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Behavior of concrete beam with embedded shape memory alloy wires

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Abstract

This paper deals with the behavior of concrete beams actuated by embedded shape memory alloy (SMA for short) wires through an extensive experimental program. Ti-50wt.% NiTi SMA wires were used. Electrical power was used to heat the SMA wires. Some of the factors affecting the deflection of the beam were examined experimentally. These factors include the cross-sectional areas of the beam and the number of SMA wires, the pre-strain of the SMA wire, the curing condition (in a water tank or in a standard fog-curing box), the curing time of the specimen, the actuation mode for the SMA wire, the volume fraction of the embedded SMA wires, and the diameter of the SMA wire, etc. The experimental results indicate that a large recovery force in the concrete beam could be obtained when the SMA wires were heated and, accordingly, the SMA wires could be used as actuators to change the deflection of a concrete beam.

Keywords: Shape memory alloy; Beam; Concrete; Actuation; Electrical current

1. Introduction

Improvements in materials and advances in computing and control technology make it possible to apply sophisticated active control technology to civil engineering structures [1, 2]. Shape memory alloys (SMAs) are one of the so-called "smart materials". From a macroscopic point of view, the observable mechanical behavior of shape memory alloys can be separated into two major categories: one is the shape memory effect (SME), in which a specimen exhibits a larger residual strain after loading and unloading that can be fully recovered upon raising the temperature of the material; the other is the pseudoelasticity, in which a specimen achieves a very large strain upon loading that is then fully recovered in a hysteresis loop upon unloading. Regarding the shape memory effect of SMA, the amount of recovery depends on the activation temperature, the initial deformation, and the percentage of marstensite phase that is present in the material. The recovery properties have led to many applications of SMAs as activated actuators. One-way shape memory occurs when a SMA is deformed at its martensitic temperature and, upon heating to an austenitic temperature, changes back to its original shape, recovering the original deformation. A two-way shape memory effect is induced by cyclic thermo-mechanical transformation training to create a favorable residual stress field in the SMA. Stress-free cooling of the austenite produces a transformation strain that is recovered hysterically during stress-free heating of the marstensite.

SMA has been proposed for large strain actuators for use in smart structures. Such applications include shape and active vibration control and acoustic control with a shape memory alloy wire or layer [3], the active control of electrometric rods with embedded two-way shape memory alloy actuators [4], a base isolation system with a shape memory alloy device that is based on the pseudoelastic effect for elevated highway bridges [5], a structure's seismic isolation [6, 7], and a shape memory alloy damper for the control of structures [8–10]. Numerical simulation such as the element-free Galerkin method can be used to calculate some large deformations of the pseudoelastic behavior of SMA beams effectively [11].

One of the other potential uses of SMA is beam deflection control. As shown in Fig. 1, upon electrical heating, a martensite-to-austenite phase transformation in the pre-strained SMA wires eccentrically embedded in a concrete beam takes

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Nomenclature

E_M	elastic module of SMA in martensite state
E_A	elastic module of SMA in austenite state
M_s	martensite transformation start temperature
M_f	martensite transformation finish temperature
A_s	austenite transformation start temperature
A_f	austenite transformation finish temperature
R_s	R-phase start temperature
R_f	R-phase finish temperature
C_A	stress influence coefficients in austenite
C_M	stress influence coefficients in marstensite

place and subsequently the SMA wires shrink with a large strain. This recovery strain of SMA can be used to generate a significant pre-stress force in the concrete or to adjust the deflection of the concrete beam on an as-needed basis. Fig. 1 shows the diagram of the control system for a shape control test. The deflection of the concrete beam is measured at the midpoint using a deflection sensor. Signals from the sensor are transmitted in real time to a controller to compare with a pre-set deflection that is called the allowed deflection. When the actual deflection exceeds the pre-set value, the system starts to supply current and actuate the SMA wires. This action continues to be performed until the deflection of the beam recovers just below the pre-set value. This potential application in civil engineering structures makes it possible to set up smart concrete structures. To date, there is little data on the deflection control of a concrete beam eccentrically embedded with SMA wire actuators in the current available literature. Only Maji [12] has performed an experimental study on active deflection control using small mortar beams with eccentrically embedded SMA wire actuators. More research regarding the actuation mechanism of a SMA actuator on a matrix concrete structure is required in the future. An investigation of the behavior of a concrete beam actuated by the embedded SMA wires is presented in this paper.

