Behavior of Retrofitted Concrete Members Using Iron-Based Shape Memory Alloys

Lara Zerbe[1], Mahmoud Reda[1], Mina Dawood[1], Abdeldjelil Belarbi[1], Ahmed Senouci[1], Bora Gencturk[2], Mohammed Al-Ansari[3], Julien Michel[4]

[1]University of Houston, Houston, USA
[2]University of Southern California, Los Angeles, USA
[3]Qatar University, Doha, Qatar
[4]Empa, Dübendorf/re-fer AG, Brunnen, Switzerland

ABSTRACT: This paper summarizes the findings of an experimental study to investigate the effectiveness of retrofitting reinforced concrete structural elements using iron-based shape memory alloys (Fe-SMA). The unique property of SMAs allows them to provide in a simple manner an active confining pressure on the member which is quite different from most existing retrofitting techniques which employ passive reinforcement techniques. The study includes two parts; (1) retrofitting of shear-critical beams, and (2) confinement of columns under concentric uniaxial compression. In the first part of this study, a total of 15 tests were performed on small-scale T-beams to investigate their shear behavior. The test variables included the type of confinement (active or passive), and the shear reinforcement index expressed by the number of SMA strips and the number of stirrups used within the shear span. The results of these tests showed an increase in the shear capacity of the beams retrofitted with an external Fe-SMA strip reinforcement, however, the tests were influenced by the adopted anchorage system and the results were not conclusive. In the second part, a total of 25 small-scale circular columns were tested under uniaxial compression. The test variables included the internal longitudinal and transverse reinforcement ratio, the number of SMA layers (0, 1, or 2), and the type of Fe-SMA confinement (active or passive). The test results showed an increase in the axial capacity and ductility of the columns with the increase in the number of Fe-SMA layers. Moreover, the internally reinforced columns showed a higher gain in capaciy and ductility when confined with Fe-SMA than the unreinforced columns. In both cases, further study is carried out with the goals of optimizing this new technique and better understanding the properties of the materials under different combinations of stresses.

1 INTRODUCTION

Rehabilitation of deteriorated reinforced concrete structures has been widely investigated to improve the performance and lengthen the lifespan of the existing structures. Several materials have been used to confine concrete structures such as fiber reinforced polymers (FRP) and steel jackets, however, most of these materials rely on passive confinement techniques where deformation and dilation of the existing members are required to engage the retrofitting system. New techniques are being investigated recently which use the approach of active confinement.

This approach is achieved by applying an initial external confining pressure to retrofit the structure, hence, no deformation of the members is required in order for the system to be effective.

Different active confinement techniques have been proposed to retrofit concrete members. One such system is the use of shape memory alloys (SMA). SMAs are materials that have the ability to recover their original shape upon heating, which is a phenomenon known as the shape memory effect (SME). By restraining the SME of the SMAs, an initial confining pressure on the retrofitted members can be achieved, acting as an active confinement. Some other active confinement systems have been reported in the literature such as the use of externally unbonded prestressed CFRP straps. The results of some studies showed that active confinement using this technique is a promising approach, however there are some practical challenges associated with the application of this technique, specifically, in applications where the beam to be strengthened is cast monolithically with a concrete slab, it can be challenging to fully wrap the beams with broad FRP straps (Lees et al., 2002, and Hoult and Lees, 2009). Janke et al., 2009, also used prestressed CFRP straps to confine concrete columns as well as steel strips. Their main objective was to study the residual load-bearing capacity of the columns using these prestressed techniques, where they observed an overall enhancement in the behavior of the prestressed confined columns compared to unprestressed and unconfined columns.
A primary advantage of the use of SMAs for active confinement is the ease of installation compared to other prestressing methods and compared to FRP strengthening systems. Furthermore, the SMA strips are not bonded to the structure, thus, they do not require a clean and smooth substrate for installation, therefore, they can be applied to severely deteriorated structures unlike traditional FRP retrofitting techniques, and they can be easily replaced in the case of damage. Some of the commonly used types of SMA are nickel-titanium SMA (NiTi-SMA), and nickel-titanium-niobium SMA (NiTiNb-SMA). Some studies were performed using these types of SMAs, which involved actively confining unreinforced concrete cylinders using SMA wires. These studies revealed significant increase in concrete strength and ductility due to the confining system compared to unconfined and passively confined cylinders using FRP, Shin and Andrawes (2009), Tan et al. (2015). Few studies were done using another type of SMA which is iron-based (Fe-SMA), one of which is the study done by Soroushian et al. (2001), where they used Fe-SMA rods as a shear repair system for a concrete bridge beam. The pre-strained SMA rods were anchored using steel angles at both sides of a shear crack. The repair system was verified by laboratory testing of one beam. The results showed that the beam was able to restore its original carrying capacity.
Another Study was conducted by Shahverdi et al. (2016) where they used Fe-SMA ribbed bars to strengthen reinforced concrete beams in flexure. They observed higher load capacity and higher cracking load in the strengthened beams compared to unstrengthened ones. In addition, they demonstrated the ease of prestressing these SMAs compared to other prestressing methods.

