EXPERIMENTAL TESTS ON MASONRY STRUCTURES PROVIDED WITH SHAPE MEMORY ALLOY ANTSEISMIC DEVICES

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SUMMARY

Within the framework of the European Commission-funded ISTECH Project [FIP *et al.*, 1995], a series of experimental campaign has been carried out, in order to evaluate the benefits induced by the application of superelastic Shape Memory Alloy (SMA) Devices (SMADs), an innovative technique for the restoration of a Cultural Heritage Structure (CUHES), especially masonry buildings. Said structures are greatly vulnerable to earthquake ground motion and traditional interventions are sometimes inadequate and often too invasive.

The experimental campaigns have been the following ones: 1) shaking table tests on masonry wall mock-ups (focused in this paper), simulating a portion of a CUHES, with the aim to evaluate the effectiveness of SMADs for the prevention of the out-of-plane collapse due to dynamic forces acting orthogonally; 2) large-scale tests on masonry walls [Bono *et al.*, 1998], with the aim to increase, by the use of SMADs, resistance and stability against the forces induced by an earthquake in the plane of the model; 3) furthermore, long period tests, regarding creep evaluation in a masonry wall sample and compression of two little brick columns, pre-stressed respectively by a SMAD and a conventional device, in order to measure the static vertical load during the time.

The use of SMADs has proved very effective in improving the seismic resistance of the aforesaid structures. The successful results of the research led to two restoration applications now under way in Italy: the Bell-Tower of the S. Giorgio in Trignano Church in S. Martino in Rio, damaged during the October 1996 earthquake [Forni *et al.*, 1997], and the transept tympana of the Basilica of S. Francesco in Assisi, damaged during the September 1997 earthquake [Croci 1998, a-c].

INTRODUCTION

The ISTECH project efforts were focused on the development of anti-seismic techniques applicable to masonry CUHESs [Castellano *et al.*, 1999]; in fact, a wide range of European CUHESs fall into this classification. Masonry buildings are greatly vulnerable to earthquake ground motion because of their low resistance and ductility. In the past, earthquakes have visited substantial destruction (see Figure 1) that translates into a significant loss of our architectural heritage [Croci, 1998 a-c, Forni *et al.*, 1997, 1998].

Traditionally, the most common solution used in the past to enhance the CUHESs seismic behavior has been the introduction of localized reinforcements, usually steel bars or cables, increasing stability and ductility. Anyway, in many cases said reinforcement techniques prove inadequate to prevent collapse.

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A typical mechanism in masonry buildings is the out-of-plane collapse of peripheral walls due to inertia forces generated by an earthquake acting orthogonally to the walls. In case of a traditional intervention by steel ties, the high stiffness of steel bars causes the transmission of high forces to the masonry during an earthquake.

Consequently, the connection can also fail due to the "punching" effect of the anchorage, especially in cases of poor quality or deteriorated materials. Furthermore, the high stiffness of a so connected structure can significantly amplify ground accelerations, a particularly important fact when there are structural elements that cannot be connected, as is often the case with tympana in church façades [Castellano *et al.*, 1999]. In effect, it has been observed from past earthquake damage [Doglioni *et al.*, 1994] that the presence of steel ties did not avoid the collapse of tympana, even though the remaining bottom portions of the façades did not collapse.

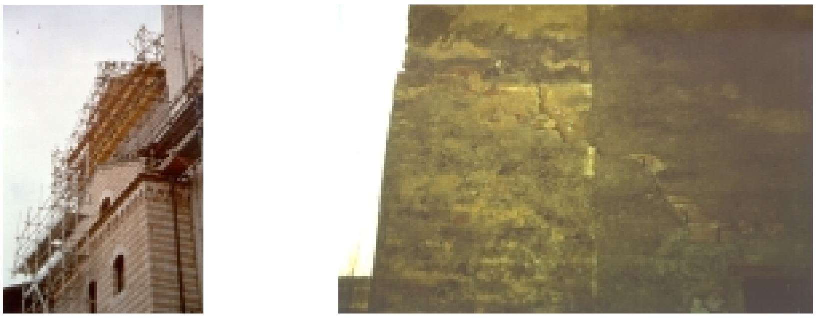

Figure 1: the Bell-Tower of the S. Giorgio in Trignano Church in S. Martino in Rio, damaged during the October 1996 earthquake (right), and the transept tympanum of the Basilica of S. Francesco in Assisi, damaged during the September 1997 earthquake (left).

