Structural Seismic Applications of Shape Memory Alloys: A Review

A. Kandola, J. Wong, J. Bhandher, K. Cowan, and S. Aldabagh

1 Introduction

Many civil structures worldwide are designed following outdated structural codes without adhering to potential pre- and post-earthquake requirements. Several factors such as time, money, and resources have led to becoming an inhibitor to allow these structures to be maintained to the current seismic-related structural codes.

About 90% of earthquakes occur on plate boundaries of active faults; a fault that is the source for another potential earthquake. Due to the unexpected nature of earthquakes in general, as well as their range in intensity, it is crucial to ensure that structures that lie between these regions, where there are commonly reoccurring earthquakes, are able to withstand the severe and negative effects of a possible earthquake.

Due to this, many researchers have conducted several studies in attempts to avoid this issue for newer infrastructures with the use of specific materials that are able to better adapt to their surrounding environment, minimize energy use, improve life cycle performance and at the same time reduce maintenance costs [7]. A promising example of such a material is shape memory alloy (SMA).

SMAs have attracted several researchers' attention due to their unique properties: shape memory effect and superelasticity. These specific properties allow for many different earthquake resistance-related applications to be implemented in civil structures. Wesolowsky and Wilson [35] reported that SMAs exhibit high use strain range (8%) in comparison to other metallic materials. This allows for a smaller volume requirement of the material in order to produce the same damping capacity [35].

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2 Types of Shape Memory Alloys

There are several different shape memory alloy types, some of which are composed of a formation of copper, zinc, nickel, and titanium [35]. These alloys can exist in different chemical configurations, however, the most common types of SMA are Nickel-titanium and Nickel-titanium-copper (Amaël 2018). Less commonly used SMA compositions include Copper-based, Iron-based, Silver-based, Gold-based, and Cobalt-based alloys. The specific application of an SMA depends on the desired physical properties. It is also worth noting that creative solutions such as the composite used by Hu (2021) as explained above can be used to overcome certain specific design challenges. The possibilities and potential for creative problem solving are part of what makes SMAs so unique—much is yet to be discovered—and new alloys could come along with new properties. They can also be combined with Polymers to create new, super elastic Fibre-reinforced polymers of FRPs.

The most common and investigated types of SMA used for seismic applications are NiTi (Nitinol) alloys [35]. NiTi alloys are generally made up of equal parts of nickel and titanium however, this could deviate with a nickel content ranging from 49 to 51% [26]. Manufacturing NiTi alloys can be difficult to produce due to titanium's reactivity, as well as, melting of the element in an inert atmosphere [10]. This is one of the many reasons why NiTi SMAs are expensive compared to other compositions. However, an advantage of NiTi-based SMAs is that they are able to handle strain more effectively compared to other types of SMAs. It should be noted that the transformation temperature can be very sensitive to the composition with small changes in the Nickel content causing large changes in the transformation temperature [10].

Other common types of SMAs are copper-based, such as Copper-Zinc-Aluminium (CuZnAl) and Copper–Aluminium-Nickel (CuAlNi). CuZnAl alloys typically contain 15–30 wt% Zn and 3–7 wt% Al [10]. They generally have a transformation temperature that ranges from −100 to +100 °C. However, this can vary depending on the overall alloy composition and types of treatments used when manufactured. One advantage of using CuZnAl alloys is the overall cost; they are one of the most cost-effective SMAs since they are made from inexpensive metals. However, their ability to recover permanent deformation can vary as the maximum recoverable strain is roughly 5% [10]. Another disadvantage stems from their martensitic phase being stabilized by long-term aging at room temperature [10]. The alloy structure can start decomposing at temperatures above 100 °C which greatly restricts their implementation.

CuAlNi alloys contain 11–14.5% Al and 3–5% Ni, with their transformation temperatures ranging from 80 to −200 °C [10]. The transformation temperature ranges, depending on the overall alloy composition, are known to be sensitive to the amount of aluminum content within the composition. Reducing the aluminum amount below 12% can allow some improvement to the mechanical properties [10].

The main advantage of using CuAlNi based SMA is the variety of useful transformation temperatures as well as the cost. CuAlNi alloys are relatively inexpensive to manufacture however, their processing requires the materials to be hot worked to produce a SMA at a specific transformation temperature.