2 SHAPE MEMORY ALLOYS

SMAs are most known for their two unique properties, which are: the shape memory effect (SME) and the super-elasticity characteristic. The SME refers to the ability of SMAs to recover their original shape (fully or partially) when heated to a certain temperature. The super-elasticity refers to the phenomenon that SMAs can undergo large inelastic deformations under a small loading and recover their original shape after unloading. Due to these unique properties, SMAs have been used in a wide variety of applications. In this study, the focus was on the ability of

SMAs to generate an active confining pressure on the concrete members due to its SME to improve their overall behavior.

In this research project, iron-based SMAs (Fe–17Mn–5Si–10Cr–4Ni–1VC (mass-%)) were used. These SMAs were provided by the company re-Fer AG from Brunnen, Switzerland. The advantage behind using this type of SMA over nickel-based SMA is mainly the lower cost of the material, however, this type of Fe-SMA does not have the superelastic characteristic (Cladera et al., 2014). The Fe-SMA used in this study was provided as thin strips having cross-sectional dimensions of 0.5×50 mm. The tension test indicated that the strips failed at a stress of 900 MPa and a strain of 0.35 mm/mm. Activation of the SMA required heating the material to 155 ^{o}C after prestraining. This was achieved by using an electrical heating cable. Activation was performed on SMA coupons by restraining them from deforming in order to record the amount of stress induced after activation and subsequent cooling to room temperature; this stress is refered to as the recovery stress. The coupons were prestrained up to 4%, 6%, or 8%.The measured recovery stress did not vary for the prestraining levels considered. Three samples were tested at each prestrain level and the average measured recovery stress for all cases was 200 MPa. In other testing, these SMAs were found to be capable of generating up to 300 MPa of recovery stress (Czaderski et al., 2015, and Shahverdi et al. 2016). Possible reasons for the slightly lower measured recovery stresses in this study include the thermal expansion of the test apparatus during the activation or possibly incomplete heating through the thickness of the SMA using the technique adopted for activation.

