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EXPERIMENTAL STUDY OF CONCRETE COLUMNS CONFINED WITH SHAPE MEMORY ALLOYS

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ABSTRACT

This experimental study focuses on investigating the cyclic behavior of reinforced concrete (RC) columns retrofitted with an innovative active confinement technique. In order to enhance the ductility and strength of RC columns, passive confinement techniques such as using steel jackets and fiber reinforced polymer (FRP) sheets have been widely accepted and used. However, previous studies have shown that the improvement in concrete strength and ductility resulting from active confinement is far more superior to passive confinement. Most of the attempts for applying active confinement using conventional materials have yielded little success due to difficulties associated with applying the confinement pressure on site. This paper proposes a new technique where the active confining pressure is applied using the shape memory effect associated with the heating of Shape Memory Alloys (SMAs); a technique that will cause large external confinement pressure to be applied on the column without excessive work or labor. In this study, four reduced-scale RC columns are prepared and tested under quasi-static cyclic loading. Two of the tested columns are retrofitted with SMA spirals with and without additional glass FRP (GFRP) wraps, the third column is confined passively with GFRP wraps only, and the fourth column is tested in its un-retrofitted condition (as-built). The load-deflection results show that the actively confined columns exhibit superior performance to passively confined and unconfined columns. This superior behavior is primarily attributed to the increase in concrete strength and ultimate strain associated with active confinement.

Introduction

Providing sufficient lateral confining pressure has proven to be one of the most effective methods to increase the strength and ductility of concrete members. Previous studies have focused on developing and studying several passive confinement techniques including the use of Fiber Reinforced Polymer (FRP) sheets or steel jackets (Samaan et al. 1998 and Li et al. 2005).

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Passive confinement techniques rely on the dilation of concrete to mobilize the external wrap or jackets under axial loading. On the other hand, the technique of applying external confining pressure, in the form of lateral prestressing, is often known as *active* confinement. Contrary to passive confinement, active confinement does not require concrete to dilate in order for the pressure to be activated. Previous studies have shown that actively confined concrete exhibits higher strength and ductility compared to passively confined concrete (Richart et al. 1928). However, finding practical, effective, and reliable active confinement techniques has been a major challenge for practitioners. The authors proposed earlier a new active confinement technique through analytical and small-scale material experimental work (Shin and Andrawes 2009, Andrawes et. al 2010). The proposed technique is based on applying active confinement using spirals made of prestrained shape memory alloys (SMAs). In this paper the same concept is studied experimentally on the element level.

Shape Memory Alloys

SMAs exhibit unique thermo-mechanical characteristics namely, superelasticity and shape memory effect (SME), which allows the SMAs to recover their original shape even after experiencing relatively large deformations (up to 8%-strain) (Vokoun et al. 2003). This unique characteristic is primarily due to the back and forth transformation between the martensite and austenite phases on the atomic level when the temperature changes. The thermo-mechanical behavior of typical SMAs is depicted in Fig.1. In martensite phase which exists at temperatures below M_f, after the loading unloading process, the SMA will have a residual strain like any typical metallic materials. However, if a high enough temperature is provided (higher than the austenite finish temperature, A_f), the residual strain will be eliminated as it transforms into an austenite phase. This SME phenomenon is associated with large recovery stress, which depends on the alloy's composition and the level of prestrain (Otsuka and Wayman 2002). The high

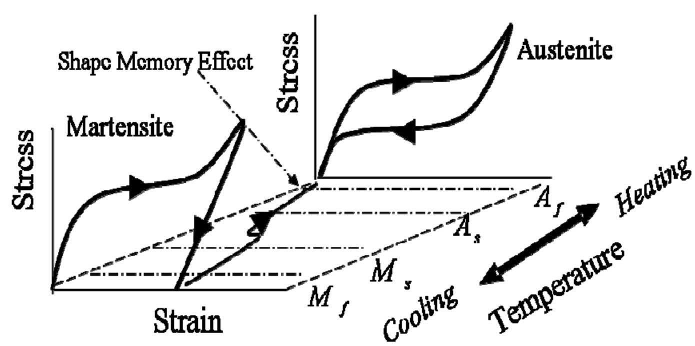

Figure 1. Thermomechanical behavior of typical SMAs.

