NEW SMA CONFINEMENT TECHNOLOGY FOR RC BRIDGE COLUMNS

Bassem Andrawes[1], Qiwen Chen[2] and Moochul Shin[3]

Abstract

Lessons learned from previous earthquakes have shown the importance of lateral reinforcement in improving ductility of concrete columns. This paper focuses on summarizing the research on developing a new technology based on using shape memory alloy (SMA) spirals to enhance the seismic behavior of reinforced concrete (RC) bridge columns. The research investigated the advantages and feasibility of this technology in both circular and non-circular columns and proved that SMA confinement is more efficient than conventional confinement using steel spirals or fiber reinforced polymer (FRP) jackets.

Introduction

Many bridge failures in the past earthquakes were attributed to the failure of one or more of the reinforced concrete (RC) columns, which in many cases was due to the insufficiency of concrete confinement. Lateral concrete confinement has been widely explored by previous researchers and many studies have demonstrated that concrete confinement can significantly improve the strength and ductility of RC structures (Richart *et al.* 1928; Sheikh *et al.* 1982; Scott *et al.* 1982; Mander *et al.* 1988; Mirmiran and Shahawy 1997; Harries and Kharel 2002; Jiang and Teng 2007). There are mainly two types of concrete confinement, passive and active. Internal transverse steel reinforcement, for new structures, external steel jackets and fiber reinforced polymer (FRP) jackets, for existing structures, are common methods for applying passive confinement. Passive confining pressure develops as concrete dilates during loading. On the other hand, active confining pressure is applied to concrete prior to loading. Previous researchers have proved that active confinement is more effective than passive confinement in improving concrete strength and ductility. In order to make use of the effectiveness of active confinement, some researchers proposed to apply active confining pressure to concrete structures (Fam and Rizkalla 2001; Miyagi *et al.* 2004; Nesheli and Meguro 2006; Moghaddam *et al.* 2010) using prestressing tendons, prestressed steel jackets or prestressed FRP straps, etc. However, due to the high cost, extensive labor and excessive equipment required, the application of active confinement in the field is still limited. Recently, a type of smart materials—shape memory alloys (SMAs) attracted the attention of some researchers because of their ability to recover their original shape and to apply active confinement to concrete without the need for mechanical prestressing (Krstulovic-Opara and Thiedeman 2000; Andrawes and Shin 2008; Shin and Andrawes 2010&2011; Dommer and Andrawes 2012). Andrawes and Shin (2008) first proposed the idea of using SMA spirals to confine RC columns to improve their ductility. Next, Shin and

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[1] Associate Professor, Dept. of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, IL 61801, USA

[2] Graduate Research Assistant, Dept. of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, IL 61801, USA

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

Andrawes (2010) conducted compressive tests on SMA confined concrete cylinders and compared the behavior with that from FRP confined cylinders. Shin and Andrawes (2011&2012) applied the SMA confinement technique to retrofit RC columns and compared their behavior with columns retrofitted using FRP jackets. More recently, Chen *et al.* (2014) investigated applying SMA confinement to non-circular concrete columns and proved its superiority in improving the ductility of square concrete elements compared to FRP confinement. This present paper focuses on summarizing the findings from these recent research studies.

Shape Memory Confinement

SMA is a type of alloys that are able to recover its original shape through phase transformation. The phase transformation between austenite and martensite phases is determined 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. Fig. 1 demonstrates the austenite and martensite fraction under different transformation temperatures. Shape memory effect (SME) is a phenomenon that is observed when martensitic SMA is deformed below M_f, it can recover to its original shape by heating the SMA to a temperature above A_f. In the SMA confinement technique (Fig. 2), SMA wires are first prestrained in their martensitic phase, then wrapped around concrete columns and heated above A_f in order to activate shape memory effect. The restraint from concrete limits the SMA from recovering their original shape; hence recovery stress develops along the wires applying active confinement to the concrete structures. This technique requires SMA to possess M_s and A_s that are both outside the ambient temperature range in order to use the SME effectively (Fig. 1). This is important for the prestrained SMA wires to maintain their deformation before the shape recovery is activated. Therefore, NiTiNb SMA is chosen for the SMA confinement technique because of its wide thermal hysteresis: $A_s = 68°C$, $A_f = 76°C$ and M_s, M_f below $-100°C$ (Dommer and Andrawes 2012). The behavior of SMA confined concrete is different from pure actively and passively confined concrete, because active confinement in the SMA confined concrete is applied to the structures prior to loading through heating and passive confinement is added as concrete dilates during loading. Therefore, the behavior of SMA confined concrete is a combination of active and passive confinement (Fig. 3).

