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Effect of hysteretic properties of superelastic shape memory alloys on the seismic performance of structures

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SUMMARY

Shape memory alloys (SMAs) are characterized by unique superelastic behaviour which enables the material to recover its original shape after experiencing large deformations. This phenomenon provides ideal recentring capabilities which can be used in the passive control of structures subjected to earthquakes. However in seismic applications, the hysteretic properties of the material play an important role in determining the structural response. Research has shown that the hysteretic properties of SMAs are highly dependent on the chemical composition, the manufacturing process, and the loading strain rate. This paper focuses on investigating the effect of variability in the hysteretic properties of superelastic SMAs when used as passive control devices in structures subjected to earthquakes. The hysteretic properties of SMAs are assumed to be defined by three independent parameters. A sensitivity analysis and two case studies are conducted to examine the effect of variability of each parameter on the effectiveness of SMAs as restrainers for bridges and bracings for buildings. The outcomes of the studies show that the slope of the SMAs hysteresis has similar effect on the structural response (less than 10% in average) regardless of the type of SMA application. However, the effect of changing the hysteretic height is more pronounced in the case of SMA bracings compared to SMA restrainers. This illustrates that, in general, superelastic SMAs are relatively stable in their effectiveness in various structural applications despite the changes in their hysteretic properties. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS: shape memory alloys; bridges; earthquakes; restrainers; bracings; hysteretic

INTRODUCTION

Shape memory alloys (SMAs) are known for their unique thermomechanical characteristics which allow the material to recover its original shape either through heating or removal of stress. These characteristics encouraged many researchers to study the feasibility of using these relatively new materials in various engineering and scientific applications. Many researchers have proposed using SMAs in various structural applications such as in cross-bracing cables [1],

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passive control dampers [2–4], steel moment connections [5], and seismic retrofit of bridges [6, 7]. In these studies, the mechanical/hysteretic properties of the SMAs were assumed to be constant. However, it is well known that the hysteretic properties of SMAs can vary significantly depending on the thermomechanical processing, composition, type of alloy, and loading strain rate. The effect of variability in the SMAs hysteretic properties on their performance in structural applications is addressed in this paper. The work presented in this context is primarily directed towards the potential application of SMAs as seismic restrainers for bridges. However, a case study is presented at the end of the paper where the application of SMAs as bracings for frames is also addressed.

MECHANICAL PROPERTIES OF SHAPE MEMORY ALLOYS

Shape memory alloys are found in two main phases, depending on the ambient temperature. At high temperatures, SMAs are found in their austenite phase, while at low temperatures they are found in their martensite phase. SMAs experience a phase transformation when subjected to either thermal or mechanical loading. The transformation from one phase to the other is associated with unique thermomechanical characteristics known as superelasticity and shape memory effect. The austenitic phase of SMAs is characterized by a unique superelastic behaviour, which allows the alloy to recover its undeformed shape once the mechanical stress is removed. Figure 1 shows a schematic of a typical stress–strain relationship for superelastic SMAs. The flat plateau is associated with the phase transformation from austenite to martensite. As illustrated in the figure, the elastic strain could reach 8% in some alloys. It is also noticed that beyond the stage of phase transformation, the alloy experiences strain hardening which results from the elastic behaviour of the martensite.

Several experimental studies have been conducted to specify the mechanical properties of SMAs [7–11]. The outcomes of these studies illustrate considerable differences in the hysteretic

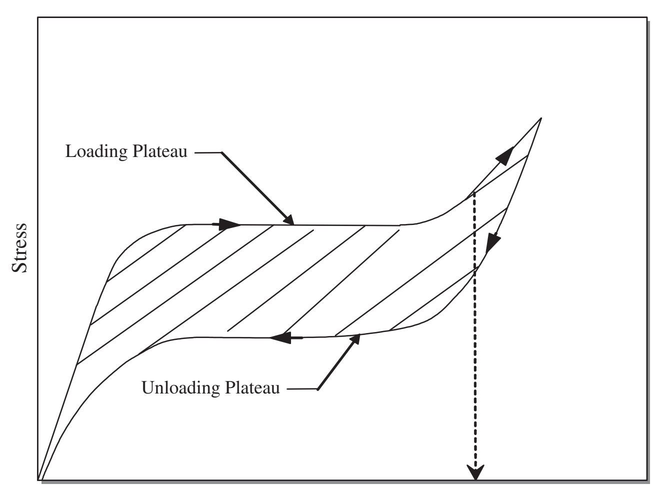

Figure 1. Typical mechanical behaviour of superelastic shape memory alloys.

properties of a given SMA, even within one phase. Research has shown that the variation in the SMA mechanical properties could be due to several factors such as alloy composition, manufacturing processing, and strain rate. These factors play an important role in defining the hysteretic behaviour of the SMAs.

