Fibre Reinforced Polymers (FRP) strips in series with Shape Memory Alloy (SMA) wires: theory, application and experimental results of a prototypal anti-seismic device in the framework of the MAMAS project

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SUMMARY:
In the framework of the MAMAS Project ("Advanced Multi-task Materials for Structural Applications in Construction"), a scientific team (CETMA, ENEA, Ferrara and Florence Universities) realised a prototypal device made by CFRP (Carbon Fibre Reinforced Polymers) strips in series with SMA (Shape Memory Alloy) NiTi wires, devoted to strengthening masonry structures when quick prompt ringing is needed to face wall overturning in the post-earthquake emergency. In fact, the fibre delamination (i.e. decrease of stiffness and load bearing ability) should be avoided, because the repair effectiveness is not guaranteed if the accumulated effect of several seismic aftershocks leads to CFRP permanent damage and subsequent failure. Thanks to the intrinsic property of super-elasticity, the SMA device provides an undamaged CFRP behaviour during all the seismic sequence, with the additional advantage of re-centring the wall subjected to out-of-plane actions. This paper describes the work from the CFRP+SMA device design to its final positive testing.

Shape Memory Alloy (SMA) Devices, Fiber Reinforced Polymers (FRP) strips

1. INTRODUCTION

The MAMAS Project ("Materiali Avanzati Multiprestazionali per Applicazioni in Edilizia/Advanced Multi-task Materials for Structural Applications in Construction") has been managed by the Italian Consortia TRE of Naples and CETMA of Brindisi (2007-2011) with funds of the Italian Ministry of Education, University and Research (MAMAS, 2007). MAMAS focussed on the investigation of innovative material properties (resistance, ductility, dissipation capacity, durability, temperature and impact integrity) capable to withstand extreme natural and anthropogenic actions (earthquakes, accidents and terrorism) to increase the safety of construction/infrastructure. In specific, a scientific team (CETMA Brindisi, ENEA Bologna, Ferrara and Florence Universities) carried out targeted activities, among the various tasks foreseen by the project itself, to conceive, realise and test a prototypal device made by CFRP (Carbon Fibre Reinforced Polymer) strips in series with SMA (Shape Memory Alloy) wires, devoted to face wall overturning in masonry buildings, in case of repeated aftershocks due to seismic events. In fact, CFRP materials are ideally suited for strengthening of concrete/masonry structure when quick prompt ringing is needed in the post-earthquake emergency. With regard to masonry, CFRP interventions can be widely applied against the most dangerous event as the wall collapse due to out-of-plane actions, but the fibre delamination (i.e. decrease of stiffness and load bearing ability) should be avoided, because repair effectiveness cannot be guaranteed if the earthquake leads to CFRP permanent damage and subsequent structural failure. Thanks to the intrinsic property of super-elasticity, a SMA device, done by thin NiTi wires and added in series with the CFRP strip itself, can provide an undamaged CFRP behaviour (i.e. under its elastic limit, enough far from the collapse load) during all the seismic sequence, with the additional advantage of re-centring the wall subjected to overturning, without almost any residual displacement. The expertise on CFRP (University of Ferrara, see Cecchi et al., 2004 & 2005) and SMA (ENEA, see Indirli & Castellano, 2008), gathered in previous research activities, was a fundamental background. The study began with a state-of the-art analysis, focussing on SMA constitutive models and experimental techniques for physical/thermo-mechanical characterisation of SMA NiTi wires. Then, the research continued with: laboratory tests on selected NiTinol (*Nickel-Titanium Naval Ordinance Laboratory*) wires, evaluating chemical composition, identifying alloy phase transformation temperatures, and performing cycled tensile tests at different temperatures, in order to select/verify the most suitable alloy for the SMA device; conceptual design and engineering of the CFRP+SMA system (from theoretical aspects to field of application, dimensioning, overturning verification, choice of materials, and finally constructive details and drawings); SMA multi-plateau device experimental characterisation. The CFRP+SMA system effectiveness has been verified thanks to a laboratory experiments performed on two 1:3 scaled masonry mock-ups, taking into account the following configurations: horizontal actions on the unreinforced mock-up, with progressive CFRP repair/strengthening, until collapse; horizontal actions on the mock-up with CFRP+SMA ringing and local CFRP repairs against the cracks, until failure. Additional researches (not object of this paper) interested Finite Element models provided by CFRP+SMA devices and vertical tying systems (post-tensioned or not, made by different materials) for tall and slender masonry structures. MAMAS ended with some recommendations and suggestions where a safety prompt intervention, applying the developed CFRP+SMA combination, results quick, effective and money saving.