recovery stress of SMAs is sought in this study to apply active confining pressure on RC columns to improve their ductility. The authors conducted the experimental tests on concrete cylinders using NiTiNb SMA spirals (Shin and Andrawes 2010). NiTiNb was specially utilized due to its wide thermal hysteresis, which enables SMAs to maintain their recovery stress even when the temperature drops to typical ambient temperature levels. Figure 2 shows the recovery stress behavior of a 0.08in-diamater, 6.4% prestrained NiTiNb wire. The recovery stress was recorded with respect to the time. During heating, the maximum recorded recovery stress was 82ksi at 108°C. After reaching a temperature of 160°C, the wires was left to cool. At room temperature (16°C), the recovery stress was 67ksi. The 0.08in diameter NiTiNb wires were utilized for the following RC columns tests. The RC columns were wrapped with the prestrained wires to form a spiral. In order to activate the confining pressure, the prestrained SMA sprial was heated by passing an electric current.

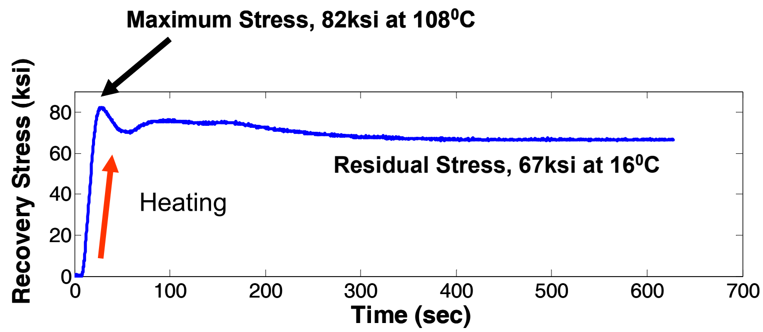

Figure 2. Recovery stress of the NiTiNb SMA wire.

Column Specimens and Retrofitting Techniques

Four reduced-scale RC single cantilever columns were built and tested under quasi-static cyclic loading. Figure 3 shows a schematic elevation and section of tested columns. The effective height of the columns was 50in and its diameter was 10in with 1in concrete cover. The column was supported by 46in x 46in x 16in footing. The column was post-tensioned using a 0.6in seven-wire strand to keep the axial load constant during testing. The column was reinforced with 8#4 longitudinal bars and #2@4in hoops. The average compressive strength of the concrete at

