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A State-of-the-Art Review on the Application of Shape-Memory Alloys for Performance Enhancement of Steel Structures

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Abstract

Steel structures are a fundamental component of construction projects worldwide, yet they continue to face challenges in mitigating seismic damage and ensuring long-term performance. Shape-memory alloys (SMAs) have emerged as a promising solution, offering unique properties that can significantly enhance the performance of steel structures. Despite years of research on SMA applications in this field, a comprehensive review paper is notably absent. This paper aims to fill this critical gap by systematically analyzing the latest advances in the field. To this end, this state-of-the-art review looks at how SMAs are revolutionizing steel structures by examining their application in various aspects, such as dampers for better vibration control, connections and joints for self-healing and stiffening, bracing systems for adaptive support, and seismic isolation for intelligent response. The topics raised in this review can serve as a valuable resource for engineers and researchers who seek to include SMAs in their designs and push the boundaries of innovation in steel structures.

Keywords: Steel Structures, Shape-Memory Alloys (SMAs), Dampers, Steel Connections, Bracing Systems, Seismic Isolation

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1. Introduction

Steel structures have long been the main component of modern construction due to their strength, versatility, and cost-effectiveness (Fang et al. 2022; Romanenko and Vodolazskaya 2021). However, the limitations of steel in bearing dynamic loads such as earthquakes and wind storms are always a concern because these events can lead to permanent deformation and failure of the structure and consequently cause economic and safety risks (Hradil et al. 2017; Khalil et al. 2022; Goshtaei et al. 2022; Samadian et al. 2024). In response to these challenges, shape-memory alloys (SMAs) have emerged as a promising material with the ability to revolutionize the field of steel structures (Shao and Huang 2023; Fang 2017). SMAs have distinctive properties such as shape memory effect (SME) and superelasticity that distinguish them from conventional steel and have the potential to improve the performance and resilience of steel structures (Fang and Wang 2020; Qian et al. 2022; Shadabfar et al. 2022).

The SME effect is a phenomenon observed in SMA, which gives the metallic alloy the ability to withstand significant deformations without permanent damage (Zhang et al. 2022; Mazzer et al. 2022). SMAs are able to "remember" their original shape and return to it when exposed to an external stimulus such as a change in temperature. This unique property allows SMAs to act as internal memory devices in a structure (Ozair et al. 2022; Xin et al. 2019; Dayyoub et al. 2022). In addition to the SME, superelasticity is another remarkable property of SMAs. Superelastic SMAs can undergo large deformations that exceed the yield point of ordinary steel without suffering permanent damage (Shao and Huang 2023; Ghafoori et al. 2022). Similar to a rubber band that is stretched and returns to its original size, superelastic SMAs also exhibit a behavior similar to " springing back" and return to their original shape once the load is removed (Chowdhury 2018; Mohammad Gholipour and Billah 2023).

The use of SMAs in steel structures offers promising prospects for improving the performance of these structures in various aspects (Molod et al. 2022; Narjabadifam et al. 2022). These attributes encompass enhanced resilience, self-healing ability, and improved safety (Alam et al. 2007; Kandola et al. 2023). SMAs have the potential to enable steel structures to recover from significant deformations caused by earthquakes and storms, absorb and release energy without sustaining permanent damage, and demonstrate self-healing characteristics through their SME (Wang and Zhu 2018; Tabrizikahou et al. 2021). By integrating SMAs into key elements, engineers can design structures that are more resistant to extreme events and reduce the probability of catastrophic failures, especially in earthquake-prone areas (Fang et al. 2023; Rahman and Billah 2020; Fang 2022). SMAs have various applications in steel structures. For example, studies have shown that the integration of SMA dampers in steel structures causes energy loss and stress reduction in the main elements of the structure (Kim et al. 2024; Hooshmand et al. 2015). SMAs can be incorporated into dampers in a variety of ways, such as using their superelastic properties to absorb and release energy under cyclic loading, or exploiting SME to generate restoring forces that counteract structural deformations (Pan and

Cho 2007; Cao and Yi 2021; Aghajani and Asadi 2023). Steel connections play a vital role in structures by transferring loads between different members (Yan et al. 2023; Li and Wang 2022). However, welded or bolted joints are susceptible to loosening or failure under extreme loads. SMAs offer a promising solution for self-tightening connections (Torabipour et al. 2023; Wu et al. 2011; Wang et al. 2015). By strategically embedding SMA wires or tendons within the connection, researchers envision a system where heating the SMAs activates their SME, inducing a pre-stress that tightens the connection and enhances its load-carrying capacity (Izadi et al. 2019; Chowdhury et al. 2019). Additionally, the superelasticity of SMAs could potentially enable connections to remain functional even after experiencing significant deformations (Chang and Araki 2016; Farmani and Ghassemieh 2016). Bracing systems are also utilized in structures to resist lateral loads from wind and earthquakes. Traditional bracing systems often rely on passive elements like diagonal braces, which can be bulky and aesthetically unappealing. SMAs present a potential solution for active bracing systems (Babaei and Zarfam 2019; Zareie et al. 2022; Haque and Alam 2017). By incorporating SMA elements within the bracing, researchers propose systems that can be activated in response to seismic events, providing additional support and energy dissipation as needed (Massah and Dorvar 2014). The inherent self-centering capabilities of SMAs could lead to bracing systems that automatically re-center the structure after an earthquake, minimizing residual deformations (Askariani et al. 2022; Ferraioli et al. 2023). Seismic isolation systems in steel structures aim to separate a structure from the damaging effects of ground motion during an earthquake. Conventional isolation systems typically use elastomeric bearings, which can be costly and prone to deterioration over time (Warn and Ryan 2012; Patil and Patil 2024; Stiemer and Barwig 1985). Researchers are exploring the use of SMA-based isolation systems as an alternative. By integrating SMA elements within the isolators, the system could offer adjustable stiffness and damping properties, allowing for a more tailored response to various earthquake scenarios (Shmerling and Gerdts 2022; Wang et al. 2020). Furthermore, the SME of SMAs could potentially be utilized to re-center the isolated structure after an earthquake, ensuring its stability.

This review paper will explore the exciting potential of SMAs in revolutionizing steel structures. We will delve into various applications where SMAs can significantly enhance the performance of steel buildings. Section 2 addresses dampers, where SMAs can be implemented to dissipate vibrations and improve seismic resistance. Further, Section 3 describes steel connections, where SMAs can offer self-repairing or self-tightening mechanisms. Next, Section 4 describes bracing systems, where SMAs can be incorporated to create adaptable and responsive support structures. Additionally, Section 5 talks about seismic isolation, where SMAs can potentially create intelligent isolation systems that adjust to earthquake intensity. Section 6 provides an economic evaluation comparing the cost of using SMAs with traditional steel construction. Finally, Section 7 provides a summary and conclusion, evaluating the overall effectiveness and future directions for SMA applications in steel structures.

2. Applications of Shape-Memory Alloys in Dampers

One method to deal with the earthquake-induced lateral force in seismic rehabilitation is to use seismic energy dissipation systems called dampers (Lan and Zhou 2018; Mehta and Purohit 2019). The advantages of dampers over alternative solutions include -but are not limited to- high energy absorption capacity, ease of installation, and ease of replacement (De Domenico et al. 2019). Two properties of SMA can be exploited to improve passive control against earthquakes: energy dissipation and recentering function (Chang and Araki 2016). However, since these materials are too expensive to be used in mass, designs should be optimized to make the most use of available resources (Qian et al. 2013). One logical and practical solution is to concentrate the available resources in a damper. The outstanding energy dissipation capability of such a damper will allow it to significantly reduce earthquake-induced energy, and since SMAs are highly resistant to fatigue as well as strength and stiffness degradation, they will be able to provide this function multiple times without needing to be replaced after each earthquake (Ozbulut et al. 2011). Another useful property of SMAs is their recentering capability, which allows structural members to regain their original conditions many times during an earthquake (Jia et al. 2018). This prevents strain concentration and permanent deformation in structures and helps them avoid failure. It also allows us to reuse the damper after an earthquake at little to no cost. With this introduction, the objective of SMA-based damper design optimization will be to maximize energy dissipation while maintaining the recentering property (Ma and Yam 2011). The recentering property can be achieved by using SMAs in the austenite phase. For the energy dissipation property, SMAs must be used in the martensite phase (Vasudha and Uma Rao 2020). The combination of the recentering and energy dissipation properties and the resulting ideal behavior are schematically presented in Figure 1.

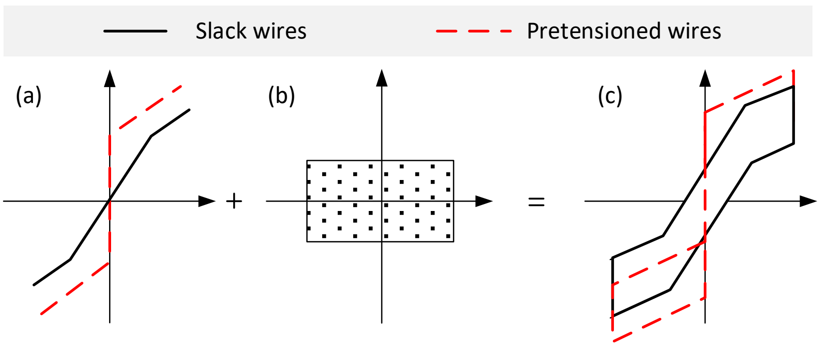


Figure 1. Behavior of SMAs: a) hybrid; b) energy dissipation; c) recentering.

In a comprehensive laboratory research called the MANSIDE (Memory Alloys for New Seismic Isolation Devices) Project, Dolce et al. (2000) designed a series of dampers with SMAs. They proposed three types of dampers with different behaviors: recentering devices, non-recentering devices, and supplemental recentering devices. The behavior of these dampers is shown in Figure 2. Their idea was to use a combination of these three dampers in each structure to achieve optimal behavior (De Domenico et al. 2019).