2. BACK GROUND AND NEW POTENTIALITIES

The effective, but unlinked, use of CFRP strips and SMA devices for repair/strengthening of seismically damaged masonry structures (including heritage) is demonstrated by several applications in the last years, taking place mainly in the framework of post-reconstruction programmes and rarely for preventive improvement. On the contrary, the beneficial combination of the two techniques, not foreseen yet, represents the core idea of our research, highlighting advantages and avoiding drawbacks. The proposed CFRP+SMA system is also conceived to cover the critical time interval immediately after the disaster, when safe, quick, easy and cheap prompt interventions should be provided by emergency teams on a wide scale.

2.1. SMA devices and FRP strips

The development of innovative SMA-based techniques, devoted to seismic protection of masonry structures, began in Italy within the EU funded ISTECH Project, coordinated by FIP Industriale and ENEA as a partner (ISTECH, 1996). The reference Indirli & Castellano, 2008 gives all the information regarding the main properties of SMA devices as anti-seismic systems, testing results, and structural configurations selected for applications. The multi-plateau device (based on the special thermo-mechanical property named super-elasticity, due to the reversible hysteretic transformation between two crystalline configurations, known as austenite and martensite, Figure 1) has the capacity to work at increasing force levels, being also less sensitive to the masonry tensile strength (Figure 2). ISTECH led to significant exploitations, in particular the reinforcement measures for the Upper Basilica of St. Francis in Assisi (Figure 3), hit by the 1996 Marche-Umbria (Italy) earthquake. At the end of the project, FIP Industriale patented the SMA device (EU Patent, 2000).
Carbon Fibre Reinforced Polymers (CFRPs), for restoring/reinforcing masonry structures, have been widely studied, tested (Figure 4) and applied in several cases of technical relevance after recent seismic events, as shown by a wide amount of articles in the literature (just some examples: Triantafillou & Fardis, 1997; Abrams, 2000; Tumialan et al., 2001; Borri et al., 2002; Casareto et al., 2003; Faella et al., 2004; Santa-Maria et al., 2004; Turek et al., 2004; Briccoli Bati et al., 2007; Valluzzi, 2007; Corradi et al., 2008; Hancilar et al., 2008).

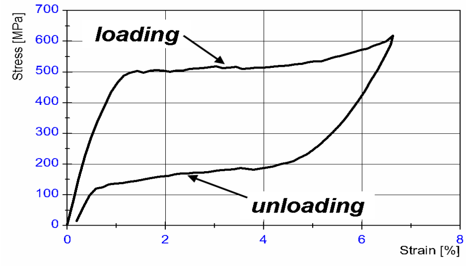


Figure 1. Cyclic tension test in the super-elastic range on a SMA wire (Indirli & Castellano, 2008).

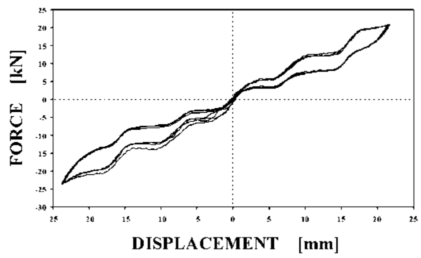
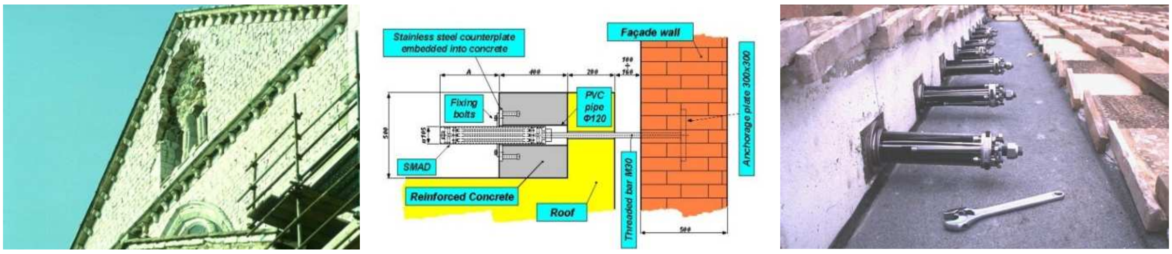


Figure 2. Multi-plateau SMA device force-displacement cycle (Indirli & Castellano, 2008).



(a) (b) (c)

Figure 3. St. Francis Basilica in Assisi: (a) earthquake damage in the transept tympana; (b) scheme of the reinforcement intervention with SMA devices in series with conventional steel ties; (c) picture of the entire SMA devices row at the end of the work (Indirli & Castellano, 2008).

