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Strengthening of concrete structures with iron-based shape memory alloy elements: Case studies

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ABSTRACT: The feasibility of new strengthening methods using a novel iron-based shape memory alloy (Fe-SMA), also known as 'memory steel', has been shown in several scientific investigations. These techniques have high potential for being cost effective ways to strengthen and prestress existing concrete structures. For more than two years, these new strengthening methods have also been available on the construction market. Several site applications have been carried out so far, including externally applied memory-steel strips and near-surface mounted ribbed memory-steel bars. This study describes selected site applications.

The first site applications present the installation and activation of end-anchored memory-steel strips ('re-plate'). The strips were mechanically fixed to the concrete substrate using a direct-fastening system with nails. Activation of the shape-memory effect and hence prestressing was accomplished either by resistive or infrared heating. On one object, successful reduction of existing crack width was demonstrated and monitored with Omega-deformation gauges. The temperature of the strips was monitored with thermocouples or a built-in sensor.

In a second application category, memory-steel bars ('re-bar') were used to strengthen a cantilever slab of a residential building in the negative bending moment area. After grooves were cut into the concrete surface, the bars were inserted and bonded at both ends with a cementitious mortar. The shape-memory effect was activated by infrared heating of the bar over its unbonded length. After the bar-temperature had reached ambient level again, the remaining groove was also filled with mortar. In this site-application, heating of the memory-steel was monitored with temperature sensors.

Building owners, contractors, as well as structural engineers responded very positively to the novel strengthening techniques. The presented examples demonstrate the successful application of new effective strengthening methods for retrofitting of existing concrete structures using memory-steel products.

1   INTRODUCTION

1.1   General

Conventional non-prestressed strengthening methods are commonly used to increase the ultimate load capacity of existing civil engineering structures. To improve the serviceability limit state design of a building, which includes reducing existing crack widths and deformations, prestressed

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measures are required. However, state-of-the-art prestressing methods are connected to high efforts and cost. Therefore, more efficient ways for strengthening in terms of serviceability limit state design are needed. Strengthening elements made from an iron-based shape memory alloy (Fe-SMA), also known as 'memory-steel', developed at the Swiss Federal Laboratories for Material Science and Technology (Empa) in Switzerland can be used for this purpose. The special ability of the material to return to its initial shape after being deformed, when heated, can be utilized to prestress and strengthen engineering structures (Czaderski et al. 2014, Czaderski et al. 2019). A number of scientific investigations have already demonstrated the function of memory-steel strengthening methods successfully (Shahverdi et al. 2016, Shahverdi et al. 2016, Izadi et al. 2017, Michels et al. 2018). Company re-fer AG from Brunnen, Switzerland is a supplier and contractor for memory-steel strengthening components (re-fer AG 2019). The material is currently available in the form of strips (Shahverdi et al. 2018) with a cross-section of 120 x 1.5 mm, or ribbed bars (Michels et al. 2018, Schranz et al. 2019) with nominal diameters of 12 mm, both shown in Figure 1. Currently, a prestress between 300 and 400 MPa can be obtained. In this study, several finished strengthening projects by company re-fer AG are described to demonstrate efficiency, ease of use and applicability of strengthening methods, using memory-steel products.

1.2   *Strengthening procedure*

Memory-steel strips are installed with a mechanical end-anchorage using direct-fasteners (nails of type X-CR by company Hilti), developed in (Schranz 2017). The strip-ends are delivered with holes at the ends for the nailing procedure. The installation process of memory-steel strips starts with temporary fixation of the strips in their required location. Afterwards, drill-holes have to be set into the concrete member, using the holes in the memory-steel strip for positioning. A powder-actuated nail-setting device is then used to set the nails into the concrete substrate. The memory-steel strip is afterwards heated to a temperature of approximately 160°C, either resistively by electricity, or by infrared heating. As soon as the memory-steel strip has cooled down to room temperature, the full prestress is developed in the element. The complete installation and prestressing process of a strip with an average length of 5 m is provided within approximately 20 minutes.

Figure 1. Memory-steel strips 're-plate' (left), Memory-steel bars 're-bar' (right)

The installation process of memory-steel bars depends on the type of strengthening application. If the concrete cover is still intact, grooves can be cut and the bars can be inserted using a cementitious mortar, which is termed near-surface mounted strengthening method (Schranz et al. 2019). The bars can also be installed in a shotcrete layer after removal of the concrete cover with a high-pressure water jet (Shahverdi et al. 2016). Depending on the application, the bars can either be heated by electricity, or infrared radiation.

