
Seismic Upgrading and Post-Event Structural Strengthening with Shape Memory Alloys

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ABSTRACT

VSL and re-fer AG share a common passion for both structural strengthening and post-tensioning technologies. These key focus areas uniquely combine together in the application of memory-steel, an iron-based Shape Memory Alloy (Fe-SMA) - a sustainable and efficient solution for structural reinforcement and seismic retrofitting in concrete and masonry.

Memory-steel, due to its prestressing effect, provides active reinforcement immediately upon application, and does not require the strengthened structure to further deform to activate the additional load-carrying capacity. This characteristic is combined with a pronounced material ductility reflecting positively on the overall structural ductility. The embedment in a mortar layer further reduces sensitivity to softening and freeze-thaw scenarios and hence represents another distinguishing advantage compared to competitive composite solutions. Mechanical and durability behaviour is complemented by an easy and straightforward installation process.

This paper presents the key material properties including the shape memory effect, stress recovery and ductility. Large-scale experimental investigations demonstrate the structural efficiency of the repair method, while on-site applications in Europe demonstrate the maturity level of this technical innovation.

1 INTRODUCTION

Following the introduction of carbon fiber reinforced polymers (CFRP) over thirty years ago, shape memory alloys (SMA) represent the next generation of innovative materials in structural repair. While nickel-titanium based alloys are well utilised in medical and aeronautical applications, their high price renders a broad use in construction impossible. Iron-based SMAs on the other hand can be offered at lower costs and hence are a

competitive solution for structural repair. Their easiness in application, combined with the advantageous material properties including the prestressing effect (shape memory effect – SME), make them an attractive solution for structures with various strengthening requirements and restrictions. For reinforced concrete structures, post-tensioning with memory-steel allows the stresses in internal steel reinforcement to be reduced and hence extend the lifespan of the subject structure, as depicted in Figure 1. Furthermore, it can be used to increase shear resistance in masonry walls that are at risk of being impacted by an earthquake.

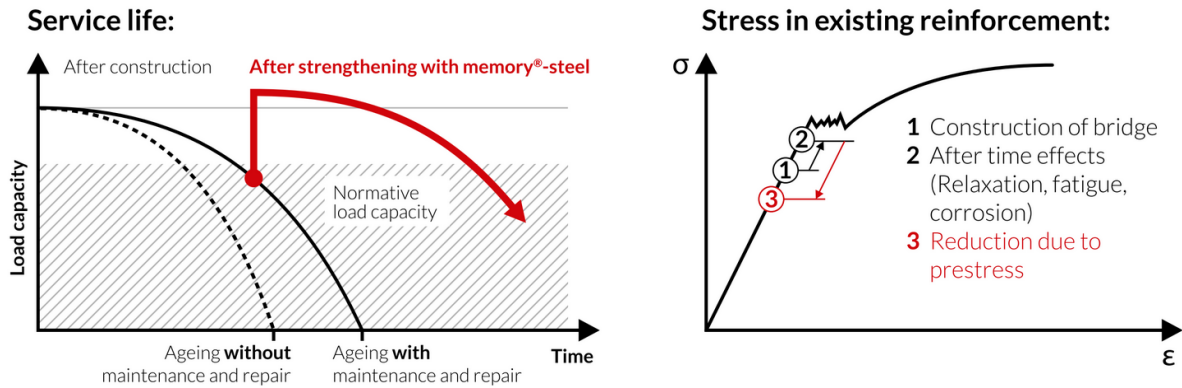


Figure 1: Extension of service life due to post-tensioning with memory-steel

2 MATERIAL PROPERTIES

2.1 Shape Memory Effect

The shape memory effect (SME) is schematically presented in Figure 2. After a pre-straining (1) to ϵ_p and the subsequent releasing to a permanent deformation $\epsilon_{l,r}$, the initial pure austenite phase is enhanced by a partial martensite presence in the crystalline structure. From this point on, upon heating to a specific target temperature and the related back-transformation of the martensite to austenite, two distinct procedures are possible. Without any restraint, the material is free to move and shrinks back towards its initial state (2). This process is known as the *shape recovery*. With a restraint however, shape recovery is not possible and is accordingly transformed into a *stress recovery* (3). This precise mechanism is used in the memory-steel repair technology presented in the sections to follow.

