Innovative SMA-Based Retrofitting Techniques for Concrete Columns

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Abstract

Shape Memory Alloys (SMAs) are advanced metallic materials that exhibit two distinct behaviors: the Shape Memory Effect (SME), which enables the recovery of pre-stress through heating in the martensitic phase, and the Superelasticity (SE), which allows for reversible strain recovery upon unloading in the austenitic phase. The main families of SMAs include Cu-based, Fe-based, and Ni-Ti alloys. However, the high cost of Ni-Ti limits its widespread use in civil engineering applications. This review paper synthesizes and compares previous experimental and numerical studies on the use of SMAs as longitudinal or transverse reinforcements in reinforced concrete (RC) columns and cylinders. This paper is divided into two main sections that introduce the research using the SE (enhancing self-centring behavior) and SME (in pre-stressing application) features of SMA in the last decades. The results showed that using SMAs in the plastic hinge region of the column was an excellent idea for reducing residual deformation and increasing the ductility of the column under seismic loading. The results related to utilizing SME features in the column enhanced its stiffness and lateral strength. In contrast, in SE cases, the existence of SMA showed reverse consequences, causing a decrease in the column's stiffness, although its strength occasionally declined. It underscores the need for further research toward cost-effective alloys, improved bonding, and the development of design guidelines for SMA-reinforced RC structures.

Keywords

Retrofitting, Concrete columns, Shape memory alloy, Superelasticity, Shape memory effect.

1. Introduction

Strengthening reinforced concrete (RC) structures is crucial to extend their service life and enhance performance under increasing demands, such as seismic loads. Strategies generally fall into three categories: repair, which restores minor deterioration; rehabilitation, which recovers lost capacity; and retrofitting, which significantly enhances performance parameters such as ductility, strength, fatigue life, and service life [1]. Over the past decades, conventional retrofitting methods—including steel plate bonding, concrete jacketing, externally bonded fiber-reinforced polymers (FRPs), external prestressing, and ultra-high-performance concrete (UHPC) laminate—have been widely applied [2-7]. While effective, these approaches often involve high labor demand, specialized tools, corrosion susceptibility, or limited long-term efficiency, motivating the search for more advanced solutions [8, 9].

The confinement of RC columns plays a crucial role in improving ductility, delaying failure, and enhancing load-bearing capacity under severe loading conditions. FRP wraps and steel jackets provide passive confinement, but they engage only after lateral expansion occurs, leading to early surface damage [10-12]. Several studies have demonstrated that active confinement enhances the ductility of concrete under compression and delays the onset of concrete damage. A good illustration of this is the Gamble et al. [13] work that had focused on using pre-stressed strands and tensile steel strips for confining full-scale RC circular columns. Saaticoglu and Yalcin [14] 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 [15, 16]. Applying active confinement by using FRP strips or steel strands has disadvantages such as the need for special mechanical tools, high time-consuming, and labour-intensive to apply sufficient pre-stressing force, which are serious concerns regarding the confinement of technical practice. These drawbacks have stimulated interest in shape memory alloys (SMAs), which can provide active confinement without the need for mechanical post-tensioning equipment [17].

SMAs exhibit two unique behaviors: the shape memory effect (SME), which allows recovery of plastic strains upon heating, and superelasticity (SE), which enables self-recovery of large deformations upon unloading [17-19]. The SMAs show other advantages, such as corrosion resistance and an easy installation process, especially in pre-stressed cases. Therefore, SMAs are an attractive choice to use in existing and new structures.

Although many studies have investigated different confinement and strengthening techniques for RC columns, systematic reviews of shape memory alloy applications remain limited. Previous reviews have generally summarized individual studies without providing a critical comparison of SE and SME behaviors and their effects on RC column behavior, incorporating the most recent findings, comparing the performance of different SMA alloys (Ni-Ti, Cu-SMA, Fe-SMA), or discussing design guidelines and alloy-specific implications. This paper addresses these gaps by consolidating the available experimental and numerical research and clarifying the practical role of SMAs in retrofitting and rehabilitation. The review focuses on RC columns, beginning with a discussion of fundamental SMA properties, followed by separate examinations of SME-based and SE-based applications, along with a synthesis of key challenges, design considerations, and directions for future research.

2. Shape Memory Alloy Overview

SMAs, often referred to as smart alloys, were first reported by Arne Ölander in 1932 [20]. The term "shape memory" was later introduced by Vernon in 1941 [21]. The unique potential of these materials was recognized in 1962 when Buehler and Wang demonstrated the shape memory effect in a nickel–titanium alloy, now widely known as Nitinol [22]. Since then, SMAs have attracted attention in diverse sectors, including aerospace, automotive, biomedical devices, robotics, and civil engineering [23-26].

Although copper- and iron-based SMAs such as Cu–Al–Ni, Cu–Zn–Al, and Fe–Mn–Si are cost-effective and readily available, their mechanical instability and inconsistent thermal performance often limit their use. In contrast, Ni-Ti alloys exhibit superior reliability and thermo-mechanical behavior, which has made them the dominant SMA for engineering applications [27-30].

2.1 Shape Memory Effect and Superelasticity

SMAs can exist in three phases: austenite, twinned martensite, and detwinned martensite, according to Figure 1 [31]. Transformation between these phases is the foundation of their two unique behaviors: the SME and SE. In SME, deformation in the martensitic state is recovered upon heating. Transformation begins at the austenite start temperature (A_s) and completes at the austenite finish temperature (A_f). Cooling reverses the process at the martensite start (M_s) and finish (M_f) temperatures [32] (see Figure 2). In SE, deformation is recovered upon unloading at temperatures above A_f. This enables large strain recovery without heating, which is particularly valuable for seismic applications [33, 34]. Figure 1 illustrates the basic crystal structures of the austenite and martensite phases, while Figure 2 shows the thermal hysteresis and transformation cycle of Ni-Ti SMAs [31-35].

Ni-Ti-based SMAs are the most studied, but they face challenges such as high cost, limited machinability, and degradation of superelasticity at low service temperatures [36]. To address these issues, researchers have investigated Cu–Al–Mn alloys, which demonstrate stable superelastic behavior at wider temperature ranges and are easier to machine [37]. More recently, Fe-based SMAs have gained attention for their low cost and promising performance in structural strengthening. However, their use in RC confinement remains relatively limited, highlighting a need for further comparative studies.

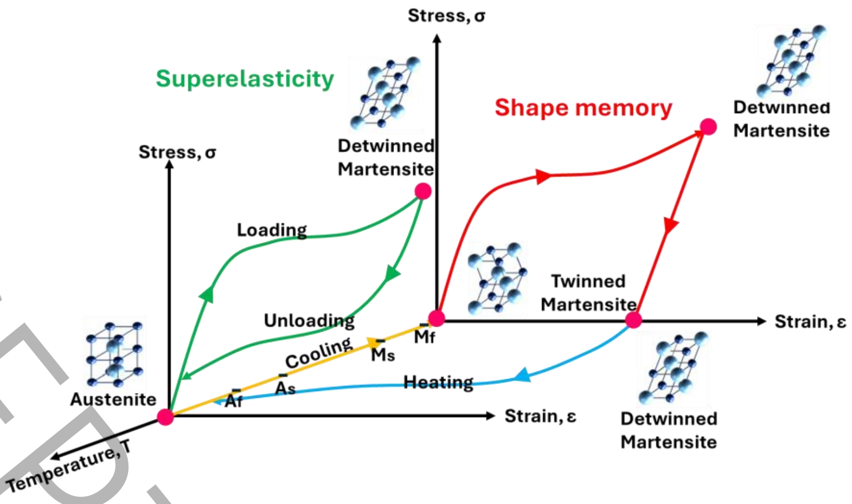

Figure 1 The crystal structures and phases of SMAs.

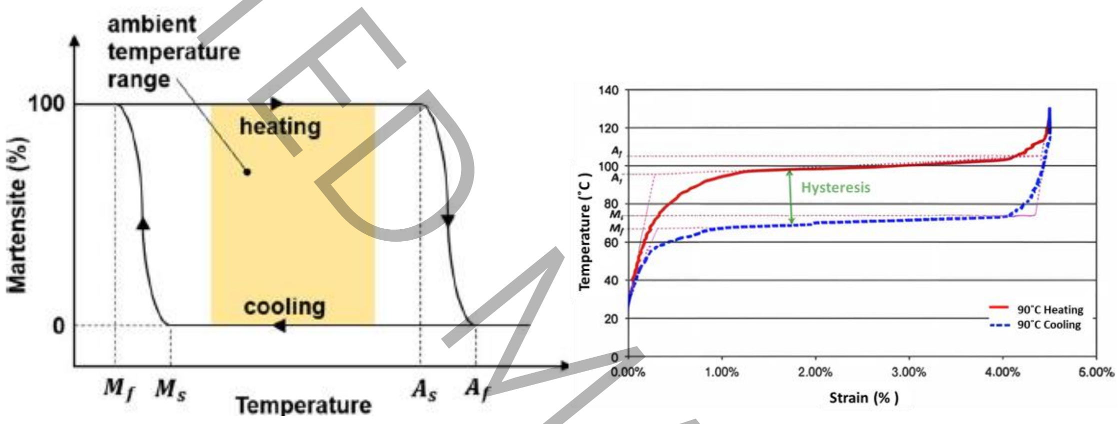

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Figure 2 a) Thermal hysteresis of SMAs [٣٨] **b) The phase transformation of Ni-Ti SMA** [31-35].

2.2 Active Confinement Using SMA

Active confinement in RC columns can be achieved through the shape memory effect. When deformed in the martensitic phase, SMAs store residual strains. Upon heating above A_f, the alloy attempts to return to its original shape, generating significant recovery stress. If the SMA is externally restrained, this stress translates into prestressing confinement pressure on the surrounding concrete [38].

A practical illustration is the use of SMA spirals around the plastic hinge region of RC columns (Figure 3). In this method, Ni-Ti–Nb wires are prestrained in the martensitic phase, wrapped as spirals, and then heated to activate recovery. The wires contract, applying continuous confinement to the column. Due to their wide thermal hysteresis, Ni-Ti–Nb alloys are particularly suitable for structural confinement in variable ambient conditions. For example, Dommer and Andrawes [39] reported transformation temperatures of $A_s = 68^{\circ}C$ and $A_f = 76^{\circ}C$, with M_s and M_f below $-105^{\circ}C$, ensuring stability across a broad range of environments. However, despite encouraging experimental outcomes, applications of SMA-based active confinement in RC columns remain limited. Most studies focus on Ni-Ti alloys, with fewer investigations into Cu–SMA and Fe–SMA alternatives. Comparative evaluations of these alloys in terms of cost, durability, and confinement efficiency are still lacking, underscoring the need for systematic reviews such as the present work.

