Shake table tests on one-quarter scaled models of masonry houses retrofitted with fiber reinforced paint

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ABSTRACT: Over the last century, the greatest proportion of fatalities caused by earthquakes have been attributed to the collapse of masonry buildings most of which were constructed by local people with no engineering background using locally available materials without following structural code. These masonry houses and buildings, which are called non-engineered structures and distributed in seismic areas around the world (Coburn and Spence, 2002), collapse very rapidly even in low intensities of ground shaking. Therefore, seismic strengthening of existing and new masonry buildings is vital regarding earthquake disaster mitigation in the world and many methods have been developed to improve their seismic capacities. However, most of methods are time-consuming and labor-intensive, but not attractive as they don't directly increase amenity of the life of residents, which slowed down the spread of these methods. In our research group, a much easier new method has been developed using SG-2000, a kind of newly developed paint. Paint is commonly used for buildings (Yamamoto, 2014). Based on the results obtained from previous tests, wallettes coated with SG-2000 have approximately 14 and 16 times larger deformation capacities in cases of in-plane and out-of-plane tests, respectively, than those of the unreinforced masonry wallette. In this research, we have conducted shake table tests using one-quarter scaled models of a masonry house retrofitted with SG-2000 to investigate its dynamic failure behavior, crack patterns, and total seismic capacities.

Key Words: masonry, seismic retrofitting, fiber-reinforced paint, shake table test

INTRODUCTION

In the last century, there were many earthquakes and they have caused a total loss of life exceeding 1.53 million people. Masonry buildings are highly vulnerable and common in seismic areas around the world. Therefore, the collapse of masonry buildings is the major cause of the deaths in the past earthquakes in the world. Besides, much of the increased populations in developing countries continue constructing these structures and using them (Coburn and Spence, 2002). Therefore, retrofitting masonry structures is one of the most important issues for reducing casualties by earthquakes in the world. Also, seismic retrofitting ultimately reduces the costs for recovery from earthquake disaster (reduces the cost 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).
To retrofit these structures, many seismic retrofitting techniques (Shotcrete, FRP and so on) have been

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developed (Amiraslanzadeh et al., 2012). However, these techniques need much time and labor, but they are not attractive for local people because these methods don't improve the quality of lives. These facts have delayed these techniques' spreading in developing countries. Considering these problems, a new retrofitting technique using glass fiber reinforced paint (SG-2000) has been suggested. The material needed for this technique is only SG-2000, which significantly reduces the amount of time and labor for retrofitting. Also, paint is usually used to make houses look fine, and many masonry structures are coated with paint. Therefore, SG-2000 can be easily used by local people as the form of paint. The experiments in-plane diagonal shear tests and out-of-plane bending tests showed that wallettes coated with SG-2000 whose ratio of fiber was 1.5 % achieved larger deformation capacities than unretrofitted wallettes did (Yamamoto, 2014).
In this study, a shake table test using one-quarter scaled model of a masonry structure retrofitted with SG-2000 was conducted to investigate its dynamic responses.

