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‘memory steel’ for Shear Reinforcement of Concrete Structures

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ABSTRACT: Strengthening of reinforced concrete (RC) structures is generally used to increase either their bending or shear resistance. The latter is usually performed with fiber reinforced polymer (CFRP) by means of the near-surface mounted (NSM) strengthening technique (bars), or by external bonded CFRP fabrics and strips. In case of a prestressed shear strengthening, several advantages can be obtained due to the prestressing force: closing of existing cracks, reducing the force in the internal stirrups, delaying the appearance of new cracks, and increasing the ultimate shear resistance. However, technical implementation is complex.

Empa and re-fer AG developed strengthening products from a new iron based shape memory alloy (Fe-SMA), also denominated as ‘memory-steel’. A shape memory alloy (SMA) has the unique property to remember its initially given shape upon heating after having been deformed over elastic extent. This memory steel can be used as a prestressing system for concrete structures.

In the current study, small scale experiments for investigating the overall principle have been carried out. These experiments demonstrated the feasibility of such a Fe-SMA shear reinforcement. Additionally, T-beams with a span of 5 m have been experimentally examined to study the application of memory steel bars for pre-stressed shear strengthening. The ribbed memory steel stirrups have been used in combination with shotcrete mortar. An important finding was the fact that the bending of the stirrups in the corners did not hinder the system to work. The application finally enhanced the structural behavior of the RC members as the shear cracks width can be reduced and new shear cracks occur under higher loads.

1 INTRODUCTION

A shape memory alloy (SMA) has the unique property to remember its initially given shape after being deformed over elastic extent. This “back deformation” (also: recovery) either happens immediately upon unloading or by heating above a critical temperature (Czaderski et al. 2014). The effect is triggered by internal changes in the crystal structure depending on the current temperature or the stress state, respectively. This shape memory effect (SME), thus led to various applications in robotics, automotive, aerospace and biomedical industries, where the material is used as actuator or damper for example (Mohd Jani et al. 2014).

The first reported steps towards the discovery of the SME were taken in the 1930s and for a long time only expensive base material such as gold or titanium were used to fabricate the memory metals. Every type of alloy has its own characteristics, better or worse shape recovery abilities and even some supplementary skills associated to the crystal transformation. Since the discovery of an SME in iron-based materials in the early 1980s, (Sato et al. 1982), a tremendous interest in new fields of application arose and many research facilities included the topic in their studies (Cladera et al. 2014). Novel alloys with main parts of manganese, silicon and iron emerged, and one analyzed the material behavior in different applications and environments. The Swiss Federal Laboratories for Materials Science and Technology, Empa, also conducted basic research and developed an iron based SMA bar with iron, manganese, chromium and silicon as the main core materials (Dong et al. 2009). This Fe-SMA showed optimized mechanical properties, a good SME and an activation temperature range convenient for applications in several industries, such as the construction sector. A patent for the material was filed in 2009. Out of it, the start-up company re-fer AG was founded in 2012 and commercializes new products such as Fe-SMA rebars and plates. Up to now, the manufacturing could have been enhanced to an industrial level and first pilot projects were realized focusing on retrofitting of existing reinforced concrete (RC) structures in civil engineering. Therefore, re-fer applied for application patents for flexural and shear strengthening.

The most widespread building material of civil structures is reinforced concrete. In view of the increasing age of such constructions, the steadily growing demand on load-bearing capacity and changes in the design philosophy have made the strengthening an efficient alternative. Figure 1 illustrates schematically conventional types of flexural and shear strengthening on a single span girder. By carrying longitudinal forces, the strengthening system provides an enhanced bending capacity of slender structures.

