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Technical Article

Shape Memory Alloy (SMA) as Smart Materials Application in Structural Engineering in the Last Decade

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Abstract

The shape memory alloys (SMAs) is a specific property some materials have to restore their original shape. This strange behavior has caused these materials to be classified as smart materials. Due to the capabilities of this material, it has been used in all industries, and in the last decade, its use has developed tremendously. In this article, while dealing with their general properties and production method, their applications especially in structural and earthquake engineering have been reviewed and investigated. For this reason, some of the works and studies done by structural engineering researchers in the recent period (from 2014 to 2024) in the field of structural engineering and with the approach of evaluating connections equipped by shape memory alloys have been mentioned. Finally, while examining the details of a Practical study in the field of steel column connection to the foundation, which was done with and without using of shape memory alloys, the advantages of using shape memory alloys in connections are summarized in the results.

Keywords: Shape Memory Alloy (SMA), Connection, Structural Engineering.

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1. Introduction

The quest for new materials with properties superior to those already attainable, more useful for a specific purpose, or exhibiting a combination of required qualities is a continuous subject of interest to researchers and engineers all over the world. A very interesting group of metallic materials make up so-called shape memory alloys (SMA), revealing a number of extremely useful practical applications, combinations of functional properties, and utility features not observed together in other metallic materials. For that reason, these materials frequently earn such attributes as smart, intelligent, or they are sometimes called living composites. Intelligence and smartness are inherent attributes of living creatures, and they can be inherited by SMA materials probably to the extent that actual users of them exhibit these virtues, but nobody should object when SMA materials are called adaptive materials. The nice, from an engineering point of view, features of SMA materials do not come at any cost. Their behavior is very complex, and their efficient use requires comprehensive experimental knowledge about their performance when submitted to various thermomechanical loadings, as well as possessing a credible theoretical model that enables SMA materials to have consistent characterization and the quantitative prediction of appearing stresses, deformations, and/or thermal effects. The history of research on shape memory alloys and shape memory effects is inseparably connected with the history of research devoted to thermoelastic martensitic transformation, a physical phenomenon responsible for shape memory effects in metallic alloys. SME's have different structures from martensite to austenite and vice versa, here only the internal structure of the martensitic phase that is very complex is shown in Fig.1.

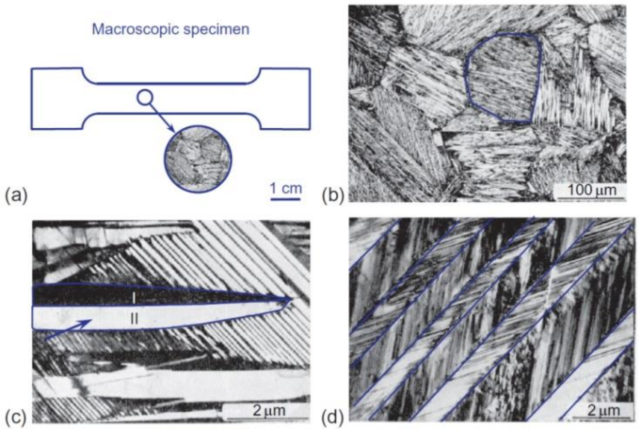

Fig.1. Multiscale organization of martensitic phase in polycrystalline CuAl alloy:
(a) macroscopic sample in martensitic state;
(b) polycrystalline structure of martensitic phase with martensitic objects—plates, confined by grain boundaries;
(c) spear-like martensitic compound composed of two habit plane martensitic variants (HPV)—indicated by arrow;
(d) a configuration of parallel habit plane martensitic variants (HPVs) with visible striations being a manifestation of their lower-level internal structure, composed of two martensitic lattice correspondence variants (CVs).

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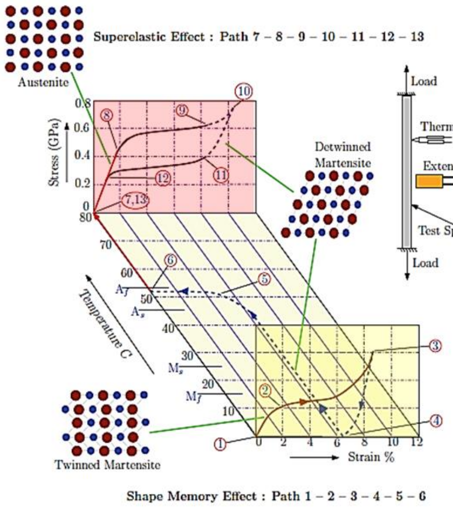
1.1. SMA Producing

