SHAKE TABLE TESTS ON RETROFITTED BRICK PARTITIONS

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ABSTRACT

This paper deals with the seismic characterization of hollow brick internal partitions, which are widespread in many European countries and have high vulnerability to seismic actions, as observed after L’Aquila earthquake in 2009 and Centre Italy earthquake in 2016. In order to reduce their vulnerability, a retrofit intervention is proposed: it consists in cutting around the perimeter of the partitions and filling the gap by a self-expanding polyurethane foam. The seismic performance of these retrofitted hollow brick partitions is investigated through full-scale experimental tests, carried out at the laboratory of the Department of Structures for Engineering and Architecture at the University of Naples Federico II. Ten bidirectional seismic tests with different intensity are performed. The inputs are selected matching the target response spectrum provided by the U.S. code for nonstructural components. The exhibited damage is shown and compared to that of the non-retrofitted partition. The damage detection proves the very good performance of the retrofitted partition. The aim of this work is to show the efficacy of the retrofit intervention, and to characterize the nonstructural components’ behaviour through the definition of parameters as the natural frequency and the damping ratio.

Keywords: Nonstructural components; Hollow brick partitions; Retrofit intervention; Shake table test; Seismic characterization.

1. INTRODUCTION

Nonstructural components (NSCs) are those systems and components attached to the floors, roof and walls of a building that are not part of the main load-bearing structural system, but may also be subjected to large seismic forces. (Villaverde 1997)

By the time of the San Fernando earthquake, it became clear that damage to nonstructural components could result in serious casualties, severe building functional impairment, and major economic losses, even where structural damage was not significant (Lagorio 1990). According to Miranda et al. (2010), nonstructural damage often results in significant economic losses and can lead to disrupt the normal functioning of many buildings and services. In hospitals, for example, the structure must remain fully operational for at least 72 hours to provide emergency response when an earthquake occurs, so the failure of nonstructural components should be prevented (Di Sarno et al. 2015). Moreover, damage costs of NSCs may account to 65%-85% of the total construction cost (Taghavi and Miranda 2003), which means that NSCs give the largest contribution to the total cost of a building. Besides the unacceptable economic losses, the damage of nonstructural components can also seriously threaten the life safety for the occupants (Singh et al. 2006). For these reasons, it is essential to include the response of nonstructural components when assessing the seismic risk of buildings.

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Few studies were conducted on the evaluation of the performance of nonstructural components, such as those referred to plasterboard partitions (Magliulo et al. 2014, Filiatrault et al. 2010), and suspended ceiling systems (Magliulo et al. 2012, Gilani et al. 2010). Limited studies were conducted in the past on the seismic behaviour of hollow brick internal partitions. Nevertheless, many reinforced concrete buildings in European countries are characterized by partitions made up of hollow brick masonry (Braga et al. 2009, Magliulo et al. 2008). The high vulnerability of these elements may result in significant damages, as observed after L’Aquila earthquake in 2009 and after Centre Italy earthquake in 2016. Petrone et al. (2014) investigated the seismic behaviour of these partitions via shake table tests, showing the high level of damage reached.

In this paper, the authors propose a simple retrofit system to apply to hollow brick partitions in order to prevent serious damage, reduce economic losses, and safeguard life for the occupants. The seismic performance evaluation is pursued via shake table tests with increasing intensity. The aim of these tests is to characterize the nonstructural components’ behaviour, through the definition of parameters as the natural frequency and the damping ratio.

2. TEST SETUP, SPECIMEN AND INPUT

Shake table tests are performed in order to investigate the seismic behaviour of the retrofitted hollow brick partitions. The experimental program is carried out at the laboratory of the Department of Structures for Engineering and Architecture at the University of Naples Federico II. The test setup consists in a shaking table, a steel frame already used in different test campaigns (Magliulo et al. 2014, Petrone et al. 2014), and the partitions, as shown in Figure 1.

![Figure 1. Global view of the test setup.](image)

The test frame is a steel frame able to excite the specimen and transfer the seismic input to the partitions. It has been designed in order to simulate the seismic behaviour of a generic storey of a structure located in a high seismicity area. The design was performed by Magliulo et al. (2014), according to the Eurocode 3 and 8.

2.1 Description of the specimen

The specimen is built in order to replicate the one used in Petrone et al. (2014). It consists in a 150 cm
wide partition and two smaller 80 cm wide partitions in the orthogonal direction, all three 2.6 m high. The three partitions are surrounded by steel frames and placed on a “I” shape RC slab. The steel frames and the slab connect the specimen with the test frame and with the shake table. The partitions are made of hollow bricks jointed with mortar. For further information about the original Non-Retrofitted specimen (NR), see Petrone et al. (2014).

