Advancing Seismic Retrofitting: Unveiling the Impact of Shape Memory Alloys on Structural Resilience and Beyond

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Abstract. Reinforced concrete (RC) buildings face significant risks from natural disasters such as earthquakes and hurricanes, necessitating prompt maintenance and retrofitting. This study explores the application of shape memory alloys (SMAs) as a promising retrofitting technique, leveraging their unique attributes such as super elasticity and shape memory effect. This research focuses on seismic retrofitting with SMAs, aiming to address gaps in understanding their behaviour under extreme loading conditions, such as seismic or impact loading. Employing a comprehensive methodology, combining quantitative and qualitative analyses, the study reviews relevant literature, categorizes key aspects, and conducts a comparative analysis of the selected papers. The investigated SMA applications include shear walls, frames, columns, and beam-column joints (BCJ). A comparative analysis was conducted for the aforementioned elements with residual HZ drift as the controlling parameter. Results indicate that SMA usage at lower levels can extend a structure's fundamental period and reduce seismic energy transmission to higher floors. The study identifies effective retrofitting techniques, with enhancing coupled beams in shear walls emerging as the most promising (34mm residual drift), showcasing superior deflection reduction. Moreover, the investigation recommends future research directions, emphasizing the need for 3D analyses and how to create a semi-experimental environment, and exploration of SMA applications in seismic retrofitting. The study's holistic approach provides valuable insights into state-of-the-art seismic retrofitting with SMAs, offering a foundation for future advancements and orientation for enhancing structures' resilience against dynamic and extreme forces using SMA.

1. Introduction

The resilience and safety of reinforced concrete buildings in the face of natural disasters are of main concern within the civil engineering and construction sectors. Natural disasters, especially earthquakes, pose a constant threat to these buildings [1]. Extreme weather conditions have the potential to cause a substantial ageing effect, which could lead to cracks, buckling, or even partial collapses [2]. This weakness raises questions about the building's ability to withstand additional accelerated loadings in addition to endangering its immediate structural integrity. For smaller buildings, rehabilitation may be a viable option, but for mid- to high-rise structures, it's essential[3]. A lot of techniques are designed to make these structures more resilient to Seismic effects. The use of bracing systems, fibre-reinforced polymer (FRP) jacketing, steel jacketing, and reinforced concrete jacketing stands out among the many.

Using shape memory alloy (SMA) as a retrofitting technique has been a newly introduced yet promising technique for their abilities and specifications [4]. Recently, shape memory alloy (SMA) was released as a novel smart alloy that can withstand (8~13%) extremely high strain. This material possesses super elasticity, frequently referred to as pseudo-elastic (SE), and shape memory effect (SME) properties, which allow it to regain its shape following the absence of external forces and temperature. [5], [6]. These materials offer beneficial damping characteristics, superior recentring abilities, and improved corrosion resistance at an affordable price [7]. Additionally, the concrete sections can be readily and actively restricted, increasing their ultimate strain capacity, flexural ductility, and shear strength by only using these effects of the alloys' shape memory. They are extremely sensitive to temperature, phase of usage, loading pattern, strain rate, and pre-strain conditions [8].

There is a knowledge gap in using SMA because of the behaviour of this technique under other types of extreme loading on different elements since this technique is relatively new [9]. Also, a theoretical gap, the lack of understanding of 3-D behaviour which will lead to ignoring depth effects and limited scope of analysis, moreover, a methodological gap, could be misleading due to the inaccurate predictions and results obtained from 2D analysis. This will lead to another difficulty in generalizing models to the 3D context in other extreme loading cases.

Thus, the main aim of this paper is to highlight the latest state-of-the-art- seismic retrofitting techniques used with SMA, by comparing different targeted areas of retrofitting, testing techniques (experimental or simulation), material of SMA used, type of loading and Horizontal drift in mm to validate numerically the best technique. The importance of this paper lies in conducting a systematic review, summarizing, and comparing different techniques to orient future research.

2. Methodology

The methodology used in this research was a combination of quantitative and qualitative analysis. This approach aimed to provide a thorough understanding of the seismic retrofitting techniques using shape memory alloy (SMA) in various structural elements.

2.1 Data acquisition and analytical methodology

The research approach used in this study was deductive methodology, where previous studies were gathered, reorganized, filtered, and sorted out to be categorized into main aspects to show the relevance between shape memory alloys and their techniques, materials, and studied elements. Scopus database was our main source of literature with a mixture of journal papers and conference blind review papers. The search was limited to results from (2014-till now), the search keywords were (“Shape memory alloy” OR “SMA”), (“SMA AND Retrofitting”), (“SMA AND Application”).

