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Iron-based shape memory alloy strips for strengthening RC members: Material behavior and characterization

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HIGHLIGHTS

- Production of iron-based shape memory alloy (Fe-SMA) strips at industrial level for civil engineering applications.
- Fe-SMA strips were characterized for application as externally fixed reinforcements for RC members.
- The relaxation behavior of Fe-SMA strips for durations of more than 1000 h was studied.
- The effects of different parameters on the recovery stress of Fe-SMA strips are investigated.
- Long Fe-SMA strips are activated in air by resistive heating.

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ABSTRACT

Shape memory alloys (SMAs), in the form of bars and strips, can be used as prestressing elements in new reinforced concrete (RC) members or for strengthening existing RC structures, owing to their special characteristic known as the shape memory effect (SME). When the SME comes into play, the material returns to its initial shape upon heating after having been deformed at ambient temperatures. If a return to the initial shape is prevented by mechanical fixation, stress develops in the SMA. A cost-effective iron-based SMA (Fe-SMA) has been developed for application in civil engineering structures. The composition of the developed alloy is Fe–17Mn–5Si–10Cr–4Ni–1(V,C) (mass%). This Fe-SMA exhibits high tensile strength, excellent shape recovery stress (prestress force), and high elastic stiffness. Moreover, its material cost is low and it is easier to manufacture than nickel-titanium (NiTi) alloys. Recently, Fe-SMA strip production has been started at an industrial scale. In this study, the experimentally determined properties of such industrially produced Fe-SMA strips are presented, and their recovery stress and recovery strain have been measured. The effects of prestraining and maximum heating temperature on the obtained recovery stress have been studied. These Fe-SMA strips can be used as external end-fixed reinforcements to strengthen RC structures.

1. Introduction

New and innovative methods to strengthen existing civil structures such as bridges and buildings and to build new structures are necessary in the construction industry. A new type of advanced materials entering the construction market are shape memory alloys (SMAs). SMAs have two main characteristic properties: “superelasticity” and “shape memory effect” (SME). SMAs with superelasticity can return to their initial shape after loading and unloading; however, SMAs with SME return to their initial shape upon heating. Such materials, for e.g. NiTi alloys, have been around for a long time, but were not considered suitable for the construction industry due to their expensive nature [1,2].

The most commonly known SMAs are NiTi alloys. These materials are used in the automotive, aerospace, robotic, and biomedical domains [3]. SMAs can be used as self-centering elements, dampers, sensors, or actuators. Furthermore, there are a multitude of reports on SMAs and their applications in civil engineering [4–9].

In civil engineering applications, SMAs can be exploited for their superelasticity or SME properties for example NiTiNb alloys [10–12]. Some demonstration projects do exist in this context [1,13–18]. However, the application of SMAs in this domain is still in the research stage [19]. The vast majority of previous studies concentrated on the superelasticity properties of SMA. Although the expensive NiTi-based alloys are the most widely used SMAs

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Nomenclature

As	austenite start temperature
b	width of the specimen
$\Delta\sigma_{relx}$	reduction in stress during the relaxation experiment
E_1	elastic modulus determined in the stress range of 20–200 MPa in tensile mode
E_2	elastic modulus determined in the stress range of 20–80 MPa after activation
$E_{act\text{-}eq}$	equivalent elastic modulus of activation
ε_{rec}	recovery strain; strain in the SMA which recovers during activation
ε_{pl}	plastic strain
ε_{Pel}	pseudoelastic strain; strain in the SMA which recovers nonlinearly by unloading
ε_u	ultimate tensile strain; maximum strain reached in axial tensile tests
ε_{el}	elastic strain
ε_p	prestraining strain
f_u	ultimate tensile strength; maximum stress reached in axial tensile tests
$\sigma_{max\text{-}relx}$	maximum stress applied to the specimen during the relaxation experiments
σ_{rec}	recovery stress; stress developed in the SMA during activation, i.e., the prestress
P_{ini}	preload applied to the specimens before activation
P_{ser}	service load
$R_{p0.2}$	offset yield point (proof stress) at 0.2% plastic strain
t	thickness of the specimens, 0.5 mm or 1.5 mm
T_{max}	maximum temperature applied during activation
t_{relx}	relaxation experiment time
Activation	triggering of phase transformation in the SMA so that a prestress is developed
Fe-SMA	iron-based shape memory alloy
NiTi	nickel-titanium
NiTi-SMA	nickel titanium SMA
NSM	near surface mounted
RC	reinforced concrete
RT	room temperature
SMA	shape memory alloy
SME	shape memory effect

[1], low-cost copper-based shape memory alloys (Cu-SMAs) and Fe-SMAs are gaining ground [2,20–22]. Cu-SMAs have superelastic properties with a low elastic modulus and low cycle fatigue resistance [22]. However, in the case of Fe-SMAs, in addition to their lower cost than the NiTi-based alloys, they have a higher elastic modulus and can be activated at relatively lower temperatures [23]. This makes them very promising for strengthening existing civil structures and for prestressing new civil structures as well.

