USE OF SHOCK TRANSMISSION UNITS AND SHAPE MEMORY ALLOY DEVICES FOR THE SEISMIC PROTECTION OF MONUMENTS: THE CASE OF THE UPPER BASILICA OF SAN FRANCESCO AT ASSISI

A.BONCI[1], G.CARLUCCIO[1], M.G.CASTELLANO[2], G.CROCI[3], S.INFANTI[2], A.VISKOVIC[4]
[1]Consultant Engineer, [2]FIP Industriale S.p.A.,
[3]University of Roma “La Sapienza”, [4]University of Chieti “G. D’Annunzio”

SUMMARY

This paper deals with the strategy to assure to masonry monuments a balanced structural behaviour controlling the linking stiffness among different structural elements or masonry portions during seismic actions, without sacrificing the natural seasonal and daily masonry breathing.

1 GENERALITIES

A traditional technique to increase the strength of masonry walls and/or improve the connection between different structural elements, thus improving the local and global seismic behaviour, is the use of reinforced injections. But in many monumental structures, the presence of frescoes and/or the limited thickness of the walls, as well as the willingness to limit as much as possible not reversible interventions, does not allow use of such techniques. In these cases, additional stiffening elements are introduced, such as steel beams. This solution, however, is not without problems as it may hinder the natural breathing of very wide historical buildings, that is relative movements due to thermal effects, seasonal water table variations, *etc*.. In some cases, especially when the building dimensions are very large, it may be useful to divide the global connections in sub-elements connected by “shock transmission units” (STUs), *i.e.* elements which allow slow relative movements but prevent any instantaneous ones.
At the same time, the traditional technique to improve the seismic resistance of a building guaranteeing its box behaviour, creating connections between horizontal stiff frames (roofs and floors) and peripheral walls, generally allows no important and useful energy dissipation, and can induce very high forces on the masonry elements. The linking technique may be improved

using an innovative material called “shape memory alloy” (SMA) in specifically designed connection devices. Several advantages may be accrued by these devices in comparison to traditional steel ties, concrete beams, *etc.*. Particularly, by using these devices it is possible to allow “controlled” relative displacements, limiting the forces and the acceleration transmitted, and inducing energy dissipation by the masonry itself. A significant example of the application of these intervention criteria may be found in the Basilica of San Francesco at Assisi, restored after being strongly damaged by the earthquake of 1997.

2 DEVICE PROPERTIES FOR THE USE IN MONUMENTS

Shock transmission units (STUs) are structural devices, used to connect structural elements, whose behaviour depends on the velocity of the relative movement between said elements. In effect, they allow low velocity movements, such as those due to thermal variations or other slow phenomena reacting with very low forces. Conversely, under high velocity excitations (*e.g*. earthquakes, strong winds, *etc*.), they are very stiff, preventing the structural elements they connect from significant relative movements, and transmitting them the design force. Thus, shock transmission units act as temporary restraints. Since many years they have been used in new structures, mainly in bridges and viaducts to connect deck to piers or abutments, as well as in buildings. However, their behaviour is also useful for the seismic protection of historical and monumental structures, to provide the stiffness needed to withstand the earthquake without inducing undesired forces under service conditions. The use of STUs in historical structures have been first proposed and applied in Italy about 10 years ago, for the dynamic connection of a new steel roof structure to the masonry walls of a church [1]. STUs are devices comprising a cylinder-piston system with two chambers filled with a special fluid and connected through an hydraulic circuit. When they are used in historical structures, a special care should be taken in the selection of materials. The connections of the devices should be designed to allow an easy replacement, respecting the criterion of reversibility of interventions.

