Transportation Consortium of South-Central States (Tran-SET)

Integrated Health Monitoring and Reinforcement of Transportation Structures with Optimized Low-Cost Multifunctional Braided Cables

Highlight | Feb. 2018

Project No. 17STTAM04

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POP: May 2017 – November 2018

Developing cost-effective shape memory alloys with structural health monitoring capabilities

Shape memory alloys (SMAs) are a smart construction material that can recover its original shape when heated after deformation (beyond its elastic limit) and recover from large deformations, triggered by unusually large strains. SMAs can limit damage sustained by structures from natural hazards (such as earthquakes and hurricanes) by limiting/controlling the deformation and crack growth of the structure. The most widespread SMA for such applications is the nickel-titanium (NiTi) SMA, which is cost-prohibitive for large-scale implementations. This study explores a lowcost and easily processed iron-based (Fe) SMA, which is capable of providing suitable mechanical properties for a structure, while demonstrating magnetic sensing capabilities. This latter property can be harnessed to create a method to monitor the stresses and strains on the structural system remotely and in a non-destructive manner. Through a series of demonstrations and laboratory tests, this effort designs, fabricates, and characterizes multi-functional high strength and selfsensing, braided cable structures using ironbased SMAs.

Problem Statement

To enhance the longevity and performance of the transportation infrastructure, high-performance materials can be integrated into health monitoring systems - obtaining realtime data on the structure conditions and identifying defects in a timely fashion. These multifunctional smart materials enable simplified design, reduce material use, and lower manufacturing complexity. A particularly appealing and interesting class of smart materials is shape memory alloys (SMAs). Superelastic SMAs can produce large recoverable deformations (triggered by a change in stress) and have been considered in a range of civil engineering applications: such as bracing systems, connectors, and concrete reinforcement. This response has been shown to limit the damage sustained by the structure from an adverse event (such as earthquakes) by controlling the deformation and crack growth. Currently, the most widespread SMA candidate for such applications is the nickeltitanium (NiTi) SMA. While it shows excellent superelastic properties, the high cost due to inherent materials cost, difficulty in processing and fabrication, and limited in supply severely limit its application in large-scale implementations in transportation infrastructure. Thus, there is a need for an alternative to NiTi that is cost-effective, easily processed, and show a comparable superelastic response.

Fe-SMA contains inexpensive alloy elements and does not require additional processing as titanium-based alloys do. Furthermore, the Fe-SMA shows an interesting metamagnetic shape memory response, where an applied stress can be easily detected using commercial magnetometers. This property can be harnessed to create a method to monitor the stresses and strains on structural systems remotely and in a non-destructive fashion. The combination of these properties enables a new kind of structural health monitoring framework where the structural and sensing elements are integrated, and quantitative information can be collected in real-time with simple instruments.

Summary

In this study, a combined approach of materials design, microstructural engineering, modeling, and component level (concrete composite) testing is applied to demonstrate the capability of a material with strong mechanical properties and self-monitoring capabilities using novel iron-based SMAs (Fe-SMA). Specifically, this study will:

- Design and optimize braided wire cables
- Fabricate Fe-SMA wires and braided cables
- Characterize mechanical and structural properties of FeSMA cables
- Characterize the magnetic response of the braided FeSMA cables under load and system-level integration.

Findings

SMAs undergo a phase transformation in their crystal structure when going from their stronger, original "austenite" form to their weaker "martensite" form. Fe-SMAs are anisotropic in nature - meaning its material properties are different when measured in different directions. This property leads to high internal stresses along the directional planes when Fe-SMAs undergo transformation to their "martensite" form. In order to mitigate and eliminate these internal stresses, the grain size of the material has to be coarse, perpendicular to the wire axis, and span the crosssection of the wire. The research team developed a simple technique (involving repeatedly subjecting the wire to high heat treatments, followed by room-temperature treatments, cyclically) to develop such properties. The technique produced resulting wires with bamboo-like grains that span the entire width.

For proper predictive damage detection and modeling of concrete, crack propagation, SMA phase transformation due to stress, and cohesive bonding between the concrete and wire must be modeled in conjunction with one another. Crack propagation modeling and experimental validation is shown in Figures 1 and 2. The specimen is subjected to a three-point bend experiment and the experiment was simulated using a commercial FE software (ABAQUS).

Figure 1. Crack propagation in concrete beam under three-point bending.

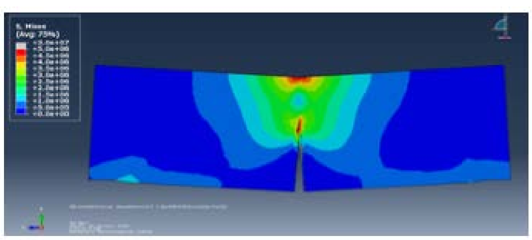

Figure 2. Computational modeling of the crack in concrete beam under three-point bending.

To model the changes in the magnetic response of the SMA wire and its detection, a computational model was created to correlate with the experimental data for the SMA wire's magnetic characterization. To create this model, an initial framework was built in COMSOL Multiphysics (a crossplatform finite element software to solve coupled systems of partial differential equations) to model the magnetic field for a variety of geometries as a small portion of the wire, near a stress concentration, undergoing a phase transformation. This model will be adaptable to variable geometries and phase transformations. Examples of the different cable configurations from Fe-SMA wires are shown in Figure 3. The PIs have established an industrial collaboration with Fort Wayne Metals to assist in the manufacturing process.

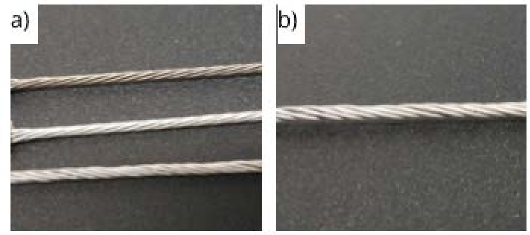

Figure 3. (a) Three different braiding patterns made from braiding setup, and (b) close-up of a single cable of Fe-SMA wires.

Impacts

Through a combined approach of structural optimization and materials design, this research aims at simultaneously achieving advantageous mechanical properties and self-monitoring capabilities in a single material for the transportation infrastructure. The developed multifunctional composites will transform the design, construction, and rehabilitation of infrastructure systems. They will also improve safety by increasing structural performance and enable damage detection; enhance durability by limiting progressive damage; increase sustainability by extending service life; and improve resiliency by providing re-centering capabilities. Additionally, the project defines a viable path for technology transfer by establishing substantive partnerships with commercial alloy manufacturers.

Tran-SET

Tran-SET is Region 6's University Transportation Center. It is a collaborative partnership between 11 institutions (see below) across 5 states (AR, LA, NM, OK, and TX). Tran-SET is led by Louisiana State University. It was established in late November 2016 "to address the accelerated deterioration of transportation infrastructure through the development, evaluation, and implementation of cutting-edge technologies, novel materials, and innovative construction management processes".

Learn More

For more information about Tran-SET, please visit our website, LinkedIn, Twitter, Facebook, and YouTube pages. Also, please feel free to contact Mr. Christopher Melson (Tran-SET Program Manager) directly at transet@lsu.edu.

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