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Testing of RC Bridge Columns Confined with Shape Memory Alloys

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ABSTRACT: This study focuses on examining experimentally a novel concept for seismic retrofitting and emergency repair of reinforced concrete (RC) bridge columns. It investigates the feasibility of using shape memory alloy (SMA) spirals to: 1) enhance the flexural ductility of vulnerable RC bridge columns and mitigate their level of damage under strong seismic events, and 2) conduct emergency repair to restore the ductility and strength of severely damaged RC columns. External active confinement pressure is applied to the plastic hinge zone of RC columns by heating prestrained SMA spirals which are wrapped around the columns. The active confinement pressure is associated with the large recovery stress of SMAs which is induced as a result of the SMA's attempt to remember its original shape. Actively confined concrete has shown superior performances to traditional passively confinement concrete; however, applying active confinement technique using conventional materials is hindered due to several practical complications. Hence, using thermally prestressed SMA spirals to apply external active confinement pressure on RC columns is simple, robust, and rapid. An experimental program is carried out to investigate this new confinement technique. The program includes: 1) Conducting quasi-static lateral cyclic tests on four 1/3-scale RC columns retrofitted with SMA spirals and other conventional retrofit methods. 2) Conducting lateral cyclic tests on two damaged-then-repaired columns using the new confinement technique. The experimental results clearly show the superiority of the new retrofit/repair technique to conventional techniques.

1 INTRODUCTION

During historical earthquakes, numerous reinforced concrete (RC) bridges have sustained significant damage or even failure. One of the main causes of the failures was the lack of flexural ductility and/or insufficient shear capacity of RC bridge columns (Chai et al. 1991; Priestley et al. 1994; Task Group 7.4 2007). Numerous research studies showed that adding external confinement to the plastic hinge zone of the RC columns could significantly improve the flexural ductility and shear strength of these columns. The external confining pressure on RC columns is traditionally applied with fiber reinforced polymer (FRP) jackets or steel jackets using and a technique known as passive confinement. The expression "passive" is attributed to the direct relation between the confining pressure applied and the dilation of concrete under axial loading. However, there is another technique where the external confining pressure applied on RC columns is independent on the dilation of concrete since the confining pressure is applied prior to concrete loading. This other technique is often known as active confinement. Research had demonstrated that using active confinement technique results in superior performance to using passive confinement technique (Richart et al. 1928); however, applying active confinement technique by prestressing conventional materials is associated with several practical complications including the need for excessive labor. Hence, this study examines the feasibility of using thermally prestressed SMA spirals for applying external active confinement pressure on RC columns. External active confinement pressure is applied to the plastic hinge zone of RC columns by heating prestrained SMA spirals which are wrapped around the columns. The active confinement pressure is associated with the large recovery stress of SMAs which is induced as a result of the SMA's attempt to recover its original shape. In this study, martensitic NiTiNb SMA wires which were prestrained to about 6%-strain by manufacturer was utilized as spirals. The experimental testing program discussed in this paper aimed at examining the cyclic behavior of RC columns retrofitted and repaired using SMA spirals.

2 RETROFIT OF RC BRIDGE COLUMNS

2.1 Column Specimens and Retrofitting Techniques

Four 1/3 scale RC columns were casted and tested under quasi-static cyclic lateral loading. Figure 1 shows an isometric view of the tested columns and the cross section of the columns. A 445 kN hydraulic actuator was used to apply the cyclic lateral loading. A constant axial load of 116 kN was applied to the top of the columns which represents 5% of the compression strength of the column. The diameter of the circular cross section of the columns was 254 mm, and the cover concrete was 25.4 mm. The dimension of the footing of the columns was 1168 mm x 1168 mm x 406 mm. Eight #4 steel bars were placed evenly in the longitudinal direction, and #2 (6 mm diameter) hoops were located laterally at 102mm. The average compressive strength of the concrete at the time of testing was found to be 44.8 MPa. Four Linear Variable Differential Transformers (LVDTs) were installed to capture the net displacement of the RC columns.

