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The development of a new fiber reinforced for seismic retrofitting of masonry structures

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Abstract

We have seen a large number of fatalities attributed to earthquakes in the 20th and 21st centuries, and more than 60% of the fatalities have been caused due to the collapse of masonry buildings. These masonry buildings, that have killed many people, made by weak materials like adobe, rubble stone, rammed earth, unreinforced fired brick, and concrete blocks, that can collapse even at low intensities of ground shaking [1].

To save the people living in masonry buildings, many kinds of techniques to seismically retrofit the masonry buildings were developed. However, a large number of fatalities were still caused by the collapse of masonry in recent earthquakes around the world. It means the knowledge of the retrofitting techniques have not been spread in the countries where people still use masonry for housing. This is because most techniques require much time and labor work, and they need incentive to pay only for the value of seismic retrofitting.

To solve these problems, a new technique was introduced. SG-2000, which is a kind of paint mixed with glass fibers and invented by SG Co., was used for retrofitting. This technique involves only coating the masonry building with the SG-2000. Therefore, the time and labor required for retrofitting is considerably reduced. Furthermore, the SG-2000 can be introduced as a form of painting, which adds aesthetic approval to the masonry buildings. The past shaking table test has shown that the house retrofitted with SG-2000 has large deformability and good energy dissipation capacity. SG-2000 had prevented the dust produced by the mortar in the joint of bricks, from spreading, which avoid the suffocation of the residents during earthquake shaking. It has also prevented the bricks from falling down, which prevents fatal injuries to the people living inside [2]. However, the level of damage to masonry walls inside the coating of SG-2000 is similar to that of masonry walls of an unreinforced masonry house, because SG-2000 does not improve the initial stiffness of the house. Therefore, it is impossible for the residents to use the house retrofitted with SG-2000 after a large earthquake even if it saves their lives.

To solve this problem, the retrofitting needs to improve not only the deformation capacity but also the strength of masonry buildings, through the composite use of two kinds of retrofitting material can increase both of masonry buildings [3]. Therefore, two kinds of paint are needed for this purpose. The normal SG-2000 improves the deformation capacity of buildings, so the paint which increases the strength of buildings is needed.

In this research, we conducted tensile tests using SG-2000 whose resin and ratio of fiber is changed to develop a new type of SG-2000 which improves the strength of buildings. Tensile tests of the new SG-2000 and in-plane tests are conducted using the composite use of the new SG-2000 and previously used SG-2000.

Keywords: masonry, earthquake, seismic retrofitting, in-plane

1. Introduction

Masonry structures are highly vulnerable to an earthquake 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. There are still growing population in developing countries that continue constructing these structures without engineering background and using them [1]. Therefore, seismic retrofitting of masonry structures is one of the most important things to do for lowering 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) [4].

To retrofit these structures, a new retrofitting technique using glass fiber reinforced paint (SG-2000, manufactured by SG Co.) 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 could be used by local people as a form of paint. A shake table test using one-quarter scaled model of a masonry structure retrofitted with SG-2000 had much durability than unreinforced one in the shaking with larger energy [2].
Current SG-2000 provides ductility, however, it does not provide stiffness, nor initial strength because the elastic modulus of SG-2000 is much smaller than that of mortar. Therefore, the residents could not use the masonry house again after an earthquake because the wall does not avoid its damage even if SG-2000 prevents the house from collapsing.

To solve the problem, we suggest the composite method using two kinds of paint. One has small deformability, but large elastic modulus and large tensile strength (hereinafter referred to as Paint-S), the other has small elastic modulus, but a large deformability (hereinafter referred to as Paint-D). We used Paint-S as a first layer of painting, and Paint-D as a second layer (Fig. 1). This two-layered coating are suppose to be used in some parts of a masonry house where the cracks occur first (only Paint-D is used in other part) because the strength or the stiffness of those parts are smaller, or they have larger stress than other parts.

By introducing this two-layered coating, the retrofitted house is expected to have both strength and deformation capacity, so it would not have a damage in a small earthquake and not be collapsed in a large earthquake. First we conducted material tests of SG-2000 that has various kinds of ratio of fiber and two kinds of resin to determine material properties of them. To investigate seismic performance of the suggested coating, we conducted in-plane tests to investigate the failure pattern of masonry wall retrofitted with the method.

