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Feasibility of Using Shape Memory Alloys in Reinforced Concrete Structural Elements

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Abstract- This article offers a comprehensive analysis of the potential application of shape memory alloys (SMAs) in reinforced concrete structures. It delves into the historical progression of SMAs and elaborates on the various types available. The distinct properties of SMAs, such as super elasticity and shape memory effect, render them highly appealing for utilization in reinforced concrete structures. An extensive review of experimental studies employing SMAs in diverse reinforced concrete applications is presented, encompassing the repair and fortification of damaged beams, deflection control, and self-healing concrete. Experimental findings indicate that SMAs have the capacity to partially rebound from deformations, mitigating residual displacements. However, their diminished yield stress and elastic modulus compared to steel may result in reduced strength and energy dissipation in RC beams. To address these issues, researchers suggest strategies like shifting the plastic hinge region away from the beam end using SMA rebars. The article also discusses the potential advantages and obstacles associated with incorporating SMAs in reinforced concrete structures. In conclusion, SMAs exhibit potential for application in reinforced concrete structures, although more research is required to thoroughly comprehend their behaviour and maximize their effectiveness.

Keywords- Shape memory alloys, concrete, super elasticity, shape memory effect, repairing, strengthening, deflection, self-repairing concrete, types, applications, review.

I. INTRODUCTION

Residential buildings and public infrastructure, including highways, bridges, ports, and dams, are the two uses of concrete that are most frequently seen. Concrete may be used to build structures of any size or form without being constrained by size or shape limitations due to its superior durability and chemical resistance than other construction materials [1].

It is not possible to build structural components that must withstand bending, tensile, or shear stresses, such as beams and slabs, using only concrete since it is a brittle material and has lower tensile and shear strengths than compressive values [2]. Widespread usage of reinforced concrete (RC) has been made to alleviate these concrete's weaknesses. The tensile and shear forces brought on by external loads are resisted by the steel reinforcement in RC. To prevent brittle fracture and to guarantee the safety and utility of the structure by suitably enhancing the bending strength of the beams, transverse steel reinforcement is specifically employed in RC beams [3].

However, the transverse steel reinforcement cannot stop inclined cracks from forming in the beam, and it starts to withstand external forces once cracks form [4]. Through these cracks, substances like salt, moisture, and carbon dioxide can enter concrete and cause the steel reinforcement to corrode, which lowers the RC member's ability to support loads and significantly reduces its durability, and causes concrete spalling [5, 6].

As the technologies for material engineering are advancing, smart materials were first introduced to the research community in the last quarter of the 20th century. A new group of smart materials has emerged in the research community that is capable to changes their mechanical properties in a controllable manner due to the material surrounding environment or external conditions. One of the emerging smart materials is shape memory alloys (SMA) which have gained significant attention in recent years due to their unique properties that make them suitable for a wide range of applications, including civil engineering [7].

These alloys exhibit two distinct properties; the shape memory effect (SME) and superelasticity are the shape memory effect (SME) and superelasticity that make them advantageous for civil engineering. These properties have led to the integration of SMAs into concrete structures for various purposes to enhance their performance, durability, and resilience, such as self-healing concrete, seismic-resistant structures, and structural control systems. SMAs can be used as reinforcement to enable self-healing properties in concrete, absorb and dissipate energy in seismic-resistant structures, and limit deformations in structural control systems. Overall, SMAs hold great potential for improving the performance and resilience of concrete structures in civil engineering applications [8].

II. RESEARCH SIGNIFICANCE

The primary objective of this article is to present a comprehensive overview of the historical evolution of Shape Memory Alloys (SMAs) and their research in the field of civil engineering, the implementation of SMAs in concrete structures, and to address the challenges and limitations encountered in the incorporation of SMAs within concrete structures.

III. HISTORICAL DEVELOPMENT

The development of Shape Memory Alloys (SMAs) and their application in civil engineering can be traced back to the discovery of the shape memory effect, the development of the first SMAs, and the evolution of SMA materials. This journey has seen numerous advancements in alloy compositions, processing techniques, and applications in civil engineering. Shape memory alloys (SMAs) are a type of smart material that possesses the unique ability to "remember" their original shape and return to it after being deformed.

The discovery of these materials can be traced back to the early 1930s, when Swedish researcher Arne Ölander made an accidental observation while studying the properties of gold-cadmium (Au-Cd) alloys. Ölander noticed that the material appeared to "remember" its original shape after being deformed. However, the practical applications of this discovery remained limited due to the high costs and poor mechanical properties of gold-based alloys [9].

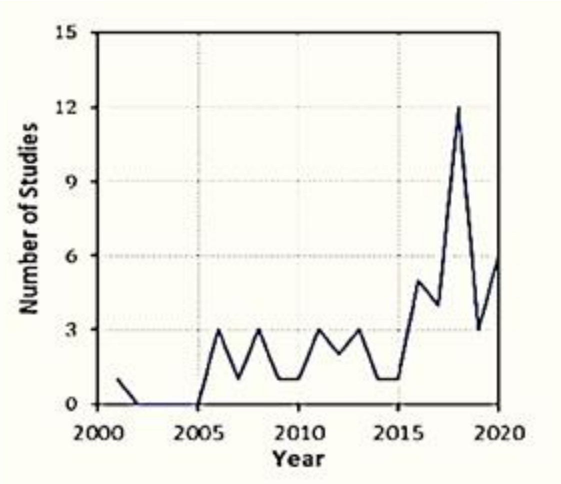
In the 1960s, researchers at the US Naval Ordnance Laboratory discovered the shape memory effect in nickel-titanium (NiTi) alloys, which they named Nitinol (Nickel Titanium Naval Ordnance Laboratory). Nitinol exhibited superior mechanical properties, shape memory effect, and superelasticity, making it suitable for various applications, including civil engineering [9]. In the years that followed, research into SMAs expanded rapidly. The first practical applications of shape memory alloys were in the field of aerospace, where the materials were used in actuators and other components that required precise control. In the 1980s, SMAs began to be used in medical devices, such as stents and orthodontic wires, due to their biocompatibility and unique mechanical properties [10].