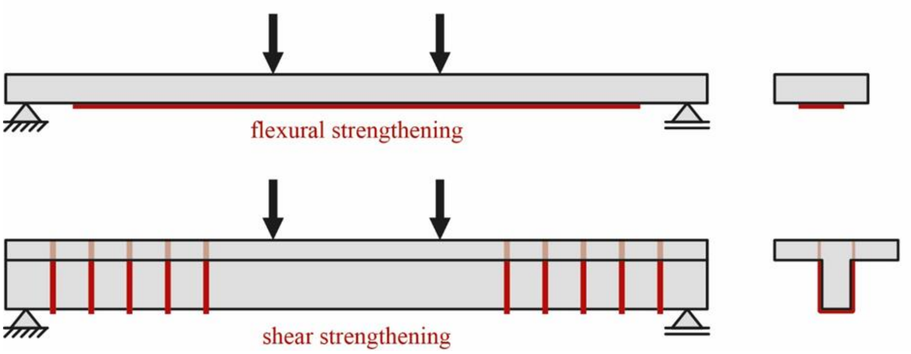

Figure 1: Schematic flexural and shear strengthening of RC beams

The application of memory-steel reinforcements for prestressing concrete members consists of three main actions, as schematically shown in Figure 2 (left). (1) Prestraining: The memory-steel reinforcements are pre-strained to a specific strain level and later fully released. (2) Activation: The memory-steel reinforcements are activated (heating and cooling back to RT while they are fixed externally to the concrete structure. (3) Service loading: when the concrete structure is loaded, the memory-steel reinforcements will carry load as shown in the left panel in Figure 2.

Heating and cooling of a ‘memory-steel’ reinforcement while it is constrained will produce a recovery stress, as shown in Figure 2 (right). (red line noted as 2). The shape memory effect (i.e., generating the recovery stress) of the ‘memory-steel’ element is due to the stress-induced martensite transformation from a parent ɣ-austenite phase (face-centered cubic, *fcc*) to an ε-martensite phase (hexagonal close packed, *hcp*) at RT and the reverse transformation (ε- to ɣ-phase) when heated beyond the transformation temperature (Lee et al. 2013). At the beginning of the heating cycle, the memory-steel will thermally expand. At austenite start temperature, As, the transformation from *hcp* to *fcc* starts and compressive stresses are created in the concrete element due to the development of tensile stresses in the SMA. During cooling, further compressive stresses build up in the concrete element due to thermal contraction of the SMA (Figure 2, right panel).

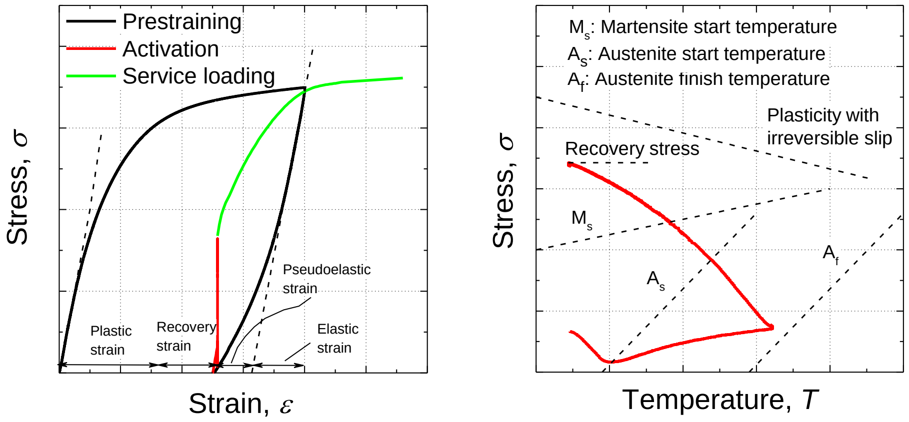

Figure 2: Left: schematic of three main actions in SMA application for prestressing a RC member. Right: schematic illustration of the activation (2nd action) and the recovery stress development development (Shahverdi et al. 2018)

The feasibility of flexural strengthening systems with Fe-SMA was shown in (Shahverdi et al. 2016; Shahverdi, Czaderski, and Motavalli 2015). For both, near surface mounted memory-steel reinforcements, and memory-steel bar bars embedded in shotcrete, significant improvement in structural behavior and serviceability was achieved. A clear enhancement of the cracking load and the deflection at failure was observed (Abouali et al. 2019). Although the system with the memory-steel in a shotcrete layer worked, no enhanced stiffness of the tested beams was observed when increasing the memory-steel cross section. A higher amount of reinforcement in the shotcrete was assumed to cause shrinkage cracks prior to the loading. In the past, production was limited to lab scale alone in which around 100 kg could be produced. However, re-fer AG in collaboration with a stainless steel producer recently manufactured memory-steel reinforcements at the industrial level.