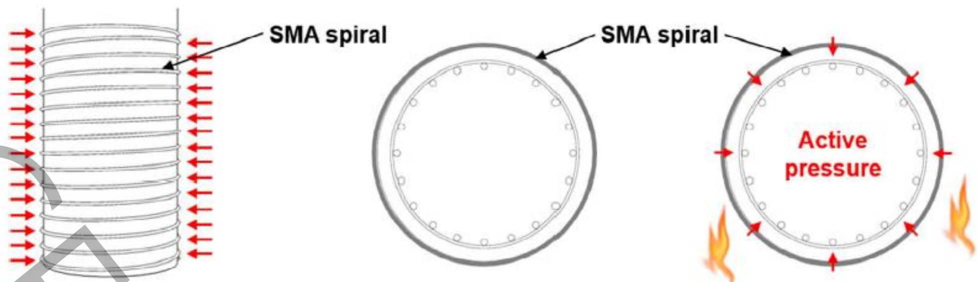

Figure 3 Applying active confinement by using SMA spirals [39]**.**

3. Applications of SMA Materials in Columns

SMAs possess two distinctive characteristics that make them highly attractive for structural applications: the SE and the SME. SE enables SMAs to undergo large reversible strains and recover their original shape upon unloading, while SME allows recovery of plastic deformation through heating. These unique behaviors have been increasingly exploited in reinforced concrete columns to improve seismic performance, enhance ductility, and reduce residual deformations. In the following subsections, the applications of SMAs in columns are discussed separately, first from the perspective of their SE behavior and then with emphasis on their shape memory response.

3.1. Focusing on the Superelastic Effect of SMAs

Several studies have investigated the use of SE-SMAs in the plastic hinge region of RC columns to enhance seismic resilience. Saiidi and Wang (2006) [40] were among the first to examine the seismic response of RC bridge columns reinforced with SMA rebars. Their experiments on ¼-scale specimens demonstrated that integrating SMA bars in the plastic hinge zone could nearly eliminate residual deformations, with up to 100% recovery of plastic strain. The SMA-reinforced column also showed improved column ductility and strength and reduced damage when repaired with Engineered Cementitious Composites (ECC). In a subsequent study, Saiidi et al. (2009) [41] combined Ni-Ti SMA and ECC to evaluate the performance of bridge columns under quasi-static cyclic loading. Results indicated that the SMA–ECC column exhibited the least damage and the highest ductility among all tested configurations. The ratio of residual to maximum displacement in the SMA–ECC column was approximately one-sixth of that observed in conventional RC columns, confirming the excellent re-centering capacity of SE-SMAs. Extending this concept to large-scale bridge systems, Noguez and Saiidi (2012, 2013) [42, 43] conducted shake-table tests on a quarter-scale four-span bridge model incorporating SMA and ECC in the plastic hinge regions. Compared with conventional steel-reinforced and post-tensioned columns, the SMA/ECC system significantly reduced permanent displacements and surface cracking. Varela and Saiidi (2014) [44] investigated the combined use of Cu–Al–Mn SMA bars and ECC in the plastic hinge region of a quarter-scale bridge column tested on a shaking table. The inclusion of ECC effectively reduced surface cracking and spalling, while the SMA bars improved self-centering capability under cyclic loading. Both analytical and experimental results confirmed that the SMA–ECC system successfully minimized residual deformation and maintained functionality even after severe seismic excitation. Additionally, they evaluated the plastic hinge length of the Cu–Al–Mn SMA column and found it to be approximately 130 mm, consistent with half the SMA length above the footing, providing a useful reference for future design models of SMA-reinforced bridge columns. Shrestha and Hao (2014) [45] validated a numerical model of SMA-reinforced bridge piers using experimental data from shake table tests, followed by a parametric study on three prototype bridge bents with single and multiple piers reinforced with either steel or SMA bars in the plastic hinge regions. Incremental dynamic analyses demonstrated that SMA reinforcement substantially reduced residual displacements while maintaining comparable peak drift response to conventional steel-reinforced bents. Notably, steel-reinforced piers exhibited a rapid increase in residual drift following yielding, whereas SMA-reinforced piers displayed a gradual drift accumulation, confirming the superior re-centering ability of SMA bars. Nikbakht et al. (2015) [46] conducted an analytical investigation on precast segmental bridge columns reinforced with superelastic SMA bars combined with central post-tensioning (PT) strands (Figure 4). Through nonlinear static and time–history analyses, they compared self-centering, SMA-reinforced, and mild steel (MS)-reinforced columns under different PT levels (40% and 70% of the strand tensile stress). The results indicated that SMA-reinforced columns achieved greater energy dissipation and lower peak lateral displacements than self-centering columns without SMA reinforcement. Although the SMA columns exhibited lower stiffness and strength up to 6% drift, their seismic resilience and re-centering capacity were superior. Increasing the PT level enhanced overall strength and energy dissipation but had minimal influence on residual displacement. The influence of SMA bar size was also highlighted: larger-diameter SMA bars provided greater strength but lower stiffness and equivalent viscous damping, whereas smaller-diameter bars (10 mm) offered more balanced performance. These results highlight the effectiveness of SMA/PT hybrid systems in enhancing the seismic response of precast segmental bridge columns.

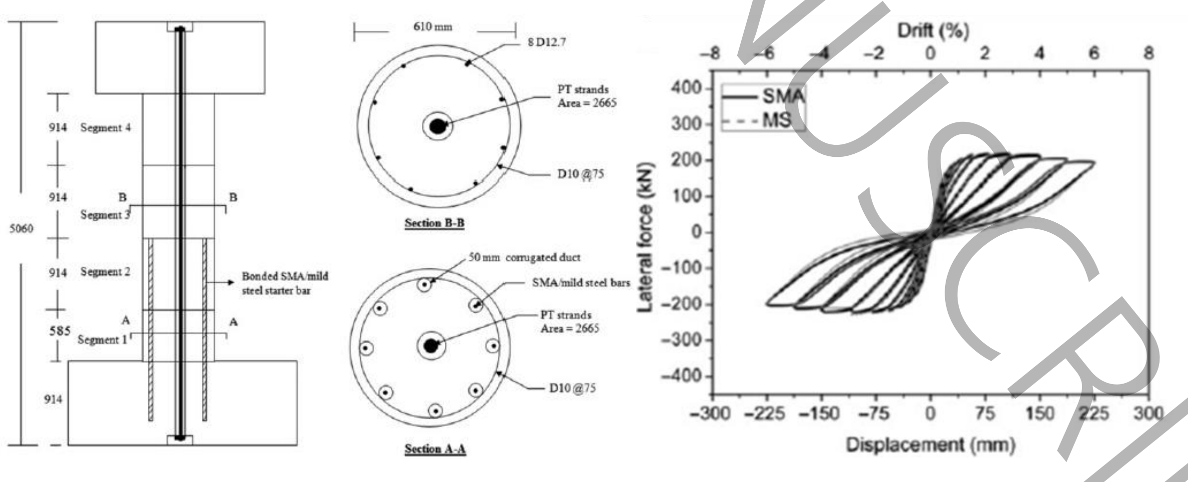

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Figure 4 a) Detail of precast bridge column segments equipped with SMA or conventional mild steel starter bars b) lateral load–deflection behavior [46]

Shrestha et al. (2015) [47] 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 under the shaking table, according to Table 1. The results of the analytical study showed that the stated method provided significant re-centring capabilities and reduced the column damage. Figure 5 shows the longitudinal and transverse residual drifts of specimens that are limited to 1% drift of all scaled near-fault ground motions. Hosseini et al. (2015) [48] carried out on using Cu–Al–Mn SMA and ECC materials in the plastic hinge zone of columns under seismic loading test (Quasi-static reversed cyclic loading). According to Figure 6, a new column constructed with a pre-fabricated ECC tube, which was reinforced with 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 SE-SMA bars can recover up to 12% inelastic strain. ECC materials showed excellent bonding with steel, shear resistance, energy absorption, and tensile ductility. Also, exhibited lower crack widths and permeability compared to conventional concrete. The results showed that although the proposed column reduced stiffness, energy absorption, and lateral strength, the permanent deformations in columns were also decreased remarkably.

Table 1 Details of the plastic hinge in columns [47]**.**

Bridge type	Reinforcement details	Plastic hinge zone
RC bridge	12-10 mm steel bars	Conventional concrete
PT bridge	8-10 mm steel bars with post-tensioning element	Conventional concrete
Rubber bridge	7-10 mm steel bars with post-tensioning element	Rubber element
Ni-Ti bridge	9-13 mm Ni-Ti bars	ECC
Cu-Al-Mn bridge	9-19 mm Cu-Al-Mn bars	ECC

