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Iron-based shape memory alloy for the fatigue strengthening of cracked steel plates: Effects of re-activations and loading frequencies

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ABSTRACT

The paper discusses the application of an iron-based shape memory alloy (Fe-SMA) for the fatigue strengthening of steel plates. The shape memory effect (SME), which is the characteristic behavior of the Fe-SMAs, was used for the prestressed strengthening of steel plates. One steel plate without any pre-cracks and two steel plates with pre-cracks were retrofitted with Fe-SMA strips. The SMA-strengthened specimens along with a reference un-strengthened specimen were then subjected to high cycle fatigue (HCF) loading. The effect of multiple re-activations and different loading frequencies (e.g., f_r = 0.005, 5, 10, and 15 Hz) on the HCF behavior of the Fe-SMA was investigated. The test results showed that the achieved prestressing level (i.e., recovery stress) in the Fe-SMAs for an activation temperature of 260 °C was in the range of 330–410 MPa, resulting in compressive stresses in the range of 35–72 MPa in the steel plates. Furthermore, it was observed that the recovery stress decreases slightly during cyclic loading, which should be considered in the design. The loss in the prestressing level was approximately 17–20% of the original prestressing; however, the re-activation (i.e., a second activation) process could retrieve a significant portion of the loss. The test results showed that the activated Fe-SMA strips could apply considerable compressive stresses to the cracked steel plate, which reduce the tensile stresses and stress intensity factors (SIFs) at the vicinity of the crack tip, resulting in a significant increase in the fatigue life of the specimens and a complete fatigue crack arrest in some cases.

1. Introduction

Shape memory alloys (SMAs) are materials that are well known for their so-called shape memory effect (SME) property. Owing to this favorable property, the deformed SMA can revert to its undeformed shape upon heating and cooling. There are two main types of SMAs, including nickel-titanium (also known as NiTi-SMAs or Nitinol) and iron-based SMAs (Fe-SMAs), with SME property suitable for engineering applications. The mechanism of the SME is explained by the effects of stress and temperature on the lattice structure of the SMAs. The austenite (face-centered cubic phase, γ) and martensite (hexagonal close-packed phase, ε) phases are the two main crystal phases of the SMAs. For the NiTi-SMAs, the SME occurs when the material is in the martensite phase. Application of stresses at lower temperatures causes the detwinning of the ε-martensite. Then, heating causes a transformation to γ-austenite, while cooling returns the material to the twinned martensite [1,2]. For the Fe-SMAs, The SME is a result of a forward phase transformation from the γ-austenite to the ε-martensite (i.e., a martensitic transformation) due to mechanical loading and a reverse transformation (i.e., ε-martensite to γ-austenite) upon heating at a high temperature [1,3–5].

The engineering applications of the SME are focused mainly on pre- and post-tensioning, self-actuating coupling and fasteners, and sensors [1,5,6]. The SME of the NiTi-SMAs has been so far utilized in different engineering applications, such as medical instruments, aerospace devices, and small mechanical systems. In the most recent application, ternary NiTi–niobium (NiTiNb) SMA was employed as a hybrid patching technique for a prestressing application [7]. This technique eliminates the need for installation of any mechanical fixtures to anchor the system to the structure [8]. However, the high cost of NiTi-SMAs is the main barrier for their large-scale applications in the domain of civil engineering. On the other hand, the Fe-SMA with a low-cost manufacturing process, excellent mechanical property, and SME behavior has recently attracted attentions for civil engineering applications [1,9].

The SME in Fe-SMA alloys is mostly promising for prestressing applications. The Fe-SMA is mechanically deformed at room temperature

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Nomenclature

ε_{pre}	prestraining level
ε_{res}	residual strain
T_a	activation temperature
T_o	room temperature
σ_r	recovery stress
σ_{max}	maximum stress of Fe-SMA in fatigue loading
σ_{min}	minimum stress of Fe-SMA in fatigue loading
$\Delta\sigma$	applied stress range
R	applied stress ratio
f_r	loading frequency
N	number of fatigue cycles
N_1	number of full-amplitude fatigue cycle
N_2	number of half-amplitude fatigue cycle
σ_a	alternating stress
σ_m	mean stress
ΔF	applied fatigue load
K_I	mode-I stress intensity factor (SIF)
ΔK_I	mode-I SIF range
$K_{I,max}$	maximum mode-I SIF range
$K_{I,min}$	minimum mode-I SIF range
$\Delta K_{I,th}$	Mode-I threshold SIF range
σ_r^{bf}	recovery stress before fatigue test
σ_r^{af}	recovery stress after fatigue test
σ_c	compressive stress in the steel plate
σ_c^{bf}	compressive stress in the steel plate before fatigue test
σ_c^{af}	compressive stress in the steel plate after fatigue test
σ_{min}^{o}	minimum stress in the first loading of fatigue cycle
σ_{min}^{1}	minimum stress in the first unloading of fatigue cycle
$\Delta\sigma^{i}$	initial stress range of Fe-SMA in fatigue loading
$\Delta\sigma^{f}$	final stress range of Fe-SMA in fatigue loading
ε_{max}	maximum strain of Fe-SMA in fatigue loading
ε_{min}	minimum strain of Fe-SMA in fatigue loading
TIR	transformation-induced relaxation
FCG	fatigue crack growth
ERH	electrical resistive heating
HCF	high cycle fatigue

