Construction and Building Materials 56 (2014) 94–105

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Feasibility of iron-based shape memory alloy strips for prestressed strengthening of concrete structures

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HIGHLIGHTS

- Iron-based shape memory alloy (Fe-SMA) strips were produced.
- The Fe-SMA strips shall be used as prestressed near-surface mounted reinforcement.
- The bond behavior of the strips embedded in grooves was investigated in lap-shear tests.
- The Fe-SMA strips were centrally embedded in a concrete bar.
- The Fe-SMA strips were activated (prestressed) by resistive heating.

ARTICLE INFO

Article history:
Received 29 November 2013
Received in revised form 27 January 2014
Accepted 28 January 2014
Available online 18 February 2014

Keywords:
Iron-based shape memory alloy (Fe-SMA)
Strengthening concrete structures
Prestressed near-surface mounted reinforcement (NSMR)
Bond
Prestressing

ABSTRACT

Near-surface mounted reinforcement (NSMR) is a strengthening method for concrete structures, such as buildings or bridges. NSMR involves strips or bars that are glued into grooves in the cover of the concrete. In this paper, a feasibility study is presented that uses iron-based shape memory alloy (Fe-SMA) strips instead of fiber-reinforced polymer (FRP) strips for NSMR. SMAs can more easily be prestressed than FRP. Because prestressing of SMAs does not require any mechanical jacks and anchor heads, the additional openings on the concrete surface beside the grooves that are needed to clamp the NSMR are significantly smaller.

The recovery stresses (i.e., the prestresses) were investigated in a tensile testing machine combined with a climate chamber. The temperature of the strips was increased up to 160 °C to provoke the phase transformation in the SMA. The bond behavior of the Fe-SMA strips glued into a groove with cement-based mortar was studied in lap-shear experiments using a 3D image-correlation measurement system. The result was compared with the bond behavior of CFRP strips glued with epoxy. Finally, two concrete bars with lengths of 70 cm were each reinforced with an Fe-SMA strip. After the concrete was cured, the Fe-SMA strips were activated (i.e., prestressed) by resistive heating, and the prestressing effect on the concrete bar was measured on the concrete surface using a mechanical strain gauge.

The study demonstrated the general feasibility of Fe-SMA strips in prestressed NSMR. The recovery stresses were in the range of 250–300 MPa. A sufficient bond behavior was observed. Concrete bars could be successfully prestressed with a centrally embedded Fe-SMA strip.

1. Introduction

At some point of their lifecycle, civil structures, such as bridges and buildings, may be in need of rehabilitation because they are in poor condition or because of a change in usage, e.g., greater live loads. Available strengthening methods include, for example, adding an additional concrete layer in the compression zone or externally bonding steel or fiber-reinforced polymer (FRP) strips with an epoxy adhesive onto the concrete surface in the tensile zone. Alternatively, small FRP strips or bars can be glued into 2–3 cm deep grooves in the cover of the concrete in the tensile zone. The latter strengthening method is known as "near-surface mounted reinforcement" (NSMR). The advantages to externally bonded reinforcement (EBR) are better bonding, better protection against vandalism and fire and better durability. Many research

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http://dx.doi.org/10.1016/j.conbuildmat.2014.01.069
0950-0618/

works have studied the behavior of NSMR (and are still ongoing) by using FRP strips or bars to strengthen concrete structures, e.g. [1–6]. It is difficult and complicated to prestress FRP NSMR because the space available in the groove to clamp the reinforcement is very small. At the University of Calgary, a system to prestress FRP NSMR was developed [7]. However, the method has yet not transferred to industry. Prestressing has the advantage that existing deformations and crack widths can be reduced so that the serviceability and durability of the structure can be increased.

Shape memory alloys (SMAs), depending on the type of alloy, are identified with several unique phenomena such as the shape memory effect (SME), superelasticity, large damping capacity or a two-way shape memory effect [8]. In civil engineering, the material is mostly used for seismic applications, see for example [9–11].

Most of the research into SMA applications in civil engineering structures has focused on binary Ni–Ti alloys (commonly known as Nitinol or NiTi), which are the most readily available SMAs. Czaderski et al. [12] presented an application in which NiTi wires were used as flexural reinforcement in a concrete beam; by changing the temperature in the SMA wires with electrical resistive heating, the stiffness and strength of the beam was changeable. Because SMAs are conductors, they can be heated directly with an electrical current, which is subsequently referred to in this paper as electrical resistive heating. NiTi wires have also been used in short-fiber concrete. The fibers were activated (prestressed) by heating the complete test specimen in an oven [13]. Furthermore, Tran et al. [14] reported recovery stresses of NiTi wires (with a specific composition and a specific thermal treatment) at room temperature of more than 200 MPa.