An important factor that controls the mechanical properties of SMAs is its chemical composition [12, 13]. The chemical composition of the alloy affects the phase transformation temperatures, which plays an important role in defining the alloys' mechanical properties. Figure 2 shows a comparison between the mechanical behaviours of two Ni–Ti alloys with slightly different composition. The figure illustrates that the alloy with a 0.2% increase in the Titanium has an approximately 16% reduction in the yield strength and a larger hysteresis area.

Research has shown that one of the main factors that influence the mechanical behaviour of SMAs is the method used to process the alloy [14]. Figure 3 shows an example of the effect of the

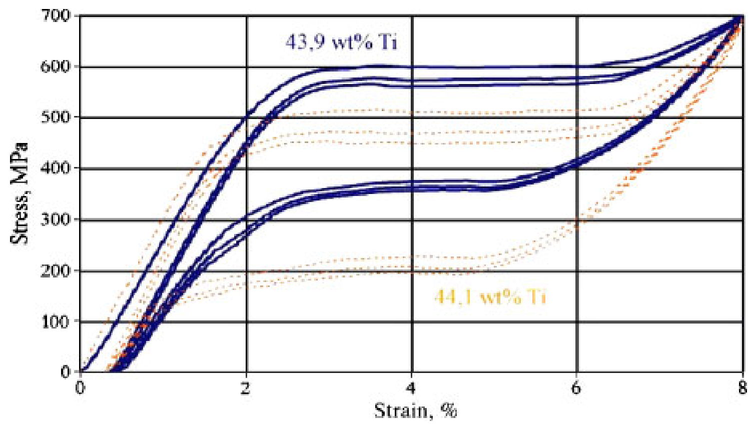

Figure 2. A comparison between the behaviour of a 43.9 wt% Ti and a 44.1 wt% Ti Ni–Ti alloys [13].

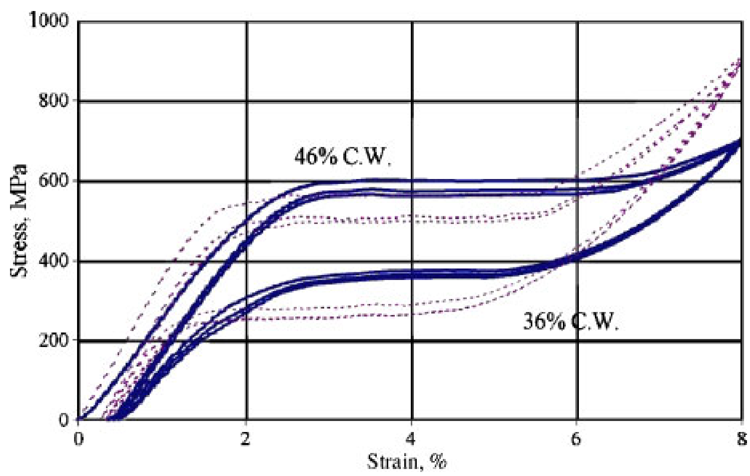

Figure 3. Effect of cold work on the loading plateau of an austenitic shape memory alloy [13].

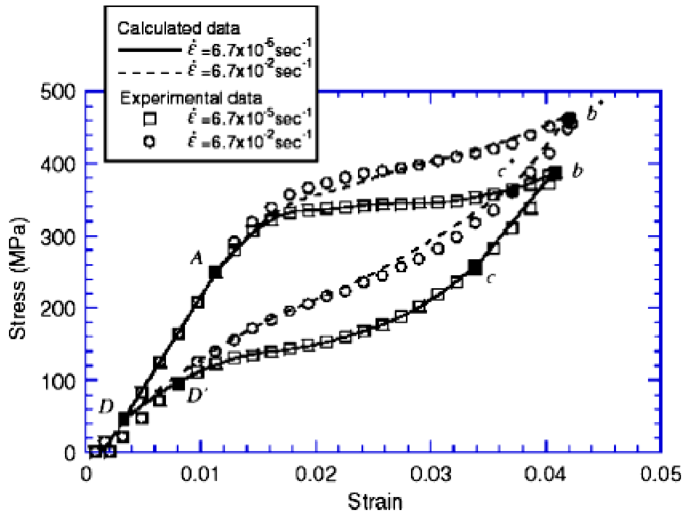

Figure 4. Stress–strain curves for superelastic SMA at different strain rates [16].

cold work percentage that the alloy receives on its hysteretic behaviour. As shown in the figure a fairly slight difference in the loading plateau is associated with different levels of cold work. In this case, one of the alloys was treated with 46% of cold work while the other was treated with 36%. The figure shows that increasing the cold work by 10% resulted in elevating the plateau by approximately 9% and reduces the hysteresis area.