SHAPE MEMORY ALLOY DEVICES

The innovative reinforcement techniques developed within the ISTECH Project use SMA in form of wired devices that reduce the risk of collapse in masonry buildings within range of strong earthquake actions. The development of an innovative connection technique was based on the idea of using the unique properties of the NiTi Alloys (i.e. the SMAs used in this study), especially their "superelasticity[1]" and high resistance to corrosion [Castellano *et al*., 1997, 1998, 1999]. The basic idea was to connect the external walls to the floors, the perpendicular walls or the roof with an SMAD that should behave as follows:

a) under low intensity horizontal actions (wind, small intensity earthquakes) the device remains stiff, as traditional steel connections do, not allowing significant displacements;

b) under higher intensity horizontal actions (i.e. strong earthquakes) the stiffness of the device decreases, allowing "controlled displacements" which should reduce accelerations amplification (as compared to stiff connections) and permit the masonry to dissipate part of the transmitted energy, mainly owing to elasticity exploitation and micro-cracks formation in the brickwalls; consequently, the structure should be able to sustain a high intensity earthquake without collapse, though undergoing some minor damage;

c) under extraordinary horizontal actions, the stiffness of the device increases and thus prevents instability. Figure 2 could summarize such behavior.

Different SMAD types, to be used as horizontal ties to prevent the out-of-plane collapse of masonry walls, were manufactured and tested by FIP Industriale and each of them aims to fulfil a particular structural need [Castellano et al., 1999]: *i)* the "self-balanced" SMAD; according to the technique described above, it should not apply any static force to the masonry and becomes active only under dynamic actions, that induce horizontal loads which are greater than the "initial force"; such a device should also offer symmetric behavior along two directions perpendicular to a wall; Figure 3 shows the constitutive behavior of one of said prototypes and illustrates the very stable behavior under cycling; *ii)* the "multi-plateau self-balanced" SMAD, an evolution of the aforesaid device; its behavior is shown in Figure 4a-b and the advantage accrued by this SMAD is its lesser sensitivity to masonry tensile strength; in effect, numerical analyses show that the optimal design force of single-plateau SMADs depends on masonry tensile strength and increases with it; with multi-plateau SMADs, the risks derived from overestimating or underestimating the masonry tensile strength can be either avoided or substantially reduced; the design engineer can select two or more force levels and corresponding displacements so as to take into account a wide range of masonry mechanical properties, and thus achieve a good level of optimization; *iii)* the not "self-balanced" SMAD, post-tensioned to apply pre-stress to masonry; this type is employed instead of the type *i)* or *ii)*, when the use of pre-stressed ties is the design choice.

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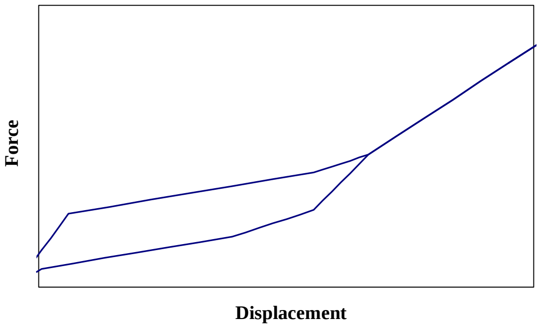
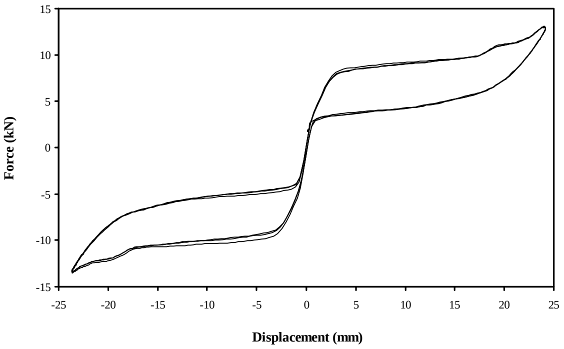
[1] *Said high tech materials are defined superelastic because of their ability to recover completely (i.e. without remarkable residual deformations) very high strains (6-10 %).*

The third type can also be used, in series with steel tendons, in any intervention aimed at pre-stressing masonry walls [Bono *et al*., 1998; Castellano *et al*., 1999].