2.2 Research Phases

The data collection phase 1 where previous literature gathered followed by phase 2 which is data analysis are shown in Figure 1. First, nine papers were selected to be our focus. Second, comparative analysis was conducted with each other, and a hierarchal significance paradigm was created to determine the most important to the least important in this retrofitting technique to guide in overall reduction of HZ deformation in structure globally.

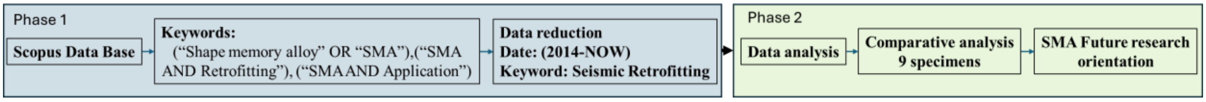


Figure 1 Research Phases

3. Literature Review

3.1 Shape memory alloy properties

According to Raj et.al. [8], the shape memory alloy’s (SMA) material property is extremely important for its applications in retrofitting RC structures. There are four main phases in the action of SMA. Deformation, Heating, Shape recovery and Cooling [10]. The initial phase is deformation, occurring at low temperatures where the martensite phase exists and is easily deformed upon loading the elongation or contraction occurred in the alloy. The martensite phase is stable at lower temperatures and high stresses. The second phase is heating where the austenite action exists. Austenite action is stable at higher temperatures and low stresses, i.e., upon heating the alloy. Followed by shape recovery mode where the alloy returns to its original form after heating. Finally, the cooling phase takes the original shape fully and the cycle continues as shown in Figure 2(a). The martensitic finish temperature (Mf) marks the end of the SMAs' (under zero load) transition from the austenite phase to the martensite phase, as seen in Figure 2(b). Moreover, an austenitic finish temperature (Af) marks the completion of the phase transition, which starts at an austenitic start temperature (As) as shown in Figure 2(c).

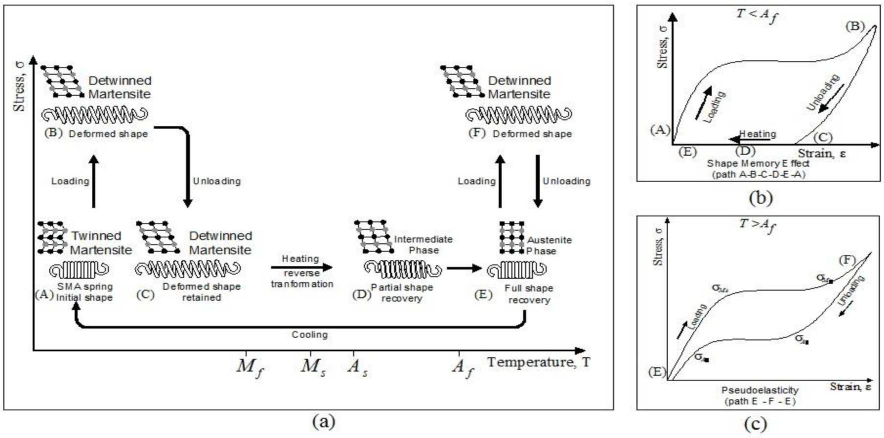


Figure 2 SMA deformation-restauration cycle [8]

3.2 Shape Memory Alloy Applications

3.2.1Shear Wall Applications

3.2.1.1Enhancement of Shear Walls Using SMA Rebars

Ghassemieh et.al. [11] evaluated the use of Abaqus software, which is based on the Finite Element Method (FEM), to apply super-elastic nickel-titanium (Nitinol-SMA) in a concrete shear wall to reduce damage to the coupling beams and open corners as shown in Figure 3. Three shear wall models under earthquake simulation conditions were evaluated as follows: SW1 (basic), SW2 (steel-reinforced), and SW3 (shape memory alloy-reinforced). By measuring the permanent drift as shown in Figure 4, each model was subjected to cyclic horizontal forces that replicated earthquakes. The study employed a constant vertical load of 488kN to mimic the pressure of a real building.

