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Practical Earthquake Protection of Multi-Story Buildings Using Shape Memory Alloy (SMA) Braces

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ABSTRACT

Shape memory alloys (SMAs) are unique materials well suited to be used in structural earthquake engineering applications. The uniqueness arises from two specific behaviors known as shape memory effect and superelasticity, and the suitability is mainly because of the superelastic behavior. Superelastic SMAs can be used as braces to protect structures against earthquakes, both for earthquake-resistant design and anti-seismic retrofit purposes. This paper reports on an applied research in this field, including also a case study. The case study building is a typical 4-story residential building with steel braced frames, located in Khorramshahr, Iran. Direct displacement-based design method is followed for the calculation of the dimensions of SMA elements. The superelastic behavior of SMAs is simulated through the phenomenological modeling, verified by experimental evaluations. Seismic performances are studied in details and it is shown that such an application is feasible and effective. Earthquake-resistant design and anti-seismic retrofit using SMA braces considerably reduce the base Shears, story accelerations, and inter-story drifts compared to the traditional earthquake-resistant design and retrofit with steel braces. It is also indicated that the residual displacements are comparably smaller in the cases of using SMA braces.

Keywords: Shape Memory Alloy, Earthquake Protection, Earthquake-Resistant Design, Anti-Seismic Retrofit.

I. INTRODUCTION

Structural Earthquake Engineering (SEE) is a branch of structural engineering, dealing with earthquake protection of structures. For providing a precise professional description, SEE can be defined as the art of using materials to create real structures properly withstanding seismic forces. In this regard, materials play a key role in SEE. Traditionally, the main materials being used in civil engineering structures include masonry materials, wood, steel, and concrete. The advancements obtained in materials engineering have brought the opportunity for using some new materials possessing unique properties that are suitable for SEE. Effective and innovative structural systems can also be used in SEE as a secondary result of this progress. There are lots of examples of using new materials in SEE that have also changed the structural systems. Smart materials are a category of materials that can change their properties regarding their environmental conditions or the stimuli applied. Shape Memory Alloys (SMAs) are known as a class of smart materials capable of producing smartness also in a passive state without a need for external source of power. The superelasticity of SMAs is well suited to be used in SEE. Various applications have been reported (see Figure 1) including as braces [1-10], dampers [11-15], isolator devices [16-20], and some other applications such as reinforcement of concrete elements [21]. Recently introduced SMA cables [22] promise further applications.

Being concentrated on the application of SMAs as bracing elements in structural frames, the research outlined in this paper was aimed at investigating the technical details through the application of a novel phenomenological model and the direct displacement-based design method. A typical residential building has been designed and retrofitted by SMA braces, and the seismic performances were studied. Following sections report on the outcomes.