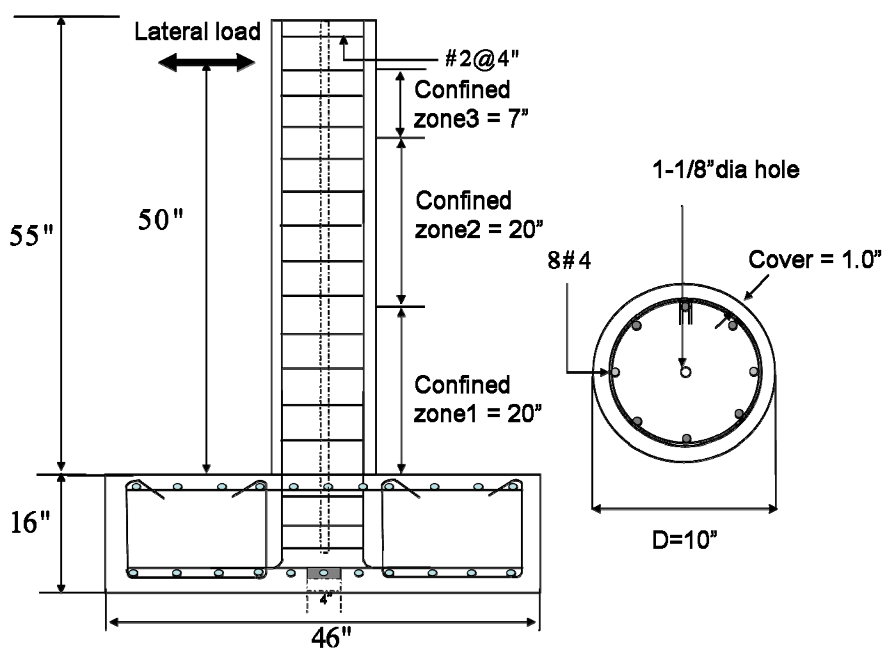

Figure 3. Schematic of the RC columns used in the tests.

the time of testing was found to be 6500psi. Figure 4 shows the test set up of the column confined with GFRP wraps and 0.8in pitch spacing SMA spirals (see Table 1). A 100-kip hydraulic actuator was used for the cyclic horizontal loads and a 100-kip hydraulic jack was used to apply constant axial load of 26kips, which represents 5% of the column's compressive strength. Additionally, four LVDTs were installed to capture the flexibility of the system on the footing and the actuator block. Also **"L, F, R"** in Figure 4 denotes the left, front and right side of column, respectively.

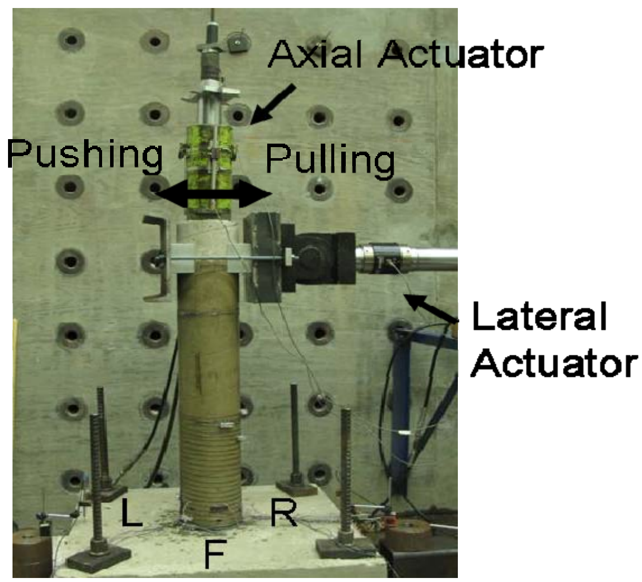

Figure 4. Test set-up of a confined column.

Each column was retrofitted using a different confining technique. One column was retrofitted entirely with GFRPs, one of the other columns was retrofitted using a hybrid technique (i.e. SMAs plus GFRPs), while another column was confined with SMA spirals only. Table 1 shows the summary of the confinement techniques used for each column at three different regions (see Fig. 3). For GFRP column, GFRP sheets (0.0043in-thick) with varying number were used throughout the column height. The lower 20in were considered to be the most critical zone (Confined zone1) and thus was wrapped with 10 layers of GFRP. In the 20in above, the number of layers was reduced to 5, while in the top portion of the column only 2 layers of GFRP layers were used. The 10, 5, and 2 layers correspond to GFRP volumetric ratio percentages of 1.73%, 0.87% and 0.35%, respectively. For the Hybrid column, the same numbers of GFRP wraps were used except in the most critical zone. The number of GFRP layers was reduced from 10 to 5 and 0.08in diameter SMA spiral was used to compensate the difference. The pitch spacing of the SMA spiral was selected such that combined passive and active confinement effects of the 5 GFRP sheets plus the SMA spiral, respectively would match the passive pressure produced by the 10 layers of GFRP used for the GFRP column. For the SMA column, 0.08in diameter SMA spirals were only utilized to apply the same pressure produced by other two columns at the most critical zone.

Table 1. Properties of the confinement types used in the tests.