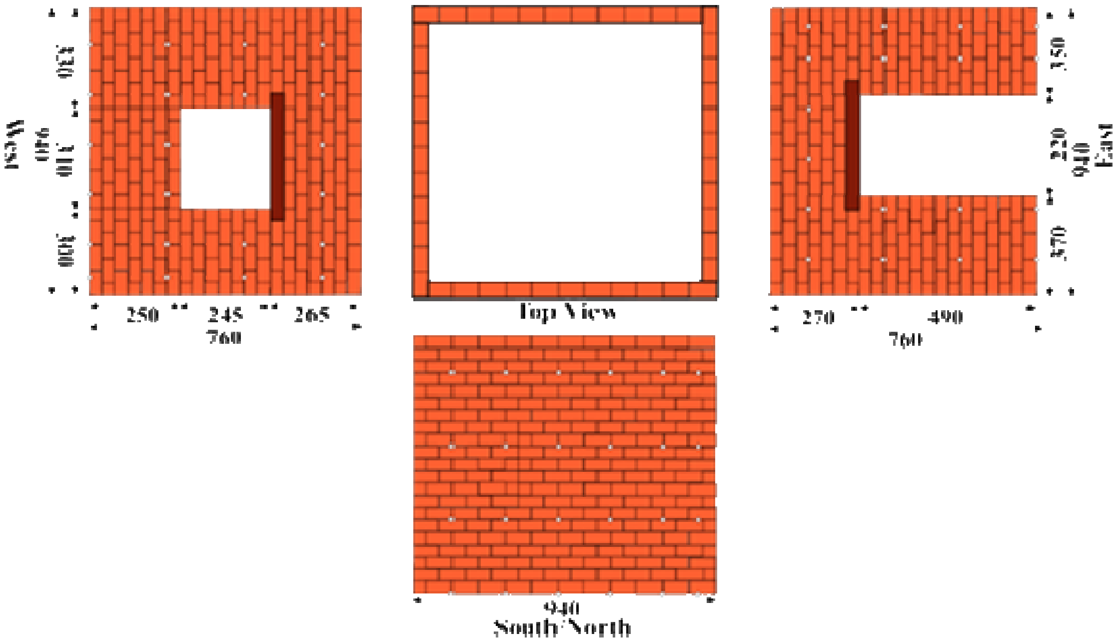


Figure 1. The dimension of the model house

EXPERIMENTAL SET UP

Specimen

The specimens were built with burnt bricks in reduced scale (1:4). Joints between bricks were filled by mortar with c/w ratio of 0.14 (cement:lime:sand=1:7.9:20). These materials were made in Japan, but the specimens were made with great attention that it could be a suitable replica of masonry buildings in developing countries, following previous experiments conducted by our research group (for example: Meguro et al., 2005). The model was one-story building with roof, with the dimensions of 940mm×940mm×760mm with 50mm thick walls and the sizes of door and window on the east/west walls were 220mm×490mm and 310mm×245mm, respectively as shown in Figure1. The dimension of the bricks used was 75mm×50mm×35mm and the same bricks had been used for the previous experiments conducted by our research group.

Retrofitting Procedure

Straws were put to make the holes placed approximately 200mm pitch as shown in Figure2 while constructing the house model. Before coating SG-2000 on the wall, steel wires were inserted to connect inside and outside of the wall. After inserting wires, we coated SG-2000 fully on the wall with 1mm thickness.

Experimental Equipment

The test was conducted using the shake table facility available in IIS, the University of Tokyo. The size of the shaking table is 1.5m×1.5m. It has six degrees of freedom and it can produce waves whose frequencies ranging from 0.1 to 50 Hz. Its maximum displacement capacities are ±100mm and its maximum capacity of weight is 2 tons.