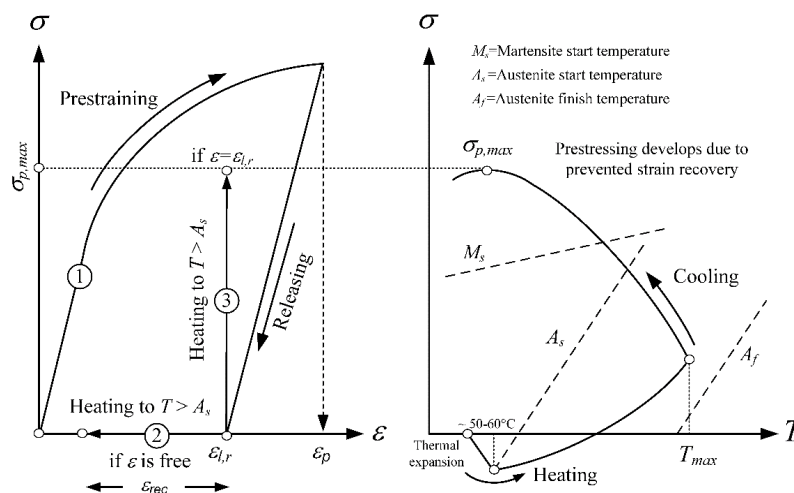


Figure 2: memory-steel pre-straining (left) and stress development upon heating (right), (Michels et al., 2018)

2.2 Stress-Strain and Recovery Stress Behaviour

Figure 3 shows the stress-strain (left) and recovery stress behaviour (right). From the unidirectional tensile tests, it becomes apparent that the material exhibits very large strains at failure with values above 20%. In comparison with conventional B500B steels, ductility is even higher. For an initial pre-strain of 6%, increasing the target activation temperature leads to higher recovery stresses. Maximum values for this alloy, also for lower pre-strain values of 2 and 4%, typically lie between 250 and 400 MPa.

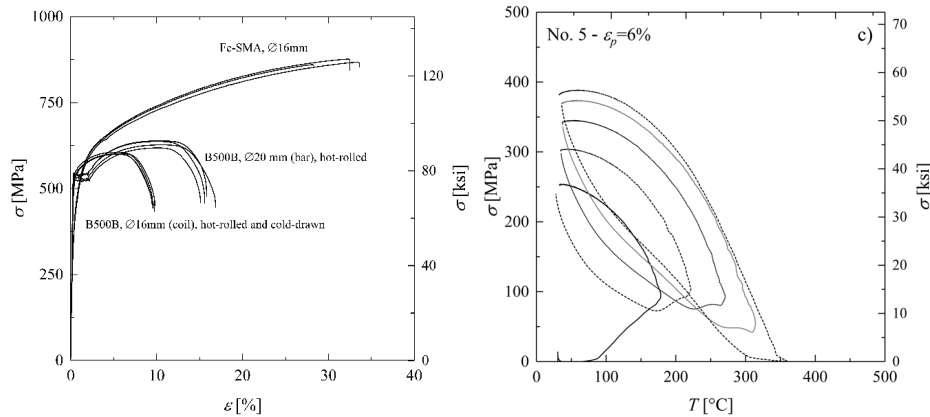


Figure 3: Stress strain (left) and stress-temperature behaviour (right) of memory-steel, (Michels et al., 2018)

3 STRUCTURAL TESTING

3.1 Flexural Strengthening of Concrete Structures

Flexural strengthening of existing reinforced concrete structures using Shape Memory Alloys is possible both in the top and bottom planes. On top, either a solution with cut grooves (similar to near-surface-mounted CFRP strips) or a full cover replacement can be applied as shown in Figure 4. In both cases, the demolished concrete is replaced with a cementitious mortar. On the bottom side, a sprayed mortar application is used to substitute the existing concrete, once the Shape Memory Alloy has been incorporated.

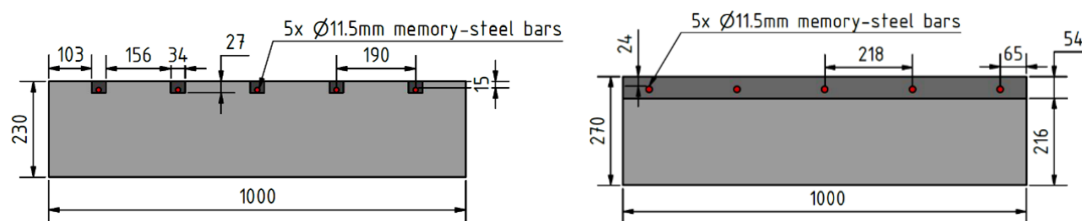


Figure 4: Near-surface-mounted (left) and cover replacement method (right) for flexural strengthening of concrete with memory-steel, (Schranz et al., 2021)



Figure 5: Cementitious end-anchorage (left) and shape memory activation with resistive heating (electric current), (Schranz et al., 2021)

The application typically foresees two stages:

- a) after an adequate surface treatment (roughening), the memory-steel rebars are placed and end-anchored with cementitious layer (see Figure 5 left).
- b) After sufficient cure, the bars are activated with heating using either a gas torch or, as shown in Figure 5 (right), via electric current known as ‘resistive heating’. The part of the bar in the free length outside of the anchorages is eventually also embedded within a spray mortar which is applied to the final structural profile, following completion of the heating/activation process. A full embedment of the bar with no exposed free length and a subsequent resistive heating is also possible.

