JSEE Vol. 26, No. 4, 2024 DOI: 10.48303/jsee.2024.2033154.1104

Research Note

A Review of Superelastic Shape Memory Alloy Applications for Enhancing Concrete Columns Behavior

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Received: 20/06/2024
Revised: 08/07/2024
Accepted: 14/07/2024

ABSTRACT

Shape memory alloy (SMA) is known as an attractive metallic material that illustrates two unique properties. First, the shape memory effect (SME) refers to the capability of high recovery stress (pre-stress) in the martensitic phase by heating. Second, the superelasticity effect (SE) refers to the recovery of its original shape after stress removal in the austenite phase. There are three main categories of SMA consisting of Cu-based, Fe-based, and Ni-Ti. Recently, due to the economic concern, especially the Ni-Ti-based, the use of these materials is very limited in civil engineering applications. The objective of this paper is to examine the potential of SMAs in enhancing the performance of concrete columns, specifically in terms of strength, durability, and resistance to seismic activity. Through analysis of relevant studies, this review discusses the various techniques involving SMAs, evaluates their effectiveness, and addresses the associated challenges. The findings of this review provide valuable insights into the advantages and limitations of employing SMAs to improve the behavior of concrete columns, serving as a valuable resource for researchers and engineers engaged in the design and construction of resilient structures.

Keywords:
Shape memory alloy; SMA; RC Column; Plastic hinge region; Ni-Ti; Cu-based SMA; Iron-based SMA

How to cite the article:
Sabbaghian, M., Kabir, M. Z. and Amooie, M. (2024). A review of superelastic shape memory alloy applications for enhancing concrete columns behavior. *Journal of Seismology and Earthquake Engineering*, *26*(4), 87-97. doi: 10.48303/jsee.2024.2033154.1104

1. Introduction

Repair, retrofitting, and rehabilitation are the three most used terms in strengthening structures. These terms are different according to their functions and characteristics. Typically, the repair is a process in which the performance of a structure is increased to a minimal degree from its original performance or to meet a need to provide an aesthetic appearance without increasing performance (ACI, 1993). On the other hand, retrofitting is a process intended to improve the performance of structures such as bending, shearing, ductility, service life, fatigue life, etc. The performance improved by retrofitting is significant compared to the initial performance of the structural members for which the members were designed (Alaee & Karihaloo, 2003). Rehabilitation is considered a process to recover the strength or performance lost in structures due to various destructive factors (Benyahia & Ghrici, 2018). Promising strengthening techniques for retrofitting and rehabilitation include externally bonded steel plates, concrete jacketing, fiber-reinforced polymer (FRP) (Daneshvar et al., 2020), external prestressing/ external bar strengthening techniques (Sena-Cruz et al., 2015), and ultra-high-performance concrete (UHPC) laminate (Sabbaghian & Kheyroddin, 2020, 2022). It is necessary to strengthen the structural components through repair, retrofitting, and rehabilitation during the service life for which the members are designed.

Furthermore, shape memory alloys (SMAs) are used to strengthen RC structures due to their special properties, i.e., super-elasticity effect (SE) and shape memory effect (SME) (Czaderski et al., 2014; Zareie et al., 2020). The SME feature can recover the plastic strain by heating, and the SE feature means the ability to recover their original, undeformed shape after load removal. In addition, the SMAs show other advantages, such as corrosion resistance and an easy installation process, especially in prestressed cases (Raza et al., 2022). Therefore, SMAs are an attractive choice to apply in existing and new structures (Sabbaghian & Kabir, 2023a, 2023b, 2024).

Concrete confinement enhanced the column's ductility and capacity of load bearing, which leads to preventing the collapse of structures exposed to severe loading conditions. So far, two main techniques have been introduced for concrete confinement, consisting of passive and active confinement. The fiber-reinforced polymer (FRP) warps and externally bounded steel jackets are the widespread techniques used to supply additional passive containment (Haroun & Elsanadedy, 2005; Priestley et al., 1994a; Priestley et al., 1994b). In this approach, the pressure of confinement is generated by the hoop stresses that develop in the transverse direction reinforcement as a result of the concrete lateral expansion under loading (i.e., the Poisson effect). One of the problems of passive confinement is the occurrence of damage on the concrete surface, while in active confinement there is no concrete expansion; therefore, concrete is maintained continuously, and pressure is implemented as a lateral prestressing pressure. Several researches showed that active confinement increased concrete ductility under compression and delayed concrete damage. A good illustration of this is the Gamble et al. (1996) work that had focused on using prestressed strands and tensile steel strips for confining full-scale RC circular columns. Saaticoglu and Yalcin (2003) investigated the seismic behavior of full-scale rectangular and circular RC columns confined by using external prestressing strands. Furthermore, prestressed FRP strips/straps were introduced to confine RC columns actively (Nesheli & Meguro, 2006; Yamakawa et al., 2004). Applying active confinement by using FRP strips or steel strands has disadvantages such as special mechanical tools, high time-consuming, and labor to apply sufficient prestressing force, which are serious concerns regarding the confinement of technical practice.