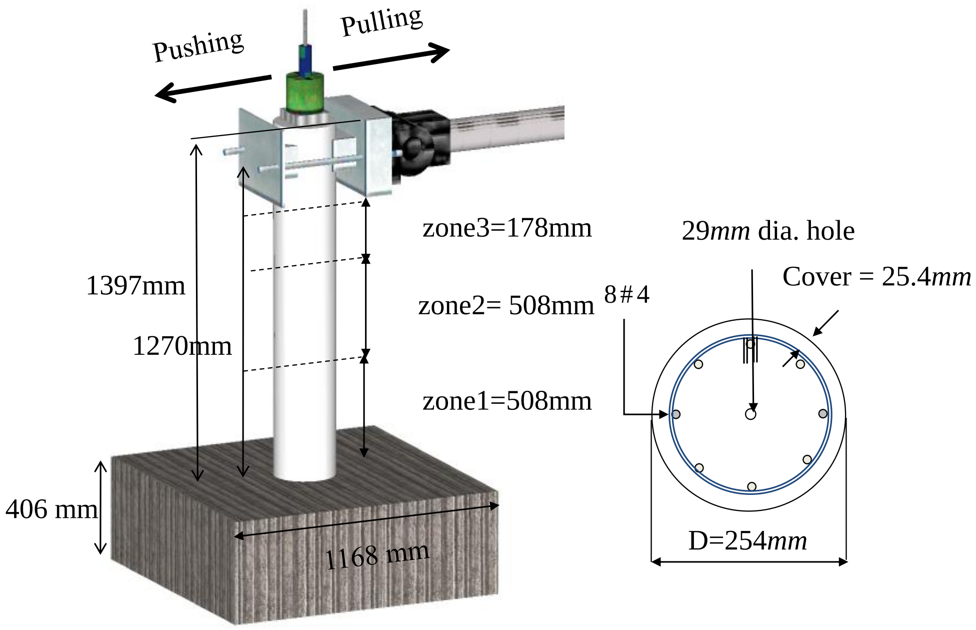


Figure 1. Schematic of the RC columns used in the tests.

Three confining techniques were used to retrofit each column. One column was retrofitted with only using GFRP wraps, another was retrofitted with the SMA spirals at zone 1 (i.e. plastic hinge zone), and the other was wrapped by using GFRP jackets together with SMA spirals at zone 1. The details of each confinement technique were summarized in Table 1. As indicated by the table, zone 1 was retrofitted differently in the three columns, since zone 1 was the expected plastic hinge zone. Zones 2 and 3 were retrofitted with the same GFRP jackets in all three columns. For the GFRP retrofitted column, zone1 was wrapped with 10 layers of GFRP. For the SMA column, 2.0 mm diameter SMA spirals were utilized to apply the same pressure produced by 10 layers of GFRP sheets at zone 1, while for the Hybrid column, 5 layers of GFRP sheets and 20 mm pitch spacing SMA spirals were used together at zone 1, where the 20 mm pitch spacing was selected to compensate the difference of confining pressure when using 5 layers of GFRP sheets instead of 10 layers. All three retrofitted columns were designed to have the same level of confining pressure. Based on the mechanical properties of the used GFRP sheets 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 sheets was founded to be 1.5 MPa. For the SMA column, it was found that a pitch spacing of approximately 10 mm would produce the same confining pressure of 1.5MPa based on a recovery stress of 439 MPa and a prestrain loss of 1.1%, which was determined in a separate study (Shin and Andrawes, 2010). Accordingly, using half of the GFRP sheets and SMA combined on the hybrid column would produce the same 1.5 MPa confining pressure.

Table 1. Confinement properties of the four tested columns

	Zone1	Zone2	Zone3
As-built Column	N/A	N/A	N/A
GFRP Column	10 layers of GFRPs	5 layers of GFRPs	2 layers of GFRPs
SMA Column	10mm pitch spacing SMA spirals	5 layers of GFRPs	2 layers of GFRPs
Hybrid Column	20mm pitch spacing SMA spirals + 5 layers of GFRPs	5 layers of GFRPs	2 layers of GFRPs
Confining Pressure	1.5 MPa	0.75 MPa	0.3 MPa

2.2 Loading Protocol and Test results

The columns were cyclically loaded by the lateral actuator with a rate of 5.1 mm/min up to 1.5% drift ratio and 15.3 mm/min thereafter. Initially a load increment of 0.5% drift ratio was adopted until a drift ratio 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.

The lateral force and displacement relationship of the four columns were shown in Figure 2 after the test was complete. As-built column yielded at 1.5% drift ratio and the maximum strength of the column was found to be 34.5 kN at 2.8% drift ratio. For the GFRP retrofitted column, the maximum strength of 35.1 kN was recorded at a drift ratio of 3.5%, and the strength of column was gradually degraded. Finally, the recorded strength was 34.6% of the maximum strength at the final drift ratio (8%). The SMA column showed the strength hardening until it failed, and it had the maximum strength of 36.8 kN at 12% drift ratio. The maximum strength of the Hybrid column was found to be 37.1 kN at the 8.0% drift ratio. Also, strength hardening behavior was observed as well, which could be attributed to the elastic behavior of the SMA spirals. The failure mechanism of both the SMA column and the Hybrid column was due to the rupture of longitudinal reinforcement. The longitudinal reinforcement of the SMA and hybrid columns ruptured at 12% drift and 10% drift, respectively.