Confinement Type	Confined Zone1	Confined Zone2	Confined Zone3
Unconfined Column	N/A	N/A	N/A
GFRP Column	10 layers of GFRPs	5 layers of GFRPs	2 layers of GFRPs
Hybrid Column	0.8in pitch spacing SMA spirals + 5 layers of GFRPs	5 layers of GFRPs	2 layers of GFRPs
SMA Column	0.4in pitch spacing SMA spirals	5 layers of GFRPs	2 layers of GFRPs
Confinement Pressure	216psi	108psi	43psi

Based on the mechanical properties of the used GFRP and using an efficiency factor of 0.5 (Lorenzis and Tepfers 2003) for the GFRP jackets, the confining pressure corresponding to 10 layers of GFRP was founded to be 216psi. Using only 5 layers of GFRP would result in half of this pressure, i.e. 108psi. Therefore, the pressure provided from the SMA spirals would have to compensate the difference. For the Hybrid column case, based on the mechanical properties of the used SMA wires and taking into account the effect of 1% SMA prestress losses, it was found that a pitch spacing of approximately 0.8in would produce the difference in the confining pressure. Similarly, the confining pressure of SMA spirals applied to the SMA column was estimated. The confining pressure from 0.4in pitch spacing SMA spirals was found to be 216psi based on a recovery stress of 63.7ksi after including 1.1 % prestrain losses.

Loading Protocol and Test Results

Figure 5 shows the load protocol that was used in the test. The columns were loaded cyclically with a rate of 0.2in/min up to 1.5% drift and 0.6in/min thereafter. Initially a load increment of 0.5% drift was adopted until a drift of 6% was reached, after which an increment of 1% was used up until 12% drift. After reaching a drift ratio of 12%, an increment of 2% was utilized.

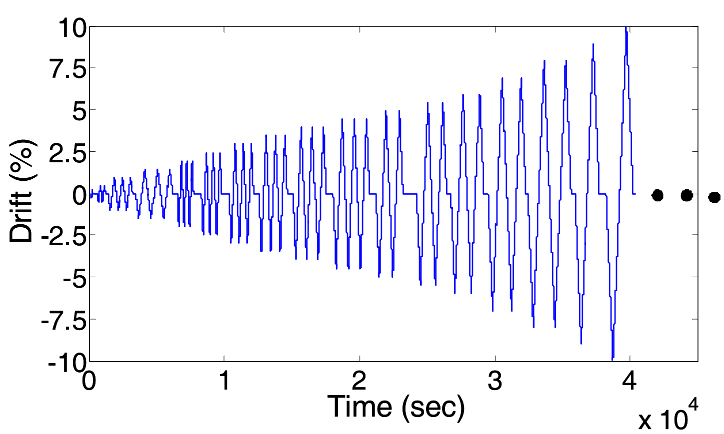

Figure 5. Loading protocol used in the study.

Figure 6 shows the lateral force versus lateral drift of the four tested columns. For the unconfined column, the column strength was 7.75kips at 2.8% drift. The column started yielding at the 1.5% drift level. Using the drift corresponding to maximum force, the ductility ratio of the unconfined column was found to be 1.9. For the GFRP column, the column strength was 7.89kips and was observed at a drift ratio of 3.5%. After the 3.5% drift, the column started showing signs of gradual strength degradation. At the 8% drift, the strength was 34.6% of the maximum strength. Finally, the ductility of the column was found to be 2.3, since the column began to yield at 1.5% drift as well. And for the Hybrid column, the strength was 8.34kips at 8% drift. After steel yielding, hardening behavior was observed, which could be attributed to the elastic behavior of the SMA spiral. The test was stopped when the load-carrying capacity reached 20% of the maximum strength due to the rupture of the longitudinal reinforcement bars at drift ratios of 12% and 14%. The ductility of the column was found to be 5.3 and it was 2.3 times that of the GFRP column. Finally, the strength of the SMA column was found to be 8.27kips at 11% drift. Also, the ductility of the column was calculated to be 7.3.