In the 1980s and 1990s, early experimental studies demonstrated the potential of SMAs for damping and structural control. With the increasing need for more hazard-resilient structural systems, these studies laid the foundation for further research into the use of SMAs in civil engineering applications and the knowledge on SMAs has been widely circulated in the civil engineering community over the last two decades. In the late 1990s and early 2000s, researchers started exploring the use of SMAs in active structural control systems.

These systems employed the shape memory effect to control and limit deformations in structures, improving their performance and stability. The 2000s saw an increasing interest in the application of SMAs for developing seismic-resistant structures. Researchers extensively studied the behavior of SMA-reinforced concrete structures under seismic loads, showing the potential for enhanced energy dissipation and reduced damage [8].

In the 2010s, the first successful implementations of SMAs in civil engineering structures were reported. Some examples include the use of SMA reinforcements in bridge piers and the application of SMA-based devices in buildings for seismic protection. Since then, researchers have continued to explore the potential applications of SMAs in reinforced concrete structures. One of the main benefits of using SMAs in this context is their ability to undergo large deformations without permanent damage, which can help to improve the overall durability and resilience of the structure [10].

The interest in SMAs gradually increased in numerous researches at the period from 2001 to 2020, as presented in Fig. 1(a). Furthermore, Fig. 1(b) shows that North America has been the leading region in conducting research on SMAs, followed by Europe and Asia [16]. Shape Memory Alloys have two distinct phases: austenite and martensite. The austenite phase has a symmetric crystalline structure and is typically stable at high temperatures and low stresses. By contrast, the martensite phase has a low- symmetry lattice structure and is typically stable at low temperatures and high stresses [9].



(a)

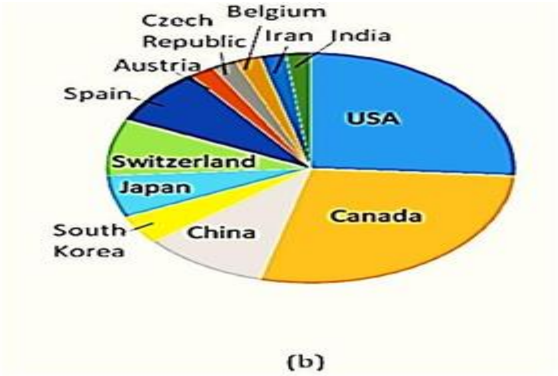


Fig 1. Distribution of the experimental studies conducted on RC structures with SMAs sorted by (a) year and (b) country [16].

The two main properties of SMAs that make them advantageous for civil engineering applications are Superelasticity and Shape Memory Effect (SME). Superelastic behavior also known as pseudo-elasticity is observed in the austenite phase. Superelasticity is a phenomenon in which an SMA can undergo large reversible strains without permanent deformation. When an external force is applied to the material in its austenitic phase, it can revert to its original shape once the force is removed.

This property is particularly useful in applications where significant deformation and energy dissipation are required, such as seismic-resistant structures. By contrast, the Shape Memory Effect (SME) is exhibited in the martensite phase of the SMAs. Shape Memory Effect refers to the ability of SMAs to recover their original shape upon heating after being deformed in their martensitic phase. This recovery can be employed in multiple engineering applications, such as self-healing concrete and structural control systems as shown in Fig. 2 [11].

In addition to their mechanical properties, shape memory alloys also are also highly corrosion-resistant and can withstand harsh environments, which makes them useful in various civil engineering applications, including self-healing concrete, seismic-resistant structures, and structural control system [12]. In summary, Shape Memory Alloys hold great potential for improving the performance and resilience of concrete structures in civil engineering applications. Their unique properties, such as the shape memory effect and superelasticity, can be harnessed to develop innovative solutions for self-healing concrete, seismic-resistant structures, and structural control systems.

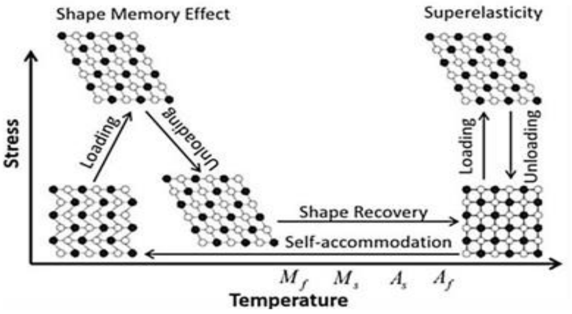


Fig 2. Shape Memory Effects and Superelasticity [11].

IV. TYPES OF SHAPE MEMORY ALLOYS

Shape Memory Alloys can be categorised into three shape memory characteristics, shown in Fig. 3 as follows [9]:

1. One-way shape memory effect (OWSME):
The one-way SMA (OWSMA) retains a deformed state after the removal of an external force, and then recovers to its original shape upon heating.

2. Two-way shape memory effect (TWSME) or reversible SME:
In addition to the one-way effect, a two-way SMA (TWSMA) can remember its shape at both high and low temperatures. However, TWSMA is less applied commercially due to the _training‘requirements and to the fact that it usually produces about half of the recovery strain provided by OWSMA for the same material and it strain tends to deteriorate quickly, especially at high temperatures. Therefore, OWSMA provides more reliable and economical solution [13].

3. Pseudoelasticity (PE) or Superelasticity (SE):
The SMA reverts to its original shape after applying mechanical loading at temperatures between the austenite-finish-temperature (Af) is the temperature where this transformation is complete and the highest temperature (Md) at which martensite can no longer be stress induced, without the need for any thermal activation [9].

Since the discovery of Nitinol, extensive research has been conducted to develop new SMA materials and improve their properties. Researchers have explored various alloy compositions to enhance the properties of SMAs. Some notable examples include copper-based alloys (Cu-Zn-Al and Cu-Al-Ni), iron-based alloys (Fe- Mn-Si), and high-temperature SMAs (NiTi-X, where X is an additional element) [15]. The choice of SMA depends on the specific application and the required properties of the material, such as temperature range, stiffness, and biocompatibility.

