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Implementation of shape memory alloy dampers for passive control of structures subjected to seismic excitations

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Abstract

Different crystallographic phases of shape memory alloy (SMA) materials were used in a damper in order to produce an effective behavior device capable of dissipating energy, while containing the recentering capability. Different methodologies were applied in the four proposed damper systems in order to optimize their implementation into the earthquake resistant structural systems. To compare the structural system performance by using the different devices, the idea of damage indicator was utilized with certain modifications. The structural damage, non-structural damage, and the damage to the contents of different systems with the permanent deformations of the systems were considered at different ground acceleration histories. The comparisons were made with the buckling restrained steel bracing system. The effectiveness of the implementation of SMA dampers in reduction of the residual deformations on the structure is presented even after very high ground motions.

Keywords: Damper; Shape memory alloy; Passive control; Seismic excitation; Damage index

1. Introduction

Traditional philosophies behind different methods of designing structures against natural hazards such as earthquakes have changed in recent years. Failure of many structures designed by the conventional methods during recent earthquakes, the improvements in the analyses methods, the advancement of informed design knowledge, and the more complicated performance demands by the building industry has led to more effective methods and strategies in structural design.

Passive control techniques have shown to be an effective and novel alternative to the conventional design methods [1]. These systems are designed to eliminate the damage to a given structure by reducing the demand of the structure or absorbing the energy of the excitation in special devices. Energy dissipating devices are currently used such as visco-elastic devices, elasto-plastic hysteretic devices, friction devices, and viscous devices. All these systems have many inherent limitations including problems related to ageing and durability, maintenance, installation complexity, the need for replacement and change to structural geometry after strong earthquakes [1]. Shape memory alloys (SMAs) known as smart materials with unique superelastic properties have many interesting characteristics which can be utilized in structures aimed at eliminating the aforementioned limitations.

SMAs are materials capable of undergoing large recoverable strains of the order of 10% without exhibiting plasticity. High damping capacity, recentering, high fatigue resistance, no need of maintenance, durability and the recovery of strains by heat are among the characteristics which have made SMAs an effective damping device or component of base isolators [2,3].

SMAs were discovered in the 1930s but gained attention in the 1960s and later in the 1980s when smart materials were introduced. Practical applications of SMAs were first limited to medical applications [4]. However, recently SMAs are finding their way in many different fields such as aerospace [5], industrial [6], and commercial [7] applications. In the last decade, researchers have also found innovative applications of SMA in civil engineering applications. Bridge restrainers [8], special dampers and dissipating braces [1,9], base isolation systems [10], special connections [11], and reinforced concrete members with variable stiffness and strength [12] are samples of such applications.

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Different theories and approaches have been used in order to predict the behavior of SMAs under thermomechanical loadings. They vary from complete theoretical models using thermodynamics and/or micromechanical formulations to experimental and phenomenological approaches. Among these categories only phenomenological models seem to be proper for engineering applications because of their simplicity and accuracy. Some representative works of this group are Liang and Rogers [13], Brinson [14] and Boyd and Lagoudas [15].

There have also been some studies which attempted to evaluate the effectiveness of the use of SMAs in passive control of structures subjected to seismic excitations. Dolce et al. [1,2] in a series of publications studied the effectiveness of SMA materials for the use in seismic applications. Dolce and Cardone [2] experimentally investigated the proper choice of alloy, the effect of temperature, SMA size and loading rate and number of cycles. Dolce et al. [1] also studied the implementation of various states of SMA material for the use of special dampers in structures. They proposed different recentering and/or dissipating devices based on experimental results. Bruno and Valente [16] showed the effectiveness of the use of SMA materials by analytical measures using simple pseudoelastic constitutive model for SMAs using damage index approach. DesRoches et al. [3] experimentally evaluated the properties of superelastic Ni–Ti shape memory alloys under cyclic loading to assess their potential for applications in seismic resistant design and retrofit. DesRoches and Delemont [8] studied the effectiveness of the use of SMA materials as restrainers for control of bridge displacements. They employed a constitutive model adapted directly from experimental data. Baratta and Corbi [17] analyzed the dynamics of a structural elastic–plastic frame, endowed with pseudoelastic SMA tendons. Masuda and Noori [18] investigated the optimization of hysteretic characteristics of damping devices based on pseudoelastic SMAs. Wilde et al. [10] performed an analytical study to evaluate the behavior of base isolation systems with SMA material for elevated highway bridges. Black et al. [19] experimentally studied the behavior of large diameter shape memory alloys. Abolmaali et al. [11] compared the energy dissipative characteristics of bolted t-stub connections using steel and shape memory alloy (SMA) fasteners.

Research work in the area of seismic application of SMAs is mostly experimental and few studies are reported which evaluated the behavior of structures with SMA materials analytically. These studies used simple constitutive models which could not fully predict the complicated behavior of SMA materials under different loading conditions and in different phases. Also the effect of loading rate was not considered in the majority of these studies, and nearly all of the aforementioned studies used only the pseudoelastic property of the SMAs.

Thus, this analytical study evaluates the dual use of the different states of SMAs for passive control of structures. A multilinear constitutive model developed by Motahari and Ghassemieh [20] is adopted to capture the most common behaviors of SMA. The damage indices proposed by Park and Ang [21] is modified for attaining a good measure for comparison between different structural systems.

Also, the unique behavior of SMA materials is explained and the selected constitutive model for the use in numerical implementations is introduced. The behavior of the proposed SMA damper considering both phases of SMA material is also evaluated analytically.

2. Behavior of shape memory alloys

SMAs exist in two crystallographic phases: one parent phase known as austenite with a high symmetry, and variants of product phase known as martensite with low symmetry. Austenite is stable at higher temperatures and lower stresses and martensite is stable at lower temperatures and higher stresses. This will cause the phases to transform into each other at the presence of stress and/or temperature changes. A reorientation process known as twinning and detwinning can also take place between martensite variants at low temperatures.