2. Material test

To investigate material properties of various paint, we conducted tensile tests. The resin and ratio of fiber varies according to Table 1.

Table 1 –composition of various paint

Resin	Acrylic silicon						Polyester			
Ratio of fiber	0	1.0	2.0	4.0	6.0	10	1.0	2.0	4.0	6.0

We made 3 samples for all kinds of paint forming from a pattern whose shape is dumbbell (Fig. 2) following JIS (Japanese Industrial Standard), and conducted axial tensile test for each sample (Fig. 3).

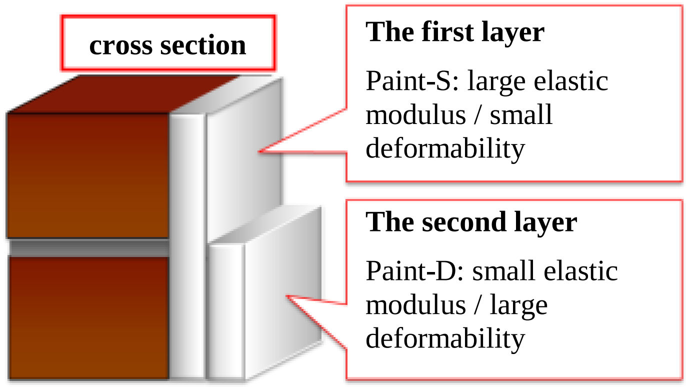

Fig. 1 – the new way of coating

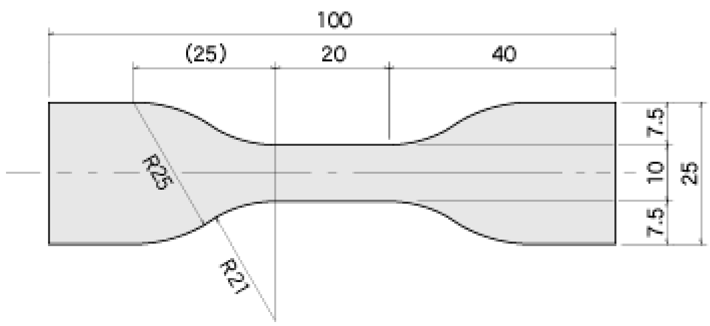

Fig. 2 – Dumbbell shape[5]

Fig. 3 – Axial tensile tests of paint

The result is shown in Table 2. The result shows that polyester resin has larger elastic modulus and maximum axial stress than acrylic silicon resin, and acrylic silicon resin has larger failure strain than polyester resin. Therefore, using polyester resin as a first layer and acrylic silicon resin as a second layer is the best way of coating for the purpose of this study.

The specimens are one-quarter scaled models, so the mass of a specimen is quarter as much as the actual masonry walls. Therefore, the strength of the mortar is adjusted in the experiment. At the same time the material properties of paint for retrofitting is necessary to be adjusted for one-quarter scaled models. From the results of the axial tensile tests, polyester resin whose ratio of fiber is 2.0 % and acrylic silicon resin whose ratio of fiber is 1.0 % were used as Paint-S and Paint-D respectively.

Table 2 – The result of axial tensile test

Resin	Acrylic silicon						Polyester			
Ratio of fiber	**0**	**1.0**	**2.0**	**4.0**	**6.0**	**10**	**1.0**	**2.0**	**4.0**	**6.0**
Elastic Modulus (MPa)	0.373	1.78	3.52	4.88	12.8	19.7	14.0	31.0	43.2	62.3
Maximum Axial Stress (MPa)	0.551	0.633	1.00	1.13	1.88	2.58	2.34	2.60	3.56	4.74
Failure Strain (%)	1.04E+3	367	160	126	82.0	62.5	38.5	24.1	11.9	14.8

3. In-plane diagonal compression test

To evaluate the seismic performance of the proposed two-layered coating method in in-plane direction, in-plane diagonal compression tests using unreinforced masonry wallettes (URM) and those retrofitted with proposed two-layered coating for burnt brick were conducted. The dimension of a specimen was 277.5 $\times$ 282 $\times$ 50 mm^3, composed of 7 brick rows of 3.5 bricks each and mortar joint thickness was 5mm. These specimens were one-quarter scaled one, so the C/W ratio was set to be 0.14 to adjust the strength of mortar considering its scale effect [6].