The rate of loading also plays an important role in defining the hysteretic behaviour of SMAs. Most of the researchers agree that loading rate affects the mechanical behaviour of the alloy [9, 15, 16]. However, results varied from one study to another on the extent of the effect, based on the range of strain rate that was used and type of alloy used. An example of these studies is the study conducted by Matsuzaki and others [16]. The effect of strain rate on superelastic SMAs was investigated analytically and was compared with the experimental results of Reference [17]. Figure 4 presents the analytical and experimental stress–strain curves at two strain rates. As shown in the figure, both of the analytical and the experimental results showed that at higher strain rate SMAs experience an increase in the hysteretic slope associated with a decrease in the hysteretic area.

BRIDGE MODEL

A sensitivity analysis was conducted to study the effect of variability in the SMAs hysteretic properties resulting from the factors discussed above on their performance as seismic restrainers for MF bridges. A simplified 2 degree-of-freedom (DOF) analytical bridge model was developed and used in the study. The 2-DOF model represents two adjacent frames in a MF bridge. The model assumes that the two frames are isolated from the rest of the bridge and thus the effect of the abutments was excluded from the model. Figure 5 shows a schematic for the model that was used in the analysis. As shown in the figure, each frame was modelled as a stick-mass element.

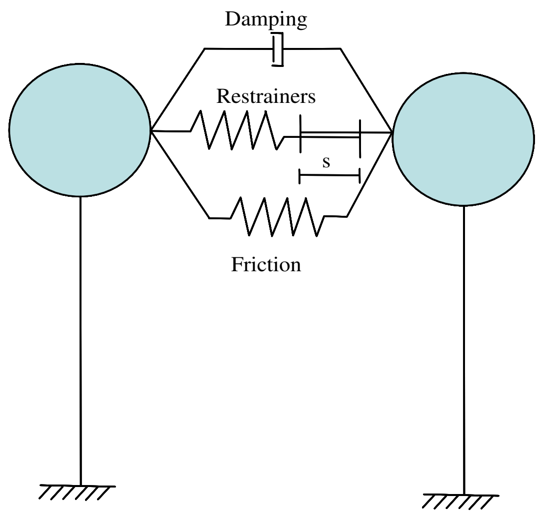

Figure 5. Simplified 2-DOF bridge model that was used in the study.

A dashpot was introduced in the model to represent the equivalent viscous damping in the structure. The SMA restrainers were implemented in the model by using a tension-only link element with a slack (S). The dynamic response of the model was governed by the following equation:

$$M\ddot{x}(t) + C\dot{x}(t) + F_{\mathrm{r}}x(t) + F_{\mathrm{fr}}x(t) + F_{\mathrm{SMA}}x(t) = -M.1.\ddot{x}_{\mathrm{g}}(t) \tag{1}$$

where M is the mass matrix, C is the damping coefficient matrix, F_{r} is the vector of the frames restoring force, F_{fr} is the vector of restoring force due to friction at the hinge bearing, F_{SMA} is the vector of restoring force resulting from SMA restrainers. The x, $\dot{x}$, and $\ddot{x}$ are the frames displacement, velocity, and acceleration vectors, respectively. On the right-hand side of the equation, the vector 1 is the influence vector and the vector $\ddot{x}_{\mathrm{g}}$ is the ground motion acceleration input. The model also accounts for impact between the two frames by applying the principle of momentum conservation. A coefficient of restitution [18] equal to 0.8 was used to relate the velocities of the two frames prior to and after impact. The non-linearity of the two frames is considered in the model by utilizing the Q-Hyst model [19] which describes the stiffness/strength degradation in the response of reinforced concrete members under cyclic loading.

Based on the results of research conducted by other researchers [20], it was found that the hinge opening in bridges is primarily affected by the period ratio ρ (i.e. ratio between the periods of the two frames) and the ductility ratio μ (i.e. ratio between maximum and yield displacements) of the bridge frames. Hence these two parameters were the only bridge parameters considered in the sensitivity analysis. The ratio of the two frame masses was taken as 1.0 with the mass of each frame corresponding to a frame weight of approximately 22 240 kN (5000 kips).