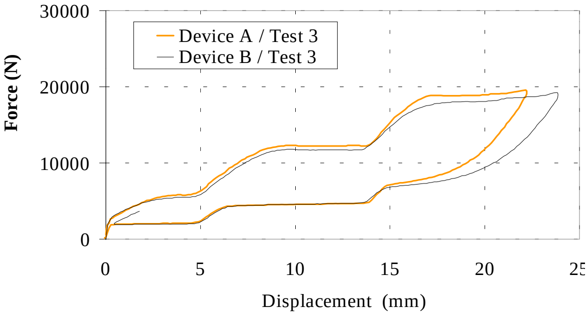
as shown by the hysteresis loop, the device can intrinsically dissipate some energy

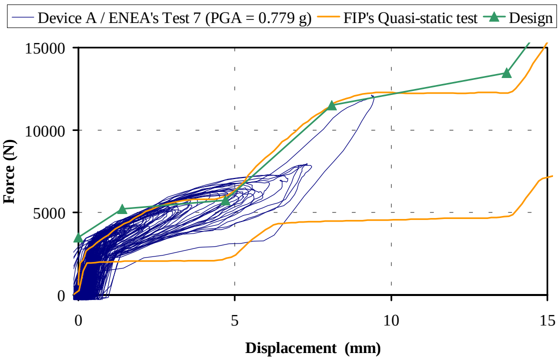
Figure 2: Design force vs. displacement behavior of a wall-floor SMAD connection.



Experimental force vs. displacement behavior of a wall-floor connection

Figure 3: Single-Plateau Self-Balancing SMAD.





characterization tests on the two prototypes used for the shaking table experimental campaign (see § 3)

Figure 4a: Multi-Plateau Self-Balancing SMAD Prototype.

Figure 4b: Comparison between SMA design, quasi-static and dynamic tests.

It is worth noting that rehabilitation interventions using any type of SMADs are reversible, which is nowadays a requirement in any intervention to CUHESs. As it is the case with traditional interventions using reinforcement bars or cables, some minor holes in the masonry texture are non-reversible.

SHAKING TABLE TESTS ON MASONRY WALLS

A set of shaking table tests on brick masonry wall mock-ups simulating a portion of a CUHES was performed. The aim of the tests was to evaluate the effectiveness of the previously described innovative technique for the prevention of out-of-plane collapse of masonry walls. Shaking table tests were performed in the laboratories of ENEA at Casaccia (Rome) and of ISMES SpA (Seriate, Italy) with the technical assistance of ENEA-ERG-SIEC-SISM (Bologna), FIP Industriale S.p.A., and University of Rome"La Sapienza". Numerical analyses in support of these tests were performed by the Istituto Superior Técnico of Lisbon [Azevedo *et al*., 1999] and by the University of Rome "La Sapienza".

Two identical masonry wall mock-ups were constructed, each connected to a stiff steel frame, and placed together on the shaking table. In fact, both of the brick walls simulate a portion of a historical building façade, whilst the steel frames represent the remaining part of the structure. Their only difference is the type of connection: the first wall is linked up to the rigid frame by two conventional steel bars while the second is connected by a pair of innovative SMADs. The geometry of the testing mock-ups is shown in Figure 5-left.

The SMADs are of the multi-plateau, self-balanced type, with a design initial force of 3.5 kN, and a first plateau force equal to 5.2 kN. Both the conventional and SMA devices (Figure 5-right) were anchored to the walls using steel plates. Load cells were interposed between each device and the anchorage

.