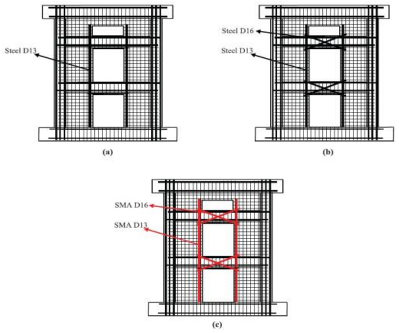


Figure 3 Steel bars vs SMA bars location in Shear wall [11]

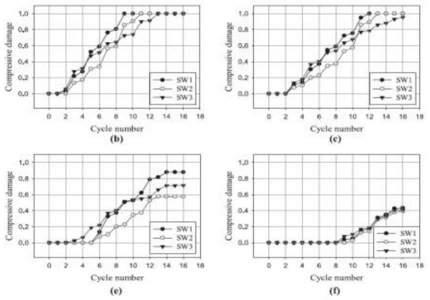


Figure 4 Zones of damages due to compression (a), Zone 1(b), Zone 2(c), Zone 3(e), Zone 4(f) [11]

Due to their high yield to strain, the results showed that utilizing diagonal SMAs in coupling beams and opening corners reduces damage more effectively than using diagonal steel rebars after they have been subjected to significant lateral loadings. Connecting beam shear wall curves showed that, in comparison to the other shear wall models, super-elastic SMAs in SW3 imposed less persistent deformation upon unloading.

3.2.1.2 Shear wall foundation enhancing with SMA Bars Wang et.al. [12] has suggested precast reinforced concrete (RC) wall system that achieves earthquake resistance by utilizing replaceable energy dissipation (ED) devices such as shape memory alloy (SMA) bars at the connection of the shear walls with the foundation. The ED angles and SMA bars were tested by applying a cyclic loading test, while the SMA-based RC wall was evaluated by applying a variety of seismic performances, testing the strength, stiffness, self-centering (SC), and ED capabilities. The investigation was conducted by using the OpenSees FEM software (2D) as shown in Figure 5. An example on specimen naming code was (P1= pre-strain percent 1%) and (B105= thickness of L plate connecting shear wall and foundation in mm).

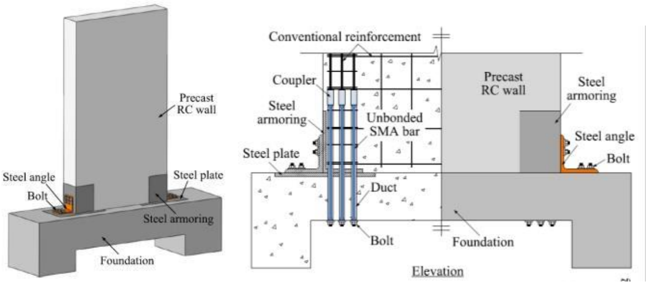


Figure 5 RC wall with ED and SMA in 3D (a), a cross-section of Shear wall to foundation connection (b)[12]

The results came to be not promising as when compared to conventional RC walls, specimens P0-B85, P1-B105, and P2-B105 performed better because of their self-centring capacity, with residual drift levels after unloading that were less than 0.2% and 0.09%, respectively. Specimen P2-B105 met the DS1 requirement set by the Federal Emergency Management Agency (FEMA) and had steel angles that were 105 mm wide and had SMA bars pre-strained at 2.0% to ensure structurally, P1-B105 showed the best performance in a residual drift along with self-centring ability.

3.2.2 SMA in Frames

3.2.2.1 *Performance of RC Frames with SMA Bars at Various Story Levels* Shiravand et al.[5] conducted a study to evaluate the seismic performance of reinforced concrete (RC) frames at different story levels through nonlinear dynamic time history analyses. The frames were analysed using the SeismoStruct software framework based on Finite Element Method (FEM) in a 2D model. The study focused on buildings with 3, 5, 7, and 9 stories. Four different cases were considered for each building: the first model with regular steel reinforcement, the second model with SMA in all story levels, the third model with SMA in the bottom story level, and the fourth model with replacing reinforcement fully with SMA (F-SMA). The results indicated that steel-reinforced RC frames generally experienced higher base shear forces due to their stiffness compared to SMA frames, except for the case of SMA positioned in the middle story levels, as illustrated in Figure 6. The standard steel-reinforced RC frames showed notable values of residual drift. The highest average residual drift was observed in constructions with SMA frames for the 3, 7, and 9-story frames, which contradicts the logic. Because SMAs have a lower modulus of elasticity, using them not only increased the total permanent displacement but also decreased the amount of drift demand that remained. The results showed that by achieving a balance between stiffness and re-centring capabilities, RC frames with SMAs in lower story levels performed better.