Shape memory alloys (SMAs) are typically made through a process called alloying, which involves combining two or more metals to create a material with unique properties. The most common SMAs are made from a combination of nickel and titanium, known as Nitinol. The first step in making SMAs is to melt the desired metals together at high temperatures in a controlled environment. This process ensures that the metals are thoroughly mixed and form a homogeneous alloy. Once the alloy is formed, it is typically cast into a specific shape or form, depending on the intended application. After the alloy has cooled and solidified, it undergoes a process called heat treatment to set its shape memory properties. This involves heating the alloy to a specific temperature and then rapidly cooling it to lock in its desired shape memory characteristics. Once the shape memory alloy has been heat-treated, it can be further processed through techniques such as rolling, forging, or extrusion to achieve the desired shape and dimensions for its final application. Overall, the process of making shape memory alloys involves a combination of metallurgical techniques and heat treatments to create materials with unique properties that allow them to return to a predetermined shape when subjected to certain stimuli.

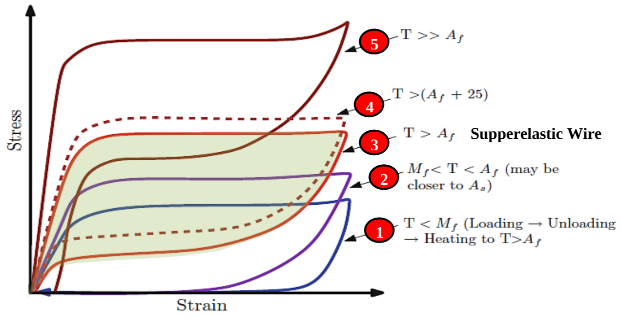
1.2. SMA Mechanical Specification

The SMAs are a fascinating class of materials that have garnered significant attention in the field of structural engineering. These unique materials possess the remarkable ability to recover their original shape after deformation when subjected to specific stimuli, such as temperature changes or mechanical loading. (Fig.2. and Fig. 3.). This distinctive property makes SMAs highly attractive for a wide range of structural engineering applications. In recent years, researchers and engineers have been exploring the potential of SMAs to revolutionize the design and performance of various structures. One of the key advantages of using SMAs in structural engineering is their ability to provide self-healing capabilities. By incorporating SMAs into structures, it is possible to create systems that can autonomously repair damage and maintain structural integrity over time. Additionally, SMAs offer excellent damping and vibration control properties, making them ideal for enhancing the performance of structures subjected to dynamic loads. This can be particularly beneficial in applications where minimizing vibrations and ensuring stability are critical, such as in bridges, buildings, and aerospace structures. In civil engineering, SMAs are being investigated for use in seismic retrofitting, where they could help improve the resilience of structures to earthquake-induced forces.



Shape memory effect (Path 6-1) and superelastic effect (Path 13-7) can be seen. This reversibility effect is a manifestation of solid-phase transformations between a stable austenitic phase, high-temperature phase and low-temperature martensitic phase.

Fig.2. Temperature-stress-strain diagram describing a thermo-mechanical test.



Curve (1) The Response of the wire under the influence of temperature lower than Mf after it was unloaded and achieved zero stress. The shape memory property was achieved by heating the wire above the Af.
Curve (2) The response of the wire above the temperature Mf<T<Af, which is almost identical to As.
Curve (3) displays the classic superelastic wire above Af.
Curve (4) displays the temperature-dependent superelastic wire.
Curve (5) The response of the temperatures far higher than Af.
Fig. 3 Response of SMA wire under different temperature regimes

By incorporating SMAs into building components, it is possible to create systems that can adapt and respond to changing external conditions, thereby enhancing overall safety and performance. From self-healing structures to adaptive building systems, the integration of SMAs holds great promise for creating innovative and resilient structures that can withstand a wide range of challenges. With ongoing developments in material science and engineering, the future looks bright for the application of shape memory alloys in structural engineering.

In this paper, an overview of the recent applications of SMEs in the structure and how they affect the performance of the structure has been examined.