To tackle these problems, unconventional methods were proposed to provide active confinement. For instance, Yan et al. (2005) suggested using FRP jackets with expansive cement concrete to apply confinement pressure on square or rectangular RC columns. Another positive approach would be to promote SMAs, which show excellent resistance to corrosion and fatigue, high damping capacity, ability to recover large deformations, and high strength compared to steel bars (Ozbulut et al., 2011). A group of SMAs that illustrate superelastic properties is called SEA. This type of material can enhance the seismic behavior of structural components (Li et al., 2015; Saiidii & Wang, 2006). Although Ni-Ti-SEA was used in the most of research, limited due to losing superelasticity at low temperatures, low machinability, and being very expensive (Zhang et al., 2008). In recent decades, using Cu-Al-Mn (CAM) SEAs developed to resolve these obstacles mentioned above and replaced Ni-Ti SEAs. CAM-SEAs demonstrate stable superelastic behavior under high strain rates of up to 1.5 s and at temperatures as low as 40°C. In addition, unlike other Cu-based compounds such as Cu-Al-Be, they do not contain destructive components and can be easily machined (Araki et al., 2011).

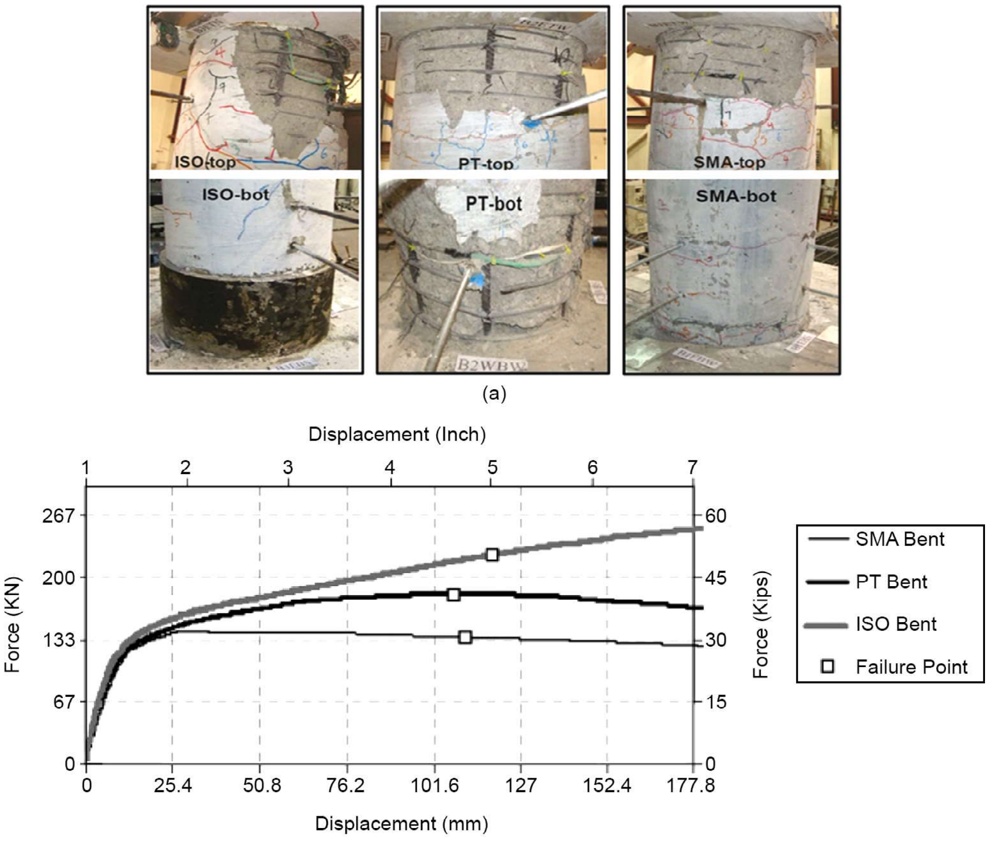
2. Utilization of SMA Materials in Columns

The SMAs show two unique features consisting of the superelastic effect (SE) and shape memory effect (SME). The first refers to the ability to undergo large deformation and recover its deformation after stress removal, and the second feature refers to the ability to recover the plastic deformation by heating. In this section, the previous studies that focused on the SE features of SMAs and the application of these materials in RC columns are collected.

