SINAI International Scientific Journal (SISJ)
Vol 1. Issue 2, October 2024

A Review on the Sway of Using Shape Memory Alloys on Enhancing the Behavior of RC Elements under Cyclic Loading

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Citation:

Kotb, K. F., Fawzy, K., Mahmoud, H. A. and Selim, M." A Review on the Sway of Using Shape Memory Alloys on Enhancing the Behavior of RC Elements Under Cyclic Loading", SINAI International Scientific Journal (SISJ), volume 1,Issue 2, pp. 81-94, 2024

Received: 26 April 2024

Accepted: 19 July 2024

ABSTRACT

Shape memory alloy (SMA) is a class of "Smart Materials" that can exhibit unique thermomechanical phenomena (shape memory effect and superelasticity/pseudo-elasticity), which involve the restoration (remembrance) of the SMA's original shape after being excessively deformed. Shape memory effect (SME) is the thermally-triggered shape recovery of SMA when the alloy is in the martensite phase (low-temperature phase). However, superelasticity effect (SE), which is observed at the austenite phase (high-temperature phase), is the ability of the mechanically stressed alloy to restore its original shape when unloaded even after being strained beyond its linear range. The aim of this paper is to highlight the importance of SMA in improving the properties and behavior of structural elements under the influence of lateral loads. Their special ability to restore buildings to their former shape after a load is removed without causing heating or a considerable amount of persistent deformation (superelasticity) is what makes them distinctive. These characteristics have the power to significantly raise various structures' security levels. A summary of current research on reinforced concrete (RC) structural elements is given in this work, with a focus on beam-column connections (BCCs) and slab-column connections (SCCs). Form memory alloy (SMA) is used to strengthen these members either internally or externally. However, there are several benefits to using SMA materials in reinforced concrete (RC) components, including reduced lifetime costs, increased durability, increased safety, and greater performance following an earthquake. After reading this article, which summarizes the knowledge now available on SMA properties and outlines several potential applications for SMAs, researchers and qualified engineers should be inspired to expand the usage of SMAs in new and evolving applications.

KEYWORDS: beam-column connection; slab-column connection; abaqus;shape memory; cyclic load; superelasticity; shape memory effect; repairing; strengthening.

1. INTRODUCTION

The impacts of aging and high-loading conditions can cause significant deterioration in reinforced concrete (RC) buildings [1-6]. In addition to the usual concrete cracking and spalling, the steel rebars embedded in the concrete might corrode, crack, and buckle as a result of the degradation. Thus, there may be detrimental effects on the resilience and efficiency of reinforced concrete (RC) structures, causing issues with performance and safety in the short and long term [7-8].

A type of connection known as an RC connection joins two or more parts made of reinforced concrete. Concrete serves as the main component of an RC connection, while steel serves as reinforcement. A ductile connection is often one that can smoothly transition loads. A ductile connection transfers load and moment to other members while also offering a strong warning prior to breakdown. Although this helps to lessen the loading at the connection's overcapacity, the force capacity of the connection is still decreased. The most common causes of connection failure are excessive displacement, concrete cracks, and steel giving. Shear failure between the beam and the column, resulting in fractured concrete and internal stirrup yielding, is the most frequent failure in an RC connection. As seen in Fig. 1, under extreme circumstances, shear failure may cause a moment hinge on the connection [9].

Fig. 30: Beam–Column Joint Failure.

The unique properties of shape memory alloys make them attractive as devices for seismic-resistant design and retrofit. Reinforced concrete structures are expected to experience large displacements during strong earthquakes. The need for energy dissipation leads to significant strains in the steel reinforcement and, consequently, damage in the plastic hinge zone. Most of the steel strain is permanent, thus leading to large residual deformations that make the structure unserviceable after the earthquake. Alternative reinforcing materials, such as superelastic SMAs, offer strain recovery upon unloading. Experimental and analytical studies of shape memory alloys show that they are effective at improving the response of buildings and bridges subjected to seismic loading. The recentering potential of superelastic shape memory alloys is the most appealing characteristic for applications in earthquake engineering [10].