Pseudoelasticity (PE); Applying stress to a material initially austenite with temperature above austenite start temperature (A_s) will cause the material to transform inelastically into martensite. This deformation will be fully recovered (on a different path) by removing the applied load (Fig. 1(a)).

Reorientation of martensite variants (Detwinning); for a material initially martensite, a large hysteresis loop due to reorientation is revealed by applying tension–compression cyclic loading (Fig. 1(b)).

Because of the thermomechanical nature of the phase transformation, the SMA behavior is rate dependent. In low rate type loadings the process can release heat and the temperature of the material remains constant which is known as an isothermal process. But in high rate loadings like earthquake excitations, the material does not have sufficient time to exchange heat with the environment and the latent heat of the material causes the temperature to change. This process is also known as an adiabatic process.

A comprehensive SMA constitutive model must be able to predict the pseudoelasticity, shape memory effect and reorientation of martensite phases. It should also be able to capture both isothermal and adiabatic processes. Existing SMA constitutive models which include all these characteristics are very complicated, incompatible with finite element formulations or numerically very extensive.

There are some simplified constitutive models in the literature which try to predict some aspects of SMA behavior with straightforward computations and algorithms [22,23]. The main shortcoming of these models is that they are devised only to model pseudoelastic response of SMAs and do not include detwinning processes. They do not also include high rate loadings or adiabatic conditions.

In this article a simplified constitutive model proposed by Motahari and Ghassemieh [19] is implemented in order to evaluate the behavior of the structures with SMA dampers. The proposed model is able to predict pseudoelasticity and detwinning processes of SMAs under both isothermal and

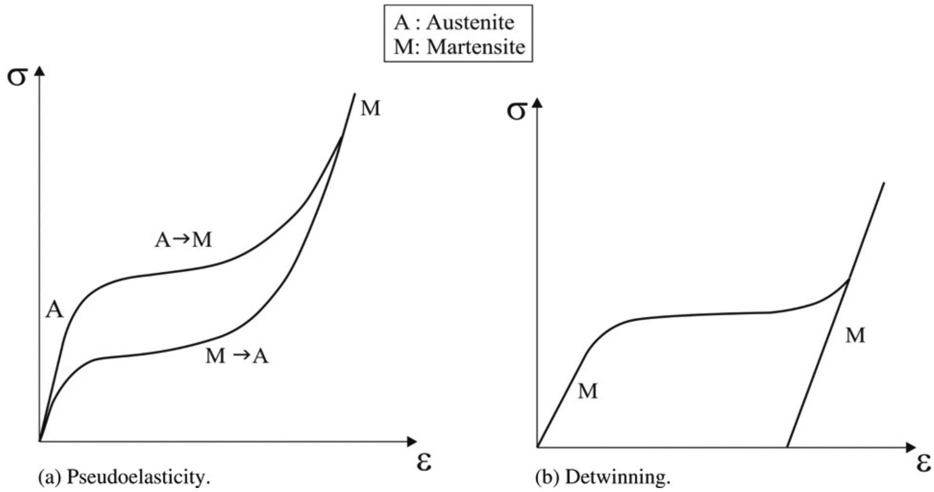


Fig. 1. Different SMA behaviors.

adiabatic conditions. The multilinear nature of the model makes it appropriate for use in the finite element formulations and structural engineering applications, because of its simplicity and robustness and completeness.

3. Proposed SMA damper

The appealing properties of the special damper for use in passive control of the structure are its dissipating capacity and its unique recentering capability. The dissipating capability decreases the demand on the main structural systems and decreases the plastic deformations of the structure members. The recentering ability causes the structures to return to its original geometry at frequent times during the excitation and thus prevents the structure from the accumulation of inelastic deformations.

Based on this premise, the objective of designing the optimized damper would be maximizing the damping capacity while maintaining the recentering capability. The recentering property can be attained by SMAs in austenite phase, but the dissipation capacity of austenite is not so much, and especially in high rate loadings, the dissipation capacity is very low and the behavior of SMA can be considered as nearly elastic [2,3]; thus the detwinning behavior of SMAs in martensite phase is used in order to increase the dissipating capacity of the damper.

The idea of devising a special SMA damper comes from the extensive experimental work of Dolce et al. [1]. They introduced three kinds of SMA dampers using SMAs in the austenite and martensite phases in order to acquire different behaviors. These kinds of dampers were used to include: recentering devices (RD); non-recentering devices (NRD); and supplemental recentering devices (SRCD). The schematic behavior of each of these groups is displayed in Fig. 2. By installing a combination of special dampers into a structure an ideal performance of the structure may be obtained. Design of these dampers requires special care due to some limitations in the use of SMA materials. Axial behavior of SMA is not stable when the size of the material increases from wires to bars [3]. Therefore the proper configuration would be to employ SMAs in austenite and martensite phases as parallel wire loops in the kernel of the damper. Complete details of such considerations can be found in Dolce et al. [1].

In this article, a single damper is introduced in order to obtain the most efficient behavior of the structure instead of using different combinations of complicated dampers as proposed by Dolce et al. [1]. The optimized behavior of the SMA damper can be achieved by numerical studies performed with different configurations for SMA materials in the damper.