SHAPE MEMORY ALLOY MODEL

A simplified one-dimensional tension-only SMA model was developed and implemented at the bridge's intermediate hinge. This model describes the force–deformation relationship of superelastic SMAs at constant temperature (i.e. the model was temperature independent). Figure 6 shows a schematic of the force–deformation relationship resulting from the simplified model. The figure also shows the parameters required to define the behaviour of the model. These parameters include: austenite elastic stiffness (K_A), martensite elastic stiffness (K_M), phase transformation starting force (F_s), phase transformation finishing force (F_f), the strain hardening ratio during martensitic transformation (S_M), and the unloading force at the end of the reverse transformation (F_u). In this model, the strain at the start and the end of the phase transformation were fixed and were taken equal to 1 and 6%, respectively.

SENSITIVITY ANALYSIS

A major task that would face a bridge engineer while designing restrainer cables/rods made of SMAs is to decide on the optimum shape of the SMA hysteresis that would result in the best performance of the restrainers in limiting the bridge's hinge opening and hence reducing the risk of superstructure unseating during earthquakes. This requires a better understanding of the sensitivity of the bridge's response to the SMA hysteretic shapes and properties. To better understand this, a sensitivity study was conducted using the SMA model that was described earlier. In order to limit the number of simulations required for the sensitivity study a preliminary analysis was conducted. The main goal of this study was to identify the parameters that most affect the hinge opening response in MF bridges and examine the effect of interactions between those parameters.

Preliminary analysis

The multifactor experimental design technique [21] was used to design the sensitivity analysis. In this technique, an analysis of variance table is constructed to decide whether there is

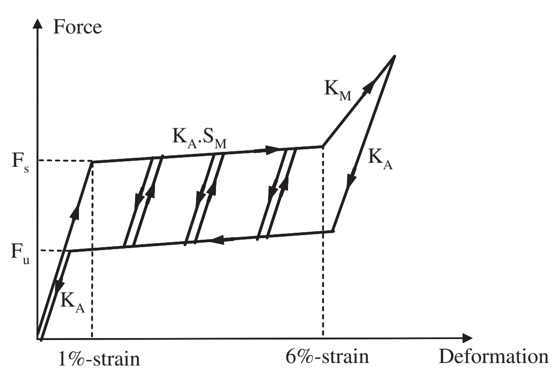

Figure 6. Force–deformation relationship of the simplified superelastic SMA model.

an interaction between a number of factors (variables) and a specific response variable. The designer of the experiment assigns a certain number of levels (values) to each of the factors considered in the analysis.

Five factors were considered for the preliminary study in which two of them were the ductility ratio of the bridge frames (μ) and the period ratio of the two frames (ρ). The remainders were parameters that describe the hysteretic shape of the SMA. Parameters α, β, and γ were assumed to be three independent parameters which fully define the hysteretic shape of the SMA. Figure 7 shows a schematic for the force–displacement relationship for the SMA restrainers with the three parameters shown in the figure. As shown in the figure, parameter β represents the hysteresis height ratio, which was defined as the ratio between the force at the end of the reverse transformation and the force at the start of phase transformation. The α and γ parameters represent the strain hardening ratios during phase transformation and post phase transformation, respectively.

Two levels were considered for each of the five factors. The two levels represent two values for the studied factor that are well separated. Table I shows the five factors considered in the preliminary study with their corresponding two levels. The 0.4 and 0.7 values for the frame period ratio factor were selected such that they would represent different levels of relative response between the two frames. The value of ductility ratio μ equal to 1.0 represents the case when the frames are elastic, while the second level of ductility ratio where μ is equal to 4.0 represents the inelastic case. Parameters α, β and γ were assigned level values that would reproduce practical hysteretic shapes for the SMAs used in the study.

Five ground motion records were used to produce the replicates at each level. The five records considered in the preliminary study were: the Beverly Hills (1994 Northridge) record, the Long Valley Dam (1980 Mamoth Lakes) record, the Bolu (1999 Duzce, Turkey) record, the Cape

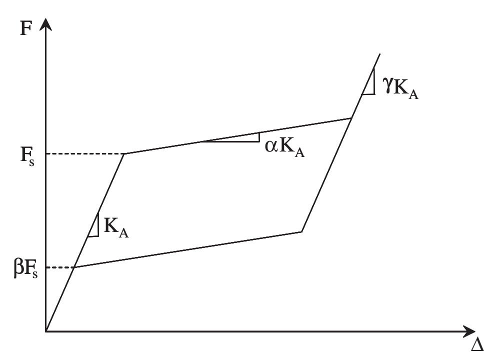

Figure 7. SMA hysteretic shape parameters considered in the sensitivity analysis.