The Foam-Retrofitted (FR) system is then applied. The retrofit intervention is realised by cutting around the perimeter of the partitions, which were clamped in “C” profiles (the yellow frames in Figure 1 and Figure 2). Because of the cut, a gap between the partition and the column is realized (Figure 2a). This gap is filled by a self-expanding polyurethane foam (Figure 2b).

The intervention is very inexpensive and requires common materials. Indeed, the polyurethane foam is a generic foam typically used to isolate voids of many details in buildings and implants.

![Figure 2. Specimen: (a) particular of the cut; (b) insertion of foam](image)

### 2.2 Instrumentation

Accelerometers and laser sensors are used to monitor the response of the setup. Seven accelerometers are placed in different parts of the steel frames and three accelerometers are applied on the main partition (in the middle, at 3 quarter of the partition’s height and at 3 quarter of the partition’s wide). One accelerometer is placed inside the shake table, in order to measure the input accelerations in both the directions. Eight laser-optical sensor are installed to monitor the displacements of the system.

### 2.3 Input

Different time histories acting simultaneously along two horizontal directions are selected as input for the shake table. The directions correspond to the out-of-plane (X) and in-plane (Y) direction for the larger partition. The time histories are artificially defined in order to match the Required Response Spectrum (RRS) provided by the AC156 “Acceptance for seismic qualification testing of nonstructural components”.

According to the International Building code, the RRS is a function of the spectral acceleration at short periods, $S_{DS}$, defined as:
where $F_A$ is a site soil coefficient and $S_S$ is the mapped Maximum Considered Earthquake (MCE) spectral acceleration at short periods. Two different earthquake histories are generated, for X and Y direction respectively, starting from nonstationary broadband random excitation with energy content from 1.3 to 33.3 Hz and one-sixth-octave bandwidth resolution. The obtained baseline has a total length equal to 30 s. The signal is then enhanced using the spectrum-matching procedure in order to not have spectrum ordinates lower than 0.9 times RRS and larger than 1.3 times RRS (according to EC8 and AC156 rules respectively). The damping ratio for the evaluation of the response spectra is set equal to 5%. Further details are given in Magliulo et al. (2012) and Petrone et al. (2014).

The input levels selected for the test campaign range from $S_{DS} = 0.10g$ to $S_{DS} = 1.00g$. Note that the range is denser than that used for NR tests. The campaign was stopped when 1% interstory drift ratio (IDR) was recorded for both directions. Overall, the campaign consists of ten bidirectional tests with different intensity values. Table 1 shows the value of $S_{DS}$ for each test and the corresponding peak ground acceleration in X and Y direction.

<table>
<thead>
<tr>
<th>Test ID</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{DS}$ (g)</td>
<td>0.10</td>
<td>0.20</td>
<td>0.30</td>
<td>0.40</td>
<td>0.50</td>
<td>0.60</td>
<td>0.70</td>
<td>0.80</td>
<td>0.90</td>
<td>1.00</td>
</tr>
<tr>
<td>$PGA_x$ (g)</td>
<td>0.09</td>
<td>0.18</td>
<td>0.27</td>
<td>0.35</td>
<td>0.43</td>
<td>0.52</td>
<td>0.61</td>
<td>0.70</td>
<td>0.78</td>
<td>0.87</td>
</tr>
<tr>
<td>$PGA_y$ (g)</td>
<td>0.08</td>
<td>0.16</td>
<td>0.24</td>
<td>0.32</td>
<td>0.41</td>
<td>0.49</td>
<td>0.57</td>
<td>0.65</td>
<td>0.73</td>
<td>0.81</td>
</tr>
</tbody>
</table>

In Figure 3, the maximum IDR in X and Y direction is plotted versus the PGA. Each blue marker corresponds to one of the ten FR tests. The higher value of IDR is recorded in X direction, for a peak ground acceleration equal to 0.87g. The 1% IDR is recorded in X direction during test No 9 and in Y direction during test No 10. It is also shown the comparison with the IDRs recorded during NR campaign (magenta markers in Figure 3). It should be noted that a higher PGA was required during NR tests to achieve IDR=1%.

Figure 3. Maximum recorded IDRs for FR and NR tests (a) in X direction and (b) in Y direction.

3. DAMAGE DESCRIPTION

In this section, the damage observed during the tests is described. It is important to specify that, due to the size, the larger (main) partition is the most representative of a real partition.