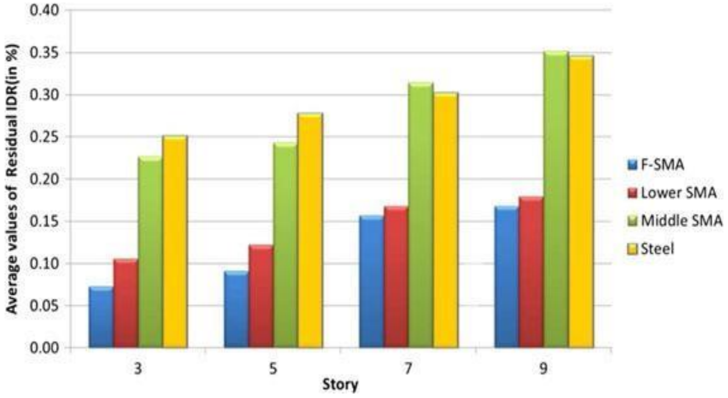


Figure 6 Residual drift demands [5]

Furthermore, because SMAs can preserve post-yield stiffness at high strains, limiting story drifts within confined story regions, using SMAs did not raise the probability of soft-story mechanisms. Because SMAs may keep story drifts within allowable ranges by maintaining post-yield stiffness at high strains. By extending the fundamental period of the structure and changing its seismic response, the incorporation of SMAs at lower story levels may lessen the transfer of seismic forces from lower to upper levels. A more controllable structural response during seismic occurrences could result from this modification.

3.2.2.3 Comparative Analysis between Steel and Cu-Al-Mn-SMA Bars Duran et.al. [13] carried out a study to simulate seismic effects on three 2/3-scaled RC frames with one bay and one story as shown in Figure 7. The first RC frame sustained quasi-static reversed cyclic loading that was used as a reference specimen, which caused flexural plastic hinges at the ends of the columns. To enhance the seismic performance of the defective RC frames, super elastic copper-aluminium-manganese (Cu-Al-Mn) shape memory alloy (SMA) bars and standard steel bars were retrofitted into the other two frames. The upgrading materials were attached to the RC frames using a tension-only retrofitting bar technique. The effectiveness of the retrofitting strategy was assessed by laboratory experiments, and the structural behaviour under seismic loading conditions was examined through analytical modelling with SeismoStruct software.

(a) (b)

Figure 7 Experimental setup (a) overall view, (b) front view [13]

Moreover, the results provided from the experimental test for the residual displacements and residual drift corresponded to the drift ratio of the 3 specimens are shown in Figure 9. Regular steel reinforcement was experiencing the most displacement-residual among the rest. The side view of the RC frame with loading conditions in SeismoStruct is shown in Figure 8.

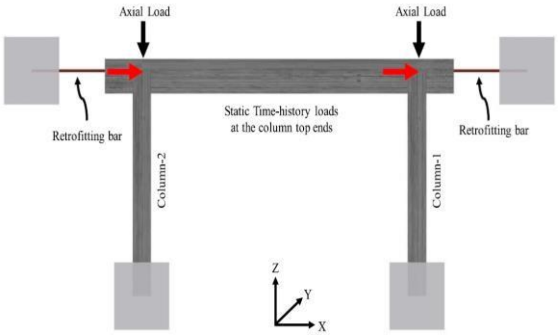
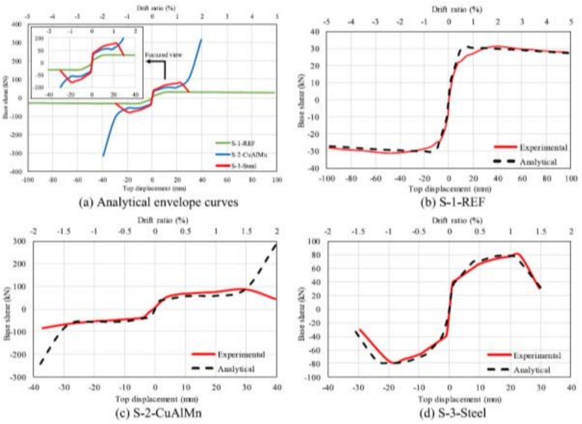


Figure 8 SeismoStruct model of the frame [13]



(a) Analytical envelope curves
(b) S-1-REF
(c) S-2-CuAlMn
(d) S-3-Steel

Figure 9 Experimental vs simulation [13]

It has been demonstrated that the irreversible plastic cracks in defective RC frames can be repaired by the superelastic behavior of the SMA bars during the retrofitting procedure. The initial stiffness of the upgraded RC frames is directly affected by the axial stiffness of the retrofitting components. Both the S-2-Cu-Al-Mn and S-3-Steel specimens dissipated more energy than the reference frame at an average drift ratio of 1.5% for all frames. The reduced energy dissipation of the Cu-Al-Mn retrofitted specimen in comparison to the steel retrofitted specimen can be explained by the shorter range of hysteretic response, as seen by the loading-unloading stress-strain curves. In addition, the difference between the analytical and experimental responses seen in the S-2-Cu-Al-Mn specimen is partially explained by the superelastic behaviour of the SMA bars.