Masonry brickwork Height	*403 cm*	*Mortar course Thickness*	*~ 1 cm*
Three-leaf brickwork Thickness	*36.5 cm*	*Reinforced concrete base Height*	*22 cm*
Masonry brickwork Width	*99 cm*	*Reinforced concrete top curb Height*	*35 cm*
Brick Dimensions	*5.5 x 11.5 x 24 cm*	*SMA and conventional connections Height*	*342 cm*
Mock-up Total height		*460 cm*	

Table 1

Test n°	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Level (dB)	-20	-10	-6	-3	-1.5	0	+1.5	+3

Table 2

Test n°	**4**	**5**	**6**	**6bis**	**7**	**8**
PGA (g)	0.4135	0.5898	0.6535	0.6114	0.7790	0.939

Table 3

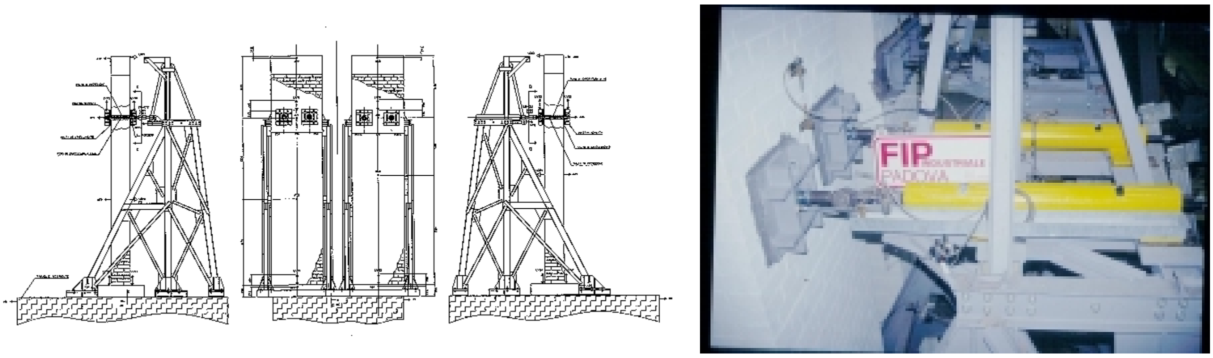


Figure 5: Mock-ups used in the shaking table tests (left) and wall connection with a steel frame through SMADs (right).

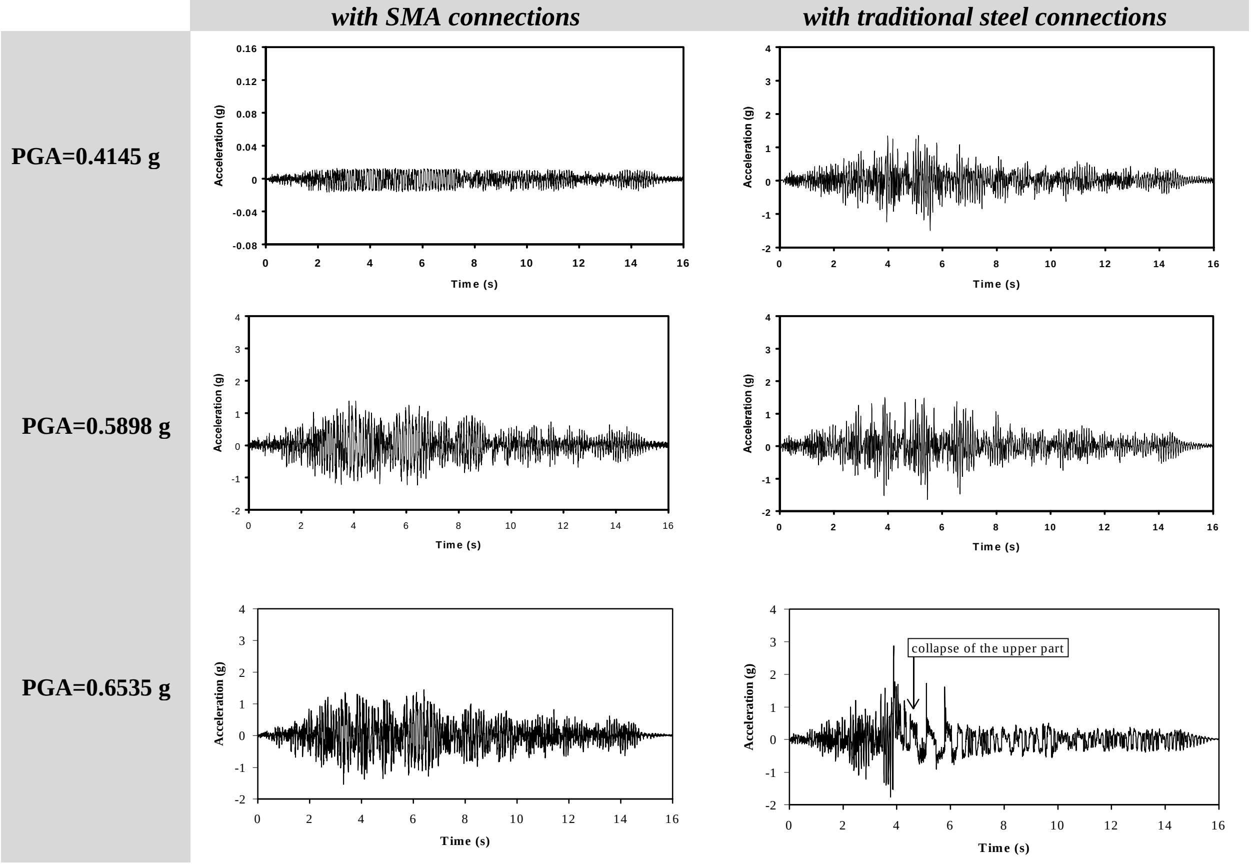
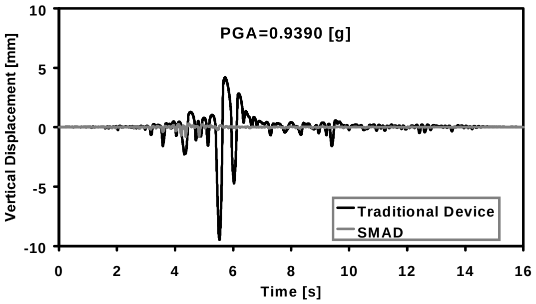
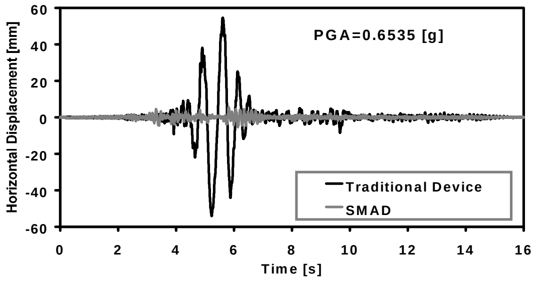


