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# Experimental study of non-circular concrete elements actively confined with shape memory alloy wires

Qiwen Chen [a], Moochul Shin [b], Bassem Andrawes [a,*]

[a] Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Newmark Civil Engineering Laboratory, 205 North Mathews Ave., Urbana, IL 61801, USA

[b] Department of Civil and Environmental Engineering, Western New England University, 1215 Wilbraham Road, Springfield, MA 01119, USA

## HIGHLIGHTS

- SMA straight wires are effective in applying bidirectional confinement to square elements.
- Moderate active confinement pressure of 1.7 MPa increased the concrete ultimate strain to 7.4%.
- Active confinement using SMAs reduced concrete dilation by almost half compared to FRP wraps.
- Under cyclic loading, SMA was able to limit stiffness degradation significantly compared to FRP.

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## ABSTRACT

This study focuses on developing a novel scheme for applying external active confinement to non-circular concrete elements that lack ductility using shape memory alloys (SMAs). A total of 13 concrete elements (prisms) are tested under monotonic and cyclic uniaxial compression load. The compressive stress–strain relationships of the SMA confined concrete elements are examined and compared with the behaviors of elements confined with conventional glass fiber reinforced polymer (GFRP) jackets. The results clearly show a significant improvement in the ultimate strain and residual (post-peak) strength of concrete elements actively confined with SMA compared to that of GFRP confined elements.

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## 1. Introduction

Concrete confinement has been widely adopted to increase strength and flexural ductility of vulnerable old reinforced concrete (RC) columns. There are mainly two types of lateral concrete confinement techniques, namely, passive confinement and active confinement. Pioneering research work on concrete confinement by Richart et al. [1,2] investigated stress–strain relationships of concrete cylinders in a major principle direction while the cylinders were subjected to minor directional stress (confining pressure). Richart et al. [1] studied effects of lateral active confining pressure in terms of improving concrete strength and ductility using a triaxial pressure vessel. The following work by Richart et al. [2] examined the behavior of passively confined concrete columns using transverse steel reinforcement. Thereafter, many researchers were motivated to investigate concrete confinement techniques to improve concrete strength and ductility. Over the last few decades, passive confinement has been widely adopted for new and existing RC structures; for new structures confinement is provided using internal transverse steel reinforcement (e.g. spirals, hoops, stirrups), while for existing RC structures with insufficient ductility, supplementary passive confinement is often applied by using external steel jackets or fiber reinforced polymer (FRP) jackets. In the case of passively confined concrete structures, confining pressure develops gradually as a result of concrete dilation while concrete is under loading. On the other hand, in the case of active confinement, the lateral confining pressure is applied to concrete prior to loading. Due to the initial confining pressure before loading, active confinement effectively delays the dilation of concrete and hence is found to be more superior to passive confinement in increasing concrete compressive strength and ultimate strain. Most of the studies on active confinement investigated the behavior of concrete using triaxial testing devices such as triaxial pressure vessel [1,3,4]. Few researches have been conducted on

* Corresponding author. Tel.: +1 217 244 4178; fax: +1 217 265 8039.
*E-mail address:* andrawes@illinois.edu (B. Andrawes).

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applying active confining pressure to RC structures in the field. Moghaddam et al. [5] used prestressed metal strips to actively confine concrete. Yamakawa et al. [6] used pre-tensioned aramid FRP belts to retrofit damaged reinforced concrete columns. However, applying active confinement techniques in RC structural elements in practice has been hindered due to practical limitations and challenges (excessive labor, time and hence increased cost) associated with applying mechanical prestressing using conventional materials such as steel or FRP.

Previous researches [7–9] have proven that using shape memory alloys (SMAs) is an easy and robust method to apply active confinement, and is superior to passive confinement technique in terms of improving the strength and ductility of circular section concrete elements. However, in these studies, the investigation of using SMA for confinement mainly focused on using SMA spirals for circular sections. In practice, besides circular columns, many existing square or rectangular RC columns are in need for retrofit or repair. Many studies have explored the methods and effectiveness of using steel jackets, external prestressing bars and FRP jackets for retrofitting square/rectangular columns [5,10–15]. However, mostly all of the studies showed that the effect of confinement was greatly reduced at the corners; hence the overall behavior of the confined element was affected. Abbasnia et al. [16] studied the corner effect of FRP confined prisms and proposed a shape factor equation to describe the reduced confining pressure as the corner became sharper. To overcome this corner issue, many researchers suggested using rounded corners when applying FRP jackets to square/rectangular sections [17–19], in order to reduce stress concentration at the sharp corners. Even though the rounded corner section is able to improve the overall behavior of the confined concrete when compared to a sharp corner section, it did not solve the problem completely as FRP wrapped concrete elements still failed at the corner due to premature rupture of FRP [16,20]. Moreover, the hardware, time and labor required for shaping round corners limits the wide application of the FRP jackets in retrofitting non-circular RC columns. The advantages of the SMA confinement technique in saving time, labor, and its proven superiority with circular columns, are the main motivations behind this study, which aims at exploring innovative and effective ways to apply SMA confinement in non-circular sections. This paper presents an experimental investigation on the feasibility of applying active confinement on concrete square prisms using SMA wires. Uniaxial compressive stress–strain relationship of SMA confined concrete prisms under monotonic and cyclic loading was also compared with that of FRP confined concrete prisms with rounded corners.