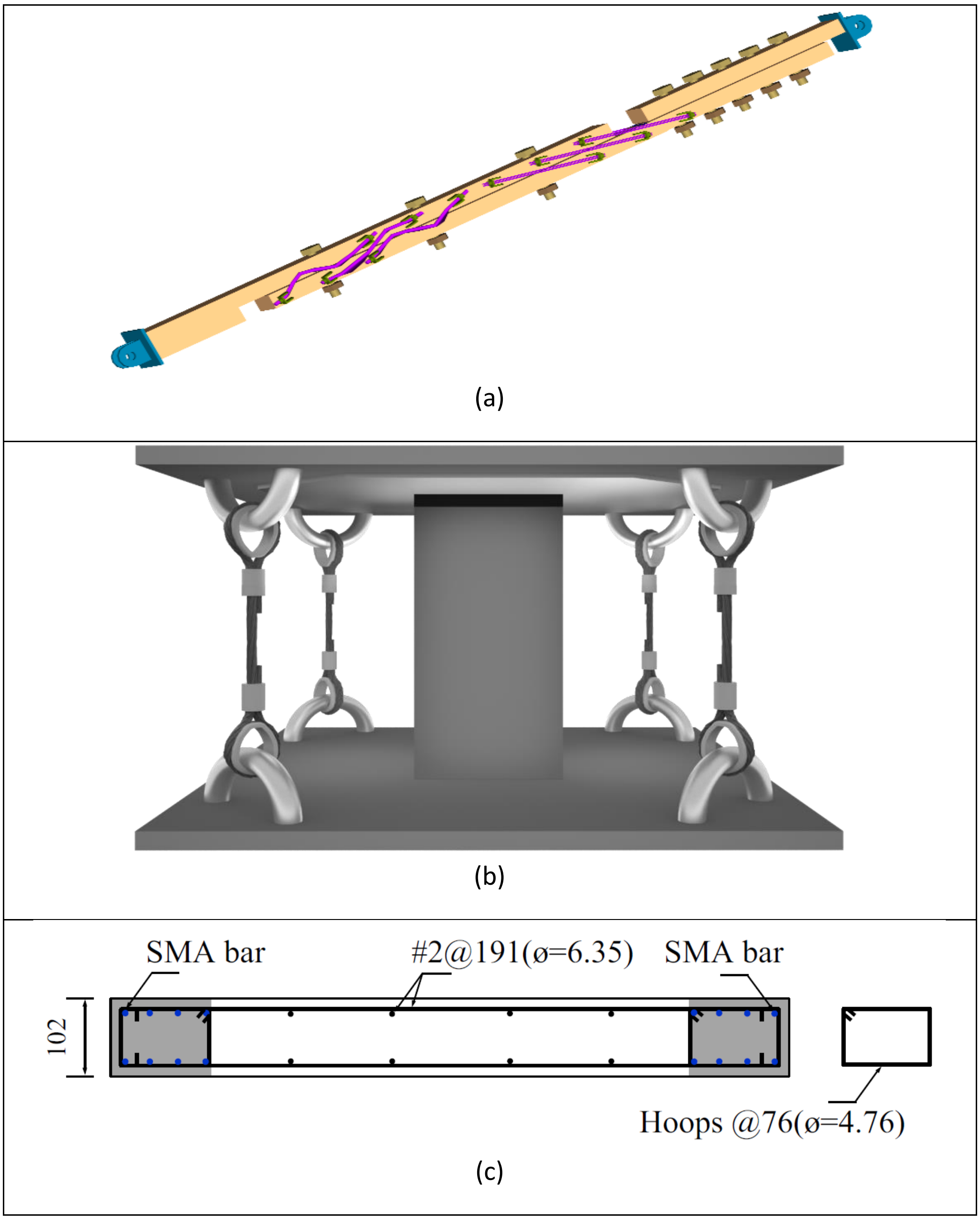


Figure 1. A summary of the most remarkable works on the application of shape memory alloys for earthquake protection of structures: (a) the shape memory alloy braces proposed by Zhang ang Zhu [14], (b) the Shape Memory Alloy (SMA)-based Superelasticity-assisted Slider (SSS) proposed by Narjabadifam [20], and (c) the self-centering reinforced concrete wall proposed by Wang and Zhu [21]

II. METHODS AND MATERIAL

In order to practically investigate the application of SMA braces for earthquake protection of structures, the seismic performances of an available 4-story steel frame residential building have first been evaluated through time history analyses using 7 ground motion accelerograms scaled to match the design spectrum. The reference code is the Iranian Code of Practice for Seismic Resistant Design of Buildings [23] and SAP 2000 [24] has been used for the analyses and simulations using a phenomenological model based on nonlinear link elements. Then the building has been redesigned with SMA braces and the seismic performances have been compared to those of traditional earthquake-resistant design of the building using steel braces. Anti-seismic retrofit of the building has also been studied using both SMA and steel braces for the higher level of excitation obtained by increasing the peak ground acceleration, and the seismic performances are compared together. The procedure has been validated by the experimental results reported by Han et al. [2].

Figs. 2 and 3 show respectively an architectural view and the typical structural plan of the building, which is located on soil type III (based on the classifications of the reference code) in Khorramshahr, Iran. The columns are designed with 2IPE16, the beams are made up of single and double sections of IPE 18 and 20, and the section used as braces is 2UNP10.