(a) (b) (c)

Figure 4. Examples of different CFRP reinforcement during tests on masonry specimens: (a) panel strengthened with CFRP strips (Borri et al., 2001); (b) creep simulation on sample strengthened with thin CFRP strips (Valluzzi, 2007); (c) CFRP fabric debonded after failure (Santa Maria et al., 2004).

2.2. Field of application of the FRP+SMA system

Many earthquakes demonstrated that the most dangerous damage, until collapse, is due to out-of-plane overturning (Figure 5), when the lack of effective connections between bearing walls is evident. The recent seismic event occurred in L'Aquila (Italy, April 6, 2009) provides clear examples of failure patterns due to this kind of actions (Indirli et al., 2012), which can be identified in global and local mechanisms, thanks to the MEDEA classification and quick investigation tool (Papa & Zuccaro, 2004; MEDEA, 2005). Prompt interventions in the city of L'Aquila can be divided into two categories:

a) the works performed by the Firemen in the days immediately after the earthquake, often timber structures (Figure 6a-e), rarely strips of various materials (Figure 6f-g);

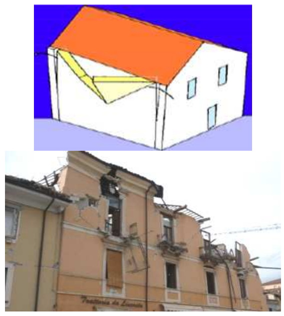
b) the put-in-safety scaffoldings, mainly inside the "red zone" of L'Aquila historic centre, with the widespread and expensive use of tubular steel elements (Figure 7a), as done after previous seismic events (Figure 7b-d). In the opinion of the authors, the CFRP+SMA device, developed in MAMAS, can represent an effective, safe and cheaper alternative to the currently used methodologies for post-earthquake prompt interventions.

3. EXPERIMENTAL ACTIVITIES OF THE MAMAS PROJECT

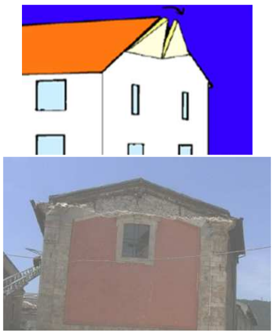
Among the various tasks performed in MAMAS, this article is focussed on the experimental activities.

(a) global mechanism whole wall overturning

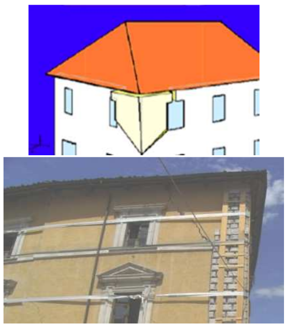
(b) global mechanism partial wall overturning



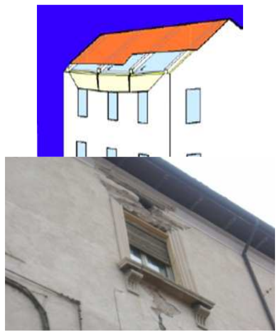
(c) global mechanism wall bending rupture



(d) local mechanism roof gable wall overturning



(e) local mechanism corner overturning (upper part)



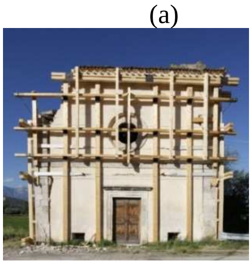
(f) local mechanism overturning (wall supporting roof)

Figure 5. Global and local collapse mechanisms associated to out-of-plane-actions detected in L'Aquila (Italy) after the April 6, 2006 earthquake (Indirli et al., 2012).

(a)

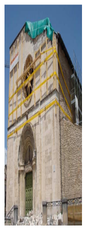
(b)

(c)

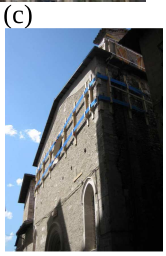


(d)

(e)

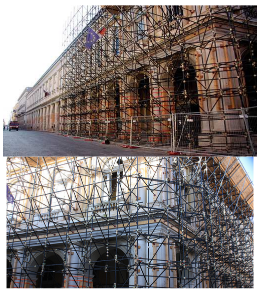


(f)



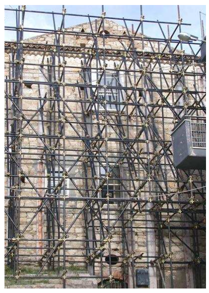
(g)

Figure 6. Examples of various prompt interventions performed by the Firemen in the days immediately after the earthquake in L'Aquila, Italy: (a-e) timber materials; (f-g) strips of various materials.