Figure 6: Acceleration time-histories measured at the wall top.

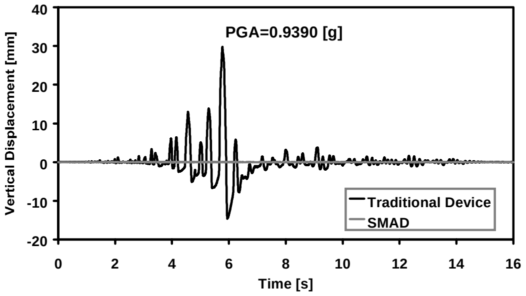
a) wall base vertical displacement



b) wall top horizontal displacement



c) middle wall vertical displacement



d) devices attachment vertical displacement

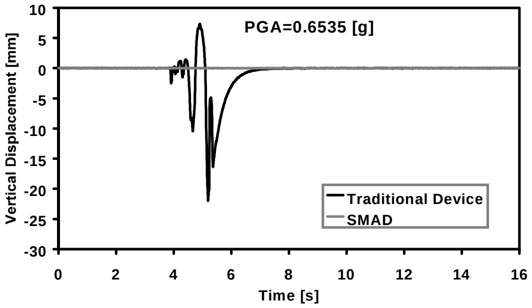


Figure 7: Devices displacement time-histories;
failures are evident in the wall with traditional steel connections.

The walls were made up of a three-leaf brickwork, using traditional full-bricks and Mape-Antique MC premixed mortar.

The brickwork was built over a reinforced concrete base, to permit mounting the mock-ups onto the shaking table. Also, a reinforced concrete was built on the top of the masonry walls with the dual function of simulating the weight of an higher wall and providing a hook-up system (necessary for wall handling and safety anchorage). Table 1 summarizes models main features.

The mock-up instrumentation comprised 7 accelerometers, 10 vertical displacement transducers placed at the points where cracking was expected, 5 horizontal displacement transducers (placed at the connections and on top of the walls), and 4 load cells.

