Seismic protection of monuments by shape memory alloy devices and shock transmitters

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ABSTRACT: European seismic-prone countries, and in particular Italy, host an impressive number of historical constructions. Protecting historical constructions from the effects of severe earthquakes by conventional strengthening methods is not always reliable. Also, conventional methods are often too invasive as well. A lot of innovative techniques that overcome some of the drawbacks of traditional techniques have been developed in the past few years to improve the seismic resistance of historical constructions. This paper aims to present innovative techniques based on the use of shape memory alloy devices and shock transmission units. Earthquake protection of the aforesaid structures through seismic devices is practical and feasible, which is illustrated in this paper via three examples in Italy: the Basilica of San Francesco in Assisi, the Cathedral of San Feliciano in Foligno, and the Church of San Serafino in Montegranaro. All these churches were recently restored after damage caused by the 1997 Umbria-Marche earthquake.

1 INTRODUCTION

Unfortunately, the high seismic vulnerability of architectural heritage all over the world is demonstrated not only by a good number of scientific studies but also by the occurrence of earthquakes in recent years that heavily damaged – and in some cases completely destroyed – ancient structures that are irreplaceable witnesses to past culture and art. This high vulnerability is often intrinsic and related to certain structural types and materials, or original mistakes in design. Said vulnerability is also due to cumulative damage from past earthquakes that is often difficult to assess without a thorough survey. Also, ageing progressively reduces the strength of materials. That is the reason why some monumental structures have recently suffered strong damage in the face of earthquakes of lower intensity than those in the past centuries. Seismic resistance has sometimes been decreased by faulty past restoration interventions as well.

Thus, restoration interventions are necessary to improve the seismic performance of most of the historical constructions located in seismic prone countries. Conventional intervention techniques do not often endow structures with sufficient resistance against a maximum expected earthquake and operate changes in the original structural configuration that are not acceptable from a cultural standpoint.

A lot of innovative techniques have been developed in the past few years to overcome some of the drawbacks of conventional techniques and improve the resistance of architectural and cultural heritage against strong earthquakes. Some of these innovative techniques implement passive control or strengthening of the structure through proper seismic devices, e.g. seismic isolators, shape memory alloy devices, shock transmission units.

Seismic isolation is now a mature technique that has been extensively applied in many countries in modern structures such as bridges, viaducts, industrial plants, and buildings. It consists of reducing the energy transmitted by an earthquake to a structure by changing the structure’s dynamic characteristics; specifically, by increasing its natural period (Skinner et al. 1993). This change is usually achieved through the use of special devices – isolators – with very low horizontal stiffness and appropriate damping – that “decouple” the structure from ground motion. Thanks to this decoupling and a consequent reduction of the transmission and amplification of horizontal accelerations into the structure, seismic isolation is the only anti-seismic technology that allows the mitigation of earthquake effects not only on the structure itself, but its contents as well. That is why it is irreplaceable for all those structures whose contents or functionality after earthquake are more valuable than the structures themselves like museums, hospitals, buildings with a critical civil defence role, etc. Some important applications to restore cultural heritage structures have also been implemented, in particular in the United
The design engineer can select two or more force levels for presenting some of these applications. Nocera Umbra will be carried out in next months. (Castellano et al. 1999). SMADs can be substituted for conventional steel ties to connect different structural elements, e.g. façades to floors or the roof. The advantage accrued over the use of steel ties is mainly due to their force limitation capacity. For example, when used as horizontal ties to connect façade walls to roof, SMADs permit controlled displacements and can limit transmitted forces, according to the device constitutive law. Figure 1 shows an example of such a law for a device of the multi-plateau type with 3 plateaux. The design engineer can select two or more force levels and corresponding displacements; these are then realized using groups of shape memory alloy wires with different lengths, properly connected within the device.