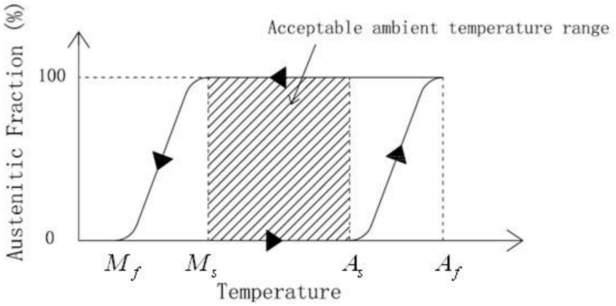


Figure 1: Austenitic Fraction vs. Temperature and the Acceptable Ambient Temperature Range for SMA Confinement Technique (Chen *et al.* 2014)

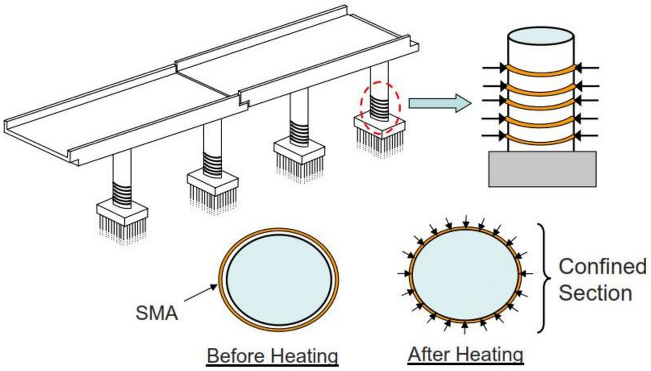


Figure 2: Schematic Drawing of Concrete Confined By SMA Spirals (Andrawes *et al.* 2010)

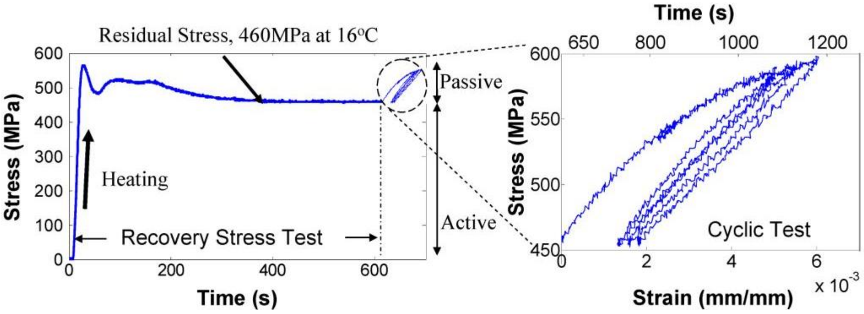
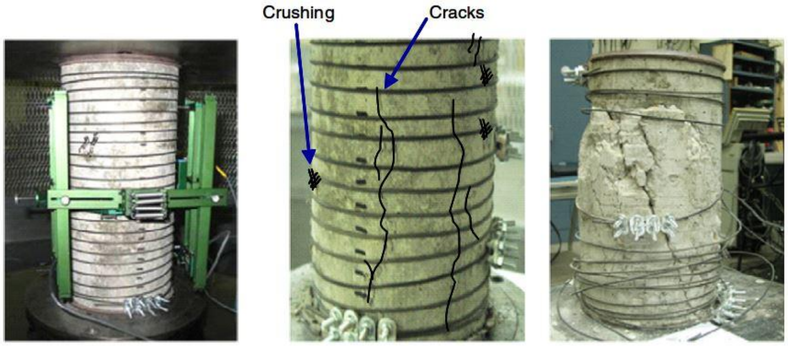