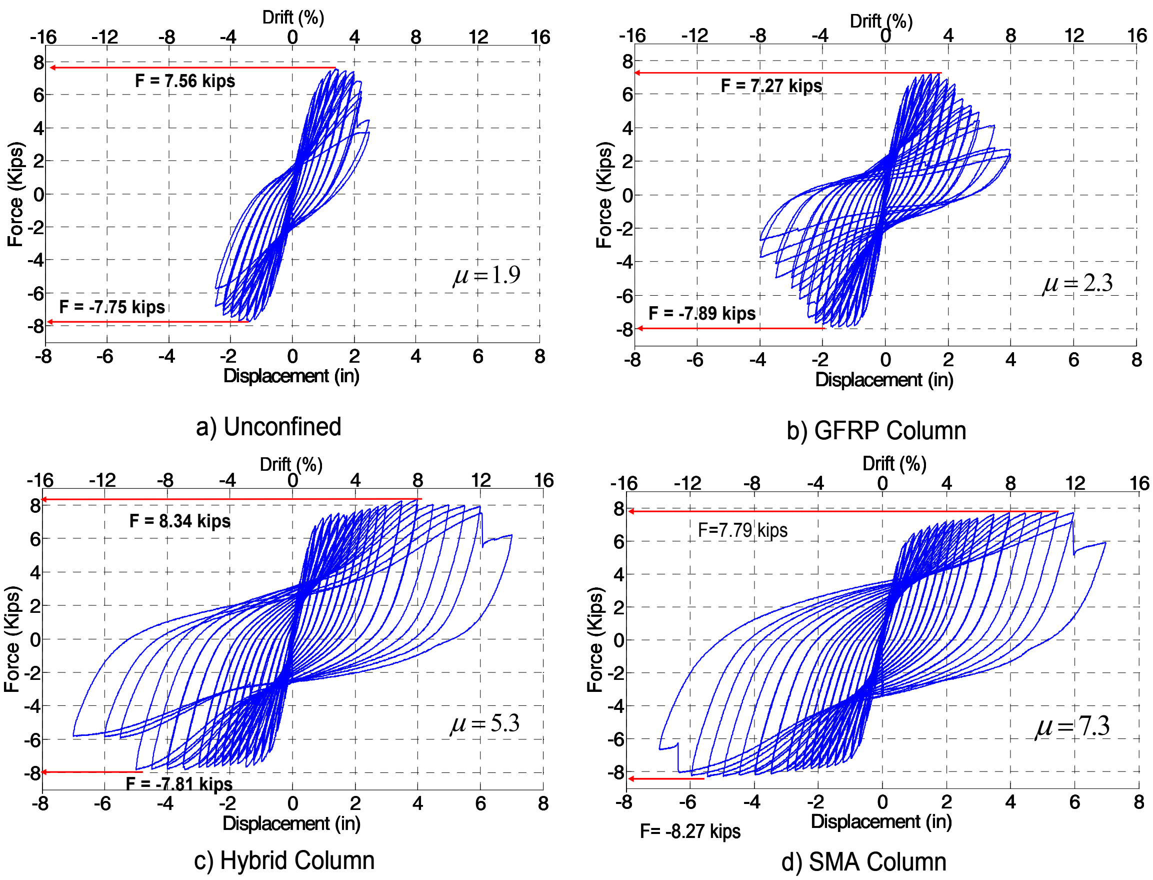

Figure 6. Lateral force versus drift relationship for each of the tested columns.

Figure 6 clearly shows that the columns with the SMA spirals were able to sustain larger force and drift and dissipate significantly more hysteretic energy compared to that of the GFRP column. Furthermore, the GFRP column started showing significant signs of stiffness degradation and strength deterioration at a drift ratio of 4%, while in the case of the Hybrid column and the SMA column, no signs of degradation was observed until the columns reached the drift ratio of 10% and 12%, respectively. Considering the point where the strength of GFRP wrapped column started degrading as the ultimate point, it could be seen that replacing 5 layers of GFRP with SMA spirals increased the drift ductility ratio from 2.3 to 5.3, i.e. an increase of approximately 130%.