(a)

(b)



(c)

(d)

Figure 7. Put-in-safety scaffoldings using tubular steel elements: L'Aquila(a); Camerino, 1997-98 Marche-Umbria earthquake (b); San Giuliano di Puglia, 2002 Molise-Puglia earthquake (c-d).

3.1. Characterisation of the selected NiTinol alloy wires

3.1.1. Chemical analysis
The NiTinol material (3 wires, diameter ∅=1 mm) has been characterised through thermo-mechanical tests. The alloy showed the following percentages: 57.7wt.% Ni, 41.6wt.% Ti.

3.1.2. DSC tests
The DSC (*Differential Scanning Calorimetry*) tests, after the sample annealing at T=700°C, provided the identification of the alloy phase transformation temperatures, as reported by Table 3.1 (see also Figure 8 for explanation).

3.1.3. Tensile cyclic tests at ambient temperature (T=25°C)
These tests have been performed (Figures 10-11) again on 3 NiTinol wires (10 on each wire, L=150 mm and ∅=1 mm), after 10 stabilisation cycles, with a maximum strain ε_{max} =8%, and different strain velocities (1 mm/min, 10 mm/min, 20 mm/min, 50 mm/min, 100 mm/mm). It can be noted that the area of the hysteresis cycle reduces if the velocity of deformation increases, with the uplift of the unloading phase. Examples of Elastic Modules and transformation stresses are reported in Tables 3.2-3.3. The average values of Elastic Modules E_I and E_{II} are respectively 40910 and 23140 MPa.

3.1.4. Tensile cyclic tests at temperature T=50°C
These tests have been performed again on 3 NiTinol wires, as shown by examples in Figures 12-13, with the same different strain velocities used before. Also in this case, decrease of the area of the hysteresis cycle and uplifting of the unloading plateau are evident. The selected NiTinol material maintains its super-elastic behaviour at T=50°C for all the deformation velocities. Taking into account all the results, it can be concluded that 50<Md<150°C. Furthermore, tests at T=25 and 50°C show that plateau stresses grow with the temperature increment (Figure 14), as reported in the literature.

3.1.5. Brief description of the SMA device and its characterisation
Previous tests on single NiTinol wires (3 samples) permitted to define design dimensional/mechanical data of the SMA device (Figure 15 and Table 3.4), which is schematically composed by three parallel plaits of 8 wires (length 400 mm) each, anchored at the ends and contained in a metallic box (Figure 9); ΔL/L is the completely recoverable strain at the end of the cycle and $N_{d,nom}$ the total design loading. The wire plait length can be manually regulated in pretension (or not), in order to calibrate a different three-plateau loading/unloading hysteretic behaviour, depending on the user's need. Three plait configurations (TF1, TF2, TF3, depending on wire pretension) have been used both for SMA device characterisation and during tests on the masonry mock up provided by CFRP+SMA devices. Examples of the multi-plateau behaviour are reported in Figure 16.

3.1.6. laboratory experiments on masonry mock-ups
Laboratory experiments were performed on two full-brick masonry 1:3 scaled mock-ups (box 150x150 and height 100 cm), i.e. a small house with an opening simulating a window, irregularly located along the perimeter; the horizontal load (with a quasi-static increment during the tests) was applied pushing 4 hydraulic jacks, while the vertical one through pre-tensioned (15 kN) steel cables acting on 2 metallic trusses (box section), placed on the top in the transversal direction (Figure 17). Five LVDTs (Linear Variable Displacement Transducers, marked with CH in Figure 17) and two strain-gauges (registering the displacement along the orthogonal directions) have been used to provide useful measurements. Material parameters are given by Tables 3.5-3.6.
Test A1 (Figure 18) on the first masonry mock-up, without any CFRP reinforcement, started with a loading jack pressure of 5 to 50 bar (steps of 2 bar), and a similar unloading. At its end, a local damage mechanism (horizontal crack), and significant residual displacements (0.2-0.5 mm) were detected. Test A2 was carried out (horizontal load until 140 bar) after repairing the damage (including a CFRP reinforcement), because the investigation of the overturning mode of the front wall (located on the opposite side of the application of horizontal load) was considered the priority (Figure 19). A horizontal crack in the front wall has been observed (high residual displacements, 3.5-4.0 mm), due to a local overturning mechanism of the upper portion. Before test A3 (until 165 bar) and test A4 (until

200 bar, maximum displacements 8-10 mm) the CFRP reinforcement has been progressively implemented in the damaged zones, with a complete ringing on three (top) and four (bottom) sides (Figure 20). Front wall global overturning was evident in the final part of the experimentation, with the decrease of the load-displacement curve slope, also due to the delamination of the CFRP strips.