3 EXPERIMENTAL INVESTIGATION

3.1 Small-scale shear-critical beams

3.1.1 Test specimens and setup

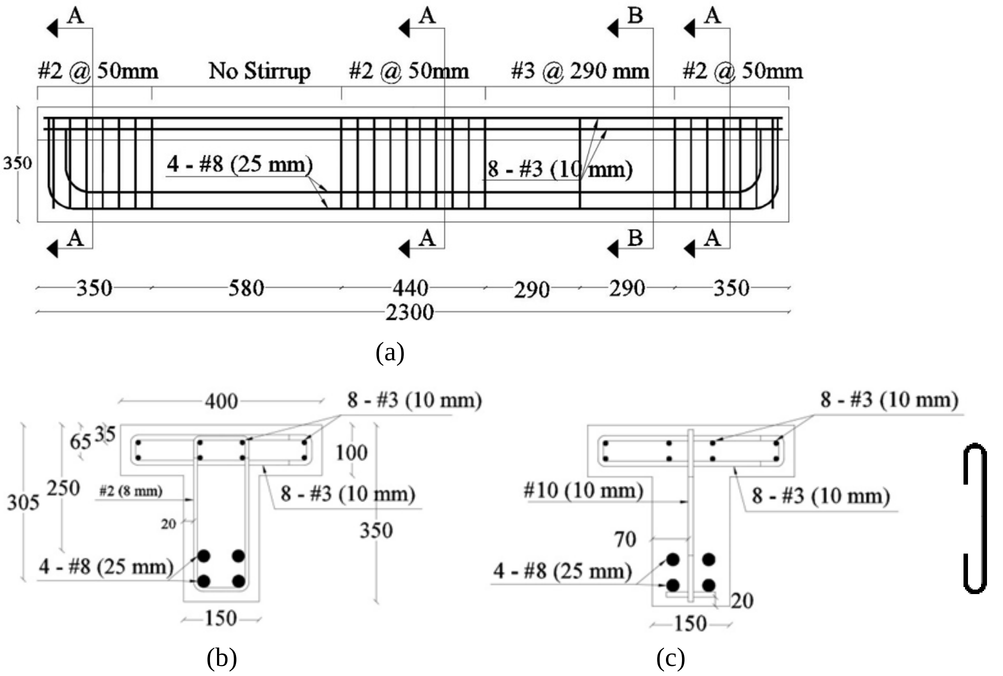
Eight T-beams were constructed to investigate their shear behavior after retrofittingusing SMA strips. The beams were designed to ensure a shear dominant failure. Two tests were conducted on each beam (one test at each end). However, one of the beam ends could not be effectively tested due to a fabrication complication. The length of each test region was equal to double the effective depth (d) of the beam. The other regions; loading points and supports, were heavily reinforced with two-leg stirrups of #2 (8 mm) bars spaced at 50 mm as shown in Figures 1(a) and 1(b).The test region either had no stirrups, one stirrup at spacing equal to d, or three stirrups at spacing equal to d/2.The cross-section in Figure 1(c) shows the 10 mm, one-leg stirrup used for the test region. Four tests were conducted without retrofitting(control tests)and the remaining eleven tests were retrofitted with the SMA strips. Table 1 shows the test matrix of the experimental program. The tests that used passive (non-activated) SMA were performed to quantify the capacity due to passive reinforcement only. The remaining tests that have active SMA, were performed to investigate the added benefit of the activated SMA compared to passive reinforcement. Also, this ensures decoupling of the effect of the various components that contributeto the shear resistance of the beam; concrete, steel stirrups, and SMA.

The beams were tested as simply supported, subjected to three point loading. The load was applied such that the tested end had a span to depth ratio (a/d) of 3.0, except for three tests which had a span to depth ration of 3.5. A steel plate was added underneath the loading and support points to avoid local failure due to stress concentration. While testing one end, an external reinforcing system was used to minimize the damage to the other end of the beam and preserve it for testing subsequently. This external reinforcing system consists of two hollow structural sections (HSS) attached to the top and bottom of the beam section, and connected to each other by two tension rods, as shown in Figure 2. The SMA strips were attached to the concrete using a mechanical anchorage system consisting of anchor bolts and angles. The tests were carried out in displacement-control at a loading rate of 0.25 mm/min. The tests were paused at regular intervals to take measurements, draw crack patterns, and record pertinent observations.

Table 1.Test matrix and results

Beam no.	**end**	**Beam ID**	**Steel Spacing**	**SMA Activation**	**No of SMA strips**	**Peak load (kN)**	**Deflection at peak load (mm)**
1	1	S/null-control-2	null	-	-	338	8.9
	2	S/null-SM/A/3-2		Active (A)	3	429	12
2	1	S/null-SM/A/1	null	Active (A)	1	303	6.8
	2	S/null-SM/P/3		Passive (P)	3	422	12
3	1	S/null-SM/P/2	null	Passive (P)	2	325	7.3
	2	S/null-SM/A/2		Active (A)	2	401	11.8
4	1	S/null-SM/P/1	null	Passive (P)	1	297	7.2
	2	S/d-SM/A/2	d	Active (A)	2	402	10.5
5	1	S/d-control	d	-	-	335	7.7
6	1	S/d2-control	d/2	-	-	455	11.3
	2	S/d2-SM/A/2/1	d/2	Active (A)	2	536	16.7
7	1*	S/null-control-1	null	-	-	311	7.6
	2*	S/null-SM/A/3-1**		Active (A)	3	329	12.4
8	1*	S/d-SM/A/3	d	Active (A)	3	424	11
	2	S/d2-SM/A/2/2	d/2		2	569	26.1