Both simulated earthquake and identification tests were conducted. Modal identification was carried out through random characterization tests. Seismic tests were conducted at 8 different intensity level, ranging from –20 dB (about 0.05 g) to + 3 dB, as summarized in Table 2. The reference earthquake is synthetic, derived from the EC-8 spectrum for soft soil and also modified to achieve a rather flat spectrum in the range of the first two modal frequencies expected for both the mock-ups (2-30 Hz). The PGA of said earthquake is 0.55 g.

The first two frequencies, resulting from the random tests, were 4.0 and 27.3 Hz for the wall with SMAD connections, and 3.5 and 25.7 Hz for the wall with traditional steel connections.

It is worth to note that such a difference between the two mock-ups should be ascribed to the walls themselves and not to the different types of connection, because the two connection types have the same stiffness for the very low excitation levels used in random tests (0.05 g). The difference between the innovative and traditional ties becomes evident under higher excitations. Table 3 reports the peak table acceleration (in the following indicated as Peak Ground Acceleration, PGA) measured during the highest intensity seismic tests.

The test results confirmed the ability of SMADs to substantially reduce the risk of earthquake induced out-of-plane collapse of masonry walls (see Figures 6-10).

The wall with traditional steel connections collapsed with the mechanisms predicted by the numerical analyses [Castellano *et al.*, 1999].

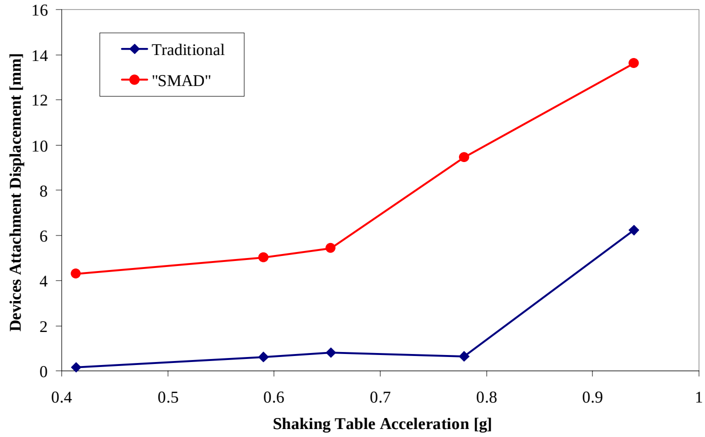


Figure 8: Devices attachment horizontal displacement versus shaking table acceleration.

The first collapse mechanism was in effect the overturning of the upper part after the forming of a horizontal crack just above the anchorage plates (*cf.* Figure 7b and 7d), occurring during test n° 6, *i.e.* with a peak acceleration on the table of 0.6535 g.

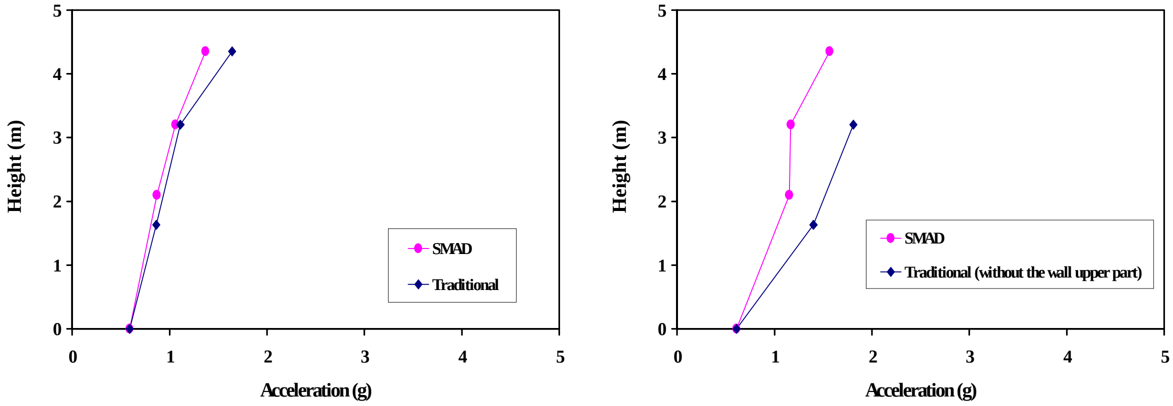
In test n° 7, the same wall showed a crack at approximately 2 m height.