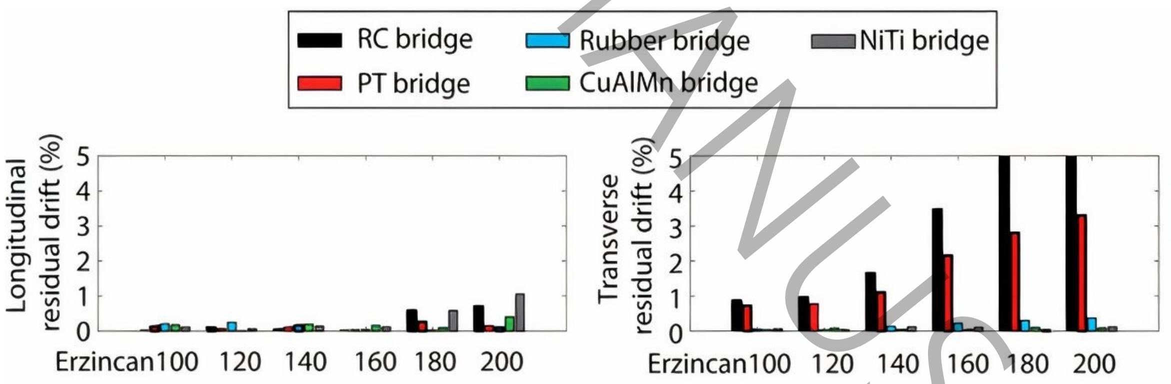

Figure 5 Longitudinal and transverse residual deformation of tested specimens

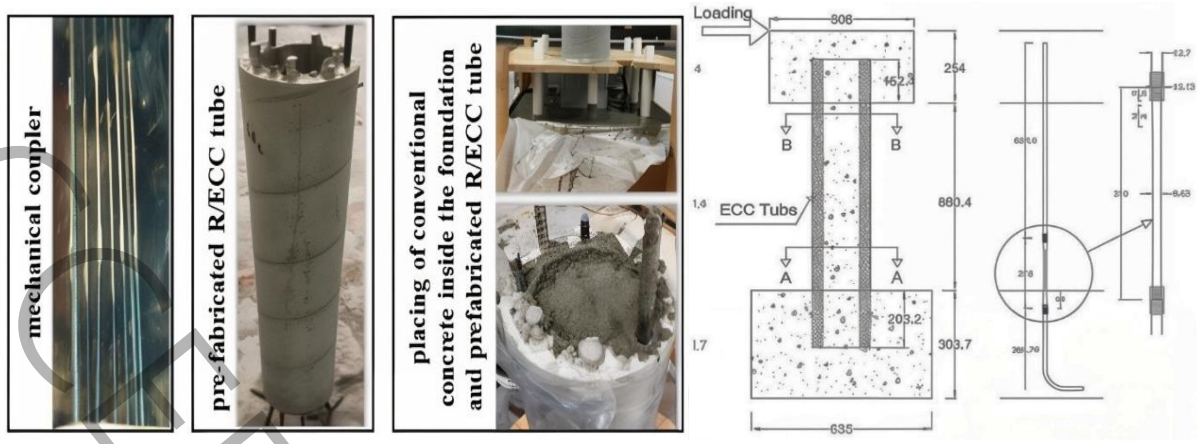

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Figure 6 a) Details of the proposed column and b) Manufacturing process [48]**.**

Tazarv and Saiidi (2016) [49] used three low-damage materials, such as superelastic Ni-Ti SMA, ECC, and UHPC for developing a precast column (with HCS acronym) according to Figure 7. The precast column showed better seismic performance compared with a cast-in-place (CIP) column with conventional materials. According to this data, the cast-in-place column damage is significantly more serious than the precast counterpart; in other words, the HCS column occurred just with ECC cover spalling at a 12% drift ratio. Moreover, the residual deformation of HCS was approximately 80% lower than the CIP column. The ductility and strength of the HCS column increased due to the occurrence of stiffness degradation. Varelal and Saiidi (2016, 2017) [50, 51] proposed an unprecedented idea of precast modules designed for disassembly to provide resilient bridge columns. The superelastic SMAs and ECC material were utilised to access resiliency to minimise 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 and Ni-Ti were designed. According to Figure 8, the precast modules consist of prefabricated concrete-filled fibre–reinforced polymer tubes and prefabricated ECC plastic hinges. At first, each of the specimens was tested under simulated earthquakes, and disassembling and reassembling of the modules were done after cracking. Then, the specimens were retested to investigate the effect of recycling column components. The results depicted that the reassembled specimen showed similar behaviour compared to the first specimen, but was more flexible.

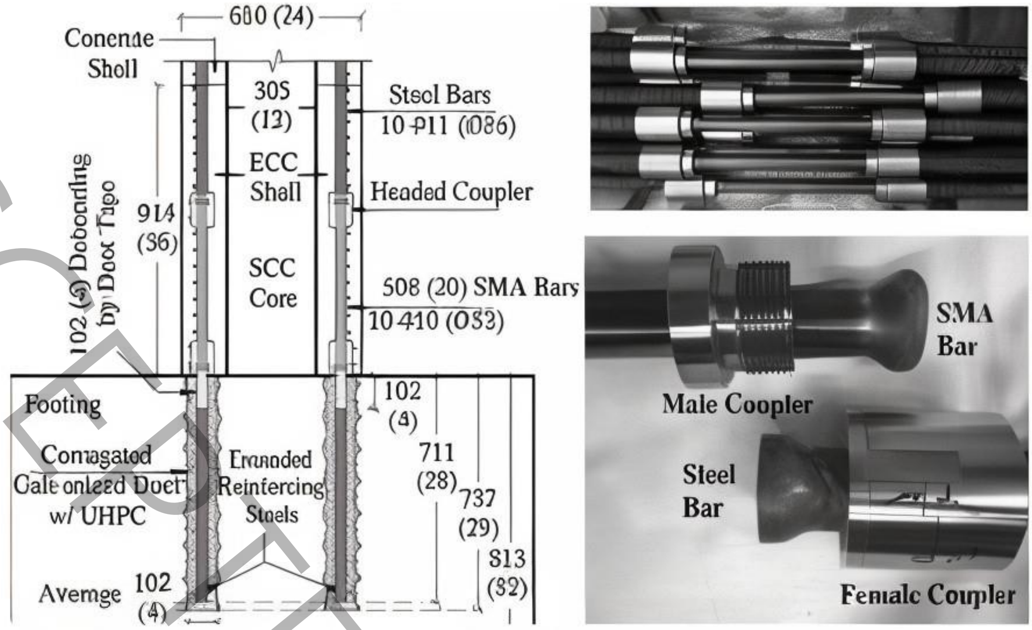


Figure 7 Base-column connection detail [49].

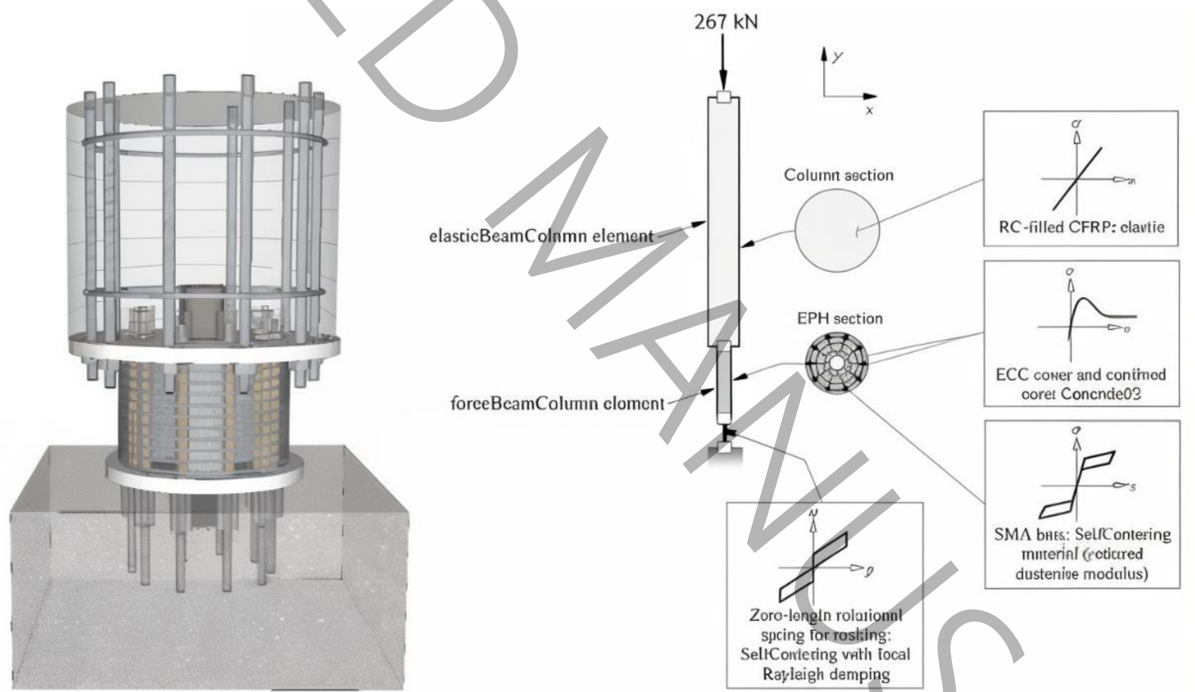
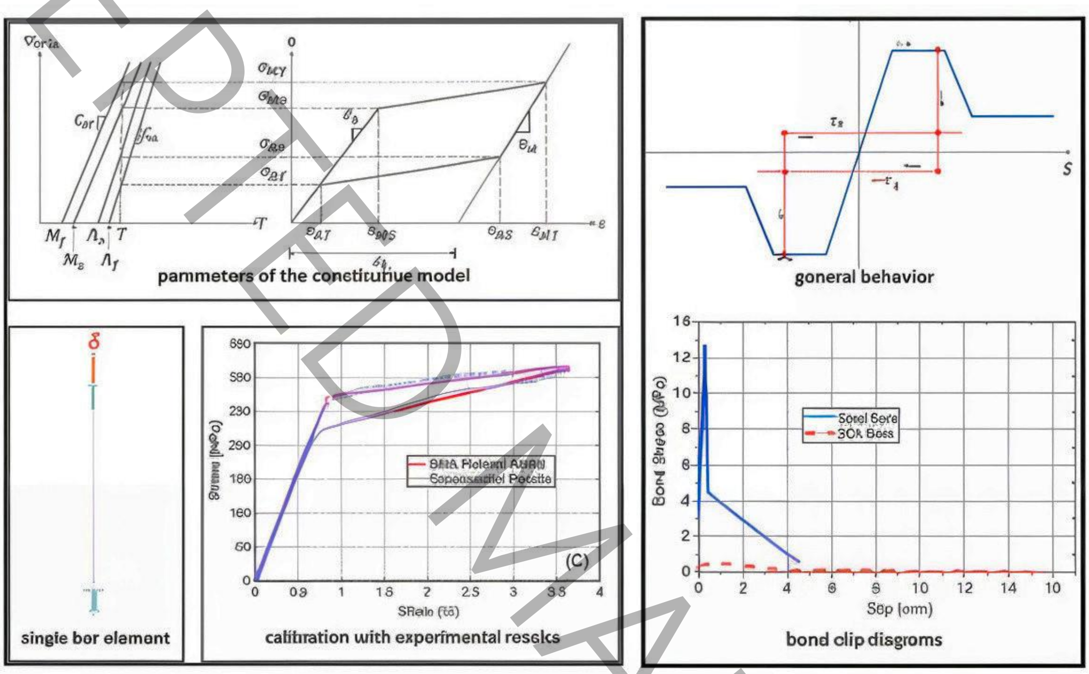


Figure 8 The details of the proposed column with precast modules [50].