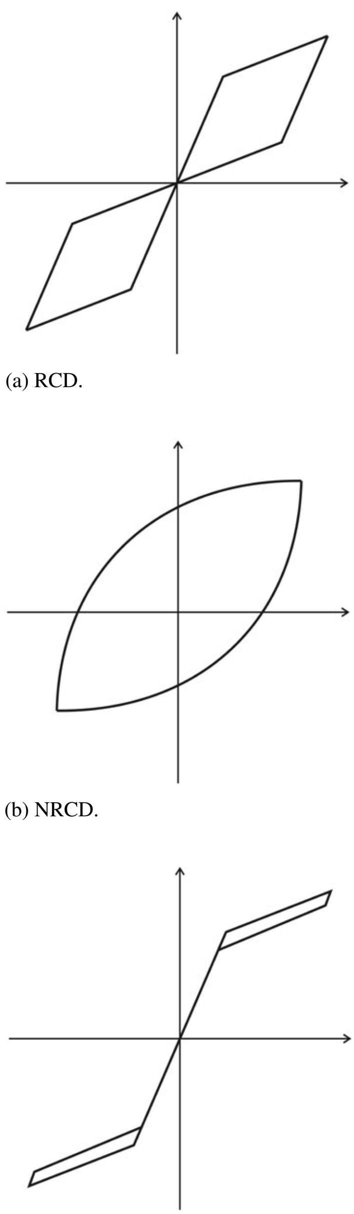
Using the selected constitutive model and with material properties taken from experimental data for most widely used typical Nickel Titanium Shape memory alloys as presented by Motahari and Ghassemieh [20], the high rate loading (earthquake excitation) responses of SMA in austenite and martensite phases were obtained. Then the combination of these two phases was studied by varying the area percentage of each phase from zero to 100%. By decreasing the austenite area percentage from 100% to zero, the full response varied from pure austenite response to pure martensite response. In the transition area, a response between the austenite and the martensite behaviors was found. The martensite phase has much more damping capacity because of the larger area under its stress–strain curve compared to the pseudoelastic response of the austenite phase. Thus, moving from austenite to martensite, the dissipation capacity of the damper increased but the recentering capability decreased when passing from a specific limit. Then the ideal configuration would be the threshold in which the response holds its recentering capacity while the dissipation capacity of the damper is maximized. For the selected material properties this is achieved when using equal total sectional areas of austenite and martensite in the damper as shown in Figs. 3 and 4. In these figures, the total section area of both austenite and martensite strands is taken to be unity.

For easier implementation of the model in the numerical program, the multilinear force–displacement model is simplified into a four-segment model as shown in Fig. 5.

The SMA Kernel should be implemented in a bracing system. The parameters which influence the behavior of the

Table 1
Properties of SMA damper systems

	Story no.	Damper 1	Damper 2	Damper 3	Damper 4
SMA kernel area (cm^2)	1st	33	33	16	16
	2nd	25	25	12.5	12.5
	3rd	16	16	8	8
SMA strand lengths (cm)		50	100	50	100
Steel part area/	1st		120/87		
Original steel bracing	2nd		87/63		
System area (cm^2)	3rd		63/40		



(a) RCD.

(b) NRCD.

(c) SRCD.

Fig. 2. Types of SMA devices as proposed by Dolce et al. [1]. (a) Recentering devices, (b) not-recentering devices and (c) supplemental recentering devices.

bracing system are the length of the SMA wires and the total area or number of wire loops and the area of the steel part of the bracing which the damper will be installed on. Based on different design philosophies, four different types of dampers are proposed. The first system is devised so that it produces the same initial stiffness and yielding force as the designed steel bracing system at each story. This will give a good premise for making comparison between the behaviors of ordinary steel bracing systems and the SMA damper system. The second system is much like the first with the difference that the length of SMA strands is increased to double in order to enhance the dissipation capacity of the damper. This system would have a lower stiffness. The other shortcomings of this system are the greater amount of SMA material used and hence the increase in total expenses. The third and fourth systems are the first two systems with half the area so that yielding starts at much lower stresses. The philosophy behind this configuration is the ability of SMA materials to undergo large strains without any degradation of strength and stiffness during loading cycles. Another important advantage of the 3rd and 4th damper systems is the lesser amount of SMA material used. The section area of the steel part of the bracing is chosen so that the plastic deformations occur only in the SMA kernel in the range of working stress. The behaviors of the four damper systems are illustrated in comparison with the counterpart steel bracing system for a typical structure in Fig. 6. In Table 1, the length and the total section area of the SMA kernel strands for different SMA damper systems and the area of the steel bracing parts are shown.

4. Implementation

In order to evaluate the response of the SMA damper when inserted in a structure, a common 3 story building proposed by Sabelli [24] was selected. To take advantage of symmetry, only a single bay of the structure is considered as shown in Fig. 7.

The ground acceleration history of Imperial Valley recorded at ElCentro scaled to $0.3g$, $0.6g$, and $0.9g$ was considered in analyses. Nonlinear time history analyses were performed by AIMS code developed by the first author using Newmark time integration techniques [25].

Because of the non-ductile behavior of ordinary concentrically bracing systems, buckling restrained steel braces (BRSB) are used in steel bracing systems. The braces in the BRSB systems have identical behavior in compression and tension and have far more stable hysteresis behaviors [26].

For finding a quantitative comparison basis between the different system behaviors, appropriate global indicators of structural and non-structural states are required. Thus, the idea of damage indices is used for this purpose. Structural damage is mainly related to the ductility and energy dissipation of

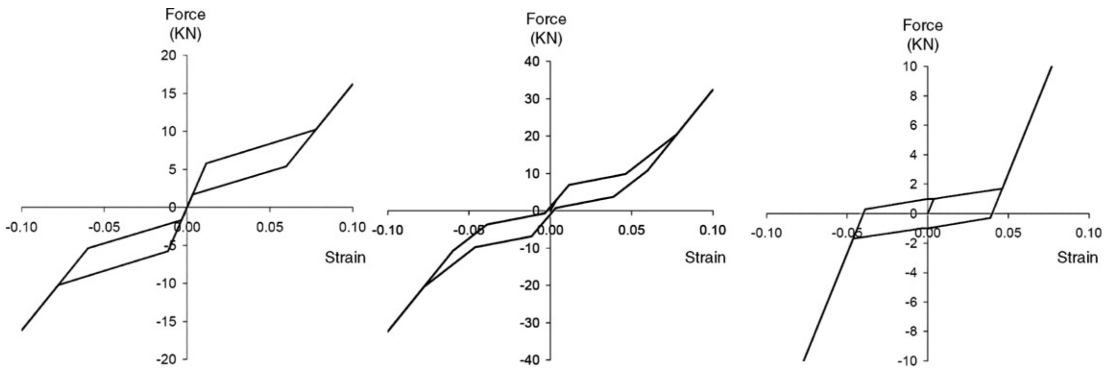


Fig. 3. The proper proportions of austenite and martensite for optimizing the damper behavior.