2. Experimental programs

2.1. Materials

The materials used for the host concrete in this paper were Type I Portland cement, crushed limestone aggregate with a maximum size of 15 mm, and fresh river sand. The proportions of cement:coarse aggregate:fine aggregate:water by weight were 1:1.88:1.14:0.364. In this mix, a high-range water reducer was used to achieve good workability. The average compressive strength of the concrete (cubic specimen) for 28 days was 21.5 MPa, its modulus of elasticity was 18.7 GPa, and the linear coefficient of expansion was $0.71 \times 10^{-5}/°C$.

The SMA used in this paper was Ti-50wt.% NiTi wire. The denotation for the material parameters of the unpre-strained SMA wires are the same as Rogers [2] and Takagi [1] and are listed in Table 1. These NiTi wires were all heat-treated at about 500 °C, and possessed a shape

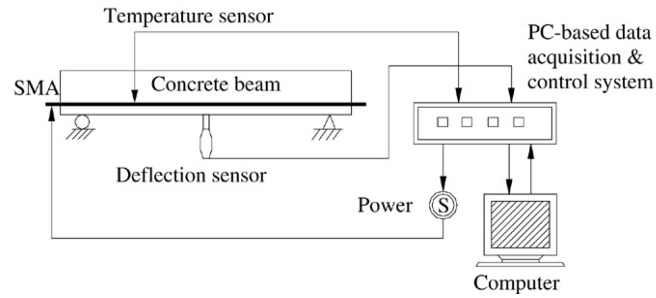

Fig. 1. The deflection control system for a beam.

memory effect accordingly. Their transformation temperature was measured by a differential scanning calorimeter (DSC) using four specimens. Three phases were shown for these wires: austenite (A), martensite (M) and R-phase (R); their corresponding temperatures are given in Table 1. The transformation temperatures in Table 1 were for SMAs in a stress-free state, where M_s and M_f are the martensite transformation start and finish temperatures, and A_s and A_f are the austenite transformation start and finish temperature, respectively.

The transition start and finish temperatures are usually linearly related to the applied stress [13]. When the SMA wires embedded in concrete beam are actuated by electrical power, a martensite-to-austenite phase transformation in SMAs will take place and the SMAs will recovery. Due to the SMA wires being restrained by concrete during phase transformation, they are in a stress-restrained state. The restraint stress of concrete makes the transition start and finish temperature of SMAs rise. In this paper, M'_s and M'_f are the martensite transformation start and finish temperatures, and A'_s and A'_s are the austenite transformation start and finish temperature in the stress-restrained state, respectively.

The SMA wire was pre-tensioned to a certain length at room temperature, and then relaxed to a stress-free state with the recovery of elastic strain. After that, the SMA wire with ends constrained was heated in a thermo-radiation furnace at a rate of approximately 20 °C/min, the load induced by the SMA wire actuator was measured by a load cell with a capacity of 100 kN, and the temperature of the wire was measured by a thermocouple. It was found that this load is a function of the temperature of the SMA wire. The plots for constrained stress vs. temperature are shown in Fig. 2. From this figure, one knows that the shape of the stress-temperature curve is dependent on the amount of pre-strain, and the maximum recovery stress corresponds to a temperature of about 200 °C. Since the wire was constrained, not all the martensite crystals can be transformed to austenite crystals [14].

2.2. Test specimens

The specimen shape used in this paper is shown in Fig. 3, and the number of test specimens is also listed in Table 2. Steel molds with wood block ends were employed for casting the specimens. The wood blocks with pre-cast holes for inserting the SMA wires were connected with side steel blocks through