Hosseini and Gencturk (2019) [52] assessed the behaviour of ECC and Cu-Al-Mn superelastic SMAs in bridge piers under seismic loading. According to Figure 9.a and Ref [48], five columns with different details, including a reference specimen and 5 various specimens' configurations with ECC and SMA rebar, are modelled in a commercial FEM package, ATENA [53]. Figure 9.b illustrates the SMA material model and the bond model between steel and SMA rebar. The behaviour 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 [48]. The shape of the hysteresis curves, permanent deformation, post-peak degradation, and lateral strength are investigated. Xing et al. (2020) [54] proposed a new approach for strengthening columns by near-surface mounted (NSM) of Ni-Ti SMA bars and CFRP jackets for taking advantage of the superelastic properties of SMA materials, see Figure 10. Seven specimens were considered to investigate the impact of bar ratios and types (SMA and CFRP) and the effect of CFRP jacketing, then tested under quasi-static reversed cyclic loading with constant axial force. The flexural behaviour, ductility, and lateral strength 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 section of the column.



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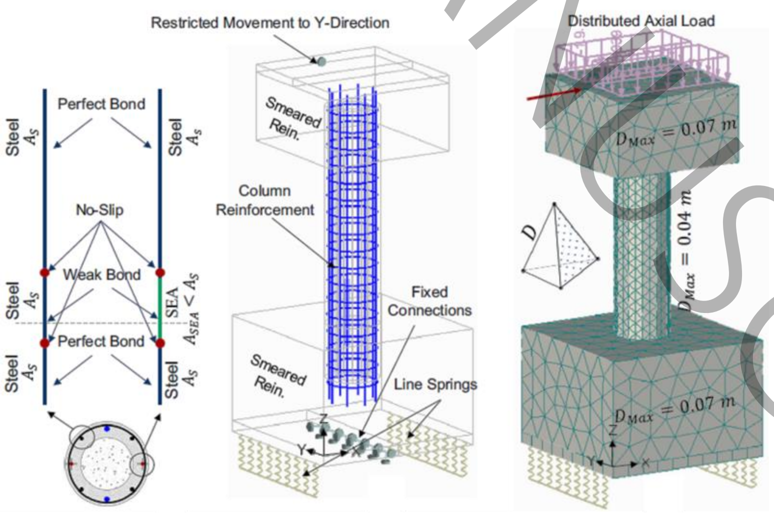

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Figure 9 a) SE material and bond model b) Details of FEM modelling [52].

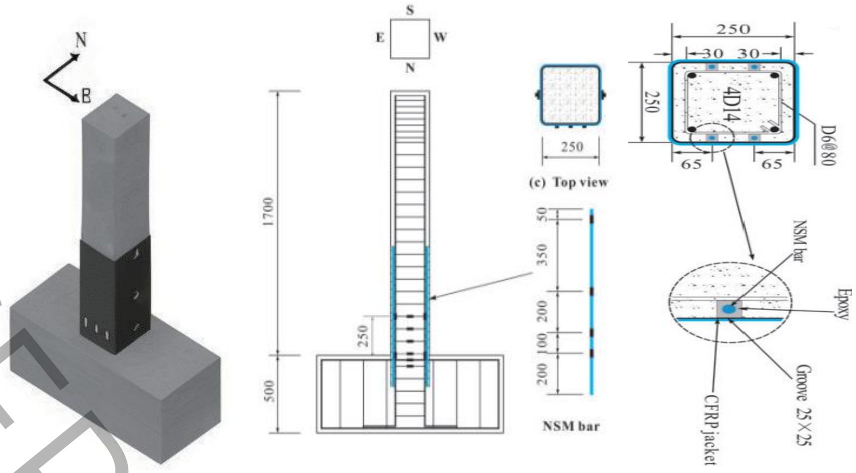

Figure 10 Proposed approach for strengthening the RC column and the strain gage's location [54].

Gholipour and Billah (2022) [55] have modelled the scaled column using ultra-high-performance fibre-reinforced concrete (UHPFRC) jacket and SMA bars in LS-DYNA software according to Figure 11a and have evaluated under lateral impact loads of different velocities. Axial load ratio (ALR), impact velocity (V_{imp}), the thickness of the UHPFRC jacket (t_U), and SMA bar type were the main considered parameters in this numerical paper to assess the column performance. 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 the tested specimens. Figure 11b illustrates the failure behaviour of specimens with various configurations.

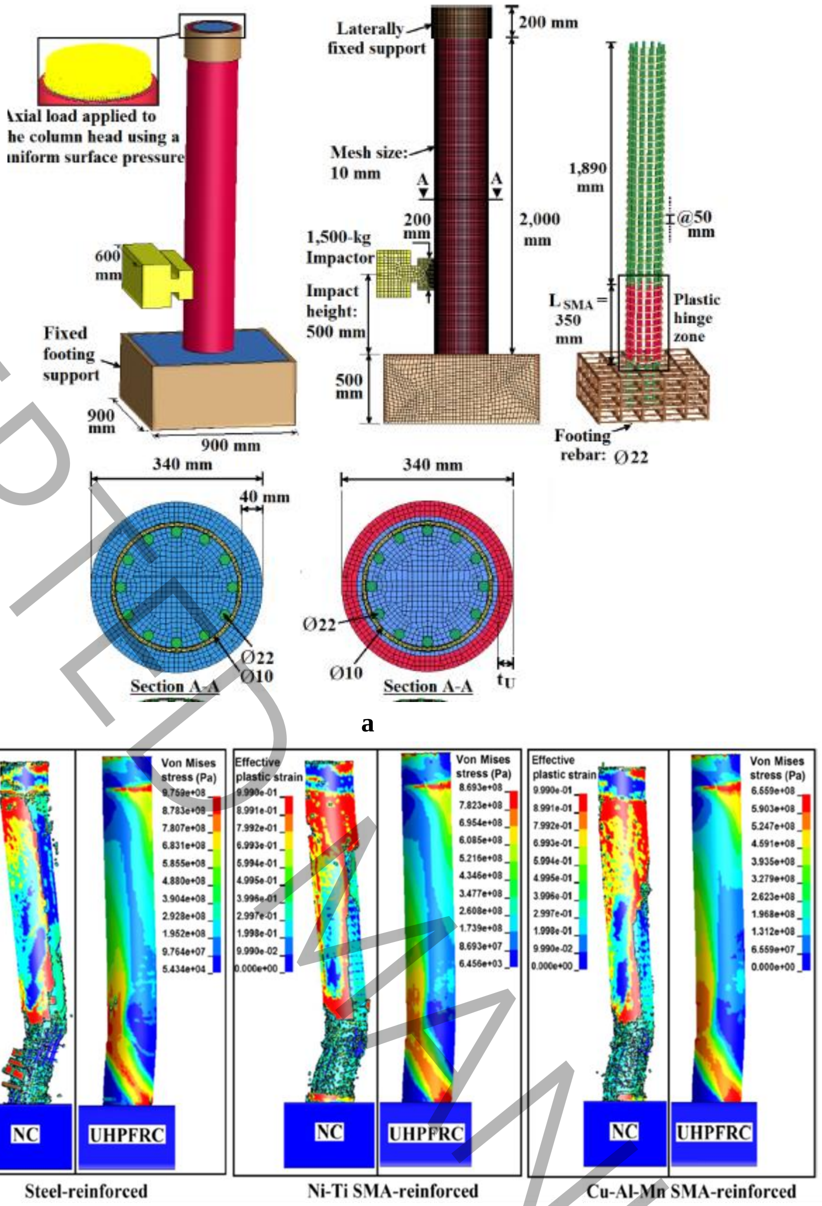

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Figure 11 a) RC column detail by LS-DYNA. b) Failure behaviour (V_{imp} = 15 m/s.) [55].

Benshams et al. (2022, 2023) [56, 57] conducted comprehensive numerical investigations on the seismic performance of bridge piers reinforced with SMAs in combination with high-ductility cementitious materials, including HPFRC and ECC, in the plastic hinge region. In these studies, Ni-Ti and Cu–Al–Mn SMAs were used as longitudinal reinforcements to improve self-centering and reduce residual deformations under near-field ground motions.

Using incremental dynamic analysis (IDA), multiple pier configurations were subjected to 28 and 56 pairs of seismic records to evaluate their collapse capacity and fragility. The results showed that SMA-reinforced piers exhibited significant reductions in residual drift and enhanced seismic resilience compared to conventional RC counterparts. Furthermore, the combined use of Ni-Ti SMAs and ductile concretes (ECC or HPFRC) provided the most favorable performance, with up to a 30% increase in median collapse capacity and substantial improvements in ductility and energy dissipation. These findings highlight the effectiveness of

SMA–ductile composite systems in improving both strength and post-earthquake functionality of bridge columns.

As summarized in Table 2, the collective findings reveal consistent trends across both experimental and analytical studies investigating the application of SE SMAs in reinforced concrete columns. In nearly all cases, SMA-reinforced columns exhibited a substantial reduction in residual drift—often exceeding 90% compared to conventional steel-reinforced columns—demonstrating the strong recentering capability of SE-SMAs. However, this improvement typically came at the cost of reduced initial stiffness and lateral strength, particularly in columns using Ni-Ti SMAs, which have a lower elastic modulus than steel.

A clear distinction can be observed between studies using Ni-Ti SMAs and those employing Cu–Al–Mn alloys. While Ni-Ti-based systems consistently achieved superior recentering and ductility enhancement, Cu–Al–Mn SMAs offered a more economical and machinable alternative, though with slightly reduced energy dissipation and transformation stability under cyclic loading. In hybrid configurations where ECC or UHPC was combined with SMA reinforcement (e.g., Saiidi & Wang (2006) [40]; Tazarv & Saiidi (2016) [49]), the material collaboration significantly mitigated concrete cracking and spalling, resulting in improved overall column durability. In contrast, SMA-only systems without advanced concrete matrices (e.g., Nikbakht et al. (2015) [46]) tended to exhibit higher deformation recovery but at the expense of stiffness and energy absorption.