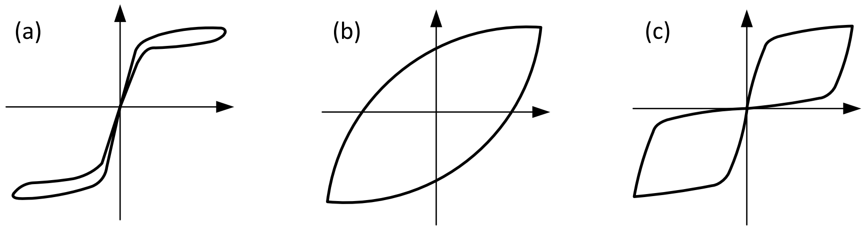


Figure 2. Behavior of SMA dampers: a) recentering; b) non-recentering; c) supplemental recentering.

When designing these dampers, it is crucial to consider a number of issues. One issue is that SMAs have a stable behavior only when they are in the form of small wires, and thicker designs cannot be expected to behave as intended (Liang et al. 2012). Therefore, these wires should only be used in tension. To resolve this issue, one can use multiple loops of wire all operating in tension. These dampers make use of two series of loops, one in the austenite phase to produce the recentering behavior and the other in the martensite phase to increase the energy dissipation capacity.

Dolce et al. have developed energy dissipation systems that offer a range of benefits. These systems can exhibit different behaviors, such as high recovery or high energy dissipation, by adjusting the number of loops and the properties of SMA. Despite their complex behavior, the mechanism of action is simple. The systems have high stiffness against small displacements, meeting functional and serviceability requirements. They also demonstrate remarkable fatigue resistance under large numbers of cyclic loads without strength or stiffness degradation. With a long service life, high corrosion resistance, and independence from loading frequency within the range of seismic loads, these systems are well-suited for general civil engineering projects (Ma et al. 2021; Bai et al. 2012; Javaherdashti and Nikraz 2010).

In another study, Yang et al. (2010) designed a device with SMA wires as shown in Figure 3 for use in steel braced frame systems.

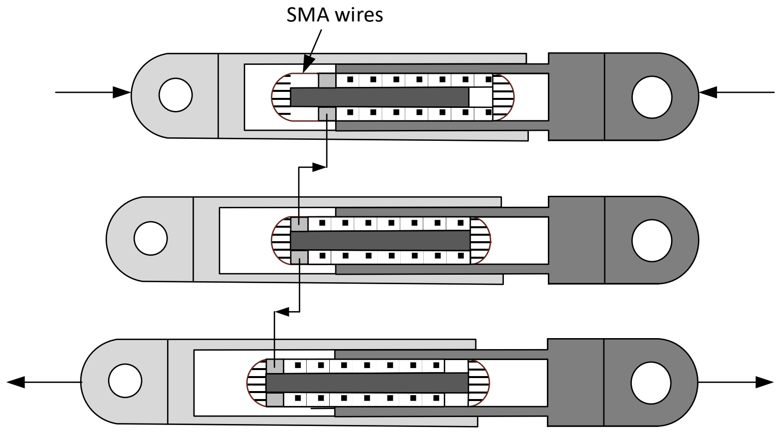
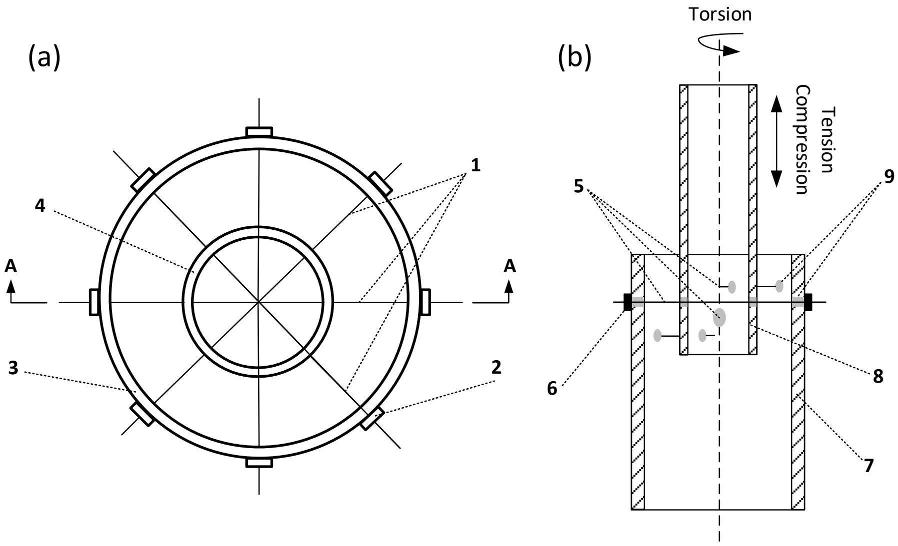


Figure 3. Configuration of the SMA wire-based damper of Yang et al. (2010).

Han et al. (2005) developed a seismic damper that exhibits good seismic behavior while simultaneously dissipating energies from a variety of tensile, compressive, and torsional loads. This damper consists of two concentric tubes and a number of nitinol wires that go into these tubes (Figure 4). This system is expected to dissipate energy through the deformation of nitinol wires, regardless of the type of load (Yang et al. 2010). In a series of experiments conducted by Han et al. (2005) on scaled models, it was observed that the amount of seismic energy dissipated by this damper is independent of the ratio of the radii of its inner and outer rings.



1. SMA wires; 2. Chuck; 3. Outer tube; 4. Inner tube; 5. SMA wires; 6. Chuck; 7. Outer tube; 8. Inner tube; 9. Hole

Figure 4. Structure and configuration of SMA damper of Han et al. (2005).

Clark et al. (1995) conducted a study introducing a seismic damper consisting of loops of nitinol wires wrapped around cylindrical support posts (Figure 5). This damper was tested in two configurations, with 100 loops wrapped in one layer and 70 loops wrapped in three layers. The purpose of their study was to collect information to further the development of seismic dampers that can be used in real structures. This study reported that while the introduced damper design principles can be used in seismic control of structures, more comprehensive analyses and further research are needed before developing a real damper based on these principles.

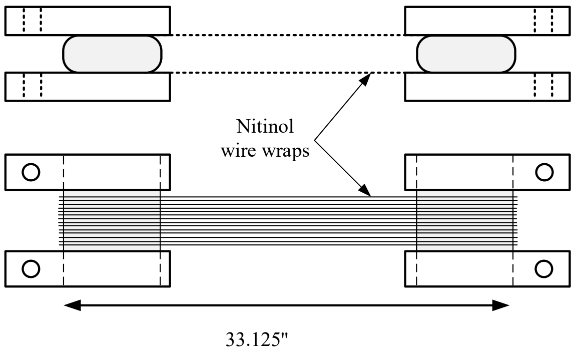


Figure 5. Structure and configuration of SMA dampers of Clark et al. (1995).

3. Applications of Shape-Memory Alloys in Steel Connections

Steel structures are composed of numerous members interconnected through various types of joints (Chen et al. 2023). Due to the high cost associated with shape memory alloys (SMAs), manufacturing entire structural profiles from these materials is economically unfeasible and practically impractical (Mohd Jani et al. 2014; Cladera et al. 2014). However, given the essential role of connections in the performance of steel structures and the fact that in many cases they are the weak points from which structural failures originate, recent years have witnessed rising interest in using the unique mechanical properties of SMAs to improve the connections of steel structures (Casciati 2019; Guan et al. 2022). This section reviews a number of studies carried out on the use of these alloys in different types of steel connections, which is indeed one of the most important applications of SMAs in structural engineering (May et al. 2020).

Ma et al. (2007) investigated the effect of SMAs on the behavior and response of an extended end-plate connection under cyclic loading by numerical modeling of a rigid beam-to-column connection with extended end plate (endplate with reinforcing plates in flanges and web) and two types of bolts made of steel and nitinol (Figure 6).

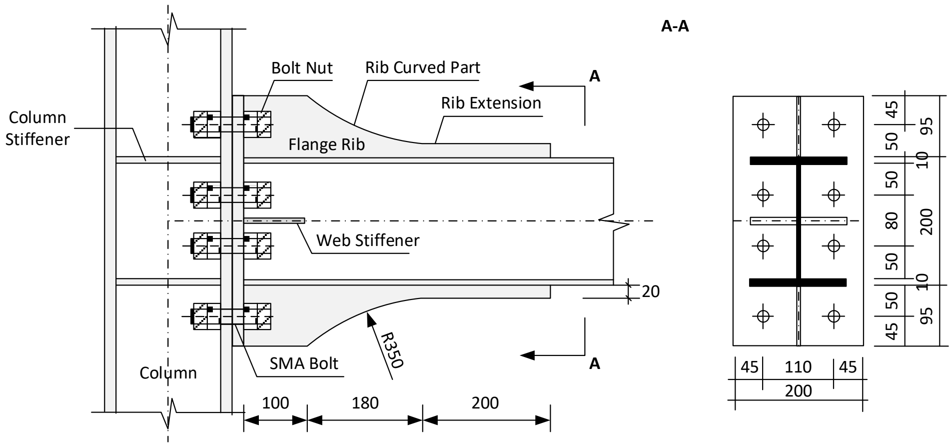


Figure 6. Beam-to-column connection of Ma et al. (2007): a) configuration; b) numerical model.

One of the most common types of failure in the conventional type of these connections (made with steel bolts) is the yielding of the beam (at a distance of about half the height of the beam from the column edge) and the occurrence of plastic deformation (plastic hinge) at this site.

According to the design principles for this type of connection, the mentioned failure mechanism should involve considerable energy dissipation through large deformations (weak beam principle). However, since these deformations are irreversible and therefore make it costly and difficult to repair or replace the damaged components, SMAs provide good opportunities to improve the seismic behavior of these connections (Aval et al. 2017; Fang et al. 2014).

