DYNAMIC TESTING OF MASONARY HOUSES RETROFITTED BY BAMBOO BAND MESHES

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ABSTRACT: The collapse of unreinforced masonry structures, which are widely distributed around the earthquake prone regions of the world, is one of the greatest causes of death in major earthquake events. This paper presents an innovative retrofitting method for masonry structures, which uses bamboo band arranged in a mesh fashion and embedded in a mortar overlay. In order to determine the effectiveness of the proposed retrofitting technique, shake table tests were conducted using retrofitted and non-retrofitted 1/4 scaled masonry houses and each house was subjected to sinusoidal ground motion inputs. Based on the experimental results, show that the retrofitted specimen exhibited good seismic performance by withstanding a more than twice input energy than non-retrofitted specimen.

Key Words: unreinforced masonry, bamboo-band mesh, shaking table test, JMA seismic intensity

INTRODUCTION

The collapse of the unreinforced masonry building induced by the earthquake events is one of the greatest causes of the human casualties around the world. Around 30 % of the world's population live in adobe construction (Houben & Guillard) and large proportion of the structures are located in earthquake prone regions. Thus, strengthening of unreinforced masonry structure is indispensable need to reduce the casualties significantly.

Till date, several types of retrofitting methods have been developed for unreinforced masonry structures. Retrofitting technique for developing countries should consider not only the effectiveness in terms of seismic performance but also the issues like economic viability, cultural adoptability and material as well as technological availability. Under the aforementioned circumstances, PP-Band Retrofitting Technique is one of the appropriate retrofitting techniques and different aspects of this method have already been researched in Meguro Laboratory, in the Institute of Industrial Science, The University of Tokyo.

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On the other hand, another strengthening technique, which uses bamboo band meshes as a strengthening system, has been proposed and different aspects are being researched in Meguro laboratory.

Bamboo-band retrofitting technique is simple enough to be understood and applied by layman without any prior expertise. Shake table tests were carried out to understand the dynamic response of masonry buildings, crack propagation, failure mechanism, and overall effectiveness of the newly developed retrofitting technique.

EXPERIMENTAL PROGRAM

Specimen Details

Two models were built in the reduced scale of 1:4 using the un-burnt bricks as a masonry units and cement, lime and sand (1:2.8:8.5) mixture as mortar with c/w ratio of 0.33. Even though the materials used were from Japan, great attention was paid to make the models as true replica of brick masonry building in developing countries in terms of masonry strength. Both models represented a one-story building with roof. As Figure 1 shows, the dimensions of both buildings were 950mm×950mm×720mm with 50mm thick walls and the sizes of door and window in opposite walls were 243mm×485mm and 325mm× 245mm, respectively. The size of the adobe brick used was 75mm×50mm× 35mm. Surface finishing was applied both on retrofitted and non-retrofitted buildings. These two building were identical in terms of geometry, construction materials, mix proportion, construction process and technique and other conditions that may affect the strength of the model house. The cross section of the band used was 8mm×0.75mm and the mesh pitch was 40mm. Surface finishing was applied to both specimens.

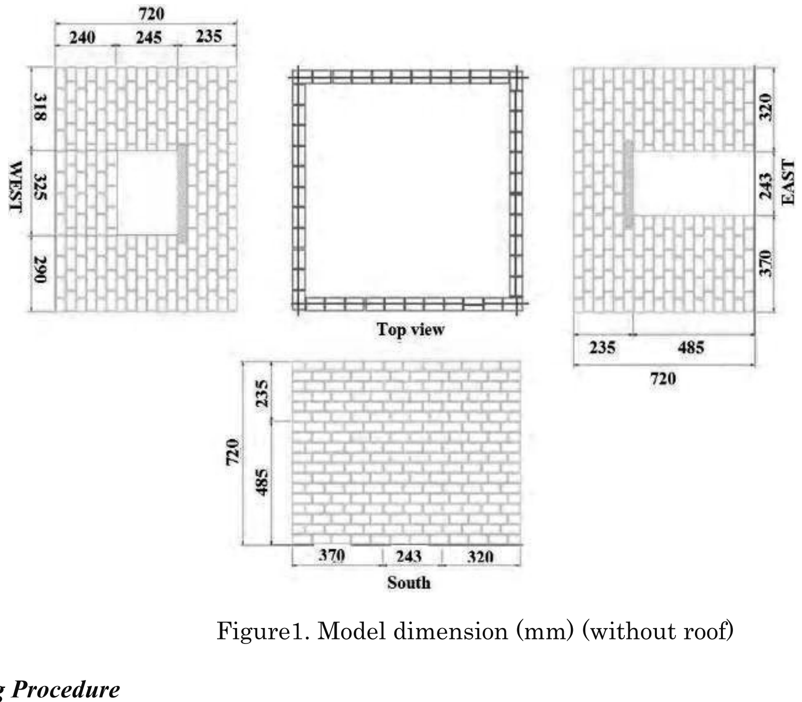
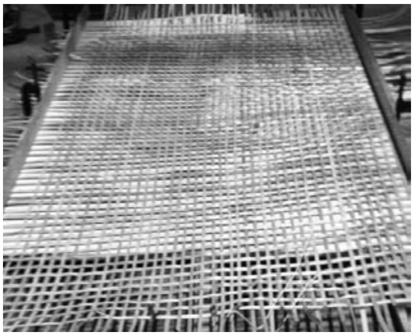