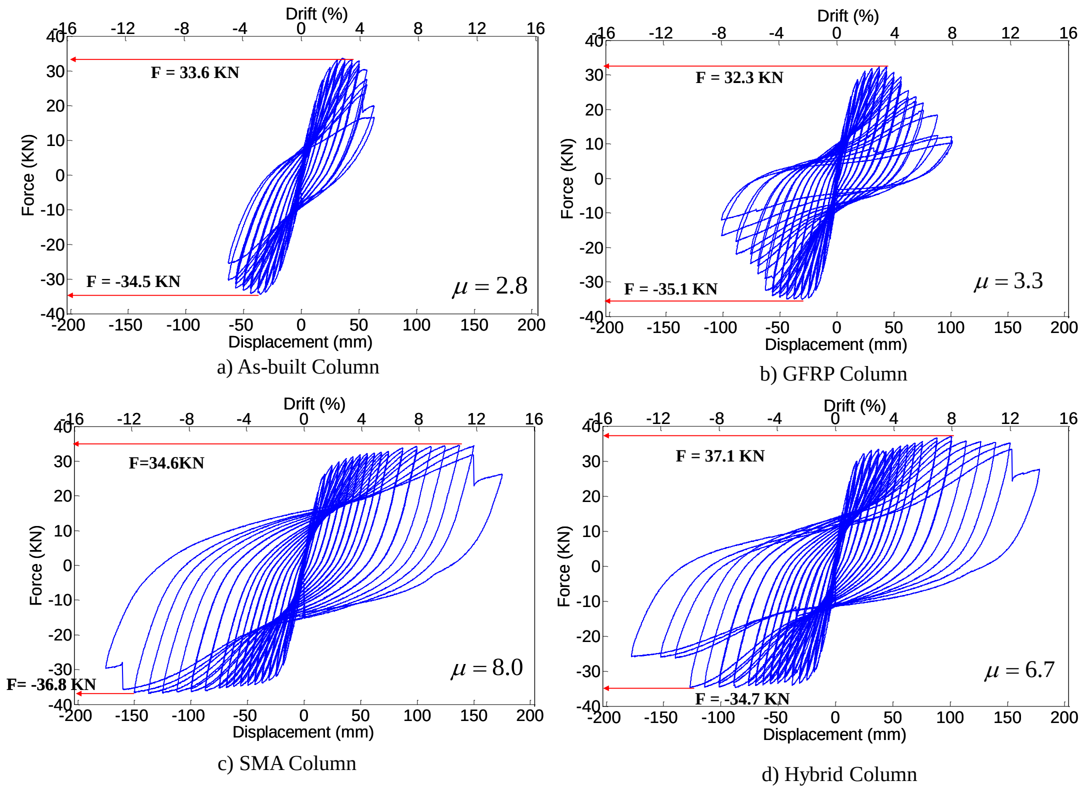


Figure 2. Lateral force versus drift relationships of the four tested columns.

In order to compare the flexural ductility of each column, the ductility ratio (μ) was calculated and shown in Figure 2. The ductility ratio is defined as the ratio between the drifts at the ultimate point (measured at 80% of the ultimate strength or where longitudinal reinforcement ruptured) and the yielding point. Based on this definition, the ductility ratios of the as-built, GFRP wrapped, SMA wrapped, and SMA plus GFRP wrapped columns were 2.8, 3.3, 8.0, and 6.7, respectively. The ductility of the SMA column and the Hybrid column was 2.4 times and 2.0 times that of the GFRP retrofitted column. Figure 2 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 wrapped column.

In order to understand the level of damage of each column, the width of the remaining core concrete of each column was measured after removing the wrappings and cleaning up the crushed concrete. As indicated earlier, the final drift ratios sustained by the columns were 5%, 8%, 14% and 14% for the as-built, GFRP, SMA and Hybrid column, respectively. The widths of the remaining core concrete of the as-built, GFRP, SMA and Hybrid columns were 102mm, 102mm, 216mm, and 191mm, respectively. The columns retrofitted with SMA spirals showed the least damage among the four columns. This clearly demonstrated that using SMA spirals is not only effective in improving the flexural ductility of the columns, but also in limiting their damage during earthquakes, which will have a significant impact on maintaining the postearthquake bridge functionality.

