FABRICATION AND CYCLIC LOADING OF SUPER-ELASTIC SHAPE MEMORY ALLOY REINFORCED POLYMER

Rachel Carder
INTRODUCTION

Fiber-reinforced polymers (FRP) have increased in demand for civil engineering applications such as construction, reinforcement, and restoration of structures. FRPs are used for these applications due to their corrosion resistance, and durability. However, their use in construction is limited when in regions with high seismic loads because they have little energy dissipation capabilities and are low ductility.

Super-elastic Shape Memory Alloy (SMA) is a material that can mechanically regain its original shape after exceeding its elastic limit. Once a load is removed from the alloy, it will recover shape with little to no residual deformation. This smart material was initially used in the medical field for surgeries, prosthetics, and dentistry but has since been applied to other fields such as aerospace, robotics, and automotive. Similar to FRP, it has also been applied to construction and restoration of structures. Due to its high resistance to corrosion, SMA can also replace steel reinforcement in concrete structures.

This study focuses on fabricating a composite incorporating both of these materials. SMA wires composed of primarily nickel and titanium (NiTi) will be imbedded in an epoxy matrix to form a polymer with the SMA wire acting as the fibers (SMA-FRP). Using the SMA wire as the reinforcing fiber will allow the composite to have high ductility, energy dissipation, and increase the strain capabilities. Each specimen will be approximately ten percent SMA wire with two different diameters of wire. This study explores the tensile behavior of SMA-FRP specimens fabricated by a modified hand lay-up technique, and observes how different diameters of wire alter the performance of the specimen.

LITERATURE OVERVIEW

Most fiber-reinforced polymers are composed with either glass (GFRP) or carbon fibers (CFRP) as its reinforcement material. These fibers are imbedded into a matrix material that prevents the fibers from being damaged by corrosion or direct loads [1]. This design yields a material that can undergo high stress. However, CFRPs and GFRPs cannot undergo environments that exceed 3% tensile strain [2]. The material’s inability to dissipate energy causes sudden brittle failures; a characteristic that can be detrimental for many structures. FRP can be used to strengthen beams, columns, and slabs of structures. Flexural and shear strengthening can occur when applied to the tension face and the web of beams [3].

Halahlia reviewed studies on how SMA can be used as reinforcement for concrete structures. [4] One study replaced conventional steel rebar with the smart material in concrete beams and tested them under seismic load conditions. The results showed that the SMA reinforced beams had a 90% crack recovery capacity whereas the steel rebar beams had a maximum of 25%. The modified beam also had recentering capabilities and improved the beam’s strength and durability. Another study investigated using SMA wires as an emergency repair technique by wrapping wire around concrete columns that had been damaged by seismic events. Their techniques could repair a damaged bridge column in under 15 hours.

Zafar and Andrawes investigated multiple ways to make SMA-FRP composites. [5] Specimens with 100% SMA reinforcement and a hybrid SMA-FRP that included other reinforcing fibers were fabricated and tested. It was found that the SMA wire’s recentering capabilities allowed the composite to recover residual strains. Therefore, the composites that had 100% SMA reinforcement had higher ductility, energy dissipation, and elongation properties than the hybrid specimens. Sharifishourabi, et al. found that the specimen’s effective elastic and shear moduli increased when percentage of SMA wires in the composite increased. [6]
METHODOLOGY

The specimens were fabricated with two materials: epoxy matrix and SMA wires. The epoxy forms the shape of the specimen and holds the SMA wires in place while the SMA wires reinforce the specimen. The epoxy matrix is a 2:1 epoxy resin-to-hardener ratio measured by volume. The epoxy was cured for seven days. Two different diameters of SMA wires were used to find an optimal size. The SMA wires were superelastic NiTi wires with diameters of 0.5 and 0.711 mm. The wires have Ms = 20.55°C, Mf = -6.6°C, As = -5.5°C, and Af = 24°C.

A special mold was made to fabricate the specimens with a cross section area of 13x4 mm² to be tested and a larger area at the ends for gripping as shown in Fig. 1. The fiber volume ratio was 10% for each specimen. The wires were set inside the mold and the epoxy matrix was poured over the wire until the mold was filled. The molds were covered for 24 hours prior to demolding. The specimens were then tested on the seventh day of curing.