Figure 3: Activation of Shape Memory Effect in SMA Wire and Its Cyclic Behavior after a Stable Recovery Stress Is Reached (Shin and Andrawes 2010)

Experimental Investigation

Shin and Andrawes (2010) conducted experiments on SMA confined concrete cylinders and compared the stress-strain behavior with FRP confinement and SMA-GFRP hybrid confinement (SMA spirals wrapped around concrete cylinders in addition to GFRP wraps). Fig. 4 shows the SMA confined concrete cylinder before, during and after uniaxial compression test and Fig. 5 compares the stress-strain relationship of concrete confined by SMA spirals with that of concrete passively confined by FRP jackets. The active confinement in the specimen Active-SMA was equal to 1.4 MPa, while the passive confinement in the specimen Passive-2 and Passive-3 were 1 MPa and 2 MPa, respectively. These experimental results proved that with SMA confinement, concrete strength and ductility were more significantly improved compared to passively confined concrete. In order to compare the effect of SMA confinement with conventional steel confinement, Chen and Andrawes (2014) conducted tests on two pairs of SMA confined and steel confined specimens with pitch spacing of 19.1 mm and 12.7 mm. The pitch spacing and the confining pressure in each pair of SMA confined and steel confined specimens were designed to be the same, aiming to eliminate the effect of pitch spacing and the amount of confining pressure in comparing the behavior of different types of confinement (SMA vs. steel confinement). As shown in Fig. 6, SMA confined concrete showed 7.0-8.7% higher peak stress, 14.2 -15.0% higher ultimate stresses, and 110.6-134.9% larger ultimate strain than their steel confined counterparts. Chen and Andrawes (2014) also conducted experiment on SMA confined concrete cylinders with different SMA pitch spacing. Fig. 7 shows the axial stress-strain relation of the three cyclically loaded SMA confined concrete specimens with pitch spacing of 19.1 mm, 12.7 mm and 6.3 mm, and a corresponding active confining pressure of 1.2

MPa, 1.9 MPa and 3.9 MPa, respectively. With SMA pitch spacing of 19.1 mm, 12.7 mm and 6.3 mm, the peak stress of the concrete increased by 16.2%, 24.6%, and 51.0%, respectively compared to that of the unconfined concrete. The ultimate axial strain of 19.1 mm, 12.7 mm and 6.3 mm SMA spirals spacing were 0.0523 mm/mm, 0.0765 mm/mm and 0.1198 mm/mm, respectively and the corresponding residual stresses were 41.4%, 48.7% and 81.8% of the peak stresses, respectively. Therefore, as pitch spacing decreases, SMA confinement becomes more efficient to improve the strength, ultimate strain, and residual stress of concrete.



(a) Before. (b) During. (c) After.

Figure 4: SMA Confined Cylinder Before, During and After Uniaxial Compression Test (Shin and Andrawes 2010)