3 EMERGENCY REPAIR OF SEVERELY DAMAGED COLUMNS

After an earthquake event, there is a dire need for an effective repair technique that could be implemented in the field in timely manner. The experimental investigation of the new confinement technique using SMA spirals was further expanded to include “emergency” repair application. Two severely damaged RC columns (the as-built column (C1) from the retrofit testing and another column (C2) which was accidentally damaged during testing) were repaired and retested.

3.1 Summary of Damaged Columns

3.1.1 Damage of As-built Column C1

When column C1 reached the drift ratio of 3.5%, cover concrete had spalled significantly, after which, the core concrete and the two longitudinal bars located near the extreme fibers started crushing and buckling, respectively. When the column reached 4.2% drift ratio, one of its longitudinal reinforcement ruptured. The maximum drift the column experienced was 5% drift ratio. Figure 3.a shows a picture of the damaged C1 column. The damage of the column consisted of: 1) crushed cover and core concrete on both sides of the column, 2) one ruptured and five buckled longitudinal reinforcement, and 3) excessive opening of transverse reinforcement.

(a) C1 (b) C2

Figure 3. Damage sustained by columns C1 (a) and C2 (b).

3.1.2 Damage of As-built Column C2

A cyclic test under the same loading protocol used for the column C1 was planned for the column C2. However, at a drift ratio of 1.5%, the hydraulic actuator went out of control exerting a maximum drift ratio of about 7% on the specimen in one direction. Due to the accident encountered during testing, no data was recorded after the 1.5% drift. Figure 3.b shows a picture of the damaged specimen under the excessive monotonic loading. Since the column failed primarily under the monotonic loading in one direction, the concrete at one side was completely crushed, while at the other side, the concrete was cracked due to excessive tension. Therefore the damage of the column C2 was unsymmetrical while the damage of the column C1 was symmetrical. In addition, since the column C2 was not subjected to significant cyclic loading at high drift ratios as the column C1, the reinforcement of the column C2 had buckled without experiencing any ruptures.

3.2 *Repair Process*

The two damaged columns were repaired by following a five-step repair process with the aim of restoring the functionalities of the columns within 24 hours. Figure 4 shows each step of the repair process. First, crushed and loose pieces of concrete were removed from the damaged region of the columns. Figure 4.a shows the concrete surface of the column C1 after removing the crushed concrete. Second, slightly buckled longitudinal reinforcing bars were straightened, and the ruptured bars were connected using rebar couplers (Figure 4.b). As noted earlier, only one reinforcing bar was ruptured and needed coupling in the column C1. For the column C2, however, no longitudinal reinforcement was ruptured, but three of the reinforcing bars severely buckled after being damaged by the excessive monotonic loading. To adjust these severely buckled reinforcing bars, it was required to cut the bars, and reconnect them with couplers. Third, pressurized epoxy was injected to fill the cracks of the concrete (Figure 4.c). From the step one though the step three, it took about three hours. Forth, quick-setting mortar was applied to the damaged region (Figure 4.d). The nominal strength of the mortar at the 24 hours was recorded as 21 MPa, which is 53% of the compressive strength of the concrete used in casting the as-built columns. While curing the mortar, the fifth step of the repair process proceeded. The columns were wrapped with the SMA spirals at the repaired region (i.e. 330 mm from the column base) with 25mm pitch spacing, and heated using a fire torch as shown in Figure 4.e. Figure 4.f shows a picture of the repaired column after the completion of the repair process. It took approximately 24 hours from the first step of repair process until the onset of the column testing. However, it is important to note that the whole repair process from the first step to the fifth step was completed in less than 15 hours.