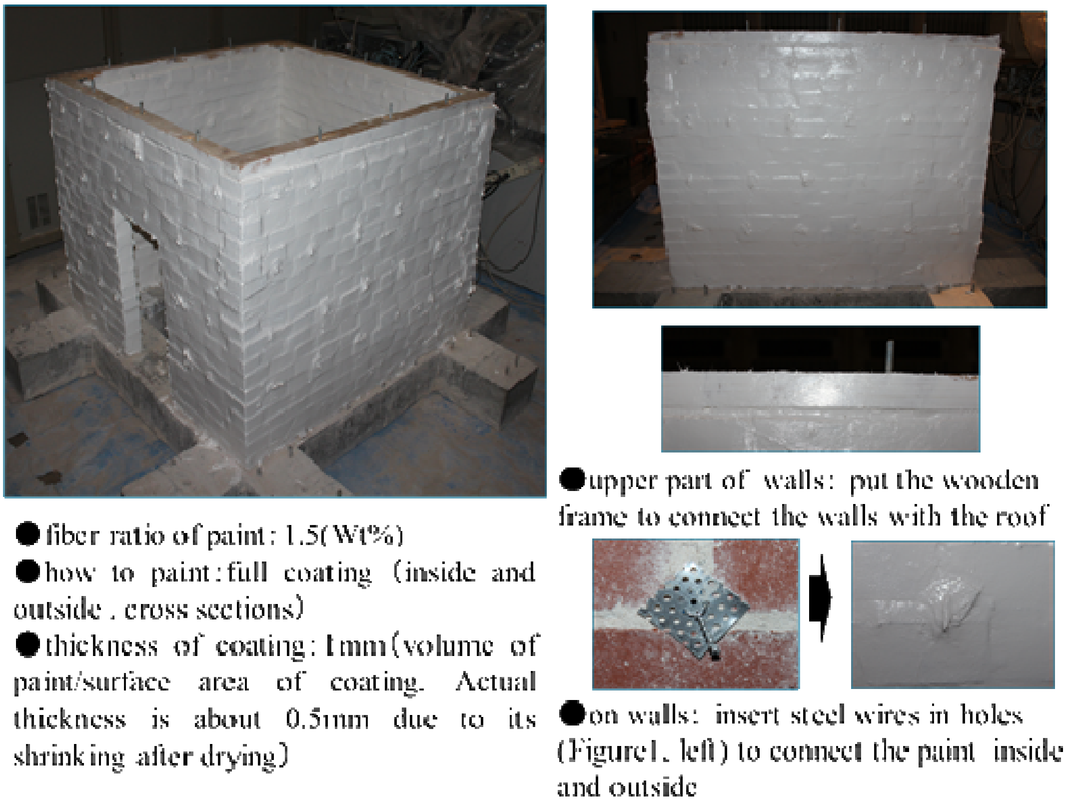


Figure 2. Retrofitting procedure

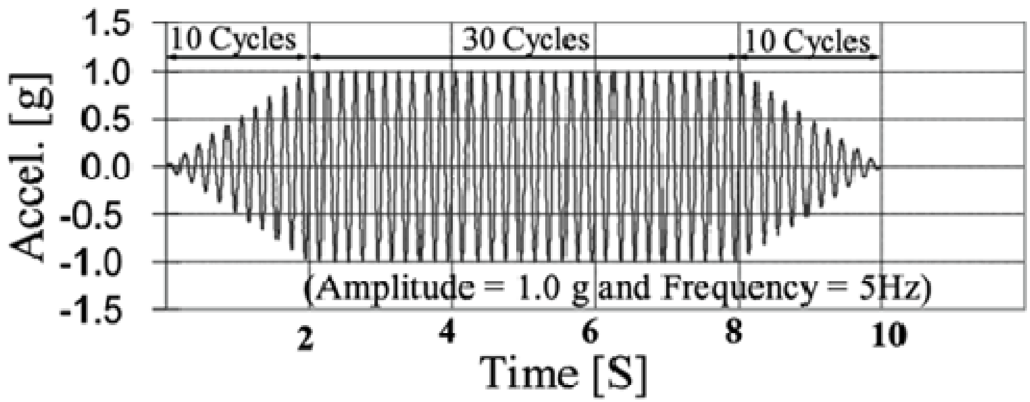


Figure 3. Typical shape of input sinusoidal wave motion (Meguro et al., 2005)

Table 1. Loading sequence

Amplitude	Frequency(Hz)							
	2	5	10	15	20	25	30	35
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							

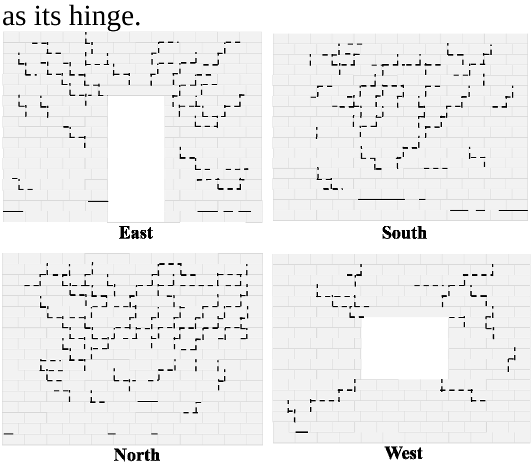
Table 2. Highlight of crack pattern and failure behavior (~Run50)

~ Run 39

There was no crack observed on the surface of coating and the cracks inside the coating could not be recognized well because of the small motions.