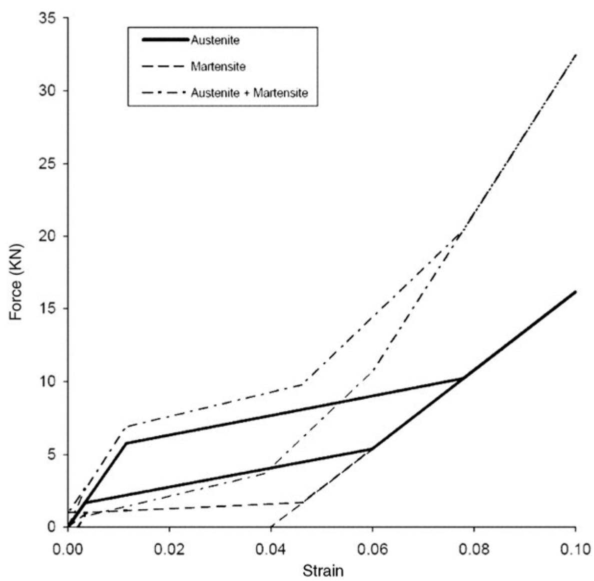


Fig. 4. Combination of different states in the damper.

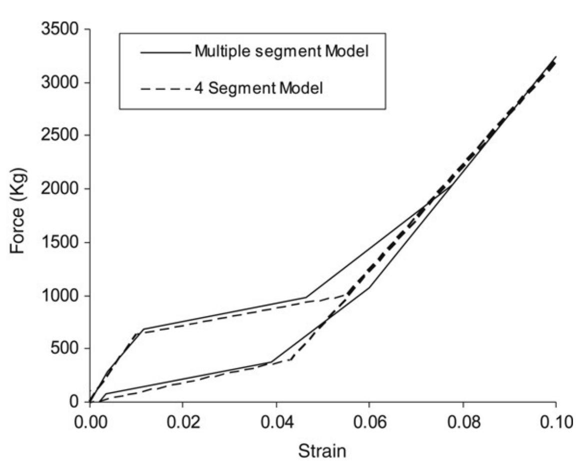


Fig. 5. Comparison of the original multiple segment model and the simplified 4 segment model.

the members while inter story drift controls the non-structural damage. The damage to the contents can also be evaluated by the maximum acceleration response of the stories of the building. In this study, a modified version of the widely adopted Park and Ang [21] structural damage index proposed by the authors are used throughout the study.

Damage of structural components under earthquake loading is generally caused by the combination of repeated stress reversals and high stress excursions. Thus the damage index of each plastic hinge of a member can be expressed as:

$$D = \frac{u_{\max}}{u_{\max,\mathrm{mon}}} + \frac{\beta}{F_y.u_{\max,\mathrm{mon}}} \int \mathrm{d}E_h$$

in which $u_{\max}$ is the maximum response, β is a non-negative parameter depending on type of structural system, $u_{\max,\mathrm{mon}}$ is the ultimate limit corresponding to monotonic loading, F_y is the yield force/moment, and $\mathrm{d}E_h$ is the incremental dissipated hysteretic energy.

In the modified version of the Park and Ang model [27], the damage of each story is then computed as:

$$D_{\mathrm{storey}} = \sum_{i=1}^{m} \lambda_i D_i, \qquad \lambda_i = \frac{E_i}{\sum_{j=1}^{m} E_j}$$

where m is the number of plastic hinges of story.

With the premise that the distribution of damage is closely correlated with the absorbed energy, the total damage of the frame is then calculated as:

$$D_{\mathrm{frame}} = \sum_{i=1}^{n} (\lambda_i)_{\mathrm{storey}} (D_i)_{\mathrm{storey}}, \qquad \lambda_i = \frac{(E_i)_{\mathrm{storey}}}{\sum_{j=1}^{n} (E_j)_{\mathrm{storey}}}$$

where n is the number of stories.

Since the aforementioned damage index method was originally introduced for moment resisting reinforced concrete structures therefore the formulations have some shortcomings in the steel braced systems. For instance, in a steel braced structure some bracings may totally collapse after a strong earthquake, but the overall structure will be safe to function, and it can be accumulated that for the life safe design objective, the behavior of the overall structure is very much related to the main frame members. Thus, in this article the damage index of the elements is averaged only on the main structural members (i.e., columns and beams of the main frame). Moreover, the bracing elements may experience brittle fractures and then the presumption that the damage of the story would be the weight

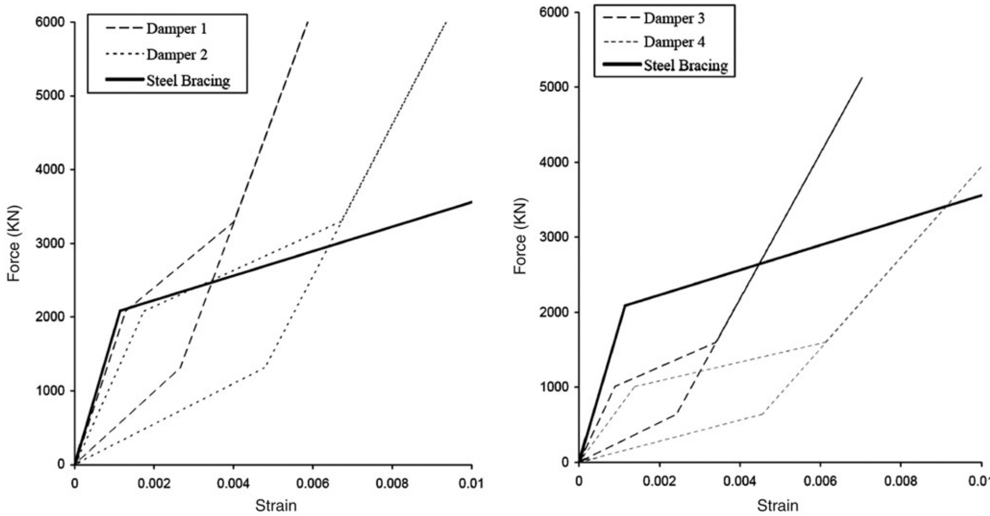


Fig. 6. Different damper system behaviors.

