DISSIPATING DEVICE FOR SEISMIC PROTECTION OF MASONRY STRUCTURES

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ABSTRACT

In the last decades, a variety of systems able to dissipate seismic input energy has been designed, enhancing the global response of structures in earthquake prone areas. Historical buildings represent a singular case: the common practice in retrofitting these structures consists in inserting traditional steel cross-ties at the corner of two perpendicular walls in order to restore the box-like behavior and distribute the seismic forces through all the resisting elements. This practice is not exempt from drawbacks, as the increased local stiffness at the corners might lead to high-stress concentration in case of seismic events and consequently to severe damage to the valuable parent material in which the cross-ties are embedded.

In this study, an innovative friction dissipative device connected in series with stainless steel anchors is presented. Progressing an existing patented prototype, results on the response of a friction device for different values of slide-resisting loads are shown. Numerical simulations and laboratory tests have been performed to evaluate the principal features of the device in order to improve and refine its design. In particular, the dissipative device was subjected to symmetrical dynamic cyclic loading for four load cases to assess its dissipative capacity and the stability of the dissipative loops under harmonic input. The obtained parameters were then implemented into a numerical model, which was able to reproduce the experimental results and highlight the need for altering the current design.

The study results in a refined design of the patented prototype able to address installation requirements to reduce size while increasing structural energy dissipation and reliability.

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1. INTRODUCTION

Designing innovative systems able to enhance the resistance capacity of a structure to seismic events is a fundamental aspect of seismic engineering. Laboratory testing, analytical and numerical analysis are often aimed to develop design strategies or validate new strengthening techniques.

To improve the response of an existing structure, two solutions are possible without involving an increase of elastic energy: a reduction of seismic demand by means of seismic isolation or an increase of the dissipative capacity of the structure through the enhancement of its ductility or the use of additional dissipative devices. While many solutions are available for new or recently built structures, only few options have the potential of being implemented in historic masonry buildings. Such choices are limited by the conservation principles, enshrined in international and national guidelines such as the Italian DPCM 2011(D.P.C.M, 2011), which states that the benefits of possible upgrade interventions in terms of seismic performance must be weighed against the impact on the original aesthetic and structural authenticity of the building. Even though human safety must be given priority, the document acquiesces to a lower safety margin with the aim of limiting the strengthening, in line with the principles of minimal intervention (ISCARSAH - ICOMOS charter).
On the other hand, the need for effective strengthening systems is compelling as damage observed after strong earthquakes have shown that historical masonry structures are particularly vulnerable to seismic events. A damage survey carried out by D’Ayala and Paganoni (2011) following the L’Aquila, Italy 2009 earthquake, showed that commonly used strengthening strategies, such as use of concrete ring beams, due to their excessive mass and stiffness, frequently determine tragic collapses especially in the case of churches and monumental buildings (D’Ayala, 2014). Moreover, results of tests carried out on unreinforced masonry samples by means of shaking table have highlighted that the façades are the most vulnerable part of existing masonry building, (Shawa et al. 2012). In case of seismic events, these elements are prone to separate from the retaining orthogonal elements and exhibit an outward rotation that may result in the failure of the whole building. To prevent this type of failure a number of technical solutions for the improvement of structural connections have been developed. These strengthening techniques for masonry structures comprise reinforced masonry ring-beam (Borri et al. 2009), shape memory alloy devices (Bonci et al., 2000) and stainless steel ties (Candela et al. 2016). Nevertheless, testing of strengthened connections is rarely performed, and design codes are vague when it comes to define the assessment and design procedures to be followed when implementing innovative strengthening system in historic structures (FEMA 356, 2000) (EN 1998-1). Moreover, the few examples of experimental procedures devised for this purpose either are not standardised or codified (Indirli and Castellano, 2008) and therefore hardly repeatable, or only applied to reduced scale elements or portion of structures (Paganoni and D’Ayala, 2014).