1.3. Literature Review

In the recent decade, many studies and researches have been conducted regarding the use of shape memory alloys to improve the performance of structures (against static and dynamic loads such as earthquakes, explosions, wind, etc.) in structural engineering. Briefly, some of these studies have been briefly considered in the following. The results of a research proposed a novel type of self-centering (SC) steel beam-to-column connection using superelastic shape memory alloy (SMA) angles and steel angles. Unlike conventional post-tensioned SC connections, their proposed SC connection utilized SMA angles to provide SC ability and moderate energy dissipation, enabling easy installation and replacement [1]. The result showed that, the proposed SC connection can help achieve the goal of earthquake resilience in structural design. Another study has developed self-centering steel beam-to-column connections as an alternative option for conventional rigid beam-to-column welded connections, to reduce or eliminate the residual deformation of the structure and mitigate or avoid structural damages. They presented a finite element analysis of a novel self-centering beam-to-column connection with shape memory alloy (SMA) tendons as reentering and energy dissipation elements and comb-teeth dampers (CTDs) as supplementary energy dissipation devices, (Fig. 4.)[2],.

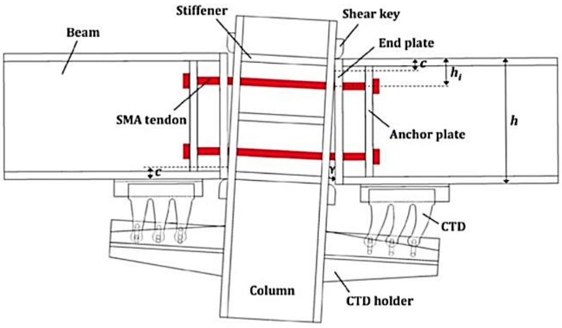


Fig. 4. Schematic deformation of the proposed SMA-based connection after gap opening.

Another research in this regard have presented a comprehensive numerical investigation on a self-centering eccentrically braced frame (SEBF) with a vertical link member consisting of inner and outer link components. These components were respectively bolted to floor beam and Chevron braces using shape memory alloy bolts, which provide self-centering driving forces. The proposed self-centering system demonstrated stable hysteresis behavior with almost no residual drifts. The proposed system also offered moderate energy dissipation, with equivalent viscous damping of up to 15% [3]. Another research and study have introduced a class of shape memory alloy (SMA)-restrained rocking (SRR) bridge columns and numerically evaluated their response under lateral loading. Following the introduction of three SRR column design variations, a displacement-based procedure was proposed for their effective seismic design. Nonlinear 3D finite element models were then developed to investigate the performance of the proposed columns under monotonic and cyclic lateral loading. The findings illustrated that the proposed SRR columns are capable of meeting their targeted performance objectives, i.e., avoiding damage under the displacement demands induced by a 2475-year seismic event, as well as providing significant self-centering and hysteretic damping [4]. In another paper and study for achieving a delicate balance between self-centering behavior and energy dissipation, has been proposed to develop the damage-control steel frame equipped with shape memory alloy (SMA) connections and ductile links showing the partially self-centering behavior. The inelastic seismic demand of the novel structure, and the emphasis was given to the spectral energy factor of the system subjected to near-field earthquake motions. Nonlinear regression analyses were conducted to develop a series of prediction equations. The good agreement between the histograms of the energy factor and predictions by the regression equations confirmed the adequacy of the proposed model. The proposed model was eventually applied to evaluating the damage-control behavior of a prototype structure under near-field earthquake motions, and the sufficiency of the model for assessing the structural damage-control behavior from a statistic perspective was confirmed [5]. In another review and research presented an innovative beam-through framed connection equipped with curved knee braces. Curved knee braces with pinned connections were employed in semi-rigid beam-to-column joints. Based on the results of analyses, it is found that traditional BTF would exhibit high mode effect due to compressive buckling of strip braces, the inter-story drift is nonuniform along building height. Employing knee braces on traditional BTF stabilizes hysteretic behaviors and improves post-yielding strength for the system, global response of the system is reduced obviously and soft-story mechanism is mitigated. Moreover, results also indicate that satisfying peak transient inter-story drift and deformation uniformity can be achieved when strength demand from knee braces is adopted as 25% of total design inter-story strength demand [6].Another study presented a low-damage solution for self-centering steel and composite beam-to-column connections, with the issue of beam- growth being particularly addressed by permitting the connections to rotate only about the top flange of the beam. Self-centering devices incorporating novel shape memory alloy (SMA) ring springs are the kernel components for the proposed connections. The fundamental working principle of the connections were depicted, followed by an experimental study on four proof-of-concept specimens, including three bare steel and one composite connections. Based on the experimental observations, preliminary design recommendations are proposed, with the focus on the design of the SMA ring springs, web plate, cover plate, and other components of the device. Empirical design equations are also proposed for predicting the moment resistance of the connections, and the predicted values are shown to agree well with test results [7]. Other researchers used iron-based shape memory alloys (Fe-SMAs) to retrofit fatigue-cracked riveted connections in steel bridges. a test setup is specifically were designed to examine the SMA-strengthened cracked double-angle connections. First, a static test was performed on the unstrengthen connection without any crack. Subsequently, two high-cycle fatigue (HCF) tests were conducted on a pre-cracked connection. Finally, the SMA-strengthened connection is subjected to the HCF loading. It is observed that the fatigue life is substantially enhanced, and the fatigue crack is arrested by the activated Fe-SMA strips [8]. In this regard, other researchers worked on steel column to foundation connection equipped with SMS and came to the conclusion that using SMA in connection can reduce the seismic response of the structure [9]. Other studies revealed the great potential of using combined superelastic shape memory alloy (SMA) bolts and steel angles for self-centering connections with variable performance targets. Eight full-scale specimens were tested, and the main parameters included SMA bolt pre-strain, bolt length, angle thickness, and layout of bolts and angles. Following the test program, a design framework for such connections was proposed, and a calculation example was provided to further illustrate the proposed design procedures. The design framework was also validated through comparing the design predictions against the test results in terms of residual connection rotation [10]. Another research particularly examined the structural performance of joints between CHS column and I-beam equipped with 12 mm diameter SMA tendons and steel angles. Two full-scale laboratory tests were conducted to investigate (1) the re-centering capability contributed by the SMA tendons and (2) the energy dissipative performance contributed primarily by the steel angles. Parallel numerical and parametric analyses through ANSYS were also conducted. Both experimental and numerical results confirmed the significance of the thickness of the steel angle and the initial prestress on the SMA tendons towards the connection's stiffness, re-centering and energy dissipative performance. A thinner angle resulted in lower connection stiffness and a lower energy dissipative ability, however a promising re-centering capability was guaranteed. Higher initial pre-stress on the SMA tendons also facilitates the re-centering performance [11]. In another study three-dimensional finite element analyses conducted to study the seismic performance of beam–column connections incorporating shape memory alloy plates. Eight beam–column connection subassemblies with shape memory alloy plates in the plastic hinge of the beam were analyzed under cyclic loading. Based on the numerical results, the reentering properties of superelastic shape memory alloy plates were found to be effective in reducing the residual drifts of a flange plate beam–column connection, while displaying an excellent ductility. In addition, shape memory alloy plates could prevent the occurrence of local buckling and damage in structural members. The new self-centering connections could also exhibit a good energy dissipation capability [12]. Other researchers studied the cyclic performance of end plate connections through normal shape memory alloy screws with high strength, (Fig. 3.) [13].

