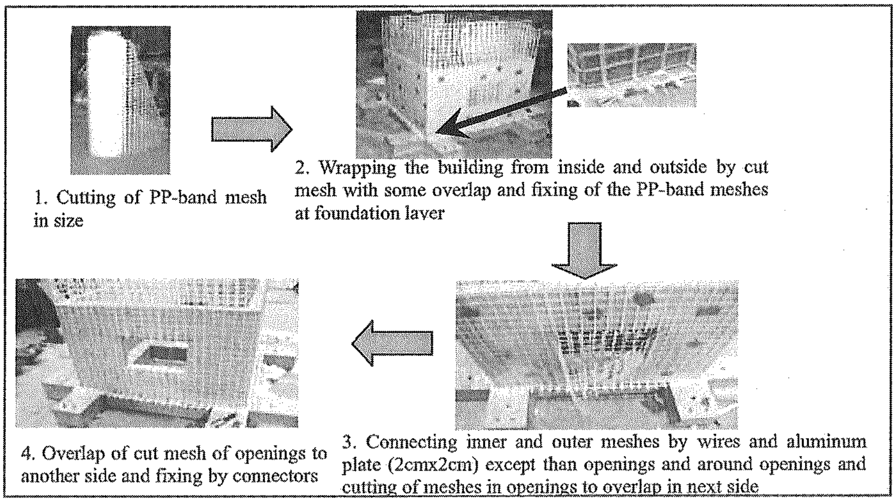


Figure 1: Retrofitting Process by PP-mesh

Most of the residential buildings in developing countries are of non-engineered type and owner built. The case of Nepal has been taken here as an example, where more than 98 % of the buildings are constructed by the owners following the advice of local craftsmen. In both urban and rural areas the traditional craftsmen, who are not given any specific training on seismic safety and do not have adequate access to information related to safer building practices, play the pivotal role (Dixit, 2004). So the implementation procedure for retrofitting technique for masonry buildings should be as simple as possible to be applicable for developing countries.

Installation procedure (Figure 1) for PP-band retrofitting technique is simple enough to understand and apply by the craftsmen and homeowners without any prior knowledge and expertise on earthquake engineering. Thus, it is expected to meet the very critical requirement of developing countries, the "easy-to-use" method, for promoting safer building construction.

INSTRUMENTATION

The tests were carried out in the shaking table facility available in the Institute of Industrial Science, the University of Tokyo. The size of the shaking table is 1.5x1.5 m^2. It has six degrees of freedom and operates in frequencies ranging from 0.1 to 50 Hz. It has a maximum displacement capacity of ±100mm and the maximum weight of the specimens that can be tested is 20 KN.

To study the global and local behaviour of the buildings during shakings, accelerations and displacements at different places were measured with accelerometers and lasers respectively. During the tests twelve accelerometers, four with three-dimensional measurement capacity and eight with one-dimensional measurement capacity were installed. Seven lasers were used to measure displacements at different locations.

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 2 shows the typical shape of the applied sinusoidal wave.

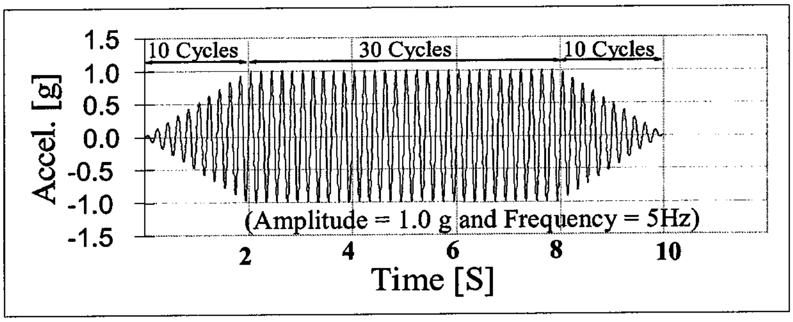


Figure 2: Typical Shape of Input Sinusoidal Motion

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. A total of 46 runs were applied to N-B-40 while as 16 more runs were applied to R-B-40 with 62 as a final run. Sequence of loadings for each successive runs is given in Table 2. The numbers in table 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.