## 2. Using shape memory alloys for active confinement

SMAs are a type of metallic alloys that exhibit a unique thermomechanical phenomenon, shape memory effect (SME). This phenomenon is basically related to the ability of the excessively deformed alloy to recover its original shape upon heating as a result of phase transformation. SME is governed by four transformation temperatures, namely martensite finish temperature $M_f$, martensite start temperature $M_s$, austenite start temperature $A_s$, and austenite finish temperature $A_f$. SMA has two different stable phases: austenite phase, which appears in high temperature (above $A_f$), and martensite phase, which is the low-temperature phase (below $M_f$). Fig. 1 shows a schematic of the SMA's stress–strain behavior in the martensite phase. When SMA is deformed at a temperature below $M_f$, it behaves bi-linearly as illustrated in Fig. 1, and significant residual deformation is observed upon unloading. However, the deformed alloy is able to transform back to its original shape through heating to high enough temperature

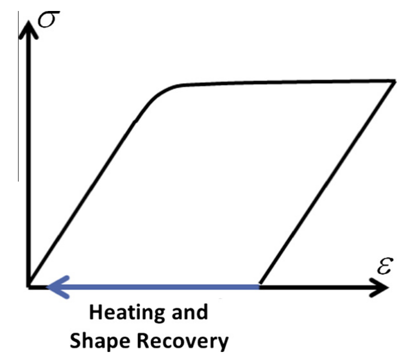


**Fig. 1.** Schematic diagram showing shape memory effect.

above $A_f$. This phenomenon is called SME. Furthermore, when prestrained SMA is constrained, internal stress often known as recovery stress will develop in the alloy upon heating it to a temperature above $A_f$. In the recent years, the shape recovery characteristic of SMA and the recovery stress associated with it inspired researchers to investigate their applications in civil engineering field. For example, Deng et al. [21] embedded NiTi SMA wires in concrete elements as a way to prestress concrete structure by heating SMA wires. Ocel et al. [22] also integrated NiTi SMA into steel beam-column connections, with the aim of recovering residual deformation in the connections by heating SMA tendons. Krstulovic-Opara and Thiedeman [23] investigated using self-stressing composites which are made from memory fibers, to apply active confining pressure on concrete through increasing the temperature. Andrawes and Shin [24] proposed an idea of using prestrained SMA spirals to provide active confinement for concrete circular sections. Shin and Andrawes [8,9] continued to conduct experiments on both concrete cylinders and circular concrete columns retrofitted by NiTiNb shape memory alloy wires to explore the SMA confinement technique for seismic retrofitting. As a continuation on the previous work on using SMA in providing active confinement for concrete sections, the work presented in this paper aims at exploring the use of SMA wires in providing active confinement for non-circular sections.

## 3. Design and preliminary finite element analysis of SMA confinement

### 3.1. SMA confinement schemes

Initially, three different schemes of applying active confining pressure to square concrete prisms using SMA wires were considered as shown in Fig. 2. The dimensions of the concrete prisms used for this study were 125.4 mm × 125.4 mm × 254 mm. The confinement pressure was applied in the form of bearing pressure exerted on two opposite faces of the prism using hollow steel tubes of 12.7 mm × 12.7 mm cross section and 1.6 mm thickness. The two opposite steel tubes were connected with straight SMA wires running perpendicular to the tubes. Mechanical clamps were utilized to anchor the SMA wires (two on each side) to the steel tubes, in which holes were drilled for SMA wires to go through. Experimental tests were carried out to examine the capacity of the mechanical clamps used and confirm their ability to prevent SMA wires from slipping. Fig. 2a shows the first SMA confined prism design (D-1), which applies SMA confinement in one direction externally using five pairs of tubes at a spacing of 58.4 mm connected using external SMA wires; while Fig. 2b demonstrates the second design (D-2), which applies confining pressure bi-directionally using external SMA wires connecting alternating pairs of steel

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