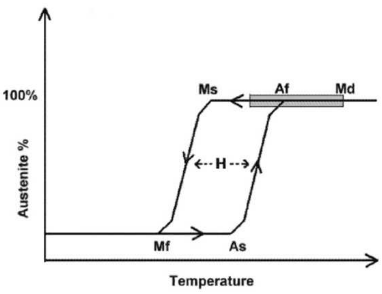


Figure 8. Martensitic transformation and hysteresis (H) upon a change of temperature. As: Austenite start, Af: Austenite finish, Ms: Martensite start, Mf: Martensite finish. Md: highest temperature to strain-induced Martensite, Grey area: area of optimal super-elasticity.

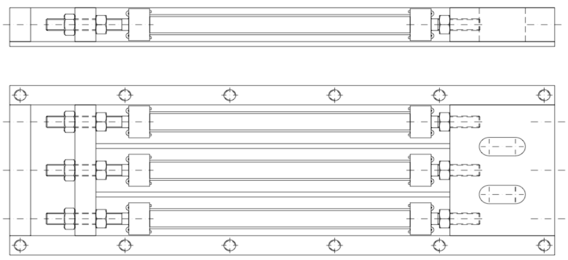


Figure 9. Sketches of the SMA device.

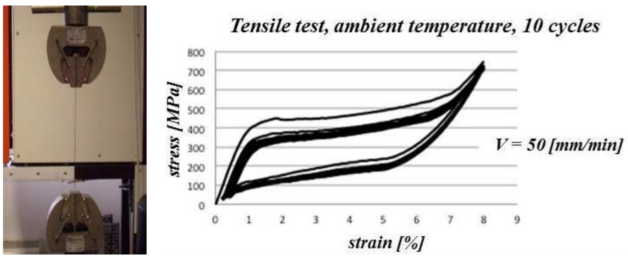


Figure 10. Tensile cyclic test at 25°C (10 cycles, V = 50 mm/min), wire n. 1.

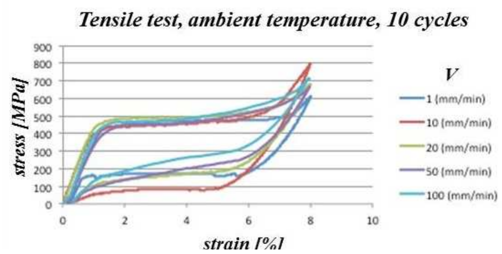


Figure 11. Tensile cyclic tests at 25°C with different velocities of deformation, wire n. 1.

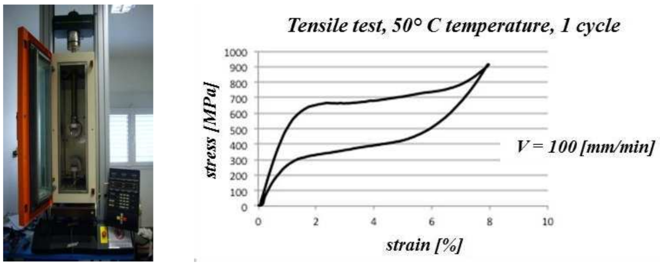


Figure 12. Tensile cyclic test at 50°C (1 cycle, V = 100 mm/min), wire n. 1.

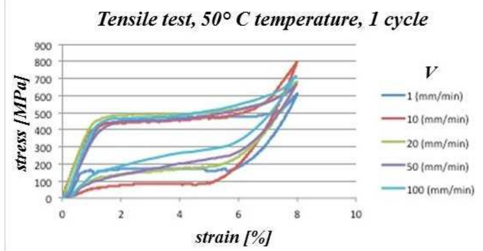


Figure 13. Tensile cyclic tests at 50° C with different velocities of deformation, wire n. 1.

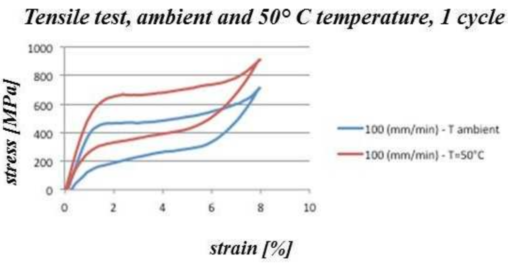


Figure 14. Comparison of the hysteretic cycles at ambient temperature (25 °C) and T = 50 °C.

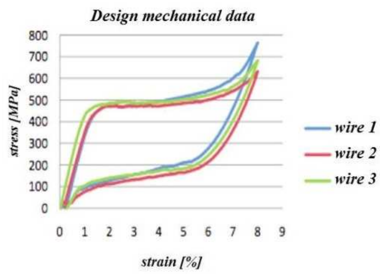


Figure 15. Design mechanical data of the SMA device (3 samples of single wire).