However, the commercial application of NiTi is limited by the high costs of raw materials and processing. In addition, their effectiveness for prestressing is often restricted by their relatively narrow thermal hysteresis [15], which is inadequate for the large and stable recovery stresses required for civil engineering applications.

As an alternative, iron-based SMAs (Fe-SMAs) such as Fe–Mn–Si based alloys [16] seem to be more feasible for this type of application due to their low cost, wide transformation hysteresis and high elastic stiffness compared to conventional Nitinol alloys. Sato et al. discovered the shape memory effect in these alloys in 1982 [17]. Since then, many researches have been conducted to improve the properties of the alloys, for example [18,19]. Some of the present authors reported on a novel Fe-SMA with finely dispersed VC particles that shows very promising properties for applications in the area of "reinforcement of new or existing concrete structures" without any training and after production under standard air melting and casting conditions [20–25]. In particular, very high recovery stresses from 300 to more than 500 MPa were measured after heating to only 130–160 °C and depending on the thermo-mechanical pre-treatment. A detailed description of the phase transformation behavior of Fe-SMAs and the difference to NiTi-SMAs from an engineering perspective is given in [26].

In present paper, the feasibility of using iron-based shape memory alloy strips instead of FRP strips is investigated. SMAs can more easily be prestressed than FRPs. Because prestressing the SMAs does not require mechanical jacks and anchor heads, the additional openings on the concrete surface beside the grooves that are necessary to clamp the NSMR are significantly smaller. Finally, Fe-SMAs can be prestressed even if they are embedded without need for a duct in the concrete.

Here, the shape memory effect of the Fe-SMA NSMR strips is used to *prestress* the strips. The preparation procedure for such a prestressed SMA tension element is the following: first, the tension element (in our case, the strip) has to be prestrained to a certain amount and completely unloaded. Then, the tension element is embedded into the concrete. After the concrete has cured, the temperature in the tension element is increased by electrical resistive heating for a very short time to provoke a phase transformation in the SMA. The full prestress develops after the material returns to environmental temperature.

The paper presents the production of the material, tensile and heating experiments on the material itself and lap-shear and concrete bar experiments.

2. Production of the Fe-SMA material

Recently, a novel iron-based shape memory alloy was developed at Empa [20–25]. To date, only small test specimens have been used for alloy characterization [20–23]. Therefore, a larger amount of material was produced to be able to study the material in more realistic sizes.

First, a batch of approximately 95 kg of an alloy with the same composition as described in [20–23] was produced. After casting, the block had a size of approximately 50 × 16 × 16 cm (conical). Then, the block was heated in an oven to 1150 °C, and the cross-section of the block was reduced to approximately 10 × 10 cm by forging. After this process, strips with a final thickness of approximately 1.7–1.9 mm were produced by several cycles of blocking and hot rolling with multiple reheating of the specimens to 1150 °C. All the deformation works was performed at room temperature on the hot samples. In the end, the widths of the strips were approximately 100 mm, and their lengths were in the range of 75–95 cm.

Next, the strips were longitudinally cut in widths of 20 mm by using a circular shear, which is a cold-deforming working step. Then, the strips were soft-annealed by heating to 660 °C before ribs were produced on the surface by cold rolling using a special mold. After that, a solution heat treatment was performed at 1100 °C for 30 min in an H_2N_2-atmosphere followed by a heat treatment at 850 °C for 120 min to produce fine VC particles, which improve the shape memory effect. The strips without ribs were not soft-annealed and cold rolled but were heat treated. The strips discussed in this paper were produced and delivered in four batches, see Table 1. Batch No. 3 had a 120-min solution heat treatment rather than 30 min to test whether a longer solution heat treatment has any effect on the recovery stress. During the first tensile experiments, the specimens had premature failure. This was attributed to the edges of the strips, which were brittle due to the cutting of the circular shear and possibly also poor clamping in the tensile testing machine. Therefore, the edges of subsequent test specimens were milled and/or ground to remove the brittle edges.

The shape of the ribs is shown on the photo given in Fig. 1. The ribs were applied at an angle of approximately 40° on one side and 130° on the other side of the strip to ensure a regular strain pattern along the strip. The ribs had a spacing c_s of 12 mm and thicknesses a_s between 0.1 and 0.2 mm. The relative rib area f_R is defined as

$$f_R = \frac{a_s}{c_s}. \tag{1}$$

Therefore, the relative rib area f_R of the tested Fe-SMA strips was in the range between 0.008 and 0.017. Although this is lower than 0.035, which is the required relative rib area for reinforcing

Table 1
Overview of the test sample numbering (Fe-SMA strips) and corresponding batches. The strips had widths of 2 cm and lengths of 75 to 95 cm.

Batch	Strip No.	Surface
1	1–3	Flat
2	4–6	Flat
2	R1–R3	Ribbed
3	7–9	Flat
4	10–21	Flat
4	R4–R14	Ribbed