A variety of materials have been developed to strengthen and mend structures to address these issues. Steel plates that are resistant to corrosion, cementitious composites with good performance, and jackets made of fiber-reinforced polymer (FRP) that are linked externally. and FRP sheets put close to the surface are some examples of these materials. Due to their distinct characteristics of superelasticity and the shape memory effect (SME), SMAs are being used to improve and repair RC structures. SMAs are capable of regaining their initial form. without deformation even after experiencing large distortions because of their superelasticity feature. Nevertheless, when heated, SMAs can recover their previous shape thanks to the SME. Furthermore, SMAs provide an easy installation method, particularly in prestressing applications. SMAs provide attractive attributes that make them an appealing option for a variety of applications, such as strengthening, building repair, and new building design. When keeping RC structures functioning while minimizing residual deformations is the main goal after a severe loading incident, they are very helpful [11-16].

The two phases that SMAs go through are austenite and martensite. SMAs have superelastic behavior in the austenite phase. This feature can be employed to mitigate the residual distortions produced by vibrations created by loads, like those resulting from seismic activity. SMAs are applied in strips and sheets. However, a handful of academics have started using SMA as reinforcing bars inside PH areas just recently, where damage may fail the entire system. Due to the benefits of both FRP and SMA, it is now possible to use them in combination to strengthen RC members both inside and externally by using composite or hybrid materials [17-21]. These composite materials are thought to enhance the general performance of structures in certain BCJ-related investigations. Among the earliest studies to look at the uses of SMAs for civil engineering applications like prestressing, vibration control, and dampening were those by Janke et al. [22] and Song et al. [23]. A thorough examination of SMAs' many isolations uses, bracing systems, BCCs, and restrainers for managing seismic reactions was carried out by Ozbulut et al. [24]. SMAs find several applications in steel, concrete, and wood constructions as reinforcements, dampers, frequency controllers, and vibration isolation systems. Zareie et al. have presented a thorough review of these applications. The use of SMAs in structural engineering has been reviewed extensively, but there is currently a dearth of comprehensive reviews covering the latest developments, important findings, potential drawbacks, and potential applications of SMAs as reinforcement (such as rebars, strips, wires, and cables) to make RC structural parts stronger and more self-centering, such as beams, columns, beam-column joints, and shear walls. Additionally, despite the large number of SMAs that have been developed thus far, there is still a dearth of thorough instructions for the choice of SMAs based on material attributes that are most appropriate for a certain application, which has generated serious and useful challenges.

2. TYPES AND MECHANICAL PROPERTIES OF SMA

To enable a direct comparison, Fig. 2 summarizes the key material properties of several SMAs, including Ni-Ti, Ni-Ti-Nb, Cu, and Fe-SMA. Ni-Ti SMAs possess an elastic modulus that falls within the intermediate range; they have high yield stress, failure, and recovery strain.

Type of SMA	Elastic modulus (GPa)	Yield stress (MPa)	Failure Strain (%)	Optimum pretrain (%)	Activation Temperature(C^0)	Recovery stress (MPa)	Recovery strain (%)
Ni-Ti SMA	38-84	379-746	40-50	6-8	100-200	100-200	6-9
Ni-Ti-Nb SMA	25-63	232-350	9-37	6-7	108-200	354-560	5-7
Cu-SMA	20-35	180-210	18	-	-	-	7-12
Fe-SMA	75-165	400-550	40	2-4	160-500	130-580	0.15-4

Fig. 31: Characteristics and physical attributes of SMAs.

Low to moderate yield stresses and elastic moduli are among the desirable features of Ni-Ti-Nb SMAs. Their failure and recovery strains, on the other hand, are moderate to high.