Saiidi and Wang (2006) investigated the seismic behavior of RC columns with SMA reinforcements. In this study, two important objectives were considered. The primary target was evaluating the possibility of using SMA rebar in the column plastic hinge region to reduce the residual displacement of RC columns. The second one was examined the SMA-reinforced column repaired with engineered cementitious composites (ECC) under a seismic loading test. Two ¼ scale RC columns were tested on a shake table, and then the SMA column was repaired with ECC materials. The result demonstrated that the SMA-reinforced column recovered approximately 100% plastic deformation and decreased the residual deformation. This technique increased the ductility and strength of columns. Furthermore, using ECC can decrease the damage in the RC column. Saiidii et al. (2009) proposed a new form using a combination of Ni-Ti SMA and ECC in the plastic hinge zone of RC bridge columns and evaluated the super-elastic characteristic of SMAs under quasi-static reversed cyclic loading. The results show that the average ratio of residual to maximum displacement in the SMA-ECC column was 1/6 of that of the RC column and 1/2 of that of the SMA column. The highest thrust capacity and the lowest damage were observed in the SMA-ECC column. In this study, residual displacement, stiffness, and strength of the column decreased, but the ductility ratio increased. Cruz Noguez and Saiidi (2011, 2012) performed a shake table test at the University of Nevada, Reno, on the quarter-scale 4-span bridge to study conventional and advanced details of the plastic hinges at the bottom of the RC columns. These details consist of conventional reinforced concrete (control), elastomeric pads embedded into columns (ISO), post-tensioning tendons (PT), ECC, and Ni-Ti SMAs. The data illustrated that the bridge column utilized SMA/ECC in the plastic hinge region, significantly decreasing the permanent displacements and damage. Furthermore, the control detail showed remarkable damage due to concrete spalling and transverse and longitudinal reinforcement rupture. Figure (1) shows the comparison of cracking in the bottom plastic hinge region of ISO, PT, and SMA specimens and the force-displacement curve of pushover analysis, respectively.

Varela and Saiidi (2014) investigated using Cu-Al-Mn SMA and ECC in the plastic hinge region of a quarter-scale bridge under a seismic loading test by shaking table. ECCs can decrease the damage, and innovative column demonstrated high self-centering capabilities. The residual deformation was decreased using this technique. Analytical and experimental data showed that the combination of ECC and SMA in the column's plastic hinge zone could be operational after severe seismic conditions. Figure (2) illustrates the tensile cracking pattern after runs7 and the SMA bars that were broken after removing the cover of the concrete.

Shrestha et al. (2015) carried out an FE model in OpenSees software to evaluate the effectiveness of using Ni-Ti SMA and Cu-Al-Mn SMA combination with ECC materials in the plastic hinge zone of RC columns (Table 1) under the shaking table. The results of the analytical study showed that the stated method provided significant



(a)

(b)

Figure 1. (a) Comparison of cracking in the top and bottom plastic hinge region and (b) Force-displacement curve under pushover analysis (Cruz Noguez & Saiidi, 2011).

(a)

(b)

Figure 2. (a) Cracking pattern at the bottom plastic hinge zone during runs 7 and (b) Ruptured SMA bars (Varela & Saiidii, 2014).

Table 1. Details of plastic hinge reigns in columns (Shrestha et al., 2015).

Bridge Type	Reinforcement Details	Plastic Hinge Zone
RC Bridge	12-10 mm Diameter Steel Bars	Conventional Concrete
PT Bridge	8-10 mm Diameter Steel Bars with Post-Tensioning Element	Conventional Concrete
Rubber Bridge	7-10 mm Diameter Steel Bars with Post-Tensioning Element	Rubber Element
NiTi Bridge	9-13 mm Diameter NiTi Bars	ECC
CuAlMn Bridge	9-19 mm Diameter CuAlMn Bars	ECC

re-centering capabilities and reduced the column damages. Figure (3) shows the longitudinal and transverse residual drifts of specimens that limited to 1% drift of all scaled near-fault ground motions.

Hosseini et al. (2015) carried out a test using Cu-Al-Mn SMA and ECC materials in the plastic hinge zone of columns under seismic loading (quasi-static reversed cyclic loading). According to Figure (4), a new column constructed with a pre-fabricated ECC tube, which was reinforced with the transverse and longitudinal steel rebar in total or partial SMA replacement at the plastic hinge zone and filled with conventional concrete, was proposed in this experimental study. Utilizing Cu-based SEA bars can recover up to 12% inelastic strain. ECC materials showed excellent bonding with steel, shear resistance, energy absorption, and tensile ductility. Also, it exhibited lower crack widths and permeability compared to conventional concrete. According to Table (2), the result showed that although the proposed column reduced stiffness, energy absorption, and lateral strength, the permanent deformations in columns were also decreased remarkably (over 90%).