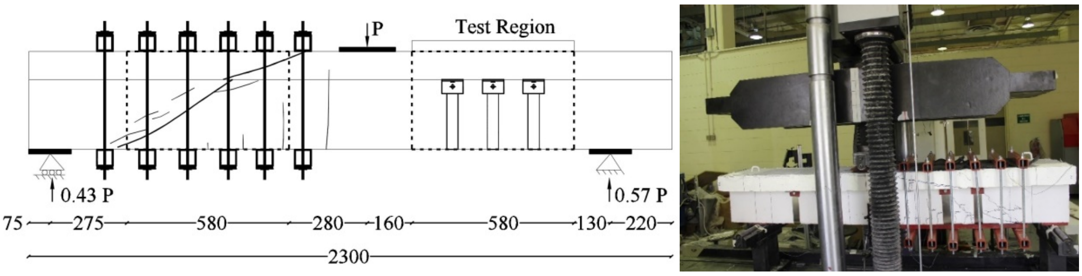
*The span to depth ratio is 3.5;   ** Only one layer of SMA strips was used



(a)

(b) (c)

Figure 1: Schematic drawing and dimensions of the test specimens; a) typical dimensions and steel distribution along the beam, b) section (A-A) and c) section (B-B).

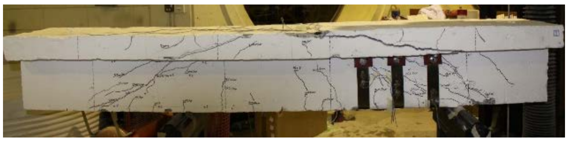


(a) (b)

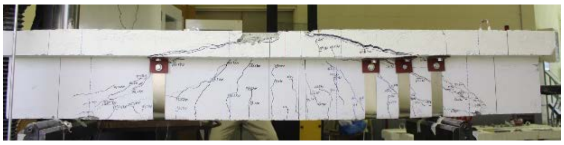
Figure 2: External Protection system and test setup; a) Schematic drawing and dimension of the external protection system and b) test setup.

3.1.2 Test results

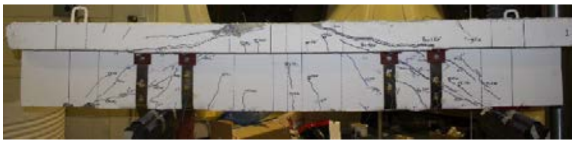
The load-deflection curves at the location of the applied load for all the specimens are shown in Figure 4. For the specimens that have no stirrups in the test region (Figure 4(a)), the capacities of the beams retrofitted with one SMA strip; S/null-SM/P/1 and S/null-SM/A/1, were less than the capacity of the control specimens which is probably due to the presence of the concrete voids at the anchorage system. However, the specimens retrofitted with more than one strip; S/null-SM/P/3, S/null-SM/A/3, and S/null-SM/A/2, except S/null-SM/P/2, showed a significant increase in both strength and ductility as compared to the control specimens. The specimen with one layer of SMA strips (S/null-SM/A/3-1) showed the same increase in ductility as the specimen with two layers (S/null-SM/A/3-2). However, it had almost the same capacity as the control specimen and 23% less than the specimen with two layers of SMA. The failure mode in both cases; passive and active, was identical. For the specimens that have one-leg stirrups in the test region (Figure 4(b)),both capacity and ductility of the retrofitted specimens with active SMA strips increased significantly compared to the control specimens. The final crack patterns of the test beams are presented in Figure 3 for all 15 tests. The failure mode for all tests was shear-tension failure with a major diagonal crack formed at the location of the applied load to the support location. The specimens retrofitted with SMA strips, firstly a few diagonal cracks formed on the web at the anchorage system location. Then, the cracks in the web increased in number and width during loading. Finally, the beams reached their peak load once the crack propagated in the flange forming one major crack from the loading point passing through the anchorage location and reaching to the support.