2   CASE STUDIES WITH MEMORY-STEEL STRIPS (RE-PLATE)

2.1   *Selected project 1: Pilot installation worldwide in an industrial storage (Villigen, Switzerland, 2017)*

The first application with memory-steel re-plates (100 mm x 1.5 mm) worldwide took place in 2017 in Villigen (CH). A change in the static system for a reinforced concrete plate became necessary due to removal of a load carrying masonry wall. The increase in spans was covered by introducing a steel profile HEB 180 S355 with 14 re-plates with a length of 5.2 m additionaly to cover serviceability and ultimate load requirements. Furthermore, twelve 80 mm x 1.2 mm, non-prestressed CFRP strips with a length of 3 m were installed to cover lack of flexural steel reinforcement at the location of the removed wall. A drawing of the strengthening measures is illustrated in Figure 2 (left). In this case, resistive heating led to successful prestressing, while temperature was controlled by thermocouples installed on the strips. It is worth mentioning that in case of resistive heating, scanning of the internal reinforcement at the location of the nailed anchorage is necessary in order to avoid direct contact and hence short circuits.

The combined use of three strengthening methods resulted in minimal loss of room height and fast completion of construction works. A combination of re-plates and CFRP represents an interesting strengthening approach, as the first can be used to cover serviceability requirements, while the latter can be introduced to cover insufficient reinforcement for increased ultimate loads. Furthermore, structural design can be performed in a way that fire protection becomes relevant solely for the re-plates, which require much less extensive protection measures than composite reinforcements.

Figure 2. Drawing of horizontal section of strengthened RC slab (left), Finished strengthening project, using re-plate, CFRP strips and a steel beam (right)

2.2   *Selected project 2: School building in Nieppe (Lille, France, 2017)*

In this application, three memory-steel strips were used to reduce the crack width of bending cracks in a concrete slab. Three re-plates with a cross-section of 100 x 1.5 mm were mechanically fastened to the concrete member (see Figure 3) and activated with resistive heating devices by company re-fer AG. The strips were heated to a temperature of 160°C, resulting in a prestress of 300 MPa or 45 kN per strip. During the activation process, decrease of crack width was measured by Omega-deformation gauges, installed at several locations on one crack as illustrated in Figure 3. A successful reduction of crack width by 0.14 mm was recorded.

Figure 3. Strengthened RC slab to reduce crack width and measurement with Omega-deformation gauges
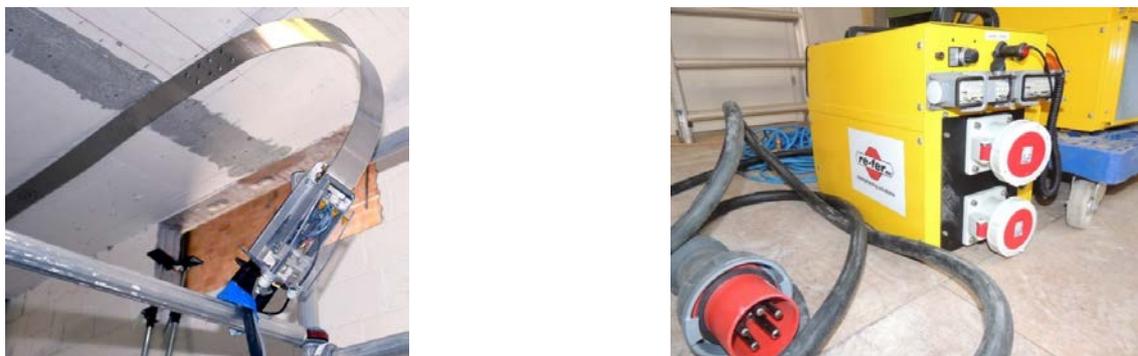

Figure 4. Installed clamps for resistive heating process (left), re-fer power supply for resistive heating (right)

2.3 Selected project 3: Strengthening of negative moment area and punching shear (Aarau, Switzerland, 2018)

In a different strengthening application, the placement of new columns required strengthening of a concrete slab due to insufficient tensile reinforcement in the top layer. In this case, infrared heating was used to activate the strips, as shown in Figure 6. The custom-designed heating devices enabled temperature monitoring on a smartphone via Bluetooth-connection to a built-in temperature sensor (see Figure 5, right). The heating process was performed over the free length of the memory-steel strips in two segments. An advantage of the infrared heating process is that no high-power supply or generator is needed for high-current resistive heating. To avoid complications for following works on the concrete floor, the concrete was firstly grooved before installation of the memory-steel elements, as illustrated in Figure 5 (left) and Figure 6 (right). After successful prestressing, a bonding coat was applied to the strips prior to filling the remaining groove with a cementitious grout. In this application, memory-steel strips with a cross-section of 120 x 1.5 mm were installed.