From a testing perspective, shake table experiments (e.g., Saiidi & Wang (2006) [40]; Varela & Saiidi (2014) [44]) provided direct evidence of improved self-centering behavior under realistic dynamic excitations, whereas numerical studies (e.g., Shrestha et al. (2014) [45]; Hosseini & Gencturk (2019) [52]) confirmed these findings under broader parametric conditions, including variable reinforcement ratios and ground motion records. Despite variations in experimental setups, both methodologies converged on similar conclusions—SMA integration is most effective when applied locally in the plastic hinge region, rather than full-length reinforcement, balancing both economy and performance.

Table 2 Overview of research on RC columns reinforced with superelastic SMAs (Arranged by year of publication)

Research	Technique	SMA type	Testing type	Modelling type	Comparison with reference					
					Columns damage	Strength	Recovery plastic deformation	Residual deformation	Stiffness	Ductility
Saiidi &Wang (2006) [40]	**SMA+ECC**	**Ni-Ti**	**STT**	**EXP**	↓	↑	**100 %**	↓	–	↑

Xing et al. (2020) [54]	**Hosseini and Gencturk (2019)** [52]	**Varelal and Saiidi (2016)** [50, 51]	**Tazarv and Saiidi (2016)** [49]	**Hosseini et al. (2015)** [48]	**Shrestha et al. (201۴)** [45]	**Nikbakht et al (2014)** [46]	**Varela and Saiidi (2014)** [44]	**Noguez and Saiidi (2012)** [42, 43]	**Saiidii et al. (2009)** [41]
SMA+EC C	**SMA+ECC**	**SMA+ECC**	**SMA+ECC & UHPC**	**SMA+EC C**	**SMA+ECC**	**SMA bar**	**SMA+ECC**	**SMA+ECC**	**SMA+EC C**
Ni-Ti	**Cu-Al-Mn & Ni-Ti**	**Cu-Al-Mn & Ni-Ti**	**Ni-Ti**	**Cu-Al-Mn**	**Cu-Al-Mn & Ni-Ti**	**Ni Ti**	**Cu-Al-Mn**	**Ni-Ti**	**Ni-Ti**
QSRCL	**SL**	**SL**	**SL**	**QSRCL**	**STT**	**QSRCL**	**STT**	**STT**	**QSRCL**
EXP	**ANL (in ATENA)**	**EXP**	**EXP**	**EXP**	**ANL (in Open Sees)**	**ANSYS**	**ANL (Open Sees) & EXP**	**EXP**	**EXP**
-	-	-	-	↓	↓	↓	↓		↓
↑	-	-	↑	↓	-	↑	-	-	↓
-	-	-	-	**up to 12%**	-	↑	-	-	-
-	↓	↓	↓	↓	↓	↓	↓	↓	↓
=	-	-	↓	↓	-	↑	-	-	↓
↑	-	-	↑	↑	-	↑	-	↑	↑

Gholipour and Billah (2022) [55]	**UHPFRC + SMA**	**Cu-Al-Mn & Ni-Ti**	**LIL**	**ANL (in LS-DYNA)**	↓	↑	-	↓	-	-

SL: Seismic Loading
LIL: Lateral Impact Loads (different velocities)
-: Not reported
↑: Increased
↓: Decreased
=: Same
EXP: Experimental
ANL: Analytical
STT: Shake Tables Test
QSRCL: Quasi-Static Reversed Cyclic Loading

3.2.Focus on the Shape Memory Effect Feature

According to studies in the past, SMAs have provided remarkable ductility and confinement capability compared to FRP and steel rebar in columns. In the case of installation, the spirals and longitudinal SMA rebar offer some advantages, e.g., considerably decreased labour costs, immediate activation of pre-stressing, etc. Krstulovic and Thiedeman (2000) [58] evaluated high-performance fibre concrete using SMA fibres to actively confine concrete cylinders. Andrawes and Shin (2008) [59] strengthened the RC columns using SMAs spirals and confined them actively by heating. Focusing on the SME property of SMAs induced by heat has been used to apply external active confinement. As an important positive point, a large amount of active confinement pressure is easily applied after heating without specific labour and tools, unlike other active confinement approaches. Choi et al (2009) [60] proposed a new technique for confining RC columns or concrete cylinders by 1mm diameter austenitic, Ti-50.3Ni (at% %) and martensitic, Ti-49.7Ni (at% %) SMA wires. Martensitic wires became pre-strained by a heating jacket, and high confining pressure was produced around the cylinder, and the strength and ductility of the specimen were increased under axial compressive load. On the other side, the austenite SMA wires only enhanced the ductility due to the small pre-stress. The comparison of the plane cylinder and confined counterpart has been shown in the stress-strain curves of Figure 12.

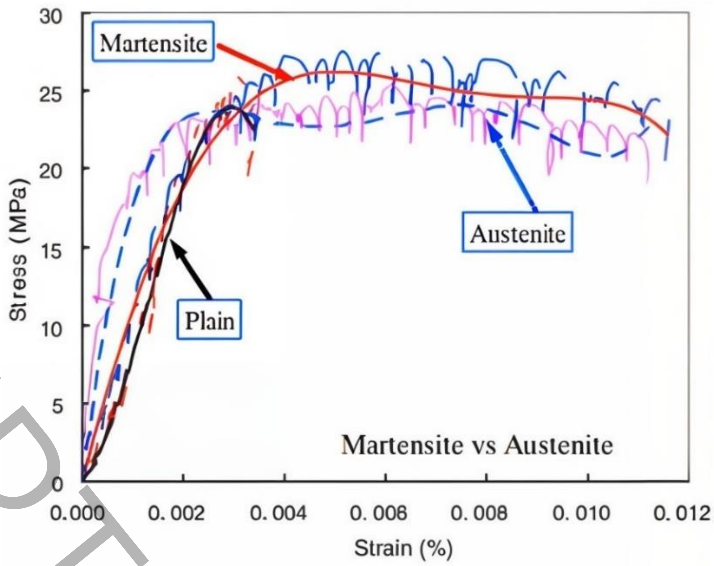
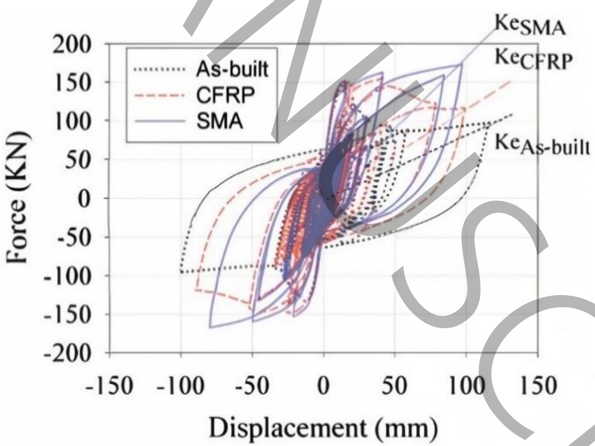


Figure 12 Strain stress curve of the plain and confined cylinder [60]

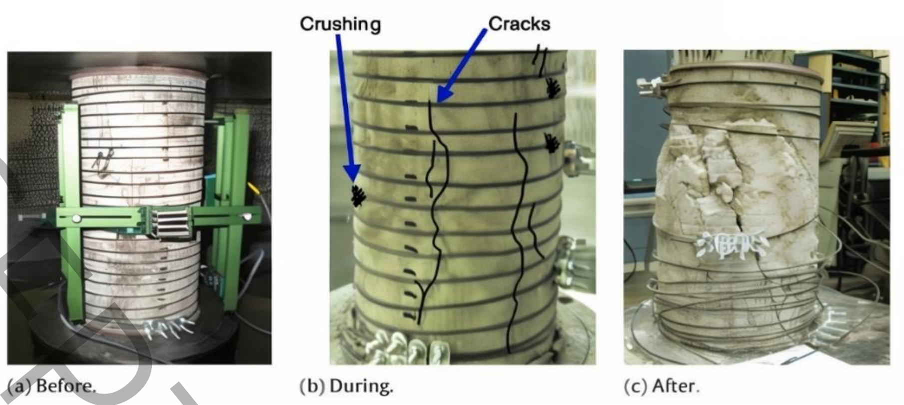
In another study, Shin and Andraws (2010/11) [61] investigated numerically and experimentally the SAMs' spiral ability to enhance the seismic capacity of the RC columns. Furthermore, using the SMA active confinement technique was studied regarding the rapid strengthening of seriously damaged RC columns. Then, the repaired RC column tested under quasi-static lateral cyclic loading fully recovered its lateral strength, and flexural ductility increased [62]. Andrawes et al. (2010) [63] presented the chance of seismic strengthening of RC bridge columns using SMA spirals. Figure 13.a shows the concrete cylinders with 3 mm SMA wires (12-loop), which were tested under uniaxial compression load. The experimental outcomes discovered that a seismic retrofitted innovative technique reduced the plastic deformations and increased the effective stiffness and strength compared with conventional CFRP confinement, according to Figure 13.b.



a b

Figure 13 a) Twelve-loop SMA concrete cylinder b) Force displacement curve of concrete columns [63].

Shin and Andrawes (2010) [64] investigated the seismic behaviour of bridge RC columns using shape memory effect properties of SMA for applying active confinement. The impact of active-SMA cylinders is shown according to Figure 14.a before, during, and after testing. The comparison between unconfined and active-SMA confinement is illustrated in the stress-strain curve of Figure 14.b. According to this curve, using SMA for active confinement increased the ultimate strain and strength. Actually, the strength of confined cylinders utilizing SMA wires was 21% higher than that unconfined counterparts.



