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Shape memory alloy-carbon fiber reinforced polymer system for strengthening fatigue-sensitive metallic structures

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ABSTRACT

This paper provides an overview of the basic elements, course of development, experimental evaluation, and numerical simulation of a thermally activated shape memory alloy (SMA) and carbon fiber reinforced polymer (CFRP) composite system for fatigue repair or retrofit of metallic structures. Nickel titanium niobium (NiTiNb) SMA wires, which are able to generate 400 MPa recovery stress upon thermal loading and maintain that stress level at a wide range of temperatures, was adopted to apply compressive stresses near the crack. Monotonic bond behavior of single and multiple SMA wires to CFRP was investigated; the debonding onset load and maximum capacity were quantified. The fatigue behavior of patches consisting of multiple wires bonded to CFRP was studied. Results indicated that the system could maintain 80% of the recovery stress, after up to 2 million load cycles, so long as the maximum applied stress was below the debonding onset level. A fatigue strengthening system, using such multiple SMA wire system as underlay and CFRP patch as overlay, was applied to fatigue sensitive steel plates for fatigue life improvement evaluation. The average fatigue life of the patched steel plates was over 26 times longer than that of the unpatched plates tested at the same load range. Finally, a numerical framework was developed to simulate the fatigue crack growth in steel plates patched with such strengthening system and was validated by the experimental data. The findings suggest that the proposed system could be a promising alternative to traditional techniques for fatigue crack repair.

1. Introduction

Fatigue strengthening of metallic elements has progressively become a major research topic for the use of fiber reinforced polymer (FRP) composites since the early experimental and numerical studies [1–3]. Relevant research has since covered various target structural components, strengthening configurations, different metallic materials, and fatigue cracking modes. Non-prestressed FRP has proved effective in strengthening plated members [4,5], very large crane girders [6], and steel beams [7]. Hu et al. [8] analyzed the CFRP strengthened steel plates and beams, with existing fatigue cracks or fatigue sensitive details, taking into account the fatigue crack induced debonding, and developed a computer program for the design of CFRP fatigue repairs. In addition to mode I crack propagation, crack propagation in orthotropic connections of members in metallic bridges, so-called distortion-induced fatigue, involves mode III cracking. This was investigated in [9], where CFRP plates were used to successfully increase the fatigue life by 4 to 10 times, for different stress ratios, compared to unstrengthened specimens. In-plane mixed mode, i.e. mode I and mode II, crack initiation followed by mode I crack propagation has also been investigated [10–12].

Prestressed FRP patches were found to be more effective for fatigue life enhancement than non-prestressed patches [13]. Huawen et al. [14] conducted 14 fatigue tests of double-edge notched steel plates that were strengthened with prestressed CFRP laminates. CFRP with prestress levels of 600, 1000 and 1200 MPa increased the fatigue lives of the steel plates by 0.7, 1.7 and 3.4 times, respectively, those of nonprestressed laminates. Hosseini et al. [15] reported the use of prestressed CFRP to completely halt the fatigue crack in tensile steel plates. In the study, using non-prestressed ultra-high modulus CFRP, the fatigue life increased by over four times. Prestressing the CFRP fully arrested the crack. Various types of prestressed bonded and unbonded reinforcement systems have been developed and extensively investigated [16,17]. Prestressing externally bonded or unbonded FRP plates usually require hydraulic jacks and heavy fixtures [13]. Most prestressed CFRP strengthening systems involve mechanical end-anchors to prevent premature debonding during stressing [18]. In Hosseini et al. [15], the prestressed CFRP strips were anchored to the substrate by means of

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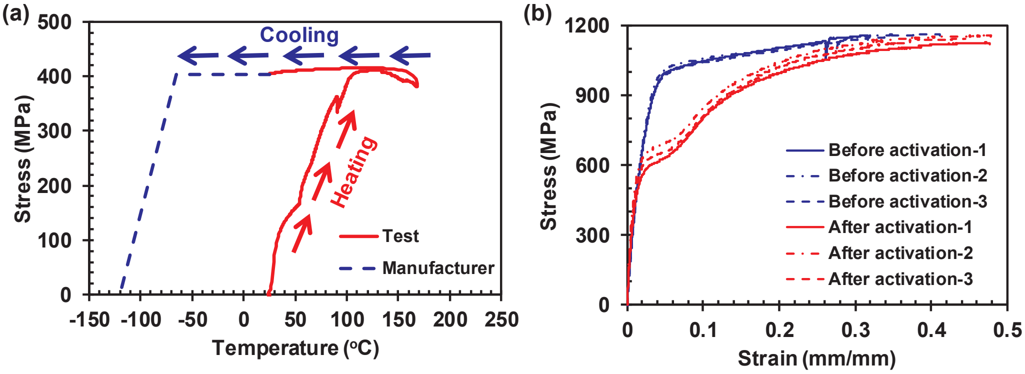

Fig. 1. Mechanical properties of NiTiNb wires: (a) thermo-mechanical behavior of single NiTiNb SMA wire; (b) stress–strain relationship before and after thermal activation.

steel anchor plates with 12 bolts, which altogether could generate 518 kN of anchorage force. The prestressing apparatus, in this study, consisted of a reaction frame, two tension rods, clamping systems and hydraulic jacks. Chen et al. [19] studied the fatigue strengthening, using prestressed-, non-prestressed- and high-modulus-CFRP, of rectangular-hollow-section steel beams with notches in the tension area. While the prestressed CFRP was the most effective system, the task of prestressing the CFRP was a major challenge that limited the potential to exploit the high tensile strength of the CFRP. In this application, the prestressing apparatus was larger than the steel beam itself. The size and complexity of the fixtures needed to apply prestressing forces is a primary barrier to the feasible adoption of the technique.

