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Development of an iron-based shape memory alloy (Fe-SMA) strengthening system for steel plates

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ABSTRACT

This paper presents the development of an iron-based shape memory alloy (Fe-SMA) system for the strengthening of steel plates. The shape memory effect (SME), which is the tendency of a deformed SMA to return to its original shape upon heating and subsequent cooling, was used in this study for prestressing steel plates. Five steel specimens were strengthened with different configurations (single-side, double-side, activated, and non-activated) of the Fe-SMA strips. A mechanical anchorage system was developed to anchor the prestressed Fe-SMA strips to the steel substrate. The SME in the Fe-SMA strips was then activated (i.e., the strips were prestressed) by heating to a temperature of approximately 260 °C using an electrical resistive heating technique. The test results showed that the achieved recovery stress of the Fe-SMA strips (i.e., the prestressing level after activation) was approximately in the range of 350–400 MPa, which led to a maximum compressive stress of −74 MPa in the steel plate. This compressive stress can be very beneficial and significantly increase the yield and fatigue strength of the steel plates. Finally, the strengthened specimens were subjected to static loading under a displacement-controlled condition up to failure. It was shown that the proposed strengthening technique eliminates the difficulties associated with conventional prestressing (e.g., by hydraulic jacks) and also offers a fast installation procedure as it does not require any surface preparation or curing for bond application.

1. Introduction

There are many steel structures in the world that need strengthening because of aging, corrosion, or lack of sufficient load-carrying capacity. This condition is even worsened for structures located in harsh environmental conditions or subjected to increasing service loads. To overcome this problem, strengthening of steel structures with carbon fiber-reinforced polymer (CFRP) composites has received much attention in civil engineering applications [1–4]. CFRP composites provide excellent mechanical properties such as high strength-to-weight ratio, high corrosion resistance, and excellent fatigue performance [5–7]. These properties have shown the effectiveness of CFRP materials to enhance the behavior of steel structures in terms of static and fatigue strength, energy absorption, and ductility.

1.1. Application of prestressed unbonded CFRP plates

The majority of existing studies on CFRP-strengthening of steel structures have used a bonded retrofit (BR) system to attach a CFRP material to steel substrates. Ghafoori et al. [8] suggested an unbonded retrofit (UR) system for the strengthening of metallic girders. Unlike BR systems, the UR systems work without any glue, and instead use pairs of mechanical clamps that work based on friction to attach the CFRP plates to steel I-beams. The UR systems have several advantages compared to the BR systems: they can be applied to rough (e.g., corroded) or obstructed (e.g., riveted) surfaces and offer fast installation (i.e., no surface preparation prior to bonding and glue application). Ghafoori and Motavalli [7] performed the first systematic study to compare the behavior of steel members strengthened by BR systems to that of those strengthened by UR systems. Furthermore, it has been demonstrated that prestressed CFRP composites can further substantially increase the static and fatigue capacity of steel structures [8–12]. The results of extensive laboratory tests in [6] showed that when metallic beams are strengthened by prestressed CFRP laminates, the performance of the CFRP-strengthened steel beams is more sensitive to the magnitude of the prestress level than the presence of the bond. Different shapes and

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Nomenclature

L_o	initial length of Fe-SMA strip
L_{def}	deformed length of Fe-SMA strip
ε_{pre}	prestraining level
ε_{res}	residual strain
T_a	activation temperature
T_o	room temperature
σ_r	final recovery stress
ε_f	final strain under static tensile loading
σ_f	final stress under static tensile loading
C	compliance factor
E_{rst}	restraint factor
$\Delta\varepsilon_{SMA}$	strain change in Fe-SMA strip
$\Delta\sigma_{SMA}$	stress change in Fe-SMA strip
ε_{tr}	transformation strain
ε_{el}	elastic strain
ε_{th}	thermal strain
ε_{rst}	restraint strain
E_{SMA}	elastic modulus of Fe-SMA
ΔT	temperature change
α_{SMA}	thermal expansion coefficient of Fe-SMA
ε_{eff}	effective strain
E_{st}	elastic modulus of steel
A_{SMA}	cross-section of Fe-SMA strip
A_{st}	cross-section of steel plate
L_{SMA}	Fe-SMA strip length
L_{st}	steel plate length
σ_{pre}	prestressing level
ε_{st}^a	strain in steel plate after activation
ε_{SMA}^a	strain in Fe-SMA strip after activation
σ_{st}^a	stress in steel plate after activation
T_{SMA}^{max}	maximum temperature in Fe-SMA strip
T_{st}^{max}	maximum temperature in steel plate
$\dot{T}_{heat}$	temperature heating rate
$\dot{T}_{cool}$	temperature cooling rate
F	static tensile load
σ_{st}^s	stress in steel plate under static loading
σ_{SMA}^s	stress in Fe-SMA strip under static loading
$\Delta\varepsilon_{SMA}^s$	strain change in Fe-SMA strip under static loading

configurations of the prestressed UR (PUR) system have been suggested for the strengthening of steel beams [6,11,13–16] and plates [17,18]. A trapezoidal PUR (TPUR) system has been developed and tested under static [11] and fatigue loading [19]. The system has been used to apply prestressed CFRP plates for the fatigue strengthening of a 120-year-old railway riveted bridge in Switzerland [13,20].

