APPLICATION OF SHAPE MEMORY ALLOYS IN THE SEISMIC RETROFITTING OF BRIDGE COLUMNS

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ABSTRACT :

This analytical study focuses on investigating a new active confinement retrofitting technique for reinforced concrete bridge columns using pre-strained shape memory alloy (SMA) hoops. The shape memory feature of SMAs is sought in this study to apply large lateral confining pressure on the columns in an easy and reliable technique. A finite element model is developed for a column adopted from the literature and retrofitted with SMA hoops and CFRP wraps. The compression stress-strain behaviors of passively and actively confined concrete using CFRP wraps and SMA hoops, respectively are implemented in the finite element model. The retrofitted column behavior is studied under displacement-controlled and seismic excitations. The results of the cyclic loading analysis indicates an increase in the SMA retrofitted column strength by approximately 34% compared to that of the CFRP retrofitted column. The seismic analysis results show that the early increase in the concrete strength associated with using SMA hoops results in a maximum and residual drift reduction of approximately 12% and 50%, respectively compared to the drifts obtained by using conventional CFRP wraps.

KEYWORDS: Shape memory alloys, Seismic retrofitting, Bridges, Concrete, Confinement

1. INTRODUCTION

Structural ductility is an important design characteristic which governs the response of structures to earthquakes. Many of the catastrophic bridge failures that occurred during past earthquakes (e.g. 1971 San Ferando earthquake, 1989 Loma Prieta earthquake, and 1995 Kobe earthquake) were attributed to the lack of ductility of bridge columns (Seible et al. 1997, Hamilton et al. 2004). Concrete confinement proved to be one of the key solutions to enhancing the ductility of vulnerable concrete columns (Mander et al. 1988). Passive confinement techniques such as using steel jackets or Fiber Reinforced Polymer (FRP) composite wraps have been widely investigated and used in bridges. These techniques are considered passive since they rely primarily on the dilation of the concrete to mobilize the confining pressure. On the other hand, active confinement is a technique where external confining pressure is applied on the concrete element before the concrete starts dilating. Research have illustrated that the strength and ductility of concrete is improved significantly with active confinement compared to passive confinement (Richart et al., 1928). Despite its superiority, the application of active confinement in structures has been hindered due to difficulties related to the on-site application methods, which involved large amount of hardware, labor, and time. This paper studies analytically a novel technique for applying active confinement using shape memory alloy (SMA) hoops. The unique shape recovery feature of SMAs is sought to apply large external active confining pressure in an easy, reliable, and cost-effective method. The effectiveness of using the novel confining technique using SMAs in improving the ductility of reinforced concrete (RC) bridge columns will be compared to that of the conventional confining technique using Carbon FRP (CFRP) composite wraps.

2. SHAPE MEMORY ALLOYS

Shape memory alloys are metallic alloys that exhibit unique phenomenon known as shape memory effect (SME). SME is a distinctive thermo-mechanical characteristic which allows SMAs to recover their original shape by heating, even after they have been deformed excessively up to 6%-strain (Otsuka and Wayman, 2002). Figure 1 shows a schematic of the stress-strain-temperature relationship typically observed in SMAs. Branch (1) in the figure represents the stress-strain behavior of typical SMAs during loading. As illustrated by Branch (2), upon unloading, large residual deformation is observed. This deformation could be eliminated as shown by Branch (3) by heating the alloy to a temperature above the austenite finish temperature, A_f. If a SMA wire is restrained from recovering its original shape, the applied heat will induce large stresses in the wire known as recovery stresses. These recovery stresses could reach up to 828MPa (120ksi) depending on the alloy's composition and manufacturing procedure. The SMAs' high recovery stress is sought in this study to apply an external active confining pressure on bridge concrete columns to enhance their ductility and seismic behavior.