Shape memory alloy (SMA) materials exhibit a unique thermo-mechanical response. The shape memory effect has been exploited to develop composites that are able to actively tune their mechanical response through thermal activation [20–22]. In these applications, the thermally induced recovery forces in the SMA modulate the properties of the composite. The bond between SMA materials and CFRP has been evaluated to understand the failure mechanism [23] and to develop a model to predict the critical parameters [24,25]. Ternary nickel-titanium-niobium (NiTiNb) SMA have been developed to ensure a wide thermal hysteresis with high activation temperatures and low reverse transformation temperatures [26], making them well suited for applications that require sustained recovery forces over a wide temperature range [27]. Iron-based SMAs (Fe-SMAs) possess similar wide thermal hysteresis traits and are promising for civil engineering applications. Fe-SMAs were used to strengthen reinforced concrete beams; the Fe-SMA provided 350 MPa of prestress and the cracking load of the beam was increased by 200% [28]. An anchorage system for the application of Fe-SMA strips on steel plates was developed [29]. Using the anchorage system, the Fe-SMA strips were attached to steel plates and thermally activated; the resulting recovery stress in the SMA was 370 MPa, and the corresponding compressive strain in the steel was 90×10^{-6} mm/mm [30].

This paper describes a novel thermally activated SMA-CFRP composite system for extending the fatigue life of cracked or crack-sensitive metallic structures. The system consists of two layers of externally bonded composites: an underlay containing multiple SMA wires that is able to apply compressive stress to the metallic substrate, and an overlay CFRP patch that reduces the stress range in the metallic substrate. The single SMA wire behavior, and its bond to CFRP matrix is presented. A multiple wire SMA-CFRP system was monotonically tested to examine the effectiveness of multiple wires in a single patch. The characterization of the system was concluded through a series of fatigue tests to assess the stability of the recovery stress under high cycle fatigue loading. Based on the full understanding of the SMA-CFRP composite patch, a strengthening system was implemented onto edge-notched steel plates to investigate the effectiveness of the approach for fatigue life improvement. Finally, a numerical framework is introduced to simulate the fatigue crack growth (FCG) of the steel members that are reinforced with the developed system.

The comprehensive review of the entire course of development, experimental evaluation, and numerical simulation of the novel system altogether highlights the connections among the elements and enables new perspectives for comparison and understanding, which were inaccessible previously by examining the individual elements separately. The strengthening mechanism of the developed SMA-CFRP system, and, to a broader sense, of any fatigue strengthening approach using prestressed CFRP, was assessed and expounded theoretically, in Section 4, and experimentally, in Section 5, for the first time. The experimental observations, the consequent inference, and the numerical simulation of the fatigue crack induced debonded region elaborate and validate the grounds for modeling of fatigue crack growth analysis in FRP patched metal through cycle-by-cycle approach, i.e. a series of static models.

2. Monotonic behavior of SMA-CFRP bond

Single and multiple SMA wires were pulled-out of a CFRP patch to investigate the monotonic bond behavior. The thorough understanding provides grounds for investigating the fatigue behavior of SMA-CFRP bond hence developing the strengthening system.

2.1. NiTiNb SMA

The developed system employs a NiTiNb SMA with wide thermal hysteresis to apply prestressing forces to steel elements. The wires in this study were provided with a diameter of 0.77 mm and a grit blasted surface. The wires were received in the martensitic phase with a 5% residual strain, at room temperature. According to the manufacturer (Intrinsic devices Inc.), the austenitic start (A_s), austenitic finish (A_f), martensitic start (M_s), and martensitic finish (M_f) temperatures, of the NiTiNb, are 47 °C, 165 °C, −65 °C and −120 °C, respectively. Fig. 1(a) illustrates the temperature vs. recovery stress relationship of the wires during heating and cooling. A 254 mm long SMA wire was restrained between two grips of a rigid testing frame. The force in the wire was measured using an 1100 N load cell. To remove slack in the wire a seating load of 8.9 N was applied before activation. The wire was activated by running a controlled current in the wire through two electrodes; the temperature of the wire was measured by thermocouples that were bonded to the wire between the two electrodes. Heating the wire, from room temperature to 160 °C, induced an increasing recovery stress of up to 400 MPa. When the wire was cooled to room temperature, the 400 MPa recovery stress was retained as shown in the figure. The dashed line in the figure shows the theoretical temperature-recovery stress relationship below 25 °C. Six samples of the wires were tested to failure under tension. The first three were tested at room