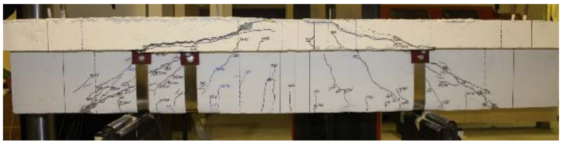
(a) S/null-control-2 (left), S/null-SM/A/3-2 (right)



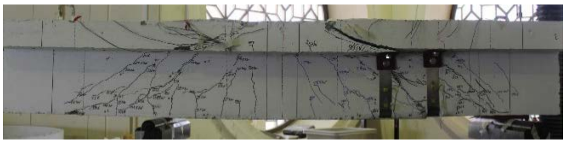
(b) S/null-SM/A/1 (left), S/null/SM/P/3 (right)



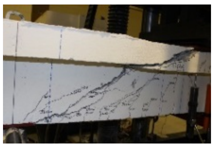
(c) S/null-SM/P/2 (left), S/null/SM/A/2 (right)



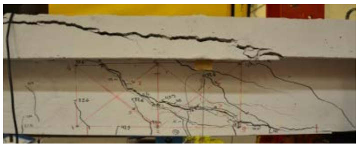
(d) S/d-SM/A/2 (left) and S/null-SM/P/1 (right)



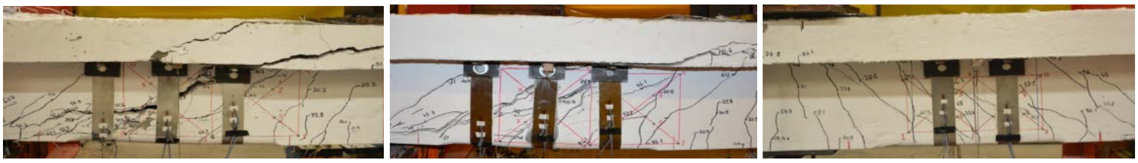
(e) S/d2-control (left), S/d2-SM/A/2 (right)



(f) S/d2-control

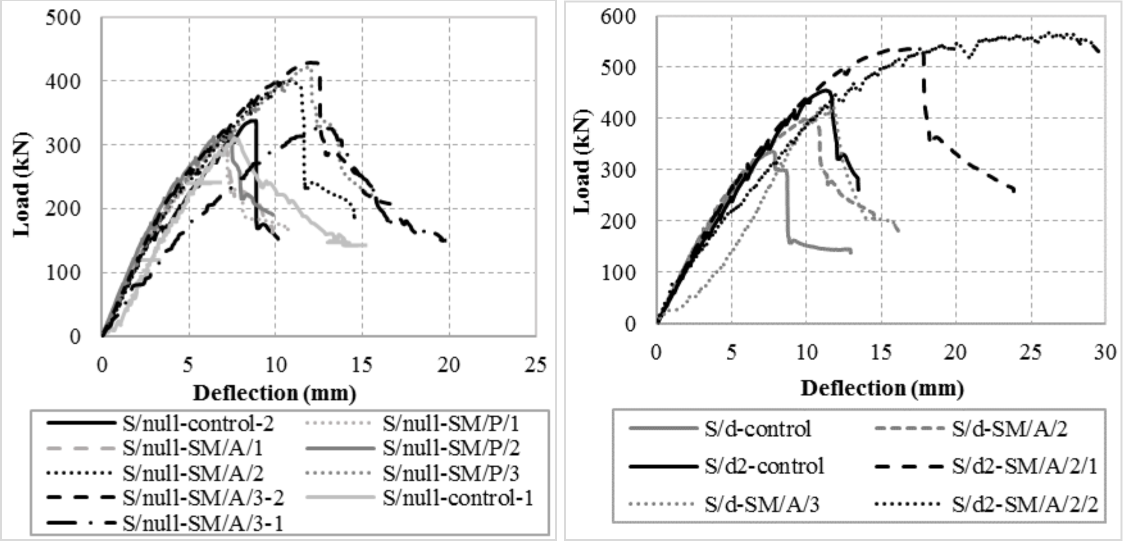


(g) S/null-control-1



(h) S/null-SM/A/3-1 (i) S/d-SM/A/3 (j) S/d2-SM/A/2/2

Figure 3: Crack Patterns for the tested shear-critical beams



(a) (b)

Figure 4: Load-Deflection curves of the shear critical beams: a) no steel stirrups, and b) one-leg stirrup, in the test region.