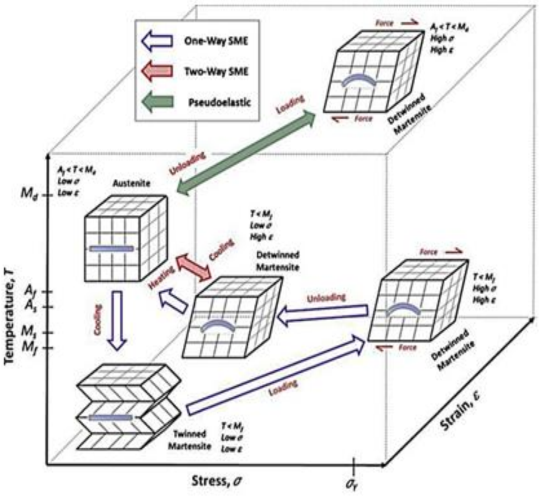


Fig 3. SMA phases and crystal structures [14].

The following section presents several types of shape memory alloys (SMAs) that are commonly used in various applications and addresses some of their advantages and disadvantages [9]:

4. Nitinol (NiTi-X, where X is an additional element):
Nitinol is a nickel-titanium alloy that is one of the most widely used SMAs. It is commonly used in medical devices such as stents, dental braces, and surgical tools.

- **Advantages:** Nitinol has excellent shape memory and superelasticity, making it ideal for applications that require high flexibility and resilience. It also has good biocompatibility and is widely used in medical devices.
- **Disadvantages:** Nitinol is relatively expensive compared to some other SMAs and can be difficult to process and work with. It also has a narrow temperature range for the shape memory effect.

5. Copper-based alloys (Cu-Zn-Al and Cu-Al-Ni):
Copper-based SMAs, such as Cu-Al-Ni and Cu-Zn-Al, are often used in applications where high damping capacity and low stiffness are required, such as in vibration damping or seismic retrofitting of buildings.

- **Advantages:** Copper-based SMAs have high damping capacity and low stiffness, making them ideal for vibration damping and other applications where low stiffness is desired. They also have good corrosion resistance and are relatively low-cost.
- **Disadvantages:** Copper-based SMAs generally have a lower shape memory effect than other SMAs and can be difficult to process and work with.

3. Iron-based alloys (Fe-Mn-Si):
Iron-based SMAs, such as Fe-Mn-Si and Fe-Pd, are less commonly used than nickel-titanium alloys but offer unique properties such as high magnetic field-induced strain and low cost.

- **Advantages:** Iron-based SMAs have unique properties such as high magnetic field-induced strain and low cost. They are also more environmentally friendly than some other SMAs.
- **Disadvantages:** Iron-based SMAs generally have a lower shape memory effect than other SMAs and can have poor fatigue resistance.

6. Gold-cadmium alloys (Au-Cd):
While not as widely used as some other SMAs, gold-cadmium alloys were the first materials observed to exhibit shape memory behavior and are still used in some niche applications.

- **Advantages:** Gold-cadmium alloys were the first materials observed to exhibit shape memory behavior and have been used in some niche applications, such as in precision instruments.
- **Disadvantages:** Gold-cadmium alloys are relatively expensive and have poor mechanical properties compared to other SMAs.

7. Other alloys:
There are also a variety of other SMAs that are used in specific applications, such as Ti-Nb-Zr, which is used in orthopedic implants, and Ni-Ti-Cu, which is used in microactuators.

The material properties of various SMAs Ni-Ti, Ni-Ti-Nb, Cu, and Fe-SMA were summarized in Table1. to provide a side-by-side comparison. Four varieties of SMAs, referred to as Ni-Ti SMA, Ni-Ti-Nb SMA, Cu-SMA, and Fe-SMA, respectively, have been primarily studied for use in civil engineering applications in prior research done between 2001 and 2020. More than half of previous investigations have focused on Ni-Ti SMAs, as seen in Fig. 4, partly due to the fact that these materials are readily available and employed in the automotive, aerospace, robotics, and biomedical sectors [16].

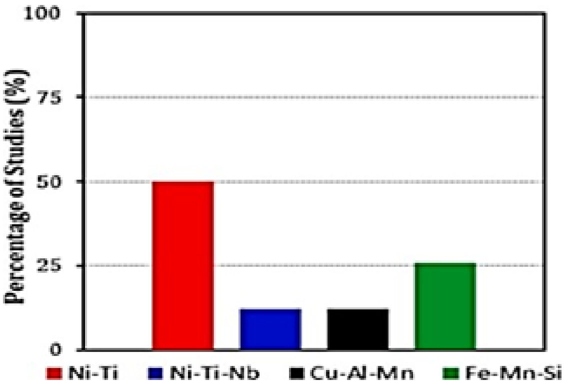


Fig 4. Distribution of the experimental studies conducted over 2001–2020 on using SMA in RC structures sorted by the type of SMA [16].

Although the most commonly used type of shape memory alloy (SMA) is nickel-titanium (Ni–Ti) alloy called nitinol in concrete structures from a practical and economical perspective, the use of NiTi-SMA in the construction field is not feasible because of its excessively high manufacturing and processing costs. On the other hand, many researchers have studied Fe-SMAs of various compositions. Owing to the superior mechanical properties, low cost with a price of only 5%–10% that of NiTi-SMAs, and high machinability of Fe-SMAs compared with those of other SMAs. Also Fe-SMAs are available for mass production and many researchers have studied Fe-SMAs of various compositions [17].

Table 1. Material and mechanical properties of SMAs used for strengthening RC structures [16].

Type ofSMA	Elastic Modulus (GPa)	Yield Stress (MPa)	Failure Strain (%)	Optimum Prestrain (%)
Ni-Ti SMA	38-84	379-746	40-50	6-8
Ni-Ti- Nb SMA	25-63	232-350	9-37	6-7
Cu-SMA	20-35	180-210	18	-
Fe-SMA	75-165	400-550	40	2-4

V. APPLICATION OF SHAPE MEMORY ALLOYS IN REINFORCED CONCRETE STRUCTURES

In this part, experimental studies that used SMA reinforcement for various reinforced concrete applications are comprehensively reviewed and systematically discussed.

Soroushian et al., (2001) [18] carried out the first investigation into the efficacy of Fe-SMA rods for the strengthening and repair of damage RC beams. They created an RC beam that was shear-deficient at the spot where the longitudinal bars were cut off, then they tested it using three-point bending. Diagonal SMA rods that were inserted externally at the bar cut-off site were then used to rebuild the damaged beam. Prestrained to 3%, the SMA rods were then activated at 300 °C. Then the repaired beam was loaded till it cracked. According to the results, the beam's original load-carrying capability was more than 90% recovered after the repair process.