The B-test sequence was carried out on the second mock-up (growing horizontal loads until the activation of the out-of-plane behavior of the front wall) with the following variations (Figure 21): the front wall was kept not completely connected, in order to facilitate the global overturning mechanism; vertical CFRP strips were applied in the wall subjected to horizontal load; a continue CFRP ringing (in series with 2 SMA devices) took place along three walls (except the front one); the 2 SMA devices were fixed at the ends of the front wall through steel plates. Before test B3 (2 consecutive similar load cycles), also the window was reinforced with CFRP strips. Before test B4, the SMA devices were removed. The main results (tests B1-B3) have been the following: the slope variations demonstrated that the system reached at least the second SMA plateau; the crack closure (residual displacements equal to 1-2 mm) speaks about the effective re-centering action of the SMA devices, also contributing to energy dissipation. Finally, the B4 test led the structure close to collapse; CFRP delamination (avoided in the tests with SMAs) was evident at least in one point (up-left corner of the window).

Table 3.1. Alloy phase transformation temperatures (°C)

Ms [°C]	Mf [°C]	As [°C]	Af [°C]
16	-18	-10	18

Table 3.2. Values of Elastic Module for the wire n. 1 (MPa) at T=25°C

V (mm/min)	E_I (MPa)	E_{pc} (MPa)	E_{II} (MPa)	E_{ps} (MPa)
1	39793	829	25349	297
10	39212	1663	24706	1544
20	39423	2433	24979	2861
50	39573	2838	22153	3724
100	39875	2753	22379	3512
E_I: Elastic Module for the first elastic stroke of the curve; E_{pc}: Elastic Module for the uploading plateau; E_{II}: Elastic Module for the second elastic stroke of the curve; E_{ps}: Elastic Module for the unloading plateau.				

Table 3.3. Values of transformation stress for the wire n. 1 (MPa) at T=25°C

V (mm/min)	σ_{sc} (MPa)	σ_{fc} (MPa)	σ_{ss} (MPa)	σ_{fs} (MPa)
1	409	508	179	161
10	414	564	171	88
20	422	626	255	87
50	370	577	305	105
100	350	506	276	123
σ_{sc} - σ_{fc}: transformation stress at the beginning - end of the uploading plateau; σ_{ss} - σ_{fs}: transformation stress at the beginning - end of the unloading plateau.				

Table 3.4. Design data for the SMA device

single wire dimensional/mechanical data					single plait data		
∅ [mm]	A [mm^2]	N_{max} [kN]	σ_{max} [kN/mm^2]	ΔL/L [%]	n° wires	A [mm^2]	$N_{d,nom}$ [kN]
1.000	0.785	0.510	0.650	8	8	6.28	4.08
∅	wire diameter	σ_{max}	maximum stress value		N_{max}	loading maximum value per wire	
A	wire area/plait area	ΔL/L	maximum strain value		$N_{d,nom}$	design loading value per plait	

Table 3.5. Parameters of the mock up construction materials

masonry full brick			mortar		
E [MPa]	ν	G [MPa]	E [MPa]	ν	G [MPa]
17000	0.1	6800	2000	0.1	800
compression strength [MPa]	tensile strength [MPa]		compression strength [MPa]		
17	1.7-2.0		2.0		

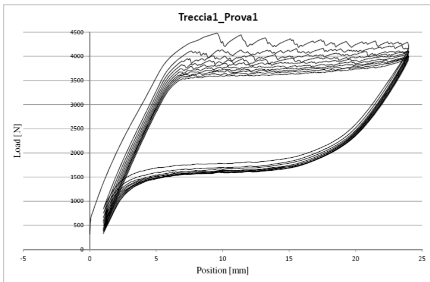
Table 3.6. Parameters of the FRP material

fibre thickness [mm]	adhesive thickness [mm]
0.165	0.73
fibre E [MPa]	adhesive E [MPa]
230000	3500
masonry E [MPa]	composite E [MPa]
1400	46500

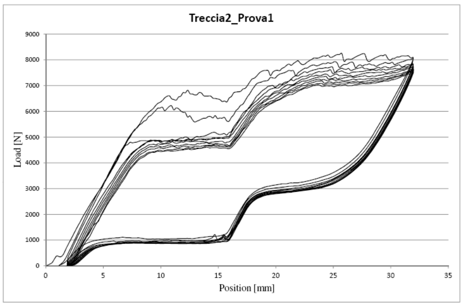
4. CONCLUSIONS

The MAMAS experimental campaign confirmed the results of previous researches done on SMA materials/devices for masonry construction strengthening/repairing. The beneficial effects of the CFRP+SMA combination can be considered a specific positive output of the project itself, because this prototypal device appears suitable for further industrial and commercial exploitation.