The Fe-SMA material was discovered by Sato et al. [24] in 1982. Fundamental research on the transformation behavior, microstructural and crystallographic characteristics, and mechanical properties of Fe-Mn-Si-based alloys were performed at the National Institute for Materials Science (NIMS), Japan [25–27]. Watanabe et al. [28] worked on the reinforcement of an 80 mm long plaster prism specimen with a 1 mm diameter prestressed wire made of Fe-27Mn-6Si-5Cr-0.05C. The wires were subjected to a pretensile strain (1%, 2%, and 3%) at room temperature (RT) and were embedded into a plaster matrix. In 2001, Soroushian et al. reported the strengthening of a bridge in Michigan, USA through external post-tensioning with Fe-Mn-Si-Cr SMA rebars [29].

At Empa, the Swiss Federal Laboratories for Materials Science and Technology, extensive studies on SMAs for civil engineering applications have been carried out over the past few years [23,30–33]. In 2003, a concrete beam was longitudinally reinforced with SMA wires [34]. In 2003/2004, NiTi-SMA wires were embedded in mortar to demonstrate the feasibility of prestressed short fiber reinforced concrete [35]. The total fiber content was 1.2% by volume. A compression stress of approximately 7 MPa was determined in the concrete prisms. A new Fe-SMA for civil engineering applications was developed by Dong et al. [30]. The composition of the developed alloy was Fe–17Mn–5Si–10Cr–4Ni–1(V,C) (mass%). For civil engineering applications, Fe-SMAs represent a promising technology in a number of areas because of their properties and lower cost than NiTi. Fe-SMAs are less expensive compared to (NiTi) alloys because their row material cost is low and they are easier to be manufactured than nickel-titanium (NiTi) alloys. The newly developed Fe-SMA can be activated at temperatures between 100 °C and 250 °C by resistive heating over a short period time (about one minute). Furthermore, it can be produced on an industrial scale at atmospheric conditions without expensive, high-vacuum processing facilities. For different applications, it can be manufactured in appropriate shapes such as ribbed bars or strips by hot and/or cold forming.

In 2012, a feasibility study began on the use of Fe-SMAs for strengthening reinforced concrete structures [36,37]. The idea was to use Fe-SMA strips as near surface mounted (NSM) reinforcements. In this project, several RC beams were strengthened with the NSM technique using prototype Fe-SMA strips [37]. The recovery stress (prestress force) after prestraining to 2.0% or 4.0% and heating to 160 °C was in the range of 250–300 MPa [36]. In another project, prototype ribbed Fe-SMA bars were produced at the laboratory level to strengthen RC structures in combination with shotcrete [38]. Both products were produced at lab scale in collaboration with the Montanuniversität, Leoben (Austria) and the Bergakademie TU, Freiberg (Germany).

The application of Fe-SMA strips for prestressing concrete members consists of three main actions, as schematically shown in Fig. 1. (1) Prestraining: The Fe-SMA strips are pre-strained to a specific strain level and later fully released. (2) Activation: The Fe-SMA strips 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 Fe-SMA strips will carry load as shown in the left panel in Fig. 1.

The heating and cooling of an Fe-SMA strip while it is constrained will produce a recovery stress, as shown in Fig. 1 (red line noted as 2). The shape memory effect (i.e., generating the recovery stress) of the iron-based SMAs is due to the stress-induced martensite transformation from a parent γ-austenite phase (face-centered cubic, fcc) to an ε-martensite phase (hexagonal close packed, hcp) at RT and the reverse transformation (ε- to γ-phase) when heated beyond the transformation temperature. At the beginning of the heating cycle, the SMA 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 (Fig. 1, right panel). Phase change temperatures for the studied Fe-SMA have been reported in [32] as follow: $M_f = -64$ °C, $M_s = -60$ °C, $A_s = 103$ °C, and $A_f = 163$ °C.

From an application point of view, it is important to have a clear understanding of the thermo-mechanical behavior of SMAs in order to fully exploit their potential. Transformation phase