Deng et al., (2006) [19] assessed the effectiveness of embedded Ni-Ti SMA wires in moderating the deflection of RC beams in one of the earlier experiments. They noted that when the embedded SMA wires were thermally activated, a significant recovery force was produced, which caused the tested beam to deflect upward instead of downward. Additionally, the recovery force was enhanced by increasing the prestrain of the SMA wires from 6.0% to 8.0%. Additionally, when the number of SMA wires increased, the recovery force increased as well. The results showed that the small-diameter SMA wires produced superior deflection control than the large-diameter SMA wires with the same total cross-sectional area of the embedded SMA wires.

Saiidi et al., (2007) [20] examined the responses of four small-scale concrete beams that were externally reinforced at the mid-section using superelastic Ni-Ti SMA bars. They compared these beams to four conventional steel-reinforced beams under four-point bending tests, with the reinforcement ratio at the mid-span as the main variable. The results of the tests showed that the residual displacements in the SMA-reinforced beams were significantly lower (approximately 1/5th) than those in the steel-reinforced beams of the same size. However, the stiffness of the SMA-reinforced beams was found to be 60% lower than that of steel-reinforced beams due to the lower modulus of elasticity of Ni-Ti bars compared to steel bars. Overall, the study suggests that a combination of high-strength steel and Ni-Ti rebars can result in reinforced concrete components that maintain adequate stiffness while also being able to partially recover from deformations.

A self-repairing concrete beam with superelastic Ni-Ti SMA wires and adhesives embedded into hollow fibers that spanned the whole length of the beam was proposed by Kuang and Ou (2008) [21]. The fundamental idea behind the technology was that at significant deformations, the brittle fibers would break, and once the SMA wires recovered the deflections of the beam with their superelasticity, adhesives would be released to fill up and heal the cracks. The experimental testing revealed that the mid-span deflection of the SMA-reinforced beam was reversed and the cracks were nearly completely healed after unloading following significant deformations (up to 2% of the span length).

Also, **Abdulridha et al., (2013) [22]** used a four-point bending test setup to study the behaviour of RC beams reinforced with superelastic Ni-Ti SMA bars at their critical zone, which is 600 mm of mid-span, as shown in Fig. 8. The loads used were monotonic, cyclic, and reversed cyclic loads. The SMA-reinforced specimens recovered 84% of their inelastic mid-span displacements under reversed cyclic loads at a displacement ductility of 9.5. However, with the typical RC beams of the same size tested in parallel, the recovery of the inelastic displacements was less than 26%. The SMA-reinforced beams' strength and ductility were also equivalent to those of specimens with conventional designs. However, the SMA-reinforced beams' energy dissipation under reversed cyclic loads was 54% lower than that of conventional beams.

Superelastic Cu-SMA reinforcing rebars and an epoxy injection network were used in **Pareek et al.'s (2014) [23]** evaluation of the efficacy of an externally activated self-repairing approach. Beams with deformed steel rebars, threaded steel rebars, and threaded SMA rebars as reinforcing alternatives were taken into consideration for this purpose. The specimen with the threaded SMA rebars reportedly demonstrated a flag-shaped hysteresis loop with a significant displacement recovery. The specimens, however, that had threaded and deformed steel rebars showed significant residual deformations. Additionally, it was found that the SMA-reinforced beam had the least remaining cracking width.

In year **2018, Pareek et al. [24]** also investigated the displacement of the plastic hinge location after the use of superelastic Cu-SMA rebars. The stated study took into account four beams, with the first beam having steel rebars and the other three having a mix of steel and SMA rebars. The longitudinal centroids of the SMA rebars were placed at the end, 0.5D from the end, and 1D from the end of the beam, where D is the depth of the beam, in order to move the plastic hinge location along the length of the beam. The beams were tested so that the mid-span did not experience any bending moments while the beam ends experienced the greatest moments. Due to their (relatively) low yield stress, the experimental test results demonstrated that the plastic hinge may be positioned to match the placement of the SMA rebars. The ability of relocating the plastic-hinge area away from the beam end was recently introduced. It should be noted that the reduced yield stress/elastic modulus of SMAs relative to steel might lead to decreased strength and energy dissipation in RC beams when SMA rebars are used at the location of the maximum moment. However, it was discovered that the shortcomings related to strength and energy dissipation were greatly resolved with the relocation of the plastic hinge.

Rojob and El-Hacha, (2015) [25] investigated the ductility of reinforced concrete beams strengthened with Fe-SMA bars under different loading and environmental conditions and compared it to a reinforced concrete beam with the same properties but strengthened with prestressed CFRP strip tested by Hadisiraji and El-Hacha (2014) [26]. In their results, they found that in terms of flexural behavior at service and ultimate loads, Beam-CFRP showed slightly better performance with 11-15% higher than Beam-SMA. However, the energy dissipation for the Beam-SMA was significantly improved with a 70% increase compared to a reduction of 6%. This is due to the ductile behavior of the Fe-SMA bar compared to the CFRP strip. The ductility index of the Beam-SMA was also increased by 41%, while the Beam-CFRP had 8% reduction. This means, with little compromise of service and ultimate loads, Beam-SMA shows a significant gain of ductility.

Shahverdi et al., (2016) [26] investigated the use of near-surface mounted (NSM) Fe-SMA strips for the flexural strengthening of reinforced concrete beams. Four processes made up the experimental process: prestraining the strips up to 1.5%, grouting them into grooves, activating them by resistive heating and cooling, and lastly loading the reinforced beams until they failed under a four- point bending test. In comparison to specimens with nonactivated SMA strips, the specimens with activated SMA strips had a cracking load that was 80% greater. For beams with active SMA strips, a substantial decrease in the mid-span vertical deflection was also found.

For flexural strengthening, **Michels et al., (2018) [28]** also mechanically affixed Fe-SMA strips to the tension side of RC beams. The strips were prestrained to 2% before being resistively heated at 160 °C to activate them. In comparison to normal beams and beams strengthened by CFRP strips, the experimental test results demonstrated a considerable increase in the flexural strength of the beams enhanced by the Fe-SMA strip. Additionally, the beams reinforced with Fe-SMA strips showed improved stiffness, which reduced the vertical deflection observed during the four-point bending tests.