After the specimens have cured for 7 days, the specimens were tested under uniaxial cyclic loading. All tests were performed with a 98-kN MTS servo hydraulic testing frame and recorded with the MTS data system. A laser extensometer was set up adjacent to the testing frame to record the displacement of the middle portion of the specimens. Figures 2 and 3 shows the test setup. Prior to testing, the ends of the specimens were scored to enhance gripping capabilities. Three tests were performed on each batch of specimens. For the first test, the load was ramped to 220 N at a rate of 10 N/sec. The load level was then cycled between this level and a zero force level for 3 cycles at a frequency of 0.01 Hz. After the third cycle the load was then increased by an additional 220 N and the process was repeated. The load cycles were continuously until rupture. For the second test, the load level was ramped up to a load level that showed superelastic behavior based on observations made on the first test. The load level was ramped at a rate of 10 N/sec and cycled for 3 cycles at a frequency of 0.01 Hz. At the end of the third cycle, the tension was released from the specimen by releasing the grips. The load level was then increased by an additional 220 N and the process was repeated until failure of the specimen.
RESULTS

Using the data collected by the MTS data acquisition system, the tensile stresses and strains were calculated. Tensile stress was found by dividing the forces by the cross sectional
area of the specimen. Strain was found by dividing the displacement in length that was recorded with the laser extensometer by the original length of the specimen. Figure 4 displays the stress strain curve of the first test run on the specimens with 0.5 mm wire. The graph is separated into three phases. The first phase, representing data collected from 0% strain to 6.8% strain, shows linear elastic behavior. In this phase, the composite showed full recovery with approximately zero residual deformations. In the second phase, between 6.8% strain and 8.0% strain, the specimen began to accumulate plastic deformations. The third and final phase, between 8.0% strain and 10.3% strain, the specimen experienced permanent deformations. The specimen failed at 10.3% strain at a force load of 7,260 N. Figure 5 displays results obtained from the second tensile test. These results show consistency with the first test. The specimen performed with superelastic behaviors until approximately 6.8% strain.

Figure 4: Stress strain curve of the first test of the specimen reinforced with 0.5 mm SMA wire.
All graphs shown are data collected from the specimens reinforced with the 0.5 mm wires. The data collected with the larger diameter of wire were inconclusive due to a number of experimental errors. The viscous nature of the epoxy matrix being used caused the specimens to have a number of large air bubbles in the specimens with the 0.7 mm wire. The air bubbles created holes and exposed the SMA wires with no epoxy coating. Furthermore, for an unknown reason, the resin did not completely cure for this batch of specimens. There were a number of specimens that had a layer of unhardened epoxy residue on the surface of the composite. Figure 6 and 7 shows these errors. This restricted the 0.7 mm batch of specimens to perform optimally. During the tests, the specimens would fail prematurely along the formed holes, therefore, the data collected by these tests were not analyzed.
During testing, a phenomenon known as debonding occurred. The SMA wires and the epoxy on the SMA-FRP were experiencing the same strain levels. However, since the wires have a larger modulus of elasticity than the epoxy matrix, the wires experience a higher stress than the epoxy. Therefore, as the strain levels increase, the wires’ diameters will begin decrease at a faster rate than the epoxy matrix. Furthermore, the wire diameter will decrease at points along the wire rather than over the entire specimen length, but as the strain levels increase, these areas with lower wire diameters will increase along the specimen. As the diameter of the wire shrinks, the wire begins to “debond” from the specimen. Figure 8 shows one of the specimens during the debonding state. The lighter colored areas are where the wire began to debond from the matrix. As the strain levels increased, the debonding spread to the rest of the specimen and failure occurred where the wires appeared to pull out of the specimen.
CONCLUSION

Composites reinforced with SMA wires were fabricated and tested. The test batches had a volume ratio of 10% SMA wire reinforcement with 0.5 mm and 0.7 mm wires. The specimens were tested in uniaxial tensile cyclic loading. Stress strain curves were then made from the collected data. The specimens with 0.5 mm wire could maintain linear elastic behavior until 6.8% strain. This test showed that to use a larger diameter of wire different fabricating methods must be used to avoid large air bubbles. In comparison to conventional FRPs, the SMA-FRP showed high ductility, high energy dissipation, and high strain capabilities. This test can be further improved by increasing the volume ratio of the SMA reinforcement and using a modified technique to prepare the specimen so that a larger diameter of SMA can be used.
ACKNOWLEDGMENTS

I would like to acknowledge the Mid-Atlantic Transportation Sustainability University Transportation Center (MATS UTC) for this research opportunity. I would also like to acknowledge the guidance and support from Professor Osman Ozbolut, Sherif Daghash, and Emily Parkany.

REFERENCES


