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Upgrading Seismic Behaviors of Reinforced Concrete Frames Equipped with Novel Super Elastic Braces

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Abstract

Intelligent systems in structural engineering are systems that are capable of automatically adapting structural behavior in response to instantaneous loads, thereby ensuring the safety of extended structural life and performance. One of the new technologies that makes it possible to achieve these goals is the production and development of smart materials. Examples of these smart materials used in structural engineering include piezo-ceramics, magnetorheological fluids, electrorheological fluids, and form-memory alloys. Shaped Memory Alloys (SMAs) are new materials that have been used in various fields of science and engineering in recent decades. In recent years, these materials attracted the attention of researchers in the field of building and earthquake engineering due to their properties such as high damping capacity, low permanent displacement and structural fatigue resistance. One of the application areas of these materials is that they are used as a brace in the structures, so the research results have shown the acceptable performance and operability of such structural systems. In this study, shape memory bracelets and steel bracelets installed as structural brackets were used as a lateral load system in the seismic improvement of concrete bending frames and factors such as residual displacement and base shear in these two load-bearing systems are compared. The model under studying is a 6-story frame that has been subjected to time history analysis. SeismoStruct software was used to analyze the model.

Key words: Shape memory alloys, permanent strain, seismic retrofitting, SMA braced frame, dynamic time history analysis.

1. Introduction

In 1932, the Swedish scientist Olander first discovered super-elasticity behavior in Au-Cd (Gold-Cadmium). In 1951, Chang and Read discovered the same reversible phase conversion in 1951, that the first phase conversion. In 1953, Buehler and colleagues at the US Naval Weapons Laboratory discovered the shape memory effect on a nickel-titanium alloy and called this alloy nitinol.

Shaped memory alloys exist in the two crystalline phases of martensite and austenite. The austenite phase is stable at high temperatures and low stresses and is responsible for the formation of super-elasticity behavior, while the martensite phase is stable at low temperatures and high stresses and is responsible for the shape memory behavior. At relatively high temperatures an SMA alloy is austenite. When the heat is drastically reduced, the phase is converted to martensite. The austenite phase has a cubic crystal structure, whereas the austenite to martensite phase crystal structure is caused by a spatial distortion process, although no macroscopic changes in the sample form occur. This formation occurs because several martensitic plates with different orientations (generally called variables) are formed from a single austenite grain. The martensitic variables are grouped into groups that each have a good arrangement and keep the sample shape intact.
In the non-stressed state, an SMA alloy has four phase conversion temperatures: Ms and Mf at

cooling time and As and Af at heating time. Ms and Mf are the temperatures at which phase conversion from austenite to martensite begins and ends, and As and Af are the temperatures at which phase conversion from martensite to austenite begins and ends (Figure 1) (Auricchio et al, 1997).

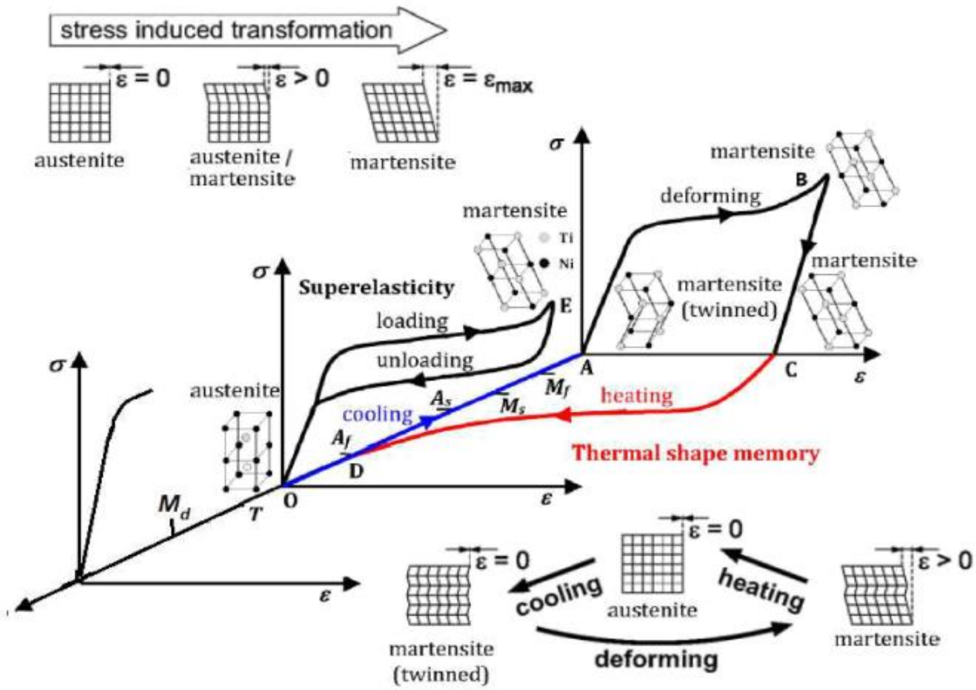


Figure 1. Mechanical behavior of shape memory alloys (Kowalczyk and Niżankowski, 2018)