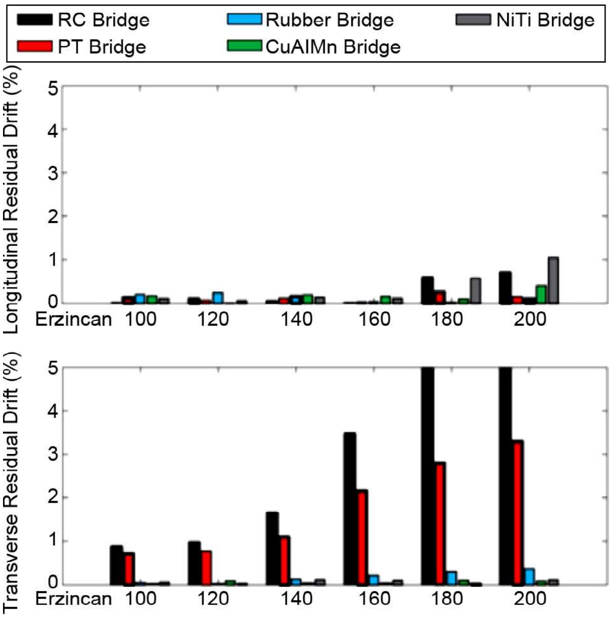
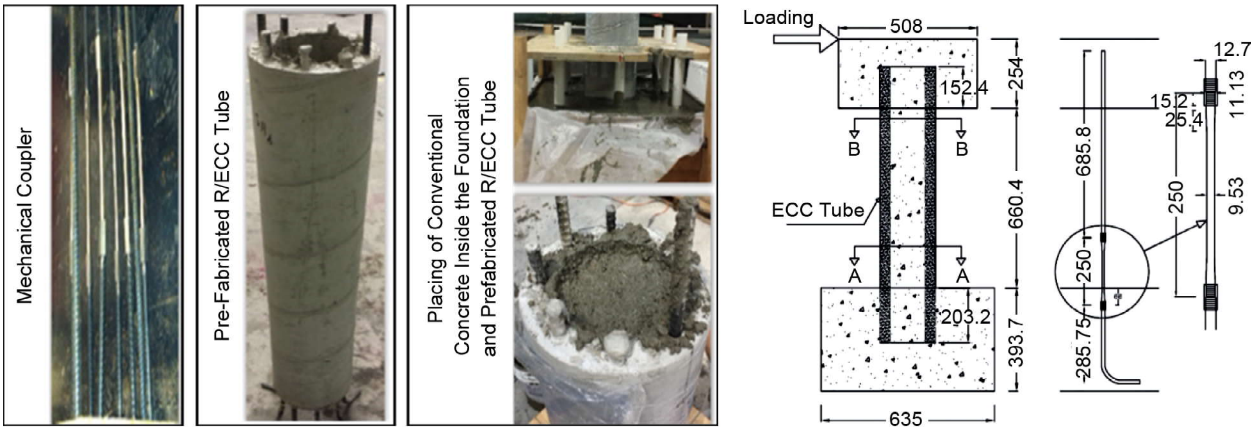


Figure 3. Longitudinal and transverse residual deformation of tested specimens (Shrestha et al., 2015).

Tazarv and Saiidi (2016) used three low-damage materials, such as super-elastic Ni-Ti SMA, engineered cementitious composite (ECC), and ultra-high-performance concrete (UHPC), for developing a precast column (with the HCS acronym) according to Figure (5) The precast column showed better seismic performance compared with the cast-in-place (CIP) column with conventional materials. According to this data, the cast-in-place column damage is significantly higher



(a) (b)

Figure 4. (a) Details of the proposed column and (b) Manufacturing process (Hosseini et al., 2015).

Table 2. Comparison of tested columns in 7% drift (Hosseini et al., 2015).

Speciment	RC-Column		HFA-Column		HFA-Tube		M45-Tube		HFA-Tube-SEA		HFA-Tube-PSEA	
Initial Stiffness, E_0 (kNm^{-1})	1288	(0.00)	11.29	(-12.38)	949	(-26.32)	10.30	(-20.01)	865	(-32.88)	853	(-33.81)
Drift at Yield, δ_y (%)	1.75	(0.00)	2.30	(32.00)	2.94	(68.26)	2.53	(44.93)	2.28	(30.47)	2.50	(43.41)
Yield Force, F_y (kN)	24.38	(0.00)	27.95	(14.65)	27.20	(11.55)	27.45	(12.58)	20.10	(-17.55)	22.67	(-7.03)
Drift at Maximum, δ_m (%)	2.97	(0.00)	3.99	(34.51)	4.01	(35.12)	3.97	(33.99)	4.00	(34.93)	3.73	(25.83)
Maximum force, F_m (kN)	27.35	(0.00)	31.76	(16.12)	30.26	(10.64)	30.95	(13.18)	22.83	(-16.52)	24.94	(-8.79)
Drift at Ultimate, δ_u (%)	7.09	(0.00)	7.15	(0.96)	7.15	(0.85)	7.11	(0.42)	7.01	(-1.13)	4.99	(-29.59)
Ultimate Force, F_u (kN)	23.25	(0.00)	26.99	(16.12)	27.72	(10.64)	26.31	(13.18)	19.41	(-16.52)	21.20	(-8.79)
Permanent Drift, δ_p (%)	4.25	(0.00)	3.94	(-7.25)	3.63	(-14.62)	3.94	(-7.33)	0.37	(-91.18)	2.84	(-33.05)
Energy Absorption, E_a (kN m)	9.51	(0.00)	9.67	(1.67)	8.36	(-12.12)	8.93	(-6.17)	3.43	(-63.97)	5.65	(-40.63)