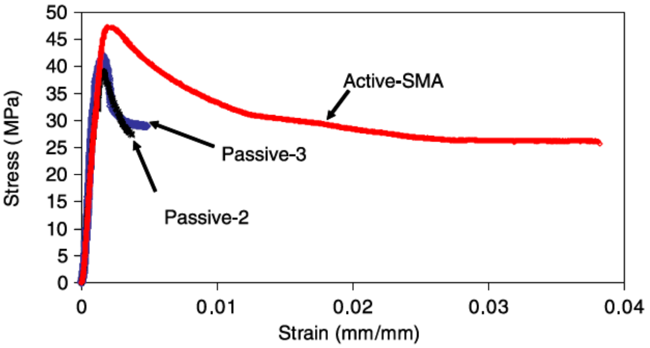
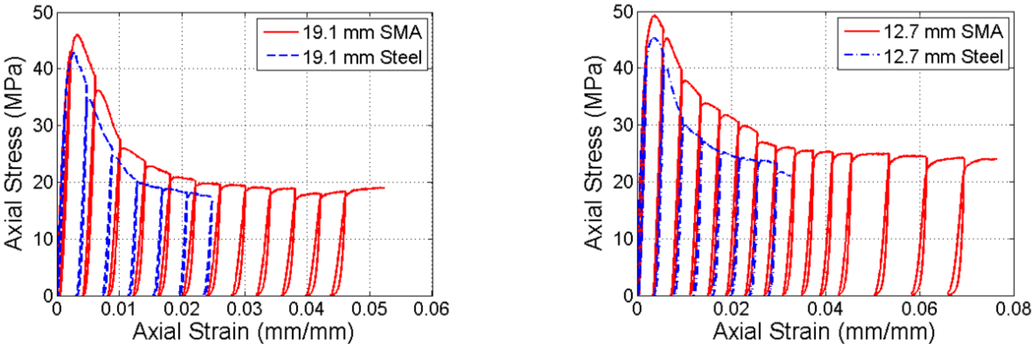
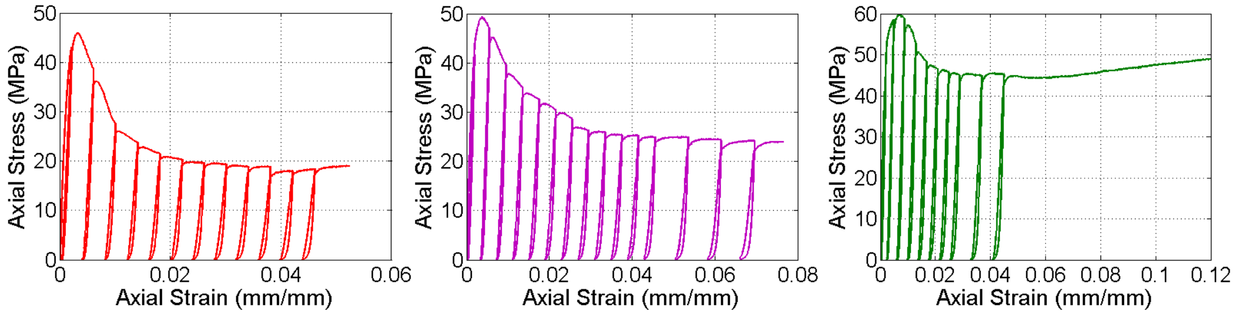


Figure 5: Comparison between the Stress-Strain Behaviors of SMA Confined Concrete and Passively Confined Concrete Using FRP Jacket (Shin and Andrawes 2010)



(a) (b)

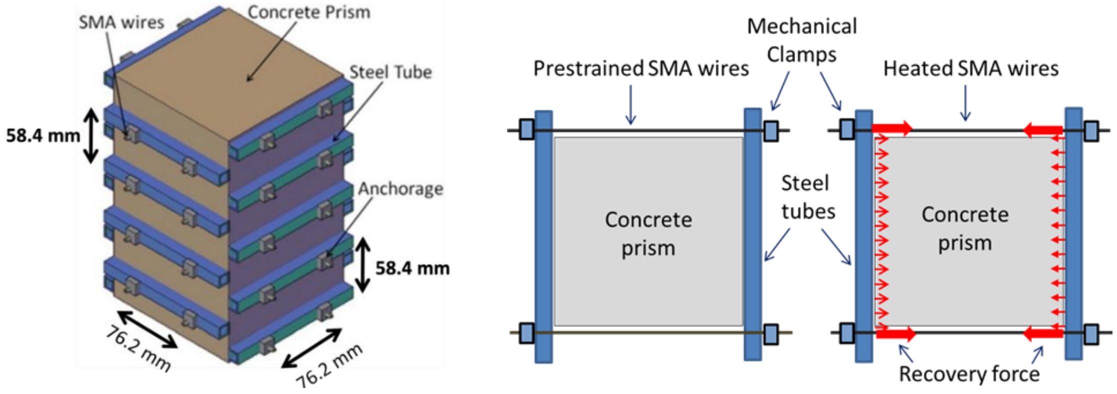
Figure 6: Comparison of SMA and Steel Confined Concrete Axial Stress-Strain Behavior (a) 19.1 mm Pitch Spacing; (b) 12.7 mm Pitch Spacing (Chen and Andrawes 2014)



