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Fatigue life improvement of steel structures using self-prestressing CFRP/SMA hybrid composite patches

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ABSTRACT

While prestressed CFRP patches are considered as attractive alternatives to traditional welding or bolting methods for enhancing the fatigue life of cracked steel structures, they commonly require hydraulic actuators and pumps, and complex setups and installations for prestressing, limiting the applicability of this method. The primary objective of this research is to investigate the use of shape memory alloys (SMAs) in combination with CFRP composites to develop self-prestressing CFRP/SMA hybrid patches. The concept of the self-prestressing is to embed prestrained SMA wires into the CFRP patches and activate them through direct heat or electric current, thereby, generating prestressing forces in the cracked member. Two types of NiTi SMA wires, namely, the body-temperature and as-drawn heat-treated NiTi SMA wires are used in the fabrication process of the patches. The results demonstrate that the developed self-prestressing CFRP/SMA hybrid patches can be used as simple and effective solutions to significantly enhance the fatigue life of cracked steel structures.

1. Introduction

Fatigue cracks form in various steel structures such as bridges, offshore platforms, ships, cranes, vehicles, aircrafts, etc. The sources of fatigue cracks are cyclic loadings induced by traffic, wind and waves loads or machinery vibrations. Under these repeated loadings, cracks potentially initiate at regions with stress concentration such as welds, holes or notches and propagate progressively to the failure of the member, which may compromise the integrity of a structure. Therefore, efficient and safe fatigue life enhancement of structures is one of the primary objectives of the repair and rehabilitation processes to prevent any possibility of partial or total failure.

The conventional repair methods of cracked steel structures typically include the methods that create an alternative load path for stresses developed around the cracks tip or those that implement prestressing techniques to arrest the further progression of the cracks by developing residual compressive stresses close to the crack tip. The repair methodologies of the first category commonly include bolting doubler/splice plates, drilling crack-stop holes, peening, or repair welding [9,10,38]. These methods, however, are still prone to crack re-initiation and require applying permanent modifications to the parent structure. These challenges have motivated researchers to find alternative methods such as the application of the externally bonded CFRP patches that allows reducing the stress range near the crack tip by bonding the patch across the crack with a proper adhesive [25,27,33,15]. This technique can be further enhanced by prestressing the CFRP patch, thereby, developing a compressive stress field close to the crack tip. While prestressing has been shown to be an effective method to completely stop the propagation of cracks, it requires the use of hydraulic actuators/pumps, and/or complex fixtures/setups [46,53,48,20,21,14,22].

This paper aims to address this challenge by taking advantage of unique properties of shape memory alloy (SMA) materials and developing self-prestressing CFRP/SMA hybrid composite patches. SMAs are able to recover back to their primary undeformed shape after undergoing permanent deformation through their two remarkable characteristics, namely, the shape memory effect (SME) and the super elasticity (SE). From these two, SME can be used to generate prestressing recovery forces in SMAs. The SME phenomena include cooling the SMA at austenite to form martensite at room temperature, deforming the martensite, then reverting to austenite at high temperature; thus, restoring the original pre-deformed shape. By constraining the SMA, as it begins to return to its original shape during the reverse phase transformation, prestressing recovery forces can be generated in the SMAs. This unique property, when combined with CFRP composites, provides several potential capabilities in civil engineering including the application of prestressing forces to concrete beams [32,8], the application of active confinement to concrete columns [3,40,41,42], among

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other applications [43,44,31,47,26,28,34]. Few studies, however, investigated the use of CFRP/SMA hybrid patches to repair fatigue damaged steel members [1,13,12].

This paper reports the conceptual development and the results of material level tests of self-prestressing CFRP/SMA hybrid composite patches made of unidirectional normal modulus CFRP fabric and prestrained nickel titanium (NiTi) SMA wires. The developed patches are applied to initially-cracked steel plates to study their effectiveness in improving the fatigue life of cracked steel structures. Two types of NiTi SMA wires, namely, the body-temperature and as-drawn heat-treated NiTi SMA wires, are used in the fabrication process. The concept of the self-prestressing is to embed prestrained SMA wires into the CFRP patches and activate them by application of direct heat or electric current, thereby, generating prestressing forces in the repaired member. The results demonstrate that the self-prestressing patches significantly enhance the fatigue life of cracked steel structures with the minimal tool and labour requirements.