Said crack completely opened up (*i.e.* crossed the wall width) during the subsequent test n° 8 (*cf.* Figure 7c), thus causing a definitive collapse of the wall with traditional connections.

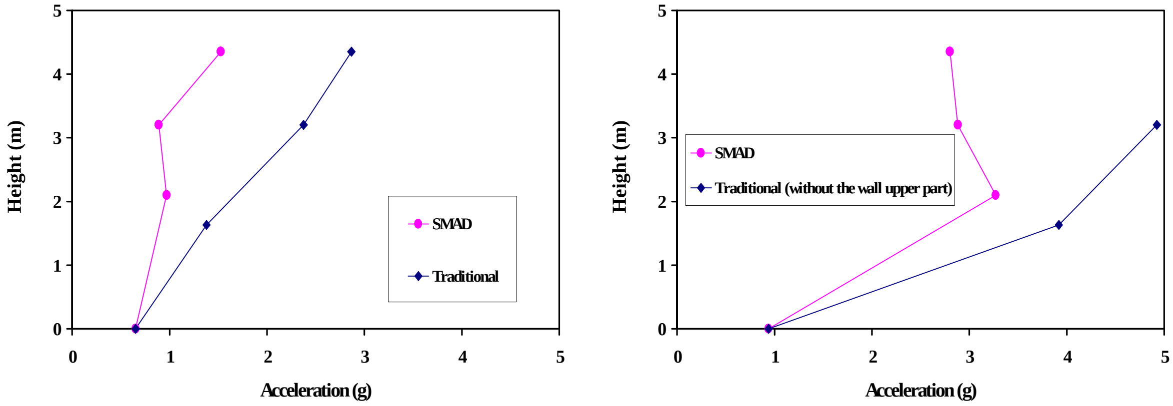
The wall with traditional steel connections showed also evident cracks at its base, always after the test n° 8 (*cf.* Figure 7a).

Conversely, the wall using the SMAD connections did not suffer any visible damage, even when subjected to an earthquake characterized by a PGA almost 50 % higher than the earthquake causing the first collapse in the wall connected by traditional steel ties.

a) PGA=0.5898 g **b) PGA=0.6114 g**



c) PGA=0.6535 g **d) PGA=0.9390 g**



collapse of the upper part of the wall with traditional steel connections *complete collapse of the wall with traditional steel connections*

Figure 9: Peak acceleration values on the two walls, measured at different heights, and comparison between SMAD and traditional connections.

The different behavior of the two walls can be understood comparing the wall top acceleration time-histories and the peak acceleration values measured at different points along the walls (*cf.* Figures 6 and 9a-d; in particular, 9c shows such a comparison in reference to the collapse of the upper part of the wall with traditional steel connections).

Furthermore, Figure 8 confirms the greater SMADs horizontal "controlled displacements" (*cf.* § 2*b*) at the connections: in test n° 8, about 15 mm (6 mm in traditional devices), in order to reduce acceleration and avoid collapse.

In fact, the acceleration reduction given by the SMADs is impressive: almost 50 % at the top, and more than 60 % at the connections level.

It is worth noting (*cf.* Figure 9c) that the top maximum acceleration reached in the wall with traditional connections in test n° 6 (2.9 g) is even higher than the one reached (2.8 g) in the SMADs wall subjected to a PGA 1.4 times higher (test n° 8, *cf.* Figure 9d).

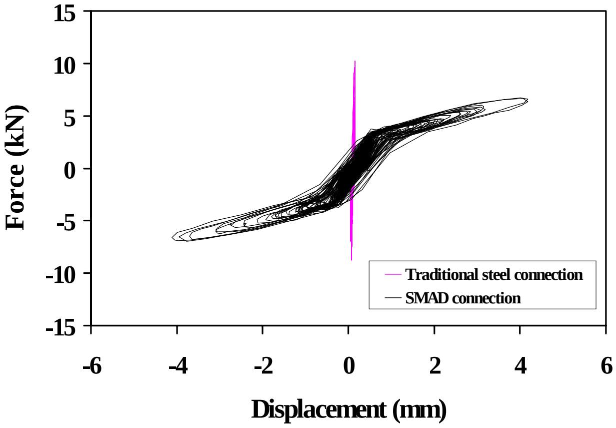
Amplification values between the shaking table and the wall top are 4.4 (traditional devices) and 2.3 (SMADs); instead, at the connections level (always test n° 6), the table acceleration is amplified by 3.6 and 1.4 (traditional devices and SMADs respectively). This shows the effectiveness of the new tying technique employing SMADs in reducing the acceleration amplification, owing to the reduced stiffness, force limitation and energy dissipation offered by the superelasticity of SMA.