Figure1. Model dimension (mm) (without roof)

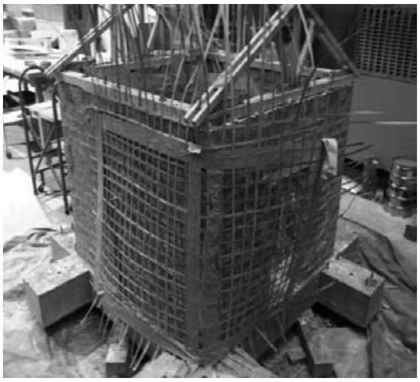
Retrofitting Procedure

Bamboo band mesh was first prepared on a square grid in a way that one band crosses over another band in different layers at subsequent crossing points. This process was quite similar to the basket weaving process. The straw, which was used to ensure hole during model construction, was removed. Straw was placed at approximately 200 mm pitch. In case of existing structures holes can be prepared by drilling through the wall. The prepared mesh was then installed both on outside and inside of the wall and wrapped around the corner of the house. The inside and outside meshes were connected by the Polypropylene strings (PP strings) which were passed through the hole. The overlapping and wrapping of the meshes was also made around the opening and roof. Figure 2 illustrates the overall retrofitting procedure.

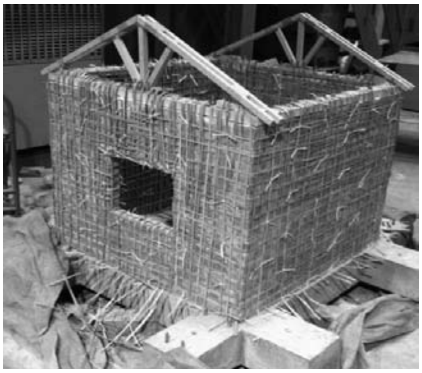


1. Preparing bamboo-band mesh in size

2. Securing holes using the straw during model construction



3. Wrapping the building from inside and outside by the mesh



4. Connecting inner and outer meshes by PP string and overlapping the meshes around the opening & roof

Figure2**.** Retrofitting process by bamboo-band mesh

Instrumentation

The test was 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 1.5m X 1.5m. It has six degrees of freedom and operates in frequencies ranges from 0.1 to 50 Hz. It has a maximum displacement capacity of ± 100 mm and the maximum weight of the specimen that can be tested is 2 tons.

Input motions
Sinusoidal motions of frequencies ranging from 35 Hz to 2 Hz and amplitude ranging from 0.05g to 1.4g were applied to obtain the dynamic response of both retrofitted and non-retrofitted structures. Figure 3 shows the typical shape of the applied sinusoidal wave. The number of cycles was constant for all frequencies. Thus, lower frequency input motion had longer duration.

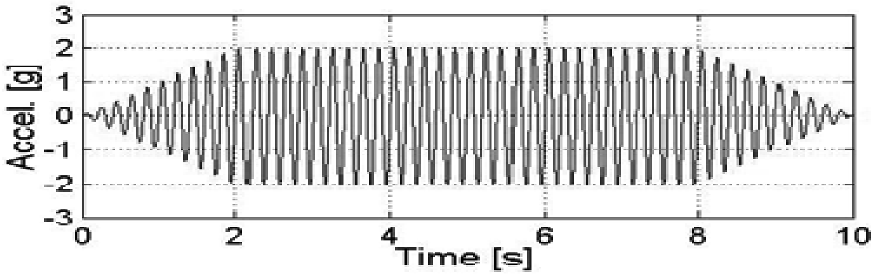


Figure 3**.** Input Sinusoidal motion

Loading was started with a sweep motion of amplitude 0.05g and frequency ranging from 2 to 50 Hz for identifying the dynamic properties of the models. The sequence of loading is given in **Table 1.** The numbers in table indicate the run numbers. General trend loading was from higher frequency to low frequency and from lower amplitude to higher amplitude. Higher frequencies motions were skipped towards the end of the runs.