Korany & Drysdale (2006) introduced a method to increase the dissipative capacity of a masonry structure through the enhancement of its ductility, using carbon fiber composite cable (CFCC) running vertically and horizontally through the walls. It is suggested that the technique is applicable to enhance out-of-plane resistance of façade walls and may be used to strengthen in-plane capacity of structural walls. On the other hand, this strengthening system does not enhance the performance of the structure at its corner connections and may not be a feasible option for historical building featuring façades more than 10 meters high.

As a further hinderance to heritage retrofit, the use of added damping devices and isolators is addressed by standards only in the case of applications to new constructions or retrofit of modern structural systems. Notwithstanding the high density of heritage structures in Europe exposed to seismic hazard, international agreed guidelines for their retrofit are still lacking.

Drawing from these observations the overall aim of the present study is to refine a patented prototype of a friction based dissipative device integrated in a typical stainless steel anchor and specifically designed for being inserted in masonry structures (Paganoni, 2015; Paganoni and D’Ayala, 2010).

2. THE DISSIPATIVE DEVICE

The proposed friction based device, shown in Figure 1a, offer an innovative alternative for the repair and strengthening of heritage structures using performance-based design, i.e. control of displacements and reduction of accelerations and concentration of stress. It is designed to be inserted at the connection between perpendicular walls (Figure 1b), as part of longitudinal stainless steel anchors grouted within the thickness of the walls: the stainless steel profiles improve the box-like behaviour of the building, while the devices allow small relative displacements between orthogonal sets of walls and the dissipation of the seismic energy input to the structure. Thus, problems such as punching failure and excessive crack opening are avoided. Extensive testing has been carried out to characterise the device and most importantly to determine how it could be added to ordinary masonry anchors minimising adverse effects on parent material at local and structural level. Contextually a performance based design procedure has been developed (D’Ayala & Paganoni, 2014). This chain of events led to the realization of a prototype, which is today under revision to meet specific installation requirements set by the producer, CINTEC International, which distributes the device worldwide.
2.1 Device assessment – Laboratory activity

The laboratory testing of the dissipative device consists of two activities. The first aims to evaluate the empirical correlation between the magnitude of torque applied to the bolts and the transferred pretension (set of tests n. 1). The second set of test aims to evaluate the stability of the device friction properties and dissipating capacity to varying amplitude and increasing number of sinusoidal cycles for different slide control forces (set of tests n. 2). The testing methodology is summarized in Figure 2.

The EN 1090-2 (UNI EN 1090-2,2011) standard provides the empirical correlation between the tightening torque (M) and the preload in the bolt (Fpc):

\[ M = k_m \cdot d \cdot F_{pc} \]  

(1)

Where \(d\) is the nominal diameter of the bolt and \(k_m\) is assumed equal to 0.2 for non-lubricated bolt conditions. Equation 1 provides only an indirect approximation of the transferred preload as it is estimated that only about 10% of the tightening torque actually results in useful bolt tensioning. The remaining 90% is lost due to various forms of friction that occur during the tightening process (Croccolo and De Agostini 2011). In addition, the preload in the bolt can be inconsistent from fastener-to-fastener and depends on the type of nuts used. For these
reasons, Equation 1 is not accurate for all situations and testing of actual fastener components is recommended to determine the relationship between the torque values and the bolt preload for all critical-use applications. Since the variable $k_m$ summarizes the factors that affect the relationship between the applied bolt torque and the resulting bolt tension, appropriate values of this variable were experimentally investigated. The bolt preload recorded by the load cells, was examined when two different types of nut were used (locking and normal nut). Initially, a simple geometry where the bolt goes through a single plate (SP) was considered. Figure 3 shows that the average values of the bolt pretension are higher when normal nuts are used. This is because the lock nuts exhibit higher friction properties so that a smaller proportion of the tightening torque is transmitted to the bolt stem as pretension.

![Figure 3. Bolt pretension when lock nuts(a) and normal nuts (b) are employed on single plate (SP).](image)

The same set of tests was repeated on the full assembly of the dissipative device to investigate the influence of its complex geometry on the recorded bolt pretension. Figure 3 shows that the pretension induced in the bolts is greater when the normal nuts are employed while Figure 4 shows that the geometry of the device also

![Figure 4. (a) Comparison between lock nuts and normal nuts on device. (b) Comparison of level of pretension in normal and lock nut on single plate and on device with the codified relationship](image)
contributes to lower the average values of the bolt pretension and that the relationship is less stable than when a single plate is used.