(a) 19.1 mm pitch (b) 12.7 mm pitch (c) 6.3 mm pitch

Figure 7: Axial Stress-Strain Relation of SMA Confined Concrete with Different Pitch Spacing (Chen and Andrawes 2014)

The above mentioned research proved that SMA confinement is superior to passive confinement technique in terms of the easiness of application in the field and the effectiveness in improving the strength and ductility of circular concrete elements. However, in practice, besides circular columns, retrofitting of many insufficient existing square or rectangular RC columns are also in great need. Previous studies showed that the effect of confinement was significantly reduced at the corners of non-circular elements when using conventional steel or FRP confinement. Chen *et al.* (2014) proposed a new confinement scheme by using SMA to apply active confinement to non-circular concrete columns. Fig. 8(a) displays the proposed SMA confinement design for a 152.4 mm ×152.4 mm concrete prism, where bi-directional confinement pressure is applied using internal SMA wires connecting alternating pairs of steel tubes. The SMA wires were inserted through two drilled holes located at a horizontal distance of 76.2 mm. Fig. 8 (b) and (c) shows the cross section of the prism at the level of any pair of tubes before and after the activation of shape memory effect. Heating the restrained SMA wires causes recovery stress to develop along the wires and hence induces the steel tubes to apply pressure on the concrete surface. Fig. 9 compares the stress-strain relation of SMA confined and FRP confined prisms with the same level of confining pressure (2 MPa). The SMA confined specimen showed a more gradual descending branch and the ultimate strain was more than seven times that of FRP confined specimen, because SMA confinement demonstrated greater effectiveness in terms of delaying the dilation of concrete and improving the ductility.



(a) (b) before heating (c) after heating

Figure 8: (a) Non-Circular Concrete Confinement Scheme and (b), (c) Activation of Shape Memory Effect through Heating (Chen *et al.* 2014)

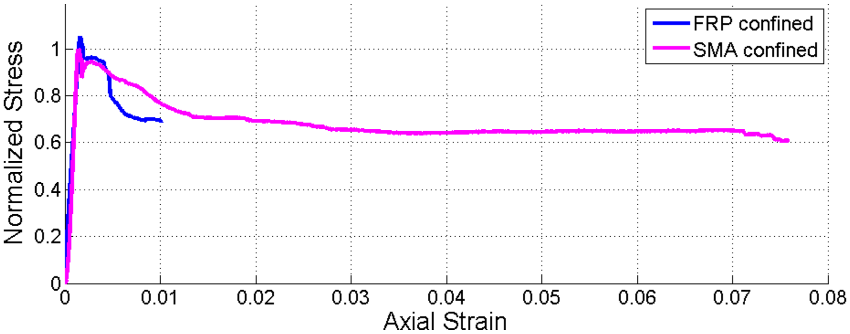
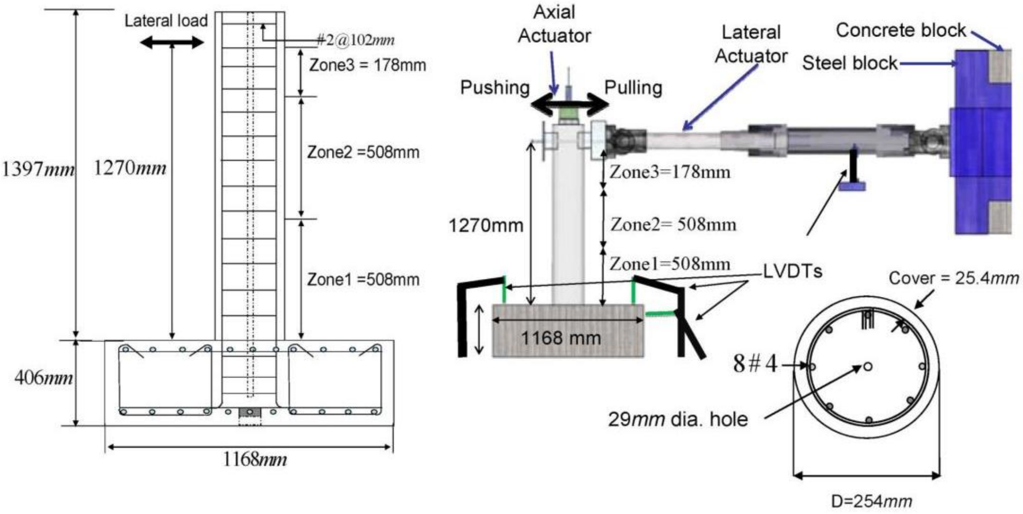
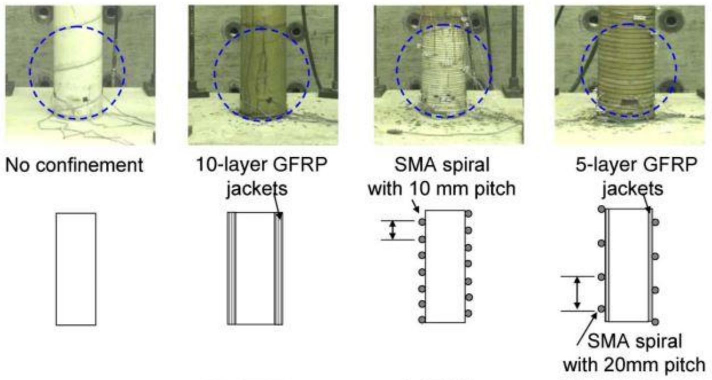