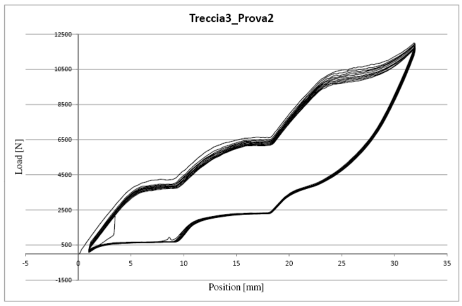
equipment for the SMA characterisation tests



10 loading cycles for the configuration TF1



10 loading cycles for the configuration TF2



10 loading cycles for the configuration TF3

Figure 16. Characterisation tests on the SMA device.

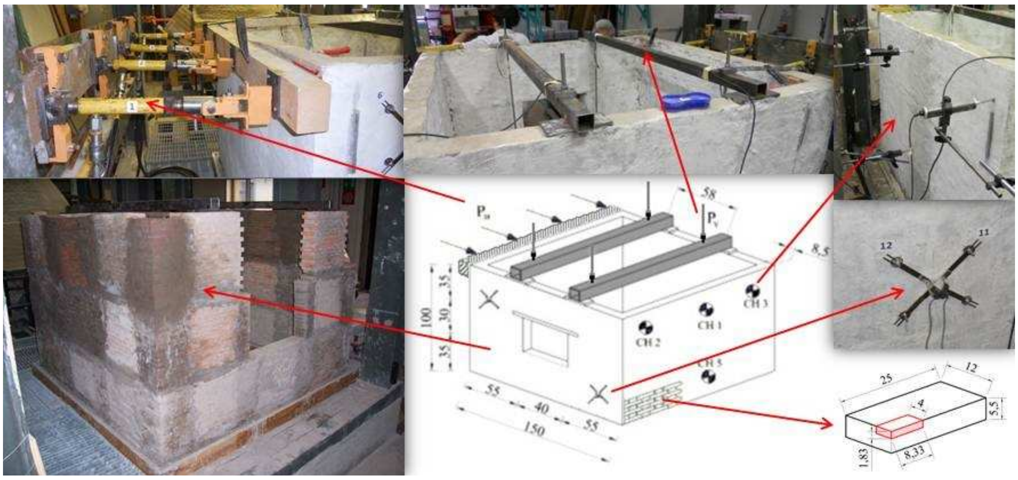


Figure 17. Configuration for the tests on the first masonry mock-up.

before the test *after the test*

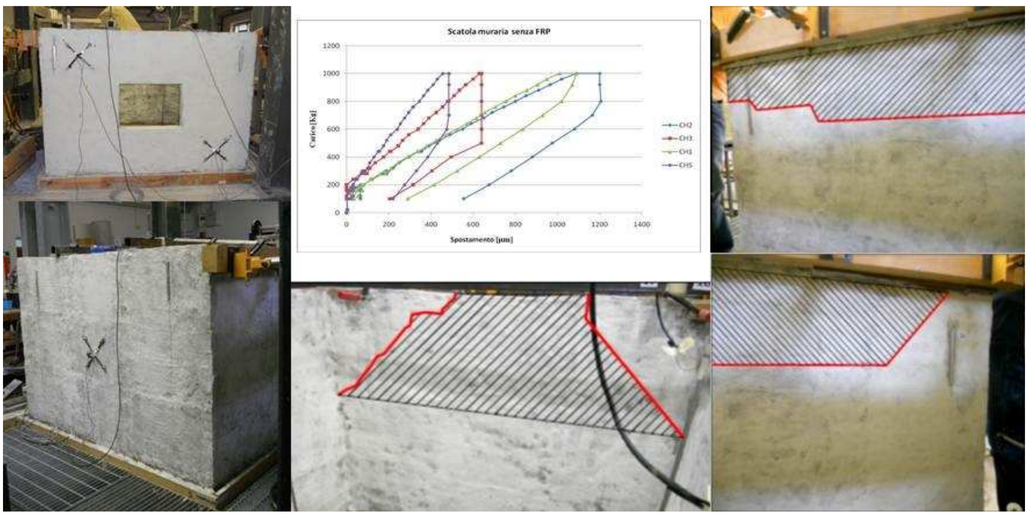


Figure 18. Test A1 on the first masonry mock-up without any reinforcement.