In order to understand the failure mechanism observed in each retrofitting technique, Figure 7 is presented. The figure shows the damage sustained by the four columns at 5% drift ratio. For the unconfined column, the column was severely damaged (see Fig.7.a.). Also it could be seen from the figure (see Fig.7.b) that at such drift, the column wrapped with 10 layers of GFRP at the confined zone1 experienced significant damage in the form of rupture of GFRP sheets, complete spalling of the concrete cover, and significant crushing of the concrete core. However, for the column wrapped with the hybrid technique, the damage was observed only in the GFRP wraps in the form of horizontal cracks. And for the case of the SMA column, only minor damage in the form of horizontal cracks in the concrete cover was observed. This limited damage could be attributed to the large active confining pressure applied by the SMA spirals, which helped in delaying the rupture of the GFRP and crushing of the concrete underneath. Despite the 50% reduction in the amount of GFRP used, the damage experienced by the 5 layers of GFRP for the Hybrid column case was much less than that was experienced by the GFRP column with 10 layers. The performances of both the Hybrid column and the SMA column were satisfactory in terms of strength and ductility with the SMA column exhibiting better ductility (38% higher) compared to the Hybrid column.

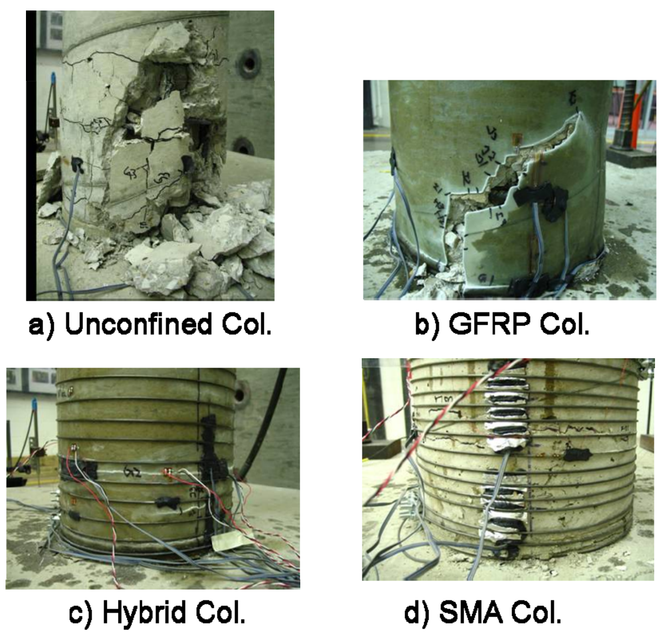

Figure 7. Damage observed in the four columns at 5% drift.

Conclusions

This experimental study focused on investigating the application of an innovative active confinement technique for RC columns using SMA spirals. Four single cantilever RC columns were retrofitted with SMA spirals and/or GFRP jackets and tested under quasi-static cyclic lateral load. The results showed that the columns with the SMA spirals were able to sustain larger force and drift and dissipate more hysteretic energy compared to those of the unconfined column and the GFRP column. The maximum force reached in the cases of the unconfined and GFRP column were 7.75kips and 7.89kips, respectively, while in the cases of the Hybrid column and the SMA column, the maximum lateral forces were 8.34kips and 8.27kips, respectively. The columns wrapped with the SMA spirals were able to withstand a lateral drift ratio of up to 12% with no signs of significant damage, while the GFRP wrapped column started experiencing severe damage at a drift ratio equal to 4%. It could be seen from the results that replacing half of the GFRP layers at the plastic hinge zone with SMA spirals increased the drift ductility by 130%. Also, using SMA spiral with 0.4in pitch at the plastic hinge zone resulted in a 217% increase in ductility compared to that of the GFRP column. This study illustrated with no doubt the superiority of the proposed active confinement technique using SMA spirals in the seismic retrofitting of RC columns compared to the passive confinement technique using GFRPs.

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