and as a result, a stress-induced martensite phase is produced because of the forward transformation. Subsequently, the Fe-SMA is heated to a characteristic temperature, and the martensite phase is reversed to the original austenite phase [1,10,11]. During the reverse phase transformation, if the deformation of the Fe-SMA is restrained, prestressing is generated owing to the attempt made by the alloy to revert to its original shape. Strengthening of structures with Fe-SMA eases the procedure of prestressing as it does not involve the problems associated with prestressing procedure using hydraulic jacks. Sufficient space and heavy prestressing equipment are often required to prestress steel and carbon fiber-reinforced polymer CFRP elements. The ease of strengthening with the smart Fe-SMA material additionally accelerates the procedure of prestressing and reduces the expenses and labor efforts.

1.1. Fe-SMAs for the prestressing of concrete structures

There are limited studies on the pre- and post-tensioning applications of Fe-SMA in civil engineering. The Fe-SMA has been utilized in different prestressed applications such as confinement and reinforcement of concrete girders [12,13], concrete columns [14], and steel plates [15,16]. In the very first application of Fe-SMA alloys, Soroushian et al. [12] reinforced a cracked detail of a highway bridge in Michigan by applying external post-tensioning Fe-SMA rods. A recovery stress (i.e., prestressing level) of 255 MPa was developed in the rods after heating the rods to an activation temperature of 300 °C. With the prestressed Fe-SMA rods, the shear cracks were arrested to a large extent, and as a result, the original load-carrying capacity of the concrete girder was recovered. In another study by Czaderski et al. [17], concrete bars of length 700 mm were reinforced with ribbed Fe-SMA strips with a thickness of 1.5 mm. The Fe-SMA strips were activated (i.e., prestressed) by electrical resistive heating (ERH) technique to produce compressive stress in the concrete bars. After heating the Fe-SMA strips to 160 °C, a recovery stress in the range of 250–300 MPa was achieved, and the concrete bars were successfully prestressed by the activation of the Fe-SMA strips. In another work, Rojob et al. [3] enhanced the flexural strength of reinforced concrete beams under service and ultimate load conditions with a so-called self-prestressing Fe-SMA technique. The Fe-SMA bars were embedded in cut grooves inside the beams and were then activated through two different heating techniques to a temperature above 300 °C.

Recently, a new type of Fe-SMA alloy, Fe–17Mn–5Si–10Cr–4Ni–1(V,C), which has a great potential for prestressing purposes [18], was developed at the Swiss Federal Laboratories for Materials Science and Technology (Empa). Studies on the stability of recovery stress under different conditions of temperature [10,19,20], creep and stress relaxation [21], and corrosion behavior [22] proved the suitability of this type of Fe-SMA as a prestressing element for civil engineering applications. In a series of experiments conducted by Shahverdi et al. [23,24], concrete beams were reinforced with activated Fe-SMA bars. The strengthening and prestressing of the concrete beams were successfully carried out to increase the static capacity of the concrete beams.

1.2. Fe-SMAs for the strengthening of steel structures

In all the studies on Fe-SMAs in the recent years, the SME of Fe-SMAs was employed for strengthening concrete structures against static and cyclic loading. However, the use of the Fe-SMAs for strengthening steel structures is at the very early stage. The strengthening of steel structures with prestressed CFRP composites have been so far applied to increase the static and fatigue capacities of steel members [25–30]. The efficiency of prestressed CFRPs for flexural, buckling, and fatigue strengthening of steel beams and plates was demonstrated [30–33]. Moreover, the performance of bonded and unbonded prestressed CFRP-strengthened steel members was studied [26,27]. As for the case of prestressed strengthening of concrete structures, the Fe-SMA can facilitate the prestressing procedure in prestressed strengthening of steel members. In the first investigation by the authors [34], the efficiency and feasibility of the Fe-SMA strips for the prestressed strengthening of steel plates were investigated. Steel plates were retrofitted with different configurations of non-activated and activated Fe-SMA strips. The SMA-strengthened steel plates were then tested under quasi-static tensile loading up to failure. The results indicated the successful application of the Fe-SMA strips to decrease the stress levels and therefore to increase the tensile capacity of the steel plates.

1.3. Fatigue behavior of the Fe-SMAs

Few studies reported in the literature explored the high cycle fatigue (HCF) performance of non-activated and activated Fe-SMAs [4,35,36]. For the first time, a series of cyclic tests were performed by Ghafoori et al. [4] to study the cyclic behavior of activated Fe-SMA. The Fe-SMAs were initially tested under strain-controlled conditions with different strain rates; the observations showed that larger strain rates result in larger stresses in the alloy. Subsequently, the Fe-SMAs were subjected to fatigue loading to characterize the recovery behavior of the material. The recovery stress had reduced to approximately 10 to 20% after two million load cycles, indicating a transformation-induced relaxation