Although Cu-SMAs have a large recovery strain, their elastic modulus, yield stress, and failure strain are all quite low. Among the remarkable characteristics of Fe-SMAs are their high elastic modulus, yield stress, and failure strain, as well as their modest recovery strains. Due to the varied compositions and thermal and mechanical treatments used for these alloys, the SMA properties displayed in Table 1 cover a wide range of values. The manufacturer and the individual application determine these characteristics, which in turn create a multiplicity of alternatives. Because of their high recovery strain, Ni-Ti SMA and Cu-SMA, two of the four SMAs previously discussed, demonstrated extraordinary superelasticity. Prior studies have extensively employed the property of SMAs to get self-centering behavior in RC structures. Studies on the periodic patterns of superelastic Ni-Ti SMAs have shown that even at 6% strain, this class of SMAs retains a residual strain of less than 1%. However, when cyclic stresses over 6% are applied, the recentering features' capacity to revert to their initial location is reduced. On the other hand, these SMAs 'recentering behavior is barely affected by the strain rate. When subjected to quasi-static cyclic stresses, superelastic characteristics similar to Ni-Ti SMAs were found in Cu-Al-Mn SMAs by Araki et al. On the other hand, materials with exceptional thermomechanical characteristics, such as Ni-Ti-Nb and Fe-SMA, display significant SME. [21-24].

3. BEAM-COLUMN CONNECTION REINFORCED WITH SMA BARS

Even though SMA materials provide advantages, including self-centering and energy dissipation, there is a lack of study about the use of SMA bars in BCJs. Furthermore, because SMA bars are more expensive, they have been specifically used in BCJs where they are crucial, like where the PHs are located. In the meantime, regular steel bars are frequently used to reinforce other components. Hybrid SMA-steel refers to the configuration of bar reinforcement that mixes steel and SMA. Researchers have found that the use of SMA bars to reinforce structures has produced remarkable results in terms of the structures' capacity to revert to their initial shape when the load is applied. Alam et al. [25-26] used an analytical model that had already been built to construct a FE model. By contrasting the FE model's output with the findings of two experiments, the model's accuracy was confirmed. In one experiment, a bridge pier was reinforced with SMA bars and spirals. In the other experiment, SMA bars in the PH region—which were joined by steel couplers—and steel bars in other places were utilized to reinforce a beam-column joint (BCJ). Cyclic loading was applied to both specimens. After reaching the yield point, experimental studies on the bridge pier and the SMA-reinforced BCJ revealed that they could recover a sizable percentage of their deformation. Consequently, there would be less need for repairs. Thus, Alam et al. made significant progress in understanding the BCJs' moment-curvature relationships. Their findings enable accurate prediction of the PH's position, crack width, and bond-slip relationship for SMA-reinforced joints under seismic loads. As demonstrated by other studies, the numerical results indicated that finite element analysis is capable of accurately predicting the load-displacement and moment-rotation curves [10].

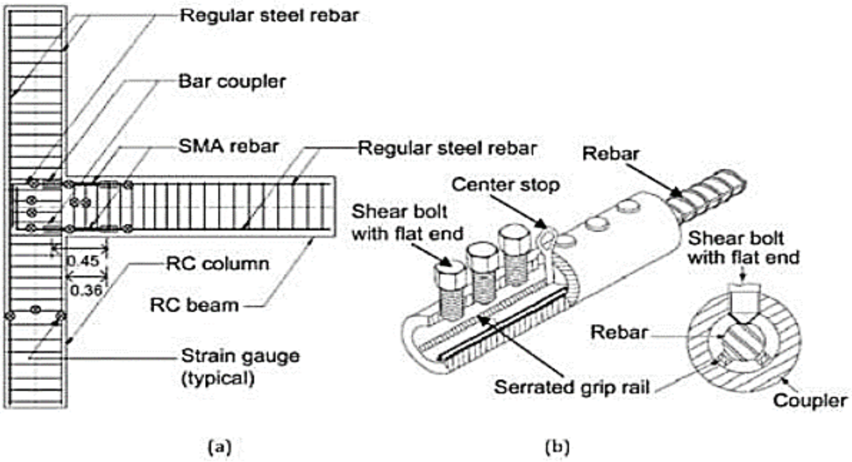

Fig. 32: Superelastic Ni-Ti SMA Bars for BCJ Details: (a) SMA and Steel bar Details; (b) Coupler.