Figure 9: Axial Stress-Strain Relation Comparison of FRP Confined Prism and SMA Confined Prism (Chen *et al.* 2014)

Besides exploring SMA confinement technique using concrete cylinders or prisms under uniaxial compression, Shin and Andrawes (2012) also tested four RC columns under quasi-static lateral cyclic loading. Fig. 10 (a) shows the elevation and isometric views of the test setup. A 116 kN axial force was applied to represent the effect of gravity loads (5% of the column's gross section compressive strength). Fig. 10 (b) shows the design of the plastic hinge zone of the four columns. Fig. 11 shows the lateral force versus lateral drift relationships of the four tested columns. The results demonstrated that the SMA and SMA/GFRP columns exhibited a slight increase in strength, a significant increase in flexural ductility and ultimate drift capacity compared to the as-built column, while the GFRP column showed only a moderate enhancement in ductility and drift capacity. When assessing the damage of the four tested columns during and after testing revealed that the damage sustained by both SMA and SMA/GFRP columns was far less than that sustained by the GFRP column, although the 75% increase in maximum drift on the SMA-retrofitted columns. These results clearly show that the SMA retrofitting technique is very effective in increasing the ductility, drift capacity and energy dissipation ability of insufficient RC columns. It is also capable of mitigating the damage sustained by RC columns during extreme seismic events.



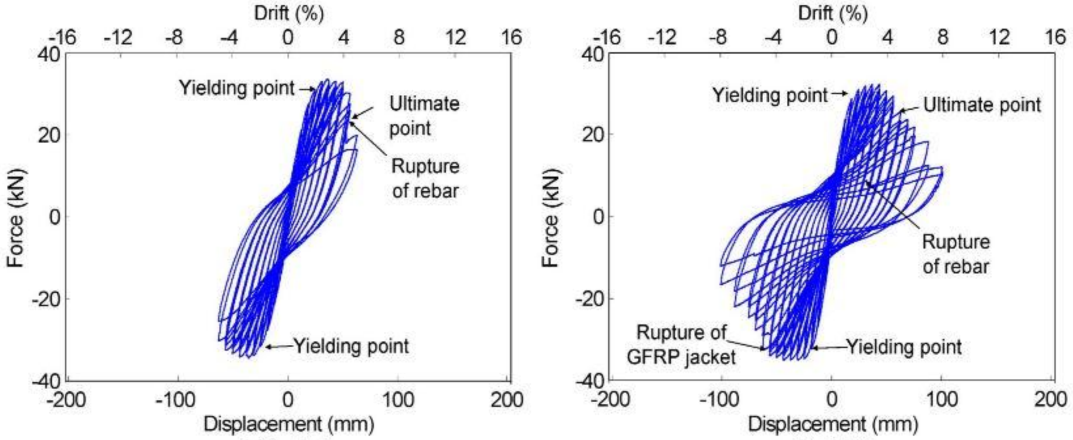
(a)