Numerical analyses and experimental results have shown that SMAD connection permits reducing accelerations on the façade wall, thus preventing the out-of-plane collapse of the wall, including the tympanum. In particular, comparison of shaking table tests on walls tied with SMAD or with conventional steel ties showed that the wall using the SMAD connections did not suffer any visible damage, even when subjected to an earthquake with PGA almost 50% higher than the earthquake causing the first collapse in the wall connected by traditional steel ties (Castellano et al. 1999).

The following sections describe the application of this type of SMAD to the Basilica of San Francesco in Assisi, the Cathedral of San Feliciano in Foligno, and the Church of San Serafino in Montegranaro respectively.

Shock transmission units (STU) have been widely used in the last 30 years in new structures – mainly bridges and viaducts or prefabricated buildings – as dynamic or temporary restraints. They are piston/cylinder devices that utilize fluid flow through orifices to provide for a reaction that is the result of a pressure differential across the piston head and is function of the velocity applied to the mentioned piston. STU are designed to work as a safety belt for a car driver: at the occurrence of a dynamic movement exceeding the so called “activation velocity” (induced for example from an earthquake) they react as a very stiff-temporary-restraint, whilst for very slow movements, such those imposed by thermal expansion, they do not provide for a major reaction.

During the last decade, STU have also been applied in the restoration of some historical masonry buildings. The first of these applications was effected in the church of San Giovanni Battista in Carife, Italy, which was heavily damaged by the Irpinia 1980 earthquake (Mazzolani et al. 1994). Part of the damage included the complete collapse of the old timber roof. A new steel truss roof was built and shock transmission units were used to connect the new roof to the masonry walls. This was done to keep roof thermal elongations from inducing high stresses on the walls and, at the same time, guarantee a situation where the roof can share the seismic actions with all the walls during a seismic attack (owing to the roof high in-plane stiffness and temporary stiff connections to the walls given by the STU).

The most recent application of shock transmission units in monuments was implemented at the Basilica of San Francesco in Assisi, Italy, described below.

2 THE BASILICA OF SAN FRANCISCO IN ASSISI

The Basilica of San Francisco in Assisi, Italy, was built in the 13th century. It was hit by many earthquakes in
its history, but none produced the extensive damage suffered in September 1997.

During said earthquake, a big portion of the vaults of the Upper Basilica, frescoed by Giotto and Cimabue, collapsed and large cracks and permanent deformations were produced throughout the vaults. Also, a portion of the tympanum of the left transept collapsed and the tympanum of the right transept was heavily damaged as well. The damage to the tympana was due to both mortar decay and the pounding of the roof against the façade wall (induced by the lack of effective connections between them).

The restoration of the Basilica included the use of many innovative materials and techniques (Croci 2000) like the seismic devices described below (Bonci et al. 2001).

2.1 Application of shape memory alloy devices

In the Basilica of San Francisco, 47 SMAD were used to connect the roof to the two tympana of the transept (24 on the left [south] side, and 23 on the right [north] side). Figure 2 shows details of said SMAD connection: an anchor plate attached to a threaded bar inserted in the façade masonry wall during its partial reconstruction; a new reinforced concrete rib built at the end of the existing r.c. roof (built in the 1950s) to stiffen it, support the roof beams and bring the roof vertical loads directly onto the transept lateral walls. The SMAD were connected on one side to the threaded bar and on other side to the rib, through a platebolded to a counter-plate embedded in concrete.

Figures 3 and 4 show the devices as built and as installed, respectively.

Figure 2. Installation scheme of shape memory alloy devices in the Basilica of San Francisco in Assisi (units are mm).

Figure 3. Shape memory alloy devices for the Basilica of San Francisco in Assisi.

Figure 4. Shape memory alloy devices installed in the Basilica of San Francisco in Assisi.
Three different sizes of SMAD were applied, with design forces ranging from 17 to 52 kN and maximum displacements ranging from ±8 to ±25 mm, to take into account the different properties required as the distance from the transept lateral walls gradually increases toward the roof top. SMAD of different sizes can be recognized in the photographs by their different length.