Copper and nickel-titanium-based alloys are the most common in the production of SMA's. Copper alloys are abundant and easy to manufacture as they are made from relatively inexpensive metals which makes them the cheapest commercial SMA. However, copper alone does not contain superior memory properties-the maximum recoverable strain is about 5% and they are quite brittle due to having large grain sizes.

3 Manufacturing

The most common methods of manufacturing are casting and powder metallurgy followed by hot or cold working, surface treatments, and heat-treatments [26]. The SMA must also go through training for two-way shape memory effect (TWSME) to achieve the property. The manufacturing process influences the mechanical properties of the SMA such as the homogeneity, ductility, machinability, and transformation temperatures.

The following methods and techniques are taken from The Unique Properties, Manufacturing Processes and Applications of Near Equiatomic Ni–Ti 9 Alloys by Karamichailidou [26]. Since Ni–Ti SMAs are more commonly used, the manufacturing methods and techniques of Ni–Ti alloys are summarized. The casting process requires raw materials with high purity to produce SMA with even composition distribution and the expected properties. Techniques used in the casting process include vacuum induction melting, vacuum arc melting, and electron beam melting. Producing NiTi using powder metallurgical methods involves powder blending, mold compaction, and sintering in a furnace. This method produces better composition homogeneity and porosity compared to vacuum melting techniques.

The conventional process that produces NiTi alloys from elementary or pre-alloyed powders involves six methods taken from The Unique Properties, Manufacturing Processes and Applications of Near Equiatomic Ni–Ti 9 Alloys by Karamichailidou [26] include; self-propagating high-temperature synthesis (SHS), conventional sintering (CS), metal or powder injection molding (MIM), space holder technique (SHT), hot isostatic pressing (HIP), and spark plasma sintering (SPS). The rapid manufacturing processes use selective laser sintering (SLS), selective laser melting (SLM), laser engineered net shaping (LENS), and electron beam melting (EBM) in addition to 3D computer-aided design which is used to create specific material designs. This technique allows for better control over the porosity volumetric function.

To obtain the desired shape of the SMA, it is formed into the desired shape after cold working and is held in the position tightly. It is then heated until the material's temperature is uniform.

Shape memory training involves deforming the material while it is in the martensite phase until the shape memory effect will start once heated. Once the material is heated to the austenite phase, it will cool to martensite. This is continued until TWSME is observed.

4 Shape Memory Effect

One distinct property of SMAs is their ability to return to their pre-deformed state. This is typically done through the addition of heat or through stress removal of the material due to the ervice-elastic martensitic transformation SMAs undergo [26]. SMAs can exhibit two types of shape memory effects: one-way shape memory effects or two-way shape memory effects [26].

4.1 One-Way Shape Memory Effect

One-way shape memory effect is known as the recovery of a material to return to its original shape through heating to a specific temperature. This is where only the shape of the parent phase can be recovered [26]. The material transitions from martensite where it's deformed to austenite. At higher temperatures, the material is in an austenite phase whereas, at lower temperatures, the material is in a martensite phase [32]. When the material starts to become heated from M_s to A_s, the phase changes from martensite to austenite. At a temperature equal to or greater than A_s, the material is 100% austenite. At a temperature equal to or less than M_s the material is 100% martensite.

4.2 Two-Way Shape Memory Effect

Two-way shape memory effect differs from one-way shape effects as they can remember both its parent and product phases when changing shape during temperature changes [26]. This property can only be exhibited through "training". Training can be done in two main ways, shape-memory training, and stress-induced martensitic transformation training. During training, the material undergoes repeated deformation and transformations between austenite and martensite [26]. At temperatures below M_f, an irreversible amount of deformation is introduced. This is typically when martensite is deformed beyond its yield strength allowing for slipping to occur and dislocations are introduced [26]. Due to this, when heated above A_f, there is

Fig. 1 Two-way shape deformation after irreversible deformation (adapted from Karamichailidou [26])

not a 100% overall shape recovery due to the dislocations formed in the crystalline structure. However, when cooling again below M_f, the martensite allows the material to form in a specific cold shape [26]. This relationship allows for shape changes to occur between a heated and cooled shape of the material through heating and cooling without the use of other stresses. Figure 1 shows this relationship.

5 Superelasticity

Shape memory alloys exhibit elastic behavior beyond that of any other normal metals. Superelastic SMA is capable of recovering from large strains specifically in the range of 8–10% [27]. Additionally, they are able to release residual stress caused by deformation by the removal of the stress and, depending on the specific compound and SMA structure used, a change in temperature.