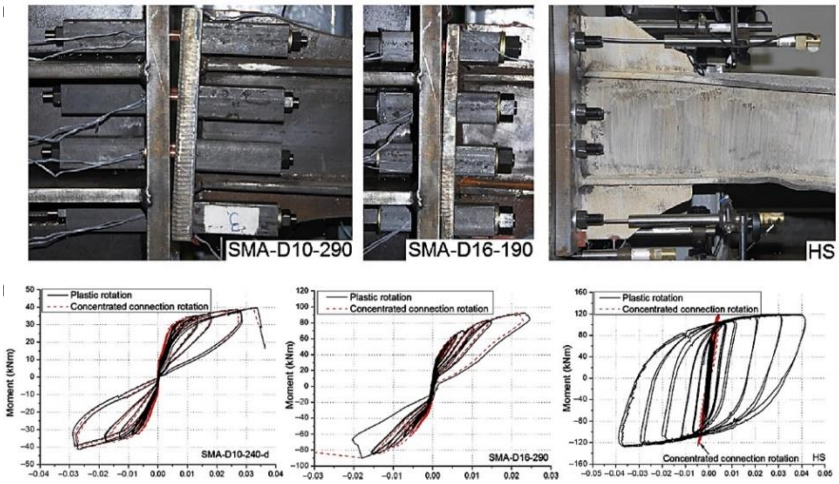
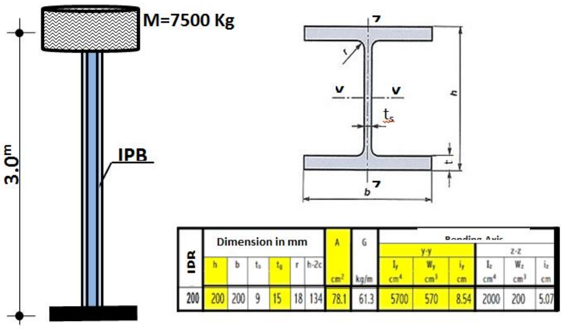


Fig. 3. Model provided for connection involving shape memory alloy screws [13].