3.2.2.4 Structural Retrofitting with Steel and Fe-SMA Reinforcements The application of ferrous-based shape memory alloys (Fe-SMA) reinforcements at the extremes of the building's structural components has been studied by El Mtili et.al. [7]. A comparison study was conducted between the Fe-SMA reinforcement case and a reference case using standard steel rebars. The study was a straightforward, and symmetrically constructed reinforced concrete frame. Moreover, SeismoStruct software was used to test the structure to perform under full nonlinear time history analysis of 5- records of earthquakes.

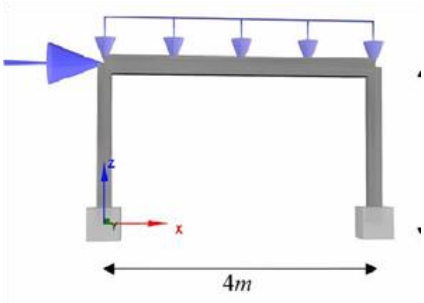


Figure 10 The Frame studied with dimensions [7]

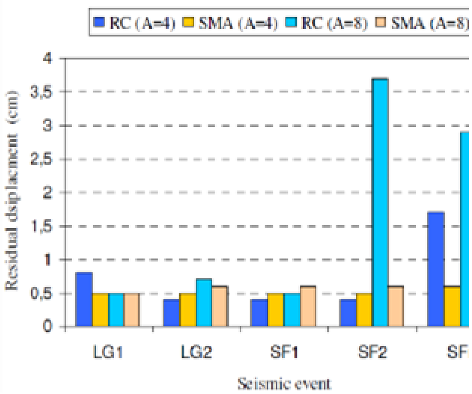


Figure 11 Moment calculated from Non-linear time history analysis simulation for RC and SMA [7]

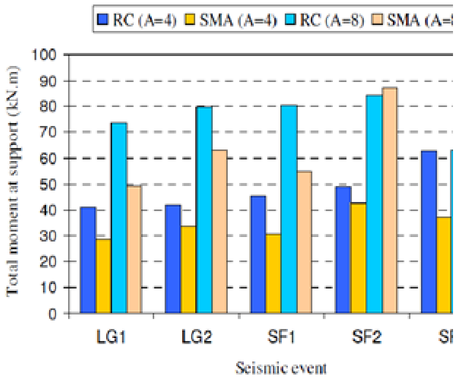


Figure 12 Residual displacement calculated from Non-linear time history analysis simulation for RC and SMA [7]

As a result, shape memory alloys are achievable to minimize residual deformations and prevent collapse due to materials' recentring ability, while their usage produces lower demands for base shear and support moment. Further research is required to explore the cases of more complicated reinforced concrete structures and determine the impact of active reinforcing rate on the structure response.

3.2.3 SMA in Columns

3.2.3.1 Enhancing Columns with SMA against Seismic Effect The seismic analysis of RC columns using stainless steel (SS) in the remaining portion of the column and SMA rebar in the plastic hinge area has been investigated by Pardeshi et al. [6]. For the analytical analysis of the SMA-SS RC column, SeismoStruct software based on fiber elements was used to analyze a nonlinear static pushover seismic analysis.

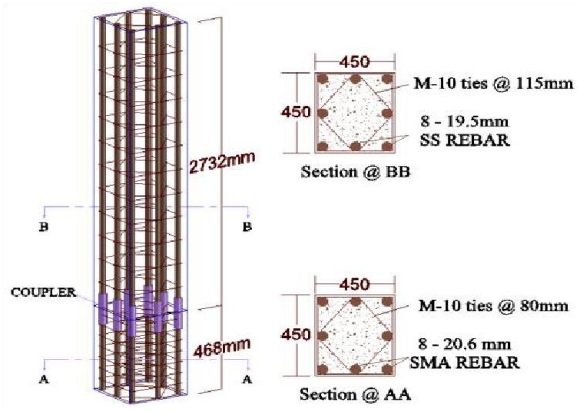


Figure 13 The reinforced SMA-SS RC column's geometry [6]

