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Experimental study of a simple reinforced concrete beam temporarily strengthened by SMA wires followed by permanent strengthening with CFRP plates

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Abstract

It has been proven that carbon fiber reinforced polymer (CFRP) sheets or plates are capable of improving the strength of reinforced concrete (RC) structures. However, residual deformation of RC structures in service reduces the effect of CFRP strengthening. In the past few decades interest in using shape memory alloys (SMA) as actuators has been gradually increasing due to SMA's capability of generating recovery stresses when heated. SMA can be applied to potentially decrease residual deformation and even close concrete cracks because of its recovery forces imposed on the concrete. However, this technique can only be applied for emergency damage repair because SMA wires need to be heated continuously to generate recovery forces. To overcome the shortcoming of the previous two methods, a new method to strengthen RC structures through CFRP plates in combination with SMA wires is proposed in this paper. The strengthening effect of the proposed method is experimentally investigated in a test specimen of a simple RC beam. Test results indicate that SMA wire recovery forces can decrease deflections and even close cracks in the concrete. The more embedded SMA wires that are added into the specimen, the greater is the reduction in residual deformation. The main reinforcing steel bars prevent the reduction of residual deformation. The strengthened specimen with CFRP plates has a relatively large stiffness in the test when the residual deformation of the beam is reduced by activation of SMA wires in advance. In addition, this study shows that there is a linear relationship between the rate of change in electric resistance of the SMA wires and the mid-span deflection of the specimen, which can be potentially used for damage detection and deformation monitoring in civil structures.

Keywords: Shape memory alloy; Carbon fiber reinforced polymer; Strengthening; Reinforced concrete structures

1. Introduction

There are a number of inherent disadvantages, such as difficult application procedure and lack of durability, in traditional methods used for strengthening reinforced concrete (RC) structures like bonding of steel plates. In recent years, strengthening of RC structures using carbon fiber reinforced polymer (CFRP) sheets or plates has attracted considerable attention around the world. A majority of the research on CFRP plate bonding for flexural strengthening of RC beams has focused on the strength enhancement (Ritchie et al. [1], Triantafillou and Plevris [2], Chajes et al. [3], Shahawy et al. [4, 5], Spadea et al. [6], Buyukozturk and Hearing [7], Ross et al. [8], Spadea et al. [9]). However, there is little research on the effect of residual deformations of existing structures on their performance. Structures already in service continuously accumulate residual deformation or strain when subjected to various loads prior to CFRP plate bonding and the residual deformation negatively impacts the performance of structures. How to reduce residual deformation of structures in service has become a challenge for both researchers and engineers around the world.

NiTi based shape memory alloy (SMA) has a number of outstanding properties as an actuator, such as large recovery stress (up to 700 MPa), high recovery strain (about 8%),

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Notations

M_s	martensite start temperature;
M_f	martensite finish temperature;
R_s	R phase start temperature;
R_f	R phase finish temperature;
A_s	austenite start temperature;
A_f	austenite finish temperature;
$\varepsilon_{\max}$	maximum pre-strain;
B	width;
H	overall depth;
L	clear span;
ρ	total area of SMA wires expressed as a fraction of the cross-sectional area;
R_0	initial electric resistance of SMA;
ΔR	electric resistance variation of SMA;
D	damage index;
u	midspan deflection;
u_y	yielding midspan deflection;
u_u	ultimate midspan deflection;
d	crack width of concrete

excellent anti-fatigue property, and variable elastic modulus with phase transition state (Jin et al. [10], Sun et al. [11], Song et al. [12], Tsoi et al. [13,15,16], Vokoun et al. [14]). Li et al. [17] suggested that NiTi SMA be used to repair damaged structural members by closing cracks or by preventing cracks from further developing in order to ensure the safety and reliability of structures. Emergency damage repair by embedding NiTi SMA wire in large concrete structures becomes necessary because sufficient waiting time is needed before permanent repair can happen to the damage of concrete structures. Li et al. [18] also found through finite-element analysis that NiTi SMA bars can modify tensile stresses in a tensile zone and crack area, which helps to close the cracks. Li et al. [19,20] further examined the relationship between recovery stress and temperature of NiTi SMA heating for various intensities of electrical current and also tested a simple concrete beam with emergency repair using NiTi SMA wires. Test results indicated that NiTi SMA wires could close cracks in the concrete and effectively reduce deformation of the concrete beam under electric heating. Therefore, there is a possibility that CFRP plates in combination with NiTi SMA wires can further improve the performance of RC structures compared with CFRP plates alone. The objective of this study is to investigate a new strengthening method of a simple RC beam using CFRP plates in combination with NiTi SMA wires. In this study, the SMA wires are placed inside RC beam during construction for temporary strengthening. Damaged RC beams can be temporarily strengthened by external SMA wires, which will be further examined in the near future.

2. Test materials

Steel wires with diameters of 3 mm and 4 mm are used as the stirrups and main reinforcing bars of the specimens, respectively. The measured yield and ultimate strength of the 3 mm steel wire are 385 MPa and 517 MPa, respectively, and those for the 4 mm steel wire are 332 MPa and 464 MPa, respectively. Normal strength concrete with a maximum aggregate size of 5 mm is used for all the specimens. 100 mm cubes are prepared to measure cube strength of concrete, f_{cu}, through testing. When tested at the age of 28–30 days, the measured cube strength of the specimens is 40.5 MPa. The measured tensile strength and elastic modulus of the CFRP plates used in this study are 2066 MPa and 105 GPa, respectively. The CFRP plate is bonded to the mid-span region of the specimen bottom using epoxy resins after activation of the SMA wires. The resins used in an actual repair are employed in this test.

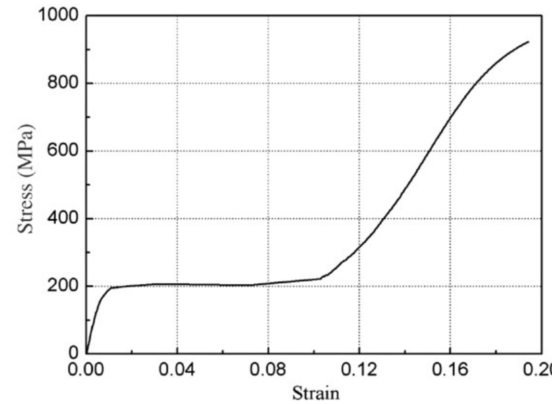

Fig. 1. Stress versus strain curve of SMA wire at room temperature.

Table 1
Phase transition temperature of NiTi SMA

Phase transition temperatures (°C)					
M_f	M_s	R_f	R_s	A_s	A_f
0.08	34.7	37.7	58.2	53	70.9

The SMA wire used in this study is 2 mm in diameter, made in China, with a composition of Ni-50.8 wt% Ti. The phase transition temperatures are summarized in Table 1 (Li et al. [19]). The stress versus strain curve of the SMA wire at room temperature is shown in Fig. 1. The ultimate tensile strength and strain of the SMA wire are about 920 MPa and 19%, respectively.

The SMA wire is first pre-strained to its maximum recovery strain, which is 8% beyond the yield strain at room temperature. It is then relaxed to a stress-free state to recover the elastic strain. However, there is a residual strain of 7.2%. Based on this stress-free state, the SMA wire is constrained at its two ends and then heated using a constant electric current. The force generated by the SMA wire due to heating is measured using a load cell with a capacity of 100 kN. The temperature of the SMA wire is measured with a thermocouple. Fig. 2 shows the curve of recovery stress versus temperature curve for the SMA wire heated using current with an intensity of 14 A.