SMAs are metals endowed with very unusual thermo-mechanical properties, comprising the superelastic behaviour, that is, the ability to recover from large deformations (greater than 10 times that of conventional metals) during loading-unloading cycles. In the loading phase, the stress-strain curve shows a "plateau" (*i.e.:* a section where stress remains nearly constant with increasing strain), similar with the one seen by yielding but instead due to the stress-induced reversible and non damaging phase transformation from Austenite to Martensite. Loading and unloading paths generate an hysteresis loop and thus energy dissipation. The SMA superelastic behaviour makes them particularly suitable to create force limiting devices. SMA Devices (SMADs) have been developed to overcome some drawbacks of traditional very stiff steel ties, used to connect masonry walls with floors and/or roof and thus reduce the risk of out-of-plane collapse of peripheral walls. In effect, SMADs work as far more flexible ties, capable of allowing controlled displacements, and limiting forces under a pre-established value [2]. The SMADs use SMAs in the form of wires, suitably connected to work always under tension and giving the device a symmetric behaviour regardless of the direction of the displacement. They are designed to have different response for different intensity of external action:

a) For low horizontal action (wind, small intensity earthquakes) the device is stiff, as a traditional steel connection, and no significant displacements are allowed.

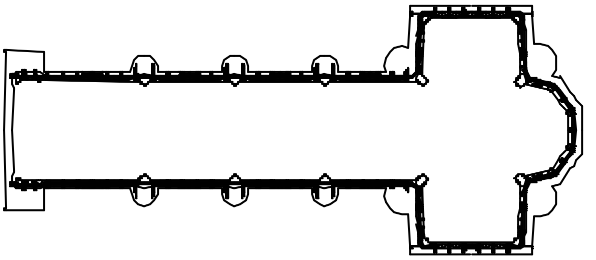


Fig. 1 : The horizontal stainless steel beam all along the Upper Basilica

b) For higher horizontal actions the stiffness of the device reduces thanks to the "superelastic plateau", and "controlled displacements" are allowed. The latter should allow the masonry to dissipate part of the energy transmitted by the earthquake mainly thanks to micro-cracks in the masonry structure, taking care to avoid dangerous macro cracks. Furthermore, SMADs transmit to the structure smaller forces than steel ties do.

c) For extraordinary horizontal actions (*i.e.* higher than the design earthquake) the stiffness of the device grows up in order to prevent from excessive displacements and instability.

Shaking table experimental tests carried out on mock-ups of masonry façade walls connected to the structure by different devices showed that there is significant improvement in seismic response by using SMA devices instead of steel bars to tie walls. Not only is the out-of-plane collapse of the wall partly below the tying level prevented but that of the wall partly above it (representing the tympanum of a church façade) as well [3].

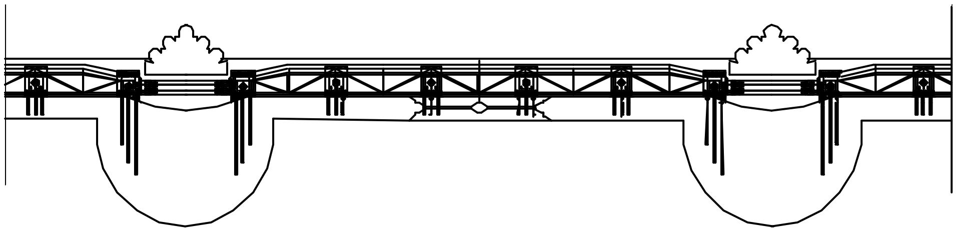
The SMA with the best performance is NiTi, an alloy that also has very high resistance to corrosion. High durability of SMADs is obtained using NiTi wires and stainless steel.

3 THE CASE OF THE UPPER BASILICA OF SAN FRANCESCO AT ASSISI

3.1 Introduction

The St. Francis Basilica is built up by two distinct Basilicas, the Upper and the Lower, one on the top of the other.

Vertical cracks are located near the centre of each bay of the side walls of the Upper Basilica. Those cracks, opened and enlarged many times by past earthquakes, were reopened by the last seismic event of 26 September 1997. Each crack starts from pavement level up to the level of the tall window base, often cracking the window cornice itself, and is visible both on the internal and on the external side. Considering that the top of the windows arrive near the roof level and, at the same time, in each bay of the Lower Basilica there is a large and tall opening for the access to the lateral chapels, the nave structure of the Basilica as a whole, results divided into vertical portions weakly connected each other in the middle of each bay. The cracked side walls under the windows level in the Upper Basilica are those with the presence of the Giotto's frescos. Thus a protection is required to avoid excessive crack openings during seismic actions normal to the walls themselves, but the use of reinforcement injections is excluded. Therefore a "dry" and almost completely reversible intervention consisting of a chain of steel trussed beams placed over the internal cornice, which is located at an intermediate height just over the Giotto's frescos and under the windows, was adopted. Each beam increases the transversal