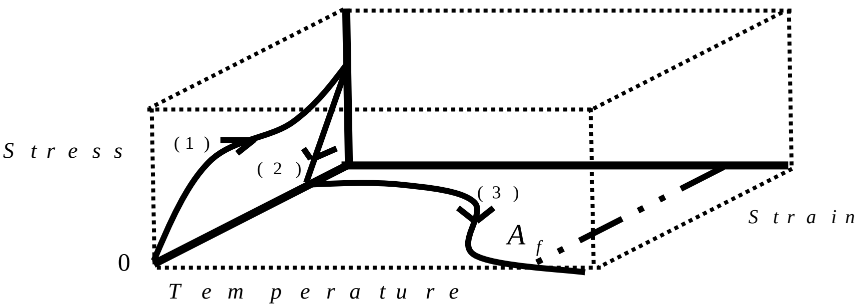


Figure 1 Stress-strain-temperature relationship observed in typical SMAs

3. ANALYTICAL CONCRETE MODELS

An important key factor that governs the analytical seismic response of retrofitted RC bridge columns is the constitutive behavior of the concrete used in the column model. In order to distinguish between the two different concrete behaviors under passive confinement (using CFRP) and active confinement (using SMA hoops), two different compression stress-strain models were utilized in the study. A description of each model is presented in the following subsections.

3.1 Concrete confined with CFRP and ties

Previous studies have shown that the stress-strain behavior of concrete confined with CFRP could be described as bilinear, where after reaching the peak point, the concrete experiences strain hardening as a result of the confinement provided by the elastic composite wraps (see Fig. 2). When the composite wraps reach their ultimate strength they rupture in a brittle manner which causes the concrete strength to drop suddenly. To describe analytically the stress-strain behavior of concrete confined with CFRP (externally) and ties (internally), the experimental-based model suggested by Kawashima et al. (2001) was adopted. The equations for the stress and strain values suggested by Kawashima et al. at the peak point are presented in Eqs. 3.1 and 3.2, respectively

$$f_{cc} = f_{co} + 1.93\rho_{CF} \cdot \varepsilon_{CFt} \cdot E_{CF} + 2.2\rho_S \cdot f_{yh} \quad (3.1)$$

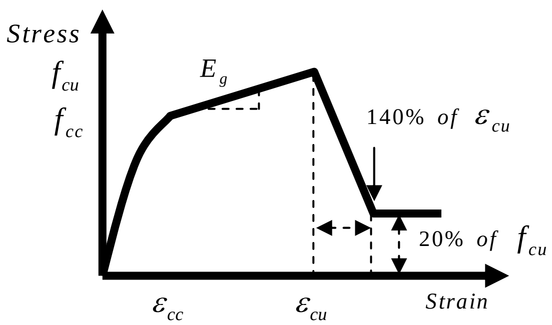
$$\varepsilon_{cc} = \varepsilon_{co} + 0.00939\frac{\rho_{CF} \cdot \varepsilon_{CFt} \cdot E_{CF}}{f_{co}} + 0.0107\frac{\rho_S f_{yh}}{f_{co}} \quad (3.2)$$

where f_{cc} and ε_{cc} are the strength and strain of the confined concrete, respectively where the concrete modulus starts degrading, f_{co} and ε_{co} are the strength and strain of the unconfined concrete at the peak point, respectively, ρ_{CF} is the volumetric ratio of carbon fiber sheets (CFS), ε_{CFt} is the spherical strain of CFS (1,800~1,900 μ) where the modulus of the confined concrete starts degrading, E_{CF} is the elastic modulus of CFS (230GPa), ρ_s is the volumetric ratio of the transverse reinforcement, and f_{yh} is the yield strength of the transverse reinforcement. In this study, a value of 0.002 was adopted for ε_{co} in Eq. 3.2. To describe the post-peak behavior of the concrete, the concrete modulus E_g and ultimate strain ε_{cu} were computed as follows:

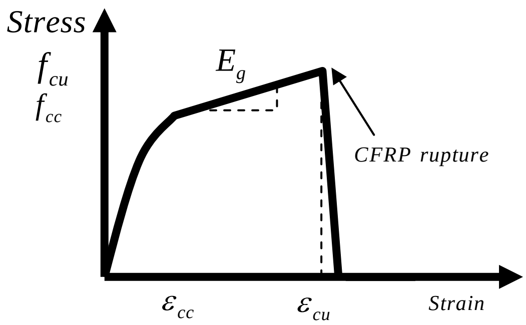
$$E_g = -0.658\frac{f_{co}^2}{\rho_{CF}\cdot\varepsilon_{CFt}\cdot E_{CF}+0.098\rho_s f_{yh}} + 0.078\sqrt{\rho_{CF}}\cdot E_{CF} \tag{3.3}$$

$$\varepsilon_{cu} = 0.00383 + 0.1014\left(\frac{\rho_{CF}\cdot f_{CF}}{f_{co}}\right)^{\frac{3}{4}}\left(\frac{f_{CF}}{E_{CF}}\right)^{\frac{1}{2}} \tag{3.4}$$

where f_{CF} is the ultimate strength of the CFS. The values obtained from Eqs. 3.1-3.4 were implemented in the finite element program OpenSees which was used in this study (Mazzoni et al. 2006). The Concrete01 uniaxial material model in OpenSees was modified to capture the concrete behavior during the composite post-rupture phase. As shown in the schematic presented in Fig. 2, the core concrete confined with CFRP and ties was assumed to be able to undertake residual stresses as a result of the ductile behavior of the steel ties. However, the cover concrete was modeled such that it would lose its entire capacity after the composite wraps are ruptured.



(a) Core concrete behavior



(b) Cover concrete behavior

Figure 2 Concrete constitutive behaviors assumed for the core and cover concrete confined with CFRP wraps

3.2 Concrete confined with SMA wires and ties

To consider the effect of active lateral pressure developed by the external SMA hoops, a modified version of the model developed by Mander et al. (1998) was utilized. According to Mander et al., the stress and strain values at the peak point could be computed using Eqs. 3.5 and 3.6, respectively.

$$f_{cc} = f_{co}\left(-1.254 + 2.254\sqrt{1+\frac{7.94 f_l}{f_{co}}} - 2\frac{f_l}{f_{co}}\right) \tag{3.5}$$

$$\varepsilon_{cc} = \varepsilon_{co}\left[1+5\left(\frac{f_{cc}}{f_{co}}-1\right)\right] \tag{3.6}$$

where f_{cc} and ε_{ee} are the peak strength and strain of the confined concrete, respectively, f_{co} and ε_{co} are the peak strength and strain of the unconfined concrete, respectively, and f_l is the effective lateral stress from internal ties and external active confinement using SMA hoops. In order to include the effect of active confinement using SMA hoops, f_l was evaluated using Eq. 3.7.

$$f_l = f_{l\_tie} + f_{l\_SMA} \tag{3.7}$$

where f_{l_tie} is the confining pressure developed by the ties at yielding (Mander et al. 1988) and f_{l_SMA} is the confining pressure developed by SMA hoops. The f_{l_SMA} parameter was related to the properties of the SMA hoops using the following formula:

$$f_{l\_SMA} = k_e(2A_{SMA}\sigma_{SMA})/(d \times s) \tag{3.8}$$

where k_e is a correction factor suggested by Mander et al. to account for the reduction in the confining pressure due to spacing between the hoops, A_{SMA} is the cross sectional area of the SMA wire, σ_{SMA} is the SMAs recovery stress, d is the diameter of the circular column, s is the hoop spacing. An energy balance approach (Eq. 3.9) was adopted to calculate the ultimate strain of the confined concrete.