Unique design solutions can be reached using SMA technology as the basic concept. Structures are relatively simple but breakthroughs emerge when a creative design approach is taken. One such example is a study done by Xiaowei [36] that explores the concept of synergy between two constituent shape memory alloys (SMAs) in a composite so that a wide super elastic temperature window can be achieved.

The study uses a nanocrystalline NiTi/NiTiNbFe dual-SMA composite in which two constituent SMAs are similarly capable of stress-induced martensitic transformation within different temperature ranges. The temperature window achieved was 336 °C, the temperature range where the composite behaved fully super elastically was 196–140 °C [36].

An application of tube-formed superelastic SMAs for structures was explored by Watkins [34] in a study of short columns where tubes of superelastic SMAs were observed 'unbuckling' after a sustained monotonous load and buckling.

This is yet another application of SMAs that relies upon the unique superelastic properties and shows that the orientation and design of macrostructures of SMA's such as NiTi and the nano-crystalline NiTi/NiTiNbFe dual-SMA composite are what make SMAs the most promising material choice for structural seismic applications.

6 Applications in Buildings

SMAs differ from conventional earthquake-resisting systems by their predicatable unique properties; self-centering, shape memory effect, and super-elastic effect to dissipate energy from the structure (Moyade and Madhekar 2018). Other properties of superelastic SMA that pertain to earthquake engineering are large recoverable strain, damping due to the hysteretic loop, transfer of force, and resistance to fatigue and corrosion [37]. A structure's ability to withstand deformation may also damage the structure, increasing repair costs [19].

Seismic SMA damper technology introduced to bracing members and tested for seismic applications include recentering shape memory alloy damper (RSMAD) (Qian et al. 2013), self-centering buckling-restrained brace (SC-BRB) [23, 28], and other structural retrofit techniques.

The New Zealand earthquake in 2011, damaged about 1000 buildings due to not meeting the design requirements of modern-day building codes. The damage costed about $40 billion NZD which was equal to 20% of the country's annual GDP [14]. This shows the need for seismic resistant systems in buildings, as a single earthquake alone can have a large negative economic impact.

6.1 Concrete Frames

A study conducted by Youssef et al. [38] examines the use of superelastic SMA rebars in the plastic hinge region of beam-column joints (BCJs) under reversed cyclic loading. BCJs are known to remain quite vulnerable during earthquakes, and because of the typical design of RC structures, reinforcing bars are expected to yield to allow energy to dissipate causing permanent deformations [38]. However, implementing SMAs as reinforcing bars could allow structures to undergo inelastic deformations.

A study conducted by Ghassemieh and Kargarmoakhar [21] tested medium rise SMA RC buildings that were built according to Canadian code in a high seismic region in Western Canada. The study considered 20 earthquakes that previously occurred in that area and evaluated the performance of the buildings. A full analysis was conducted of the seismic performance factors, nonlinear static pushover, and incremental dynamic response. Evidence showed that under maximum earthquake activity, the SMA RC buildings passed performance tests with values within the acceptable range. The probability of collapse in the SMA RC buildings was 4% to 17% lower than conventional RC buildings.

SMA-reinforced RC elements can also harness the power of SMAs while performing well in flexure and compression. Alam et al. [5] explores validation of the FE program (SeismoStruct) simulation in regards to RC-SMAs where SMA reinforcements were added to the plastic hinge area with regular steel in the remaining areas. The experiment used SMA reinforced column-beam joint and tested reverse cyclic loading as well as an SMA-RC column tested under dynamic loading. The beam-column joint was reinforced with superelastic SMA at the plastic hinge region of the beam, along with regular steel in the remaining portion of the joint, and was designed according to Canadian standards. The authors also validated their models by simulating the shake table test of a quarter-scale SMA RC column. The FE results yielded moment-rotation, load–displacement, and energy dissipation capacities, all of which were compared with the experimental results. The numerical results indicate that the FE program could simulate the behavior of SMA-RC elements with reasonable accuracy [6].

6.2 Concrete Walls

Concrete walls are meant to provide enough strength to resist vertical loads and stiffness against lateral loads [2]. During the event of an earthquake, concrete walls (especially high-rise buildings) experience the inertia forces that accumulate downwards from the top of the building. This causes the walls at lower stories to experience higher vibrations and can lead to total failure or collapse of a structure as it is carrying all the accumulated load plus additional earthquake-induced forces.