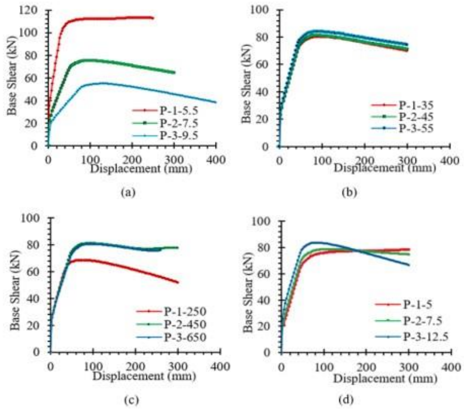
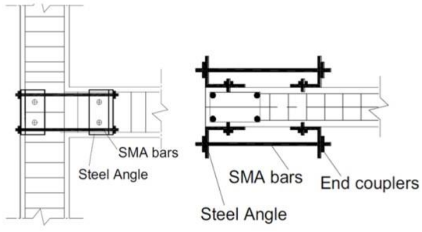


Figure 14 Results of analysis considering (a) Aspect ratio, (b) compressive strength, (c) yielding strength, and (d) Axial load [2]

Thus, the aspect ratio, the axial load, and the yield strength of the reinforcement all have a significant impact on the column's lateral strength and ductility under seismic loading. The yield strength of the rebar and the axial load, aspect ratio, and compressive strength are the primary determinants of the crushing and yielding base shear of the SMA-SS RC column. The SMA-SS RC column's ductility is non-correlated to the compressive strength of concrete and has no apparent impact on crushing drift or yield. Nonetheless, the SMA-SS RC column's yielding and crushing base shear seismic performance appears to be influenced by compressive strength. The reinforced SMA columns demonstrated adequate ductility before collapsing.

3.2.4 Beam column joint (BCJ)

3.2.4.1 Seismic Performance Analysis of BCJ Retrofitted with SMA Bars Elbahy et al.'s study *[14]* studied the seismic performance of three reinforced concrete frames: the first is a standard steel RC frame, the second retrofits the beam-column-joint (BCJ) at the first floor, and the third retrofits the BCJ at the first floor and the fourth floor. The six-story RC frames, situated in a high-seismic location (California), are subjected to nonlinear time history analysis by the application of seral recorded earthquakes. Additionally, the damage level, the Maximum Inter-Story Drift (MID) ratio, the Maximum Residual Inter-Story Drift (MRID), the Maximum Roof Drift Ratio (MRDR), the Residual Roof Drift Ratio (RRDR), and the earthquake intensity at collapse are compared between the frames. SeismoStruct was used to model the frames.

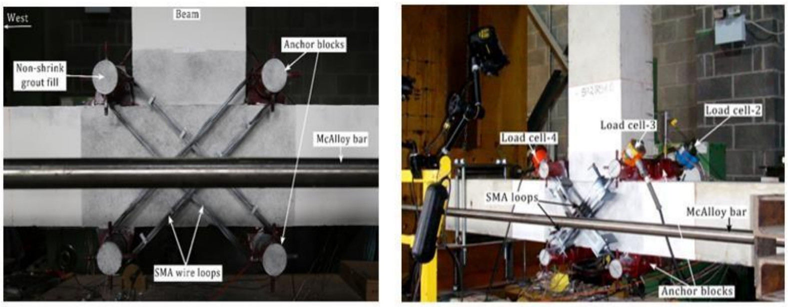


(a) (b)

Figure 15 Retrofitted technique (a) elevation view (b) plan view [14]

Thus, in terms of seismic performance, the two modified frames outperform the original steel RC frame. Furthermore, a small decrease (10–15%) in the temporary drift values, a considerable decrease (50– 70%) in the permanent drift values, and an increase in seismic capacity were all indicative of this improvement. Damage was also lessened at the same earthquake intensity. The steel RC frame has fallen because of the magnitude of the earthquake. The modified steel RC frames withstood higher seismic intensities in terms of damage patterns because they generated less damage at failure than the original steel RC frame. Consequently, it is more economical to retrofit the steel RC frame with outside SMA bars restricted to the first floor.