$$U_{SMA} + U_{sh} = U_{con} + U_{sc} \tag{3.9}$$

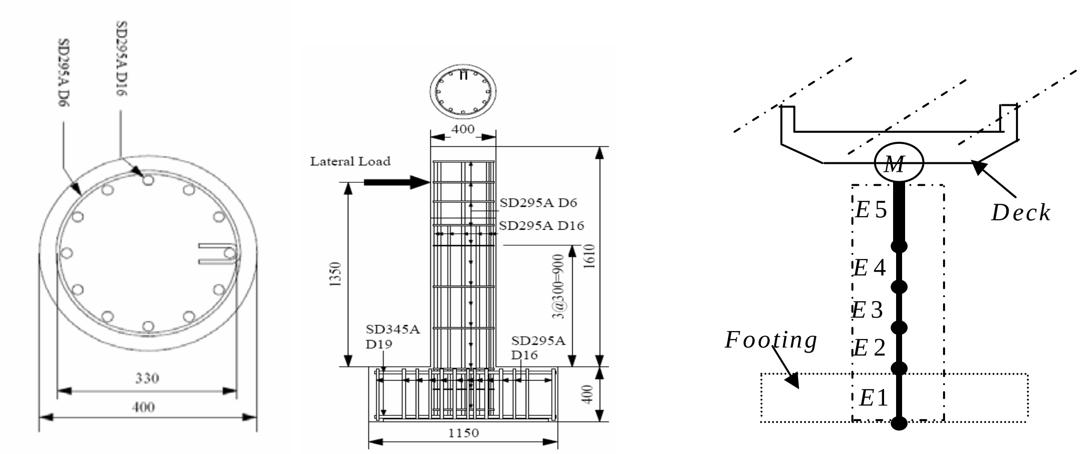
where U_{SMA}, U_{sh}, U_{con}, U_{sc} are the ultimate strain energy capacity per unit volume of core concrete for the SMA hoops, transverse reinforcements, core concrete, and longitudinal reinforcements, respectively. To evaluate the SMA lateral pressure (f_{l_SMA}) in this study, a recovery stress of 413.8MPa (60ksi) was assumed considering the prestress losses in SMA wires due to slack and concrete elastic strain. The values obtained from the modified Mander et al. model was implemented in the OpenSees Concrete04 uniaxial material model and used in the analysis.

4. BRIDGE COLUMN MODEL

In order to provide validation for the analytical results obtained from this study, the column model adopted in this study was based on the experimental work presented by Kawashima et al. (2001) which focused on investigating the effect of using CFRP wraps on the seismic behavior of RC columns. OpenSees was utilized to model and analyze the RC column adopted in the study. The column tested by Kawashima et al. was confined with lateral ties and CFRP wraps. A summary of the circular column's properties and dimensions are presented in Table 1. A view of the column and its analytical model is also presented in Fig. 3. The column had a circular section with a diameter equal to 400mm (15.75in). The effective height of the column was 1350mm (54.7 in) and the length of the region wrapped with CFRP was 1000mm (39.37in) from the base. An axial compression load of 185KN (41.6 kips) was applied at the top of the column. The compressive strength of the unconfined concrete was 30MPa (4.35ksi) and the yield strength of the longitudinal and lateral reinforcements were 374MPa (54.2ksi) and 363MPa (52.6ksi), respectively. OpenSees fiber section technique and the nonlinear displacement-based beam-column element were utilized to develop the model of the column at the confined region (elements E1-E3 in Fig. 3) and the footing (E4). An elastic beam-column element was used for the remaining part of the column (E5). A uniaxial material model with isotropic strain hardening (Steel02) was used to describe the behavior of the longitudinal reinforcement fibers. A lumped mass (18858 kg) was assigned at the top of the column. To verify the analytical model, the column was subjected to the same loading protocol used in the experiment (displacement control with 0.5%-drift increments). Figure 4 shows the force displacement relationships obtained from analysis and experiment for the column when wrapped with one layer of CFRP ($\rho_{CF} = 0.11\%$). The figure indicates an acceptable agreement in the behaviors of both analysis and experiment. The analytical model showed a slightly higher peak strength peak of 4% compared to the experimental column which was considered to be insignificant. Thus, it was concluded that the analytical model was capable of capturing the behavior of the retrofitted column.