average of the constituent member damages with dissipated energy as the weighting function would not be logical. It is proposed that the total damage of a story is equal to the maximum damage of the stories' columns. For example, if a column of a story collapses during a strong earthquake, the main objective of life safety is not satisfied. Therefore, the damage of a story should indicate the maximum damage of its column members.

It is to be noted that the damage of SMA dampers is taken to be zero in their working limits because of their very high fatigue resistance. This characteristic seems to be one of the most interesting features of this material in decreasing the damage of the entire building since it sustains no damage to the structure even after long duration of a given earthquake. The damage indicator proposed by the authors seems to be more appropriate for comparison with the SMA braced structure because of the zero damage inherited in the SMA dampers. This reasoning may also be extended to buckling restrained bracing systems because of the stable hysteresis inherited in such systems [26].

The following damage level classification was proposed by Park and Ang [21]: no damage for $D < 0.1$, minor damage for $0.1 < D < 0.25$, moderate damage for $0.25 < D < 0.4$, severe damage for $0.4 < D < 0.1$ and total damage for $D > 1.0$.

The non-structural damage of the structure is evaluated by the maximum inter-story drift because of the shear deformations of the infill panels and is defined as:

$$\delta = \frac{\Delta u_i}{h_i}$$

where Δu_i is the difference between two consecutive stories of the ith and the $(i-1)$th and h_i is the story height. The total non-structural damage of the structure is assumed to be equal to the maximum non-structural damage of the stories. According to Naeim [28], $\delta < 0.001$ indicates no damage, $0.001 < \delta < 0.002$ minor damage, $0.002 < \delta < 0.007$ moderate damage, $0.007 < \delta < 0.015$ severe damage, and $\delta > 0.015$ corresponds to total collapse of non-structural components.

For studying the effects of excitations on equipment, machinery, and other contents of typical buildings, two limit values of $0.2g$ and $2g$ for the maximum acceleration of the stories are considered as the minimum and maximum limits of the damage to contents as stated in Bruno and Valente [16].

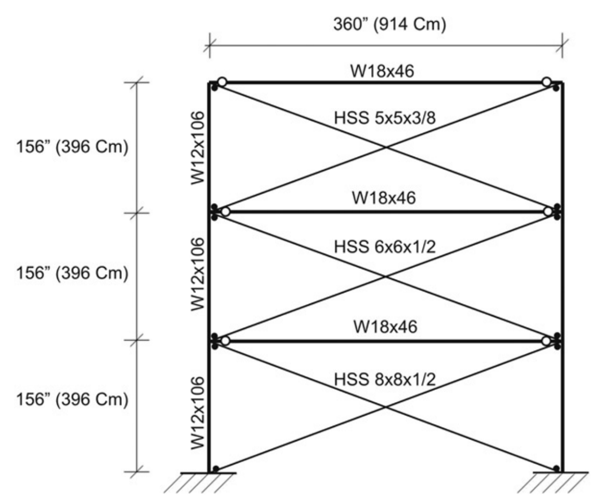


Fig. 7. Geometry and sections of a single bay of the structure.

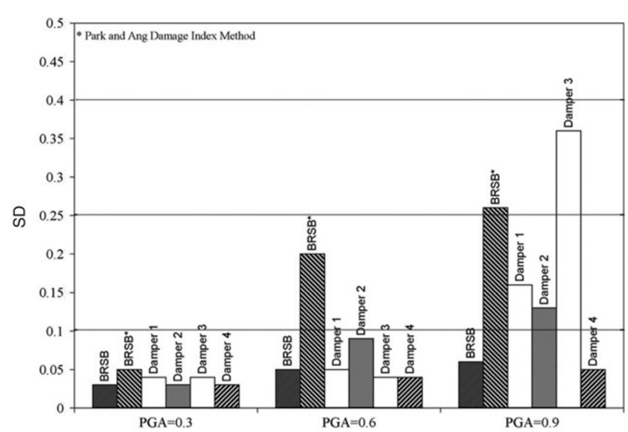


Fig. 8. Structural damage (SD).

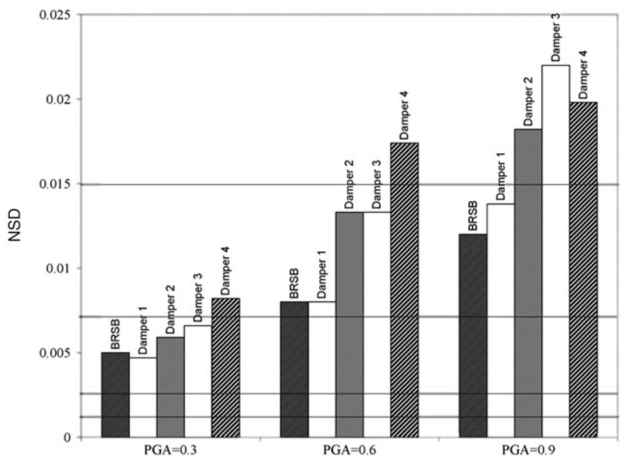


Fig. 9. Non-structural damage (NSD).