Prestressing a reinforced concrete structure is an even more efficient technique in terms of durability and serviceability, as cracks and deformations can be substantially limited. Jointly, an improved bearing capacity under service loads due to a delayed appearance of tensile stresses on the concrete is obtained. This technique is a common construction method and a large number of bridges are fully or partially designed in the prestressed concrete technique, especially to overcome large spans and to guarantee the mentioned satisfactory behavior under service loads. Prestressed tendons are mainly used in longitudinal direction (flexural reinforcement). Very unusual is the usage of prestressing for shear reinforcement, because it is very complicated from a technical point of view. Figure 3 shows an example of a shear strengthening on a Swiss bridge. It can be seen that such solutions are very laborious and complex, and the durability of the steel construction is questionable.

Advantages of prestressed shear strengthening are:

- Existing shear cracks can be reduced or partially closed
- New cracks occur at higher loads and the crack widths are smaller
- Existing internal stirrups are relieved
- Introduction of the strengthening effects are immediate (active prestressing) without large deformation

In the current study a new solution for prestressing of RC member to enhance their shear capacity is presented. The problems with conventional prestressed shear strengthening are:

- Practical implementation is very complicated
- Friction losses at the deflection points
- Many steel parts are needed (corrosion)
- Due to short height, preload losses are magnified

With the ‘memory steel’ stirrups, prestress shear strengthening is possible and above mentioned problems are also overcome.

Figure 3: Bridge over the Swiss motorway A1 with shear strengthening.

2 MATERIAL PROPERTIES

2.1 memory steel stress-strain behavior

The memory steel stirrups used in this study were provided by the company re-fer AG in Switzerland. For the material production, roughly the following steps were performed. Initially, a batch of several tons of the alloy was cast. Subsequently, billets with dimensions of approximately 140 × 140 × 6000 mm^3 were produced. In the next step, the billets were heated in an oven to a temperature higher than 1100°C. Cross-section is continuously diminished at elevated temperatures by hot-rolling until the required diameter is reached. The ribs are applied at the very last stage prior to coiling. The rib geometry is in line with the British Standard BS 6744 for the use of stainless steels in concrete.

The ultimate tensile strength of the material averages 850 MPa, an average strain of 28% at maximum stress has been detected, which is by a factor of 2 higher than for the conventional hot-rolled or cold-drawn reinforcing bars, respectively. The elastic modulus determined from the stress-strain results was approximately 160 GPa (Michels et al. 2018).

2.2 Prestraining and shaping

The memory steel bars were first prestrain to about 6 % and then were shaped to U-shape stirrups.

2.3 Activation of memory steel

The prestress in memory-steel bars is triggered by an increase of temperature. To activate the memory-steel it is necessary to heat the cross section to around 160 to 180°C. Figure 4 illustrates the power supply used to activate memory-steel bars in this study. The specification values are listed in Table 1. Due to the electrical resistance of the material, resistive heating (also: Joule heating) can be used transforming electrical energy into thermal energy. A heating device for this procedure is provided by the re-fer and is shown in the following picture. The alloy exhibits recovery stresses (σ_p) in the range of 250 to 460 MPa depending on the level of prestrain (ε_p) and the activation temperature (Tmax) (Shahverdi et al. 2018).

Table 1. Specification of the power supply

max. current I_{max}	$800\ A$
Voltage U	$44\ V$
max. power P_{max}	$30\ kW$

Figure 4: Power supply device to activate ‘memory steel’ stirrups

2.4 *Concrete*

The concrete used in this project was ordered from the company Toggenburger AG in Switzerland. Test cubes have been produced and tested at the age of 28 days and on day of the experiments. Concrete strength of about 45 MPa on cube at the age of 28 days has been determined from the cub tests.

2.5 *Internal steel reinforcement*

In order to avoid flexural failure, four longitudinal steel reinforcements with diameter of 30 mm in two layers with end anchorages after the support were used, Figure 5 and Figure 6. Conventional construction steel B500B with diameter 8 mm was used as internal stirrups and eight steel reinforcements of diameter 12 mm were used as longitudinal reinforcements in the flange.