than the precast counterpart; in other words, the HCS column occurred just ECC cover spalling after 12% drift ratio cycles. Moreover, the residual deformation of HCS was approximately 80% lower than the CIP column. The ductility and strength of the HCS column increased by occurring stiffness degradation.

Varela and Saiidii (2016) proposed an unprecedented idea of precast modules designed as disassembly to provide resilient bridge columns. The super-elastic SMAs and ECC material were utilized to access resiliency due to minimizing permanent drift and damage, respectively. That idea caused the rest of the column to remain elastic. Two one-fourth scale columns by precast modules in different types of SMA bars Cu-Al-Mn (CAM) and Ni-Ti were designed. According to Figure (6), the precast modules consist of prefabricated concrete-filled fiber-reinforced polymer tubes and prefabricated ECC plastic hinges. At first, each of the specimens was tested under simulated earthquakes, disassembling and reassembling of the modules wer done after cracking then the specimens were retested to investigate the effect of recycling column com-ponents. The results depicted that the reassembled specimen showed the similar behavior compared to the first specimen but was more flexible.

Hosseini and Gencturk (2019) assessed the behavior of ECC and Cu-Al-Mn super-elastic SMAs in bridge piers under seismic loading.

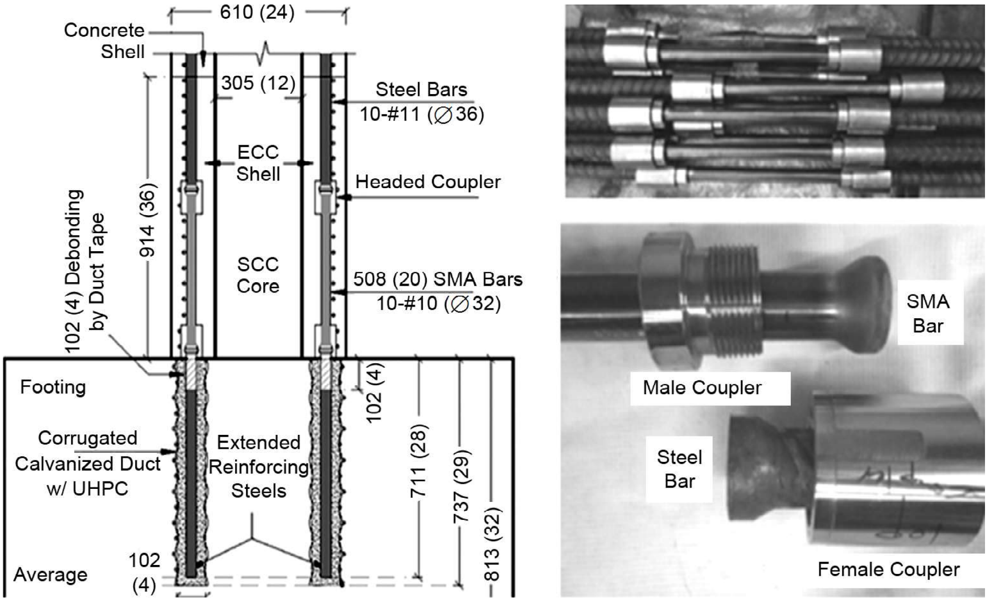


Figure 5. Base-column connection detail (Tazarv & Saiidi, 2016).