During seismic events, reinforced concrete structures (RC walls) are susceptible to extreme deformation caused by the yielding of the steel bars [1]. In order to counteract this, superelastic SMA bars can be incorporated in the wall's plastic hinge region and the wall's boundary [33]. The low tensile strength of RC walls is combined with SMA bars to resist loads in tensile zones, where the SMA bars have the ability to sustain large deformation and recover their inelastic strain due to their superelastic property. Thus, the use of SMAs could significantly reduce the likeliness of permanent deformation in concrete walls, and the structure could still remain serviceable afterward [22, 33].

A case study conducted by Abdulridha and Palermo [3] tested the difference in strength between a conventional concrete wall and an SMA reinforced concrete wall under cyclic loading. After monitoring both walls, the data recorded showed that both walls incurred flexural cracks near the wall base, and as the load increased, incline shear cracks started to develop and the cracks became more prominent. These cracks were perpendicular to the longitudinal bars. More shear cracks occurred in the middle region of the conventional wall. The SMA wall sustained more loading before failure than the conventional wall was able to sustain. The SMA wall also showed superior capacity to recover inelastic displacements and increased ductility performance by 45%. The average recovery capacity for the SMA wall was 88%, whereas the average recovery capacity for the conventional wall was only 24%.

Concrete is not as flexible, therefore, SMA's cannot eliminate damage that is caused in concrete walls after an earthquake, but they do work to reduce the damage and repair costs. Nitinol is a great choice of alloy for controlling residual displacements in a concrete wall. However, given its high initial cost, its implementation is limited to just critical flexural regions rather than the entire wall.

6.3 Steel Frames

The applications of SMAs for steel-frame structures rely upon a few key characteristics of SMAs. The first is its super-elasticity, specifically how it is able to return to its original shape after being deformed. This can be applied to steel-framed buildings by placing SMAs at the joints, allowing the frame to self-center joints after earthquakes or other large, discontinuous forces. These SMAs are typically applied by "bracing" joints that are oriented diagonally as seen in Fig. 2.

SMAs are also capable of dissipating energy by means of stress-induced martensite transformation (in the case of superelastic SMA) or martensite reorientation (in the case of martensite SMA) [17]. Many design possibilities present viable energy dissipation and self-centering properties. Dolce et al. [18] produced a prototype SMA brace designed to resist seismic forces and self-center after sustaining deformation. Asgarian and Moradi [8] investigated a variety of brace configurations, dynamic responses of frames with SMA braces showed energy dissipation capabilities comparable to the ones with BRBFs. Furthermore, it was reported that even though SMA can exhibit recentering properties for strain values in the 8–10% range, a conservative value of 6% strain should be adopted in order to include a factor of safety to ensure the braces continue to work reliably [8].

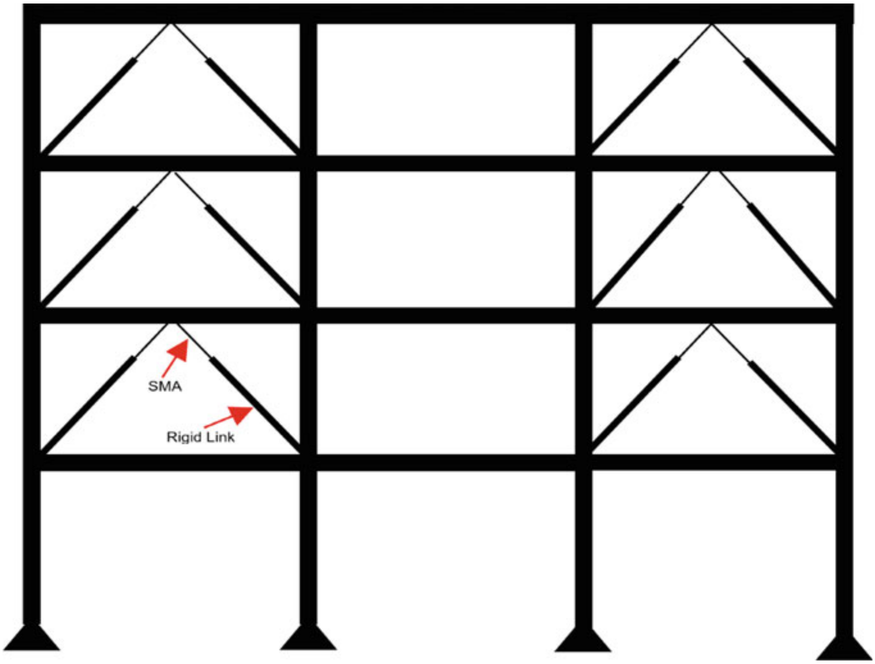

Fig. 2 Schematic representation of SMA braces for steel-framed structures (adapted from Moradi et al. [29])