A comparison of the moment-rotation plots of the connections in the two models by Ma et al. (2007) reveals that the residual deformation (residual rotation) in the connection with SMA bolts is close to zero and is much lower than that in the connection with steel bolts. This paper also illustrates that the shallower slope of the curve for the connection with nitinol bolts indicates a lower initial stiffness compared to the conventional connection with steel bolts. Additionally, the rate of energy dissipation, as indicated by the area enclosed by the hysteresis loops, is higher in the conventional connection than in the SMA connection. However, it should not be forgotten that SMA performs better than steel in larger deformations, and while the conventional will stop dissipating energy once it eventually fails at a given stress and deformation, the SMA connection will continue carrying loads without failing under the same conditions (Ravi and Krishnan 2019).

Building upon the research by Ma et al. (2007), Fang et al. (2014) conducted an experimental study on seven types of extended end plate connection with nitinol bolts and a similar conventional connection with high-strength steel bolts. This study reported interesting findings regarding the application of SMAs in the connections of steel structures. In this study, SMA connections with nitinol bolts were labeled as SMA-D (Db) - (Lb), where Db represents the bolt diameter in millimeters and Lb denotes the bolt length in millimeters. Notably, two connections, SMA-D10-240-d and SMA-D10-240, differed only in bolt layout. As in the study of Ma et al. (2007), the conventional rigid connection was designed to fail through plastic hinge formation in the beam, while the connections with super-elastic nitinol bolts were engineered to prevent yielding in the system, with bolt dimensions and plate thickness adjusted accordingly. Specifications and configurations of the connections tested by Fang et al. (2014) can be found in Figure 7 and Table 1.

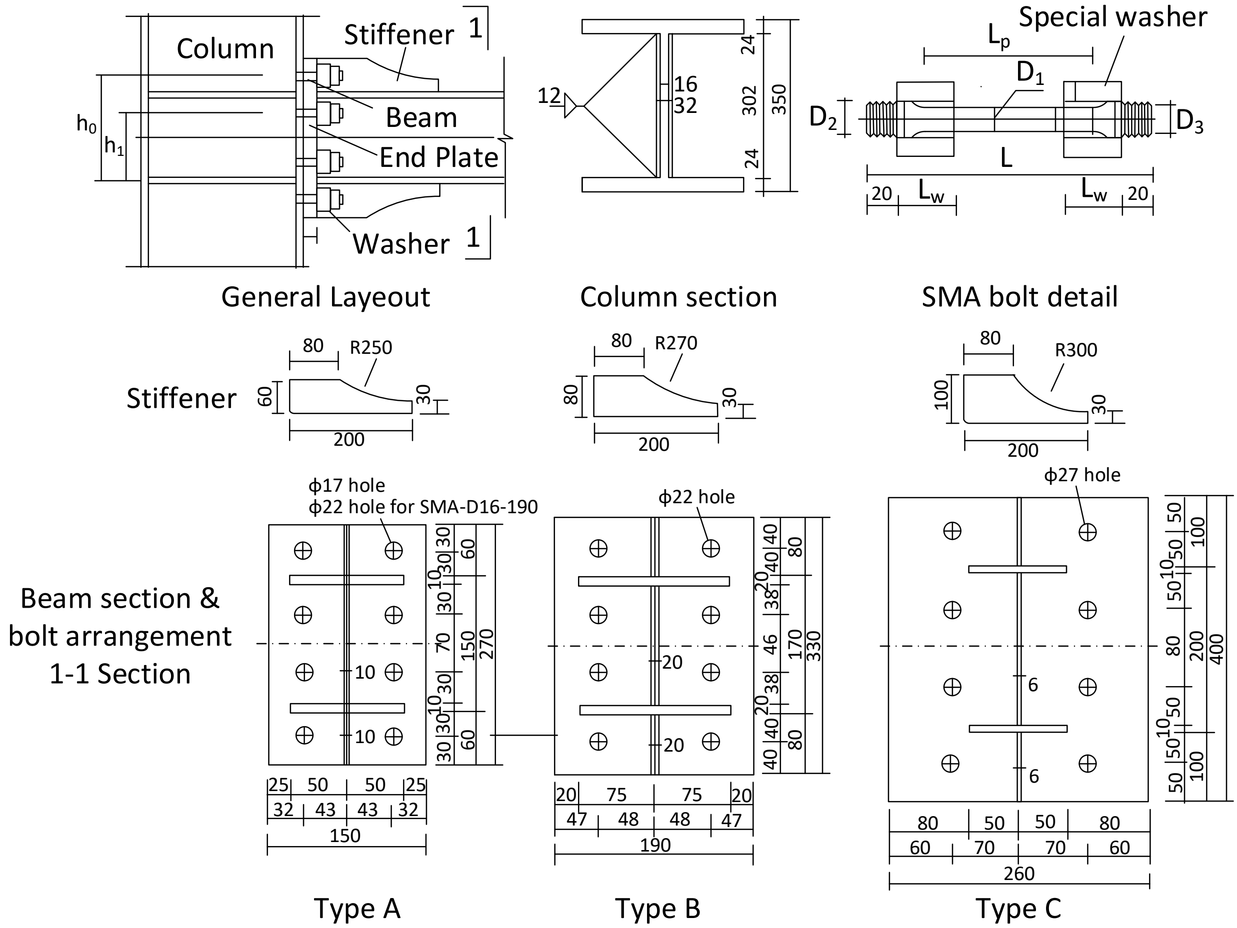


Figure 7. Configuration of the connections (adopted from Fang et al. (2014)).

Table 1. Specifications of the connections (adopted from Fang et al. (2014)).

Connection No.	Connection Name	L_b	L_p	L_w	D_1	D_2	D_3	t_p	Arrangement
1	SMA-D10-190	191	134.5	48.7	9.9	12.4	10.1	24.7	A
2	SMA-D10-190	241	183.5	74	9.9	12.4	10	24.6	A
3	SMA-D10-190	241	183.3	80	9.9	12.4	10.1	24.7	B
4	SMA-D10-190	292	233.2	98.9	9.9	12.4	10.1	24.6	A
5	SMA-D10-190	190.5	133.5	49	15.9	18.9	15.6	16.4	A
6	SMA-D10-190	241	183.5	73.8	15.8	18.9	15.4	24.8	B
7	SMA-D10-190	290.5	232.7	98.9	15.9	18.9	15.5	24.7	B
8	HS			M20-10.9				24.7	C

Beam-to-column and column-to-foundation connections are typically among the most vulnerable parts of structures during earthquakes. Using SMAs, these connections can be designed to have high energy dissipation capacity without residual deformation (Wang et al. 2019).

Ocel et al. (2004) investigated the application of SMAs in semi-rigid beam-to-column connections in steel structures. They studied two types of connections (called S_1 and S_2), where four SMA rods in the martensite phase were used to connect the flanges of the beam to the flange of the column, therefore acting as a means of force transfer from the beam to the column (Figure 8). The first test performed on this connection exhibited a high energy dissipation capacity and ductility, with no reduction in connection strength during the initial cycles. Following the first test, SMA rods were heated to return to their original state (before deformation), and then the connection was tested again. In this subsequent test, the connection showed reproducible and stabile cyclic behavior. In a separate test involving subjecting the connection to a dynamic load, the connection behavior was the same as in the quasi-static test, but with lower energy dissipation capacity.

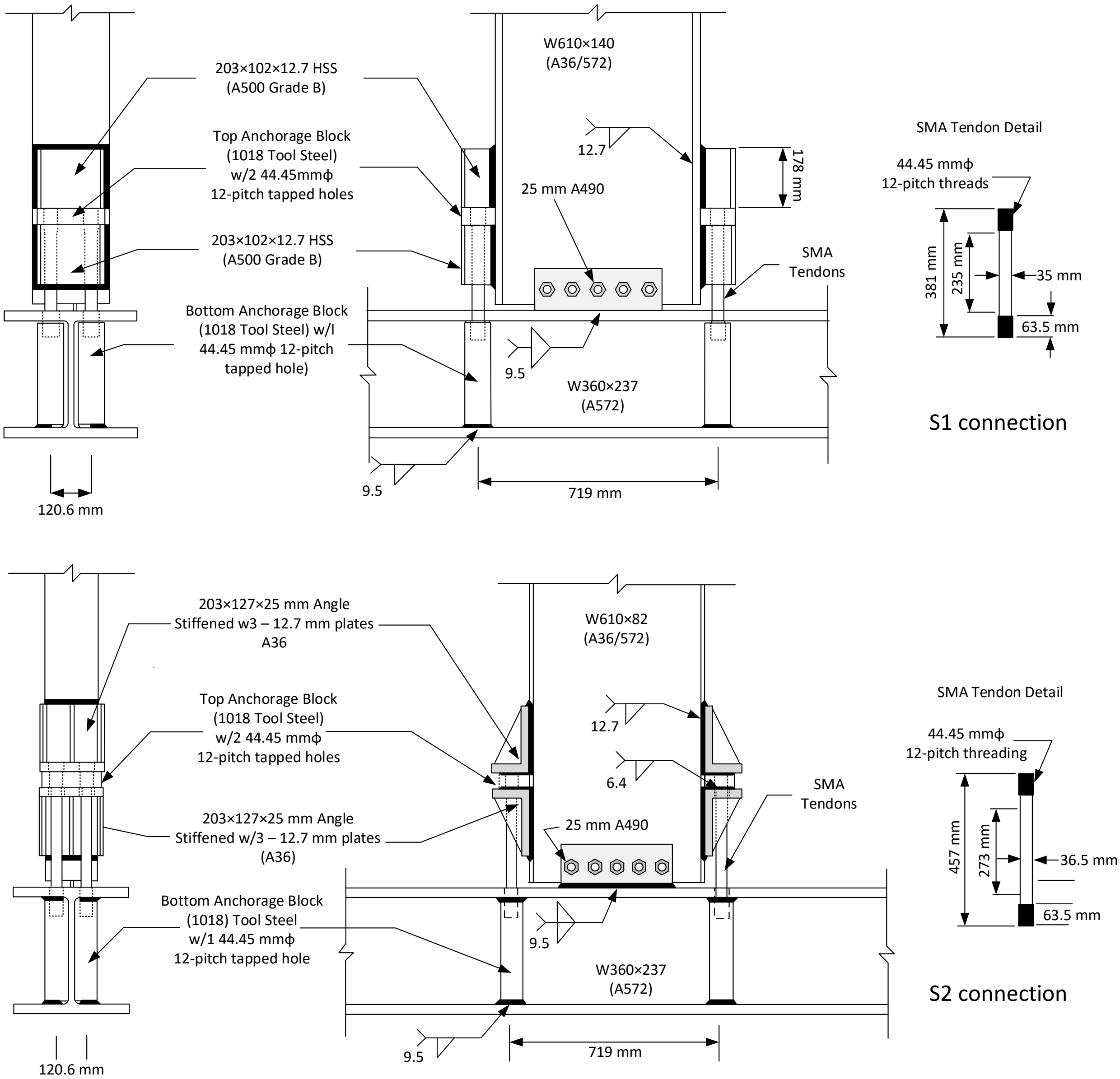


Figure 8. Structure and configuration of the connections (adopted from Ocel et al. (2004)).