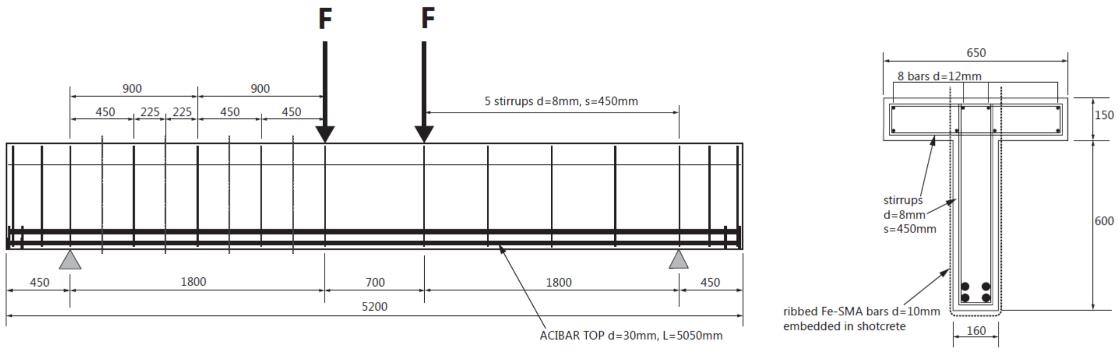

Figure 5: Detailed drawing of the internal reinforcement for the test beams.

Figure 6: Left: A photo of the internal reinforcement for Beam No. 1, Right: A photo of the end anchorage system for the longitudinal bars of diameter 30 mm.

2.6 Shotcrete mortar

In the application of shear strengthening with memory-steel stirrups the concrete subbase of an existing structure is roughened by mechanical removing of approximately 10 to 15 mm of the concrete surface and the shotcrete is applied after attaching the memory-steel bars. For these experiments, Sika Monotop 910N was used and applied by Sika people. Shotcrete mortar is sprayed onto the surface. Using the high pressure of the splash a compacted and load bearing layer is created. Either the so-called wet-mix or the dry-mix process can be used depending on the application or the length of transport routes. Whereas all ingredients for the shotcrete are mixed before jetting in the wet-mix method, in dry-mixing the compound is brought together with water just at the spraying.

2.7 Grout

A self-levelling grout from the Company Sika was used to backfill the drilled holes in the flange of the concrete. The SikaGrout-314 has additive shrinkage compensators and is an expanding cement-bonded mortar for the repair of concrete structures and static strengthening. After 7 days of hardening, 65 MPa of compressive strength is given in the datasheet.

3 EXPERIMENTAL SETUP AND PROCEDURES

In the framework of this study, six large scale beam experiments under four-point bending tests were considered. Beams were designed in a way that shear failure will happened at the ultimate loading. In this paper, only are a part of this study is presented. One Beam (Beam 1) was tested without any shear strengthening up to failure (reference beam without any strengthening). Then, this beam was repaired and again tested up to failure (Beam 4 is the repaired Beam 1), see Figure 7. After loading of Beam 1 and appearance of large cracks, the cracks were injected, the concrete cover in the 'shear span' was removed, 'memory steel' stirrups were installed, and a shotcrete layer was applied to the embedded the memory steel stirrups, see Figure 7.

4 RESULTS AND DISCUSSIONS

A four-point bending loading was applied on Beam 1 and Beam 4 up to failure. The crack development on the shear span of each beam was monitored with 3D digital image correlation systems. In Figure 9, the crack width of Beam 1 versus Beam 4 are compared. As expected, crack width in Beam 4 where prestressing forces exist are much smaller, e. g. at the load level of 300 kN a maximum crack width of 1 mm in Beam 4 has been determined while a crack with of more than 4 mm has been determined in Beam 1 at the same load level.

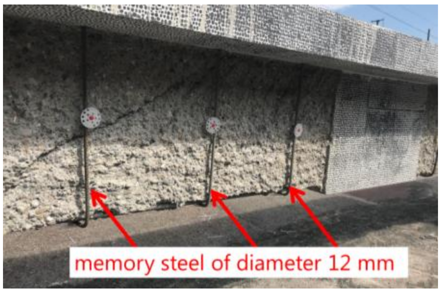

Figure 7: installed memory steel of diameter 12 mm on Beam 1->Beam 4.