The behavior of shape memory alloys in cyclic loading and their energy dissipation is remarkable. This property is widely used in various engineering applications. Many researchers have investigated the cyclic behavior of SMAs under tensional, pressure, shear and torsional loads.

Han et al. (2003) studied the energy dissipation of SMA wires. Vibration control experiment of a two-storey steel frame installed with the SMA wires-based damper and examine the effectiveness of the SMA damper. The dimensions of the frame are 2 m high, 1 m long, and 0.25 m wide, which is shown in Figure 2. As shown in the Figure 2, four mass blocks with 20 kg weight each, and cross lines means eight SMA damper installed in this frame. The experimental results of the vibration decay histories of the uncontrolled frame and the frame with the SMA dampers are shown in Figure 3 and 4, respectively. It takes about 45 s for the uncontrolled frame to decay its vibration from the initial displacement to half of the initial displacement which is shown in the Figure 3 on the other hand Figure 4 illustrate that it only takes less than 1 s for the controlled frame to decay its vibration from the initial displacement to half of it. In order to compare the speed of vibration decay for the controlled and uncontrolled frame, non-dimensional displacement co-ordinate is used in to display the vibration decay history.

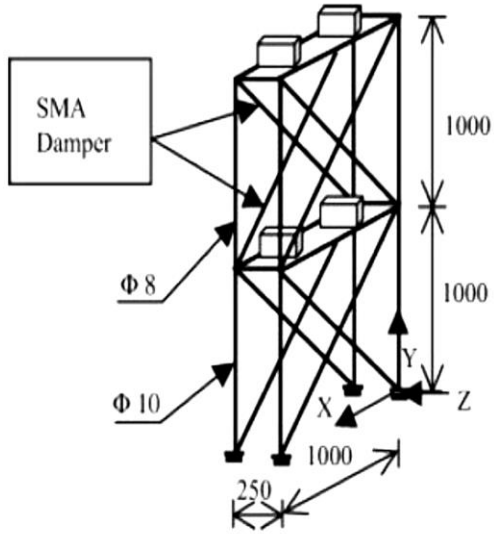


Figure 2. Two-storey frame with mass blocks and cross SMA dampers (Han et al., 2003)

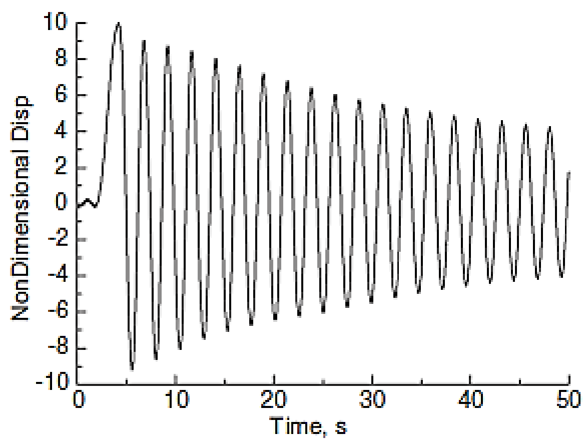


Figure 3. Vibration decay history of the uncontrolled frame (Han et al., 2003)

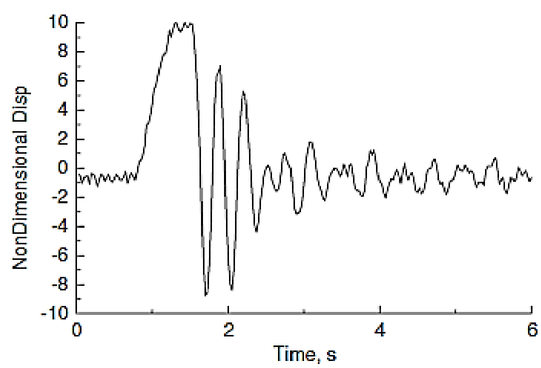


Figure 4. Vibration decay history of the frame with the SMA dampers (Han et al., 2003)

Auricchio et al. (2006), in their research, they compared the performance of the two types of super-elastic SMA braced systems and buckling restrained steel braces in two 3-storey and 6-storey frames. The systems are shown in Figures 5 and 6. For comparison purposes, super-elastic SMA braces are designed to provide the same yielding strength, Fy, and the same axial stiffness, K, as steel braces. In this way, the structure with the innovative bracing system will have the same natural period of the one with steel braces, and both SMA and steel elements will yield at the same force level.