A feasibility study of using fully welded iron based SMA flange plates in the plastic hinge of steel beam-column connections was conducted by Moradi and Alam [30]. The SMA plates were located in the plastic hinge region to restore deformations and lessen the damage to the beam-column connection. The cyclic behaviour of a steel plate and an iron-based plate was analyzed using three-dimensional nonlinear finite element analysis models which showed lower residual interstory drift angles and lower residual drifts when extra flange plates were placed in the beam web in addition to the SMA plate at the plastic hinge. It was also shown that SMA plates prevented local buckling in the beam section, demonstrated more stable hysteresis and no strength degradation, as well as lower amounts of energy dissipation in comparison to the steel connection [30]. In this analysis, the rate and temperature or the SMA model was considered independent and did not account for accumulated residual deformations.

Another application of SMA in beam-column connections is reduced length (RL) prestressed (PT) steel and SMA strands studied by Chowdhury et al. [15]. In this study, finite element (FE) analysis was used to investigate the lateral load drift response of PT connections and as well as the feasibility of FeMnAlNi, FeNCATB, CuAlMn, and Niti SMA in this application. CuAlMn and FeNCATB SMA were identified as alloys with the best performance in shorter lengths than the PT steel strands. RL PT steel strands have desirable traits for this application such as initial stiffness, post decompression stiffness, strength, and moment capacity of the connection [16]. It was found that PT connections with the previously identified alloys can recenter drifts of 5% and are effective in dissipating energy compared to steel strands. This shows that copper and iron based SMA's are an effective option for beam-column connections however, require more dynamic analyses [15].

The cyclic response of PT steel beam-column connections with stiffened angle connections and Fe-based SMA angle connections and bolted end plate connection was investigated through full factor analysis by Chowdhury et al. [15]. The role of SMA angle connections is to replace the need of repairing other energy dissipating elements after an earthquake [15]. The SMA bolted end plate PT connections dissipate energy while the load capacity and self centering capacity remain the same. The four main controlling components are gage length, end plate length, bolt diameter, and pretension force in the bolts [15]. These components should be carefully designed as the behaviour of components are sensitive to changes. The most important factors related to energy dissipation of the end plate connections are the SMA bolt diameter and pretensioning stress [15]. The energy dissipation capacity of the connection increases when the diameter of the SMA bolts and pretensioning stress increase [15].

7 Applications in Bridge Columns

Incorporating SMA material as an alternative to steel reinforcement in bridge column design enhances the structure's seismic performance. Current seismic design approaches for bridge structures do not focus on post-earthquake serviceability (Liu et al. 2018).

The study conducted by Xiu et al. [37] compares the seismic performance of reinforced concrete (RC) columns with unbonded prestressing steel strands (UBPS column) and RC columns with unbonded prestressing steel in series with NiTi SMA strands (UBPS-SMA column). The unbonded strands distribute the deformation uniformly which decreases tensile strain and prevents yielding. The lateral displacements caused by seismic activity cause the strands to elongate and increase the tensile force on the strands. The increased tensile force increases the flexural strength of the column and causes seismic demand on the foundation [37]. Using quasi-static analysis and seismic analysis of the columns, using SMA strands in series with steel strands is shown to improve the displacement and self-centering behavior of the column. Due to the cyclic stress–strain relationship SMA's, when a load is applied and the SMA stress reaches the constant stress plateau (loading plateau), the UBPS-SMA column experiences a lower peak axial load ratio and smaller displacements than the UBPS column.

A study conducted by Jung et al. [24] investigates the use of SMA-glass fibre reinforced polymer (GFRP) jackets in combination with high strength concrete (HSC) columns. The concrete column was wrapped with GFRP and a NiTiNb SMA spiral on the outer layer. MTI simulation framework was used to combine material testing and numerical solution of bridge supported by HSC SMA-GFRP columns. The seismic behaviour of the hypothetical bridge was observed under various seismic loading intensities. Results indicated that HSC cylinders with SMA-GFRP jackets have higher maximum strength, ultimate strain, and residual strength than their unconfined control counterparts. As well as, HSC reinforced with SMA-GFRP columns being able to withstand greater peak ground acceleration (PGA) from bidirectional ground motions.