Figure 10 shows the force reduction and displacement increase in the SMAD connections, compared to the very stiff steel connections. The max force peak is reduced by 45 % in test n° 6, when the traditional devices wall collapsed at the connections (force=13.3 kN). Furthermore, the SMAs wall didn’t show any damage till an equal force was reached in test n° 8. Figure 10 shows also the SMAD force-displacements loops at increasing earthquake intensities.

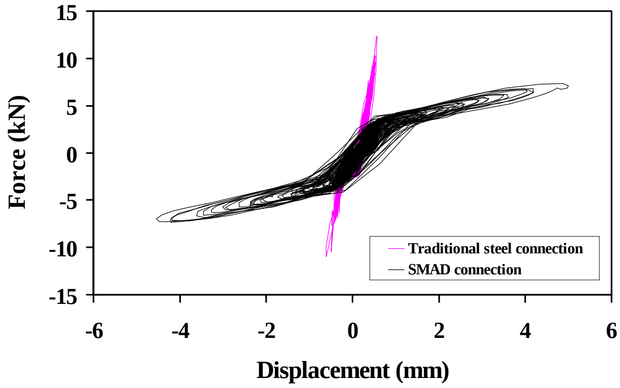
The devices remain in their first plateau (*cf.* Figure 4 § 2) up to test n° 6 (PGA=0.65 g). In test n° 7, it is worth noting a stiffness increase (*cf.* Figure 4b).

The second plateau is reached only in test n° 8, where a displacement of about 15 mm was recorded (*cf.* Figure 8).

***a)* PGA=0.4135 [g]**



***b)* PGA=0.5898 [g]**



***c)* PGA=0.6114 [g]**

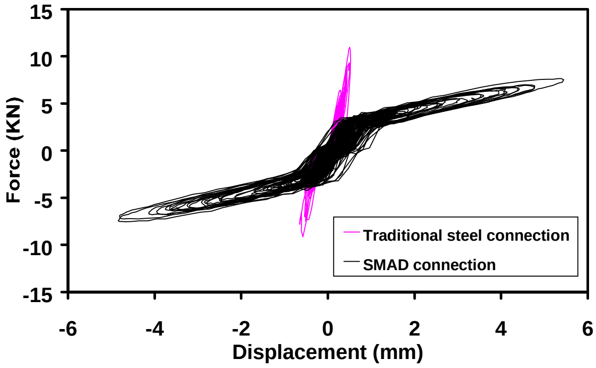


Figure 10: Force vs. displacement loops measured in the connections at increasing seismic intensity.

CONCLUSIONS

Theoretical and numerical studies permitted the development of innovative rehabilitation techniques based on the use of Shape Memory Alloy technology. The feasibility of using Shape Memory Alloy Devices with different behaviors was demonstrated trough the construction of a number of prototypes which underwent extensive testing. Shaking table tests showed that a new tying technique using Shape Memory Alloy Devices can be highly effective to prevent the out-of-plane collapse of peripheral masonry walls, *e.g.* church façades, poorly connected at floor level. The SMAD ties, compared to traditional ties, can increase resistance against out-of-plane seismic vibrations of such masonry walls by at least 50 % (in terms of maximum PGA bearable without damage), owing to a reduction in top acceleration of at least 50 %. Furthermore, unlike traditional steel ties, SMADs ties can also prevent the collapse of tympanum structures. The ease of application of Shape Memory Alloy Devices will be demonstrated by two applications now under way in Italy: the Bell-Tower of the S. Giorgio in Trignano Church in S. Martino in Rio, damaged during the October 1996 earthquake and the transept tympana of the Basilica of S. Francesco in Assisi, damaged during the September 1997 earthquake.

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