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Cyclic flexural behavior of hybrid SMA/steel fiber reinforced concrete analyzed by optical and acoustic techniques

Muhammad M. Sherif[a,*], Evelina M. Khakimova[a], Jonathon Tanks[b], Osman E. Ozbulut[a]

[a] Department of Civil and Environmental Engineering, University of Virginia, Charlottesville, VA 22901, USA
[b] Department of Chemical Science and Engineering, Tokyo Institute of Technology, Tokyo 152-8550, Japan

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ABSTRACT

Superelastic shape memory alloys (SMAs) are smart materials that can recover 6–8% elastic strains due to their phase transformation. SMAs also possess unique characteristics such as good energy dissipation, excellent re-centering capabilities and corrosion resistance. Recent studies have incorporated the use of superelastic SMA fibers in cementitious composites to achieve re-centering and crack-closing capabilities. Consequently, it is important to investigate the performance of fiber reinforced concrete (FRC) members under cyclic loading. This study investigates the use of hybrid steel/SMA fibers as reinforcement in concrete members subjected to cyclic flexural loading. Digital image correlation (DIC) was used to monitor the full field displacements and strains of the concrete beam specimens. Fiber density and statistical spatial point pattern functions were used to assess the fiber distribution. Two acoustic emission sensors were attached to each side of the concrete specimens to characterize crack development. A correlation between the crack width propagation and cumulative energy captured by the acoustic emission sensors was established. Results showed that the hybrid specimen with equal fiber volume ratios for steel and SMA fibers exhibit a lower mid-span deflection and smaller crack width.

1. Introduction

Concrete is an essential construction material that has a high compressive strength, but a relatively weak tensile strength. Reinforced concrete members crack because of excessive loading, chemical reactions and volumetric changes, allowing water and harmful solutions to seep into the members. The intrusion of harmful solutions initiates and increases the corrosion of steel reinforcement. Recently, several investigations have been conducted on the use of corrosive resistant and CFRP reinforcement bars to mitigate steel corrosiveness [1–7]. Nevertheless, the problem of crack opening in concrete members under tension has not been addressed [8].

The functionality of a structure can be enhanced and its serviceability can be increased by developing concretes that possess crack-closure (i.e. ability to reduce and control crack size) and re-centering capabilities (i.e. ability to return to initial un-deformed position upon unloading). Cracks with a stabilized behavior might be achieved by adding steel fibers into the concrete matrix. However, once the fibers experience permanent strains they may not maintain the re-centering or crack-closing behavior [9].

Researchers in various engineering applications have explored the use of smart materials such as shape memory alloys to improve performance of structures. Due to their solid-to-solid phase transformations (i.e. austenite to martensite and vice versa), SMAs have a unique feature of remembering their original shape. The phase transformations in SMAs can be triggered by inducing stress (superelastic effect) or by inducing heat (shape memory effect). Fig. 1(a) and (b) illustrate the stress-strain curves for superelastic and shape memory effect SMAs, respectively. Superelastic SMAs can go up to 6–8% elastic strains, while shape memory effect SMAs can recover 6–8% of inelastic strains upon thermal activation. Further, SMAs have favorable energy dissipation capacity, high corrosion resistance and long fatigue life [10,11]. Civil engineering researchers have explored the use of SMAs in various forms such as damping devices [12,13], beam-column connectors [14,15], or reinforcing and prestressing bars [16–20]. A detailed review on the use of SMAs in structural applications is provided in [21].

In recent years, researchers have also assessed the behavior of SMAs in cementitious composites. Choi et al. [22–24] investigated the crack closing behavior of cement mortar beams reinforced with *shape memory effect* NiTi and NiTiNb SMA short fibers at the tension side. The beams were loaded in a third-point flexural bending test configuration. The fibers were placed over a small notch at the center of the beam. The beams were loaded to a maximum deflection, after which the cracked specimens

* Corresponding author.
E-mail address: msherif@virginia.edu (M.M. Sherif).