Tamai and Kitagawa (2003) proposed technique that utilizes SMA rods with diameters ranging from 20 to 30 mm to link columns with foundations (Figure 9). The experimental results of this study showed the excellent performance of this type of connection.

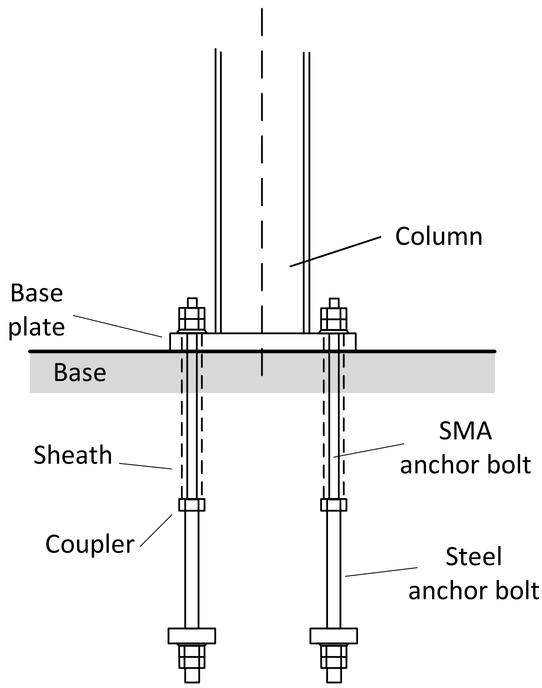


Figure 9. Shape memory alloys (SMAs) in column-to-foundation connections (adopted from Tamai and Kitagawa (2003)).

4. Applications of SMAs in Bracing Systems

One of the most widely used methods for seismic rehabilitation of steel (and even concrete) structures is to use bracing systems (Patil and Sangle 2015; Al-Safi et al. 2021; Meena et al. 2021). Today, concentric braces are more commonly used for this purpose than other lateral bearing systems. Adding concentric braces to a structure significantly increases its horizontal stiffness and reduces its lateral displacement (Gutierrez-López et al. 2023). Despite the many advantages of using concentric braces in structural frames, these systems have several major drawbacks (Qiu and Zhu 2017).

Evidence from numerical and laboratory modeling as well as empirical observations of existing structures has shown that concentric bracing systems have low energy dissipation capacity and high buckling potential under cyclic loading and tend to accumulate residual deformation during earthquakes. Hence, eccentric bracing systems have been introduced to avoid some issues of concentric braces (Kazemzadeh Azad and Topkaya 2017). In this type of lateral bracing system, a beam component of the frame, which is called the link beam, is supposed to yield under high shear forces and flexural moments applied to its location, thus increasing the system's seismic energy dissipation capacity by undergoing plastic deformation. Buckling-retrained braces, in which bracing members are not allowed to buckle, have also been suggested to be a suitable option for avoiding the problems of conventional bracing systems (Tsai et al. 2007).

In the first decade of the 21st century, the emergence of new designs for bracing systems based on super-elastic SMAs, which can recover their original form after loading while also providing high ductility and energy dissipation, paved the way for remarkable developments in the field of seismic rehabilitation of structures (Qian et al. 2010). In this section, a number of studies carried out in this area are reviewed. It should be noted that since SMAs are fairly expensive and mostly produced in the form of wires, there are only a few designs where the bracing member is made entirely of SMAs, and the super-elastic SMAs are mostly used as a part of a member or as a means for seismic energy dissipation (damping) in the bracing system.

Salichs et al. (2001) performed a series of tests on an experimental model of a one-story frame with one degree of horizontal freedom, which was diagonally braced by super-elastic state nitinol wires (Figure 10). In these tests, the system was exposed to three conditions: without bracing, with steel bracing, and with nitinol bracing. An alternating cyclic load was applied to the frame support, and the recorded response spectra were subsequently compared.

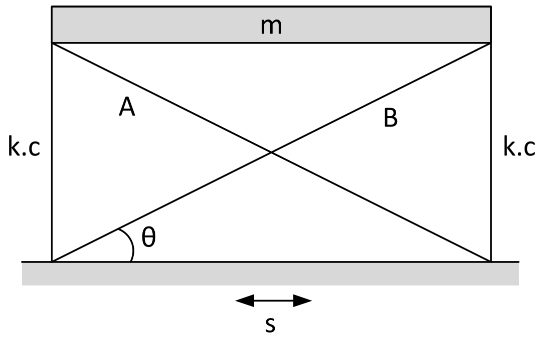


Figure 10. Configuration of the one-story one-degree-of-freedom framing systems in the tests of Salichs model (adopted from Salichs et al. (2001)).

The findings indicated that incorporating bracing systems into a structural frame would reduce its fundamental period (increase its fundamental frequency). Additionally, the fundamental period of the frame with steel braces was found to be shorter than that of the frame with super-elastic SMA braces. Overall, this study demonstrated a remarkable reduction in the peak displacement of the SMA-based frame thanks to the high damping capacity of SMA wires, enhancing its ability to withstand damage and failure compared to steel braces of equivalent stiffness (Yang et al. 2010; Wilson and Wesolowsky 2005; Qiu and Tian 2018).

Boroschek et al. (2007) also conducted a series of tests on steel frames to investigate the impact of incorporating SMAs in braces. This experimental study included creating a physical model of a three-story steel frame with lateral bracing using diametrically arranged copper-based SMA wires. Cyclic loads were then applied to the systems using a shaking table. The study reported a significant reduction in the peak horizontal deformation during the earthquake as well as the unrecoverable residual deformation after the earthquake (Boroschek et al. 2007; Meshaly et al. 2014).

Han et al. (2003) investigated the seismic performance of a two-story steel frame that was braced using steel-SMA composite wires (Figure 11). To achieve this, they developed numerical models of the structure both with and without the braces.

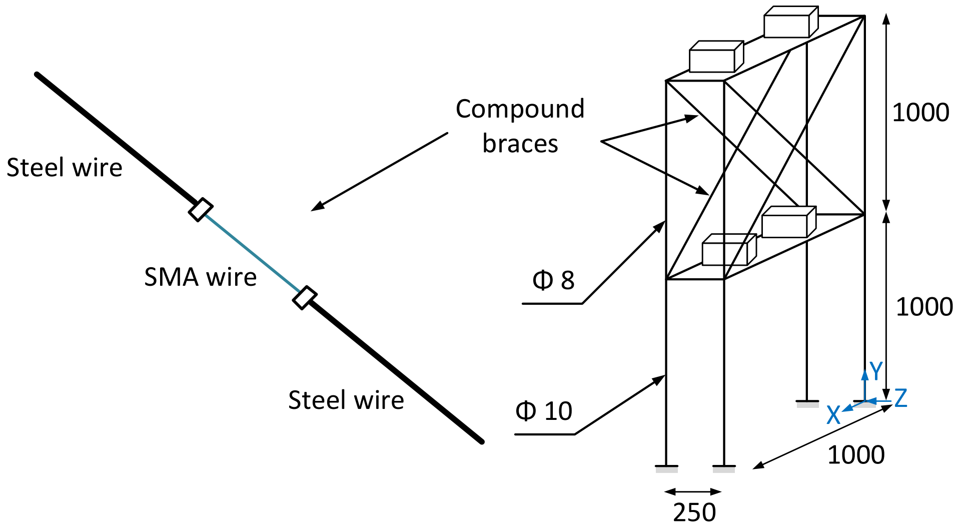


Figure 11. Configuration of the braced frame and composite braces connections (adopted from Han et al. (2003)).

A study conducted by Auricchio et al. (2006) compared the performance of a bracing system equipped with super-elastic SMAs to a conventional buckling-retrained bracing system in two three-story and six-story steel frames through numerical modeling (Figure 12). To increase the accuracy of this comparison, they assumed that the braces have the same lateral stiffness. The results showed that the super-elastic SMA bracing system had a shorter length, which was addressed by adjusting the configuration of the SMA braces with the addition of a rigid section along the length of the SMA member. This adjustment ensured that the frames maintained the same floor-to-floor height in all modeling scenarios.