Table 1. Loading sequence

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

CRACK PATTERN AND FAILURE BEHAVIOUR

At the end of each sinusoidal ground motion, inspection of the specimen was carried out. In addition, observed cracks were marked to highlight their locations. The crack formation for both specimens is shown in Figure 4 and Figure 6 after 42nd run of input motion. The initial crack patterns for both specimens were similar. However, these cracks widen in each successive loading in case of non-retrofitted model and new cracks appeared and propagated in the retrofitted model. For non-retrofitted model, no major crack was observed up to run 25. Initial crack was appeared from Run 26.At run 26; minor cracks were observed close to connection between roof and south wall. Run 31 caused crack in point close to connection between roof and south and north wall.

Similar cracks were also observed in top of east wall and its adjacent wall. 'X' shaped cracks were observed in south wall in the run 33. In addition, cracks from the corner of the door opening propagated up to the top layer of the wall. Existing cracks appeared from the previous run were propagated up to the bottom of the wall at run 38. Run 40 caused the falling of surface finishing from south wall. Large damages were observed in the run of 43 at which separation between east wall and its adjacent walls was occurred with the significant detachment of surface finishing from the walls. The run 44 caused the total separation of top part of the East-North corner from the specimen. At run 45, all the top part of the north and south wall totally separated from the specimen and roof was totally supported by east and west walls which are perpendicular to the shaking direction. The run 47 led the non-retrofitted building to total collapse (see Figure 5).

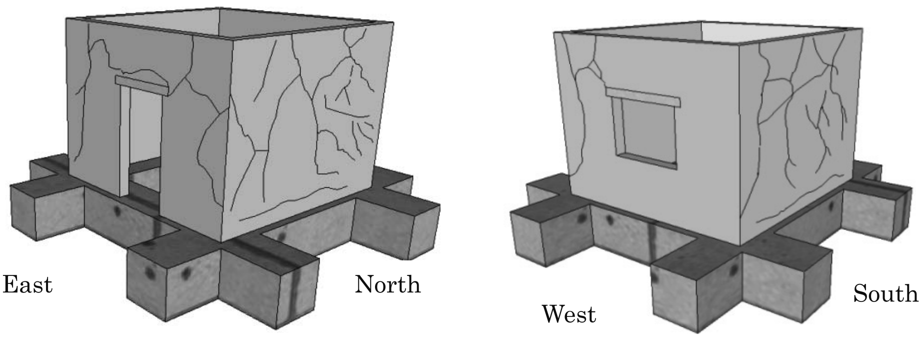


Figure 4.crack patterns of non-retrofitted building model after 42nd run

Figure 5. non-retrofitted building model after 46 run (left) and 47 run (right)

In case of the retrofitted building model, similar cracks in the case of non-retrofitted building started from top corner of the door opening in the run 27. Run 28 caused the propagation of the existing vertical cracks to the top corner of the door opening. In addition, some vertical and diagonal cracks were also observed around the window opening. The new inclined cracks were appeared in south wall at the run 40.Lots of cracks were observed at run 43. The inclined cracks originated from the corner of the window opening were extended to the top and bottom layer of the wall. 'X' shaped cracks were appeared in north and south wall with few detachment of surface finishing from the specimen. At run 47, most of the existing cracks were extended to the top and bottom layer of the walls. Most of the new cracks were concentrated in the bottom parts of the walls. This run caused the significant detachment of surface finishing from the specimen. Widening of existing cracks with the formation of few new cracks was continued to the run 49. At run 50, most of brick joints were cracked and few brick units fell down from the bottom part of the door opening. There was a large gap in some part of the specimen between the brick units and the mesh was broken at the corner of the wall. At run 52, the building lost the overall integrity and collapsed completely (see Figure 7).