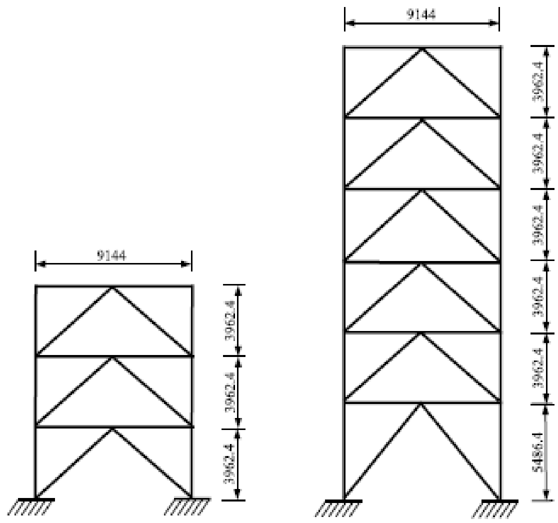


Figure 5. Elevation view of the 3- and 6-storey frame (Auricchio et al., 2006)

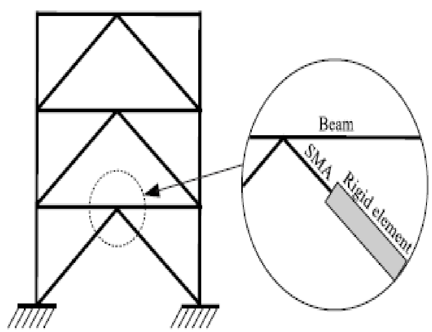


Figure 6. The super-elastic SMA brace installed in the 3-storey frame (Auricchio et al., 2006)

For brevity, we only consider the 3-storey frame since for the 6-storey frame similar considerations apply. The record in question is the 1979 Imperial Valley earthquake with 0,67 g PGA value. Attention is focused on both the displacement time-history (Figure 7).

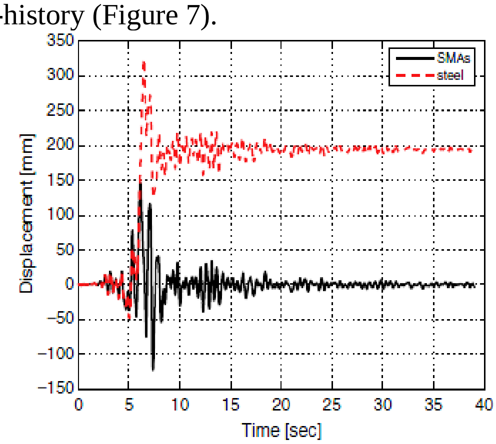


Figure 7. Displacement time-history exhibited by the top floor of the 3-storey frame (Auricchio et al., 2006)

By observing Figure 8, which is related to the 3-storey frame, we notice that super-elastic SMA braces and buckling-restrained steel braces provide similar performance in terms of maximum inter-storey drift. In particular, its average value is 1.36% if we use super-elastic 1 SMA braces and 1.52% in case we use steel braces.

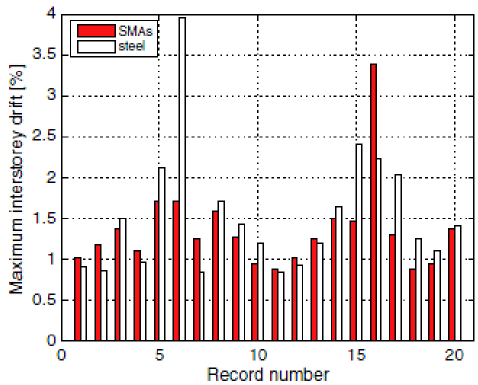


Figure 8. Maximum inter-storey drift exhibited by the 3-storey frame (Auricchio et al., 2006).