As part of the testing process, cantilever slabs (total length 5 m) were loaded to failure as shown in Figure 6 at Empa (Switzerland). The structure is representative of a deck slab on a box-girder bridge section, loaded in the transverse direction. In total 4 slabs were tested:

- i. reference reinforced concrete section without any additional reinforcement,
- ii. cover replacement strengthening with activated memory-steel rebars,
- iii. near-surface-mounted with memory-steel reinforcement without activation,
- iv. near-surface-mounted with activated memory-steel rebars.

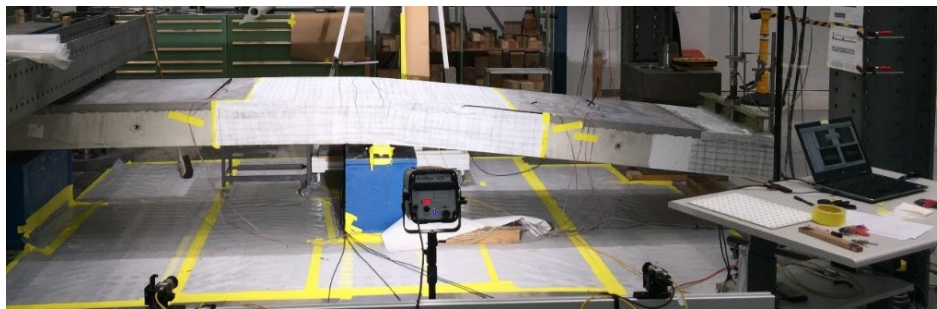


Figure 6: Experimental setup of large-scale slab testing in flexure, (Schranz et al., 2020)

By measuring the tip-deflection during the activation process, an average recovery stress of 290 MPa could be back-calculated. The subsequent loading to failure is shown with the load-tip deflection curves in Figure 7.

For all retrofitted slabs, the increase in the load-carrying capacity is apparent. Furthermore, structural ductility as a result of the memory-steel material ductility is a further advantage. All slabs failed by concrete crushing over the central support with a simultaneous yielding of the inner steel bars. When zooming in (right graph), an increase in cracking load with activated (prestressed) memory-steel rebars (blue and green curve / cracking load >20 kN) compared to the reference slab (6 kN cracking load) non-activated one (red curve) can be observed. This demonstrates clearly the effect of the post-tensioned bars.

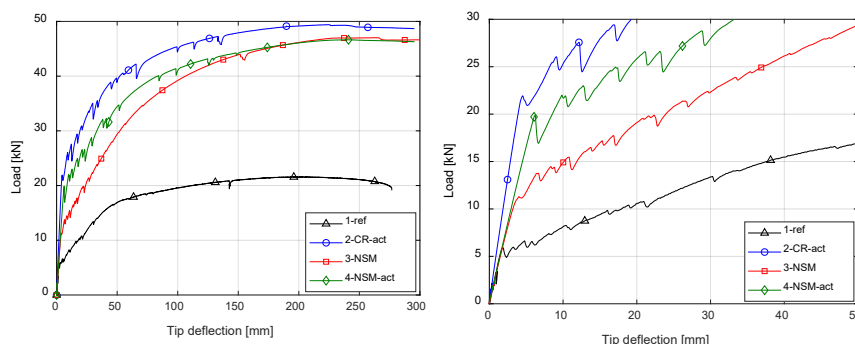


Figure 7: Force-deflection curve of large-scale structural loading test in flexure, (Schranz et al., 2021)

3.2 Shear Strengthening of Concrete Structures

Shear strengthening of reinforced concrete structures with memory-steel rebars can be executed according to Figure 8 and 9 showing a series of large-scale experiments at Empa (Switzerland). After a surface roughening, the bars are installed and embedded in sprayed mortar layer. Resistive heating is then applied to activate the bars.