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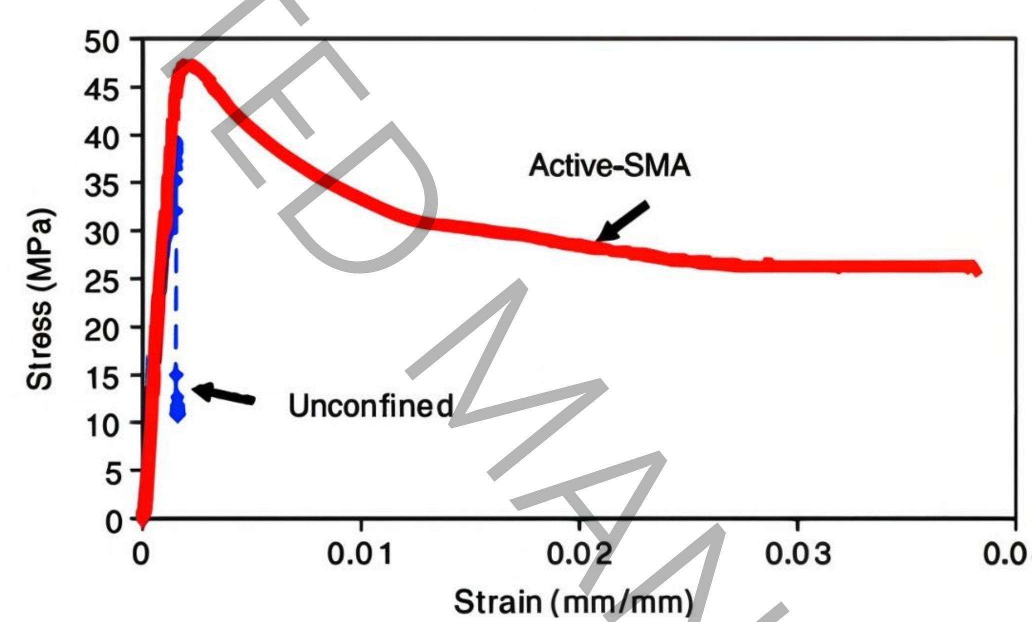


b

Figure 14 a) Behaviour of active-SMA cylinders b) the stress–strain curve [64].

Shin and Andrawes (2011) [62] investigated the quasi-static lateral cyclic behaviour of the extremely damaged RC column repaired rapidly with an active confinement SMA approach. Pre-strained SMA spirals were used to achieve active confinement. The results of the experimental assessment illustrated that the stiffness, ductility, and lateral strength were increased by utilizing SMA wires. The repaired column was compared with the as-built one according to Figure 15. The initial stiffness of the repaired specimen was 54% higher than another one.

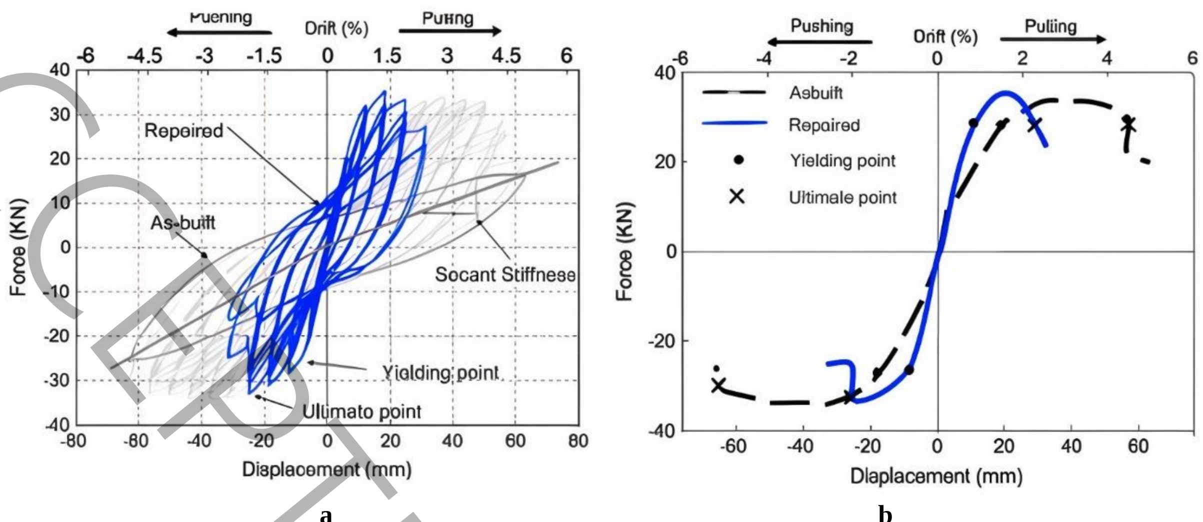
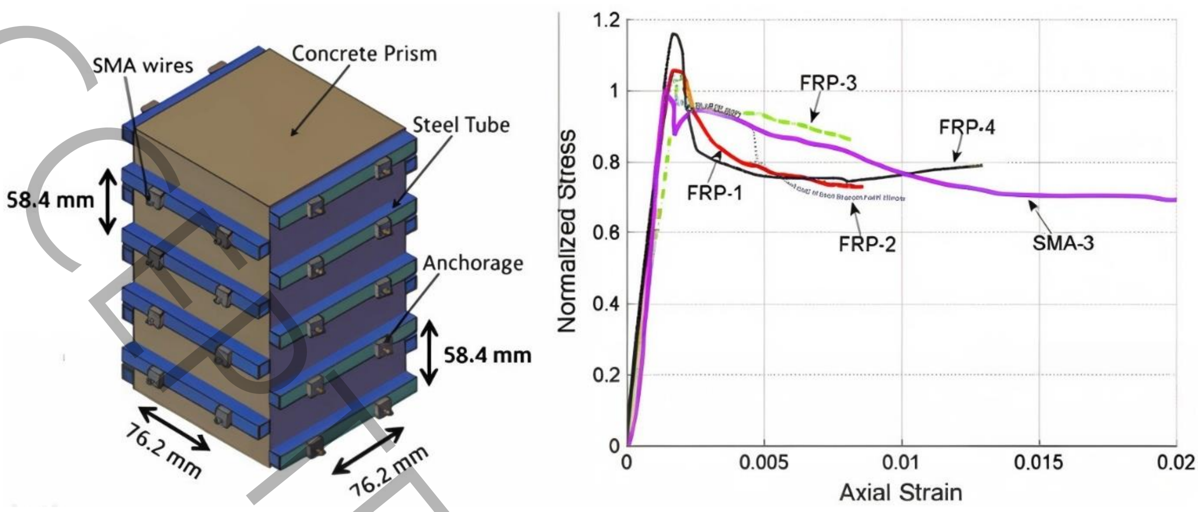


Figure 15 Force-displacement curve of as-built and repaired column a) hysterics b) backbone curve [62]**.**

Choi et al. (2012) [65] evaluated the effect of Ni-Ti-Nb and Ni-Ti SMA wire jackets in the case of RC column strengthening with lap splices under a seismic loading test. The SMA wires' jackets demonstrated the advantages such as no danger of peel-off, easy installation, no need for adhesive, and strong corrosion protection in comparison with FRP or steel counterparts. According to data, using Ni-Ti-Nb wires as a strengthening material in RC columns was more adaptive than Ni-Ti wires. Furthermore, Ni-Ti-Nb SMAs depicted a better temperature range for civil engineering applications. This proposed approach of strengthening RC columns increased the ductility without strength degradation. In addition, strengthening RC columns with a lap splice indicated better performance than without one (Figure 16).

Figure 16 The column's failure modes with lap splice a) without SMA wire b) retrofitting by SMA spiral wires [65].

Chen et al. (2014) [66] proposed a new scheme of rectangular concrete columns using SMA wires to apply active confinement in order to increase the ductility, according to Figure 17.a. In this study, the behaviour of thirteen concrete elements was inspected under cyclic and monotonic uniaxial compression load. The comparison between the confinement of concrete columns using SMA wire and GFRP jackets is shown in Figure 17.b. The results explain a remarkable enhancement in the residual post-peak strength and ultimate strain of rectangular concrete elements using SMA wires.

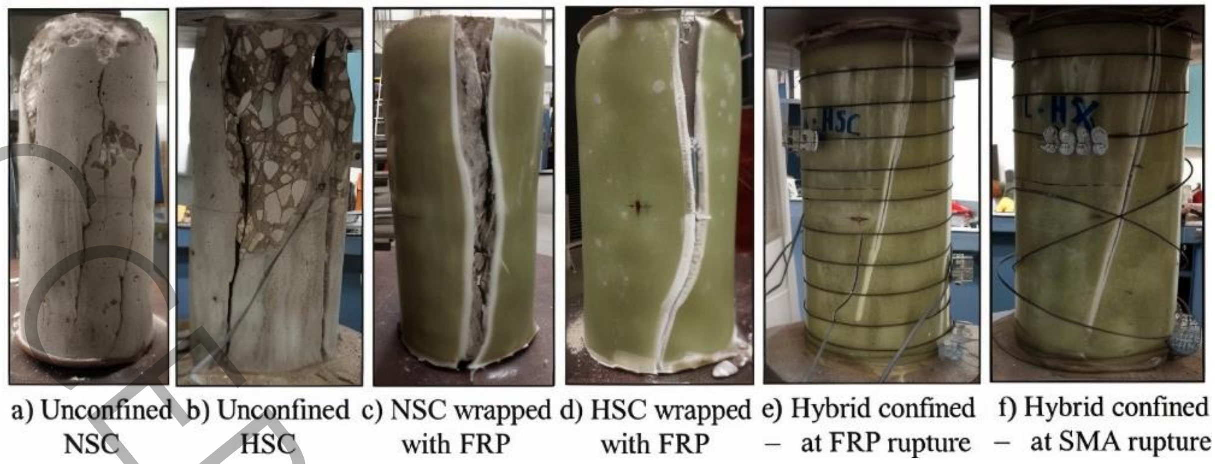


a b

Figure 17 a) Scheme of rectangular concrete columns using SMA wires b) Stress-strain curve of FRP and SMA [66]

However, the SMA materials were used to strengthen new structures, and the application of these materials in the case of the rehabilitation of damaged structures is noticeable. A worthy example related to using the SMA bar to strengthen the RC BCJ is the Jung et al. (2017) [38] paper that tested bidirectional dynamic loading using a shaking table. The result demonstrated that using Ni-Ti-Nb SMA spirals for the active confining of concrete columns improved the flexural ductility and strength of the specimen and delayed the damage of concrete under seismic loading. Furthermore, the residual deformation of specimens decreased. Deogekar and Andrawes (2018) [67] studied the effect of glass FRP tubes and SME wires on concrete confinement. At the primary step, they made high-strength concrete (HSC) and normal-strength concrete (NSC) cylinders and confined them with the hybrid technique of FRP and thermally pre-stressed 1.9 mm Ni-Ti SME to apply active confinement, as shown in Figure 18.a. For the numerical part of the work, they used the schematic of the column according to Figure 18.b and considered pushover analysis; for the experimental part, they applied uniaxial cyclic loading. According to the results, the strength of FRP hybrid confinement was reported to be 93.9% higher than that of passive confinement. Moreover, the ultimate drift of the concrete-filled fibre tube bridge column by SMA spirals in the plastic hinge region was increased by 154%, according to numerical results.

