Static shear friction tests on the model marble columns of the Parthenon for the aseismic retrofitting

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ABSTRACT

The static shear friction tests between the marble drums have been conducted to understand their behavior when the drums undertake the translational loads, and to investigate the effects of the shear keys designed for aseismic retrofitting of Parthenon columns. The test results have given the load-displacement characteristics at the interfaces between the drums. The tests have also demonstrated that the shear keys are effective against seismic loads, and that the interface behavior depends mainly on the materials of the shear keys.

INTRODUCTION

Parthenon, the main historical monument in Greece, was constructed on the Acropolis hill on 5th century B.C.. Since the seismicity has been high in Greek areas, Parthenon has been subjected to a number of destructive earthquakes during its history. The behavior of this monument under seismic actions for 25 centuries was completely satisfactory and it has survived against the earthquake ground motions. However, during the various phases of the monument's history, radical alterations have occurred concerning the general geometric configurations, the interconnections of structural members, and the state of the materials, of all which impose the necessity to study its earthquake resistant capacity.

At the 1st International Conference on Structural Studies, Repairs and Maintenance of Historical Buildings, the authors [1][2][3] presented the probabilistic approach to generate the reference motions for the protection of historical monuments
against earthquakes, and at the same time, presented the seismic response analysis of Parthenon Columns. In these studies, the reliable input motions for the response analysis of Parthenon columns were generated, analyzing statistically the earthquake records for a period of 100 years and taking into account the amplification due to the topography of the Acropolis hill. Furthermore, the dynamic response analysis using these input motions was concluded that Parthenon in the existing state was not safe against earthquake ground motions derived probabilistically for returns period of 100 and 1000 years and that the seismic loads might cause the translational displacement between drums when the shear keys which already lost their functions due to weathering. According to the analytical results, the substitution of the old wooden shear keys by new ones made of titanium alloy might be effective in strengthening Parthenon columns.

In the present research, the static shear friction tests of the interfaces between the marble drums have been conducted to understand the behavior of the drums that undertake the seismic translational loads, as well as, to demonstrate the effects of the shear keys designed for asseismic retrofitting of Parthenon columns.

TEST MATERIALS AND PROCEDURE

TEST MATERIALS
The cylindric marble drum, a one-sixth scale model of Parthenon column, had a diameter of 300mm and a height of 150mm (See Fig.1). The hole of the truncated cone was drilled at the center of the interface to install the shear key among the drums. In the present research, three types of shear keys were examined: (1) a shear key made of lead; (2) a shear key made of titanium alloy; (3) a shear key combined a titanium alloy pin with two lead cups (See Fig.1). Since the lead is soft and ductile, it was expected that the shear key could not damage the marble drum and that the shear key might behave as a high hysteretic damping material. On the other hand, the titanium alloy has a few advantages that it is strong and highly weatherproof, and that its rate of thermal expansion is nearly equal to the rate of the marble. The combination of titanium alloy and lead was developed by us to adopt advantages specific to both of the materials. Table 1 shows the representative properties of these materials.

For the interface sliding tests, the surface roughness is the important factor. Fig. 2-1 and Fig.2-2 describe the surface roughness of the model marble drum, measured in the direction of the rotational diameter and in the direction of the circumference, respectively. The surface roughness, Rmax, defined as the relative height between the highest peak and the lowest peak through along the profile over a specified gage length, was about 27\(\mu\)m on average.
TEST DEVICE AND TEST SERIES

Fig. 3 and Photo 1 show a device for the simple static shear tests. The list of test series is provided in Table 2, showing that not only the structures with the three types of shear keys but also the structure without shear key were examined. The monotonic loading tests, as well as, the cyclic loading tests were carried out under the normal load condition that the normal stress on the interface was equivalent to the estimated actual stress at the middle level of the columns’ height of Parthenon. To take into account the effect of the weight of a beam and a pediment on the column, the normal load took a value of 1060kgf corresponding to the column without any member on its capital, and took values of 2830kgf or 3530kgf corresponding to the column with a beam and a pediment on its capital.

As shown in Fig.3, the 20mm thick steel plate preventing the rotation of the specimen was attached on the upper drum to transmit the translational loads applied by the horizontal hydraulic actuators. The translational loads were measured by the load cells of strain gage type. On the other hand, the vertical loads applied by the hydraulic actuator was kept constant during a test by means of a servomechanism. The translational displacements and the rotational displacements were measured through the displacement transducers.