Using a linear regression over the measurement on lock nuts when used with the device an experimental equation relating the applied torque to the bolt pretension can be derived as:

\[ M = 2.77 F_{pc} \]  \hspace{1cm} (2)

Comparing Equation 2 to Equation 1 and considering that the nominal diameter of the bolts is 8 mm,

\[ M = k_m d F_{pc} = k_m \cdot 8 \cdot F_{pc} = 2.77 F_{pc} \]  \hspace{1cm} (3)

Allows to compute the specific value of \( k_m \) applicable to the device:

\[ k_m = 0.36 \]  \hspace{1cm} (4)

In the second set of tests, the locking/slip-control forces are applied to the prototype by tightening four bolts gripping the assembly, to increasing reference values of torque. Test identifiers A, B, C, and D refer to 5, 10, 17, 20 Nm of applied torque load per bolt, respectively. Two pressure cells were installed below the head of two bolts to record the variation of the pretension transmitted throughout the test. The testing apparatus also comprises two LVDTs to measure the relative displacement of the slider respect to the fixed part and two strain gauges to measure the local strain where the greater deformations are expected, namely near the bolts and the pins (Figure 5).

\[ \text{Figure 5. Testing apparatus (a) and testing methodology (b)} \]

Figure 6 shows good performance of the device, with regular loops of rectangular shape as expected for a friction-based sliding device. A change in slip load, supposedly due to the progressive wear of the frictional surfaces, is observed throughout the fatigue testing sessions. Accordingly, a parameter \( \Phi \), calculated as the average over each cycle of the ratio between the recorded values of slip load \( (F_{//}) \) and slide-control force \( (F_{\perp}) \), is computed and the progression of \( \Phi \) throughout 20 cycles of load is recorded. The values of \( F_{\perp} \) are computed averaging the bolt pretension loads recorded by the pressure cells and multiplying this value by the number of bolts. They are therefore real-time values that may differ from the initial value imposed by providing a nominal torque to the pressure bolts before the start of tests.
Figure 6. Experimental results of testing campaign. Test Id A, B, C, D correspond to 5 Nm, 10 Nm, 17 Nm, 20 Nm applied bolt torque respectively.
Nevertheless, irrespective of the values of applied torque on bolts there is in most cases a pronounced increase of $\Phi$ after the initial cycle and some variation over 20 cycles. The observed variation in $\Phi$ can be ascribed to a number of factors: firstly, the repeated rubbing of the plates, which provokes wearing of the surfaces and enhances the material roughness, thus increasing friction. Secondly, the number of cycles also affects the perpendicular pressure, which increases from the initial nominal value imposed. This could be due to the effect of repeated cycles on the locking of tension bolts and to the presence of debris between the friction plates: metal dust created by the wearing of the surfaces in contact might remain within the assembly, thus creating additional pressure.

Table 1 summaries the values of slide control forces computed using the empirical equation (1) derived from the EN 1090-2 standard with $k_m$ equal to 0.36 and those experimentally recorded in each bolt. It is worth noticing that the values of $\Phi$ drawn from the experimental data exhibit less variation throughout the tests than those computed theoretically.

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Applied torque [Nm]</th>
<th>Slide control force (per bolt) [KN]</th>
<th>Slide control force (total) [KN]</th>
<th>Sliding force [KN]</th>
<th>$\Phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>5</td>
<td>1.79</td>
<td>1.25</td>
<td>7.14</td>
<td>5.00 ± 8</td>
</tr>
<tr>
<td>B</td>
<td>10</td>
<td>3.57</td>
<td>2.10</td>
<td>14.29</td>
<td>8.40 ± 14</td>
</tr>
<tr>
<td>C</td>
<td>17</td>
<td>6.07</td>
<td>3.00</td>
<td>24.29</td>
<td>12.00 ± 20.5</td>
</tr>
<tr>
<td>D</td>
<td>20</td>
<td>7.14</td>
<td>4.00</td>
<td>28.57</td>
<td>16.00 ± 26</td>
</tr>
</tbody>
</table>