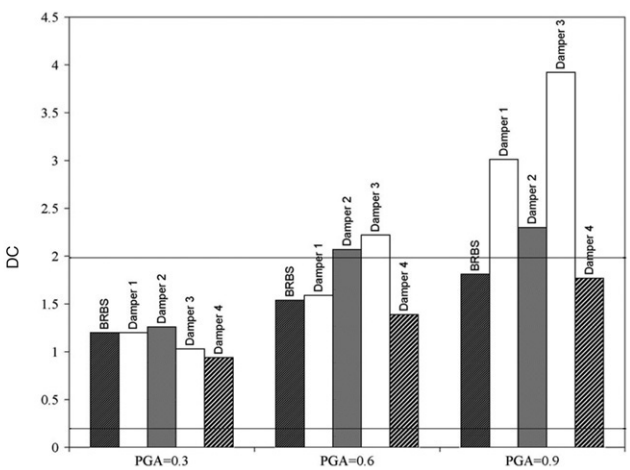


Fig. 10. Damage to contents (DC).

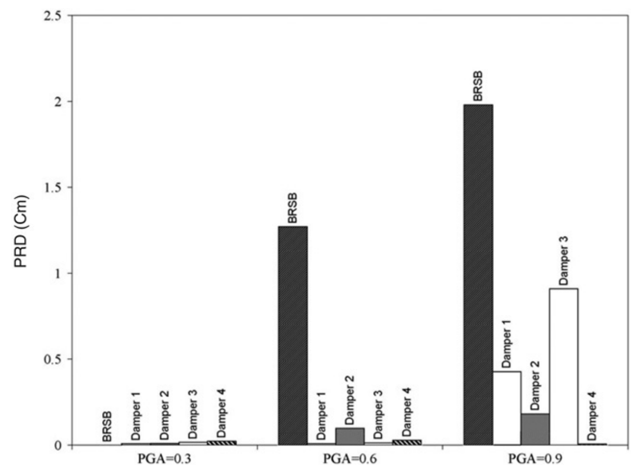


Fig. 11. Permanent roof displacement (PRD) of different systems.

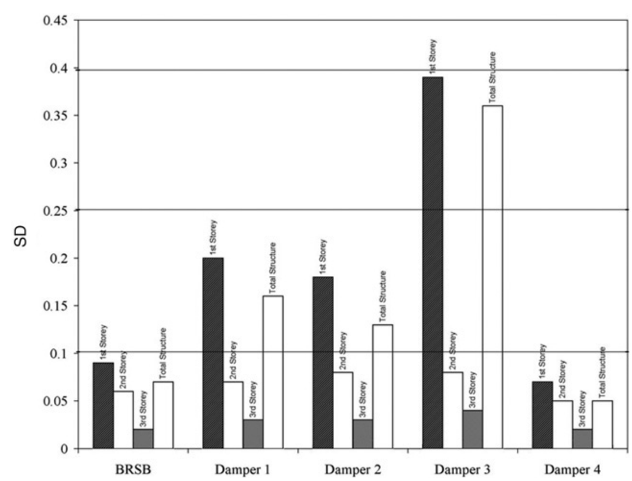


Fig. 12. Structural damage distribution over stories of different systems for PGA = 0.9.

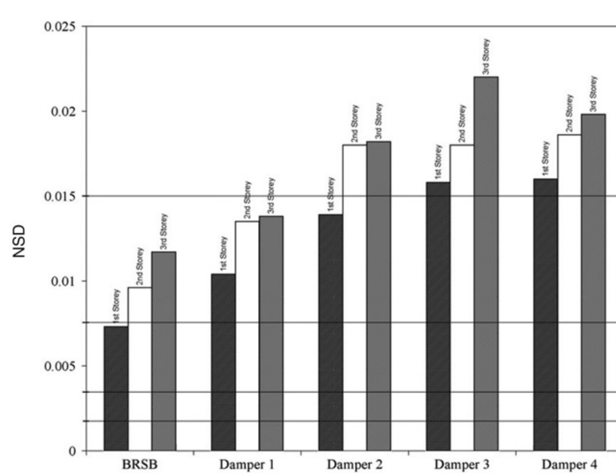


Fig. 13. Non-structural damage distribution over stories of different systems for PGA = 0.9.

5. Results

The structural damage (SD), non-structural damage (NSD), the damage to contents (DC), and the permanent roof displacement (PRD) of different systems under different ground motions are shown in Figs. 8 through 10. The damage of BRSB systems is evaluated by both the modified Park and Ang [27] damage index and by the damage index proposed by the authors in this article.

Fig. 8 shows the structural damage of different systems, which indicates that all the systems have a similar performance at relatively low earthquakes. But at higher excitations different damper systems show diverse behaviors. The reason for this disorder is the different paths and changes in stiffness that the damper will undergo when subjected to high loadings and the changes in the frequency content of the response history. Among different damper systems, Damper 3 shows to have the worst behavior under high earthquakes because of its low energy dissipation capability and the low yielding stress. Damper 4 is shown to be able to reduce the structural damage of the structures powerfully [Fig. 8].

Fig. 8 shows that the modified Park and Ang [27] damage index method gives higher damage indices for BRBS system than the proposed damage model. This is due to high indices calculated for the bracing systems. Intuitively, it can be assumed that the Park and Ang [27] damage index can be used for conventional steel bracing systems when the degradation

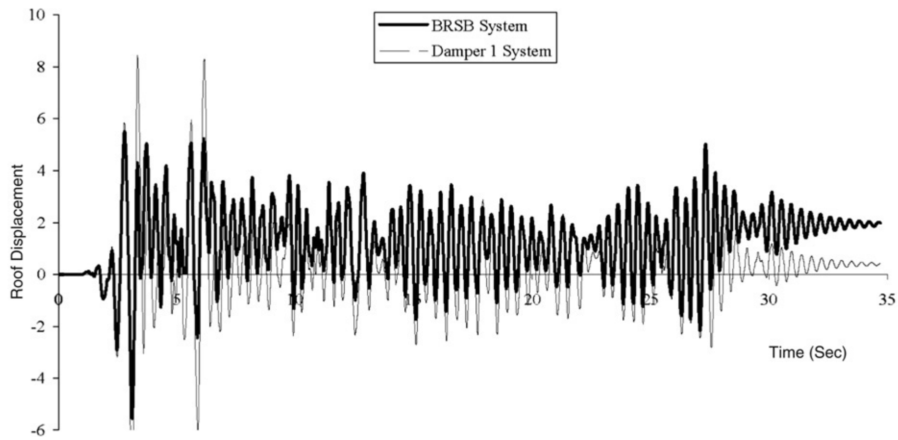


Fig. 14. Roof displacement history of BRSB and Damper 1 systems for PGA = $0.9g$.

and buckling of the bracing systems are not considered in the analyses. This is due to the high damage calculated for bracing members which indirectly show the effect of the neglected degradation and buckling of the braces.