Abdelrahman and El-Hacha (2020) [68, 69] investigated the use of Ni-Ti SMA spirals for active confinement and CFRP sheets for passive confinement of RC columns. Their findings revealed that incorporating SMA spirals led to a substantial improvement in column performance. In particular, RC columns actively confined with SMA spirals exhibited marked increases in both strength and ductility compared with unconfined specimens subjected to different load eccentricities. (Figure 19).



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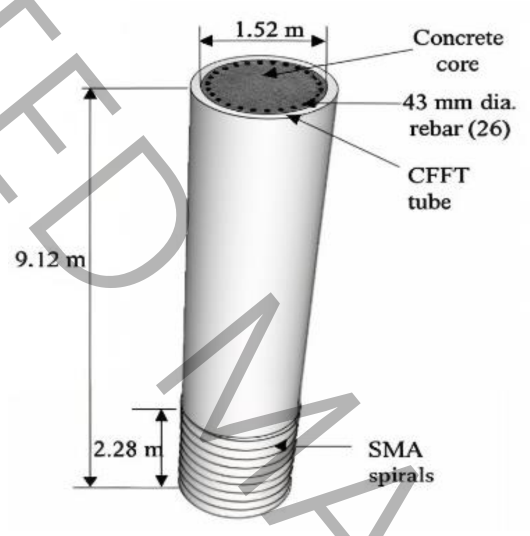
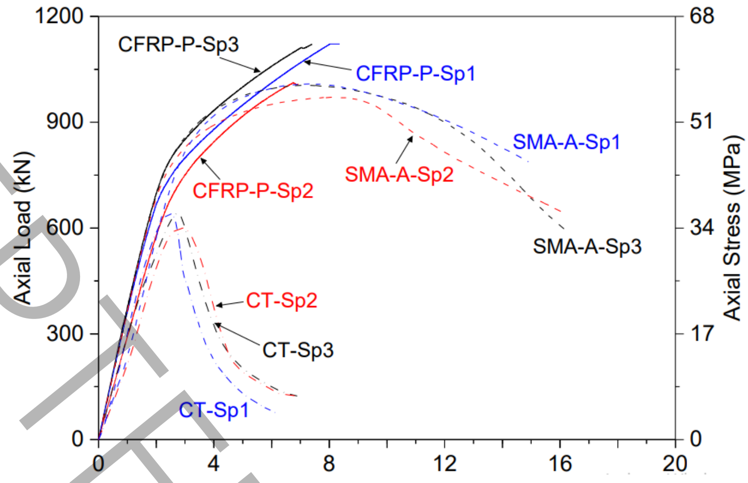


b

Figure 18 a) RC column confined using FRP tube and SMA wires b) the failure modes of the tested cylinders [68]**.**

Suhail et al. (2020) [70] tested the concrete columns actively confined by heat-activated pre-stressing (HAP) of SMA (Figure 20) and compared with passively confined using SMA wires without HAP, basalt fibre-reinforced polymer (BFRP), and carbon fiber-reinforced polymer (CFRP) jackets counterparts. In this study, the advantages and disadvantages of SMA active confinement, including heating and structural parameters such as damage, ductility, and strength of specimens, were evaluated. According to the results, the performance of active confinement was found to be better than that of a passive type, such as using CFRP and BFRP. Furthermore, the ductility and residual strength of specimens utilizing SMAs were remarkably higher than another one.

A review of relevant studies indicates that the active confinement provided by the SME of SMAs is effective in enhancing the drift capacity and energy dissipation of deficient RC columns. The active confinement pressures applied in previous research ranged from 0.4 to 2.0 MPa, with a pressure of 1.2 MPa being sufficient to increase a column's energy dissipation capacity by up to four times. Additionally, active confinement by SMA spirals significantly reduces residual deformations in columns, as it delays damage transfer to the reinforcing rebar by actively confining the concrete core. Notably, all existing studies have utilized Ni-Ti-Nb SMA spirals for active confinement. Therefore, exploring the potential of Fe and Cu-based SMAs for the active confinement of RC columns represents an intriguing research opportunity for future studies.



a

b

Figure 19 a) The load-displacement curve and b) failure mode of RC columns confined with SMA and CFRP [68]**.**

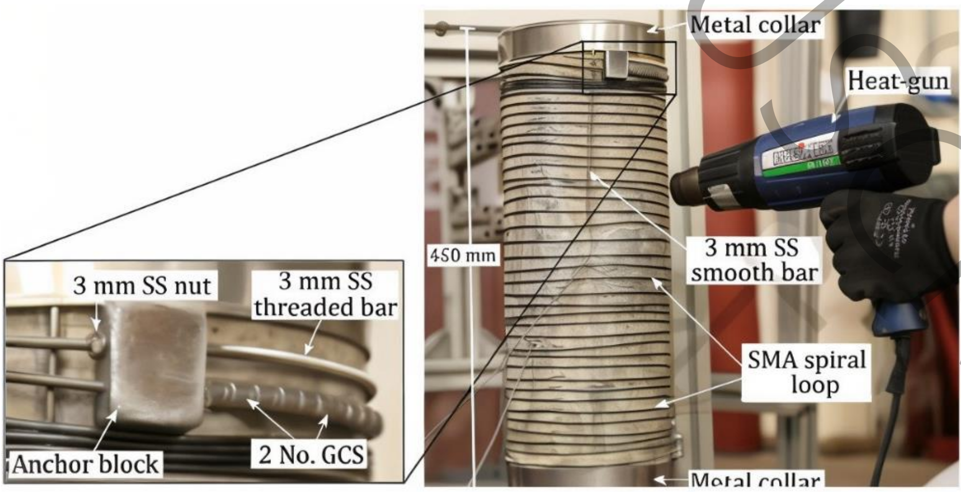


Figure 20 Manufacturing concrete cylinders actively confined by SMA wires [70]**.**

As summarized in Table 3, studies focusing on the shape memory effect (SME) of SMAs consistently highlight their effectiveness in providing active confinement and enhancing the post-yield performance of RC columns. Unlike SE applications, where the material re-centers under mechanical unloading, SME-based systems rely on thermally activated recovery stress, allowing the SMAs to generate significant confining pressure once heated. This makes them particularly useful for both rapid strengthening and post-damage rehabilitation of RC columns. A key comparative observation across studies is that Ni-Ti–Nb SMAs outperform conventional Ni-Ti in terms of temperature stability and recovery stress retention. For instance, Choi et al. (2012) [65] and Shin & Andrawes (2011) [62, 63] demonstrated that Ni-Ti–Nb spirals maintained their prestressing capacity over a wider thermal range, which is crucial for field applications where temperature fluctuations occur. The use of Ni-Ti–Nb wires also avoided the brittleness and limited transformation range observed in pure Ni-Ti systems. Comparing different confinement configurations, studies show that SMA spirals or wire jackets applied externally (e.g., Shin & Andrawes, (2010) [61] ; Choi et al. (2012) [65]; Abdelrahman & El-Hacha (2021) [68]) produced uniform confinement pressure and substantially increased strength and ductility, while hybrid systems combining SMA and FRP (Deogekar & Andrawes (2018) [67]; Suhail et al. (2020) [70]) achieved even higher strength and drift capacity by merging active and passive confinement mechanisms. In particular, Suhail et al. (2020) [71] reported that SMA-active confinement improved residual strength and ductility more effectively than CFRP or BFRP jackets, confirming the superior adaptability of SME-based systems. In terms of quantitative outcomes, the active confinement pressures generated by SMA spirals ranged from 0.4 to 2.0 MPa, which, according to Andrawes et al. (2010) [63] and subsequent studies, can increase the energy dissipation capacity by up to fourfold compared with unconfined or passively confined specimens. Moreover, columns confined with SME-SMAs exhibited strength gains of 20–90% and ductility enhancements exceeding 50%, depending on the SMA type and activation level. However, these benefits often came at the expense of increased complexity in installation and the need for controlled heating systems to activate the shape memory effect.

Table 3 Summary of research on RC columns reinforced with SME SMAs (organized by year of publication)

Research	Technique	SMA type	Testing type	Modelling type	Columns damage	Comparison with reference				
						Strength	Recovery plastic deformation	Residual deformation	Stiffness	Ductility
Shin and Andrawes (2011) [61]	**SMA external spirals**	**Ni-Ti-Nb**	**QSRCL**	**EXP**	↓	↑	-	-	–	↑

Shin and Andrawes (2011) [62-64]	**SMA external spirals**	**Ni-Ti-Nb**	**QSRCL**	**EXP**	-	=	-	-	↑	↑
Choi et al. (2012) [65]	**External wire jackets**	**Ni-Ti and Ni-**	**CT**	**EXP**	-	↑	-	-	=	↑
Chen et al. (2014) [66]	**SMA wires**		**CT & CT**	**EXP & NUM**	-	↑	-	-	-	↑
Deogekar and Andrawes (2018) [67]	**GFRP tubes and SME wires**	**Ni-Ti**	**CT**	**EXP & NUM**	↓	=	-	-	=	↑
Abdelrahman and El-Hacha (2020) [68]	**SMA wire spiral+ CFRP**	**Ni-Ti**	**CT**	**EXP**	↓	↑	-	-	↑	↑
Suhail et al (2020) [70]	**SMA wire spiral+ FRP**	**Ni-TiNb**	**CT**	**EXP**	↓	↑	-	-	↑	↑

EXP: Experimental
ANL: Analytical
QSRCL: Quasi-Static Reversed Cyclic Loading
CT: Compression Test
CL: Cyclic Test
-: Not reported
↑: Increased
↓: Decreased
=: Same

4. Design Guidelines for SMA-Reinforced Columns

The development of design guidelines is critical for enabling the practical application of SMAs in reinforced concrete columns. While experimental evidence on SMA-based systems is substantial, engineering guidance remains limited. The following recommendations synthesize available research and provide practical design considerations for both SE- and SME-based applications.