2. Material and Modelling

Different behavioral models have been proposed to express the super-elastic behavior of shape memory alloys. In this paper, the behavioral model of (Fugazza, 2003) which is obtained by making some corrections on the proposed model of (Auricchio & Sacco, 1997) is used. In the proposed model of (Auricchio & Sacco, 1997), the different modulus of elasticity for the austenite and martensite phases is assumed, but in the proposed model (Fugazza, 2003), the same values are assumed for the phases for convenience. This model simulates the super-elastic behavior of the SMA by considering the sub-rings therefore, in any seismic loading that has incomplete phases conversions, it provides a better estimate of the behavior of the SMA. Also, in deriving this model the assumption of small deformation between stresses and strains is presented by a set of linear equations. In this section, firstly a time-continuous model is presented, then by integrating the term integral (Backward-Euler) into the time-continuous equations, the time-discrete equations are obtained which can be described by considering an appropriate tangent modulus of SMA behavior. Reinforced concrete frame with super-elastic shape memory alloys braces in 6-storey frame have been used for modeling. Height of floors is 3200 mm considered. The position of the braces in frame is shown in Figure 9. In this study, SeismoStruct v.7 software, which is capable of modeling the super-elastic behavior of shape memory alloys, is used. This software is used to define beam and column elements as inelastic displacement-based frame element and to define braces as inelastic truss element.

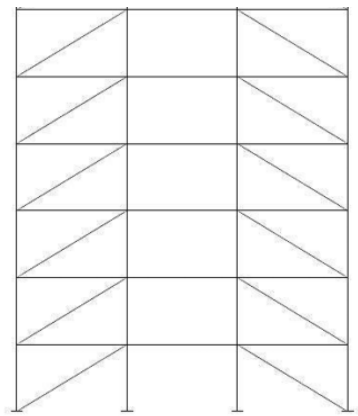


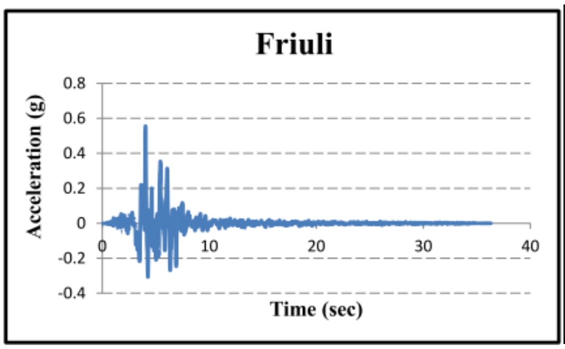
Figure 9. Elevation of 6-storey frame with braces view

The properties of super-elastic SMA which is used as the brace is summarized in Table 1.

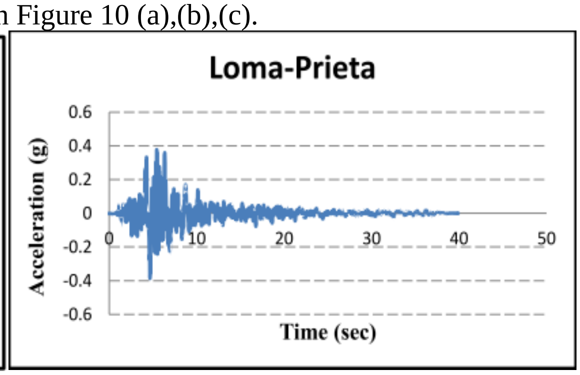
Table 1. The properties of super-elastic SMA which is used as the brace.

$E^{SMA}(GPa)$	80
$\sigma_S^{AS}(MPa)$	414
$\sigma_F^{AS}(MPa)$	550
$\sigma_S^{SA}(MPa)$	390
$\sigma_F^{SA}(MPa)$	200
$\varepsilon_l(\%)$	3.5

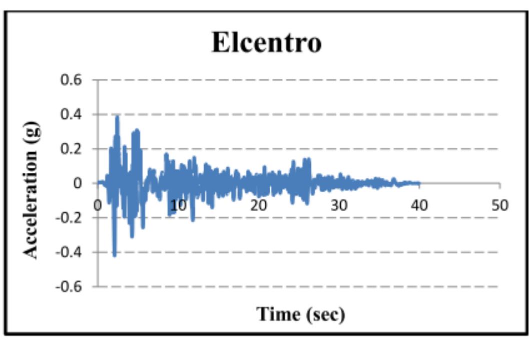
The model will be studied in a non-linear time history analyzing method, for optimal conclusions 3 time-history records (Fruili, Elcentro and Loma-Prieta) are used to the studied frame in the SeismoStruct software. The acceleration-time records are shown in Figure 10 (a),(b),(c).