3.1 In-plane test of URM

Unreinforced masonry specimens (URM) were tested 56 days after the construction (Fig. 4). The loading rate was 0.15 mm/min. Fig. 6 (left) shows the results giving the diagonal compression force along with vertical deformation of URM. From the results, the maximum compression force and the failure deformation and the stiffness of URM are 0.5363 kN and 1.146 mm and 0.4680 kN/mm respectively on average of 3 samples.

3.2 In-plane test of the retrofitted specimen

Masonry specimens to be retrofitted were coated 28 days after its construction with Paint-S. Paint-D was used 14 days after the first coating. The retrofitted specimens (hereinafter referred to as two-layered specimen) were tested 14 days after the second coating (Fig. 5). For the retrofitted specimens the two-layered coating was applied only on the front surface shown in Fig. 5. The first layer is coated with Paint-S in thickness of 0.5 mm and the second layer is also coated with Paint-D in thickness of 0.5 mm. Other surfaces were coated only with Paint-D with thickness of 1 mm. The loading rate was 0.25 mm/min. In this experiment polyester resin with glass fiber whose ratio is 2.0 % was used as Paint-S, and acrylic silicon resin with glass fiber whose ratio is 1.0 % was used as Paint-D. Fig. 6 (right) shows the results giving the diagonal compression force and vertical deformation of the two-layered specimen. The maximum strength was 2.755 kN and the failure deformation was 4.991 mm. The specimen had much larger maximum strength and failure deformation than the URM had. After the failure, it had residual strength until its deformation reaches 13.28 mm. The stiffness of the specimen was 0.5887 kN/mm.