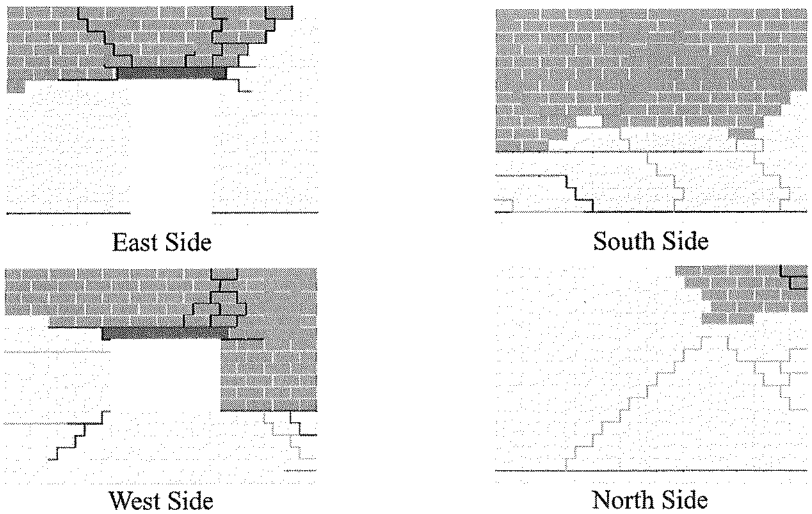
Table 2: Loading Sequence

Amplitude	Frequency							
	2Hz	5 Hz	10 Hz	15 Hz	20 Hz	25 Hz	30 Hz	35 Hz
1.4 g		59	58	57				
1.2 g		56	55	54	53			
1.0 g	62	52	51	50	49			
0.8 g	61	47	44	41	38	35	32	29
0.6 g	60	46	43	40	37	34	31	28
0.4 g	48	45	42	39	36	33	30	27
0.2 g	26	25	24	23	22	21	20	19
0.1 g	18	17	16	15	14	13	12	11
0.05 g	10	09	08	07	06	05	04	03
Sweep	01, 02							

Loading steps for both non-retrofitted and retrofitted models

Loading steps for retrofitted model after non-retrofitted model building collapsed

CRACKS PATTERN AND ENERGY DISSIPATION MECHANISM



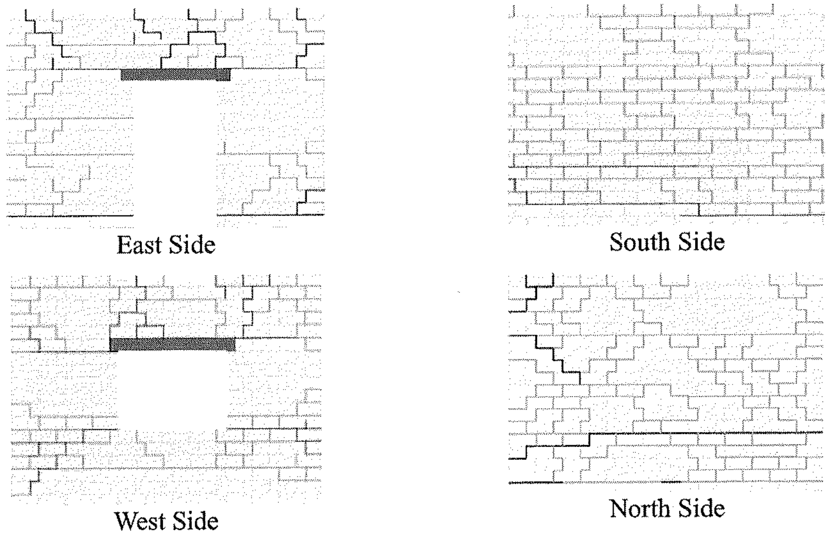
—— Initial cracks after 41st run (a_{max} = 0.8g, f= 15 Hz, d_{max}=0.9mm, v_{max}=0.08m/s)

------ Final cracks before collapse at 46th run (a_{max}=0.6g, f= 5 Hz, d_{max}=6 mm, v_{max}=0.19m/s)