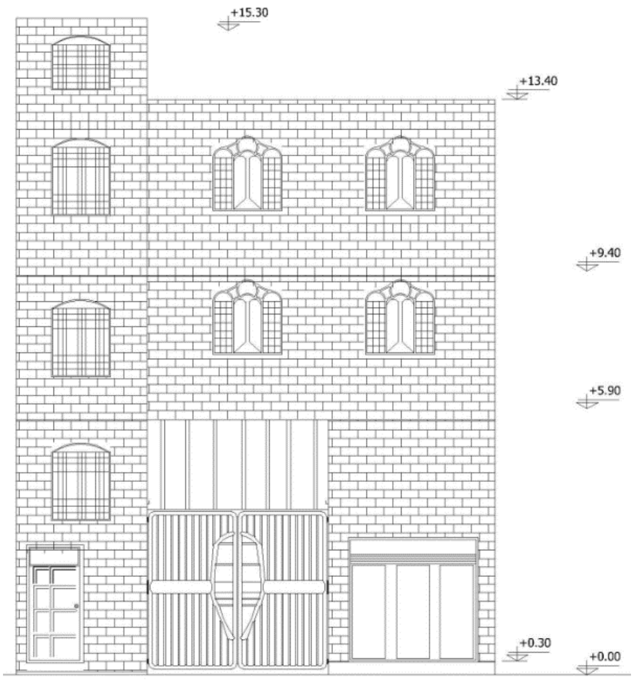


Figure 2. An Architectural View of The Case Study Building

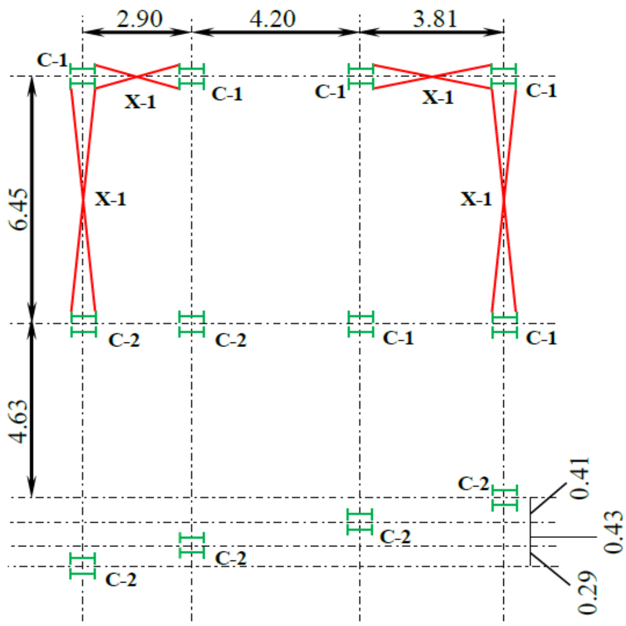


Figure 3. The typical structural plan of the case study building

Details regarding the earthquake excitations are given in Figure 4 showing the target spectra at both the design and retrofit levels, the 7 earthquake accelerograms (Tabas-Dayhook, Parkfield- Temblo, Westmorland- Fire Station, New Zealand- Matahina Dam, Manjil- Abbar, Loma Prieta- Saratoga, and Whittier Narrows- Doweney) matched to scale the target spectra, and the spectra obtained as average on the accelerograms.

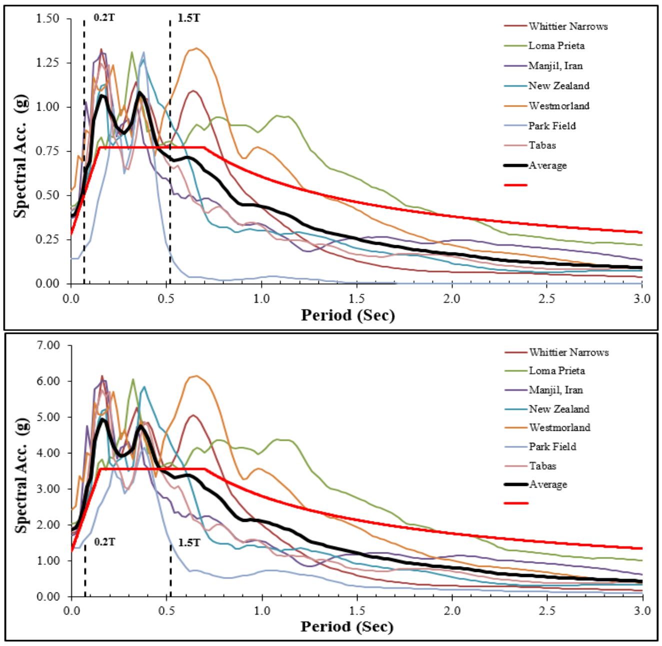


Figure 4. The Earthquake Excitations Scaled To The Target Spectra At The Design (S-Design) And Retrofit (S-Retrofit) Levels

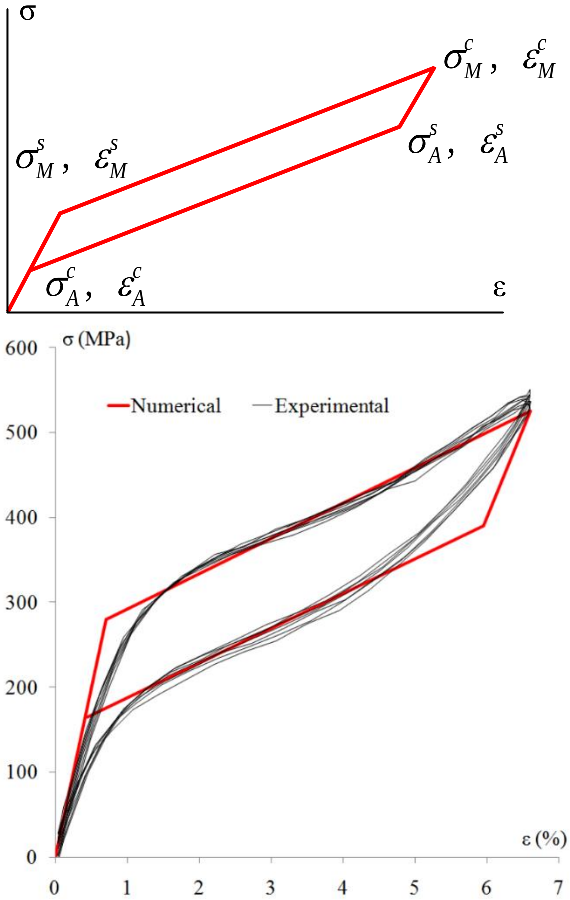


Figure 5. The Superelastic Behaviour Of The Smas

As far as the verification is considered, the phenomenological model of the superelastic behavior of the SMAs obtained by the combination of multilinear elastic and plastic link elements has been validated by the experimental results provided by Cardone and Narjabadifam [6] based on the stress-strain relation given in Figure 5.

$$\boxed{\sigma_A^c,\ \varepsilon_A^c = 165MPa,\ \ 0.0045}$$

$$\boxed{\sigma_M^s,\ \varepsilon_M^s = 280MPa,\ \ 0.007}$$

$$\boxed{\sigma_A^s,\ \varepsilon_A^s = 390MPa,\ \ 0.0595}$$

$$\boxed{\sigma_M^c,\ \varepsilon_M^c = 525MPa,\ \ 0.066}$$

The analytical results have also been verified by the experimentally validated displacement history of the braced frame modelled in ANSYS [25] by Han et al. [2]. Figure 6 shows the experimental set up. The finite element model is shown in Figure 7, and the compared responses are given in Figure 8.