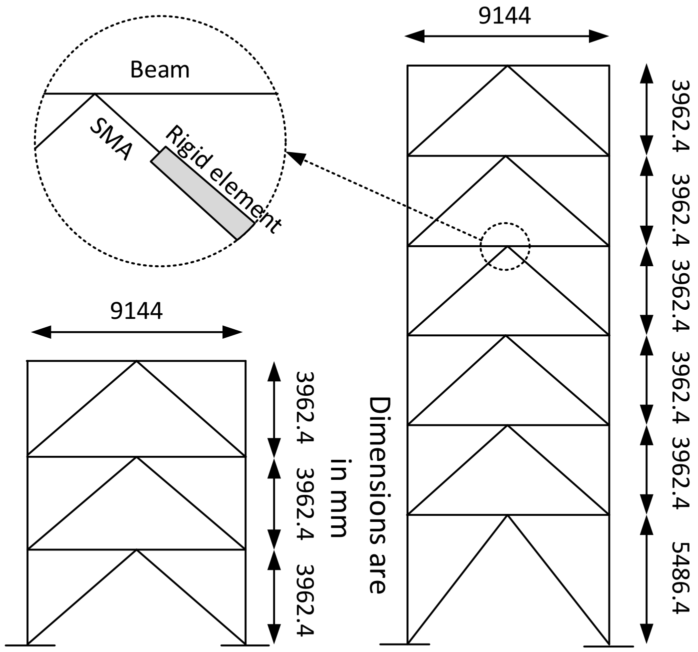


Figure 12. Frames and configuration of SMA braces in Auricchio's model (adopted from Auricchio et al. (2006)).

After applying the behavioral models of Figure 13 and different seismic mappings to the models, Auricchio et al. (2006) obtained the peak roof and residual roof drift diagrams shown in Figures 14 and 15.

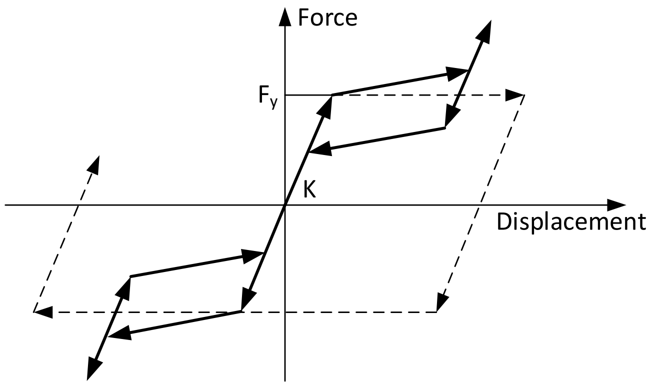


Figure 13. Behavioral models applied to the braces in Auricchio's model (adopted from Auricchio et al. (2006)).

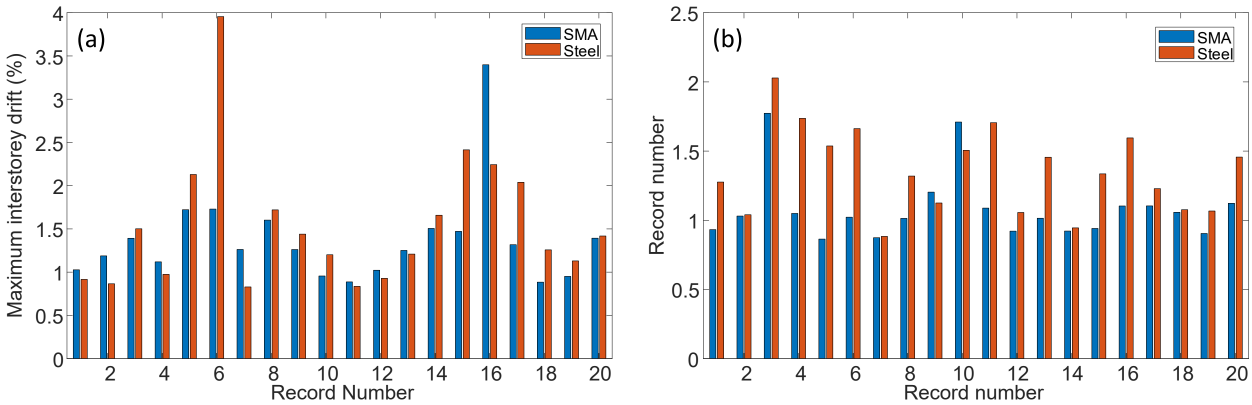


Figure 14. Peak roof drift in the study of Auricchio et al. (2006): a) three-story frame b) six-story frame.

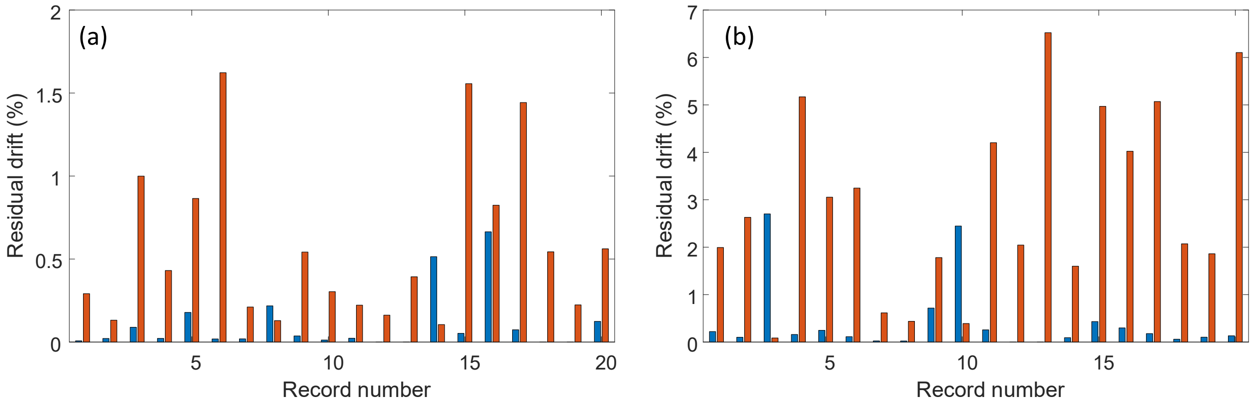


Figure 15. Residual roof drift in the study of Auricchio et al. (2006): a) three-story frame b) six-story frame.

As shown in Figures 14 and 15, the use of SMAs in the braces has slightly decreased the inter-story drift. Furthermore, the bracing system with SMA components has significantly reduced residual drift, which can be attributed to the strain recovery properties of these super-elastic materials.

Miller et al. (2012) designed a composite buckling-restrained bracing system with super-elastic SMA wires as shown in Figure 16. The behavioral mechanism of the braces of this study is illustrated in Figure 17.

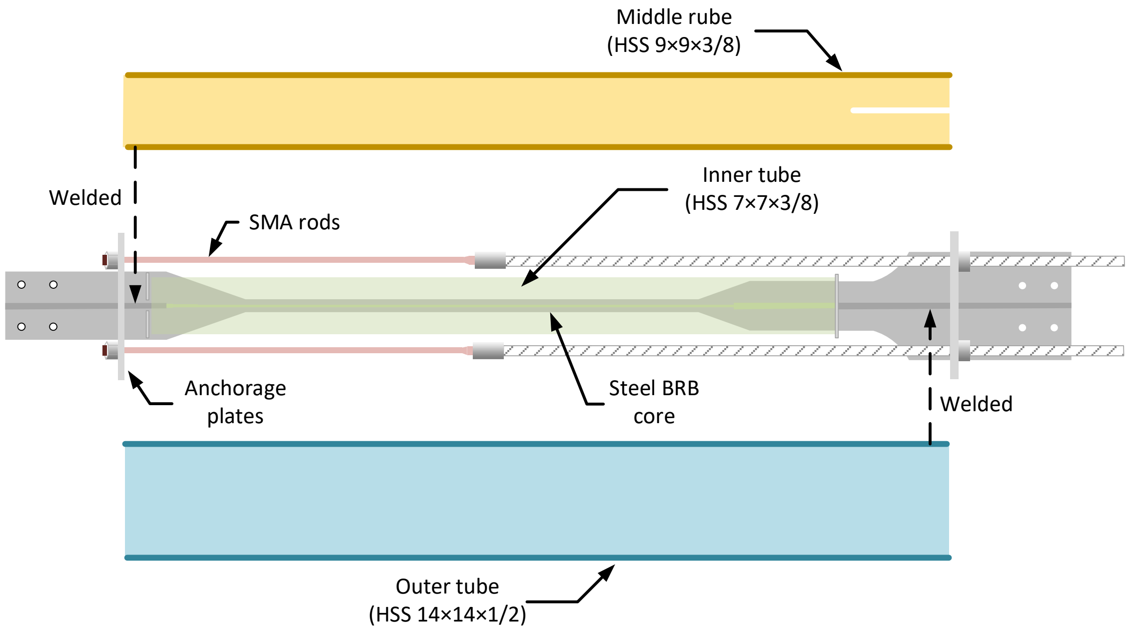


Figure 16. Configuration of composite braces designed by Miller et al. (2012).