In-plane damage usually occurs as result of interstorey drifts of the structure. Typical damage consists in corner crushing, sliding shear, diagonal compression and diagonal cracking.

For the smaller partitions:
- no damage is observed until test 7;
- horizontal and vertical cracks are observed in the lower part of the small partitions after test 7;
- wider and wider cracks are observed after the following tests (Figure 4a).

For the main partition:
- no damage is observed until IDR=0.52%;
- a thin horizontal crack is observed in the bottom-right corner after IDR=0.52%;
- the crack involves all the corner after IDR=0.59%;
- the corner cracks get wider and wider after IDR=0.80% (Figure 4b).

![Figure 4. Damage at the end of the campaign: (a) wide cracks in mortar joints between the bricks for the smaller partitions; (b) corner crushing for the main partition.](a) (b)

The out-of-plane mechanism of failure does not occur. This is due to the self-expansion of the foam, which fills horizontal hollows of the bricks and prevents the overturning of the partition.

At the end of the campaign, the main partition is almost intact unless the small crashing in the corner, as shown in Figure 4b. This result is interesting if compared to the damage observed for the NR partition (Petrone et al. 2014). Partitions are drift-sensitive nonstructural components in their in-plane direction, so NR and FR damages should be compared for the same interstorey drift. Therefore, it makes sense to compare the two final damage states, which were both achieved for IDR=1% in the in-plane direction for the main partition (Y direction). Wide horizontal and vertical cracks are observed for NR partition, while only the crushing of a small piece of the corner occurs for FR partition. Thus the retrofitted partition has a very high performance.
4. RESULTS

The laser sensors and the accelerometers allow to monitor the displacements and the accelerations of specific points of the setup. Maximum relative displacements and maximum accelerations at the top of the setup are listed in Table 2 for each test of FR specimen. Results from test 10 are not included, since the accelerometers went out of range during the execution.

Table 2. Results: (a) maximum recorded relative displacements and (b) maximum recorded top accelerations

<table>
<thead>
<tr>
<th>Relative displacement (mm)</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Test 4</th>
<th>Test 5</th>
<th>Test 6</th>
<th>Test 7</th>
<th>Test 8</th>
<th>Test 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>X direction</td>
<td>3.10</td>
<td>4.49</td>
<td>8.36</td>
<td>10.19</td>
<td>16.26</td>
<td>17.99</td>
<td>21.56</td>
<td>23.67</td>
<td>27.71</td>
</tr>
<tr>
<td>Y direction</td>
<td>2.69</td>
<td>3.60</td>
<td>5.22</td>
<td>7.14</td>
<td>10.42</td>
<td>11.55</td>
<td>14.72</td>
<td>16.95</td>
<td>20.87</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Top Acceleration (g)</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Test 4</th>
<th>Test 5</th>
<th>Test 6</th>
<th>Test 7</th>
<th>Test 8</th>
<th>Test 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>X direction</td>
<td>0.24</td>
<td>0.56</td>
<td>0.78</td>
<td>0.92</td>
<td>1.17</td>
<td>1.36</td>
<td>1.47</td>
<td>1.61</td>
<td>1.89</td>
</tr>
<tr>
<td>Y direction</td>
<td>0.22</td>
<td>0.46</td>
<td>0.67</td>
<td>0.84</td>
<td>1.00</td>
<td>1.27</td>
<td>1.54</td>
<td>1.73</td>
<td>1.97</td>
</tr>
</tbody>
</table>

4.1 Dynamic identification

Besides the seismic input described in section 2.3, further random excitations are selected as input motions before the execution of the first test and after each test starting from the sixth one. Overall, five random tests are performed in X and Y directions: before the test 1 (Random 1), after test 6 (Random 2), after test 7 (Random 3), after test 8 (Random 4) and after test 9 (Random 5). The results from these test are used for the dynamic identification.

The transfer curve method is applied between the base and the top acceleration time histories for X and Y direction (Figure 6). This method allows to evaluate the natural frequency of the setup and the
variation of the frequency during the seismic tests. It is expected to observe a reduction of the natural frequency, since the setup gets more deformable when it suffers a damage. The frequencies, denoted by the peak in the transfer curves of Figure 6, are reported in Table 3.

![Figure 6](image)

**Figure 6.** Transfer curves between base and top acceleration time histories for five random vibration test (a) in X direction and (b) in Y direction.