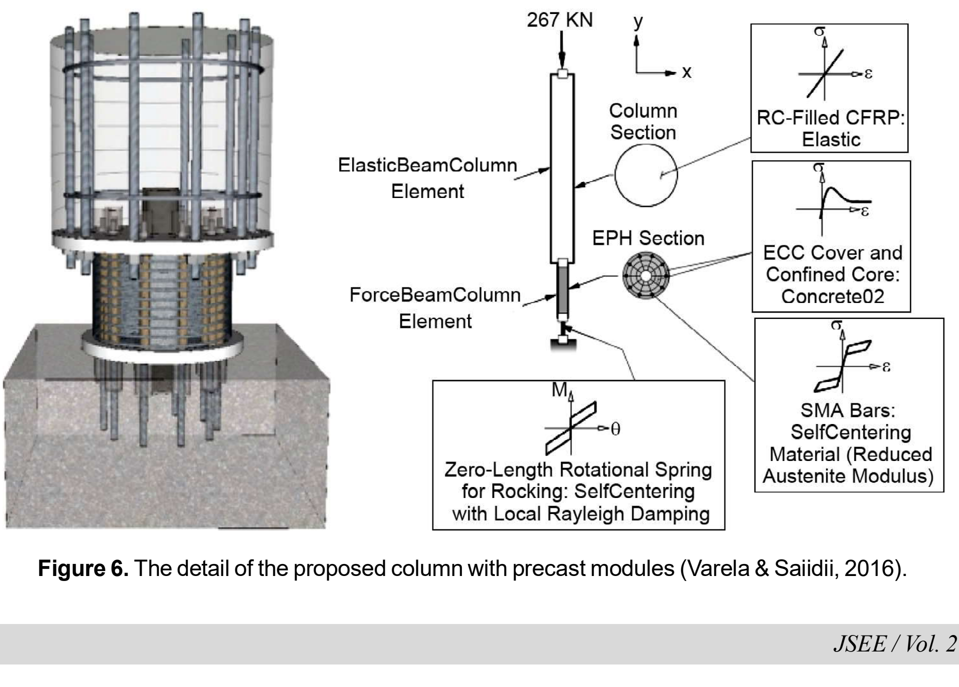


Figure 6. The detail of the proposed column with precast modules (Varela & Saiidii, 2016).

According to Figure (7) and (Hosseini et al., 2015), five columns with different details, including a reference specimen and five various specimens' configurations with ECC and SMA rebar, are modeled in a commercial FEM package, ATENA (Bures et al., 2017). Figure (7b) illustrated the SMA material model and the bond model between steel and SMA rebar. The behavior of SMA rebar and ECC materials is simulated using a one-dimensional constitutive model and a constitutive model for concrete with smeared reinforcement. The FEM results are compared with the experimental study (Hosseini et al., 2015). The shape of the hysteresis curves, permanent deformation, post-peak degradation, and lateral strength is investigated.

Xing et al. (2020) proposed a new approach for strengthening columns by near-surface mounting (NSM) of Ni-Ti SMA bars and CFRP jackets for taking advantage of the super-elastic properties of SMA materials, see Figure (8). Seven specimens were considered in order to investigate the impact of bar ratio and types (SMA and CFRP) and the effect of CFRP jacketing and then tested under quasi-static reversed cyclic loading with constant axial force. The flexural behavior, ductility, and lateral strength