Table I. Factors and levels considered for the design of the sensitivity analysis.

Levels	ρ	μ	α	β	γ
1	0.4	1.0	0.0	0.1	0.3
2	0.7	4.0	0.2	0.9	0.9

Mendocino (1992 Cape Mendocino) record, and the WAHO (1989 Loma Prieta) record. The records were scaled such that their spectral acceleration at the fundamental period of the structure (1.0 s) would be equal to 0.85 g.

Results of the preliminary analysis

The analysis of variance table was constructed using JMP, a statistical software package developed by SAS Company. The software conducted a full factorial design where all the possible combinations between the five factors were considered. In this case 32 combinations were considered for each ground motion. Figures 8 and 9 show the maximum hinge displacement ratio (MHDR) and the maximum drift ratio (MDR) results of the preliminary study, respectively. The MHDR response is defined as the maximum hinge opening of the bridge with restrainers normalized by the hinge opening of the bridge without restrainers, while the MDR response is defined as the maximum drift of the stiffer frame in the case of the bridge with restrainers normalized by the maximum frame drift of the bridge with no restrainers. Previous research [22] have shown that installing restrainers in the bridge's intermediate hinge increases the displacement demand of the stiffer frame. Thus a major concern while conducting this study was to explore the effect of variability in the SMAs hysteretic properties on the frames drift.

The vertical axis of the plots shown in Figures 8 and 9 represents the three hysteretic parameters and their possible combinations with the two bridge parameters. The horizontal axis represents the *P*-values, which typically lies between 0.0 and 1.0. The figures show that all of the combinations involving the β factor resulted in *P*-values that are larger than 0.9. This behaviour was backed by the fact that the *P*-value associated with the β factor was approximately 0.74 and 0.64 in the case of the MHDR and MDR response, respectively. These *P*-values were considered as high values relative to the values corresponding to the α and γ parameters. These results indicate that the hysteretic height has less effect on the hinge opening value compared to the

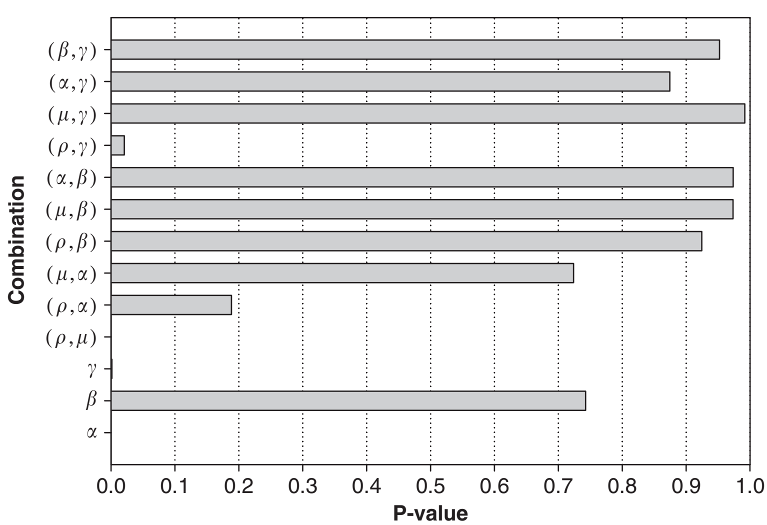

Figure 8. *P*-values associated with the MHDR response using different factor combinations.

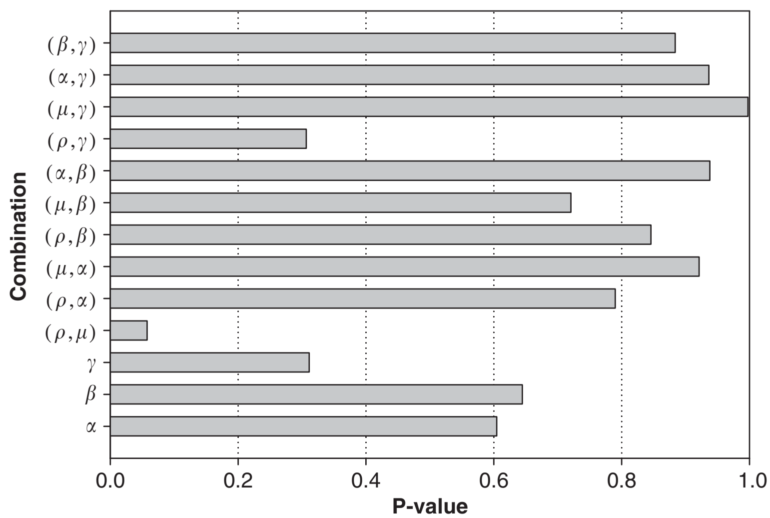

Figure 9. *P*-values associated with the MDR response using different factor combinations.

other two hysteretic parameters. Based on this conclusion, the effect of the β parameter was neglected in the studies presented in this paper.