**Table 3.** Frequencies for the random vibration tests

<table>
<thead>
<tr>
<th>Frequency [Hz]</th>
<th>Random 1</th>
<th>Random 2</th>
<th>Random 3</th>
<th>Random 4</th>
<th>Random 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>X direction</td>
<td>6.25</td>
<td>4.88</td>
<td>4.88</td>
<td>4.88</td>
<td>4.69</td>
</tr>
<tr>
<td>Y direction</td>
<td>5.86</td>
<td>5.27</td>
<td>5.27</td>
<td>5.27</td>
<td>5.27</td>
</tr>
</tbody>
</table>

The natural frequency is 6.25 Hz in X direction and 5.86 Hz in Y direction, so the system is stiffer in the direction of the two smaller partitions (X direction). A reduction of the frequency is observed from random no. 1 to random no. 2. After random no. 2 the frequency remains the same, except for a little reduction from random no. 4 to random no. 5 in X direction. The reduction is due to the progressive deformation of the steel frame, to the damaging of the partitions and to the detaching of the foam.

### 4.2 Hysteretic curves

The top acceleration, representative of the total inertial force, is plotted versus the relative displacement for intensity levels corresponding to tests 3, 6 and 9, in X and Y direction (Figure 7).

![Figure 7](image)

**Figure 7.** Top acceleration versus relative displacement for tests 3, 6 and 9 (a) in X direction and (b) in Y direction
The stiffness, represented by the slope of the curve, tends to decrease test by test. Moreover, the hysteretic curves show a hardening trend for increasing deformation. Such a trend is probably due to the increasing compressive strain given by the vertical columns in contact with the partitions, as suggested by Preti et al. (2015). This effect is more evident in Y direction, which is the in-plane direction for the main partition.

4.3 Damping ratio

The damping ratio of the setup is evaluated according to the Energetic Method (EM). Assuming dissipation exclusively viscous, the damping ratio $\xi$ is given as:

$$\xi = \frac{W_D}{4\pi E}$$

(2)

where $W_D$ is the area enclosed within each hysteresis cycle (Figure 7), calculated for each hysteresis cycle of a single test, and $E$ is the elastic energy. This procedure provides as many values as the number of hysteresis cycles in each test, therefore the median value is considered. Damping ratios are shown in Table 4.

Table 4. Damping ratios for the seismic tests in X and Y direction

<table>
<thead>
<tr>
<th>Damping ratio [%]</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Test 4</th>
<th>Test 5</th>
<th>Test 6</th>
<th>Test 7</th>
<th>Test 8</th>
<th>Test 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>X direction</td>
<td>4.60</td>
<td>7.30</td>
<td>7.20</td>
<td>8.70</td>
<td>9.30</td>
<td>9.40</td>
<td>9.50</td>
<td>9.40</td>
<td>9.40</td>
</tr>
<tr>
<td>Y direction</td>
<td>5.40</td>
<td>5.00</td>
<td>8.60</td>
<td>11.7</td>
<td>12.2</td>
<td>12.2</td>
<td>12.0</td>
<td>12.5</td>
<td>12.5</td>
</tr>
</tbody>
</table>

For both directions, an increase in the damping ratio is exhibited test by test. It varies from 4.6% to 9.4% in X direction and from 5.4% to 12.5% in Y direction. The variation is essentially due to the progressive damaging of the setup.

5. CONCLUSIONS

Shake table tests are a powerful tool to characterize the seismic behaviour of nonstructural components. In this study, the results of shake table tests on retrofitted hollow brick partitions are discussed. The retrofit intervention is realised by cutting around the perimeter of the partitions and filling the gap by a self-expanding polyurethane foam.

The partitions are subjected to interstorey drifts up to 1%, for a PGA of around 0.9g. The natural frequency of the setup, evaluated through the transfer curve method, is equal to 6.2 Hz in X direction and 5.8 Hz in Y direction, whereas the Y direction corresponds to the in-plane direction for the main partition. At the end of the campaign the frequency decreases up to the 25% because of the damaging of the setup.

The energetic method is used to evaluate the evolution of damping ratio during the tests. Because of the progressive damaging of the setup, the damping ratio increases up to the 100% in X direction and to the 130% in Y direction.

The benefits given by the retrofit intervention are proved by the damage detection. Indeed, the main partition does not exhibit major damage, but suffers of crushing only in a little portion of one corner. The good behaviour may be mainly due to the following reasons:

- the gap reduces the interaction between frame and partitions;
- the foam expands and fills the horizontal hollows of the bricks, realising a comb effect that prevent the overturning of the partition.

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6. REFERENCES