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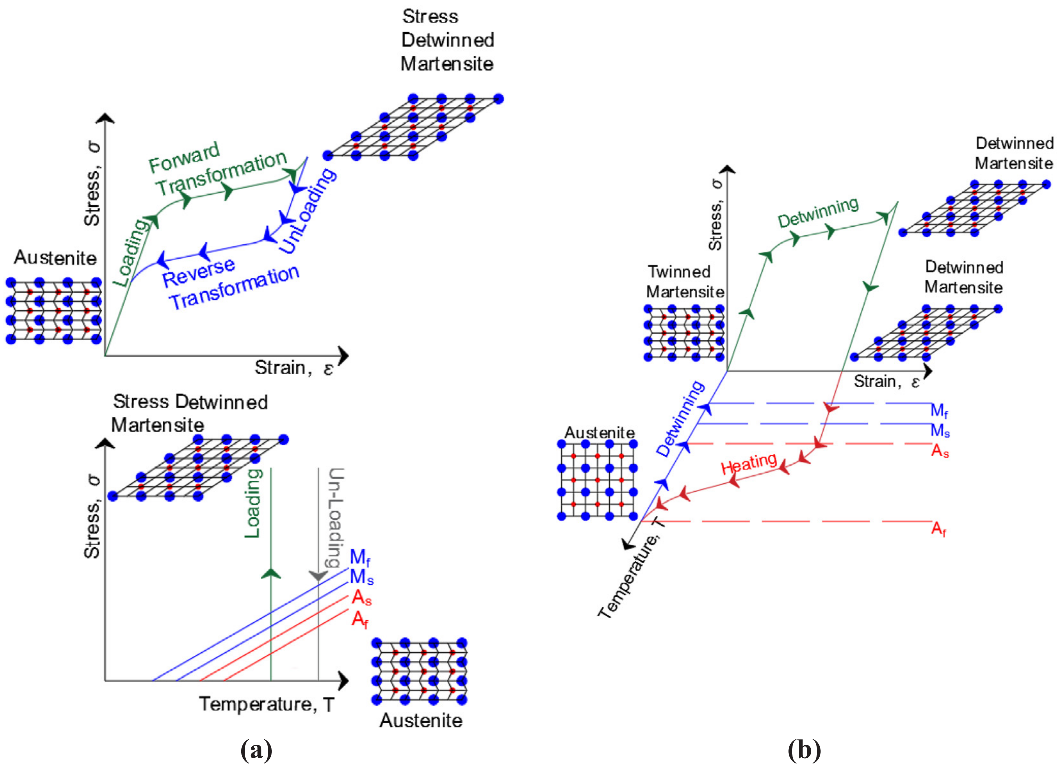

Fig. 1. Typical stress-strain response of (a) superelastic and (b) shape memory effect SMAs.

were heated to thermally activate the shape memory effect SMAs. It was concluded that the dog-bone shaped fibers provide higher bond strength, allowing better interaction between the fibers and mortar, and achieving crack-closing capabilities. Shajil et al. [25,26] explored the performance of *superelastic* SMA fiber reinforced mortar beams with respect to self-centering behavior. Li et al. [27] investigated the effect of integrating *superelastic* NiTi SMA fibers into engineered cementitious composites (ECCs). It was observed that the SMA fiber reinforced specimens significantly recovered the mid-span deflection during unloading and demonstrated a crack recovery behavior. Sherif et al. [28] investigated the use of randomly distributed SMA fibers in mortar specimens. It was observed that specimens with 0.5% to 1.0% of SMA fiber volume ratio achieved re-centering, and crack recovery behavior.

Most of the previous studies investigated the use of SMA fibers that are intentionally placed at the tension side of the beam. Further research is needed to investigate the effectiveness of randomly distributed SMA fibers. In addition, all previous studies on SMA fiber reinforced cementitious composites studied the effect of SMA fibers in matrices consisting of paste and fine aggregate (mortars). As the fiber reinforced mortars have better properties than their concrete equivalents due to the nature of fiber-matrix interactions, it is important to study the reinforcing effectiveness of SMA fibers in concrete, composing of both fine and coarse aggregates. As compared to mortar-based composites, concrete composites have greater stiffness and abrasion resistance and are more representative of real structural systems.

This paper assesses the effectiveness of randomly distributed SMA fibers in concrete while monitoring the behavior of the flexural specimens using digital image correlation (DIC) and acoustic emission (AE). Fiber reinforced concrete beam specimens with (i) only SMA fibers, (ii) only steel fibers and (iii) the combination of steel and SMA fibers were prepared. All fiber reinforced concrete specimens had a fiber volume ratio of 0.6%. Flexural bending tests were conducted under an incrementally increasing displacement loading protocol. Results were analyzed in terms of mid-span deflections, ultimate capacity, residual strength, residual displacements, crack width propagation and fiber distribution. The acoustic emission parameters such as duration, average frequency, cumulative energy and rise amplitude were studied to obtain further information about the flexural behavior of tested specimens. A correlation between the crack width monitored by DIC and cumulative energy captured by AE was established.

2. Description of optical and acoustic techniques

2.1. Digital image correlation

Digital Image Correlation (DIC) represents an effective real time, full field, and non-contact optical surface measurement system [29]. The rapid advances in correlation algorithms have led to the use of DIC in various engineering applications [30,31]. The method can be used for static and dynamic testing [32]. The DIC technique uses a series of sequential images captured during experimental procedure to track the speckle patterns applied on a specimen. Using a single optical device, placed perpendicular to the surface of the specimen, the two-dimensional (2D) deformations and strains can be acquired. Post-processing of the images includes the correlation of patterns within a gridded subset space in the sequential images to describe deformations and strains. As cracks are represented by discontinuities in the displacement field, propagation of a crack can be precisely monitored, and the full history of a crack can be generated using the DIC capabilities.

2.2. Acoustic emission

Acoustic emission (AE) is the generation of transient elastic waves that are caused by the release of energy from localized sources within a specimen. Acoustic emissions testing can be used as a non-destructive method to evaluate and monitor structural integrity of members [33–36]. The acoustic waves within a material matrix can be detected by attaching one or more AE sensors, made of piezoelectric material [37,38]. The transducers record electric waveform response caused by an energy release event in the system. The analysis of the waveforms properties provides information about the crack propagation, density of cracks, and failure mechanism.