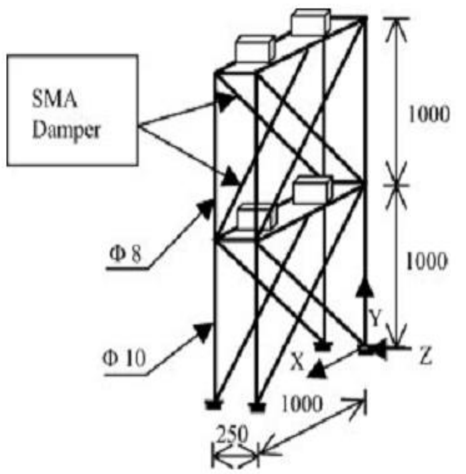


Figure 6. The Experimental Set Up Of Han Et Al. [2]

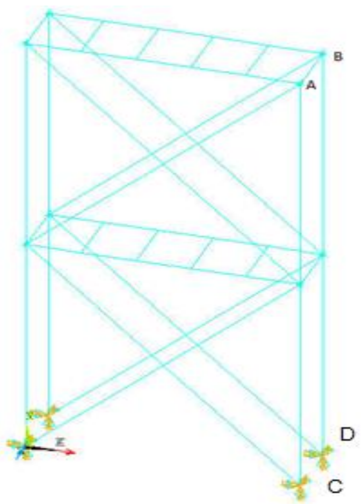


Figure 7. The Finite Element Model Of The Experimental Model Structure Of Han Et Al. [2]

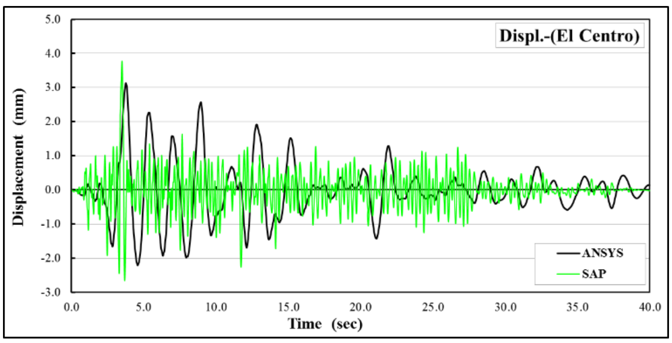


Figure 8. The Comparison Between The Second Story Displacement Responses Of The Sma-Braced Frame Modelled In Sap And Ansys, When Subjected To El Centro Earthquake (As Studied By Han Et Al. [2])

III. RESULTS AND DISCUSSION

In this section the seismic performances of the modern earthquake-resistant design and anti-seismic retrofit with SMA braces are compared to those of traditional earthquake-resistant design and anti-seismic retrofit with steel braces. The earthquake-resistant design is briefly discussed in the sub-section A. The anti-seismic retrofit is discussed in the sub-section B with more details.

A. Earthquake-Resistant Design with SMA Braces

For the purpose of design, the maximum strain in the SMA materials has been taken as 0.065 regarding the maximum strain at the end of the plateau (see ε_M^c in Figure 4) in order to prevent the austenitic to martensitic transformation in the material. The length of the SMA element is obtained based on the target inter-story drift given in the reference code. Similarly, the criterion in the calculation of the cross-sectional area of the SMA element is σ_M^c, as given in the Figure 5. Table 1 reports the designed sections.

TABLE 1. DESIGNED SMA ELEMENTS

Story	X Direction		Y Direction	
	L_{SMA} (cm)	A_{SMA} (cm^2)	L_{SMA} (cm)	A_{SMA} (cm^2)
1	86.0	10.48	118.3	14.46
2	76.0	10.71	95.8	13.49
3	82.6	7.20	110.3	9.65
4	82.6	3.46	110.3	4.62

Figure 9 compares the average story accelerations experienced in the building equipped with SMA braces and traditional steel braces. As can be seen, the modern earthquake-resistant design with SMA braces reduces the story accelerations at the amounts of 20%, 27%, 44%, and 44%, respectively in the 1st, 2nd, 3rd, and 4th story levels.