Fig. 9 shows that the non-structural damage of the structures generally increases when the BRSB are replaced by SMA dampers except in Damper 1 system because of its identical stiffness and yielding stress as the BRSB system. The damage to the contents of all the SMA bracing systems except Damper 4 is higher than the BRSB system.

In Fig. 11, the permanent residual deformations remaining on the structure at the roof level are shown. SMA damper systems decrease the residual deformations drastically. This would be one of the features that make the SMA dampers favorable to the BRSB systems.

Figs. 12 and 13 shows the distribution of the structural and non-structural damage over different stories, which indicates that the structural damage index decreases, and the non-structural damage increases, as the story number increases. This is due to the relation of structural damage to the axial forces due to gravitational dead loads which are generally higher in lower stories while non-structural damage or the story drift is mainly related to lateral loads and the capacity of the story bracing system.

The time history of the BRSB and Damper 4 systems for the response of the structure to $0.6g$ PGA ground motion are shown in Fig. 14. It is shown that the SMA damper system does not sustain any residual or permanent deformation on the structure.

First floor bracing force–displacement histories for different structural systems subjected to $0.9g$ PGA ground acceleration history are shown in Figs. 15 and 16. As can be seen only the Damper 3 system has completed the forward austenite to martensite transformation. The hardening occurred in this system after completion of the forward transformation decreased the damping capacity of the system compared to other systems which have not completed the forward transformation. This has caused higher axial forces in this system, and the columns of the first floor have experienced higher damages. As shown in Fig. 14, the SMA system has no practical permanent deformations after the earthquake. This can be readily related to the recentering behaviors of the Dampers as shown in Fig. 16. But the BRBS sustains noticeable residual displacements which are due to the accumulative plastic deformations of its bracing systems as shown in Fig. 15.

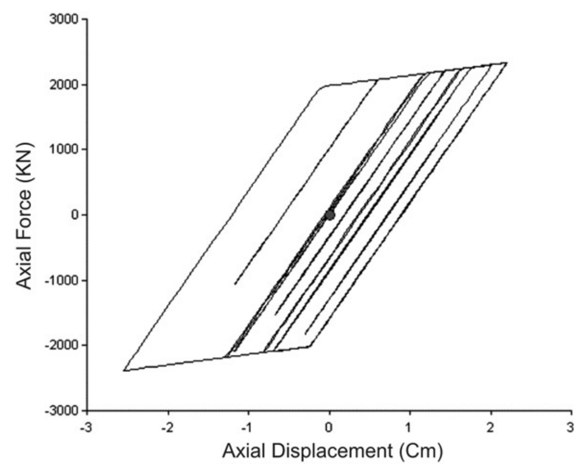


Fig. 15. First floor bracing force–displacement history for BRSB system subjected to $0.9g$ PGA ground acceleration history.

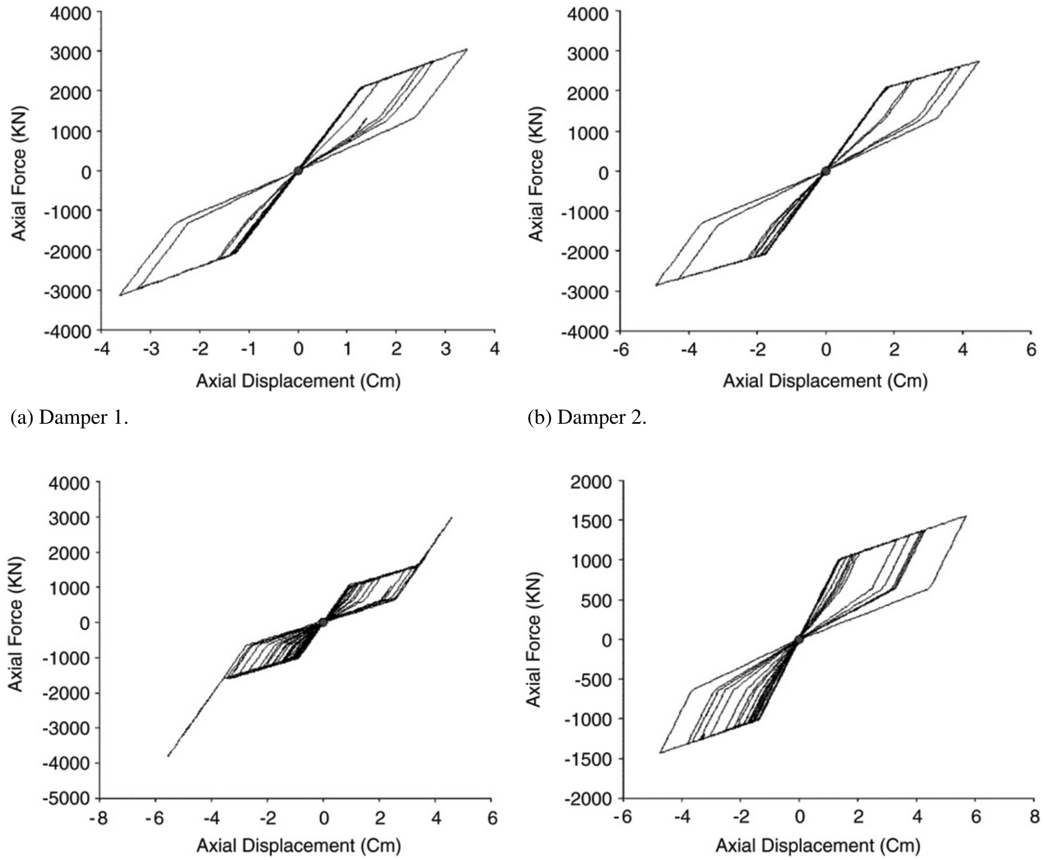
Generally, the results of this study imply that the SMA damper systems slightly increase the frequency content of the responses because of the numerous changes in the stiffness which occurs in the structure throughout the loading history.