EXPERIMENTAL RESULTS

For a total of 10 tests, the friction capacity and the corresponding friction coefficient are summarized in Table 2. Although the friction coefficients defined as the translational stress divided by the normal stress give the values from 0.40 to 0.80, the effect of the shear keys on the friction capacity can not be clearly recognized. It is consequently understood that whether or not the shear keys are used, as well as, what type of shear keys are chosen have little influence on the translational load by which the sliding between drums begins to occur. After the load reached the friction capacity, however, the translational loads increased with the displacements when the shear keys were used, but the loads did not increase when the shear keys were not, shown in Fig.4 and Fig.5. These figures also demonstrate that the load-displacement characteristics depend on the material and the structure of the shear key. In the one-way monotonic loading test using the shear key made of lead, the load increased by slow degrees after the critical friction until the load reached the ultimate strength which was smaller than those of the tests using the other type of shear keys. On the other hand, the translational loads increased remarkably with the displacements in the test using the shear key made of titanium alloy and in the test using the shear key combined a titanium alloy pin with lead cups(See Fig.1-(3)).
particular, when the shear key of titanium alloy was used, the load increased rapidly at the displacement which was less than 1mm, and the marble drums were severely cracked. These cracks originated at the central hole, extending in the direction parallel to the drum's axis. When the shear key combined a titanium alloy pin with lead cups was used, however, the load-displacement relationship showed much more ductile characteristics that the load increased with the displacement up to more than 10mm, and yet in this case, the drums were not damaged. The above experimental results indicate that the strengthening method and the shape of a shear key should be considered when the stiffer materials than the marble drums such as titanium alloy are utilized to retrofit the columns. If the old shear keys are replaced by the new ones combined titanium alloy with lead to retrofit Parthenon columns, it is necessary to design the shape and structure of the new shear keys so that each material can function properly for its purpose.

Figs. 6 and 7 illustrate the translational load-displacement relation obtained from the cyclic loading tests on the drums without shear key, and on the drums with the shear key of lead, respectively. In these figures, the effect of the ductile shear key to the resistant capacity can be recognized as follows. When a shear key was not used, the load remained roughly constant with the increase of displacement after the load reached the critical friction resistance, and the friction coefficient ranged from 0.77 to 0.88 during the interface sliding (See Fig.6). On the other hand, when the shear key of lead was used, the load increased gradually with the displacement after the load reached the critical friction resistance, although the cyclic loading caused the slight degrading of load-displacement characteristics (See Fig.7). And in this stage, the load was approaching to the ultimate strength which was 1.5-2.5 times as high as the critical friction resistance. It is consequently believed from the hysteresis loops shown in Figs.6 and 7 that the shear keys, even if the soft and ductile shear keys such as lead ones are utilized, can undertake the translational load after the load reached the critical friction resistance, and that they contribute to the increase of the resistant capacity against seismic translational loads.
CONCLUSIONS

The experimental results indicate that shear keys are effective against seismic translational loads. Replacing the old shear keys by new ones, therefore, may be adopted for the asseismic retrofitting of Parthenon. When the shear key combined a titanium alloy pin with lead cups, proposed in this study, are utilized to retrofit Parthenon, its shape and structure should be discussed so that each material can function for the purpose of retrofitting.

ACKNOWLEDGMENTS

The tests were performed at the time when all the authors affiliated in the University of Tokyo Metropolitan.

REFERENCES

Fig. 1 Model marble drums and shear keys

Table 1 Material properties of specimen

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (g/cm³)</th>
<th>Young's Modulus (kgf/cm²)</th>
<th>Tension Strength (kgf/cm²)</th>
<th>Compressive Strength (kgf/cm²)</th>
<th>Shear Strength (kgf/cm²)</th>
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<tr>
<td>Marble</td>
<td>2.72</td>
<td>7.70x10⁶</td>
<td>550</td>
<td>1200</td>
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<td>Lead</td>
<td>11.36</td>
<td>1.40x10⁶</td>
<td>120-230</td>
<td>9500</td>
<td>69-133</td>
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<td>Titanium</td>
<td>4.42</td>
<td>11.55x10⁶</td>
<td>9500</td>
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</tbody>
</table>

* titanium alloy: Ti-6Al-4V

Fig. 2 Surface roughness of marble drum
Fig. 3 Device for static shear test

Photo. 1 A view of static shear test
### Table 2 Test series and summary of critical friction resistance

<table>
<thead>
<tr>
<th>TEST</th>
<th>SHEAR KEY (SEE FIG.1)</th>
<th>NORMAL LOAD (kgf)</th>
<th>LOADING METHOD</th>
<th>CRITICAL FRICITION RESIST. (kgf)</th>
<th>FRICTION COEFFICIENT</th>
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</thead>
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<tr>
<td>1-E1</td>
<td>no key</td>
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<td></td>
<td>805</td>
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<tr>
<td>2-E2</td>
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<td>2830</td>
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<td>1695</td>
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<tr>
<td>3-L1</td>
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<td>1060</td>
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<td>608</td>
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<td>824</td>
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<td>10-LL</td>
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**Fig. 4**
Load-displacement relationship of monotonic loading test with lead shear key, titanium shear key, and without shear key

**Fig. 5**
Load-displacement relationship of monotonic loading test with combination type shear key of lead and titanium

**Fig. 6**
Behavior of interface without shear key under cyclic loading

**Fig. 7**
Behavior of interface with lead shear key under cyclic loading