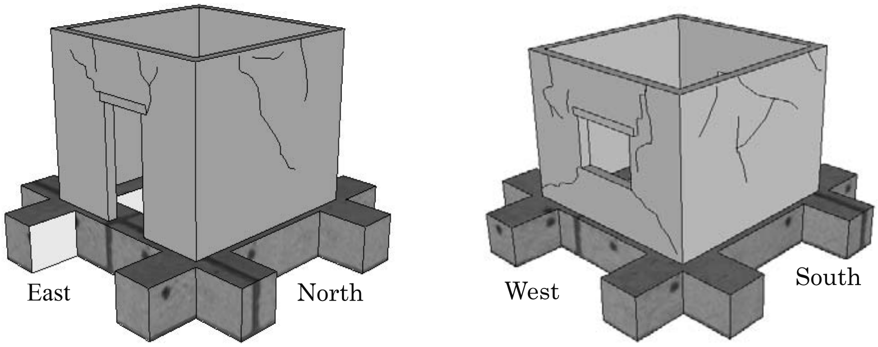


Figure 6. Crack patterns of retrofitting building model after 42 run

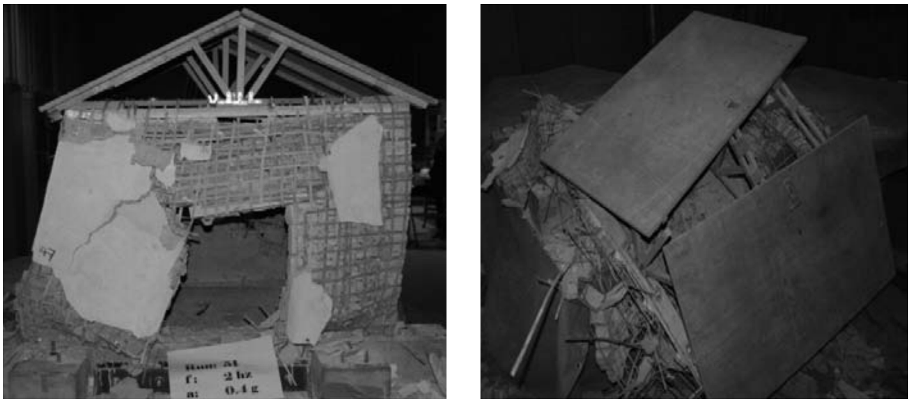


Figure 7. retrofitting building model after 51 run (left) and 52 run (right)

PERFORMANCE EVALUATION

The performance of the models was assessed on the damage level of the building at the different level of shaking. The damage level categories are specified on the Table 2. The Japan Meteorological Agency (JMA) seismic intensity scale is a measure used in Japan to indicate the severness of ground motions. JMA seismic intensity is a single number ranging from 0 to 7 and it describes the degree of shaking at a point on the Earth's surface. The JMA intensities were calculated based on the input motions to the structure at different runs. Table 3 shows the performance of model houses with different JMA intensities.

Table 2. Damage categories

D0: No damage	No damage to structure
D1: Light Structural damage	Hairline cracks in very few walls. The structure resistant capacity has not been reduce noticeably.
D2: Moderate structural damage	Small cracks in masonry walls, falling of plaster block. The structure resistant 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 is observed.
D4: Partially collapse	Serious failure of walls. Partial structural failure of roofs. The building is in dangerous condition.
D5: Collapse	Total or nearly collapse.

The collapse of the non- retrofitting building is observed at 47^{th} run at JMA 5^{+}. The retrofitted model performed moderate structural damage level at 47^{th} run at which the non-retrofitted model collapsed. Moreover, moderate performance continued to 48^{th} run. The retrofitted building sustained JMA 6- before going to complete collapse.

Table 3. Seismic performance of building models with different JMA intensities

Non-retrofitted building model								
Acceleration	**Frequency (Hz)**							
(g)	**2**	**5**	**10**	**15**	**20**	**25**	**30**	**35**
1.4								
1.2								
1.0								
0.8		**D5**	**D3**	**D3**	**D2**	**D2**	**D1**	**D1**
0.6		**D5**	**D3**	**D2**	**D2**	**D2**	**D1**	**D1**
0.4		**D4**	**D3**	**D2**	**D2**	**D1**	**D1**	**D1**
0.2	**D5**	**D0**	**D0**	**D0**	**D0**	**D0**	**D0**	**D0**
0.1	**D0**	**D0**	**D0**	**D0**	**D0**	**D0**	**D0**	**D0**
0.05	**D0**	**D0**	**D0**	**D0**	**D0**	**D0**	**D0**	**D0**