2. Material properties

2.1. Steel plates

To conduct the fatigue tests, mild carbon steel plates with the dimension of (500 × 90 × 6) mm and (500 × 50 × 5) mm were selected for testing the patches with body-temperature and heat-treated SMA wires, respectively. The tensile properties of the steel plates were characterized through uniaxial tensile tests on three steel coupons using a 250 kN MTS universal testing machine and according to the specification of ASTM E8/E8M-13 [5]. The material properties of the 5 mm and 6 mm thick steel coupons including the modulus of elasticity, the tensile yield and ultimate strength were measured by averaging the response of three specimens and are listed in Table 1.

2.2. Carbon fibre reinforced polymer (CFRP) fabrics

Unidirectional normal modulus carbon fibre sheets were used to make CFRP-only and the CFRP/SMA patches. The material properties of the CFRP sheets supplied by the manufacturer (BASF Construction Chemicals Australia Pty Ltd) are presented in Table 2.

2.3. Epoxy adhesive

Structural epoxy adhesive (Araldite 2014-1) was used to produce CFRP-only and CFRP/SMA hybrid patches and to attach them to the steel plates. Araldite 2014-1 is a two-component high-temperature and high-strength paste adhesive. The glass transition temperature of the epoxy adhesive was measured by conducting dynamic mechanical analysis (DMA) tests on adhesive specimens (two samples) following the procedure given by ASTM D7028-07 [4]. The measured glass transition temperature was very close to 85 °C, the value provided by the manufacturer. The material properties of the epoxy adhesive given by the manufacturer (Huntsman Advanced Materials) are presented in Table 3.

2.4. Shape memory alloys (SMAs)

NiTi SMA wires, 1 mm in diameter, were used to produce the CFRP/SMA patches. Two types of SMA wires were selected for this study: the body-temperature Nitinol SMA wire and the as-drawn (40% cold work, raw material) Nitinol SMA wire that requires the heat treatment process to gain shape memory effect. The SMA characteristics can be improved by a combination of cold work together with a subsequent heat-treatment process. Increasing the cold work reduces the shape memory properties, but increases the yield strength. On the other hand, heat treatment process will restore the shape memory effect but decrease the yield strength. The choice of amount of cold work and the heat-treatment temperature establish the combination of these two properties [18,37].

Table 1
Material properties of steel plates.

Description	6 mm Steel Plate	5 mm Steel Plate
Modulus of elasticity (GPa)	212	203
Tensile yield strength (MPa)	345	298
Ultimate tensile strength (MPa)	532	435

Table 2
Nominal material properties of CFRP sheets.

Description	Normal Modulus CFRP
Fiber reinforcement	Carbon high tensile
Fiber elastic modulus (GPa)	230
Ultimate tensile strength (MPa)	4900
Thickness (mm)	0.17
Fiber density (g/cm^3)	1.76

Table 3
Nominal material properties of epoxy adhesive.

Properties	Araldite 2014-1
Elastic modulus (GPa)	4.0
Tensile strength (MPa)	26
Ultimate tensile elongation (%)	0.7
Glass transition temperature (°C)	85

The chemical composition of both types of Nitinol SMA wires mainly comprised of two elements, Nickel and Titanium. According to the information given by the manufacturer (Memry Corporation), the chemical composition for the body-temperature Nitinol SMA wires was 55.5% Nickel and 44.5% Titanium and for the as-drawn raw Nitinol SMA wires was 55.84% Nickel and 43.85% Titanium, as specified by ASTM F2063-12 [7]. It is worth mentioning that the cost of raw SMA wires is approximately one-third of the cost of body-temperature SMA wires for which the heat treatment process is conducted by the manufacturer. More information on the properties of the SMAs can be found in Abdy [1].

3. Self-prestressing CFRP patches with Body-Temperature NiTi SMA wires

Three types of patches were fabricated including one CFRP-only and two CFRP/SMA types with prestrained body-temperature NiTi SMA wires. The patch dimensions were (250 × 50) mm, which were selected based on the previous studies investigating the effects of CFRP bond length, bond width and bond locations on the fatigue performance of steel members [29,51]. The CFRP-only type was fabricated using two longitudinal CFRP layers and named CFRP-2L. The CFRP/SMA types included two patches that were fabricated using two longitudinal CFRP layers that sandwiched one transverse CFRP layer as well as 9 and 15 prestrained body-temperature SMA wires, respectively. These patches were named CFRP-(2 + 1)L/9BT-SMA(P) and CFRP-(2 + 1)L/15BT-SMA(P). More information on the details of the fabrication process can be found in Abdy [1].

3.1. Preliminary recovery stress tests

Before conducting the fatigue tests, an experiment was performed to obtain more information about the austenite and martensite phase transformation of the body-temperature SMA wires. The values of the austenite transformation start and finish temperatures (A_s, A_f), as well