Table 1 Specifications of the column tested by Kawashima et al. and adopted in this study

Property	Value
Section Diameter (mm)	400
Effective Height (mm)	1350
Longitudinal Reinforcement ratio (%)	1.89
Volumetric Ratio of Lateral Reinforcement (%)	0.13
Compressive Strength of Concrete (MPa)	30.0
Longitudinal Reinforcement	SD295 D16 (Yield Strength =374MPa)
Lateral Reinforcement	SD295 D16 (Yield Strength =363MPa)
Volumetric Ratio of CFRP (%)	0.11
Axial Force (kN)	185



(a) Column details (b) Analytical model

Figure 3 Schematic of the column tested by Kawashima et al. and adopted in this study

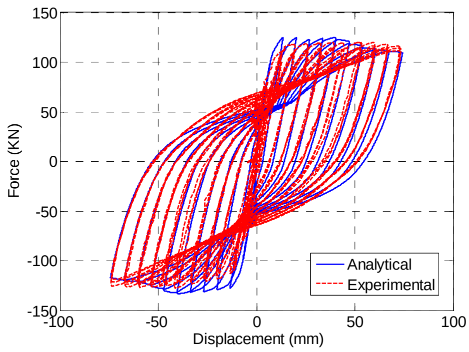


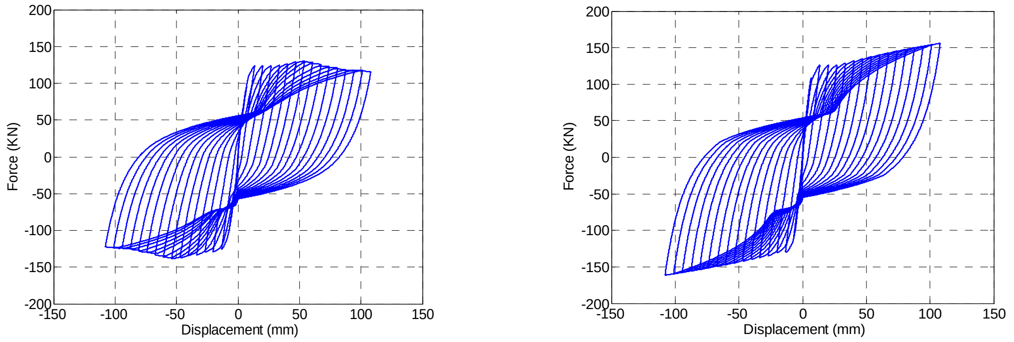
Figure 4 Comparison between the force-displacement behaviors of the analytical and experimental column

5. ANALYSIS

The analytical model of the column was used to compare the efficacy of SMA hoops and CFRP wraps in improving the seismic behavior of RC bridge columns. Two layers of CFRP were used to confine the RC column, which had a volumetric ratio ρ_{CF} of 0.22%. The confining pressure developed by the CFRP wraps at rupture was found to be 2.40MPa (348.9psi). A similar active confining pressure was applied using SMA hoops. For a SMA wire with a 5mm-diameter (0.2in) and a 413.8MPa (60ksi) recovery stress, a hoop spacing of 11.7mm (0.46in) would be needed to develop an active confining pressure of 2.40MPa (348.9psi). The behavior of the column when retrofitted with SMA hoops and CFRP wraps were studied under cyclic loading and seismic excitation. The analysis details and results are presented in the following subsections.