Youssef et al. (2008) looked at the use of superelastic Ni-Ti SMA bars in the PH area of RC BCJs that were being loaded seismically. The particular characteristics of the SMA reinforcement specimen are shown in Fig. 3. With similar dimensions, the residual drift ratios of the conventional joint and the SMA (SMA)-reinforced joint were 4.94% and 1.98%, respectively. The results showed that using the SMA bar reduced energy dissipation, although the PH's location moved aside from column faces [27].

In a 2011 study, Nahdi et al. investigated a specimen of a reinforced concrete beam-column connection by adding SMA bars made of nickel and titanium to the PH area. After being repaired with concrete, the damaged BCJ was subjected to repeated lateral stresses. The results show that during cyclic loading, almost all of the permanent deformation in the RC BCJ was reversed, necessitating only minor repairs. Moreover, SMA (SMA) was used to remove the PH from the column faces, and both the repaired and original specimens' capacities for dissipating energy were comparable [28].

Yurdakul et al. (2018) The reinforcement of a BCJ with insufficient shear capacity was investigated by using diagonally positioned, externally adhered, and post-tensioned superelastic Ni-Ti SMA bars. Three specimens were used as controls, while two specimens were retrofitted with steel and SMA bars. Applying an axial force to the top of the column caused the three specimens to undergo quasi-static cyclic displacement with a drift ratio of up to 8%. In comparison to the other two types of BCJs, those reinforced with SMA showed a greater ultimate lateral load-bearing capacity (Fig. 6). While control BCJs failed brittlely, SMA-enhanced BCJs demonstrated little damage and ductility. By post-tensioning SMA rebars to yield, the retrofitting approach was enhanced. [29].

The introduction by Qian et al. (2022) is well crafted. The RC beam-column joint (BCJ) was enhanced by using superelastic Ni-Ti SMA bars and ECC (Engineered Cementitious Composite) materials. The researchers proposed using ECC materials in key areas of BCJs to improve their ability to withstand deformation. The PH region of the beam was fitted with SMA bars instead of the usual longitudinal bars, resulting in decreased energy dissipation and residual deformations. An experiment was carried out to evaluate the performance of BCJs in terms of self-centering ability, residual deformation, displacement ductility, energy dissipation capacity, bearing capacity, and causes of failure. To examine the seismic behavior of the BCJs, a finite element model of the SMA-ECC joints was created. The study highlights the potential of ECC materials to enhance the ductility and energy dissipation capacity of structures, making them a favorable choice for accommodating PH displacement. In addition, the properties of SMA bars can be greatly improved to enhance their self-healing and self-centering capabilities. The utilization of SMA and ECC composites enhances self-centering, energy dissipation, and ductility while also delaying the decrease in structural stiffness of the joint. [30].

To strengthen the interaction between reinforcement and concrete, researchers have experimented with deformed bars, hooked bars, and, most recently, SMAs. Since SMAs cause a deformed concrete member's strain to recover, their usage as reinforcement has become more common. When a material is distorted (in the martensitic phase) and heated above the so-called "Austenitic" transformation temperature, it undergoes the shape memory effect. When the material cools back to its initial martensitic phase, all of the distortion is restored. Previous studies have successfully induced strain recovery in plain concrete beams and SMA-reinforced concrete cylinders evaluated in four-point bending. This study on the slab column connection, one of the most important connections in moment-resisting reinforced concrete structures, is the consequence of the beam experiment's encouraging findings, which showed the production of nearly linear cracks beneath the reinforced section of the beam.