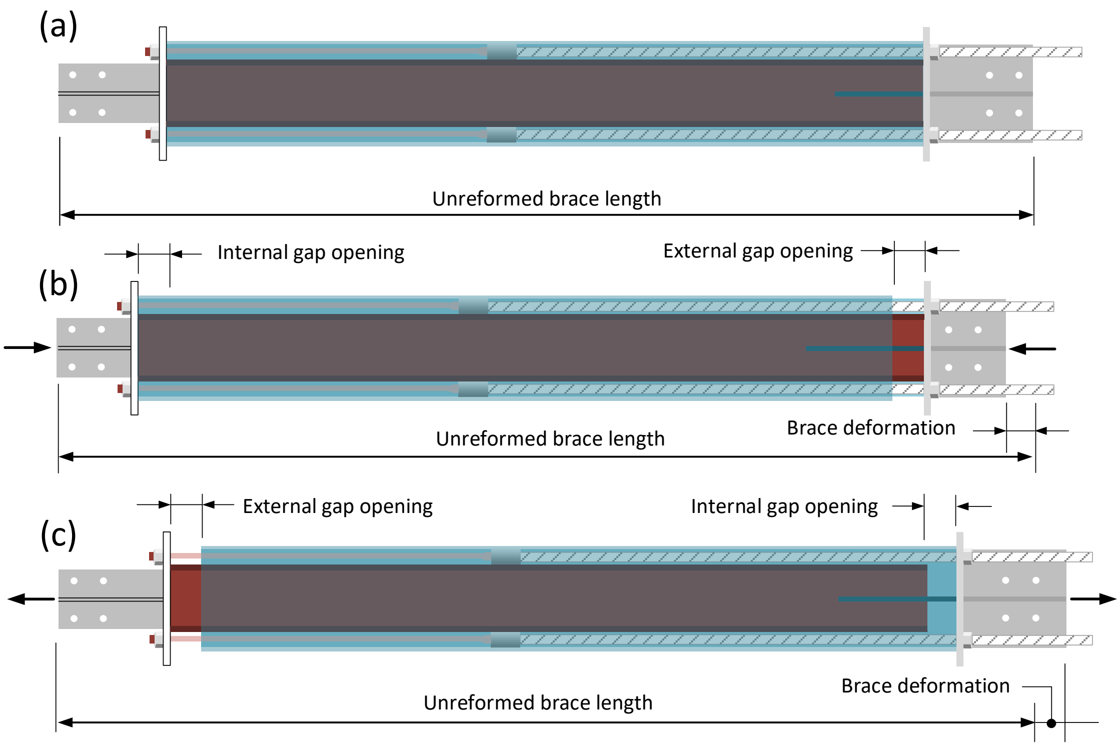


Figure 17. Behavioral mechanism of the braces designed by Miller et al. (2012) under: a) no load, b) compression, c) tension.

As mentioned earlier, in buckling-restrained bracing systems, the absence of buckling in the members before yielding and subsequent plastic deformation in the yielded areas offers very good energy dissipation. By adding SMA wires to this system, Miller et al. (2012) modified these braces so that they not only provide high energy dissipation capability but also very small residual deformation.

Ozbulut et al. (2010) introduced another application of SMAs in structural engineering, where they conducted both experimental and numerical studies on the seismic behavior of a three-story steel frame. They compared this frame, braced with steel members, to a similar frame where the steel members were replaced with composite braces consisting of a steel section attached to an SMA-based system.

As shown in Figure 18, adding a system of these super-elastic alloys not only had a significant impact on peak acceleration and inter-story drift but also led to considerably improved structural performance in terms of deformation recovery after loading.

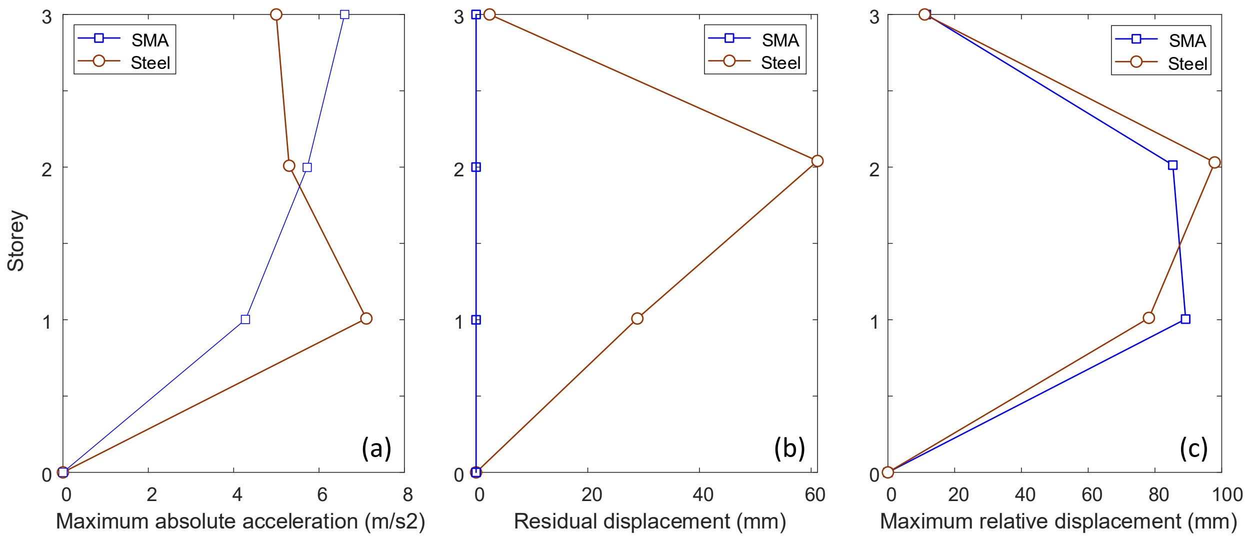


Figure 18. Plots showing a) absolute acceleration, b) residual drift, and c) peak drift at various floors of the three-story frame studied by Ozbulut et al. (2010).

After designing a device with SMA wires and adding it to a steel braced frame system in two different modes, Yang et al. (2010) investigated the seismic behavior of these systems by numerical modeling and compared their performance in a three-story steel frame as shown in Figure 19.

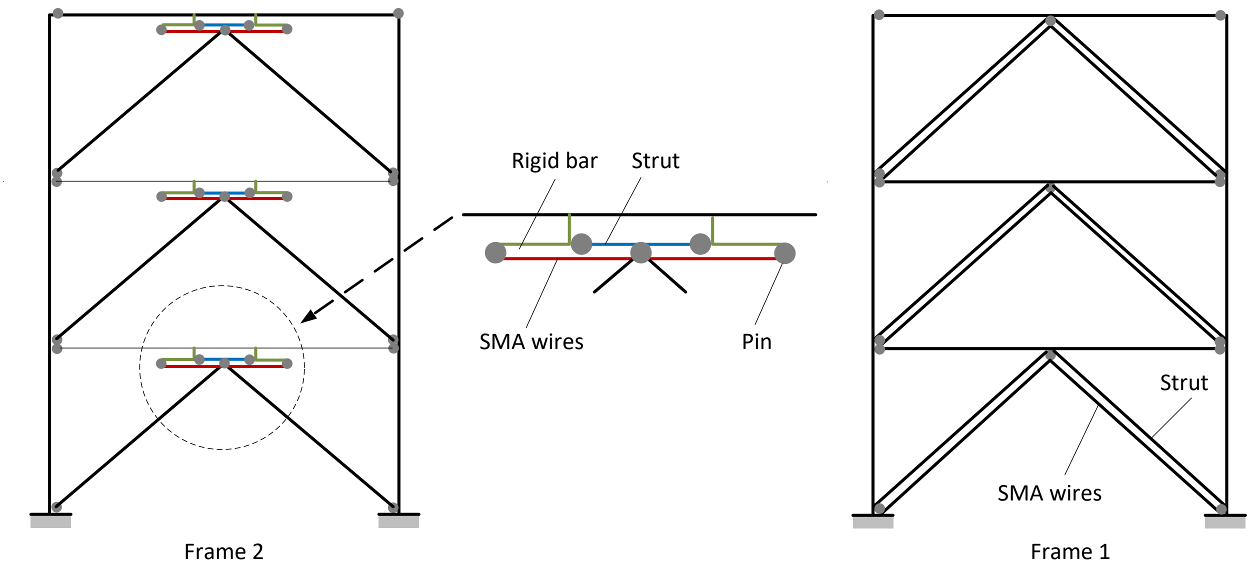


Figure 19. Three-story braced frames modeled by Yang et al. (2010).

After observing the seismic response of the constructed models, Yang et al. (2010) stated that the two bracing systems have roughly equal seismic energy dissipation capacity, which is somewhat close to that of buckling-restrained bracing systems. However, they have significantly higher deformation recovery under cyclic loading than other conventional bracing systems and show negligible residual deformation after loading. They stated that the use of SMAs in bracing systems can greatly decrease the earthquake damage to structures by minimizing their residual deformation.

The applications of SMAs in braces are not limited to steel structures, as these super-elastic alloys can also be used in the seismic rehabilitation of concrete structures.

Expanding on the MANSIDE Project, Dolce et al. (2001a; 2001b) embedded the dampers described in the previous section into a bracing system, and then compared the performance of the resulting SMA-based system and the braces with steel damping system in the seismic rehabilitation of concrete structures.

Regarding the seismic behavior of these SMA-based braces, it can be stated that they perform much better than their steel counterparts in terms of residual displacement under cyclic loading.

Dolce et al. (2004) also performed a series of tests to investigate the static and dynamic behavior of a real concrete building containing braces with super-elastic nitinol.

5. Applications of SMAs in Seismic Isolation

Today, a large number of people live in earthquake-prone areas, where there is a notable risk of earthquakes of varying intensity and frequency (Bilham 1999; He et al. 2021). Over the years, there has been great progress in the design and construction solution for making structures earthquake-resistant and reducing the impact of earthquakes on their potentially vulnerable components (Kelly 1986; Julián et al. 2014). One of these solutions which has become quite popular is seismic base isolation (Christopoulos and Zhong 2022). This solution involves creating a discontinuity between the foundation and the main structure (substructure and superstructure) to allow them to move relative to each other (Ghasemi and Talaeitaba 2020; Leblouba 2022). This increases the fundamental period of the structure, which leads to reduced base shear. The important point about these systems is that because of the presence of non-structural components or facilities in the building, the rigid displacement in the superstructure should not exceed a certain limit or last longer than a certain time (Hokmabadi et al. 2014). Also, the deformation of the seismic base isolation systems should be minimized in order to minimize the post-earthquake repair and reconstruction expenses (Ocak et al. 2022). As a result, the energy dissipation and super-elasticity properties of SMAs are perfect for improving the performance of seismic isolators. This section reviews a number of studies on the use of SMAs in various types of seismic base isolation systems, which is indeed one of the most important applications of these alloys in the field of seismic rehabilitation (Cardone et al. 2006). It should be noted that since one of the main civil engineering applications of seismic isolators is in the construction of bridge piers and substructures (Chen et al. 2022; Kordestani et al. 2020), the use of SMAs in this area is also discussed below.