3.2.4.2 SMA Diagonal Compression Loops in BCJ Retrofitting The effectiveness of prestressed SMA diagonal compression loops in seismic retrofitting of RC beam-column joints (BCJ) core has been evaluated by Suhail et al. [15]. One of the specimens had dynamic confinement retrofitted using prestressed diagonal Nitinol-niobium (NiTiNb) SMA loops, while the other specimen served as a control. In the experimental testing, SMA wires' shape memory property was examined for usage in the first technique—quick heat-activated prestressing—while the second technique involved standard mechanical post-tensioning of SMA wires. In the finite element analysis (ABAQUS), a wide range of prestress values (post-tension force) are taken into account. The efficiency of the retrofitting process is evaluated based on increases in the specimens' strength, ductility, energy dissipation capacity, damage reduction, and ease of application. Consequently, the dynamic confinement of the RC BCJ core reduces joint shear strain in the core region while improving strength and energy dissipation capability. However, the ductility of a non-seismically detailed BCJ may not be improved by this method, and BCJ specimens seem to become less flexible when the active confinement levels increase. It does not seem to have any further advantages for the modified specimen's lateral load-carrying capability beyond a certain point. Consequently, the retrofitting method can raise the ultimate strength by 20–30% and the energy dissipation capacity by 60–70%, based on the applied confinement level. However, according to the authors, no significant increase in ductility of the retrofitted specimens may be achieved using this technique.



(a) (b)

Figure 16 SP-2 installed (a) with RS-A and (b) with RS-AM [15]

3.3 Literature Review Summarization

The following tables summarize the literature review for shear walls as shown in Figure 17 and for frames in Figure 18.

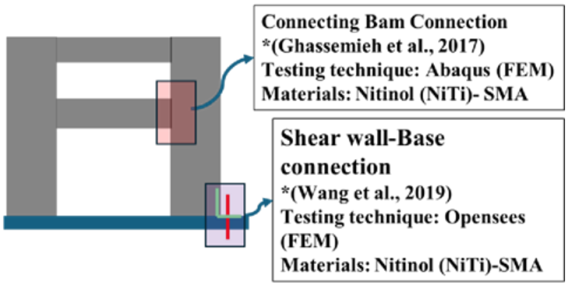


Figure 17 Literature review of SMA on Shear Wall

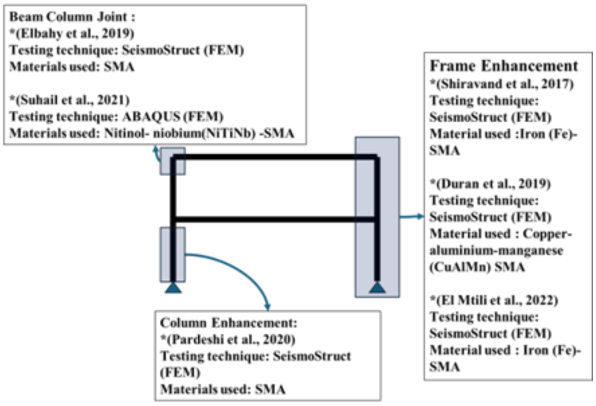


Figure 18 Literature review of SMA usage in Frames

4 Outputs

A summarization of the previous literature with a comparison between the minimum and maximum HZ-permanent deflections is shown in Table 1. The difference between the control specimen and the permanent deflection was calculated and tabulated as HZ-Deflection (mm) Thus, the smaller the deformation, the better Alloy and technique was implemented. It was found that enhancing the connection between the spandrel beam and shear walls with a permanent deflection of 34 mm was the best option. Followed by, enhancing the frame with bars of SMA Copper-aluminium-manganese (CuAlMn) based. They reduce residual stresses and final deformation. The third was using shape memory Nitinol- niobium (NiTiNb) alloy. It was recommended to enhance the lower levels for less total drifts. These results summarize the current research state-of-the-art and gives an orientation for future research on how to enhance concrete structures. SMA needs more research for seismic retrofitting. As its ability to regain its original shape could be the answer to these events.

5 Conclusion

In a nutshell, this paper summarizes the latest state of the art of using SMA. Due to its new properties, the SMA is considered for structure retrofitting to enhance RC sections to withstand sudden or extreme loading. Only 2D studies were found and the experiments or simulations provided were on enhancing sections on a local scale not on a global 3D scale. Thus, to adopt 3D scale simulation, an orientation of the best practice should be reviewed to be implemented. The outputs of this paper are: 1) different techniques of SMA usage with different materials were investigated. All sources gathered were dated back 10 years to ensure the latest relevant state-of-the-art for the RC enhancement using SMA. 2) Eight studies were selected for their relevance and targeted different positions of the structures. 3)The targeted areas were shear walls (internal enhancement), shear wall-foundation connection, and replacing reinforcement with SMA in frames, columns, and Beam-column joints. 4)The most effective technique was using Nitinol-SMA in Spandrel beams between shear walls with an HZ drift of 34 mm. 5) The least effective was enhancing the connections between the beam-column Joint with the outside nitinol-SMA rod 360mm. This was determined by comparing the deflection reduction for each technique between the control specimen and the tested experiment.