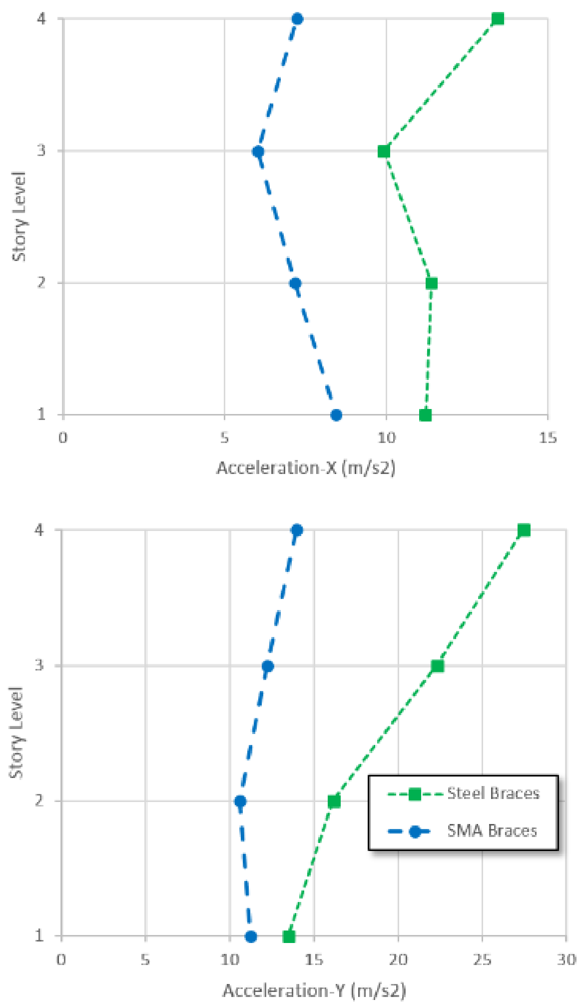


Figure 9. Maximum Story Accelerations (On Average Over The 7 Accelerograms) Experienced In The Building With Traditional Steel And Modern Sma Braces

B. Anti-Seismic Retrofit with SMA Braces

The suitability of the SMA braces for the purpose of anti-seismic retrofit has been evaluated through the comparison of seismic performances of the case study building in three cases of (1) not retrofitted, (2) retrofitted by steel braces, and (3) retrofitted by SMA braces. Seismic performances have been studied in terms of (a) story displacements, (b) story accelerations, (c) inter-story drifts, (d) story shears, and (e) residual displacements. Figs. 10-14 show the results, respectively.

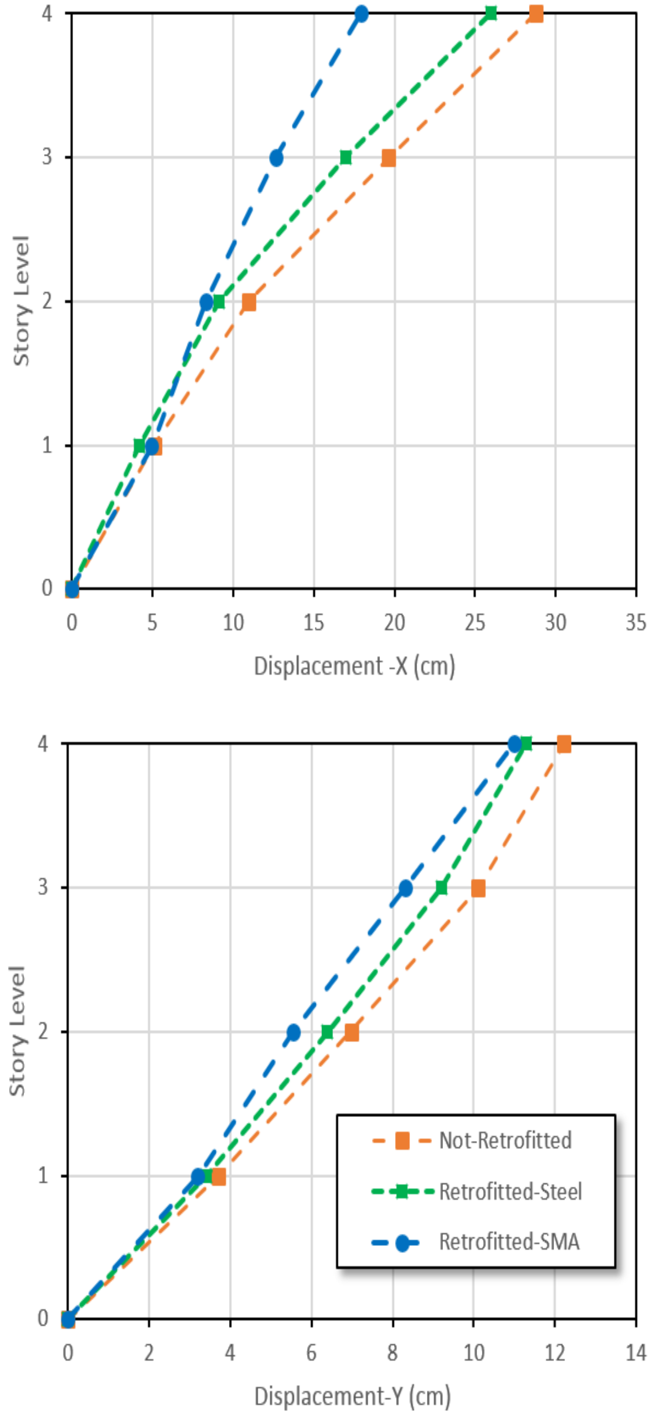


Figure 10. Maximum Story Displacements (On Average Over The 7 Accelerograms) Experienced In The Building Retrofitted With Traditional Steel And Modern Sma Braces, Compared Together And To Those Of The Building Not Retrofitted

Figures 10 and 11 respectively show that the displacements and accelerations are both well controlled in the case of retrofitting by SMA braces.