1.2. Application of shape memory alloys (SMAs)

Although strengthening with prestressed CFRP composites has been shown to be very effective, the prestressing procedure is sometimes difficult or even impossible because of a lack of space, as prestressing often requires space and equipment (e.g., hydraulic actuators). Shape memory alloys (SMAs) are advanced materials that offer an easy prestressing procedure, as there is no need for hydraulic actuators, and have been recently used for the prestressed strengthening of civil structures.

The two main characteristics of SMA materials are superelasticity and the shape memory effect (SME). Both features refer to the ability of SMAs to recover their primary shape after permanent deformation. Superelasticity refers to the property whereby a SMA undergoes a large amount of deformation upon loading and recovers its original shape after unloading (without heating). The SME property of SMAs is a thermomechanical ability of a deformed SMA to regain the original shape after being subjected to heat. Owing to these two properties, SMAs have been developed in different engineering fields such as vibration damping, self-actuating fasteners and couplings, and pre- and post-tensioning [21–25]. The application of superelasticity in civil engineering construction has been mainly focused on passive damping and energy dissipation [26–28], whereas the SME property of SMAs has been used in the pre- and post-tensioning of civil structures [21,25,29].

In fact, while the deformed SMA is restrained during heating and subsequent cooling, the material induces prestressing forces. Consequently, SMAs can be activated (i.e., prestressed) without any hydraulic actuators. This method makes prestressing technique easier and therefore, more applicable in the field of civil engineering. The first exploitation of the SME property was performed with nickel–titanium (NiTi) SMAs, (i.e., nitinol) [21]. By heating the NiTi SMA wires, a recovery stress is generated inside the material, which is used for external prestressing applications [30–32]. Furthermore, a SMA–CFRP hybrid patching technique has been recently developed [33]. The patching system employs a ternary NiTi–niobium (NiTiNb) SMA with a wide thermal hysteresis, which sustains recovery stresses upon cooling to freezing temperatures. The SMA–CFRP hybrid system provides several distinct benefits. Most notably, this approach does not require the installation of any mechanical fixtures to anchor the system to the structure or apply the prestressing [34]. The integrity and effectiveness of the system does, however, rely on adequate bonding between the SMA wires and the CFRP tabs and the level of surface preparation of the steel substrate prior to the bond application [35].

1.3. Fe-SMA materials for prestressed strengthening of structures

Iron-based SMAs (Fe-SMAs) are another type of SMA that are used in civil engineering [36,37]. Advantages such as the low cost of raw materials, easy manufacturing process, stable recovery stresses, and high elastic stiffness increase their attractiveness and applicability in the civil engineering domain [24,38]. Fe-SMAs show an SME as a result of a mechanically induced phase transformation from the austenite (face-centered cubic, γ) to martensite (hexagonal close-packed, ε) phase and its reversion upon heating [38–40].

Recently, a new Fe-SMA, Fe–17Mn–5Si–10Cr–4Ni–1(V,C), in the form of bars and strips was developed at Empa, Switzerland [41]. Ghafoori et al. [42] studied the cyclic deformation and fatigue behavior of the alloy. They showed that while the stiffness of the alloy remained almost constant during high-cycle fatigue loading, a decrease in the recovery stress was observed, which was assumed to be mainly a result of a transformation-induced relaxation under fatigue loading [42]. Moreover, they proposed a formulation based on a constant life diagram CLD approach for a safe design of the alloy as a structural prestressing element under a high-cycle fatigue loading regime with different stress ratios (R). Furthermore, Hosseini et al. [43] studied the evolution of recovery stress of the alloy under different restraint conditions. They studied the cyclic behavior of the prestressed alloy followed by a second thermal activation. It was shown that although the magnitude of the recovery stress decreased during cyclic loading, which confirmed the conclusion in [42], the second thermal activation could retrieve a significant part of the relaxed recovery stress [43].

In another investigation performed by Czaderski et al. [44], a feasibility study was conducted on concrete bars. The concrete bars were successfully prestressed with a centrally embedded Fe-SMA strip. The strips were heated to a temperature of 160 °C to provoke the SME of the embedded Fe-SMAs [44]. Compressive stresses measured in the concrete bar section showed the general feasibility of applying the SME of Fe-SMA strips in prestressing. In another study to employ Fe-SMA strips, Shahverdi et al. [36,37] reinforced concrete beams with