before the test *after the test*

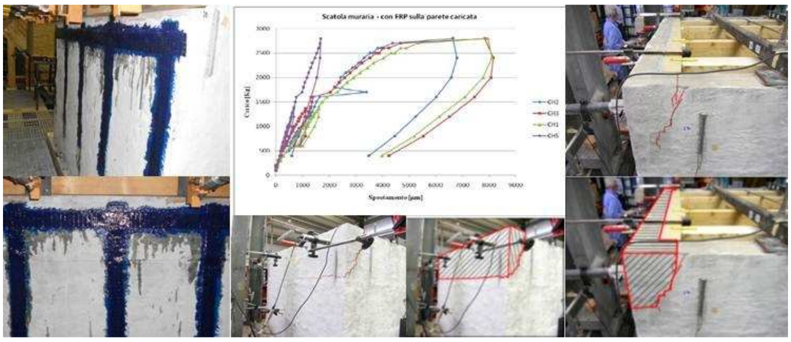


Figure 19. Test A2 on the first masonry mock-up with CFRP reinforcement.

before the test *after the test*

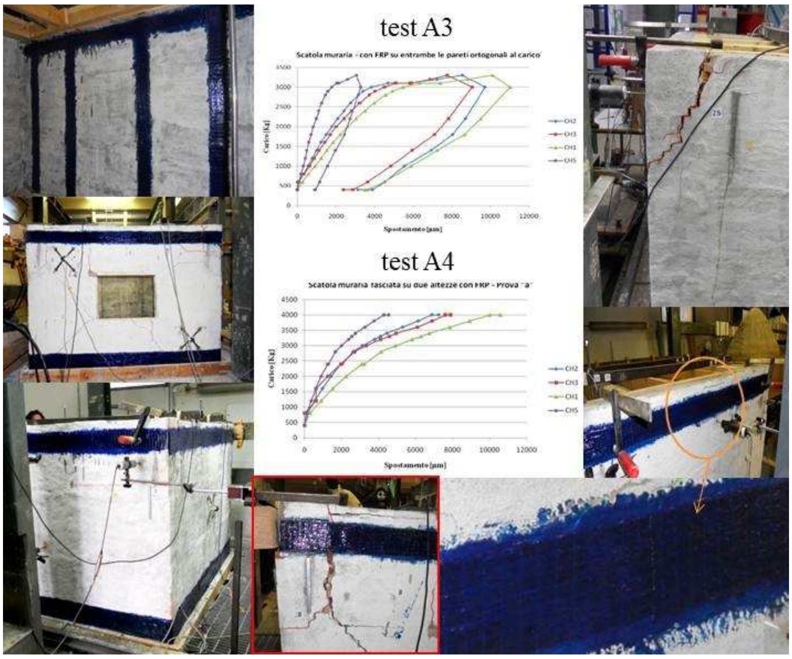


Figure 20. Tests A3-A4 on the first masonry mock-up with CFRP reinforcement complete ringing. CFRP delamination was evident at the end of test A4.

before the test B1 *after the tests B1-B3* *after the test B4*

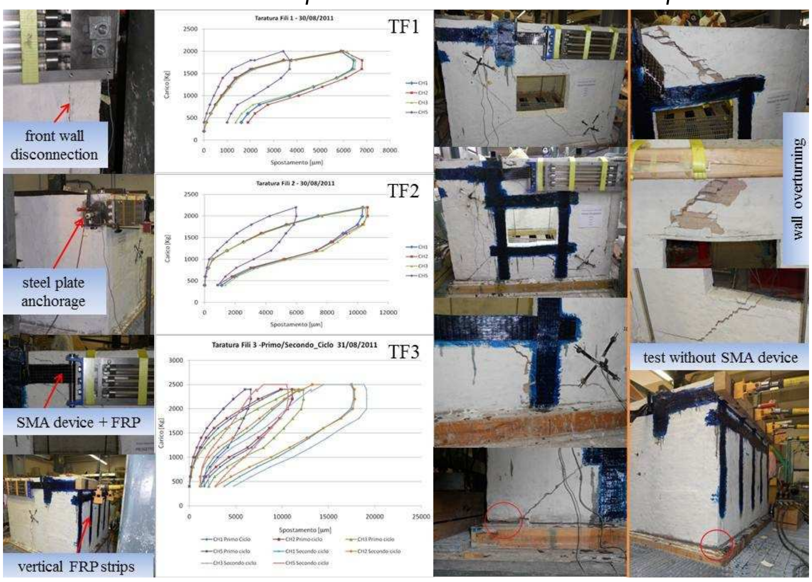


Figure 21. Tests B1-B3 on the second masonry mock-up with CFRP +SMA devices; test B4 without SMAs.

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