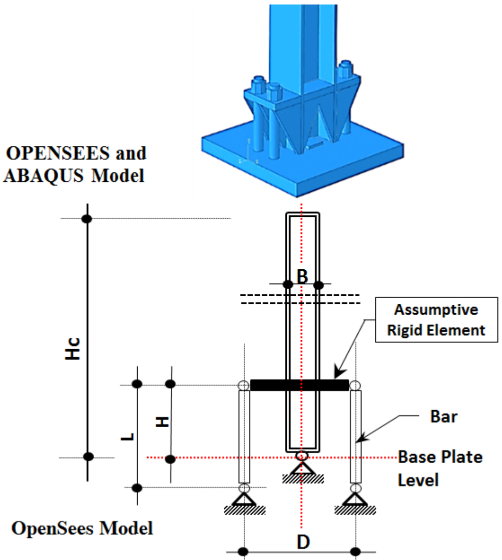
2. A Case Study of SMA Application in Structure

Here, an interesting and applied work done by Jamalpour et al is reviewed [9]. This study focused on airial water steel tank structure with IPB column and fixed connection to the foundation (Fig.4.) They studied a connection of a steel column to the foundation in two cases: a) connection of the column to the foundation by steel rods, b) connection of the column to the foundation equipped with SMA rods, by numerical analysis (Fig. 5. and Fig. 6.).



IPR	Dimension in mm						A	G	Bending Axis					
									y-y			z-z		
	h	b	t_s	t_g	r	h-2c	cm^2	kg/m	I_y cm^4	W_y cm^3	i_y cm	I_z cm^4	W_z cm^3	i_z cm
200	200	200	9	15	18	134	78.1	61.3	5700	570	8.54	2000	200	5.07

Fig. 4. Structure (column) with a lumped mass and geometric specification.



B = Profile Number (profile height)
D = Distance between the rods, D = B + 2 ×, (operating distance between rods column, about 5 to 10 cm)
H = height (elevation) of rods-column connection on the base plate
Hc = column height, L = length of the rod, R = radius of the rod

Fig. 5. Theoretical connection model and versions in OpenSees and ABQUS.

The mechanical characteristics (stress-strain behavior diagram) of steel bars and SMA bars material are shown in Fig. 6. and Fig. 7.

The seismic acceleration records of El Centro, Tabas, Loma and Northridge earthquakes were selected from Fig.8, and then the structure was exposed to base stimulation by the records and extracted the analytical results.

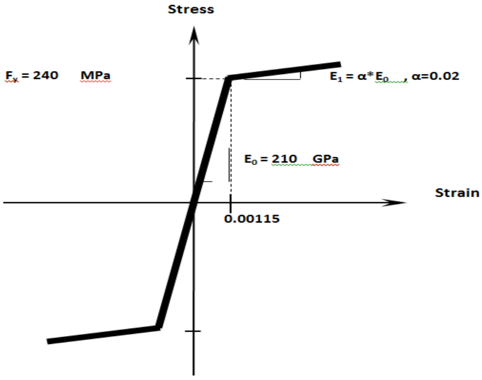
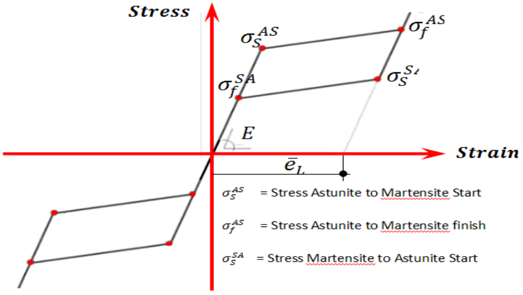


Fig. 6. Steel specification and mechanical behavior (stress-strain curve).



Supperelastic Shape Memory Alloy (NITI)		Mechanical Properties
Astunite Phase	Martensite Phase	
50	50	Elastic Modulus (Gpa)
$\sigma_{st}^{AS} = 400$	$\sigma_{st}^{M} = 200$	Yield Stress (Mpa)
$\sigma_{f}^{AS} = 650$	$\sigma_{f}^{M} = 50$	
6%	6%	Elastic Strain (%)

Fig.7. Superelastic stress-strain curve for SMA (nitinol shape memory alloy) rods.