Collapsed part after 46th run

Figure 3: Cracks Pattern of Non-retrofitted Building Model

Initial crack patterns in both models, non-retrofitted and retrofitted were similar. These cracks widened in each successive loading in case of non-retrofitted model. However, more new cracks appeared and propagated in the retrofitted case. Figure 3 and Figure 4 show the crack patterns of the non-retrofitted and retrofitted models respectively. In case of non-retrofitted building model, diagonal cracks started from top corners of both openings in the run 27. Horizontal cracks at base level of east and north walls were observed in the run 28; run 35 caused wide diagonal cracks from lower corners of window and reached up to corners of the wall; further, flexural cracks at bottom layer of south side wall also occurred. Another horizontal crack propagated at the 6th layer from bottom on the south side wall in the run 41. Run 44 caused a long horizontal crack at the 6th layer from top and a vertical crack in the top middle part of the south side wall. This wall bent inside tentatively by 14 mm and partially separated from bottom wall. The top part of the west wall above the door opening was totally separated from the specimen (partial collapse). The run 46 led the non-retrofitted structure to total collapse.



—— Initial cracks after 41st run (a_{max} = 0.8g, f= 15 Hz, d_{max}=0.9mm, v_{max}=0.08m/s)
.... Cracks after 60th run (a_{max}=0.6g, f= 2 Hz, d_{max}=37.3mm, v_{max}=0.48m/s)

Figure 4: Crack Patterns of Retrofitted Building Model

In case of the retrofitted building model, similar cracks as non-retrofitted building started from top corner of the opening in the run 27. Horizontal cracks at base layers of east and south walls were observed in the run 28, cracks propagated horizontally from top and bottom corner of the openings in the run 29, some diagonal cracks were observed at top part of the walls with openings in the run 35, many cracks in all four walls were observed in the run 44, and many new cracks were observed until the run 46. The process of widening of the cracks already occurred and propagation of new cracks continued to 14 more times until the run 60.

In later stages, there was significant permanent deformation of the structure. At the final stage of the test, run 62, with 63.4mm base displacement, 10 times more than the input displacement applied in run 46 and 4 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.

FAILURE BEHAVIOR AND PERFORMANCE EVALUATION

The performances of the non-retrofitted and retrofitted models are assessed based on the damage level of the buildings at different levels of shaking. Performances were evaluated in reference to three levels of performances: Immediate Occupancy, Life safety and Collapse Prevention based on damage levels described in (FEMA 356, 2000). The criteria for different performance levels in case of non-retrofitted case were taken as criteria for Unreinforced Masonry Walls defined in FEMA 356, Table C1-3: Structural Performance Levels and Damage. The equivalent JMA intensities were calculated based on the input motions to the structures at different runs. Table 3 below shows the performances of non-retrofitted building models with different JMA intensities.

Table 3: Performance of Non-retrofitted Building Model in Different JMA Intensities

Acceleration (g)	Frequency (Hz)							
	2	5	10	15	20	25	30	35
1.4								
1.2								
1.0								
0.8			PC	LS	LS	LS	IO	IO
0.6		TC	LS	LS	LS	IO	IO	IO
0.4		PC	LS	LS	LS	IO	IO	IO
0.2	IO	IO	IO	IO	IO	IO	IO	IO
0.1	IO	IO	IO	IO	IO	IO	IO	IO
0.05	IO	IO	IO	IO	IO	IO	IO	IO

Index	JMA ~4	JMA 5-	JMA 5+	JMA 6-	JMA 6+	JMA 7

IO: Immediate Occupancy
PC: Partial Collapse
LS: Life Safety
TC: Total Collapse
CP: Collapse Prevention

Partial collapse of the non-retrofitted building was occurred at the 44th run at intensity JMA~4 (Photo 1) and total collapse at the 46th run (Photo 2) at intensity JMA 5- but it should be noted that the model was already cracked in different loadings as discussed in previous section. The damage criteria for retrofitted building model are taken from FEMA 356, Table C1-3 for reinforced masonry walls. The drift limit criteria which are only 0.6% and 1.5% for life safety and collapse prevention level for reinforced masonry building was exceeded by the tested model retrofitted by PP-band technique. However, the overall damage level was not much as described in FEMA in relation to the drift. More drift than reinforced masonry building is logical if the characteristics of the PP-band mesh, which is many times less stiff than steel, is considered. So the drift criteria for reinforced masonry buildings could not be directly applied in this case and performance evaluation was done based on the overall damage to the structure. Table 4 below shows the performance of the retrofitted building model at different JMA intensities.