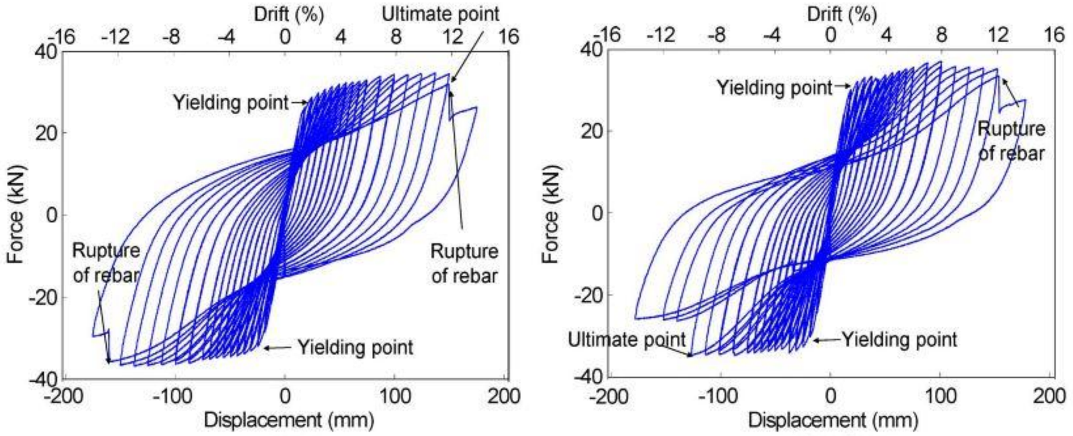
(a) As-built (b) GFRP (c) SMA (d) SMA/GFRP

(b)

Figure 10: (a) Schematic Drawings of Column Tests Setup; (b) As-built and Retrofitted Columns Design (Shin and Andrawes 2012)



(a) As-built (b) GFRP



(c) SMA (d) SMA/GFRP

Figure 11: Force-Displacement Relationship Comparisons of the Four Tested Columns (Shin and Andrawes 2012)

Furthermore, Shin and Adrawes (2011) examined the feasibility of using SMA confinement as emergency repair measure for severely damaged concrete columns after being subjected to extreme event. Fig. 12 demonstrates the five-step repair process aiming to restore the strength and ductility of damaged columns within 24 hours. First, remove crushed and loose pieces of concrete from the damaged region of the columns (Fig. 12a). Second, straighten the slightly buckled longitudinal steel bars and connect fractured or severely buckled bars with rebar couplers (Fig. 12b). Third, use injected pressurized epoxy to fill the cracks (Fig. 12c). Then, apply quick-setting mortar at the damaged region (Fig. 12d). As the mortar was curing, the last step was to wrap the column with the SMA spirals at the repaired region and heat the SMA wires using a propane torch (Fig. 12e). Fig. 12 (d) shows the repaired column after all the process was completed. The whole repair process was less than 15 hours. Fig.13 compares the lateral force-displacement relationships of the as-built and the repaired column. The results shows that the emergency repair on the severely damaged column was able to fully restore the lateral strength of the as-built column. Moreover, the initial stiffness of the repaired column was 54% higher than that of the as-built column and 930% greater than the residual stiffness of the damaged column. The overall displacement ductility ratio (i.e. ratio between the lateral displacement at the ultimate and yielding points) of the repaired column (ductility ratio=2.9) was comparable to that of the as-built column (ductility ratio=2.8). Therefore, this proposed repair technique is effective to restore the functionality of damaged concrete structures in emergency situations.