The deformed shape of the Damper 3 system at the peak roof displacement is shown in Fig. 17. At this stage the column of the first floor has entered the plastic region which is not considered favorable in structural design.

In order to consider different earthquake time histories, two other time histories with different frequency contents, namely Kobe and Loma Prieta, are included in the analyses. Fig. 18 shows the structural damage indices for different systems under different ground acceleration time histories scaled to $0.9g$. As shown in this figures the results follow a general trend for different time histories.

6. Conclusion

Different innovative SMA damper systems were proposed in this article. These dampers were designed so that they



(a) Damper 1.

(b) Damper 2.

(c) Damper 3.

(d) Damper 4.

Fig. 16. First floor bracing force–displacement history for different damper systems subjected to $0.9g$ PGA ground acceleration history.

produce different initial stiffness and yielding forces compared to the initial steel bracing system. Two phases of austenite and martensite were used in the damper in order to achieve an efficient behavior of both the recentering and the high energy dissipating capability. For attaining a comparative basis for the different structural systems, the idea of damage indicator was utilized with some modifications and suggestions. The structural damage, non-structural damage, and the damage to contents of different systems with the permanent deformations of the systems were considered at different levels of ground acceleration histories. For gaining the measure of effectiveness for implementation of SMA dampers in the structural systems, the innovative damping systems were compared with the BRSB systems which are known to have the best seismic performance in steel bracing structural systems.

Based on different design philosophies, different SMA dampers were designed to produce different yielding forces and stiffness. The systems also differed in the amount of SMA material used. Different damper systems were implemented in a given structure and the behavior of the systems was compared analytically. SMA damper systems were able to reduce the structural damage of the systems noticeably while showing some limitations in producing relatively large non-structural damages.

The results also show the effectiveness of the implementation of SMA dampers especially in reduction of the remaining

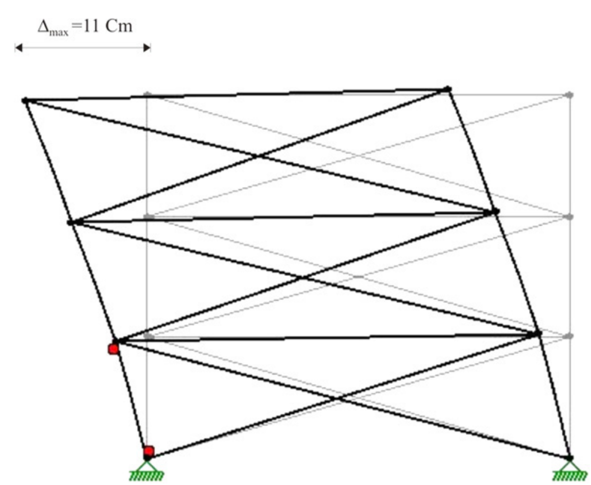


Fig. 17. Deformed shape of the Damper 3 system at the peak roof displacement.

deformations on the structure even after very high ground motions. The structures with SMA dampers are designed in such a manner that no damage occurs in the structural members, and the bracings are the only energy dissipating mechanisms. Thus, due to the high fatigue resistance of SMA material there is no need for replacing of the dampers after earthquake which may significantly reduce the post earthquake repair costs. It should also be noted that the price of the SMA material is decreasing

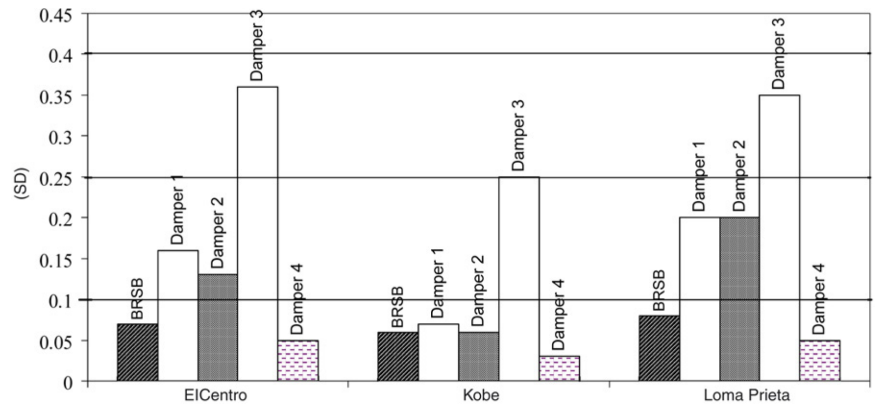


Fig. 18. Structural damage index for different earthquake time histories scaled to $0.9g$.

due to the increase in demand in different emerging applications and technologies. It is expected that by exploring more applications and by increasing the production of SMA, the price would continue to decrease.

It may also be possible to define a new damage indicator which takes into account the residual deformations of the structural members as well. In conventional structures this was not required since there is a general direct relationship between maximum actions and deformations of the structure and the residual deformations. In structures which have no residual deformations it may be concluded that the total damage is much lower than the one calculated by conventional methods. Finally, it must be pointed out that there should be a methodology for optimal design of SMA dampers supported by extensive experimental data which do not exist to date and can be one of future important improvements in this emerging field of structural control.

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