### Table 1. Experimental results - summary.

#### 2.2 Device assessment – Numerical computation

The validation process carried out through the laboratory experience aims to identify a number of meaningful parameters that can be used to describe the performance of the anchoring device for different loading conditions. These parameters were also implemented into a numerical model that was developed using the commercial software ABAQUS (ABAQUS CAE v. 6.11). Furthermore, the detailed stress and strain fields obtained from the numerical model underline the areas where high stress concentration are likely to occur and were thus essential to refine the new design of the device.

The numerical model is composed by four components (Figure 1a) assembled as in Figure 7a. The interaction properties between the surfaces in contact is user-defined. The materials of the prototype parts are simulated as elastic, as the focus is on the contact mechanics rather than on the stress field. Such hypothesis eases the computational process and is justified by the fact that frictional sliding occurs well before yielding of any of the part, even localised, as it will be verified a posteriori. The model is fully constrained to one end and loaded at the other, thus simulating the testing set-up, where specimens are gripped into the jaws of the testing equipment: whereas one jaw is fixed, the other moves according to the input signal. The same displacement time-histories defined during the testing campaigns and recorded by the testing instrumentation are used as input for the FE models, thus ensuring correspondence between experimental and computational activities.
To reflect the physical model, the slide control force is applied by modelling four bolts and tightening them to a specific value of load. Abaqus provides a built-in method to apply tightening forces in bolts or fasteners. The load can be defined either in terms of a concentrated force or of a prescribed change in length, and applied across a specified bolt cross-section surface. Initially, the bolt load was assigned as concentrated force equal to 4 KN. Initially it was assumed that friction coefficient does not change through the analysis, so that the friction force resisting the sliding was constant during the time step.

The friction contact is applied by the software according to the Coulomb law (Equation 3), which expresses the friction coefficient in terms of slip load to perpendicular pressure ratio, $\Phi$, and number of surfaces in contact, n.

\[
\mu = \frac{F_{//}}{n \times F_{\perp}} = \frac{\Phi}{n}
\]

Normally when the dissipating device is made of two external plates and an internal slider, the number of pair of surfaces in contact is two. This because the internal part has the same plane dimensions of the external elements and has a negligible thickness (Freddi et al, 2017) (Latour et al, 2011). On the other hand, the geometry of the proposed friction device makes the external plates bend around the slider element when the bolts are tightened. Thus, the lateral surfaces are acted upon by a positive pressure and contribute to the friction resistance. The inspection of the slider after 150 symmetrical load cycles confirms that both the horizontal and vertical faces of the slider exhibited evidence of resistance through friction, as shown by the severe signs of wear (see Figure 11). The deformed shape obtained from the numerical model (Figure 7b) well reproduces the concentration of stresses near the edges, as shown in Figure 8a, and it was possible to evaluate the contribution of each surface by integrating the shear stresses over the contact area. A nearly linear correlation was found between the forces acting on each surface, which means that they are equally contributing to the slide-control force. Hence the friction coefficient can be computed considering four pair of contact surfaces ($n = 4$ in Equation 5). Figure 8b shows the values of the ratio between the forces acting upon the lateral and central surfaces ($\alpha$) for increasing values of bolt load.

Considering the values of $\Phi$ recorder experimentally and listed in table 1, the mean value of $\mu$, 0.4, was assigned to the friction coefficient in the computational model. This value is deemed appropriate also considering the involved materials and the grade of wear found a posteriori between the surfaces in contact after the experimental tests.

Figure 7. Numerical model, a) Von Mises stress field and b) deformed shape following the tightening of the bolt for a value of 4 KN.

Figure 8. (a) Numerical model, contact area for the patented model, (b) Correlation between the forces acting on each side of the dissipative device.
The sliding force required to exceed the friction resistance was computed integrating the stresses over the external surface of the slider and was found equal to 26.4 KN. This value of $F_{\text{sl}}$ is close to the one found experimentally, equal to 26 KN.