Zerbe et al., (2017) [29] investigated the effectiveness of retrofitting reinforced concrete structural elements using iron-based shape memory alloys (Fe-SMA). Their study included two parts: retrofitting of shear-critical beams and confinement of columns under concentric uniaxial compression as shown in Fig. 5(a) and Fig. 5(b). In the first part, 15 tests were performed on small-scale T-beams to investigate their shear behavior. The results showed an increase in the shear capacity of the beams retrofitted with an external Fe-SMA strip reinforcement. In the second part, 25 small-scale circular columns were tested under uniaxial compression. The test results showed an increase in the axial capacity and ductility of the columns with the increase in the number of Fe-SMA layers. The internally reinforced columns showed a higher gain in capacity and ductility when confined with Fe-SMA than the unreinforced columns. Further study is needed to optimize this new technique and better understand the properties of the materials under different combinations of stresses.

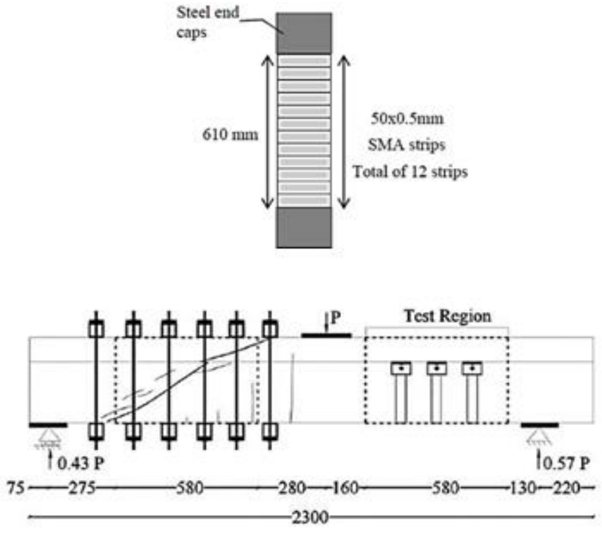


Fig 5. External Protection system: (a) retrofitting of shear-critical beams, (b) confinement of columns under concentric uniaxial compression [29].

Rojob and El-Hacha (2017) [30] also used near-surface-mounted (NSM) Fe-SMA rebars to prestress RC beams. The SMA rebars were grooved into the tension side of the RC beams with an initial prestrain of 6%, and they were then activated at temperatures exceeding 300 °C. The yield, ultimate load-bearing capacity, and ductility of the RC beams after prestressing were all found to have increased by more than 30%. The referenced study came to the conclusion that SMA strengthening can be preferable to FRP strengthening since it results in an improvement in both strength and ductility as opposed to FRP strengthening, which frequently shows a strength ductility ratio.

Abd Hamid et al., (2018) [31] investigated the superelastic behavior of using shape memory alloy, NiTi as reinforcement in concrete beams under monotonic loads. They used control beam sized 125 mm x 270 mm x 1000 mm and was reinforced with 3 numbers of 12 mm diameter bars for compression, 3 numbers of 12 mm bars for tension or hanger bars, and 3 numbers of 6 mm diameter at 100 mm c/c for shear, respectively. While replacing the steel rebar in the critical section of the beam with the bare minimum of 200mm of 12.7mm superelastic Shape Memory Alloys as shown in Fig. 6.

In their results, they observed that the contribution of the SMA bar in combination with high strength steel to the conventional reinforcement showed that the SMA beam has exhibited an improve performance in term of better crack recovery and deformation., they found that using of SMA as reinforcement increased first crack load and the ultimate loads by 38.83% and 42.92% respectively, and the crack width at maximum load decreased with 41.67%. They noticed that the superelastic properties of SMA bar increases the stiffness of the SMA beam under lower load. However, the results showed that the SMA reinforcement has lower modulus of the elasticity than the steel reinforcement, and the stiffness of the SMA-reinforced beams was found to be 67.59% lower than that of steel-reinforced beams with respect to the increasing of load. Therefore the usage of hybrid NiTi with the steel can substantially diminish the risk of the earthquake and also can reduce the associated cost aftermath [31].

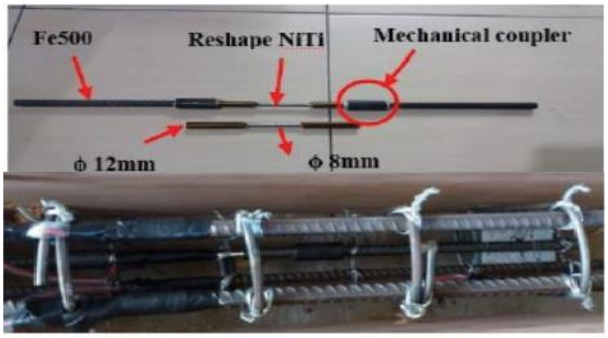


Fig 6. Ni-Ti rebar with the bar break coupler to splice the NiTi rebar with steel [31].

In order to adapt beam-column connections, **Oudah and El-Hacha (2018) [32]** suggested relocating the plastic hinge region away from the column's face. As illustrated in Fig. 7, a vertical slit was inserted for this purpose at a distance from the end of the beam equal to the effective depth, and the connection was strengthened with superelastic Ni-Ti SMA rebars. Three examples were taken into consideration: one served as a control specimen with standard detailing, while the other two had SMA, steel rebars, and a vertical slit in the beam. In comparison to the control specimen, the SMA-reinforced beam-column connection performed better in terms of self-centering, lowering joint distortion, minimising the pinching shear impact, and moving the plastic hinge area. Additionally, the SMA rebar-made specimen showed a larger drift capacity than the other two specimens examined while recovering the majority of the residual displacements.

Shahverdi et al., (2019) [33] demonstrated the feasibility of a Fe-SMA shear reinforcement using memory steel bars and shotcrete mortar. Six large scale T-beams were tested up to shear failure happened and repaired with memory steel stirrups and shotcrete mortar, see Fig. 8. Beams were put under a four-point bending stress until they cracked. With the use of 3D digital image correlation devices, crack development on each beam's shear span was observed, and they found that maximum crack widths decreased by 75% in repaired beams compared to the control beam at the stress level of 300 kN. Also, the repaired beams had a higher load mid-span deflection than the control beam, correlated to the higher stirrups cross-sections and prestressed force due to the activation of memory steel stirrups. Finally the concluded that memory-steel stirrups embedded in a shotcrete layer provide a feasible solution for shear strengthening.