Retrofitted building model								
Acceleration	**Frequency (Hz)**							
(g)	**2**	**5**	**10**	**15**	**20**	**25**	**30**	**35**
1.4		**D5**						
1.2		**D4**						
1.0		**D4**						
0.8		**D3**	**D3**	**D2**	**D2**	**D2**	**D1**	**D1**
0.6	**D5**	**D3**	**D2**	**D2**	**D2**	**D2**	**D1**	**D1**
0.4	**D5**	**D3**	**D3**	**D2**	**D2**	**D1**	**D1**	**D1**
0.2	**D5**	**D0**	**D0**	**D0**	**D0**	**D0**	**D0**	**D0**
0.1	**D0**	**D0**	**D0**	**D0**	**D0**	**D0**	**D0**	**D0**
0.05	**D0**	**D0**	**D0**	**D0**	**D0**	**D0**	**D0**	**D0**

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

Figure 8 shows the performance of the model house with respect to the duration of shaking. The non-retrofitted specimen collapsed at a time when a retrofitted performed heavy structural damage.

The collapse time was extended to 70 sec for retrofitted specimen than non-retrofitted specimen. 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 inputted to the specimen from the ground.

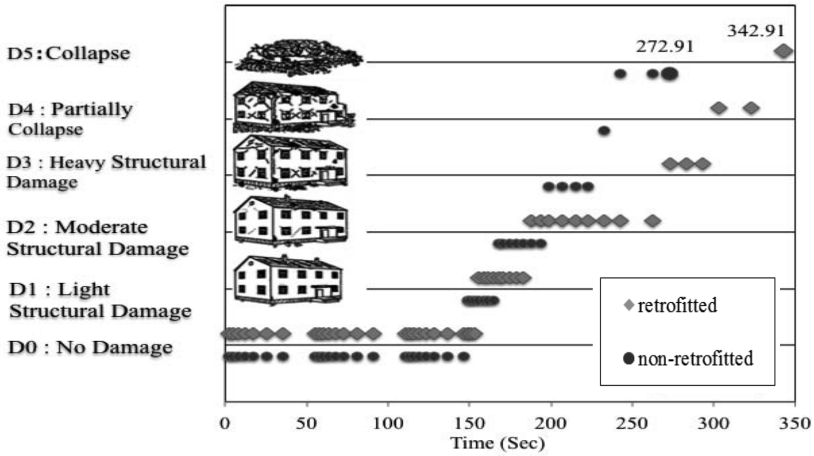


Figure. 8 Damage level comparison

Fig 9 shows the performance of the specimen based on arias intensity. From the results, retrofitted model could withstand more twice bigger input energy better than non-retrofitted model.

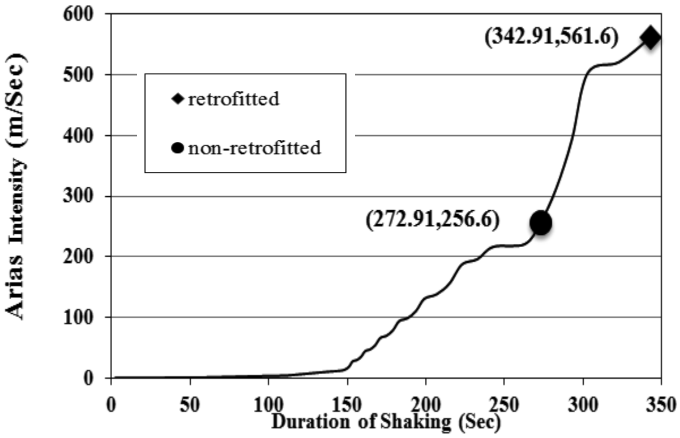


Fig 9. Seismic capacity comparison

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CONCLUSIONS

This paper discussed the result of a shaking table test carried out using non-retrofitted and retrofitted hose model by the bamboo band mesh as a strengthening system. The dynamic behavior of models was analyzed and failure behaviors and performances were evaluated. The result showed that the bamboo-band mesh retrofitting technique enhances the seismic resistant capacity of the masonry building model significantly. The retrofitted masonry building could withstand more than twice input energy than non-retrofitted specimen. Bamboo is universally available construction material and its use for retrofitting works not only enhances the seismic resistant capacity of new and existing building but also promote the local business in the vicinity.

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