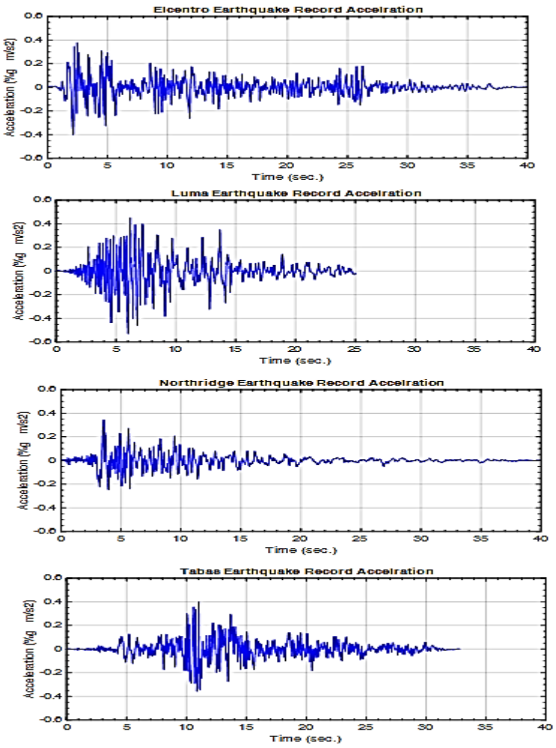


Fig. 8. Earthquake acceleration records under study (Elcentro, Loma, Northridge and Tabas).

The results of hysteresis response analyses of column-foundation connection (base shear versus column drift) equipped with steel and also SMA rods under selected earthquake effects are shown in Fig. 9.

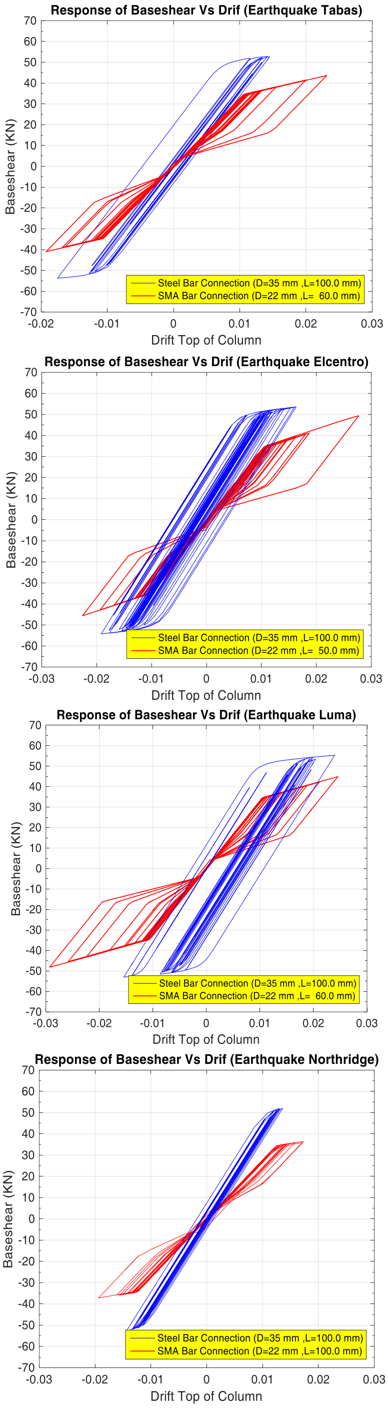


Fig. 9. Comparison hysteresis Response of column top drift-based share under different 4 earthquakes and different connections (with steel rods and SMA Rods.

3. Conclusion

Investigations in studies conducted in the last decade indicate that shape memory alloys (SMAs) have found a wide variety of applications in industries and these applications have made significant progress in the field of civil and structural engineering. With a special review on connections, which is the special topic of this paper, it can be claimed:

1. Shape memory alloys (SMAs) are suitable materials for structural engineering applications, especially in the field of connections in steel structures.
2. In the review of the papers of the last decade in the field of steel structure connections, whether connecting beams to columns or columns to foundations which are equipped with shape memory alloys (SMAs), the behavioral performance of the connection and accordingly the behavioral performance of the structure has improved.
3. The use of connections equipped with shape memory alloys (SMAs) and improving behavior in performance causes energy consumption in connection (structures) under the effect of dynamic loads (such as earthquakes) and the use of such joints in earthquake-prone situations reduces structural damage.
4. Due to the super-elastic property and self-centering performance of shape memory alloys (SMAs) especially Nitinol (NiTi), such connections can be considered among low-damage connections.

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