stiffness of

Fig. 2 : One bay of the steel beam with couples of STU at each end

one bay of the side wall between two external buttresses and is connected to the beams in the adjacent bays through STUs, in such a way to contemporary guarantee the global horizontal connection (Fig. 1). The transept south tympanum masonry wall of the Upper Basilica partially collapsed during the September 1997 earthquake [4]. Before this event the tympana walls were directly supporting the main reinforced-concrete beams of the roof structure. With such a structural solution there was no possibility to control the forces exchanged between tympanum and roof during a seismic action; furthermore, pounding of the beams against the walls was present. The SMAD characteristics seem to be particularly advantageous in this case. In fact traditional connections by steel bars between the Basilica's roof and the tympanum appear to be too stiff and dangerous for the tympanum itself.

3.2 The intervention with shock transmission units in the nave

The intervention in the nave consist in the employ of a steel girder made by a horizontal plate with an above trussed ribbing, placed on the cornice located at 7m from the pavement all along the Basilica from the façade to the apse (fig. 1), and passing through the narrow chinks behind the pillars (fig. 2). The section profile of this beam is shaped in order not to be seen by people standing in the nave. The beam is locally fixed in many points all along the walls, in connection with the pillars and in the transept corners. These links to the wall are carried out through suitable fixing plates on which the girder is leaned with the interposition of PTFE elements and horizontally fixed by pins. These pins do not allow any horizontal movements in the transept and in the apse area, while all along the nave, where the considerable length could cause movements due to thermal variations, such links allow longitudinal displacements. Thus in the nave the steel beam is divided in portions corresponding to the bays (fig. 2) connected each other, behind the pillars, by a couple of STUs to guarantee a global stiff linking during seismic events (fig. 3). Design forces of the two types of STUs used are 22 t and 30 t. Because of the particular position of the installation, stainless steel is used both for the beam and for the STU. Moreover, to avoid the danger of percolation on the Giotto's frescos as well as to reduce maintenance, the fluid used inside the STUs is not a low viscosity oil (often used for bridge applications), but a high viscosity silicon putty.

3.3 The intervention with shape memory alloy devices on the transept tympana

In order to modify the roof-tympanum interaction, the roof structure was disconnected from the tympanum wall and a new concrete truss was built to support the roof beams and to bring the roof vertical loads directly on the transept lateral walls. At the same time it was rebuild the collapsed portion of the left tympanum (using stones from the original quarry) and removed the deformation that both the transept tympana suffered. Than the new concrete truss was connected to the tympanum walls by SMADs spaced 50cm apart, in such a way to better distribute the exchanged forces. Three different groups of devices were designed and installed, in order to take into account the different properties required as the distance from the transept lateral walls increases up to the roof top. The different force-displacement behaviour of these groups can be perceived by their different length (Fig. 4). Numerical analyses were carried out to select the SMAD properties [5]. On the basis of the results of numerical analyses and experimental tests, it was chosen to employ mainly SMADs of the "multi-plateau" type (fig. 6), obtained using three sets of SMA wires with different lengths, working in sequence for different values of the external action.

Fig. 3 : The installed STUs.

Fig. 4 : The three sets of installed SMADs

4 ACKNOWLEDGEMENTS

The restoration project of St. Francis Basilica in Assisi has been made by Prof. Eng. G. Croci and Prof. Arch. P. Rocchi, with the participation of Eng. G. Carluccio and Eng. A. Viskovic, under the supervision of Dr. A. Paolucci, the artistic co-ordinator of the Ministry of Cultural Heritage, Arch. C. Centroni, Superintendent of Umbria.. The on site installation of the STUs and the SMADs was carried out by FIP Industriale S.p.A.. under the supervision of Engg. M.G.