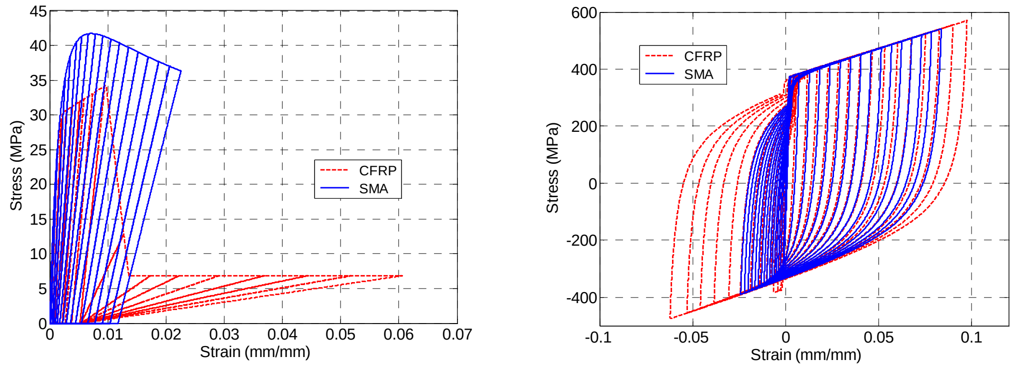
5.1 Cyclic Loading

The displacement-controlled cyclic protocol utilized in this study had a 0.5%-drift increment until a maximum displacement corresponding to 8%-drift. Figure 5 shows the force displacement relationships of the column when retrofitted with CFRP wraps and SMA hoops. A close comparison between the two behaviors would reveal an increase in the peak strength of approximately 34% in the case of the column retrofitted with SMA hoops compared to that was wrapped with CFRP. The column confined with SMA hoops was able to maintain it load-carrying capacity until the end of the loading, while the CFRP wrapped column started loosing its capacity at a displacement corresponding to a drift equal to 4%. A comparison between the stress-strain relationships of the core concrete and longitudinal steel in both cases (see Fig. 6) illustrates that the CFRP wraps had experienced rupture which resulted in a significant reduction in the column stiffness and increase in the demand on the longitudinal reinforcement. On the other hand, the maximum compressive strain experienced by the concrete and steel of the SMA retrofitted column was reduced by 70% and 65%, respectively compared to that was observed in the case of the column wrapped with CFRP. The early increase in the concrete strength associated with active confinement played an important role in limiting the level of damage in the column.



(a) CFRP wraps (b) SMA hoops

Figure 5 Force displacement relationships of the RC column retrofitted with CFRP wraps and SMA hoops under displacement-controlled cyclic loading



(a) Concrete core (b) Longitudinal reinforcements

Figure 6 Comparison of the stress-strain relationships of the confined concrete longitudinal steel reinforcement of the columns retrofitted with CFRP wraps and SMA hoops under cyclic loading

5.2 Earthquake Loading

The behavior of the retrofitted column was also investigated under seismic excitation. The analytical column was subjected to a scaled record from the 1980 Victoria, Mexico earthquake (6604 Cerro Prieto Station record). The record was scaled to a spectral acceleration of 1.5g at the fundamental period of the column (0.18 sec.). Figure 7 depicts a comparison between the lateral displacement time histories of the columns retrofitted with CFRP wraps, SMA hoops, and internal ties only, i.e. as-built. The force displacement relationships of the three columns are also shown in Fig. 8. A summary of the maximum drift and residual drift results in the three cases is presented in Table 2. Both retrofitting techniques resulted in a smaller drift compared to the as-built case. However, the early increase in the concrete strength associated with using SMA hoops resulted in a drift reduction of approximately 12% compared to the maximum drift in the case of using CFRP wraps. The decrease in the demands on the longitudinal steel reinforcement in the case of the column retrofitted with SMA hoops resulted in a 50% reduction in the residual drift compared to the case when the CFRP wraps were used. The hysteretic behavior shown in Fig. 8 illustrates that the SMA retrofitted column experienced did not experience any stiffness or strength degradation like the other two columns. The active confining pressure resulted in an early increase in the concrete strength and therefore delayed the damage of the concrete and/or steel reinforcement.

