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Shape memory alloys for seismic retrofitting of social housing in an integrative perspective

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ABSTRACT: Traditional buildings are conceived as a set of different construction layers with different roles, thus generating complex information to coordinate during rehabilitation and retrofitting. When architectural features are not a concern, such as in most of the social housing heritage, a new external envelope can be superimposed to the building in order to solve, with a single intervention, functional, architectural and, in particular, seismic problems. The new structure, connected to the existing building with shape memory alloys-based seismic devices, can prevent collapses and dissipate horizontal loads granting a calibrated operability. This paper shows the feasibility of the proposal through the numerical results of nonlinear static and dynamic analyses applied to two structural typologies, namely masonry and concrete frame with masonry infill, in different seismic zones. Finally, the method is verified for a real case study.

1 INTRODUCTION

The effects of the recent earthquakes in Italy highlighted the necessity to improve the seismic behaviour of the existing building heritage, through interventions of structural rehabilitation and retrofitting. In this context, post Second World War social housing buildings, suffering today also of detrimental aesthetical and functional conditions, represent a wide field of action. The different construction layers, each with a different role, functional, structural or architectural (Brand, 1994), generate complexity of management when some intervention is planned.

Therefore, on the wake of Lovell’s studies (2010), this paper presents a strategy that promotes the integration between performances and building systems, leading to the definition of a structural envelope, which, through the biomimetic design process of Benyus (2002), was called “building exoskeleton”. This is an enclosing cage superimposed to the existing construction, able to answer to many different requirements, structural, functional and architectural.

This study presents the application of shape memory alloys devices as connectors between the “exoskeleton” and the existing structure, to prevent collapses through the passive dissipation of horizontal loads, with a calibrated operability in relation to the earthquake intensity.

To evaluate the effectiveness of the proposed method, the results of nonlinear static and dynamic analysis were developed through the software SAP2000, considering the seismic response of the buildings before and after the intervention.
2 THE PROPOSAL

The international patent of Balducci (2011) introduced the possibility to use dissipative towers to mitigate the effects of earthquakes in hospitals and schools. The towers can be strategically located along the perimeter of the buildings and they present dampers in their base able to reduce significantly the lateral drifts through passive dissipation of the seismic input. With respect to the traditional methods, the construction phase of the towers does not interfere with the functionality of the buildings, reducing all the indirect costs; additionally, maintenance, inspection and substitution of the dampers result simpler due to their concentrated localization.

The “building exoskeleton” re-elaborates and merges traditional and Balducci’s methods, as shown in figure 1, providing an integrate solution: the three-dimensional structural envelope, while improving the seismic behaviour of the structure, offers additional space for services and functions, increasing the economic value of the building and improving its energy performances and its architectural characteristics.

Furthermore, the position of the dampers and the effectiveness of the choice, which avoids also uncertainties connected with an altered behaviour of the panels, is explained in figure 2.

The selection of shape memory alloys for the dampers depends on their intrinsic properties – recentring and energy dissipation capabilities, excellent corrosion and fatigue resistance, large elastic strain capacity, hysteretic damping – that have a great potential in retrofitting.

![Figure 1. Evolution of the dissipative system](image1)

![Figure 2. Input energy dissipated by the dampers in different configurations](image2)
2.1 *Shape memory alloys dissipative devices (SMADs)*

The first intervention of rehabilitation using shape memory alloys (SMAs) was projected by Indirli et al. (2001) for the bell tower of St. Giorgio in Trignano, Italy, after the significant damages caused by the earthquake of the 1996. Four hybrid prestressed ties, made by steel and SMAs, were located at the internal corners of the tower to improve its flexural resistance.

Croci (2001) and Castellano et al. (2001), after the earthquake of the 1997, studied a method based on SMAs to reduce the seismic input on the tympanum of St. Francesco in Assisi, Italy, connecting the element with the roof through superelastic multi-plateau SMADs.

Subsequently, the unique intrinsic properties of SMAs led to the creation of damping devices, as the one projected by Krumme et al. (1995) and shown in figure 3, in which SMA wires work always in tension, while the input loads can be tensile or compressive.

Dolce and Marnetto (1999), figure 3, created a more complex variation of the precedent device, consisting of the coupling behaviour of NiTi wires with re-centring capabilities and of steel elements with energy dissipation properties.

The SMADs used in this research are verified with a numerical study while laboratory tests are still needed. NiTi wires, wrapped around studs in order to work always in tension, provide tensile and compressive responses. The device was modelled after the device of Dolce et al. (2000), with an inner and an outer tube to which studs are connected. The outer studs are able to displace in both the longitudinal directions, in this way allowing the wires to work always in pure tension. This device, other than allowing the passive dissipation of the seismic energy, is projected for stress-induced transformation, thus providing re-centring capabilities at the end of an earthquake.

A numerical database for the SMADs was developed with three possible options, with same stiffness and damping properties but different value of precompression displacement (figure 4).

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*Figure 3. On the left Krumme et al.’s device (1995); on the right Dolce and Marnetto’s device (1999)*

*Figure 4. Examples of force-displacement diagrams for three typologies of SMADs (respectively 0, 5 and 10 millimetres of initial precompression from the left) modelled in SAP2000 with damper-friction spring link elements.*
3 THE ANALYSES

This study considered two building typologies, due to their diffusion in Europe: the use of the finite element software SAP2000 required the application of a “frame model” for masonry buildings and of a “strut model” for the concrete frame with masonry infill.

The seismic behaviour of the buildings was analysed before any intervention and after the introduction of an “exoskeleton”, a steel frame with parietal cross braces designed to resist to wind loads and connected to the building with SMADs.