To analyze the performance of reinforced beam-column joints (RC-BCJ) with steel rebars and SMAs, Mahmoud M. Higazey et al. created a comprehensive finite element (FE) model in 2023. Pictured below is the model: Fig. 4. Fig. 5 shows the results of a parametric study in ABAQUS that optimized the employment of SMA bars to enhance the seismic resistance of RC-BCJ structures while keeping their energy dissipation capacity. This followed the model's validation using experimental data. Considerations such as the ratio of SMA to steel reinforcement, bar lengths, elastic modulus, concrete compressive strength, and axial load applied to the column were all part of the analysis. The model's predictive power for the optimal SMA bar length to deflect the PH away from the column face along the beam was demonstrated by the finite element simulation results. Furthermore, the modeling findings demonstrated that reinforced concrete-concrete joint assemblies can be significantly strengthened by including SMA bars alongside steel reinforcement. Research found that high-strength concrete, which considerably raised joint resistance, was the most important component [31].

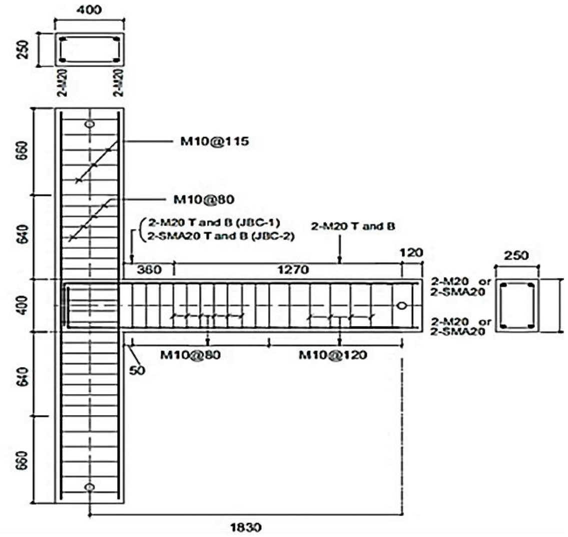

Fig. 33: Reinforcement Details of Specimens.

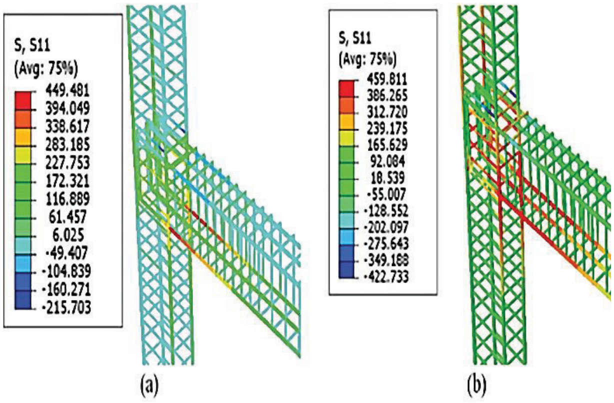

Fig. 34: Stresses of SMA Plates and Wire.

The four stirrups, which are positioned on the corners of the slab, give confinement to the joint, and the slab column connection is in charge of transferring load from the beam and column to the slab. It's a crucial site, especially in earthquake-prone areas. When the structure is shaken, the slab will attempt to shift in relation to the column to give the joint area sufficient ductile and energy-dissipative capacity without endangering the column. By constructing a slender column without offering it any constriction, the junction was weakened. This was done for the slab to exhibit the intended failure mode rather than the column.

4. COLUMNS

In buildings and bridges, columns serve as the principal building blocks that support the weight of the structure. Thus, to improve seismic performance, it is imperative to reduce permanent drift after a significant earthquake so that the structure can continue to function with little need for maintenance. Because SMAs are super-elastic, using them in critical areas reduces residual displacement. Super-elastic SMA bars can return to their original shape once the load is removed and have a larger linear elastic range of 4-12%.