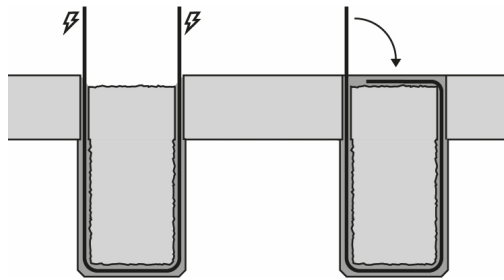


Figure 8: Schematic shear strengthening of reinforced concrete sections and memory-steel re-bars, (Czaderski et al., 2021)



Figure 9: Surface roughening, rebar installation, sprayed mortar application, resistive heating, (Czaderski et al. 2019)

Five beams were loaded to failure, all beams failed in shear. The load-deflection curves are shown in Figure 10 (left). Reference Beam 1, after having reached failure and exhibiting crack openings of >10 mm alongside internal stirrup failure, was also repaired and reloaded. In this case, a 30% higher load-carrying capacity compared to the reference beam with three memory-steel stirrups at each end was observed. Two more beams (2 and 3) were strengthened with three memory-steel stirrups on each side, once with activated bars and once without. A further two beams (5 and 6) were strengthened five stirrups on each side. In addition to higher load carrying capacities with increasing memory-steel stirrups, it could be observed that the strain increase in the internal steel stirrups developed much slower in the case of the activated bars (see Figure 11 right). Yielding of the internal steel stirrups (at around 2.5‰) occurred at a load level of about 350 kN for Beam 3, but only at a load level of almost 500 kN for Beam 2. Diagonal shear cracks also appeared at lower load levels when the memory-steel stirrups were activated. This leads to the conclusion of a general relieve of the existing structure in shear in case of a prestressed reinforcement.

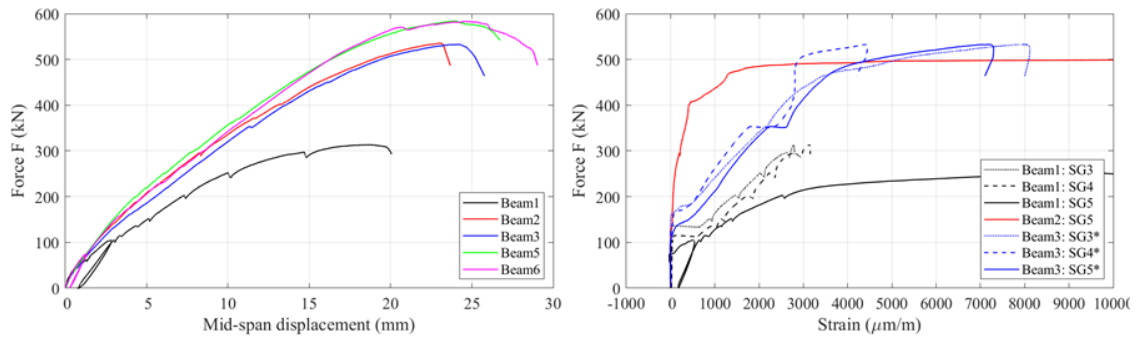


Figure 10: Force-deflection curve of large-scale structural loading test in shear (left) and force-internal stirrup strain evolution, (Czaderski et al., 2021)

3.3 Strengthening of Masonry Walls

Masonry walls can be easily and efficiently strengthened by inserting memory-steel rebars into precut grooves (within the masonry) and by anchoring them into the overhead and base concrete floor slabs. After activation of the memory-steel bars by gas torch, the groove is then filled with a mortar. This technique allows the application of an additional vertical load to the masonry wall and hence an increase in the shear resistance. The easy and straightforward installation process also benefits the end solution with no space being lost after the intervention.

An experimental campaign at the University of Tehran investigated the seismic enhancement possibilities using the above-mentioned technique. In addition to vertical SMA post-tensioning (Figure 11 left), a diagonal application was also included in the strengthening research program (Figure 11 right).

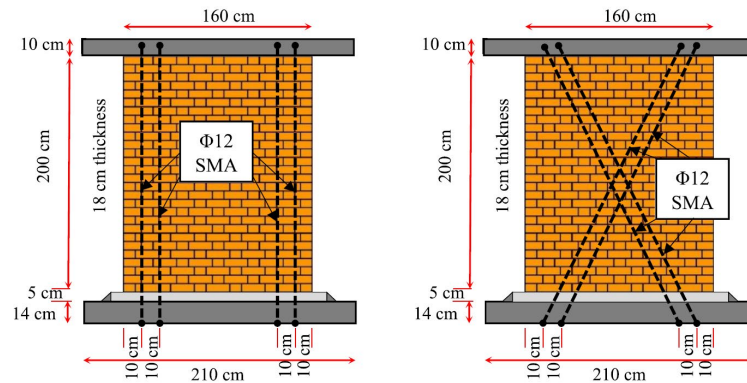


Figure 11: Vertical and diagonal application of memory-steel re-bars for seismic upgrading of masonry, (Rezapour et al., 2025)

The following Figure 12 presents the load-lateral drift curves for the non-strengthened masonry wall and the two applications using vertical and diagonal memory-steel rebar strengthening. Failure occurred predominantly by diagonal shear cracking for all test walls. The effect of the prestressing becomes apparent in higher load-carrying-capacity and higher energy dissipation, the diagonal setup being the most efficient one.