The nonlinear analyses considered three different areas - zone 1, 2 and 3 - within the Italian territory, characterized by different levels of seismicity: zone 1 corresponds to Brescia (Brescia), zone 2 to Borgo Tossignano (Bologna) and zone 3 to Aielli (L’Aquila). The pushover analysis evaluated the capacity of the buildings at the different performance levels, defined by the Italian code (2008) and the FEMA 356 (2000), applying horizontal loads for two orthogonal directions, for two load distributions, for positive or negative eccentricity, with eight combinations for each building in total in each of the three seismic zone. The time history analysis assessed the interstory drift of a control point in relation to the the Italian code (2008) using seven spectrum compatible accelerograms generated for each of the three zones with the software SIMQKE for the performance level of immediate occupancy (IO).

3.1 Masonry buildings

The building modelled for this example has a plan of 10x40 meters and four floors 3 meters high. The “frame model” used to describe the masonry structure is the SAM method by Magenes and Calvi (1996), then implemented by Magenes and Della Fontana (1998) and shown in figure 5. The method proposes the description of the walls through linear elements: in the finite element program, axial columns represent piers while beams represent spandrels. A rigid portion individuates the physical intersection between piers and spandrels.

In SAP2000 shear hinges are located considering the minimum value between the three representative collapse modes respectively for piers – combined compressive and bending and overturning failure, diagonal shear failure, sliding shear failure – and for spandrels – combined compressive and bending failure and shear failure.

The results of the nonlinear analyses underlined critic seismic responses and interstory drifts in the transversal direction (Y axis) in all the three zones, as in figure 5 and 6, requiring a retrofit intervention with the superimposition of the “exoskeleton” as shown in figure 6.

Figure 5. On the left the SAM model; on the right the result of the pushover analysis in Y direction.
3.2 Concrete frames with masonry infill

The plan of the building is 10x40 meters with eight floors 3 meters high. The “strut model” is realized using for each panel two diagonal struts with pure compressive behaviour, connected to the frame at the joints. The geometrical properties and the behaviour of the struts are defined following the consideration of Al-Chaar (2002), Panagiotakos and Fardis (1996).

The model required the introduction of different groups of hinges in relation to the collapse modes for the columns – combined compressive and bending failure and shear failure –, for the beams – bending failure and shear failure – and for the panel, described with axial hinges.

The pushover and time history analyses underlined the necessity of retrofitting, this for both X and Y direction, as in figure 7 and 8. Again, the “exoskeleton” is able to reduce the interstory drift of the building under the restriction imposed by the Italian code (2008) as in figure 8.

3.2.1 Real case study

The building chosen as the case study is located in the San Bartolomeo neighbourhood, in the city of Brescia (Italy) and it has a concrete frame, irregular both in terms of spans and for the dimension of the columns (figure 9).
The concrete frame presents brick infill of “Trieste” type along the perimeter and around the staircase. The building, which is almost symmetrical in both directions, is characterized by a rectangular plan with dimensions 10 meters per 40 meters and four floors 3,1 meters high over a ground floor of 1 meter for a total elevation of 13,4 meters.

The modelling of the panels in the software SAP2000 is realized with the “strut model” with the same consideration discussed in the previous paragraph.

Pushover analysis underlined the necessity of an intervention (Figure 10) that was realized verifying three types of SMADs, namely 0, 5 and 10 mm of precompression. In figure 11 the hysteretic energy properties of the three SMADs are compared to the modal damping energy and to the total input energy for one of the accelerograms at the life safety performance level.

The time history analyses verified an interstory drift under the limits imposed by the regulation but, within this example, the considerations of Morandi et al. (2011) were exploited to achieve a clearer interpretation of the in-plane behaviour of the single panels, with the introduction of different performance limits and their relative definitions:

- Operational level is verified when no panel reaches an interstory drift of 0,2%;
- Immediate occupancy level is verified when no panel reaches an interstory drift of 0,3%;
- Life safety level is verified when no panel reaches an interstory drift of 1%.

To evaluate the necessity of the procedure the limits were at first verified for the interstory drifts of the control points, coincident with the centre of masses of each floor, as in figure 12. In figure 13 the behaviour of the single panels before and after the intervention with the three typologies of SMADs are evaluated: the 5mm and 10mm precompressed SMADs allow to achieve the satisfaction of the three performance levels defined by Morandi et al. (2011).
CONCLUSIONS

The properties of SMAs have been considered for an integrative intervention for social housing heritage, in particular for applications in seismic passive control providing interesting numerical results. Due to their re-centring capacity, after earthquakes, the devices can reset the original configuration of structures and they provide good control of displacements for different solicitations. The design of “exoskeletons”, providing additional spaces, performances and architectural quality, increases the proposal significance.

On the other hand, the use of shape memory alloys, with their high cost per unit weight, requires further evaluations in terms of economic convenience. Despite a feasibility study is not available yet, the outcomes obtained by Dolce and Marnetto (2000) in their study of bracing systems for framed structures are promising. Using the SMA instead of traditional technologies results indeed in negligible additional expenses with respect of the cost of the device itself, while providing better seismic performances. Additionally SMADs requires no maintenance, because of their corrosion and fatigue resistance, and they can be effective also after several earthquakes. With reference to the mentioned results, it appears that the
realization of an intervention based on the use of SMADs would be more convenient than the application of a traditional technology, even without considering the additional collateral benefits obtained by the introduction of a “building exoskeleton”.

5 REFERENCES


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