In continuation of their previous work in the MANSIDE Project, Dolce et al. (2001a; 2001b) investigated the performance of their dampers in a seismic isolation system for seismic rehabilitation of structures. In this system, super-elastic SMA wires are wrapped around three cylindrical appendages connected to a series of tubes that can move in certain directions, one of which is attached to the structure and another to the foundation. Upon the emergence of a displacement between the structure and its foundation, the applied energy gets dissipated through the elongation of wires. Examination of the behavior of this seismic isolator under cyclic loading has shown that it exhibits varying degrees of stiffness depending on the loading intensity and can greatly reduce the amount of energy transferred to the superstructure.

Following the work of Dolce et al. (2001a; 2001b) in Italy, Ponzo et al. (2017) further investigated the performance of seismic isolators with SMA dampers. They created physical models of a steel frame with four types of seismic isolators and recorded their seismic response on a shaking table. They observed the highest deformation recovery in the isolators that incorporated super-elastic SMAs and concluded that given their good energy dissipation capacity under strong earthquakes, these isolation systems are the best option among the models tested in that research.

Corbi (2003) studied the behavior of a single-story braced frame with two modes of bracing, elastoplastic and super-elastic (SMA), and proposed a seismic isolation system for multi-story structures (Figure 20). This study demonstrated that the frame with super-elastic braces exhibited significantly lower residual deformation than the other frame.

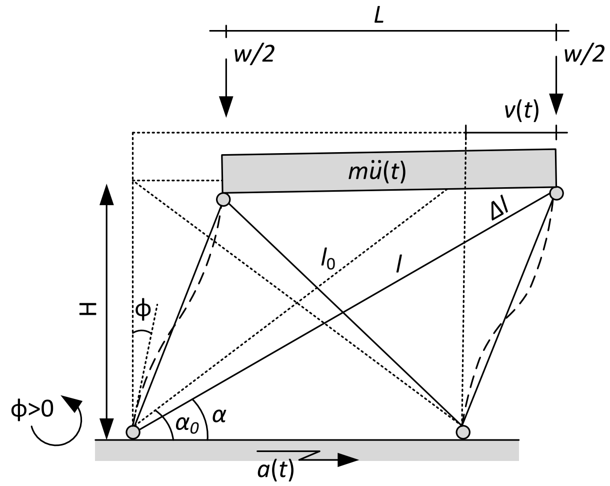


Figure 20. Configuration of the single-story braced frame of Corbi (2003).

Corbi (2003) investigated the behavior of their designed seismic isolation system by placing it on the first floor of a seven-story frame as shown in Figure 21 and then plotted the time history diagrams of drift in the first and seventh floors of this structure. The results showed a reduction in these drifts and also improved recovery after loading. Furthermore, the presence of the SMA-based seismic isolator in the frame led to the dissipation of significant amounts of seismic energy at the isolation level (first floor).

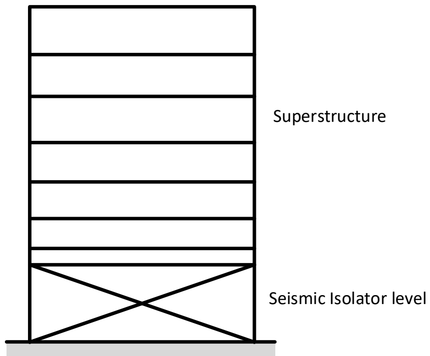


Figure 21. Seismic isolation of a seven-story frame at the first floor by Corbi (2003).

Also, from about a decade ago, some have started using SMAs in rubber bearing seismic isolators, a few examples of which are given below.

Xue and Li (2007) designed a rubber bearing (support) with diagonal SMA wires as illustrated in Figure 22, and showed that the seismic isolation of structures with this system will lead to improved seismic energy dissipation and residual deformation compared to conventional rubber bearing isolation systems.

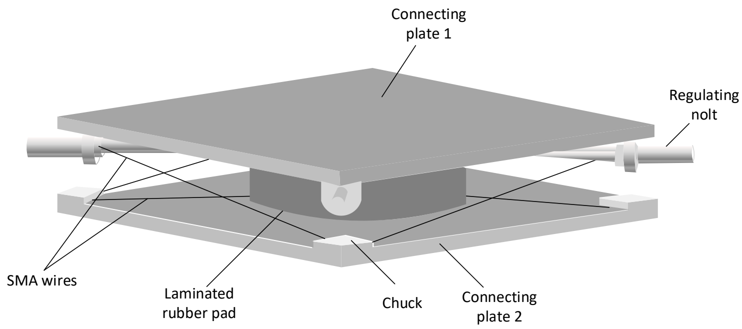


Figure 22. Rubber bearing isolator with SMA wires of Xue and Li (2007).

Dezfuli and Alam (2013) designed four types of rubber bearing isolators with orthogonally and diagonally arranged SMA wires and two different effective thicknesses (thickness of the rubber cushion) as shown in Figure 23, and then compared their performance with each other and with conventional rubber bearing isolation systems.

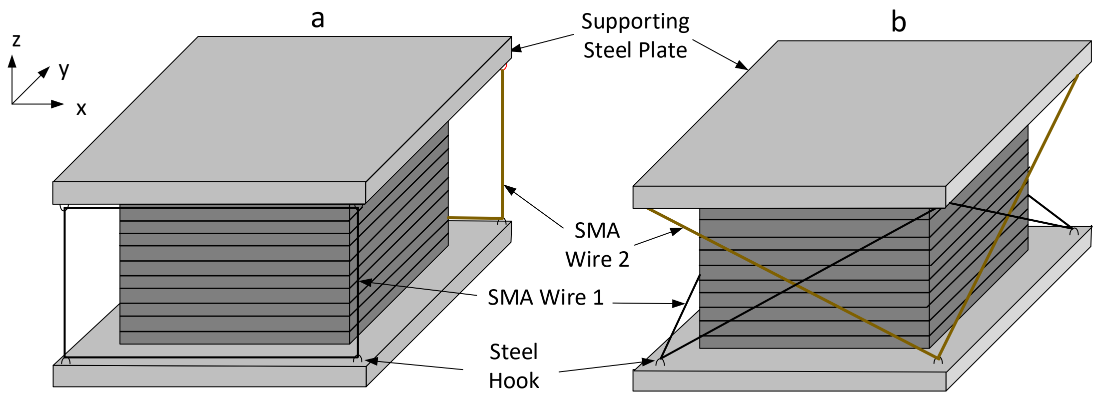


Figure 23. Rubber bearing isolator with SMS wires of Dezfuli and Alam (2013): a) with diagonal SMA wires; b) with orthogonal SMA wires.

As shown in Figure 24, Dezfuli and Alam (2013) found that adding SMA wires to the conventional rubber bearing isolator increases its horizontal stiffness. Among the isolators with super-elastic wires, the one with orthogonal wires had higher horizontal stiffness. It was also reported that as the effective thickness of these isolators increases, their horizontal stiffness decreases.

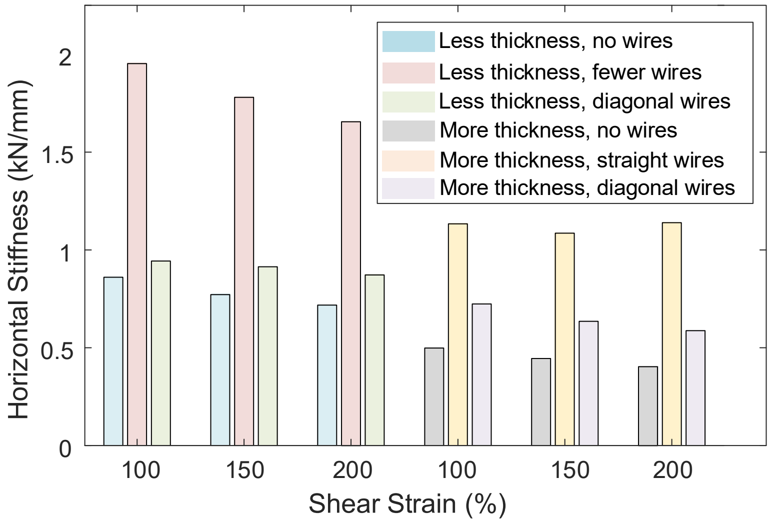


Figure 24. Horizontal stiffness of the isolators modeled by Dezfuli and Alam (2013).

Presenting the diagram shown in Figure 25, Dezfuli and Alam (2013) concluded that the amount of energy dissipated in rubber bearing isolation systems is directly related to the thickness of their rubber section. They also stated that adding super-elastic SMA wires to these systems can be expected to help them offer better energy dissipation. Overall, the results of this study showed that embedding SMA wires in rubber bearing isolators with orthogonal arrangement will lead to more energy dissipation (Figure 25).

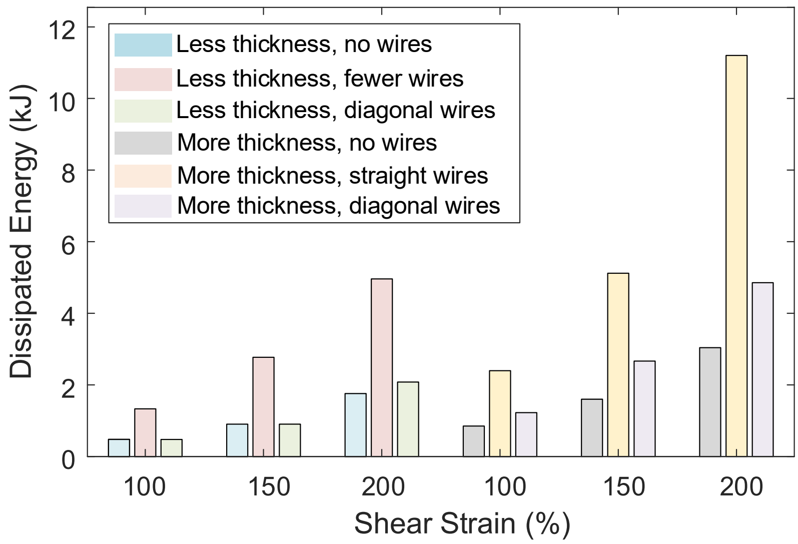


Figure 25. Energy dissipation in the isolators modeled by Dezfuli and Alam (2013).