Figure 5. Installation of re-plates in grooves for even concrete surface after strengthening (left), monitoring of heating temperature via re-fer app (right)
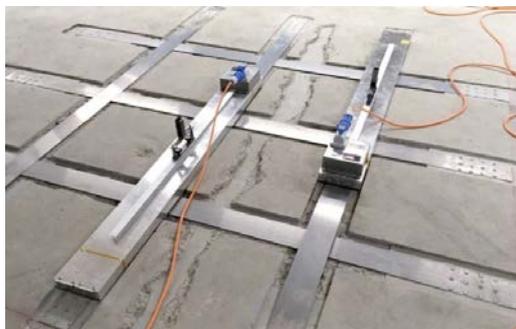

Figure 6. Heating process with infrared heating units (left), strengthened RC slab before grouting (right)

2.4   Further selected projects

Figure 7. Residential building, Hinwil (CH): Strengthening of cantilever RC slab with 5 m span against deformation due to negative bending moment, 18 re-plates with lengths up to 7 m were used (left), Residential building, Zumikon (CH): Combined use of re-plate and CFRP strips for strengthening of RC slab, installation of 14 re-plates (right)

Figure 8. Hospital,Thun (CH): Strengthening of RC slabs due to lack of top reinforcement, 10 re-plates with lengths up to 11 m Residential building (left), Schwyz: Strengthening of RC slabs due to removal of several load-carrying walls (right)

Figure 9. Multi-story building in Goldach (CH): Strengthening of RC slabs over 14 stories due to new openings (left), Residential building in Brunnen (CH): Strengthening of RC slabs due to removal of load-carrying walls, a total of 12 re-plates was installed (right)

In figures 7 to 9, further representative strengthening projects are depicted.

3   CASE STUDIES WITH MEMORY-STEEL BARS

3.1   Selected project 10: Negative bending moment area of concrete slabs (Münchenstein, Switzerland, 2018)

During modification of a multi-story residential building, two concrete slabs were strengthened in the negative bending moment area. Ten Ø16 mm memory-steel bars were installed in a near-surface mounted application to increase ultimate-, as well as serviceability load capacity. Figure 10 (left) provides a horizontal section of one of the strengthened slabs. At first, grooves with a depth of about 3 cm and a width of about 3 cm were cut into the floor slab using a diamond saw. Afterwards, the bar-ends were bonded to the concrete with a cementitious mortar of type SikaGrout-311 over a length of about 30 to 40 cm, as depicted in Figure 10 (right). After curing of the mortar, the bars were heated by infrared units to a target temperature of 190°C (see Figure 11, left). The heating process was monitored with temperature sensors, attached to the bar surfaces. The heating process led to activation and hence prestressing of the bar and concrete slab. As illustrated in Figure 11 (right), the remaining length of the groove was also filled with mortar after successful activation and cooling to room temperature. This type of installation did not lead to complication of further works on the concrete floor due to full embedment of the memory-steel components.
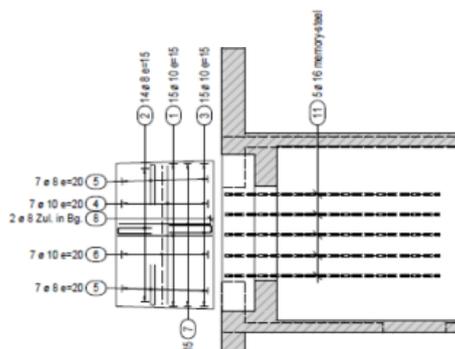

Figure 10. Drawing of horizontal section of strengthened RC slab (left), filling of groove for end-anchorage (right)

Figure 11. Activation of end-anchored re-bars with infrared heating units (left), RC slab, strengthened with near-surface mounted re-bars (right)

3.2 Selected project 11: Prestressed shear strengthening (Baden, Switzerland, 2019)

Figure 12. U-shaped re-bars for prestressed shear strengthening. Sprayed mortar will be used subsequently to embed the bars prior to activation by

Currently, re-bar is applied in form of stirrups as a prestressed shear reinforcement within a large-scale renovation project of a theater, which is classified as cultural heritage. Besides other deficiencies, structural upgrading regarding the shear capacity of several reinforced concrete beams is needed. For the installation, holes are drilled in the upper slab, and the lateral and bottom sides of the web are roughened by waterjetting. The U-shaped stirrups are then installed and temporarily fixed to the concrete, prior to the application of the sprayed mortar, as shown in Figure 12. After sufficient curing, resistive heating will be used for activation.

4 FIRE PROTECTION

Various tests under elevated temperatures (Ghafoori et al. 2019) have shown that the behavior of memory-steel is comparable to conventional reinforcing steel and can be protected against fire accordingly. It is emphasized that required fire protection is much less extensive than for instance in case of carbon fiber reinforced polymer (CFRP) strips.

5 CONCLUSIONS AND OUTLOOK

In this paper, selected projects were presented to demonstrate the successful application of memory-steel in practice. Experience from the completed projects proves effectiveness, ease of installation, and successful introduction to the construction industry. Increasing demand for such strengthening methods as well as positive feedback indicate very good reception by building owners, contractors and engineers.

Current research at Empa focuses on the efficiency of memory-steel bars for active shear strengthening, the general bond behavior of re-bars to cementitious substrates, or the application of memory-steel plates for fatigue strengthening of steel members. Furthermore, studies aiming at increasing the overall obtained recovery stress have delivered very promising results and will help to produce even more efficient prestressing products in the future (Yang et al. 2019). Efforts by company re-fer AG to optimize current techniques, as well as development of new technologies, such as on-site measurement of prestress in the memory-steel elements, are ongoing.

6   ACKNOWLEDGEMENTS

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