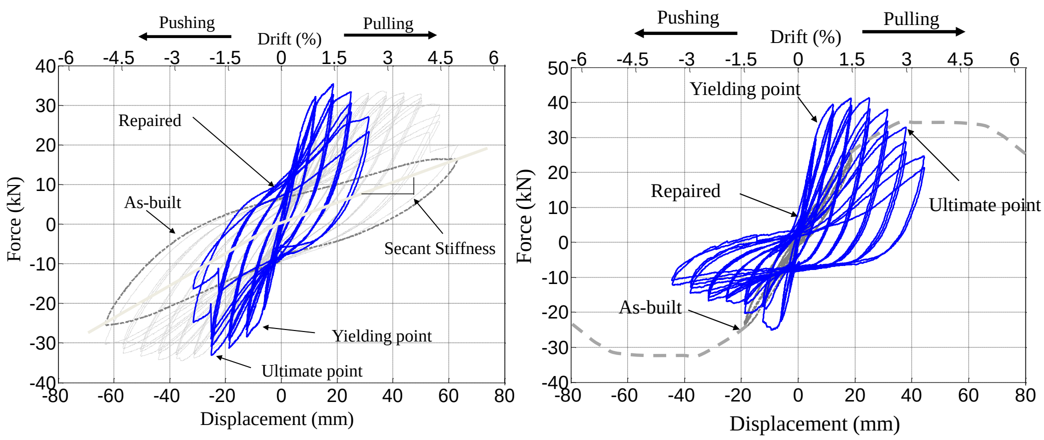
(a) Concrete removal (b) Steel adjustment (c) Epoxy injection

(d) Mortar application (e) Heating SMA spirals (f) Repaired column

Figure 4. Five-step emergency repair process.

3.3 *Emergency Repair Test Results*

The lateral force and displacement relationships between the as-built and the repaired column P1 were compared in Figure 5.a. The repaired column started yielding at a drift ratio of 0.7%, and the average maximum strength recorded was 34.2 kN. At a drift ratio of 2%, the strength of the repaired column dropped abruptly by 28% due to the rupture of one of the longitudinal reinforcement. Also another reinforcing bar was ruptured in the following cycle, and it resulted in the reduction of the strength by 48% of its maximum strength. Based on the comparison between the average strengths of the repaired and as-built columns, it was concluded that the emergency repair technique using SMA spirals performed on the severely damaged column was capable to fully restore the as-built column's lateral strength. Furthermore, the average initial stiffness of the repaired column was found to be 3.4 kN/mm, which is 54% higher than that of the as-built column and 930% higher than the residual (secant) stiffness of the damaged column.



(a) C1 (b) C2

Figure 5. Comparison between lateral force vs. displacement relationships of the as-built (dashed line) and the repaired (solid line) column: C1 (a) and C2 (b).

Figure 5.b shows the lateral force and displacement relationship between the as-built and the repaired column C2. The repaired column started yielding at a drift ratio of 0.6%, and the maximum strength recorded was 41.3 kN at 1.5% drift ratio. The cyclic behavior of the repaired column C2 was unsymmetrical, and the lateral strength of the column degraded gradually unlike the repaired column C1 whose strength abruptly dropped. A main reason for the unsymmetrical behavior of the repaired column C2 was due to the slippage of the coupled reinforcing bars located at one side of the repaired column during testing. And this slippage of the reinforcing bars from the couplers caused significantly less strength of the repaired column when it was "Pushed" (see Figure 5.b). On the other hand, when the column was "Pulled", it showed satisfactory behavior since the reinforcing bars resisting tension were relatively in fair condition and only sustained minimal damage during the first round of testing. In the pulling side, the strength of the repaired column exceeded that of the as-built column by 21% (based on the predicted maximum strength of the as-built column, 34.5 kN). The dashed line of the as-built column was anticipated behavior based on the as-built column C1 behavior since both columns were identical. Also, the average initial stiffness of the repaired column was 4.2 kN/mm, which exceeded the initial stiffness of the as-built column by 47%.

4 CONCLUSIONS

This study focused on examining the feasibility of an innovative retrofit/emergency repair technique using SMA spirals for RC bridge columns. First, four 1/3-scale RC columns were cast, three of which were retrofitted with GFRP wraps, SMA spiral, and SMA spiral plus GFRP jackets, while one column remained in the as-built condition. The columns were 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 as-built column and the GFRP retrofitted column. Also, SMA spirals helped mitigating the damage of the RC columns. Second, two columns (C1 and C2) that were severely damaged in a previous testing were repaired using the new confinement technique, and retested under quasi-static cyclic lateral load. The repair process of each column was conducted in less than 15 hours and the columns were tested in less than 24 hours. Test results demonstrated that the lateral strengths and the initial stiffness of both repaired columns were fully restored or even enhanced. It is important to note that the recovered properties of the repaired columns are mainly attributed to the ability of the SMA spirals to apply and maintain active confining pressure on the damaged region of the columns, which increased the strength of the already damaged concrete and delayed its damage by increasing its ultimate strain. This paper showed that the proposed repair technique is effective and could be implemented successfully in a short time and thus could be used in emergency situations to maintain or restore the functionality of damaged lifeline structures.

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