On the other hand, Figure 8 shows that the *P*-values corresponding to the interaction between the frame period ratio ρ and each of the hysteretic parameters α and γ is relatively small, while the *P*-values associated with the frame ductility ratio μ were relatively large. This indicates that the interaction between the frame ductility ratio and the hysteretic shape of the SMA restrainers has a minor effect on the hinge opening response and the frame drift response, hence, the only interactions considered in the sensitivity analysis were the ones involving the period ratio, ρ.

Sensitivity analysis

Based on the results presented in the previous subsection, the bridge frames ductility ratio μ were assumed to be constant in this study and equal to 1.0, which represents the elastic case. The sensitivity study was performed in two paths. The first path focused on studying the effect of variability in the SMA initial strain hardening ratio α, while the second path focused on the SMA secondary strain hardening ratio γ. The hysteretic height of the SMA restrainers was assumed to be constant throughout the study and thus the parameter β was assumed to be equal to 0.4. Twenty ground motion records with various characteristics were used in the study. The records were scaled such that the record's spectral acceleration value at the fundamental period of the structure would be equal to 0.8 g. The fundamental period of the structure was assumed to be constant and was equal to 1.0 s.

Results of the sensitivity analysis

Effect of initial strain hardening ratio (α). In order to study the effect of variability in the initial strain hardening ratio α on the MHDR and MDR responses the secondary strain hardening ratio γ was assumed to be constant and equal to 0.7. The effect of interaction between the frames period ratio and the hysteretic parameter α is illustrated through the 3-D plots presented in Figures 10 and 11. In those figures, the vertical axis represents the studied response, while the two horizontal axes represent the two parameters, α and ρ. Each of the 3-D plots presents the mean response of the suite of records that was used in the analyses.

Figure 10 shows that increasing the initial strain hardening ratio α reduces the maximum hinge opening by approximately 5–10% depending on the period ratio of the two frames. However, at extremely high period ratios where ρ was equal to 0.9, the parameter α seems to have a negligible effect on the response of the hinge opening. This is due to the fact that at high period ratios the frames tend to move in phase rather than out of phase resulting in a relatively small hinge opening. This would cause the SMA restrainers to remain elastic and thus the parameter α would be insignificant.

Figure 11 shows a trend that is mostly opposite to the trend that was observed earlier in Figure 10 where the maximum frame drifts increase whenever the maximum hinge opening is reduced. This was expected since limiting the relative displacement between the two frames requires introducing additional force to join the two frames. This force is introduced through the use of restrainers. Whenever the restrainer force is increased and in order to maintain equilibrium at the hinge, a large force has to be transferred to the bridge frames increasing the frame drifts. The figure shows a slight increase of approximately 1–4% in the maximum drifts with an increase in parameter α. However, at large period ratios the frame drifts are almost unaffected by the parameter α.

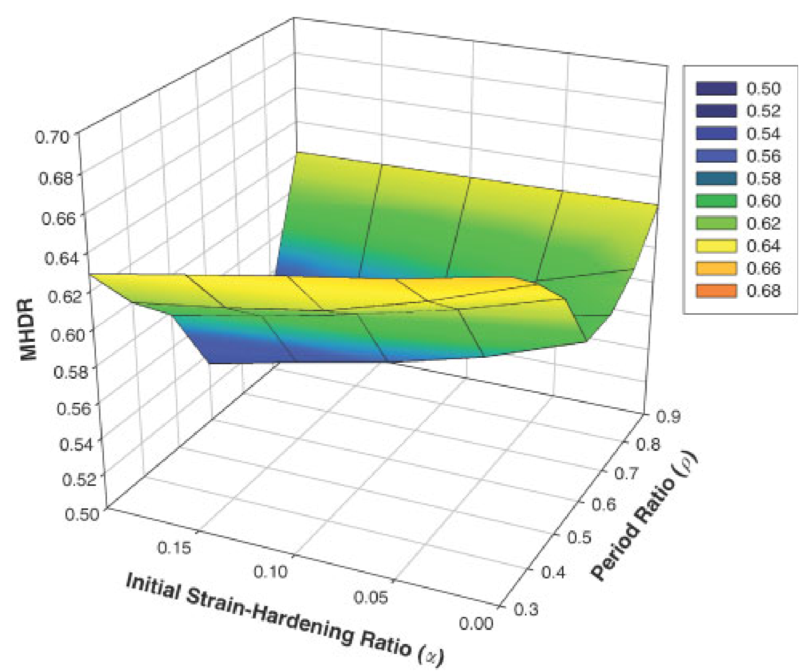

Figure 10. Mean MHDR response at various α and ρ values.