Table 2 shows a good agreement between the values of sliding force recorded during the experimental campaign and those obtained from the numerical model for different values of bolt load.

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Applied torque [Nm]</th>
<th>Resisting force per bolt [KN]</th>
<th>Sliding force [KN] $\mu$</th>
<th>Applied bolt load [KN] $\mu$</th>
<th>Sliding force [KN] $\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>5</td>
<td>1.25 ± 8 0.40</td>
<td>8.25</td>
<td>1.25 0.4</td>
<td>8.25</td>
</tr>
<tr>
<td>B</td>
<td>10</td>
<td>2.10 ± 14 0.42</td>
<td>13.86</td>
<td>2.10 0.4</td>
<td>13.86</td>
</tr>
<tr>
<td>C</td>
<td>17</td>
<td>3.00 ± 20.5 0.43</td>
<td>19.80</td>
<td>3.00 0.4</td>
<td>19.80</td>
</tr>
<tr>
<td>D</td>
<td>20</td>
<td>4.00 ± 26 0.41</td>
<td>26.40</td>
<td>4.00 0.4</td>
<td>26.40</td>
</tr>
</tbody>
</table>

Figure 9 shows the linear correlation between the sliding force and the sliding control force for both methods of investigation.

![Figure 9. Correlation between the sliding force and the sliding control force for both methods of investigation.](image)

2.3 Design of the revised prototype

As stated before, fatigue tests have shown that the ratio between slip load and applied perpendicular force increases with the number of cycles. This variation is mainly caused by the wearing of the contact surfaces, which led to cold welding and interlocking phenomenon. The tested prototype is also deemed not optimal from the point of view of site installation, as the width of the device (65 mm) is too large to fit in the anchor drilled holes that Cintec international typically prepares for the installation of their retrofitting anchors (50mm). A reduced size would also reduce the impact of authentic fabric being lost when installing the anchors.

For these reasons, a new prototype, shown in Figure 10, has been designed, featuring a cylindrical shape for the sliding part rather than a rectangular one. This choice is justified by laboratory tests performed on the assembly, that show how a sharp square shape led to high stress concentration and consequently to high wearing of the edges (Figure 11).
As a consequence, the debris metallic material deposits between the contact interfaces, increasing the friction coefficient. This eventually causes the sliding demand to increase significantly, exceeding the typical inertia forces developed during a seismic event and hence hindering the desired sliding. A rounded shape is hence proposed for the slider, resulting in larger contact area, smaller localized stresses and hence less pronounced wearing effect. The design was also revised to comply with the industry needs, decreasing the width to 50 mm. The revised device will undergo a campaign of tests, after the design has been optimized by using computer simulations.

A numerical model of the revised device was implemented. Figure 12 shows the improvement in pressure distribution moving from the old and new design of the device. Whereas the old design has only the elements on the edge affected by the pretension applied on the bolts, the new design allows for a wider contact area. This results in smaller values of stress in the contact area (262 MPa for the old device, 165 MPa for the new one), which will cause less severe wear.
CONCLUSIONS

The paper deals with the experimental and computational assessment of an innovative friction-based dissipative device for masonry structures. The aim of the experimental work reported was to assess the performance of the dissipative device for different values of resisting loads when a cyclic load is applied. The results showed that the resisting load varies throughout the duration of the test and a coefficient $\Phi$, defined as slip load to perpendicular pressure ratio, was plotted against the cumulative number of cycles to evaluate the friction coefficient of the assembly. It is worth noticing that for high values of applied load the friction coefficient varies very sensibly throughout the test. Drawing on the experimental tests, a correlation between the applied tightening torque on bolts and the bolt pretension was sought and an empirical value of $k_m$ was defined.

The comparison between two possible designs is proposed: on one side, a patented device featuring square edges, on the other a revised design characterized by a cylindrical shape. The computational analysis showed how the revised assembly provides a wider contact area, which leads to a lower superficial stress field. This reduction will reduce the superficial wear effect of assembly in the contact zones and consequently lead to a longer use of the device itself. The comparison between the experimental results and the numerical model shows that the latter is effective in reproducing the general response of the device.

REFERENCES