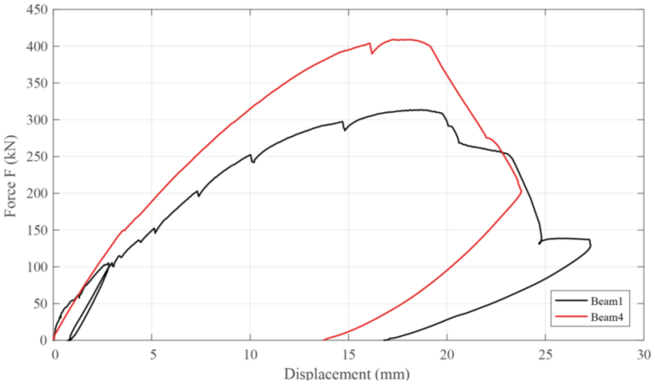

Figure 8: Load-mid-span deflection curves of Beam 1 and Beam 4.

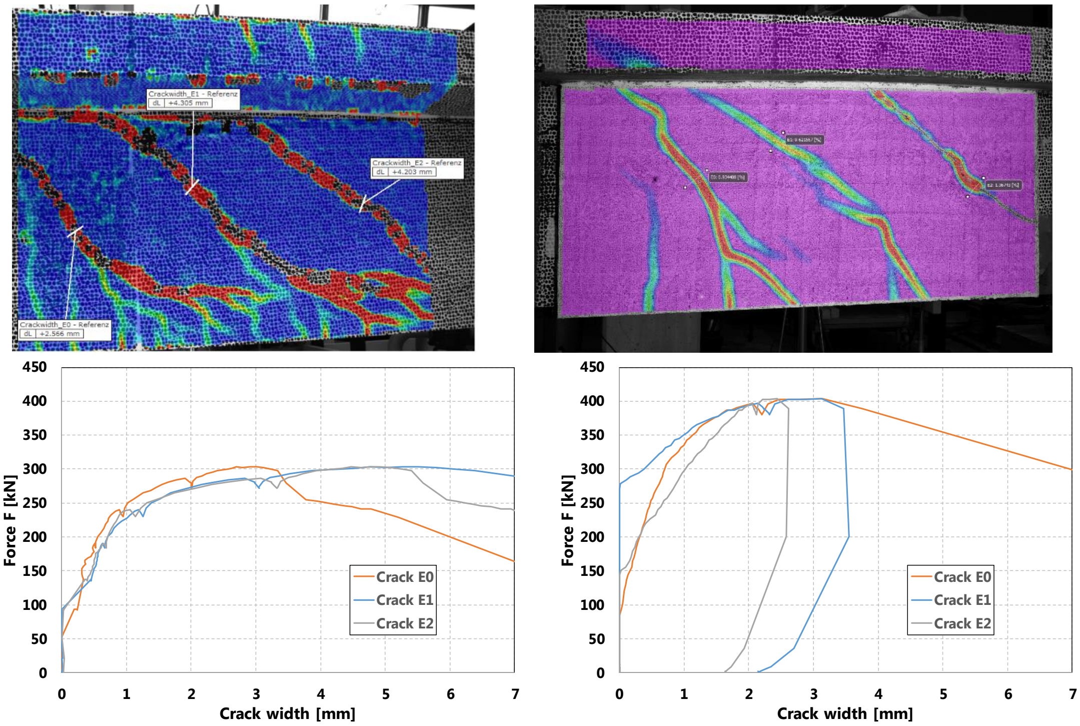

Figure 9: Comparison of the crack width of Beam 1 (reference beam), left, and Beam 4 (repaired beam), right, at load of 300 kN.

Load mid-span deflection of Beam 1 and Beam 4 are depicted in Figure 8. A higher load have been carried out by Beam 4 at the same mid-span deflections in comparison with Beam 1. This is correlated to the higher stirrups cross-sections in Beam 4 compared to Beam 1 in one hand and existing of the prestressed force due to the activation of 'memory steel' stirrups. The later will be further investigated by comparison of the behavior of other test beams, i.e. application of activated memory steel stirrups vs. application of non-activated memory steel stirrups.

5 CONCLUSIONS

Application of 'memory steel' reinforcements in the form of U-shaped stirrups as a prestressing technique for shear strengthening of RC beams was studied and presented in this work. Following conclusions can be drawn.

- memory-steel stirrups embedded in a shotcrete layer provide a feasible solution for shear strengthening.
- The practical application (roughening concrete surface, fixing the memory steel stirrups, shotcrete, activating) is easy.
- Effect of prestressing was determined by smaller crack width of Beam 4 compared to Beam 1.

A pilot project for application of memory steel reinforcement to shear strengthen RC members has been planned to occur soon in Switzerland.

6 ACKNOWLEDGMENTS

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