Figure 26 makes a comparison between the isolators designed by Dezfuli and Alam (2013) in terms of residual horizontal deformation of the bearing after loading. It can be seen that in all cases, adding SMA wires has improved the recovery of horizontal deformations. Figure 26 also demonstrates the generally better deformation recovery performance of the orthogonal wire arrangement compared to the diagonal arrangement. However, interestingly, this diagram also shows that the diagonal arrangement provides lower residual deformation than the orthogonal arrangement at the highest bearing thickness (the largest strain).

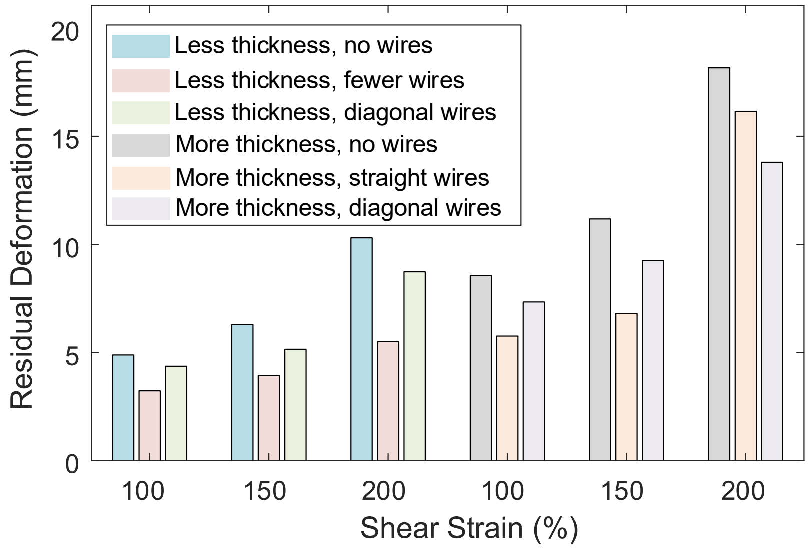


Figure 26. Residual deformations in the isolators modeled by Dezfuli and Alam (2013).

The rest of this section is devoted to the use of SMAs in another type of seismic isolation system that is composed of a rubber bearing and a lead core. Seo and Hu (2016) examined the seismic performance of a number of lead-core rubber bearing seismic isolation systems in a braced frame (Figure 27).

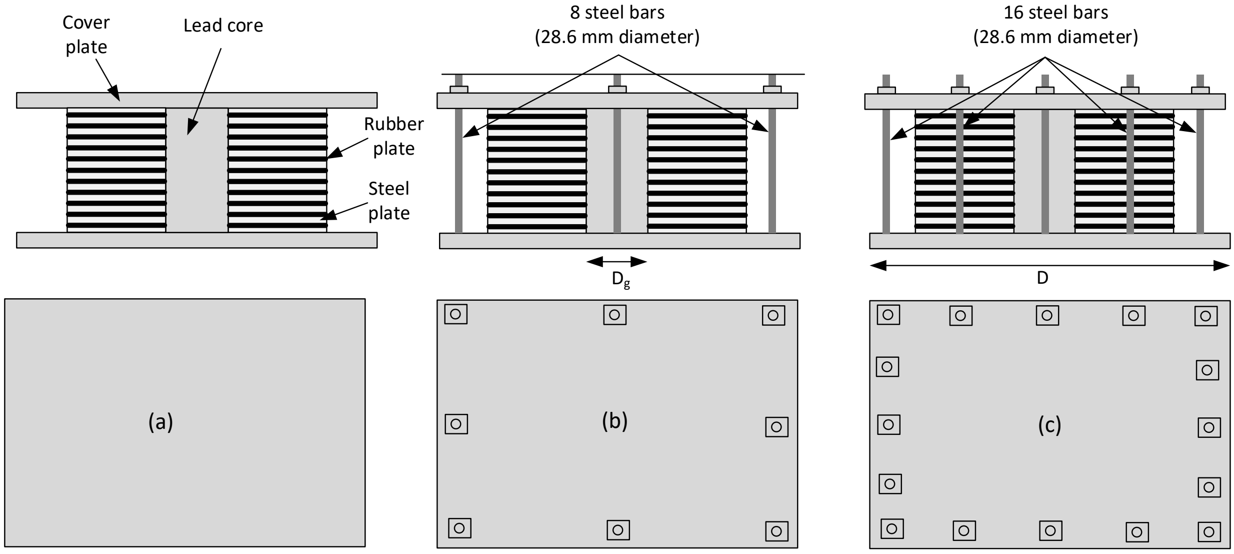


Figure 27. Lead-core rubber bearing isolation systems tested by Seo and Hu (2016): a) conventional design; b) with 8 steel or SMA rods; c) with 16 steel or SMA rods.

Since adding a seismic isolator to a structure will increase its fundamental period, the fundamental period of the isolated structure is a function of the characteristics of the used isolation system. Therefore, the structures modeled by Seo and Hu (2016) have different fundamental periods and consequently different spectral accelerations. Adding steel rods to this lead-core rubber bearing isolation system makes a greeter reduction in the period of the isolated structure than adding super-elastic SMA rods. Naturally, increasing the number of rods added to the isolation systems further reduces the fundamental period of the structure. In the next step of their research, Seo and Hu (2016) plotted the force-displacement diagrams of each modeled seismic isolation system. The obtained results showed that using SMA rods in this isolation system effectively reduces its residual deformation. Also, super-elastic SMA rods outperformed steel rods in postponing the yield of the conventional lead-core rubber bearing isolator, or in other words, improved the system's load-bearing capability thanks to their unique ductility properties.

Casciati et al. (2007) modified a seismic isolation system by adding SMA rods to its design. The experiments conducted by these researchers showed the notable role of SMA rods in reducing the drift of the superstructure and increasing the energy dissipation of the system (Figure 28).

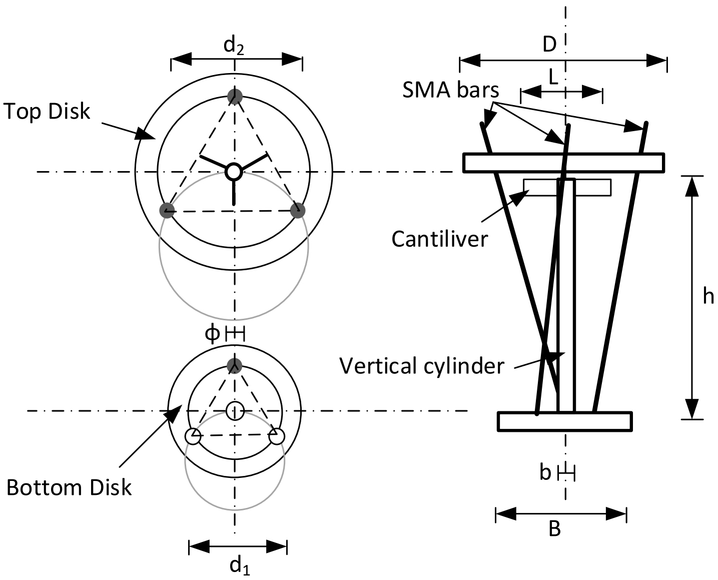


Figure 28. Configuration of the seismic isolator designed by Casiati et al. (2007).

6. Summary and Conclusions

In general, structural and seismic engineering can greatly benefit from the use of SMAs in both austenite and martensite phases. Since the mechanical properties of SMAs are a function of temperature, SMA-based systems need to be designed with careful consideration of the potential effects of temperature. Thus, to take advantage of the super-elastic properties of austenitic SMAs, their austenite finish temperature, i.e., the temperature at which the direct martensitic transformation ends, must be lower than the minimum ambient temperature. Similarly, to make use of SMAs in the martensite phase, their martensitic finish temperature, i.e., the temperature at which the inverse martensitic transformation ends, must be greater than the maximum ambient temperature.

Considering the large size of civil engineering structures and the massive loads that they are commonly subjected to compared to other fields of engineering and science, only very large amounts of SMAs will have a notable effect on the performance of these structures. Therefore, the cost of SMAs remains one of the main obstacles to the wider use of these alloys, especially in large-scale structures. The expensiveness of SMAs, particularly in the case of nitinol, is due to the difficulty of the manufacturing and forming process. Although the price of these alloys has decreased significantly over the past two decades (for example, the price of nitinol has decreased from $1,000 per kilogram in 1996 to $150 per kilogram in 2006), SMAs are still expensive compared to other materials used in civil engineering. One of the least expensive types of SMAs is the iron-based type with the formula Fe-Mn-Si-X (where X could be various metals), which may be usable in civil engineering. For comparison, Fe-Mn-Si-Cr costs about one-tenth of nitinol price. In general, iron-based SMAs have good weldability and a wider range of phase transformation temperatures. Also, these SMAs exhibit better bond strength than nitinol when used in reinforced concrete members.

In contrast, nitinol has far better super-elasticity and shape-memory properties than iron-based SMAs. It should be noted that Ni-Ti-X SMAs behave similar to nitinol (Ni-Ti) but are less expensive, although they are more expensive than iron-based SMAs. Another group of SMAs are copper-based alloys like Cu-Zn-Al and Cu-Zn-Ni, which are even less expensive than the other two SMA types, but do not have acceptable ductility.

In conclusion, it appears that there are massive opportunities in the production of low-cost SMAs with application-specific behavioral characteristics, and when cheap enough, these alloys will turn into a mainstay of structural and earthquake engineering.

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