(a)



(b)



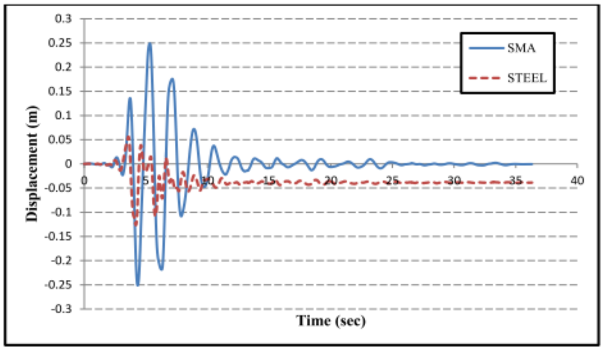
(c)

Figure 10. Fruili time history record (a) Loma-Prieta time history record (b) El-Centro time history record (c)

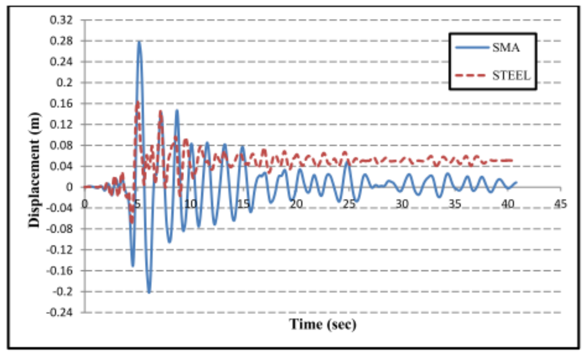
3. Results and Discussion

3.1. Comparing the Time – Displacement of Floors

A comparison of the relative displacement diagrams of the 6 storey frame under the selected records is shown in Fig. 11 (a) (b) (c). The results show that initially the relative displacement of the frame with SMA braces is greater than the relative displacement of the frame with steel braces but eventually the relative displacement of the frame with SMA braces is much less than the relative displacement of the frame with steel braces.



(a)



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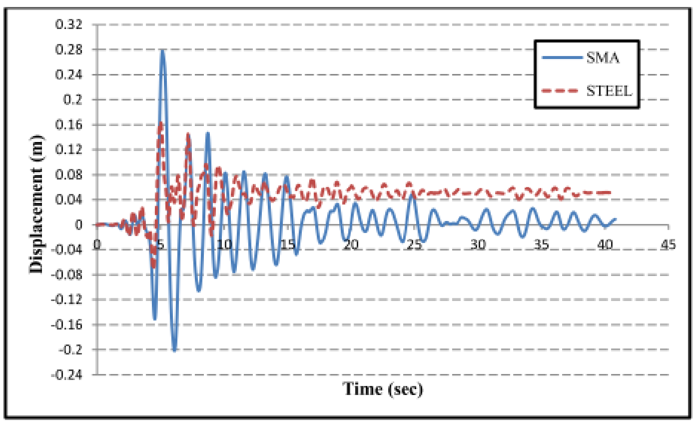

(c)

Figure 11. Time-displacement diagram of the frame under Fruili time history record(a) Loma-Prieta time history record (b) El Centro time history record (c).

3.2 Residual Displacement

As the re-centering property is one of the most important properties of SMAs, Fig. 12 summarizes the results of residual displacement at the top floor as control points. Comparison of the results of steel and SMA braced frames shows a significant reduction in the residual displacement in the SMA braced system.

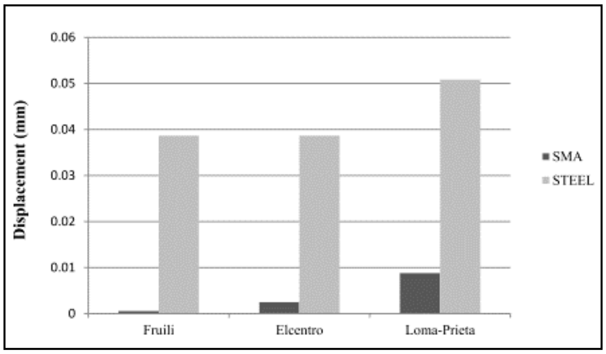

Figure 12. Results of residual displacement under selected time history records

3.3 Base Shear

A comparison of the base shear diagrams of the 6 storey frame under the selected records is shown in Fig. 13, 14 and 15. The results show that the peak base shear requirement is more on the frame with steel braces (i.e. 1600 kN for Fruili records)as compared to frame with SMA brace (i.e. 1400 kN for Fruili records). The results also indicate that the steel brace has more capability to re-center itself or at least re-center itself earlier.