Gisha George et al. (2022) investigated the behavior of a full-scale circular column, as depicted in Figs. 6 and 7, that was exposed to reverse cyclic loading in the critical area. The column had a height of 3 m and a diameter of 600 mm. Different kinds of SMA bars, including those based on nickel, iron, and copper, were used to reinforce the column. Throughout the experiment, the axial stress applied to the column stayed at 10%. The column has lower ductility but increased strength and maximum displacement due to the critical region reinforcement with NiTi and FeNCATB SMA. As illustrated in Fig. 8, it also exhibits a continuous drift ratio that is higher than 0.1%. The column has more load capacity, ductility, maximum displacement, and lesser residual drift. The essential area is strengthened with FeMnAlNi. It also has a large capacity for dissipating energy, as seen in Fig. 9 [32-33].

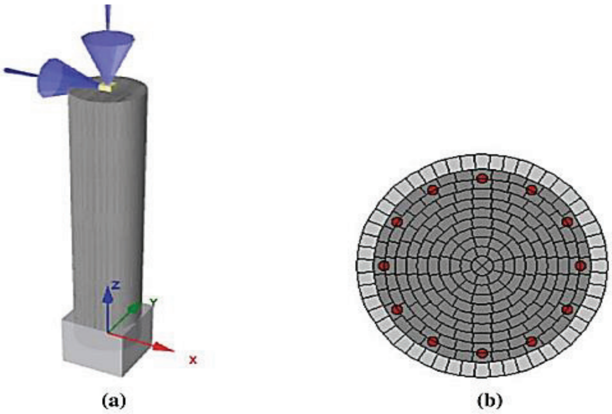

Fig. 35: Dimensions and Details of Specimens.

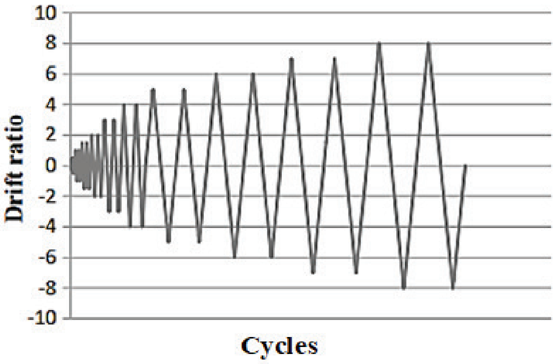

Fig. 36: Loading Protocol.

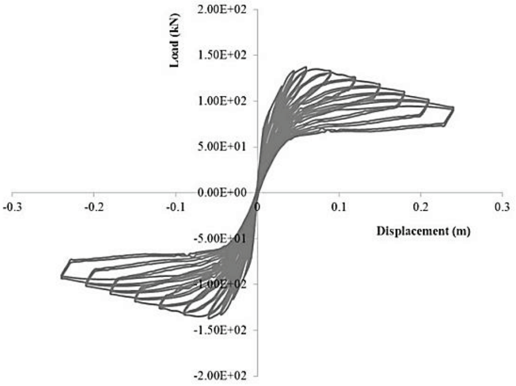

Fig. 37: Hysteresis curve of SMA-RC-Cu.

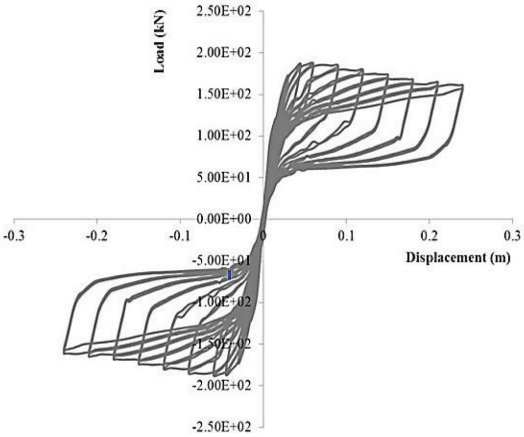

Fig. 38: Hysteresis curve of SMA-RC-Fe2.