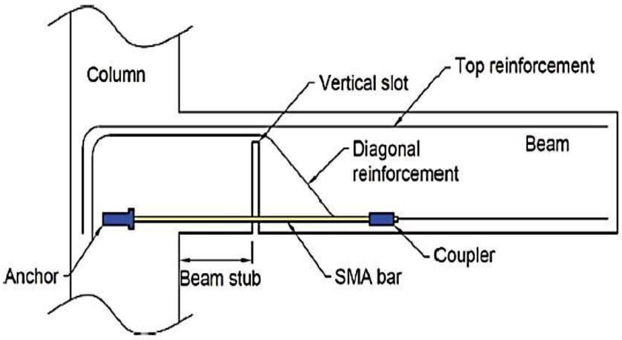


Fig 7. Schematics of the strengthening technique used for the beam-column joint with SMA rebars [32].

Fe-SMA strips were studied by **Montoya-Coronado et al., (2019) [34]** for shear strengthening of weak RC beams. To do this, prestrained Fe-SMA strips that had been thermally activated at 160 °C were externally wrapped around a series of RC beams. The shear strength of the reinforced beams was reported to have increased significantly (up to more than 80%), resulting in flexural failure as opposed to shear failure for the unstrengthened beams. The stronger specimens also showed increased ductility, demonstrating the efficacy of the suggested strengthening method.

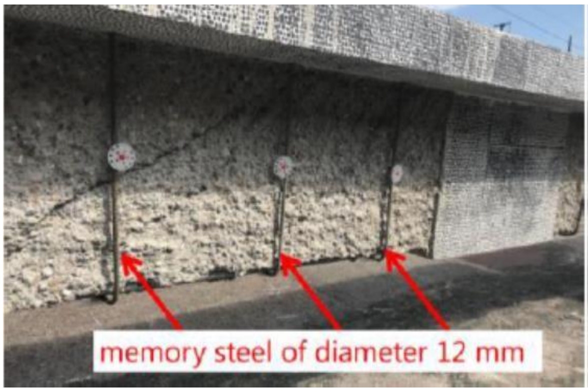


Fig 8. Installed memory steel of diameter 12 mm on Beam 1->Beam 4 [33].

For four years, **Shahverdi et al., (2019) [35]** observed the long-term performance of RC beams that had activated Fe-SMA strips added to them in an outdoor exposure setting. The sustained loads placed on the beams were greater than their breaking loads. The mid-span deflections for the beams reinforced with active and non-activated SMA strips were the same, indicating a steady prestressing force in the beams. Depending on the parameters of the surrounding temperature, stress relaxation in the range of 3%–10% has also been recorded for Ni–Ti–Nb SMAs.

The strengthening of reinforced concrete (RC) beams in flexure using near-surface-mounted (NSM) Fe-SMA reinforcements was investigated in a research by **Abouali et al., (2019) [36]** using a 3D nonlinear finite element model in ABAQUS. The accuracy of the suggested models was confirmed by comparisons between the output of FE (finite element) models and experiments reported in the literature. They used the validated FE model to identify the effects of various design parameters on the performance of RC members strengthened with Fe-SMA reinforcements. Finally, an RC beam strengthened with NSM CFRP strip was modeled and compared to the NSM Fe-SMA strengthened RC beam. This study indicated that NSM Fe-SMA strengthening of a concrete beam with a low steel reinforcement ratio results in enhancement of stiffness and more than a 60% rise in the load carrying capacity for either prestressed or unprestressed beams. Also, they found that ductility and energy absorption of the CFRP strengthened beam is significantly less than the Fe-SMA strengthened beam.

In a different investigation, Ni-Ti-Nb SMA spiral wires were employed by **Rius et al., (2019) [37]** to reinforce RC beams against shear. The beam specimens shown in Fig. 9 were wrapped with SMA spirals, which were then heated to 200 oC and activated. The modified beams showed generally ductile behaviour, which contributed to a notable improvement in their shear strength. The results demonstrated that the pre-cracked beams that had undergone retrofitting with SMA spirals after being loaded to 98% of their shear capacity functioned comparably to the specimens that had undergone pre-cracked retrofitting. The stated study came to the conclusion that, despite some losses in recovery stresses caused by geometric flaws, retrofitting the beams with Ni-Ti-Nb SMA spirals is promising.

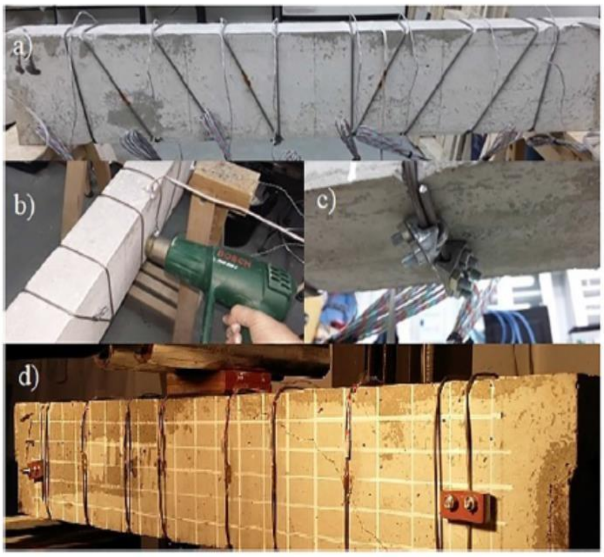


Fig 9. (a) Rear view of a strengthened beam, (b) activation process by means of heat gun, (c) detail of the anchoring using U-Bolt saddle clamps, and (d) front view of a beam with left and right outermost wire anchors [37].

Raad and Parvin (2020) [38] studied flexural strengthening of reinforced concrete (RC) beams by prestressed fiber reinforced polymers (FRP) and iron-based shape memory alloys (Fe-SMAs) using the near surface mounted (NSM) technique. ANSYS nonlinear finite element analysis (FEA) software was employed to model RC beams which were validated using the data from an existing experimental study in the literature. Parameters considered were rod length and NSM rod material type under three prestressing levels 20, 30 and 40%. The results showed that the validated FEA beam models and experimental results were in good agreement with less than 10% difference.