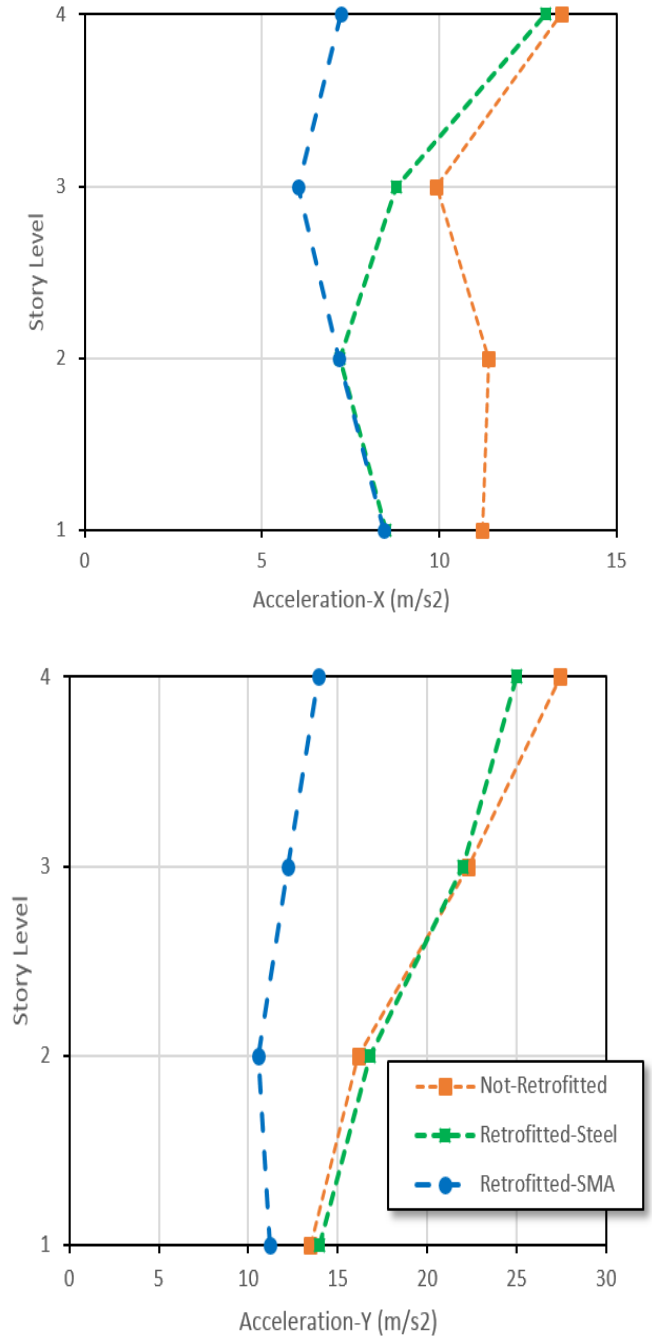


Figure 11. Maximum Story Accelerations (On Average Over The 7 Accelerograms) Experienced In The Building Retrofitted With Traditional Steel And Modern Sma Braces, Compared Together And To Those Of The Building Not Retrofitted

For the inter-story drifts, the maximum value allowed by the reference code (2.5%) has also been considered in order to practically judge about the performances. It has been demonstrated that the inter-story drifts are not acceptable if the building has not been retrofitted or even if retrofitted traditionally by the steel braces (see Figure 12).