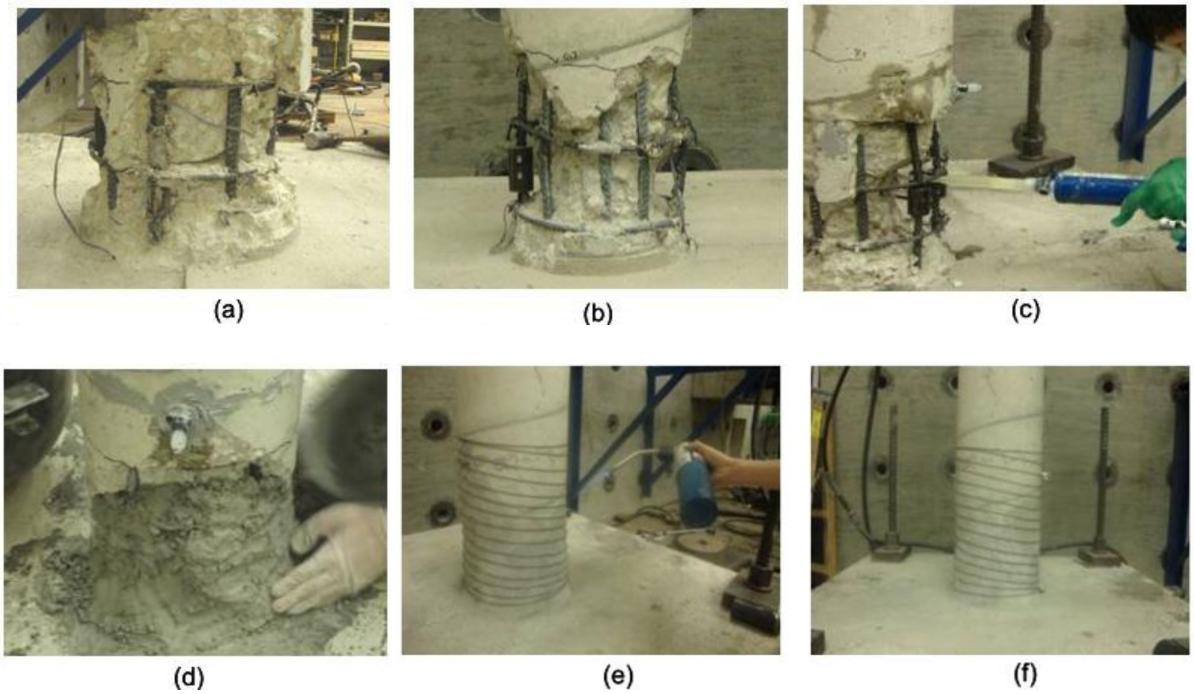


Figure 12: Pictures of the Fve-step Emergency Repair Pprocess. (a) Concrete Removal; (b) Steel Adjustment; (c) Epoxy Injection; (d) Mortar Application; (e) Heating SMA Spirals and (f) Repaired Column (Shin and Andrawes 2011)

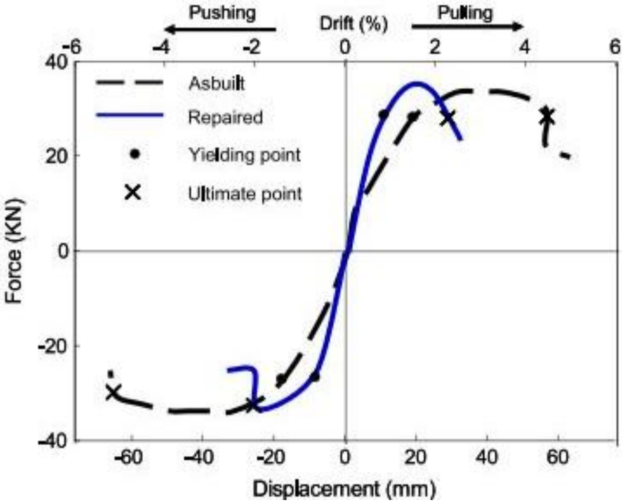


Figure 13: Backbone Curves of the Repaired and As-built Columns

Conclusions

This paper summarized the findings of the recent research conducted on the new technology of using SMA confinement in the seismic retrofit and repair of RC bridge columns. Experimental studies were conducted on both circular and non-circular concrete elements under both monotonic and cyclic loading. SMA confinement demonstrated more effectiveness in improving energy dissipation capacity and ease of application compared to conventional FRP and steel confinement. The feasibility of using SMA spirals to apply emergency restoration of severely damaged columns within 24 hours has also been proved. This research showed that the new SMA confinement technology is very promising and should be further studied.

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