When NSM CFRP rods were replaced with GFRP, higher ductility was observed for all prestressing levels (20, 30, and 40%) due to higher tensile strain of GFRP material. Beams reinforced with Hybrid CFRP-GFRP had superior performance in terms of deflection and load-carrying capacities as compared to beams strengthened solely with CFRP and GFRP rods. Fe- SMA strengthened beams resulted in significant ductility improvement ranging from 54 to 80% at all prestressing levels when compared to CFRP, GFRP, and Hybrid CFRP- GFRP strengthened beams.

Cladera et al., (2020) [39] suggested employing U-shaped Fe-SMA strips externally anchored to the T-beam web for the shear strengthening of RC T-beams, as illustrated in Fig. 10. The strips were first thermally activated at 160 °C after being prestrained. The shear capacity of the reinforced beams was shown by the experimental test results to be 30% higher than that of the reference beam. The emergence of cracks in the reinforced beams was postponed, and the breadth of the fracture was decreased. However, the specimens' ductility was lower than anticipated, which was explained by the way the SMA strips were anchored to the T-beam's web.

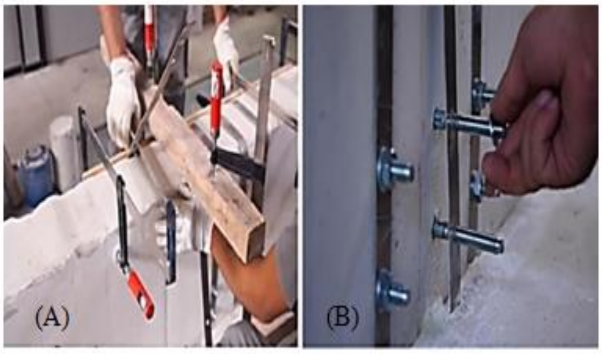


Fig 10. Steps of the active strengthening method: A) pre-strained strips placed on the web. B) Anchorage by mechanical fasteners [39].

Czaderski et al., (2021) [40] used stirrups made of activated and non-activated Fe-SMA buried in a mortar layer to reinforce large-scale T-beams against shear. In order to implant the U-shaped stirrups, a mortar layer was first sprayed over the holes that had been bored within the flange, shown in Fig. 11. In comparison to non-activated stirrups, the activated SMA stirrups reduced the deflection of the beam, the quantity and breadth of fractures, and the stresses in the internal steel at the serviceability limit state more than they did. The shear capacity of the beams also underwent a substantial improvement. As a result, at SMA stirrup reinforcement ratios of 0.31% and 0.47%, respectively, an improvement of 71% and 86% in the load-carrying capacity of the reinforced beams were observed.

Fig 11. Installed memory-steel stirrups on one of the test beams and application of spray mortar to one of the test beams [40].

Yeong-Mo et al., (2022) [41] investigated numerically the prestressing effect by Fe-based shape memory alloy bars on bending behavior of reinforced concrete beam using ANSYS software. Ten specimens were constructed to evaluate the bending behavior of concrete beams reinforced with Fe-SMA bars. Figure 12 shows the photos of the Fe-SMA bars, assembly of the Fe-SMA bars and the stirrups, mold for casting the concrete and the concrete casting process for the experiments.

The results showed that the FE simulation model was able to capture the bending behavior of the RC beam prestressed with the Fe- SMA bars, but slightly overestimated the prestressing effect. The bending load predicted by the FE simulations was 20-30 kN higher than that obtained in the real experiments. The prestress induced by the activation of the Fe-SMA bars was influenced only slightly by the sequence of the activations of multiple Fe-SMA bars. FE simulations of the RC beams prestressed by different numbers of the Fe-SMA bars qualitatively reproduced the experimentally observed bending deformation behaviors very well. The developed FE model can be used for an optimization study to select the best possible design parameters for prestressing the RC beam with the Fe-SMA bars [41].

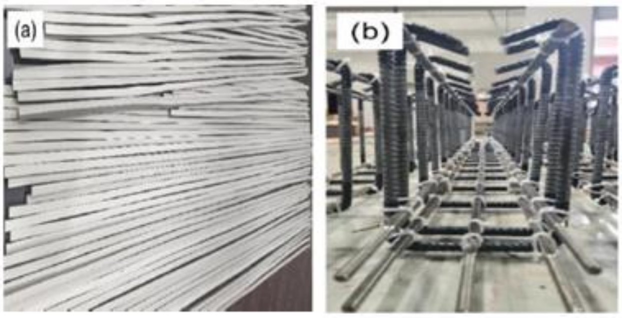


Fig 12. Photos of (a) Fe-SMA bars used for the experiments, (b) Fe-SMA and stirrup assembly [41].

Ji et al., (2022) [42] conducted an experimental and analytical evaluation of the shear performance of a reinforced concrete (RC) beam reinforced with Fe-based shape memory alloy (Fe-SMA) stirrups. They prepared five specimens with different spacing (300 and 200 mm) between the Fe-SMA stirrups and whether they were activated or not. They found that the specimen reinforced with Fe-SMA stirrups at 200 mm spacing had 27.1% higher shear strength than the specimen reinforced at 300 mm spacing. The activation of Fe-SMA stirrups increased the shear strength by up to 7.6% and reduced the number of shear cracks compared to non-activated specimens, indicating that Fe-SMA stirrups could improve the usability of concrete members by increasing their shear strength and stiffness and controlling crack formation.

In addition, the researchers conducted finite element method (FEM) analysis using LS-DYNA software to predict the shear performance of the RC beam reinforced with Fe-SMA stirrups. The predicted ultimate load and displacement of each specimen had errors less than 1.4% and 9.4%, respectively. The FEM analysis also predicted the change in failure mode and stiffness improvement due to the activation of Fe-SMA stirrups. These results suggest that the proposed FEM analysis model can effectively predict the behavior of an RC beam reinforced with Fe-SMA stirrups [42].