Table 1 Literature Review Comparative analysis

Techniques	Results	SMA Material	Testing technique	Loading	References	HZ Drift (mm)	Overall Ranking
Shear wall (1) **Spandrel Beams**	**• Presented SMA reduces damage to the shear wall due to its higher yield strain** **• Presented SMA within coupled beam improves functions of the shear wall after being subjected to heavy lateral loadings**	**Nitinol** **(NiTi)**	**Abaqus (FEM)**	**Cyclic loading**	[5]	**34** **P1-B105**	**1**
Shear wall (2) **[Connection with footing]**	**• Pre-strain in SMA bars boosts RC wall specimens' self-centering capacity.** **• SMA bars that are prestrained can continue to be tight even after the lateral force is removed.** **• Resilient to earthquakes and aftershocks, RC walls maintain their self-centring properties and cyclic behaviour.**	**Nitinol** **(NiTi)**	**Simulation Opensees (FEM)**	**Cyclic loading**	[6]	**115** **P1-B105**	**8**
Frame (1)	**• Lower story RC frames with SMA operated similarly to FSMA structures and did not suffer a reduction in their capacity to recenter** **• Story drifts within acceptable limits because SMA in concentrated story areas did not increase the chance of developing yield stiffness under high strains** **• SMA at lower story levels extends' the fundamental period and reduces the transmission of shakes to higher levels**	**Nitinol** **(NiTi)**	**SeismoStruct (FEM)**	**Dynamic time history**	[1]	**51** **(Full-SMA)** **54** **(Lower levels SMA)**	**2** **3**
Frame (2)	**• The strength of the retrofitting materials and their geometric dimensions directly influence the increase in strength** **• The modified RC frames had relatively lesser crack widths than the reference specimen** **• Using SMA significantly improved the RC frames' lateral stiffness in terms of peak-to-peak stiffness, secant stiffness, and beginning stiffness**	**Copper-aluminum-manganese (CuAlMn)**	**Experimental / SeismoStruct (FEM)**	**Quasi-static reversed cyclic loading**	[7]	**75**	**7**
Frame (3)	**• SMA yields lesser demand in terms of base shear and support moment** **• SMA reducing residual deformations because of the recentering property of these materials**	**Iron (Fe)**	**SeismoStruct (FEM)**	**Pushover & nonlinear time history**	[3]	**60**	**4**
Column	**• The aspect ratio, compressive strength, yield strength of the rebar, and axial load all significantly affect the crushing drift and yielding base shear of the SMA-SS RC column.** **• The same goes for the flexibility of SMA-SS RC columns, but not the compressive strength.**	**Nitinol** **(NiTi)**	**SeismoStruct (FEM)**	**Nonlinear static pushover**	[2]	**75**	**7**
Beam column joint (1)	**• SMA retrofitted frame reduced the maximum drifts by 10% to 15%** **• Residual drifts by 50% to 70% which leads to a reduction of the damage scheme**	**Nitinol** **(NiTi)**	**SeismoStruct (FEM)**	**Nonlinear time history**	[8]	**360** **(1st floor)** **216** **(1st & 4th)**	**10** **9**
Beam column joint (2) SP1 **(rapid heat-activated)**	**• The retrofitting method increases the ultimate strength by 20 to 30%**	**Nitinol-niobium (NiTiNb)**	**Experimental / Abaqus (FEM)**	**Cyclic loading**	[9]	**64**	**5**
Beam column joint (2) SP2 **(SMA loops)**	**• Energy dissipation capacity by 60% to 70% based on the confinement level**	**Nitinol-niobium (NiTiNb)**	**Experimental / Abaqus (FEM)**	**Cyclic loading**	[9]	**70**	**6**

5.1 Research Limitations

The current research was conducted on 2D bases only; no 3D scaled models were found. Also, there is no code for using SMA to guide a design or best zones to be enhanced against extreme loads as it is a relatively new material.

5.2 Recommendations

3D analysis must be conducted to understand the effect of SMA enhancement in an experimental or semi-experimental environment. A scaled 3D model combining most of the seismic enhancement techniques could be a better option to investigate the effect of SMA with extreme loads. All the studied simulations were FEM. However, Applied Element Method (AEM) 3D simulation could be a better alternative for experimental testing. Blast or impact loading is relatively more severe than seismic loading thus SMA could be a solution to this problem. Hence, it is recommended to investigate the usage of SMA to enhance the structure behaviour against these loads.

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