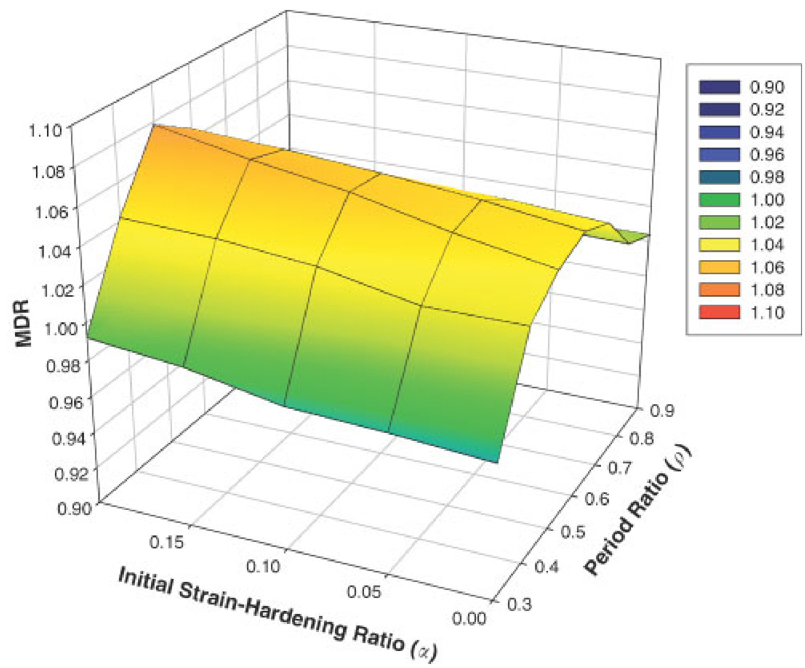

Figure 11. Mean MDR response at various α and ρ values.

Based on Figures 10 and 11 it could be observed that the initial strain ratio has a higher effect on the hinge opening value compared to the frame drifts. Thus, an increase in the initial strain ratio of the SMA restrainers would reduce the hinge opening with approximately no increase in the ductility demands of the bridge frames.

Effect of secondary strain hardening ratio (γ). In this case, the α parameter was assumed to be constant and was taken equal to 0.05. The effect of interaction between the two studied parameters ρ and γ is represented in a 3-D format in Figures 12 and 13, which represent the mean values of the MHDR and MDR responses, respectively. The MHDR results shown in Figure 12 indicate that for most of the period ratio values a reduction is observed in the hinge opening response when SMA restrainers with larger secondary strain hardening ratio were used. The amount of reduction in the hinge opening varied depending on the ρ values. However, a maximum average reduction of approximately 10% was observed at ρ equal to 0.5. At large values of ρ, the γ parameter seems to have no effect on the MHDR results. This was expected due to the relatively small hinge opening values experienced by the bridge due to the highly in-phase motion of the two frames. At such small hinge opening the SMA restrainers do not experience a phase transformation. Even when the phase transformation was initiated in some cases, there is a large probability that it would not be completed, i.e. the martensite would not reach its elastic range.

On the other hand, the MDR results in Figure 13 varied between 0.92 and 1.04, which means that retrofitting the bridge with the SMA restrainers might cause an increase in the ductility demand of the frames in some cases. From the figure it is noticed that such behaviour is mostly