Run 42

A small damage to coating was observed at around the bottom of the east wall, which has the smallest stiffness of all walls.
According to the motion of the wall when shaking, some parts inside the coating were thought to be damaged. On the out-of-plane direction, most of the part from the middle to the top is damaged inside and these damaged parts have been shaked by making those cracks as its hinge.



Run 50

There were heavy damages to mortar joints inside the coating. Also, the coating was heavily damaged on the bottom part of the east wall and therefore there was a separation between the first and the second layer of bricks. There were not so much damages to the coating on the west wall, which had larger stiffness than on the east wall. Therefore, the east wall rotated when shaking with the west wall as the center of rotation.
The gray area indicates where the coating had been totally separated from bricks due to the lack of adhesion.

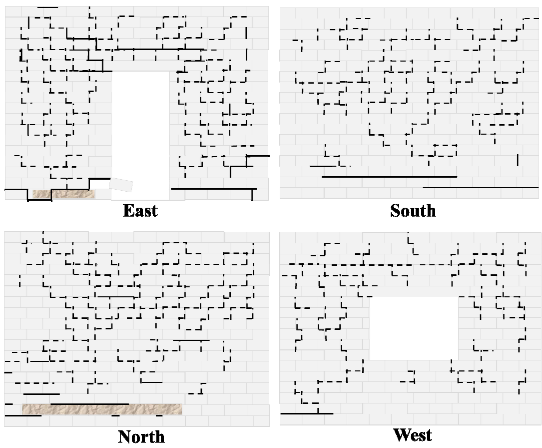


Table 3. Highlight of crack pattern and failure behavior (Run50~54)

<table>
<tr><th>Run 52</th><th rowspan="2">Run 54</th></tr>
<tr><td></td></tr>
<tr><td>Some part of the wall on the east wall was separated from the house, but did not fall down as the coating connected the part and the south wall.</td><td rowspan="3">Totally collapsed. However, the coating connected bricks after the structure had been broken, which produced some rooms inside the rubble.
</td></tr>
<tr><td>Run 53</td></tr>
<tr><td>All part of the east wall was separated with the diagonal cracks on the coating that had been produced in the previous runs. So far there was no dust and no bricks falling down inside the house.
</td></tr>
</table>

CRACK PROPAGATIONS AND FAILURE BEHAVIOUR

The crack patterns were investigated and marked after each run. Broken lines were drawn on the part where cracks are only inside the coating, and Solid lines were drawn on the part where the coating was also damaged. The highlight of the crack patterns were in the Table 2.

ANALYSIS BASED ON JMA SCALE

Damage Evaluation

he damage levels of house models during shake table test have been evaluated based on the same damage categories used in previous experiments carried out by our research group as shown in Table 3 (for example: Meguro et al., 2012). Also, all the runs have been conducted in a certain order based on the JMA seismic intensity scale. This JMA scale is an indicator of the strength of earthquake ground motions used in Japan. The comparison between the performances of two model houses (non-retrofitted and retrofitted with SG-2000) is shown in the Table 4.

From these results, it is concluded that the house retrofitted with SG-2000 could save the lives of the residents, but could not be used after a large earthquake because of its heavy structural damage.

Energy Dissipation Capacity

The energy dissipation capacity is one of the key parameters for discussing three seismic capacities of structure that a house has to have in order to resist an earthquake. It is calculated by cumulating the area of each cycle in the hysteresis loop of the graph of total force and horizontal displacement at the top of the house model.

The energy dissipation capacity of the retrofitted house was much larger than that of non-retrofitted house as shown in Figure 4.