Amr M. Hilal (2020) offered a simple technique that takes advantage of SMAs' superior properties. The SMA plates were tensioned and positioned exactly prior to confinement. The temperature was altered after the plates were positioned on the columns, which led to the SMA plates compressing the columns. The experimental program included six concrete column prototypes in a circular shape, each with a diameter of 100 mm and a height of 600 mm. Fig. 6. The characteristics examined in the experimental program include the kind of confinement (passive or active) and the tension force applied to the outside stirrups prior to confinement. It was observed that active SMA confinement enhanced the column capacities and that active confinement altered the behavior of the columns. Finite element models were used to confirm the experimental results; these models were run through the ABAQUS program, as illustrated in Fig. 7. The article discovered that the column capacities rose by 17% to 38% when compared to the unconfined column. The experimental program's results and the finite element analysis were quite close, indicating that a large-scale study might potentially use this simple technique in the future to examine a range of concrete columns [33].

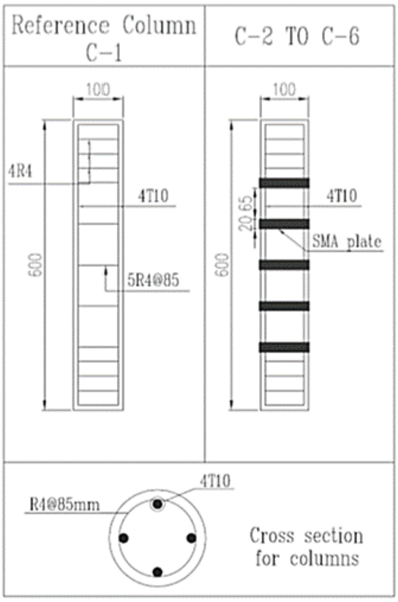

Fig. 39: Reinforcement Details of Specimens.

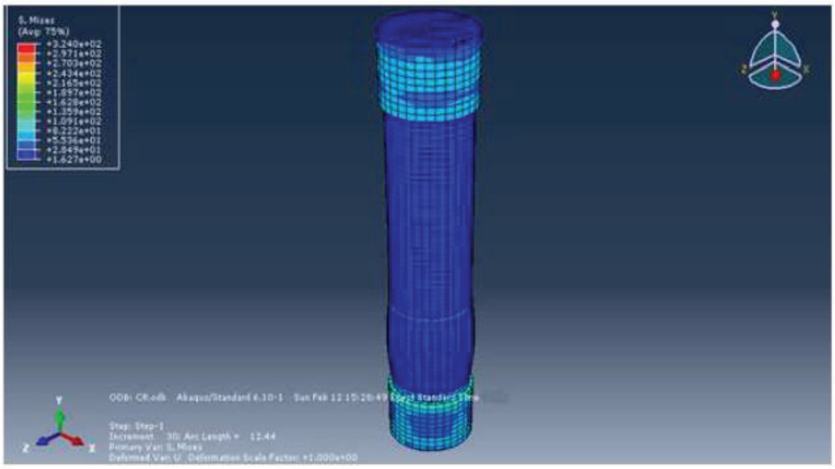

Fig. 40: Deformed Shape of Specimens.

The objective of this study is to investigate the impact of different wrapping methods of significant deformation SMA spirals on the lateral cyclic behavior of bridge columns. Quasi-static experiments are conducted to compare the seismic performance of RC columns confined with Ni-Ti Nb SMA spirals of variations in wrapping heights and spacing. The confined columns are subjected to cyclic lateral loadings and compression, and their behavior is compared to that of the as-built column. The test results show that Ni-Ti-Nb SMA with a significant degree of straining enhances the ability of the material to dissipate energy and its ductility while only slightly affecting the peak lateral strength of the bridge piers. Although the crack range in the SMA specimens is larger than in the control column, the SMA spirals reduce the concrete crushing zone and delay the buckling of steel bars. Decreasing the spacing between the SMA spirals strengthens the reinforcement effect, particularly in terms of ductility and energy dissipation. The configuration of damage between specimens reinforced with different wrapping methods shows minimal variation. [34].