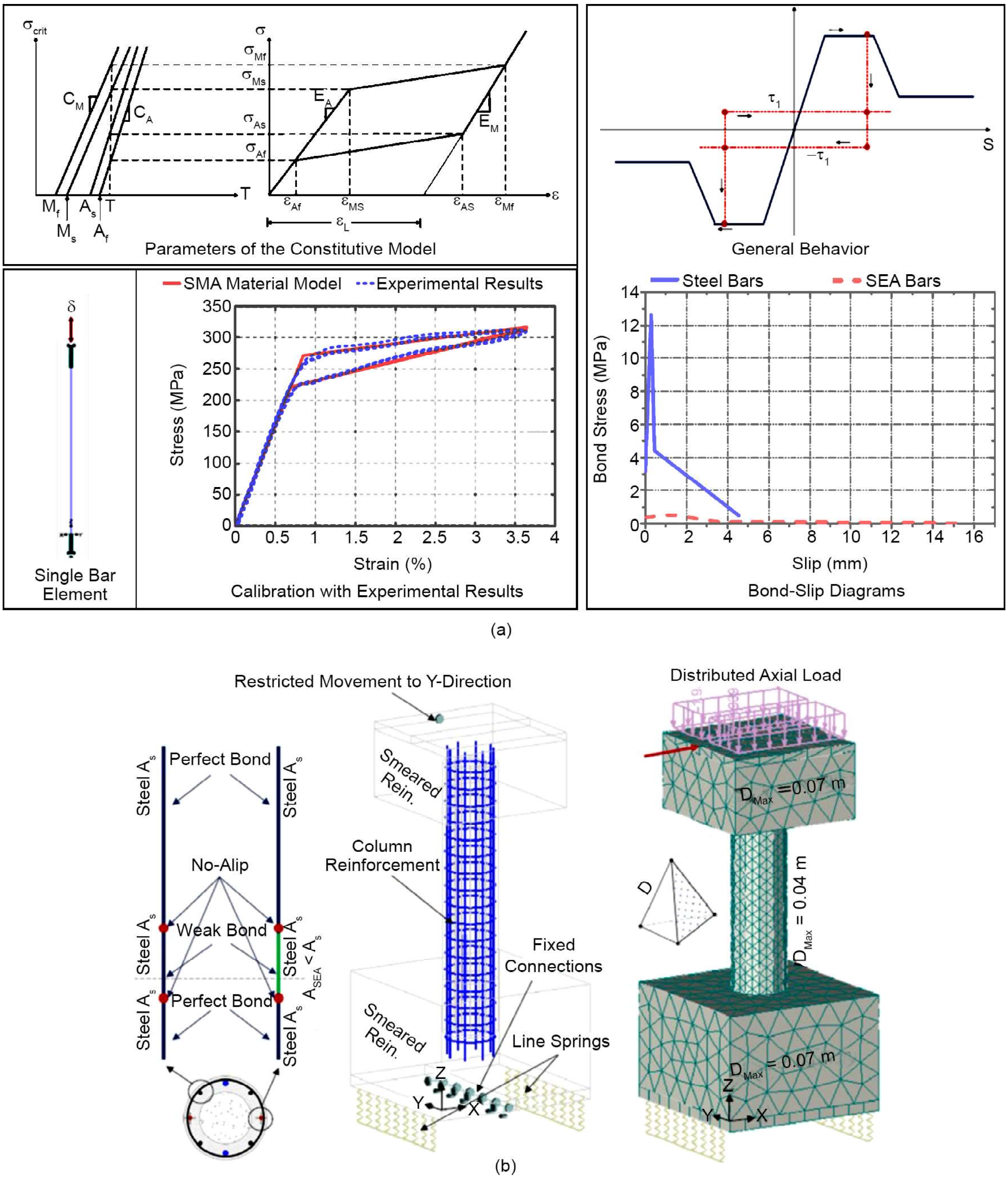


Figure 7. (a) SEA material and bond model and (b) Details of FEM modelling (Hosseini & Gencturk, 2019).

of columns strengthened using NSM bars were increased without stiffness degradation. Moreover, the combination of NSM bars and CFRP jacketing showed better lateral performance than other specimens due to providing additional confinement at the critical point of the column section.

Gholipour and Billah (2022) have modeled the scaled column using ultra-high-performance fiber-reinforced concrete (UHPFRC) jackets and SMA bars in LS-DYNA software according to Figure (9a) and have evaluated it under lateral impact loads of different velocities. Axial load ratio (ALR), impact velocity (V_{imp}), the thickness of the UHPFRC jacket (tU), and SMA bars type were the main considered parameters in this numerical paper to assess the column performance.

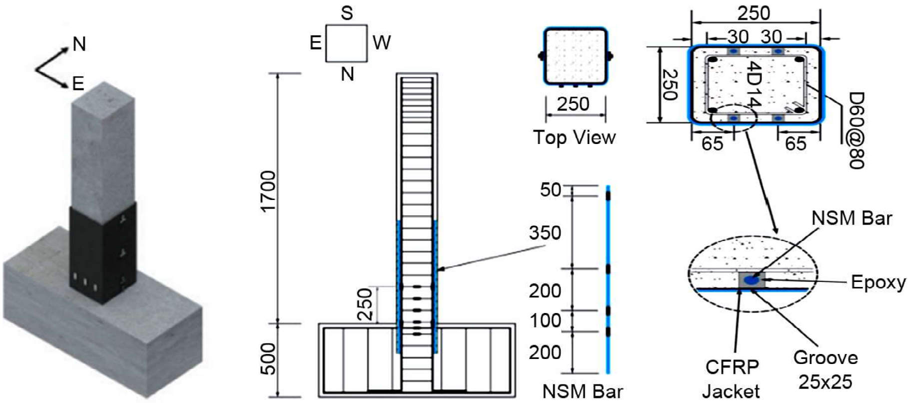


Figure 8. Proposed approach for strengthening RC column and strain gages location (Xing et al., 2020).