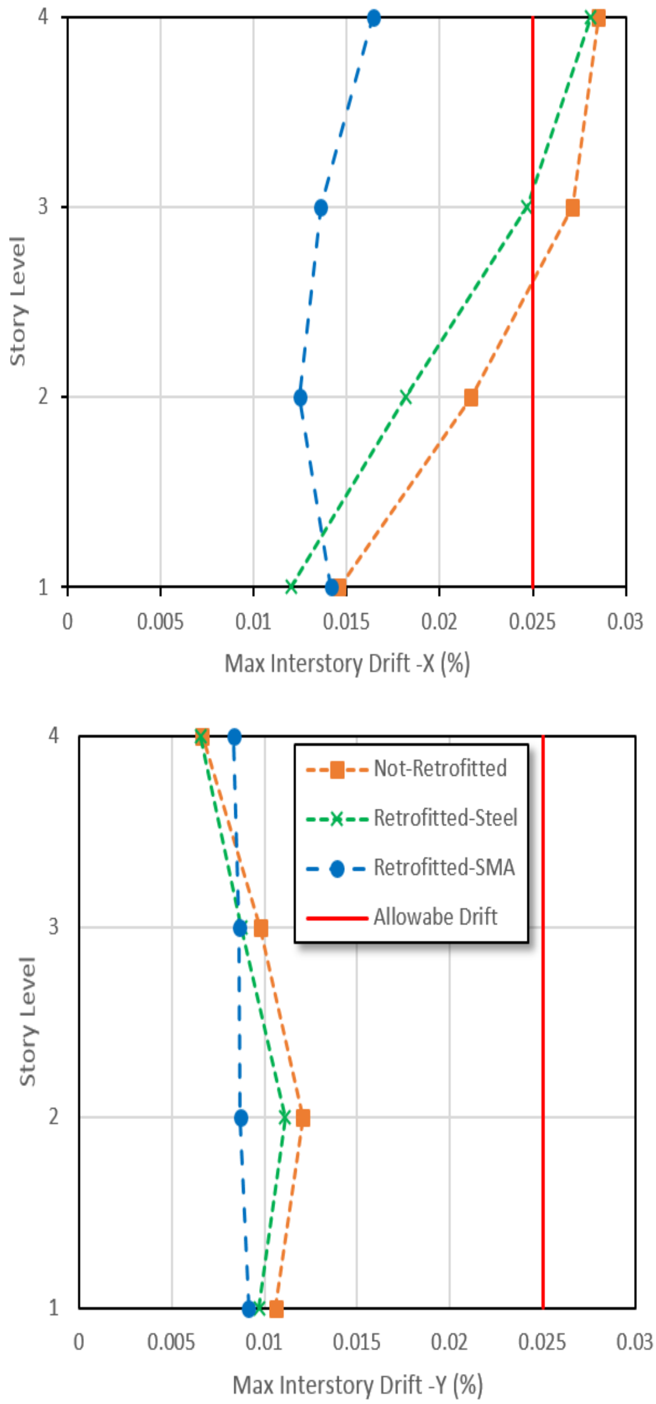
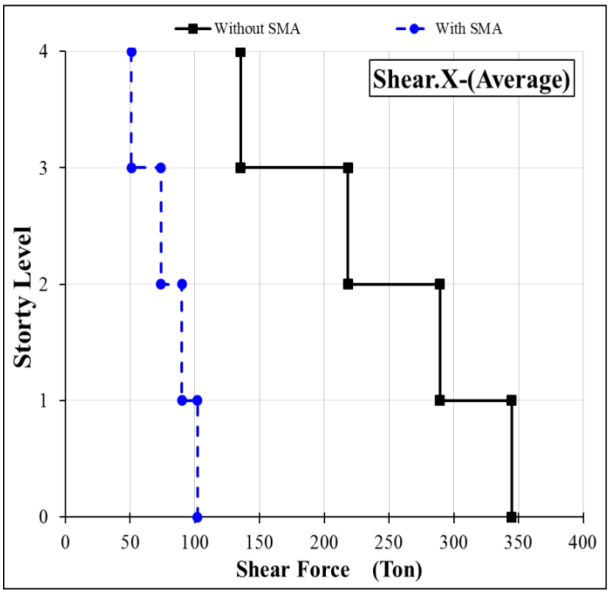


Figure 12. Maximum Inter-Story Drifts (On Average Over The 7 Accelerograms) Experienced In The Building Retrofitted With Traditional Steel And Modern Sma Braces, Compared Together And To Those Of The Building Not Retrofitted

As it is shown in Figure 13, the reductions in the story shears are more evident, indicating that the plateau in the superelastic behavior of the SMAs allows the energy dissipation without transferring the earthquake energy to the other parts of the structure, reducing consequently the seismic demand on the other structural and non-structural elements.



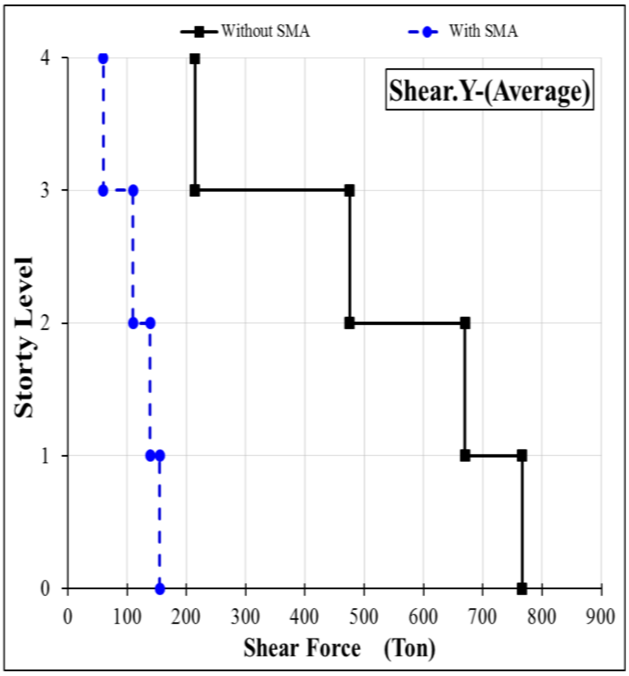
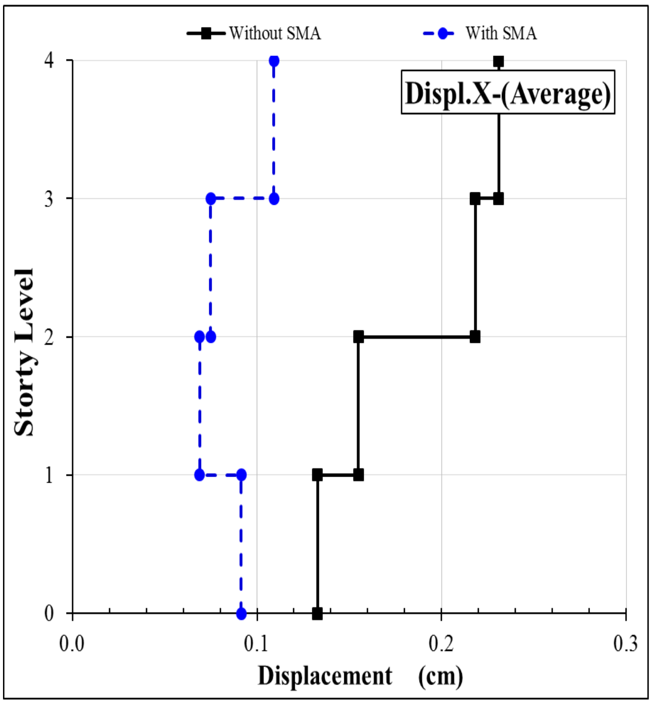