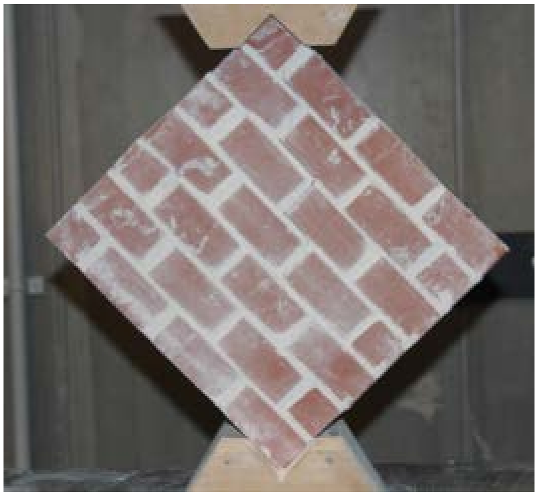

Fig. 4 – In-plane test of URM

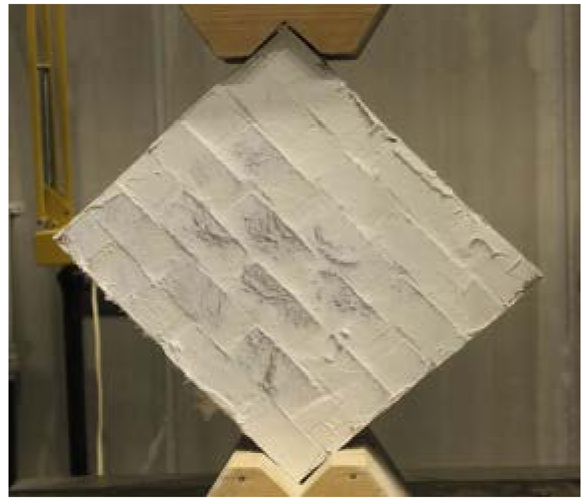

Fig. 5 – In-plane test of two-layered specimen

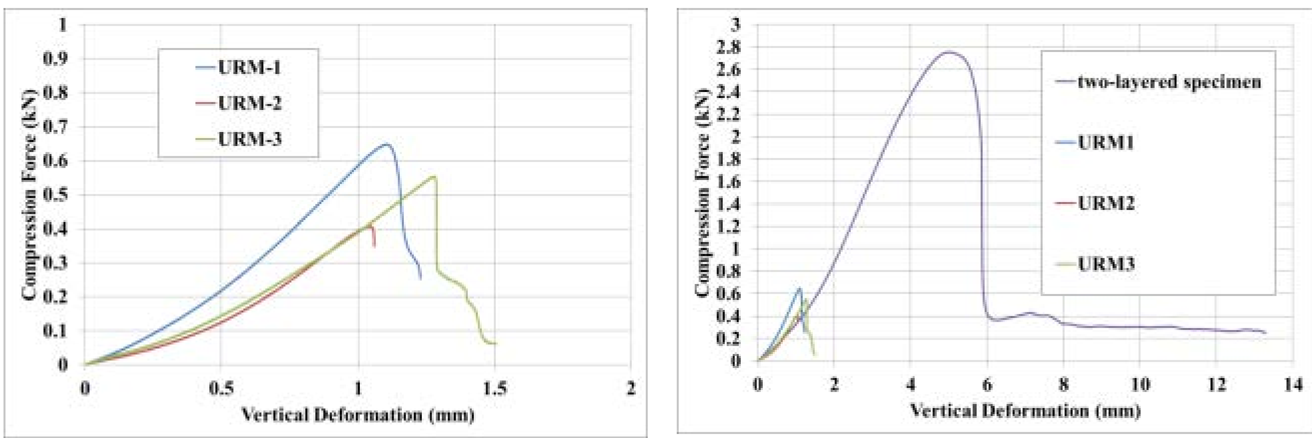

Fig. 6– In-plane test : URM (left) / Comparison between retrofitted specimen and URMs (right)

3.3 Discussions about the results of in-plane test

Usually there are two phases of deformation in in-plane tests of burnt brick masonry specimens. The first phase is before the failure of mortar joints (Fig. 7, left). The second phase is after the failure of mortar joints (Fig. 7, right). Before the crack appears, a masonry specimen gets shear deformation. After the failure of mortar joints, each part slides along with the failure in the joints. Therefore, the stress the coatings are subjected to and the strain of them varies before and after the failure of the mortar. In the testing of URM, once a large crack appears on the surface that can be seen the crack propagates rapidly, and once the specimen goes to the second phase, the reaction force falls down. On the other hand, in the testing of retrofitted one, the coating not only produces the confined effects but also prevents the propagation of large cracks. The elastic modulus of the mortar is much smaller than that of bricks, so the strain is mainly distributed to mortar joints. Considering the failure pattern of the retrofitted specimen (Fig. 8), the deformation of the specimen is supposed to be in the second' phase (Fig. 9). From the material properties of Paint-S and Paint-D the result can be explained. In the testing of the retrofitted specimen, the reaction force is produced by tensile stress of coating and the friction resistance or interlocking in mortar joints [7]. Therefore, this is expressed as:

$$\mathrm{F}_r = (f_t + \mu \mathrm{F}_r/\sqrt{2})/\sqrt{2} \qquad (1)$$

where F_r is the reaction force of the specimen and f_t is the tensile or shear force of the coating, and μ is the coefficient of friction and interlocking on mortar joints. The specimen is supposed to be a square shaped. From the results of various shear tests conducted in the past, coefficient of friction is around 0.6 ~ around 1.0. Therefore, μ would be higer than those values. From Fig. 9 if the specimen's deformation is in the second' phase, the shear strain of the coating on the front and back surfaces and the tensile strain of the coating on the side of the mortar joint and tensile strain of each mortar joint is $x_v/\sqrt{2}/5$ and $(\sqrt{(x_v/\sqrt{2})^2+5^2}-5)/5$ respectively where x_v is vertical deformation. Therefore, the tensile stress from the coating on the sides is $x_s = 1.78(\sqrt{(x_v/\sqrt{2})^2+5^2}-5)/5$ [MPa] using the tensile modulus of acrylic sylicon resin whose ratio of fiber is 1.0 %. At the same time, the shear stress from the coating on the front and back sides are expressed as $x_1 = \frac{31.0}{2(1+0.36)} x_v/\sqrt{2}/5$ [Mpa] for the Paint-S and $x_2 = \frac{1.78}{2(1+0.34)} x_v/\sqrt{2}/5$ [Mpa] for the Paint-D on the front and back surface using Poisson's ratios of polyester and acrilic resin. The width of each mortar joint is considered to be 5 mm. From these strains, f_t can be expressed as:

$$f_t = 280 \times (0.5 \times x_1 + 0.5 \times x_2) + 280 \times 1 \times x_2 + 2 \times 50 \times 1 \times x_s \quad (2)$$

where each term indicates the shear force from the coating on the front surface and the shear force from the coating on the back surface, and the tensile force from coating on the sides respectively.