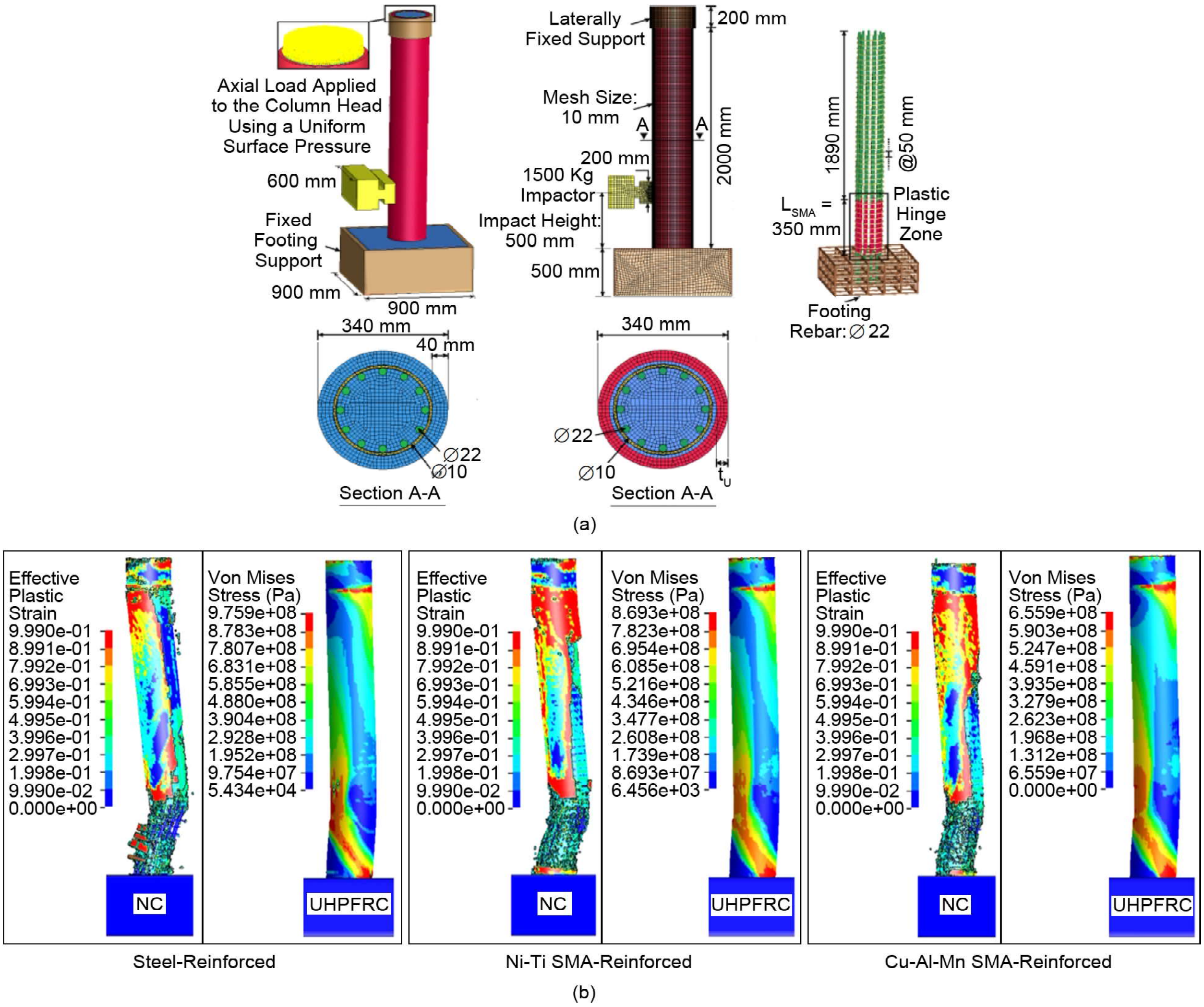


Figure 9. (a) RC column detail by LS-DYNA; b) Failure behavior (V_{imp} = 15 m/s.) (Gholipour & Billah, 2022).

The results showed that the lateral strength of the specimen was dependent on the ALR value. It was shown that the range ALR between 0.1 and 0.15 had a positive influence; on the contrary, as the ALR value becomes greater than its critical value of 0.125, a negative impact on SMA-reinforced UHPFRC columns lateral strength was detected. Furthermore, the UHPFRCC jacket thickness of 60 mm was the optimum value based on the performance of tested specimens. Figure (9b) illustrates the failure behavior of specimens with various configurations.

3. Conclusions and Remarks

Shape memory alloys (SMAs) are increasingly popular for strengthening reinforced concrete (RC) columns due to their unique properties of superelasticity effect (SE) and shape memory effect (SME). The SE feature facilitates enhanced self-centering behavior in columns, while the SME property makes SMAs suitable for prestressing RC columns, overcoming challenges associated with conventional techniques. Despite being introduced years ago, the utilization of SMAs in civil construction applications remains limited. This paper reviewed experimental and analytical studies focusing on exploiting the superelastic properties of SMAs in column strengthening. The majority of research demonstrated the positive impact of SMA wire and spirals in actively confining RC columns or concrete cylinders, leading to improved strength, ductility, and stiffness. Utilizing SMA longitudinal or spiral bars also showed promising behavior in severe seismic conditions, recovering deformation after stress removal, reducing residual deformation, and increasing ductility.

However, stiffness degradation and occasional reductions in column strength were observed. Limitations in the literature were identified, and recommendations for future research were proposed, including investigating active confinement on columns with rectangular cross-sections, exploring alternative activation approaches for SMA spirals, and evaluating systems to mitigate strength or stiffness degradation when utilizing super-elasticity features.

The authors found limitations in the literature related to using SMAs in columns and have some recommendations, such as:

- Investigation of the effect of active confinement on columns with rectangular cross-sections
- Examination of other approaches of activating SMA spirals to apply maximum confinement
- Evaluating systems to maintain the strength or stiffness degradation when the super elasticity features are used

Disclosure Statement

No potential conflict of interest was reported by the authors.

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