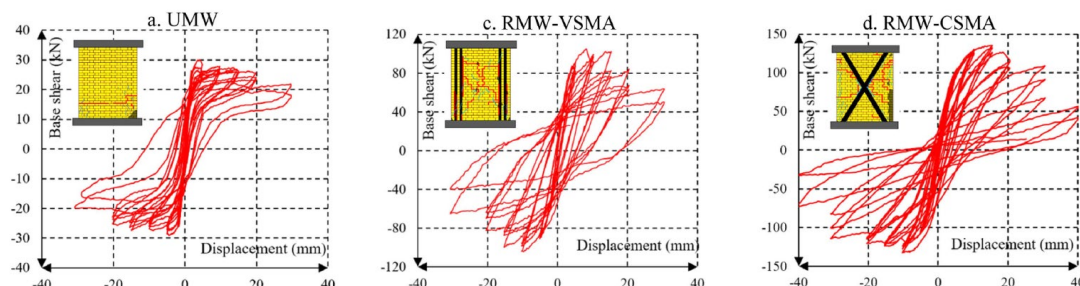


Figure 12: Load-lateral displacement (drift) for non-strengthened masonry (left), vertical memory-steel application (middle) and diagonal memory-steel application (right), (Rezapour et al., 2025)

4 REFERENCE CASES



Figure 13: Flexural strengthening of bridge girders and deck soffits

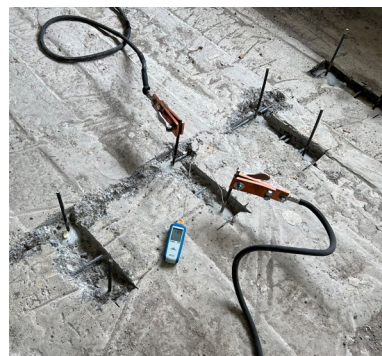


Figure 14: Shear strengthening of bridge girders

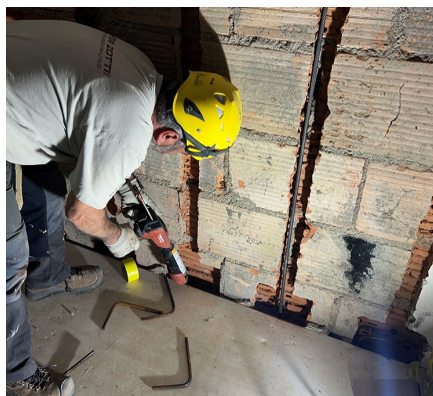


Figure 15: Seismic strengthening of masonry walls

CONCLUSIONS

The main conclusions can be summarized as follows:

- memory-steel is an active structural strengthening system – the structure does not need to deform further in order to activate the additional capacity.
- As shown in the experiments, this strengthening solution reflects positively on the structure's behaviour under service load with delayed cracking, reduced deformation and a relief of stress in the existing reinforcement.

- Memory-steel is very ductile and therefore does not restrict the deformability of the structure under ultimate load (see test results), and allows all structural components (internal reinforcement, concrete) to be used to full capacity.
- It can be seen that the installation and activation process is straightforward, not requiring sophisticated tools such as hydraulic jacks and others. In the case of deficient bridge strengthening for instance, memory-steel can be easily integrated into conventional concrete repair methods (e.g. additional mortar layers) and contribute to an extension of the structure's extended lifespan.
- For masonry structures, seismic upgrading is easy to implement as many on-site projects have documented. Experimental investigation has confirmed the structural efficiency with, among other benefits, an overall increase in shear resistance.
- Forces can be applied in a targeted manner and distributed over large areas. There are no localised concentrations of force as with post-tensioning cables.
- The system is always anchored in the healthy core concrete of the structure and protected against fire and corrosion by the mortar covering. With correct covering, external temperature influences also have less impact – an added advantage over, for example, surface-mounted reinforcement products (resins show softening at high temperatures, or slight deterioration at low temps and freeze-thaw cycles).

5 REFERENCES

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