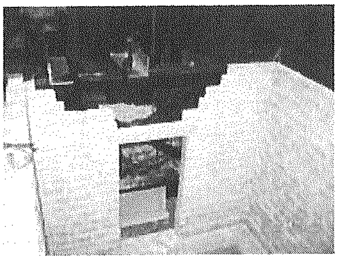


Photo 1: Partial Collapse of Non-retrofitted Building Model at the 44th run (Seismic Intensity, 4 JMA Scale)

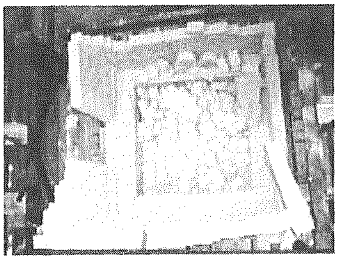


Photo 2: Collapse of Non-retrofitted Building Model at the 46th run (Seismic Intensity, 5- JMA Scale)

Table 4: Performance of Retrofitted Building Model with Different JMA Intensities

Acceleration (g)	Frequency (Hz) 2	5	10	15	20	25	30	35
1.4		LS	LS	LS				
1.2		LS	LS	LS	LS			
1.0	CP	LS	LS	LS	LS			
0.8	LS	LS	LS	IO	IO	IO	IO	IO
0.6	LS	LS	IO	IO	IO	IO	IO	IO
0.4	LS	LS	IO	IO	IO	IO	IO	IO
0.2	IO	IO	IO	IO	IO	IO	IO	IO
0.1	IO	IO	IO	IO	IO	IO	IO	IO
0.05	IO	IO	IO	IO	IO	IO	IO	IO

Index	JMA ~4	JMA 5-	JMA 5+	JMA 6-	JMA 6+	JMA 7

IO: Immediate Occupancy
LS: Life Safety
CP: Collapse Prevention
PC: Partial Collapse
TC: Total Collapse

The retrofitted building performed at life safety level of damage at 46th run at which the non-retrofitted building was collapsed. Moreover, life safety level of performance was maintained until 61st run, 15 more runs after the 46th run, leading to intensity JMA 6+.

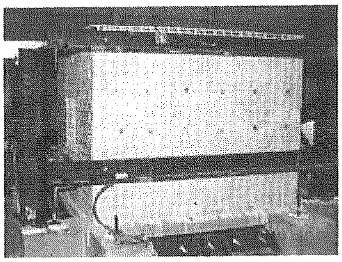


Photo 3: Retrofitted Building Model after 46th run (Seismic Intensity 5- JMA Scale)

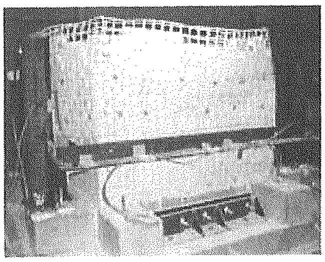


Photo 4: Retrofitted Building Model after 61st run (Seismic Intensity 6+ JMA Scale)

Photos 3 and 4 show the retrofitted building after the 46th run and 61st run respectively. In the 62nd run, another JMA 6+ intensity shaking, the building got the collapse prevention level of damage, which is crushing, extensive cracking, damage around openings and corners and some fallen units according to FEMA 356 definition. As the model was already considerably deformed beyond the limit of measurement system, test was stopped after the 62nd run.

Considering the pre-damage level of building during previous loadings including very high intensity shakings it can be interpreted that the retrofitting technique can achieve reasonable safety even in worst case scenario of earthquake like JMA 7 intensity. Further, this technique may also be applicable to retrofit earthquake damaged buildings as it was effective even after masonry had severe cracks. It should be noted again that this building model survived 15 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 62nd run.

CONCLUSION

Two brick masonry building models, identical in terms of masonry strength and geometry were constructed and one model was retrofitted with an easy-to-install and economic retrofitting technique. Both 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. The result showed that the PP-band retrofitting technique enhanced the seismic resistance capacity of the building model significantly; specifically the life safety performance capacity of the building was enhanced from JMA~4 intensity to JMA 6+ intensity and collapse prevention safety level was achieved until the final stage. From the result, it was found that this retrofitting technique can enhance safety of existing masonry buildings even in worst case scenario of earthquake ground motion like JMA 7 intensity and thus is one of the optimum solutions for promoting safer building construction in developing countries.

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