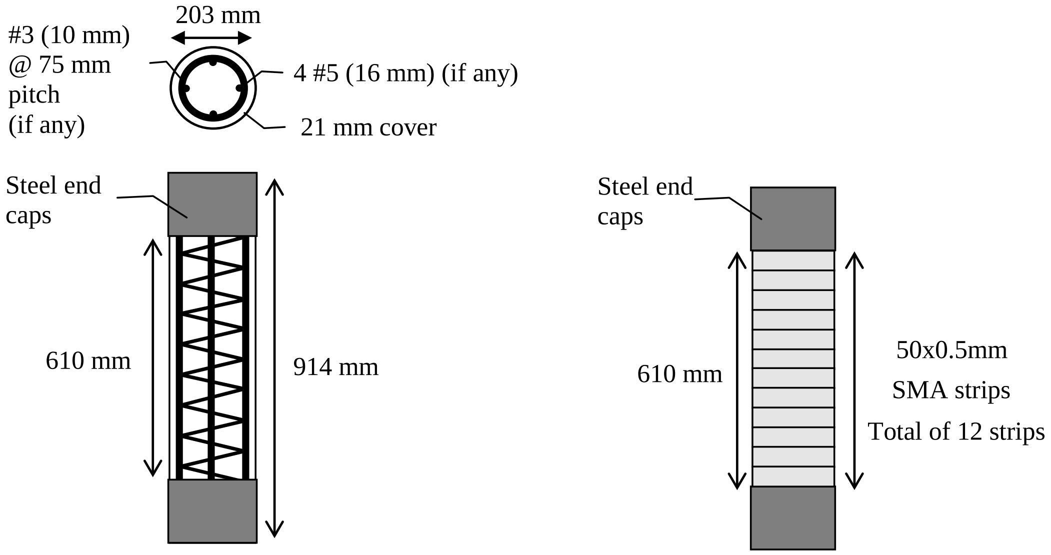
3.2 Small-scale circular columns

3.2.1 Test specimens and setup

The retrofitting technique investigated in this study was used to actively confine small-scale circular columns tested under concentric uniaxial compression loading. A total of 25 columns were tested all having the same dimensions as shown in Figure 5(a). Table 2 shows the detailed test matrix used for this study. The test variables included: the ratio of the longitudinal reinforcement (0% or 2%), the ratio of the transverse reinforcement (0% or 2%), the type of confinement (passive or active), and the number of SMA layers (0, 1, or 2 layers).All retrofitted columns had the same SMA configuration, where individual strips were wrapped around the column along its entire length without any space between them, as shown in Figure 5(b).

3.2.2 Test results

The main goal of this study was to examine the uniaxial compressive behavior of reinforced and unreinforced concrete columns confined with SMA strips. Figures 6(a) and 6(b) show the applied load versus the axial shortening relationships for unreinforced and reinforced columns, respectively. In general, it was observed that the use of SMA as an additional confinement increased the axial compressive capacity and the ductility of the columns. However, this increase was more significant in the cases where internal transverse and longitudinal steel reinforcement was present.