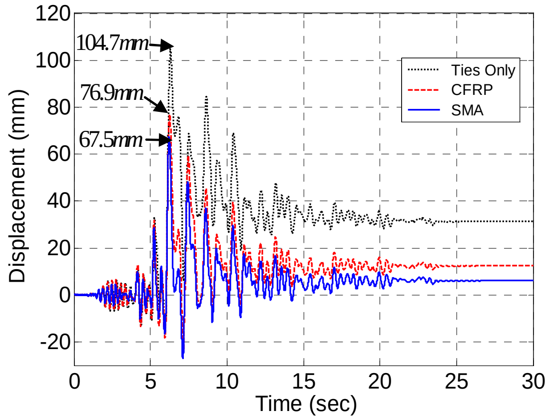


Figure 7 Displacement time histories of the columns retrofitted with SMA hoops, CFRP wraps, and internal steel ties under the scaled 6604 Cerro Prieto record from the 1980 Victoria earthquake, Mexico.

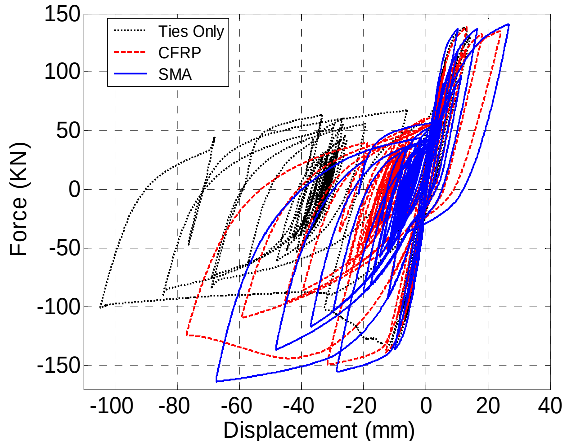


Figure 8 Force displacement relationships of the columns retrofitted with SMA hoops, CFRP wraps, and internal steel ties under the scaled 6604 Cerro Prieto record from the 1980 Victoria earthquake, Mexico.

Table 2 Maximum and residual drifts of the retrofitted columns under a scaled record from the 1980 Victoria earthquake, Mexico.

	Ties only	**CFRP**	**SMA**
Max drift (%)	7.75	5.70	5.00
Residual drift (%)	2.31	0.91	0.45
Ratio of the max. drifts	**CFRP/Ties only**	**SMA/Ties only**	**SMA/CFRP**
	0.74	0.65	0.88

6. CONCLUSION

A new active confinement retrofitting technique using pre-strained SMA hoops was investigated analytically in this study and compared with traditional passive confinement using CFRP wraps. An experimentally tested RC column from the literature was adopted in this study to validate the analytical results. A finite element model was developed for the column using OpenSees and subjected to displacement-controlled cyclic loading and seismic excitation. The compression stress-strain behaviors of passively and actively confined concrete using CFRP wraps and SMA hoops, respectively were implemented in the finite element model. A comparison was conducted between the column behaviors when retrofitted with SMA hoops and CFRP wraps. The results of the cyclic loading analysis indicated an increase in the SMA retrofitted column strength by approximately 34% compared to that of the CFRP retrofitted column. The maximum compressive strain experienced by the concrete and steel of the SMA retrofitted column was reduced by 70% and 65%, respectively compared to that was observed in the case of the column wrapped with CFRP. When the column model was subjected to a scaled record from the 1980 Victoria earthquake, Mexico, it was illustrated that the early increase in the concrete strength associated with using SMA hoops resulted in a drift reduction of approximately 12% compared to the case when CFRP wraps were used. Furthermore, the SMA retrofitted column exhibited less residual drift and stiffness/strength degradation compared to the column wrapped with conventional CFRP.

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