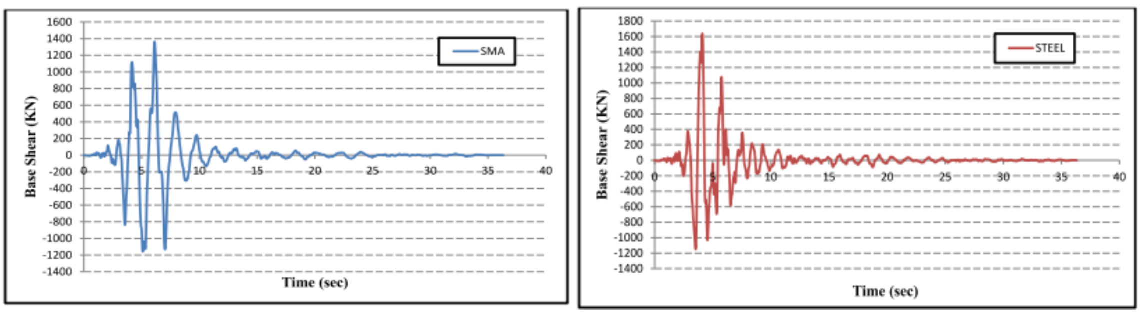

Figure 13. Base shear of the frame under Fruili time history record

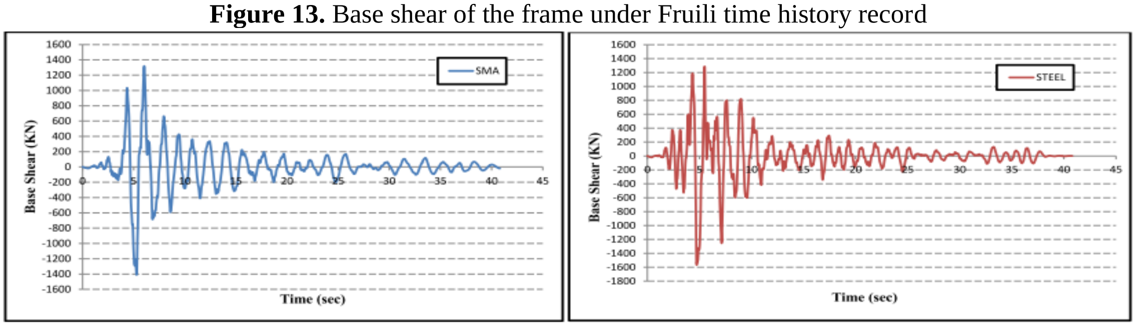

Figure 14. Base shear of the frame under Loma-Prieta time history record

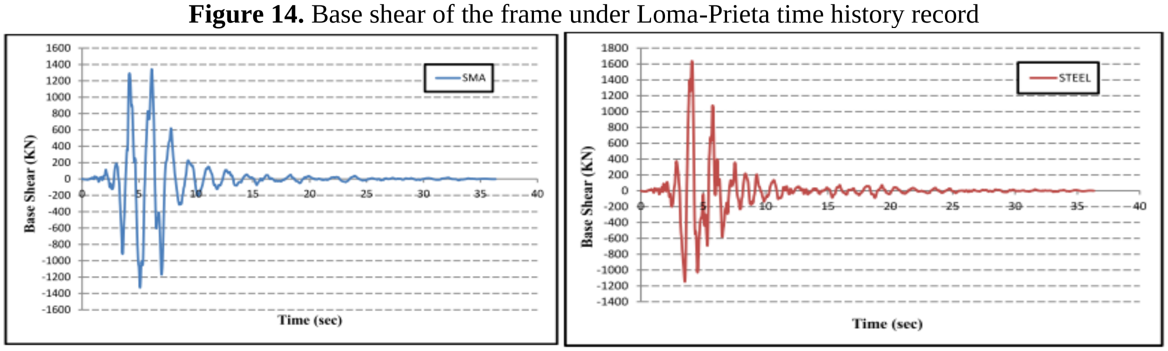

Figure 15. Base shear of the frame under Elcentro time history record

Conclusions

Regarding relative displacement case we are observed as re-centering subject the frame which is improved by shaped memory alloys is propounded a good behavior in comparation with steel braced frame on upgrading behavior in seismic loads.

Shaped memory alloys braced system performs a good behavior in reducing the residual deformations after dynamic time history analysis, while steel braced frame does not accomplish good behavior in the residual strain case, So SMA brace performs very good behavior in re-centering case, which is not significant in the steel braces.

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