Table 4. Damage categories (EMS-98)

Category	Damage extension
D0: no damage	No damage to structure
D1: light structural damage	Hair line cracks were observed 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 was observed.
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 was totally or partially collapsed.

Table 5: Performance evaluation based on input motion intensity by JMA scale

Non-retrofitted																			
Retrofitted with SG-2000																			
Amplitude (g)			0.2	0.2	0.2	0.2	0.2	0.2	0.4	0.6	0.8	0.4	0.6	0.8	0.4	0.6	0.8	0.4	0.6
Frequency (Hz)			30	25	20	15	10	5	35	35	35	30	30	30	25	25	25	20	20
JMA scale			~4																
Run No.	01	···	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36

Non-retrofitted																		
Retrofitted with SG-2000																		
Amplitude (g)	0.8	0.4	0.6	0.8	0.4	0.6	0.8	0.4	0.6	0.4	0.8	1.0	1.2	1.4	0.4	0.6	0.8	1.2
Frequency (Hz)	20	15	15	15	10	10	10	5	5	2	5	5	5	5	2	2	2	2
JMA scale								5-			5+		6-				6+	7
Run No.	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54

D0: No damage	D1: Light structural damage	D2: Moderate structural damage
D3: Heavy structural damage	D4: Partially collapse	D5: Collapse

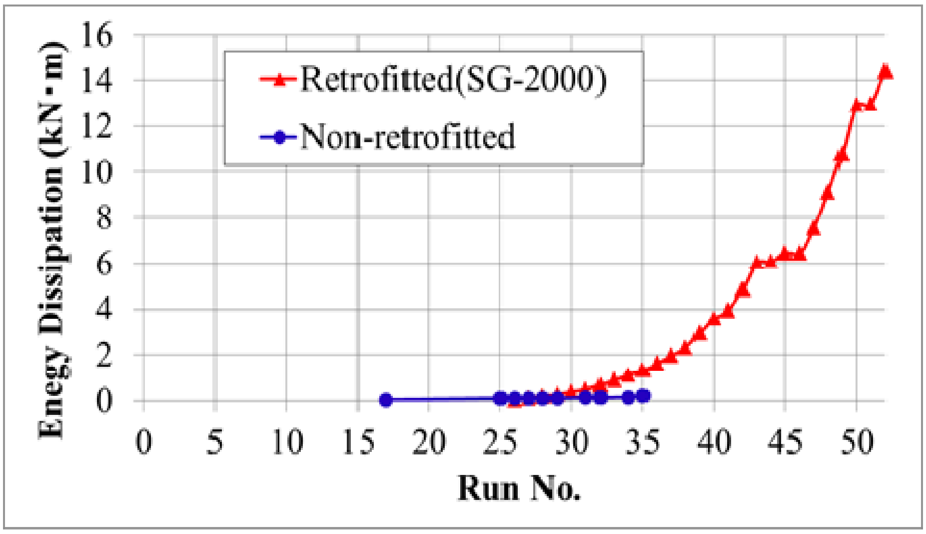


Figure 4. Comparison of energy dissipation capacity between non-retrofitted and retrofitted structures

CONCLUSIONS

We compared the results of shake table tests using 1/4 scaled masonry of unretrofitted and retrofitted with SG-2000 as the retrofitting material. As the SG-2000 did not improve the structure's stiffness, the damage inside the coating was observed in the same way as the unretrofitted house. On the other hand, SG-2000 connected bricks after the mortar joints of them had been broken. It is concluded that SG-2000 improves both the structure's deformation capacity and energy dissipation capacity, and make the structure resistant against much larger ground motions. Also, SG-2000 covers the mortar joints and bricks, and therefore it prevents the dust from spreading and bricks from falling down inside the house. From the failure pattern of the retrofitted house, SG-2000 could save the lives of residents in earthquake, but could not enable them to use the house again because of its heavy structural damage.

Future researches should improve SG-2000 as it prevents heavy structural damage so that the residents can use the retrofitted house even after a large earthquake.

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