From the equations (1) and (2), F_r is calculated according to μ. Table 3 shows the estimated reaction force where μ is 0.6 or 0.8 or 1.0. From the failure strain of the polyester resin whose ratio of fiber is 2.0 %, the maximum vertical deformation where the Paint-S has reaction force is calculated by the equation: $(\sqrt{(x_v/\sqrt{2})^2+5^2}-5)/5 = 0.241$. The maximum deformation is 5.197 mm. After that the shear stress from Paint-S is ignored. In the conditions of μ, F_r is calculated in various vertical deformations (1.0 mm / 5.0 mm / 13 mm). The calculated values taken from Table 3 are plotted on the graph of measured values taken from Fig. 6 (Fig. 10). From Fig. 10 the calculation is identical where μ is 1.0 although there is some gaps between the measured values and the calculated values where x_v is 5.0 mm.

Table 3 – The estimated reaction forces where the vertical deformation is 1.0 mm or 5.0 mm or 13mm

μ	0.6			0.8			1.0		
x_v [mm]	1.0	5.0	13	1.0	5.0	13	1.0	5.0	13
F_r [kN]	0.2696	1.379	0.1965	0.3145	1.609	0.2293	0.3774	1.931	0.2751

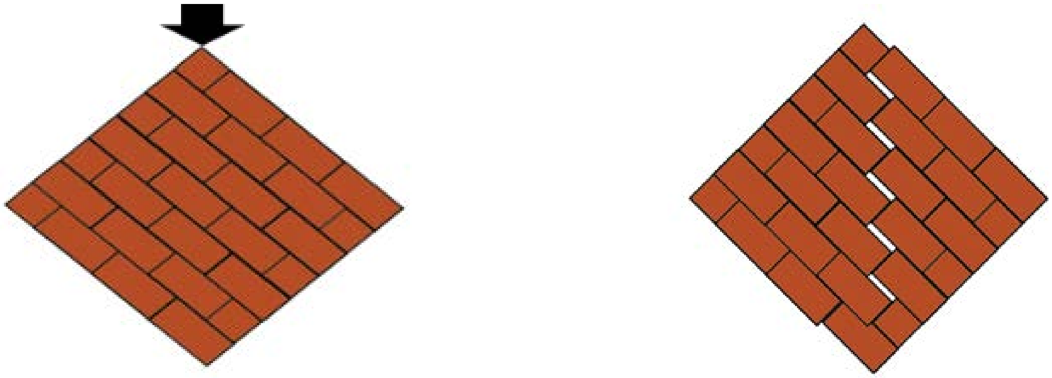

Fig. 7 – Two phases of strain distribution: the first phase (left) / the second phase (right)