(a) **(b)**

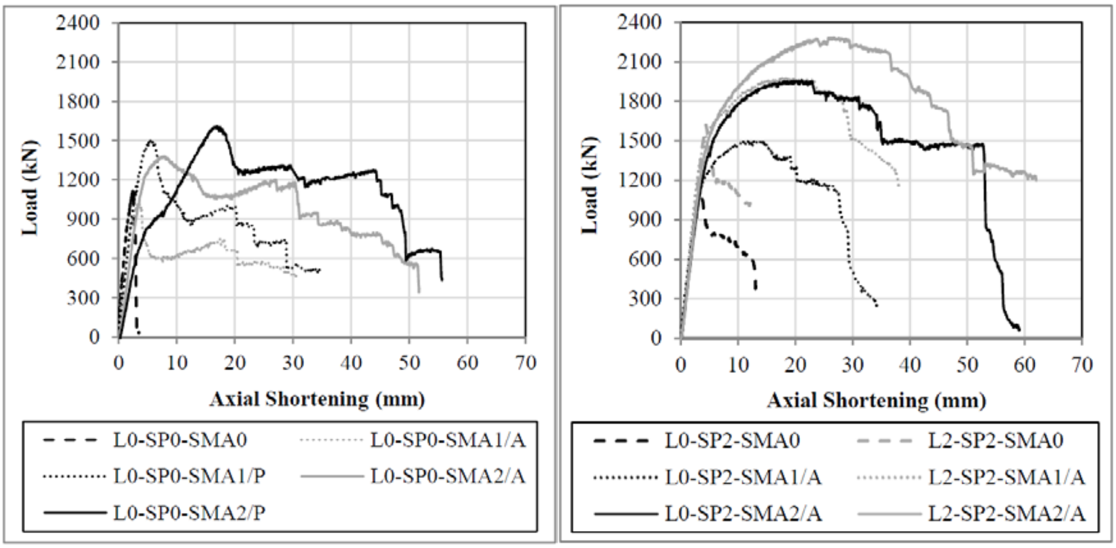
Figure 5: a) Typical column dimensions and internal reinforcement, b) SMA configuration.

Table 2. Test matrix for small-scale columns

Specimen ID	**Longitudinal reinforcement ratio (%)**	**Transverse reinforcement ratio (%)**	**Number of SMA layers**	**Type of confinement**	**Number of tests**
L0-SP0-SMA0	0	0	0	-	2
L0-SP0-SMA1/P			1	Passive	2
L0-SP0-SMA1/A				Active	3
L0-SP0-SMA2/P			2	Passive	2
L0-SP0-SMA2/A				Active	2
L0-SP2-SMA0	0	2	0	-	2
L0-SP2-SMA1/A			1	Active	3
L0-SP2-SMA2/A			2	Active	2
L2-SP2-SMA0	2	2	0	-	2
L2-SP2-SMA1/A			1	Active	3
L2-SP2-SMA2/A			2	Active	2

Throughout the testing procedure, in the case of unreinforced columns confined with SMA, a significant drop in the load was observed when the concrete began to crack. However, the columns did not fail suddenly as in the case of the control specimen (not confined with SMA) and they still carried more than half their peak loads with very reasonable ductility until the SMA strips began to rupture. After that, the load dropped significantly with the rupture of each SMA strip until failure. In the case of reinforced columns confined with SMA, the columns did not experience any drop in load after reaching their peak load. In fact, the columns were able to maintain their peak capacities in a ductile behavior until the first rupture of the SMA strips was observed, then a gradual drop in load was recorded, which correlated to the rupture of each SMA strip. It was observed in both cases that the failure of the columns changed from brittle to more ductile when confined with SMA, and the failure mode was classified as failure due to the rupture of the SMA.

Moreover, the use of two layers of SMA had a higher effect on the axial load capacity and ductility of the columns than the use of one layer. Only unreinforced columns were tested for active and passive confinement. The columns with active confinement had slightly less increase in the axial load capacity than those with passive confinement. This can be explained by the localization of stresses induced due to the activation of the SMA at the weak sections at the anchorage location, which caused a premature rupture of the SMA strips. Moreover, the SMAs were prestrained to 6% which reduces the remaining strain to reach the tensile failure since, by activation, it does not fully recover that strain. This was also observed by Janke et al. (2009) when using prestressed CFRP confinement.



(a) (b)

Figure 6: Applied load vs. axial shortening relationship of (a) unreinforced columns, (b) reinforced columns.

4 CONCLUSIONS

The research program presented in this paper studied a relatively new technique known as active confinement using Fe-SMA to retrofit concrete beams and columns. The conclusions presented herein are preliminary and further studies are underway to provide more conclusive remarks. Based on this study, the following conclusions can be drawn:

- The use of active confinement for retrofitting concrete members is a promising technique to improve their strength and ductility characteristics.
- The capacity and the ductility of the beams and columns increased with the increase of amount of SMA used in all cases.
- The internally reinforced members in both beams and columns adopted a more consistent behavior and a higher increase in capacity and ductility than the unreinforced ones.
- The wrapping technique of the SMA and the anchorage systems used for this study clearly affected the behavior and the capacities of the members, therefore, further research is to be carried out to optimize these details and minimize their effect on the behavior of the RC elements.

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