Castellano, G. Carluccio and A. Viskovic; the mathematical models and the analyses of these interventions have been done by Engg. A. Bonci and A. Viskovic. The experimental laboratory tests were carried out by FIP Industriale (test on SMADs) and by ENEA (shaking table tests on mock-ups with SMADs) under the supervision of Engg. M. Indirli, M.G. Castellano, A. Bonci and A. Viskovic, within the "ISTECH" Research Project partially funded by the European Commission (Contract No. ENV4-CT95-0106, 4th Framework Programme) .

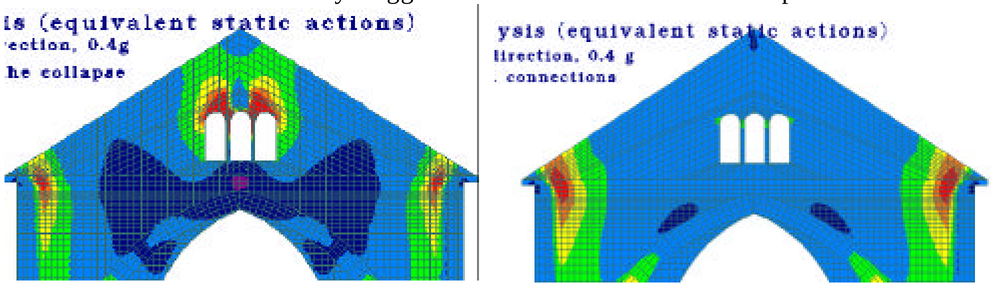


Fig. 5 : Comparison between the original situation and the situation after the intervention

5 REFERENCES

[1] Candela, M., *et al*. "L'impiego dei dispositivi a vincolo provvisiorio nel restauro antisismico di un edificio di culto" in *L'Ingegneria sismica in Italia1991,* 5° Convegno Nazionale, Palermo, 1991.

[2] Castellano, M.G., "Innovative technologies for earthquake protection of architectural heritage", in *More than two thousand years in the history of architecture*, International ICOMOS Congress, Bethlehem, Palestine, October 2000.

[3] Indirli *et al*., "Experimental tests on masonry structures provided with shape memory alloy antiseismic devices" " in *Proc. of 12th WCEE*, Auckland, New Zealand, 2000.

[4] Croci, G.; Bonci, A.; Viskovic, A. – "Use of shape memory alloy devices in the Basilica of St. Francis of Assisi" in S*hape memory alloy devices for Seismic Protection of Cultural Heritage Structures*, Final Workshop – ISTECH Project, June 2000.

[5] Biritognolo, M.; Bonci, A.; Viskovic, A. – "Numerical models of masonry façade walls with and without SMAD's" in S*hape memory alloy devices for Seismic Protection of Cultural Heritage Structures*, Final Workshop – ISTECH Project, June 2000.

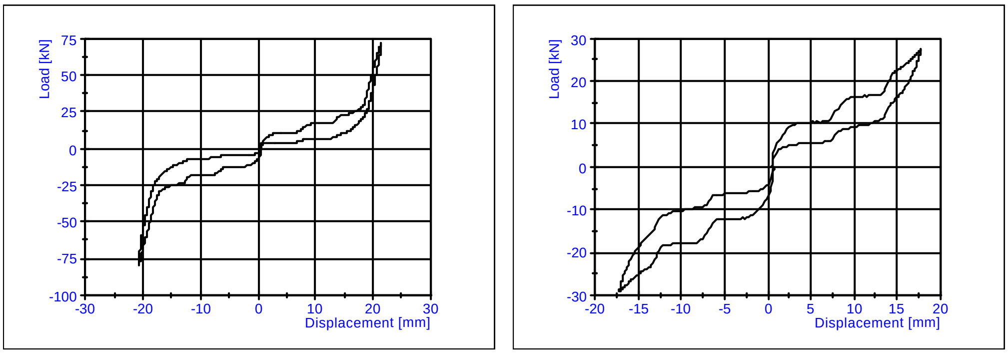


Fig. 6 : Experimental tests, force vs. displacement loops, on “multi-plateau” “self-balancing” SMAD prototypes