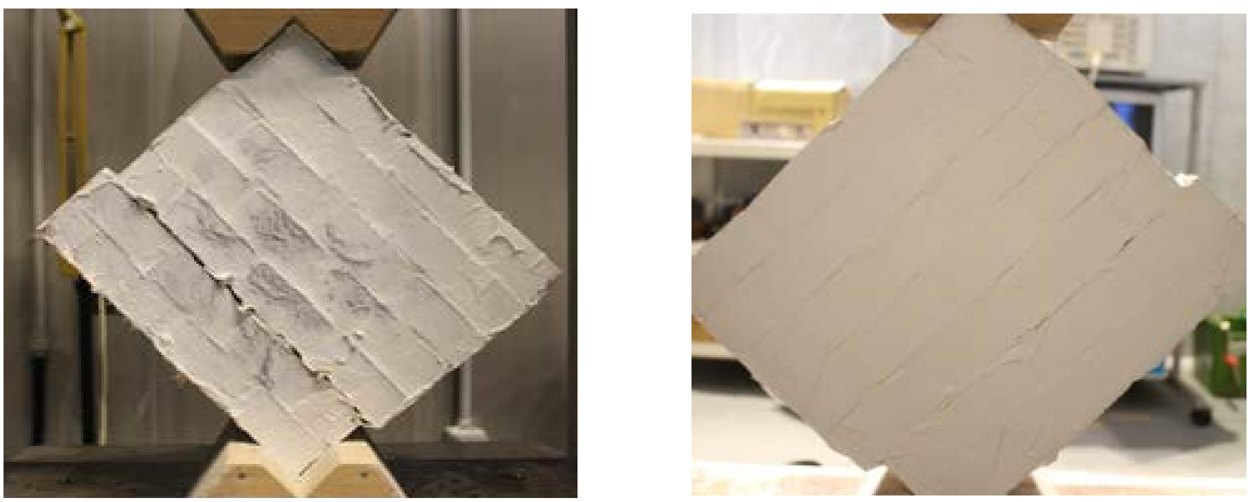

Fig. 8 – In-plane test of two-layered specimen (after the first layer's failure):
The front surface with two-layered coating (left) and the back surface with only Paint-D (right)

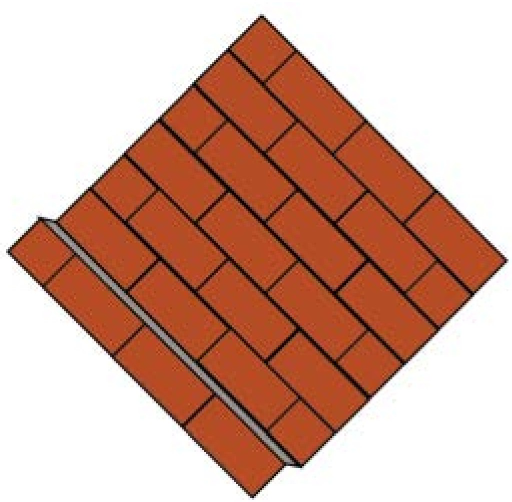

Fig. 9 – The second' phase of strain distribution

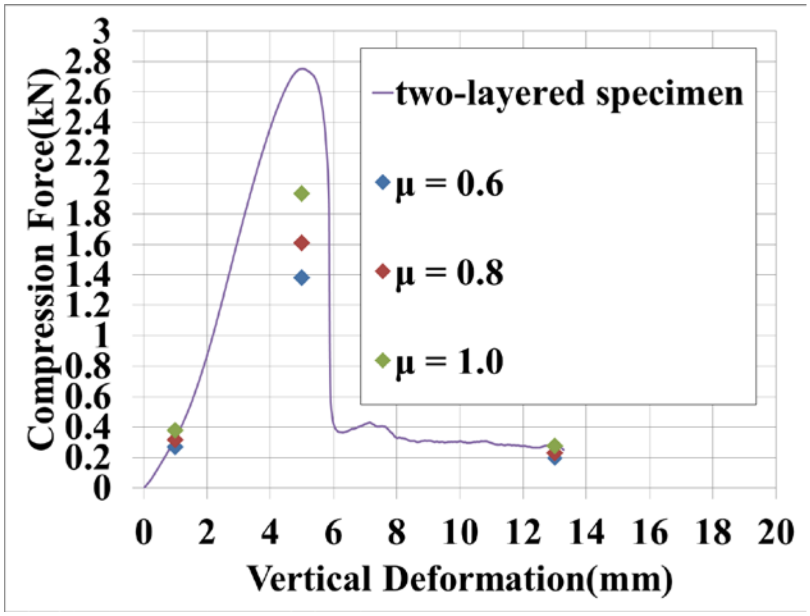

Fig. 10 – The comparison between measured values and calculated values of two-layered specimen

4. Conclusions

The two-layered coating suggested in this study where Paint-S is used as the first layer and Paint-D is used as the second layer worked for improving both the strength and deformation capacity of masonry wall. How the coatings contribute to the reaction force was calculated with some estimation of the strain distribution and contribution of friction and interlocking on mortar joints. Further study should investigate the strain of each material in detail using strain gages. Also, the shaking table test is to be conducted to disclose the dynamic response of this coating.

5. Acknowledgements

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6. Copyrights

7. References

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