This was the world’s first application of shape memory alloys to a building to improve earthquake resistance.

2.2 Application of shock transmission units

Shock transmission units were used to connect the different parts of a steel truss installed at an intermediate height along the perimeter of the basilica (Fig. 5). The aim of said truss is to increase the stiffness of the side walls and thus avoid the aggravation of vertical cracks created by past earthquakes and reopened by the last one. The STU allow the truss to behave as it were continuous and rigidly connected to the masonry during an earthquake, whereas the truss and the masonry walls can undergo displacements independently under normal service conditions. Thirty-four shock transmission units of two types were installed (220 and 300 kN maximum force respectively and maximum displacement of ±20 mm) in groups of two or three in each position (Fig. 6). Said devices were made of high strength stainless steel to both reduce dimensions and increase durability.

It is worth noting that the cost of the shape memory alloy devices and the shock transmission units installed in the Basilica of San Francesco in Assisi comprised less than 1% of the total restoration cost.

3 THE CATHEDRAL OF SAN FELICIANO IN FOLIGNO

The Cathedral of San Feliciano in Foligno, Italy, was built in 1133 on the site of an early basilica, enlarged during the XV century and further modified in the XVI, XVIII centuries as well as at the beginning of XX century. The main façade, originally built in 1133, was modified in 1904, when the mosaic was added.

During the 1997 earthquake, Foligno’s Cathedral suffered heavy damage, including the detachment of the façade, with a horizontal displacement of 8 cm off the covering vaults. Such a detachment was caused by an incipient overturning collapse mechanism due to the ineffective restraints on the orthogonal vertical walls and the roof.

Improvement of the connection of the façade wall to the vertical walls and the roof was thus deemed necessary to increase safety levels regarding façade overturning.

The effectiveness of the connection to the vertical walls was improved through the insertion of traditional steel ties at a height of about 15 m, about 3/5 of the façade height, while the one between façade and roof was effected with 9 shape memory alloy devices (Fig. 7).

Said devices are of the same type of those used in the Basilica of San Francesco in Assisi, i.e. with the force vs. displacement law shown in Figure 1, with 2
instead of 3 plateaux. Each of them (Fig. 8) is characterized by a design force of 27 kN and maximum displacement of ±20 mm, and end in tang plates, connected through pins to the clevis of the anchor frames. On one side, the anchor frame is welded to a new V-shaped beam, welded in turn to the existing beams of the modern steel roof (built in the 1950s). On the other side, the anchorage frame is connected to the masonry façade wall through anchor rods. A gap around the ends of existing steel beams, bearing on a PTFE – stainless steel sliding plate, permits relative displacements between façade and roof (which are controlled by the shape memory alloy devices) (Figs 7, 9).

4 THE CHURCH OF SAN SERAFINO IN MONTEGRANARO

The church of San Serafino in Montegranaro and the adjacent convent were built in 1603 on the ruins of a previous church built in the XIII century and collapsed in 1431. The 1997 Umbria-marche earthquake caused the collapse of one of the wood trusses of the roof. Actually, the lack of proper connections between the roof and both the lateral walls and the façades could have caused even further damage due to out-of-plane collapse of peripheral walls (Fig. 10). The retrofit was thus based on the installation of two SMAD to connect the front façade to the lateral walls (Fig. 11) and of cross bracings with steel ties to connect the lateral walls. Each SMAD works in tension only and is characterised by a 39 kN load capacity and a 20 mm design stroke.
CONCLUSIONS

Shape memory alloy devices and shock transmission units can be regarded as powerful tools in the hands of the engineer to reduce the earthquake vulnerability of cultural heritage structures. Both of them are axial devices aimed at connecting different structural elements, but through completely different behaviours. Their installation is simple and their cost is comparatively far lower than the total cost incurred in restoring cultural heritage structures, much like the cost of seismic devices used in modern structures when compared to the construction costs.

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