Ge and Saiidi [20] assessed the seismic response of the SMA and engineered cementitious composite (ECC) columns designed to replace the State Route 99 Alaskan Way Viaduct (AWV-SAC) connection bridge in Seattle Washington. The AWV-SAC bridge reconstruction paper by Baker et al. [9] overviewed the use of NiTi SMA bars in plastic-hinge zones with EEC in bridge columns. In the study by Ge and Saiidi [20] the analytical models showed the SMA column to have a larger maximum displacement than a RC column. In addition, minimized residual displacements in the SMA and ECC columns when under full amplified ground motion analysis as well as other advantages of SMA's were observed.

The cost of SMAs in bridges can be very high due to the large-scale framework. The cost of Ni–Ti has decreased over the past decade by 85% from $1000 USD to $150 USD per kg [14]. However, in comparison to other materials in the market, it is still considered a costly alternative. Adding on to that cost is the expense of implementing

SMAs in bridges which requires careful instrumentation and calibration. There are new low-cost compound materials that are being developed as a replacement for Ni–Ti, such as Fe–Mn-Si-Xi. The need for a low-cost SMA is currently in great demand, especially for bridge construction. The benefit of using SMA's over other alternatives such as steel devices is that SMAs require no maintenance or replacement.

8 Summary and Conclusions

This paper provided an overview of SMAs and their structural seismic applications. SMAs have many different applications due to their highly unique properties. The nature of their cyclical martensite reactions allowing the material to seemingly 'remember' its shape, as well as their capacity for superelasticity, make SMA's viable solution to many civil applications. Though the limitations of this material begin to be more dependent on the specific design solution and the composition of the SMA used, the applications within the discipline of civil engineering are highly open-ended. Currently, SMA's are being used in construction, retrofitting, and repair of steel frames, columns, bridges, as well as dampers and braces.

SMAs are known to have an initially higher cost to manufacture. However, this higher cost can be beneficial for the future due to its superior mechanical properties specifically in seismic regions. Depending on the specific project, there are several different compositions one can choose according to their specific budget (NiTi, CuZnAl, CuAlNi, etc.). Titanium is a highly reactive metal; it is more difficult to manufacture the NiTi alloy. NiTi alloys are more expensive than copper-based alloys but have far superior shape memory properties.

Based on the unique properties of SMAs, they are considered to be more cost-effective in comparison to other materials. By using SMA technology, potential damage from earthquakes to structures can be prevented, making it a cost-effective option in the long-run. Where SMAs are integrated, their super elasticity and shape memory properties benefit structures safely (Table 1).

Table 1 Summary of research findings on the structural seismic applications of SMAs

Application	References	Key observations
Beam-column joints	Youssef et al. [38]	Implementing superelastic SMA reinforcing bars will allow the structure to undergo inelastic deformations
Medium rise SMA RC buildings in high seismic regions in Western Canada	Ghassemieh and Kargarmoakhar [21]	SMA RC buildings had a lower probabiltity of collapse compared to conventional RC buildings
Plastic hinge region of concrete walls	Shahnewaz and Alam [33]	SMAs reduce the likeliness of permanent deformation in concrete walls when applied in the plastic hinge region
SMA-steel reinforced concrete slender shear wall	Abdulridha and Palermo [3]	The SMA wall sustained more loading before failure and was better able to recover inelastic displacements
Fully welded iron based SMA flange plates in beam-column connections	Moradi and Alam [30]	SMA plates in the beam web and at the plastic hinge prevent local buckling in the beam section
Reduced length, prestressed steel and SMA strands in beam-column connections	Chowdhury et al. [15]	Prestressed connections with CuAlMn or FeNCATB SMA are effective in dissipating energy compared to steel strands
PT steel beam-column connections with stiffened angle connections and Fe-based SMA angle connections	Chowdhury et al. [15]	The SMA bolt diameter and pretensioning stress largely contribute to the energy dissipation capacity of the connection
RC columns with unbonded prestressing stell in series with NiTi SMA strands	Xiu et al. [37]	SMA strands in series with steel strands improve displacement and self-centering behaviour of the column
SMA-glass fibre reinforced polymer jackets with high strength concrete columns	Jung et al. [24]	Can exhibit higher maximum strength and withstand greater peak ground acceleration than unconfined columns

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