Figure 13. Maximum Story Shears (On Average Over The 7 Accelerograms) Experienced In The Building Retrofitted With Traditional Steel And Modern Sma Braces

A more interesting discussion has been followed by the study of residual displacements. The results are given in Figure 14. Comparison between the residual displacements in the retrofitted buildings retrofitted with SMA braces and steel braces indicate that the building equipped with SMA braces can recover almost all the deformations, owing to the unique superelasticity of the SMAs. The maximum residual displacement in the building retrofitted by the SMA braces is approximately 1 mm, when it is larger in the building retrofitted by steel frames due to the acceptance of damages based on the philosophy of the using behavior factors in the traditional design procedure. These small residual displacements can also be recovered due to the shape memory effect demonstrated by Dolce et al. [16].



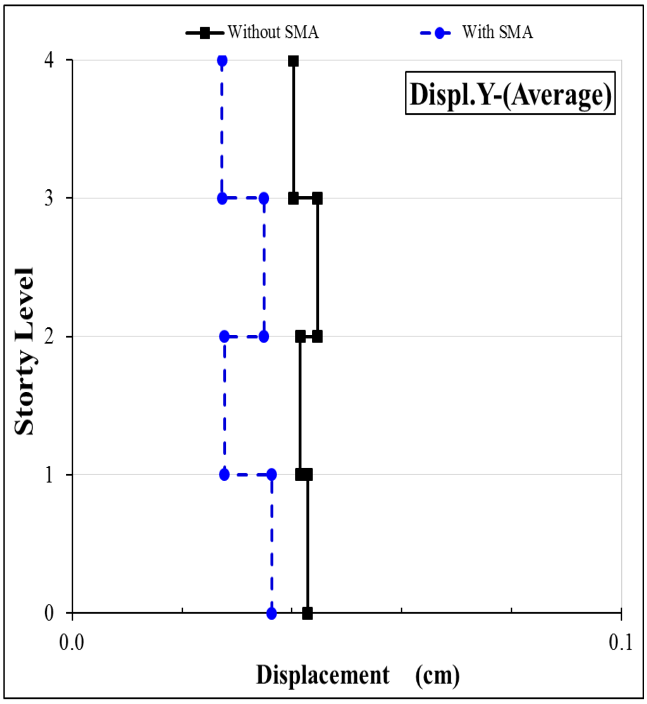


Figure 14. Maximum Residual Displacements (On Average Over The 7 Accelerograms) Experienced In The Building Retrofitted With Traditional Steel And Modern Sma Braces

IV. CONCLUSION

The outcomes of an applied research on the practical application of the austenitic Shape Memory Alloys (SMAs) in the earthquake protection of the buildings was outlined in this paper. The methodology of the research was described after a brief literature review. The numerical model used for the simulation of the superelastic behavior of the SMAs was introduced as a novel combination of the multilinear elastic and plastic link elements. The verification was detailed, and the results were presented and discussed. Results showed that:

(1) SMA braces are technically suitable for earthquake protection of the civil structures.
(2) SMA braces can be used both in earthquake-resistant design and anti-seismic retrofit projects.
(3) Recently introduced SMA cables will increase the interest of the researchers to further investigate the practical issues, increasing at the same time the desire for practical application.
(4) SMA braces control the seismic responses through the energy dissipation without transferring the earthquake energy to the other parts of the structure.
(5) SMA braces reduce the structural responses at an average rate of almost 40% compared to those of traditional steel braces (see Figs. 10-14).
(6) SMA braces provide the buildings with a recovery capability, eliminating the damages expected by the traditional design.
(7) Application of the SMA braces can also protect the non-structural elements due to the reduction of the seismic demand.

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