Khalil et al., (2022) [43] tested experimentally three circular columns under an axial compression force. The confinement of reinforcement-type steel strips and (Fe-SMA) spiral stirrups, main reinforced steel bars, as well as numerical simulation using finite elements, were all researched. The (Fe-SMA) spiral stirrups were considered strengthening techniques, internal and external confinement. Axial compressive load, load-displacement curve, and strain-reinforcement bars are all terms used to define the cause of failure. Strengthening by Fe-SMA stirrups external reinforcement maximum gains in compressive strength of around 69.99% for stirrups steel reinforcement columns and 51.64% for Fe-SMA stirrups internal reinforcement.

More recently, Lee et al., (2023) [44] conducted an experimental study to evaluate the seismic performance of a concrete column retrofitted with an iron-based shape memory alloy (Fe-SMA) under cyclic loading. The study also monitored internal damage using an ultrasonic pulse velocity (UPV) test. Three reinforced concrete (RC) columns were tested: a non-retrofitted RC column as a control, a carbon fiber-reinforced polymer (CFRP) column, and an Fe-SMA retrofitted column. The UPV test was used to measure the through-thickness velocity during cyclic loading, allowing for quantification of damage levels and evaluation of retrofitting effectiveness.

The results showed that the Fe-SMA retrofitted RC column exhibited distinct behavior during cyclic loading compared to the control and CFRP specimens, with a relatively lower velocity reduction and degradation rate throughout the loading cycle. The experimental results demonstrated a maximum improvement of 175% in seismic performance of the Fe-SMA retrofitted RC column compared with the controlled column The Fe-SMA retrofitting procedure was found to be more efficient than CFRP, and surface damage was observable after seismic loading [44].

VI. CHALLENGES AND LIMITATIONS

Shape Memory Alloys (SMAs) are unique materials that have the ability to return to a pre-defined shape after being deformed, by applying heat or external stress. In recent years, there has been growing interest in using SMAs in reinforced concrete structures due to their potential benefits and unique properties. However, there are also challenges associated with their use.

1. Potential Benefits:

1.1 **Self-healing:** SMAs can be used to create self-healing concrete structures. When cracks appear in the structure, the SMAs can be heated to activate their shape memory effect, closing the cracks and restoring the structure's integrity. This can help to reduce maintenance costs and prolong the service life of the infrastructure [12].

1.2 **Seismic resistance:** SMAs have excellent energy-dissipation capacity and can help to reduce the damage caused by earthquakes. When used as reinforcement in concrete structures, they can absorb and dissipate the energy from seismic movements, providing better performance under seismic loading [8].

1.3 **Corrosion Resistance:** SMAs are known for their corrosion resistance, which can be advantageous in aggressive environments where traditional steel reinforcement may corrode and deteriorate over time. This can lead to longer-lasting structures and reduced maintenance costs [12].

1.4 **Lightweight:** SMAs are lighter than traditional steel reinforcement, which can lead to reduced dead loads and a lighter overall structure. This can be beneficial in certain applications, such as bridges and high-rise buildings [8].

2. Challenges:

2.1 **Cost:** One of the main challenges of using SMAs in reinforced concrete structures is their high cost compared to traditional steel reinforcement. The cost of SMAs is significantly higher due to the complex manufacturing processes and the use of expensive materials, such as nickel and titanium [8].

2.2 **Limited availability:** The availability of SMAs is limited compared to traditional steel reinforcement, which can make it difficult to source large quantities for construction projects.

2.3 **Design complexity:** The use of SMAs in reinforced concrete structures introduces new design complexities, as engineers need to account for the unique properties of the material, such as its shape memory effect and superelastic behavior. This requires advanced modeling techniques and a deep understanding of the material behavior [16].

2.4 **Temperature sensitivity:** The shape memory effect in SMAs is temperature-dependent, which means that their performance can be affected by changes in ambient temperature. This can be a challenge in designing structures that are exposed to varying environmental conditions [8].

2.5 **Long-term performance:** The long-term performance of SMAs in reinforced concrete structures is still not well understood, as they have not been extensively used in this application. Further research and investigation are needed to fully understand their behavior and address potential concerns [35].

VII. CONCLUSION

Based on discussion on previous sections, few conclusions can be made up. SMAs were discovered in the 1930s with limited practical applications due to high costs and poor mechanical properties. SMAs were first used in aerospace and medical devices before expanding into civil engineering applications in the 1980s and 1990s and successful implementations of SMAs in civil engineering structures were reported in the 2010s. Shape Memory Alloys (SMAs) are advantageous for civil engineering applications due to their superelasticity and shape memory effect. Ni-Ti SMAs are the most commonly studied in civil engineering applications due to their availability and usage in various industries, but Fe-SMAs have gained interest due to their superior mechanical properties, low cost, and high machinability.

According to earlier research, RC beams, columns, and beam-column junctions were the subjects of around half of the investigations that were done. The fact that SMAs are simple to apply to horizontal structural elements explains why so many research have an emphasis on beams.

SMAs offer advantages over conventional steel for strengthening and self-centering RC structures, including excellent shape recovery, enhanced ductility, and easy installation. Superelastic SMAs, such as Ni-Ti and Cu-SMAs, can reduce residual displacements and lead to self-centering behavior, but may result in low initial stiffness compared to conventional steel. Fe-SMAs, with their high elastic modulus, can be used as internal reinforcements, especially as prestressing elements, and are well-suited for applications where the SME needs to be exploited.

The use of SMAs, such as Ni-Ti-Nb and Fe-SMA longitudinal reinforcements, can enhance stiffness, crack resistance, and reduce deflection and residual displacements under extreme loads. Activated SMAs can be utilized in existing RC structures to add self-centering behavior and reduce the need for repair activities. SMAs offer significant potential benefits for reinforced concrete structures, such as self-healing capabilities, improved seismic resistance, and corrosion resistance. However, their high cost, limited availability, and design complexities present challenges that need to be addressed before they can be widely adopted in the construction industry.

Future studies are needed to evaluate the feasibility of using SMAs for prestressing columns, beam-column joints, and walls, and to further explore the combined prestressing effect of longitudinal and transverse SMA reinforcements. Research is still in the initial stages, and further understanding is needed on aspects such as bond behavior, stress relaxation, and integrity of the concrete substrate after the thermal activation of SMA.

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