۴.1. General Design Recommendations

Saiidi et al. [71, 72] proposed preliminary design guidelines for superelastic Ni-Ti SMA-reinforced ECC piers and FRP-confined concrete piers in bridges. AASHTO recommends that such low-damage columns—with substantially reduced residual drift—can be considered for seismic design categories C and D. The suggested design method is displacement-based, differing from the conventional force-based method for reinforced concrete columns, with a recommended damping ratio of 3.2% instead of the conventional 5.0%. To address the low damping, it is suggested that the displacement demand be increased by 20% compared to conventional columns. The recommended SMA reinforcement levels range from 1% to 4%, with a maximum ratio of design axial load of 0.15 [73]. Furthermore, Billah and Alam [74, 75] proposed a seismic design approach based on the performance of reinforced concrete columns of a bridge utilizing SE Ni-Ti SMA. According to their method, serviceability necessities are satisfied when the residual drift is under 0.25%, whereas a residual drift exceeding 1% indicates a collapse damage state for the SE SMA-reinforced RC columns in bridges.

4.2. Plastic Hinge Length and Displacement Parameters

A key parameter in displacement-based design is the plastic hinge length (*Lp*), which represents the region of the column experiencing substantial inelastic behavior under extreme loading. In conventional RC columns, the plastic hinge is often assumed to have a constant curvature distribution to simplify force and displacement calculations. Analytical derivation of *Lp* is complex because it depends on several variables, including member size, height, longitudinal reinforcement ratio, yield strength, and concrete compressive strength.

Billah and Alam [74] proposed a practical expression for calculating the plastic hinge length of SMA-reinforced RC bridge piers under combined axial and reverse cyclic loading:

$$\frac{L_p}{d} = 1.05 + 0.25\frac{P}{A_g f_c'} + 0.08\frac{L}{d} + 0.0002 f_{y-SMA} - 0.16\rho_l - 0.019 f_c' + 0.24\rho_s \tag{1}$$

Where d is the diameter of the circular column (mm), L is the column length (mm), A_g is gross cross-sectional area, $P/(A_g \acute{f}_c)$ is the axial load ratio, f_{y-SMA} is the yield strength of SMA bars (MPa), $\acute{f}_c$ is the concrete compressive strength (MPa), ρ_l and ρ_s are the longitudinal and transverse reinforcement ratios, respectively (expressed as decimal; e.g., 1% = 0.01). The proposed equation is valid only within the following calibrated ranges (Eq. (2) to (6)):

$$0.05 \le \frac{P}{A_g f_c'} \le 0.20 \tag{2}$$

$$0.8 \le \rho_l \le 3.0 \tag{3}$$

$$200MPa \le f_c{}' \le 750MPa \tag{4}$$

$$30MPa \le f_c{}' \le 75MPa \tag{5}$$

$$3 \leq \frac{L}{d} \leq 5 \tag{6}$$

These conditions must be satisfied to ensure the accurate prediction of L_p for SMA-reinforced RC piers. Outside these limits, the model may not reliably represent the spread of plasticity.

5. Discussion:

Columns serve as the primary vertical load-bearing elements in RC buildings and bridges. The failure of a single column can lead to the progressive collapse of the entire structure. To prevent such failures, deficient RC columns often require strengthening to enhance their flexural capacity or improve their confinement to withstand lateral forces. SMAs offer a promising solution for reinforcing RC columns due to their superelasticity and shape memory effect. SE-SMAs can impart self-centering capabilities to RC columns, while the SME can be used to prestress columns, presenting an alternative to conventional prestressing methods that often pose practical challenges. SE-SMAs are typically integrated as internal reinforcements within the plastic hinge regions of columns to achieve self-centering behavior. Additionally, SMAs can be incorporated in the form of embedded or external spirals and wire jackets to enhance the confinement of RC columns. Specifically, the recovery stress produced by the SME of SMAs can be harnessed for active confinement, resulting in improved ductility and energy dissipation capacity, which surpasses the passive confinement offered by traditional steel spirals. The reinforcement of RC columns using the SME can significantly enhance stiffness and crack resistance, while also reducing deflection under extreme loads. Additionally, employing these SMAs can decrease residual displacements during cyclic loading, which is particularly beneficial for imparting self-centering behavior to existing RC columns. For this application, activated SMAs can be used as embedded or near-surface mounted reinforcements in existing RC columns. Consequently, SMA-equipped structural components can partially recover their deformations under extreme loads, thereby reducing the need for extensive repair. However, selecting the optimal prestressing level is critical, as excessive prestressing force can diminish the ductility of the structural components.

6. Challenges of Using SMA in RC

Before the widespread adoption of SMAs in RC columns, several challenges must be addressed. One critical aspect is ensuring that the activation temperature for SMAs does not damage the concrete's cementitious matrix, as microcracks can form above 200°C and compressive strength decreases significantly between 300°C and 800°C [76]. Additionally, embedding SMA rebars in shotcrete can cause shrinkage-induced cracks, reducing the technique's effectiveness [77]. The smooth surfaces of SMAs also lead to poor bonding with concrete compared to ribbed steel bars, resulting in larger crack widths [78-81]. Techniques like using end hooks, roughening the surface, or sandblasting can improve bond strength, but more research is needed to investigate SMA bond characteristics, especially for post-installed SMA rebars in retrofit applications [54]. The corrosion resistance of SMAs varies with their composition; Fe-SMAs with higher chromium content exhibit better performance, while Ni-Ti SMAs show satisfactory resistance. However, Ni-Ti-Nb SMAs have higher corrosion potential, and the corrosion characteristics of superelastic Cu-Al-Mn SMAs need further investigation [82-84]. Recovery stress relaxation over time also requires a detailed study, including whether multi-step heating to activation temperature results in lower stress relaxation. For instance, Fe-SMA rebars exhibited a stress relaxation of 10% after being subjected to 2000 hours (approximately 83 days) of testing [85]. The relatively low elastic modulus of Ni-Ti SMAs compared to steel can compromise structural stiffness, but solutions include partially replacing steel with SMA rebars or using advanced materials with high elastic modulus in critical regions. Fe-SMAs show a significant reduction in elastic modulus upon activation, necessitating further exploration [23, 86]. Additionally, activated SMAs exhibit reduced prestressing force under increasing cyclic loading, and further research is needed to assess the effectiveness of prestressing under cyclic strains, especially during earthquake-induced excitations [87, 88] Despite these challenges, significant opportunities exist for the future application of SMAs in RC structures. Combining SMAs with materials like ultra-high-performance concrete can enhance performance, and developing new SMA compositions that provide high recovery stresses at lower activation temperatures can improve feasibility. Improved manufacturing techniques, such as large-scale commercial production of ribbed SMA rebars, can enhance bonding with concrete [23]. Expanded research on the corrosion characteristics, stress relaxation, and bond behavior of SMAs, particularly for new compositions and under various loading conditions, is essential. Exploring the potential of Fe-SMAs for prestressing RC columns can lead to innovative strengthening solutions, and creating detailed design guidelines for SMA-reinforced columns will facilitate broader adoption and implementation in construction practices. Table 4 summarizes these challenges and highlights their corresponding implications for SMA–RC column applications.

Table 4 Summary of main challenges associated with the use of SMAs in RC columns

Category	Main Issue	Implication / Required Research
Activation temperature	**Heating above 200 °C may damage the cementitious matrix.**	**Develop low-activation SMAs (Fe, Cu-based) compatible with concrete.**
Bond behavior	**Smooth SMA surfaces lead to weak interfacial adhesion and larger crack widths.**	**Employ surface treatments (sandblasting, ribbing) and study post-installed SMA bonds.**
Corrosion resistance	**Durability depends on alloy type; limited data for Cu–Al–Mn and Ni-Ti-Nb.**	**Investigate corrosion under realistic exposure and cyclic wet–dry environments.**
Stress relaxation	**Recovery stress may decrease over time (≈10% over 2000 h).**	**Assess relaxation under multi-cycle activation and sustained loading.**
Elastic modulus	**Lower modulus reduces stiffness and load capacity.**	**Adopt hybrid (SMA + steel) systems or UHPC/ECC matrices.**
Cyclic loading	**Prestress decreases under repeated seismic strains.**	**Evaluate prestress retention and fatigue degradation.**
Manufacturing	**High cost and lack of ribbed SMA bars limit large-scale application.**	**Develop industrial ribbed SMA rebars with improved bond and lower cost.**

7. Conclusions and Remarks

SMAs have attracted significant attention for the strengthening and retrofitting of RC columns due to their two distinct characteristics: the SE and the SME.

The SE property allows RC columns to recover large inelastic deformations upon unloading, providing self-centering capability and substantially reducing residual drifts under seismic loading. In contrast, the SME property enables active confinement and prestressing through thermally induced recovery stresses, offering a simple and durable alternative to conventional prestressing systems. Although SMAs have been known for decades, their widespread use in civil engineering applications remains limited.

This review comprehensively synthesized experimental and analytical studies on SMA-based RC column retrofitting and confinement. A comparative analysis indicates that:

Findings consistently show that SMA wires and spirals, which apply active confinement through SME, lead to improved strength, ductility, and stiffness due to their ability to generate recovery stress and control residual strains. Conversely, superelastic SMA reinforcements—whether in longitudinal configurations—demonstrate significant deformation recovery and ductility enhancement under cyclic and seismic loading, though sometimes accompanied by stiffness degradation or minor strength reduction at large drifts.

Overall, SE-based and SME-based approaches offer complementary benefits: SME confinement primarily improves strength and ductility, whereas SE reinforcement enhances self-centering and energy dissipation capacity. Nevertheless, challenges remain regarding the high cost of Ni-Ti alloys, limited applications in full-scale members, and the absence of unified design frameworks.

Based on the review, the authors identify key limitations in current studies and propose several recommendations for future research:

- Investigate the influence of active confinement on rectangular RC columns, which better represent real structural configurations.
- Explore new activation methods for SMA spirals to achieve more effective and uniform confinement pressure.
- Develop hybrid systems or design approaches that can mitigate strength and stiffness degradation while utilizing superelastic properties.
- Additionally, future efforts should focus on optimizing SMA alloy compositions (e.g., Cu–Al–Mn or Fe-SMA as cost-efficient alternatives to Ni-Ti), integrating SMA with advanced materials such as ECC or UHPC, and formulating standardized analytical and design guidelines to facilitate their practical application in seismic retrofitting of RC structures.

Disclosure statement

No potential conflict of interest was reported by the authors.

Data availability

Data will be made available on request.

Funding:

We would like to clarify that this research received no external funding from any organization or agency.

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