Gholamreza Gholipour et al. (2023) investigated how lateral impact loads affected the dynamic response of bridge piers reinforced with SMA. Using LS-DYNA finite-element simulations [35-38], the profitability of a SMA-reinforced pier is contrasted to a column reinforced with steel bar. Variations in a number of characteristics related to the construction and loading are taken into consideration while evaluating the impact performance of the columns. These variables include the impact velocity (Vimp), the axial load ratio, the kind of SMA rebar, and the length of the SMA rebar (LSMA). The impact resistance and recoverability of the columns are significantly improved by adding SMA bars surrounding PH areas and modifying the impact loading height of the columns, according to the results of the Finite Element (FE) simulations. This is accomplished by reducing the degree of damage and residual column displacements. Furthermore, when SMA rebars are utilized, flexure is usually the main reason for column failure. More specifically, flexural modes are more likely to cause More columns reinforced with Ni-Ti SMA rebars than those strengthened with Cu-Al-Mn SMA rebars will fail. When the LSMA exceeds 0.5 during impact loads with velocities greater than 15 m/s, the negative impacts of SMA rebars on the impact resistance of the columns are noted. Additionally, a coefficient of restitution (ALR) greater than 0.1 greatly improves the columns' resistance to impact [39-40].

5. CONCULSIONS

The following findings may be made after examining the impact of utilizing SMA in enhancing the performance of RC columns and connections under the influence of cycles:

1. Shape Memory Alloy (SMA) bars offer advantages over normal steel, including lower losses due to friction and corrosion, greater ductility, and good shape recovery. However, their expensive cost limits their usage in reinforced concrete (RC) constructions.
2. Superelastic SMA bars used as internal reinforcements in RC beam-column junctions (BCJs) can significantly reduce residual displacements by nearly 90%.
3. Substituting steel reinforcements with superelastic SMA bars decreases the initial stiffness of RC structures due to the lower elastic modulus of SMAs.
4. Combining superelastic SMA bars with advanced concrete in areas with low elastic modulus effectively improves the energy dissipation capability of RC BCJs.
5. SMA bars enhance seismic performance in slab-column connections by absorbing and dissipating energy during earthquakes, reducing seismic forces transmitted to the connection. This increases structural resilience and mitigates potential damage.
6. Shape memory bars act as supplementary reinforcement in slab-column connections, working alongside conventional steel reinforcement to enhance load-carrying capacity and overall performance. SMA bars demonstrate effectiveness in resisting both static and dynamic loads.
7. SMA reinforcement in RC columns and connections enhances structural softness and stress, as the superelastic behavior allows for significant deformations without significant strength degradation. This improves overall ductility and delays brittle failure under cyclic loading.
8. SMA materials possess shape memory, enabling them to return to their original shape after deformation. In RC columns and connections subject to cyclic loads, SMA's ability to recover reduces residual deformation and improves damage recovery compared to traditional reinforcement.

9. Integrating SMA into RC columns and connections improves seismic performance by enhancing energy dissipation, ductility, and the capacity to recover from deformations. This leads to reduced damage and increased safety during seismic events.
10. Challenges exist in utilizing SMA, such as high material costs, compatibility with current construction techniques, long-term durability, and the need for reliable design guidelines. Further research and development are necessary to overcome these obstacles and effectively apply SMA for improved RC performance under cyclic loads.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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APPENDIX A: LIST OF ABBREVIATIONS

BCCs	Beam-Column Connections
FRP	Fiber Reinforced Polymer
RC	Reinforced Concrete
SCCs	Slab-Column Connections
SE	Super Elasticity Effect
SMA s	Shape Memory Alloy
SME	Shape Memory Effect