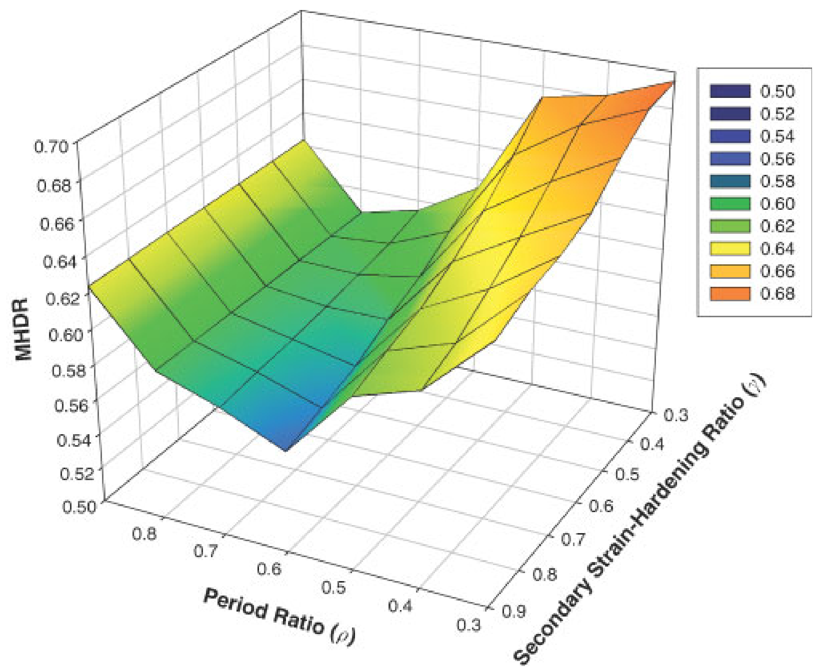

Figure 12. Mean MHDR response at various γ and ρ values.

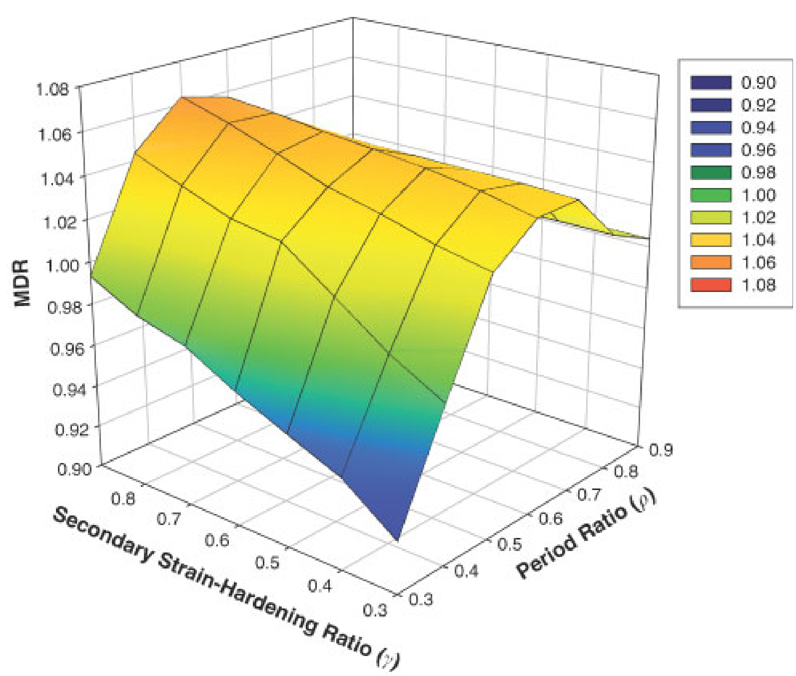

Figure 13. Mean MDR response at various γ and ρ values.

expected at moderate period ratios. A general trend was observed in the figure whenever the γ parameter increases, the MDR response increases as well. The average increase in the MDR response was approximately 4%. However, at large period ratios the drift values seem to be unaffected by the SMA secondary strain hardening ratio. This is due to the incomplete phase transformation that the SMA restrainers go through. Since the hysteretic properties showed an insignificant impact on the frame drift, the drift results will not be considered in the case study presented in the following section.

CASE STUDIES ON BRIDGES

This section presents two case studies using the same bridge and SMA models that were used in the sensitivity analysis. The main objective behind the case study is to verify the results obtained from the sensitivity study and get a closer look at the sensitivity of the hinge opening to each of the hysteretic parameters that were considered in the sensitivity study. The first case study focuses on assessing the effect of SMAs hysteretic height while the second case study assesses the effect of the hysteretic slope.

Effect of hysteretic height

In this study the frames period ratio ρ and ductility demand ratio μ were assumed to be constant and equal to 0.7 and 1.0, respectively. The strain hardening ratios represented by the parameters α and γ were assumed to be constant as well and equal to 0.0 and 0.9, respectively. Two types of SMA restrainers with two hysteretic heights were considered in the study. The β values corresponding to the two types of restrainers were 0.1 which represents a SMA with a thick hysteresis and 0.9 which represents a SMA with a narrow hysteresis. The bridge model was subjected to several ground motion records with various characteristics. Since the outcome results and patterns were quiet similar, the results of the WAHO record from the 1989 Loma Prieta earthquake was selected and presented in this section. The record was applied after being scaled to a 0.85 g spectral acceleration at the fundamental period of the structure.

Figure 14 presents a comparison between the hinge opening time histories in the case of using the two types of SMA restrainers. As shown in the figure, the hinge opening responses in the two cases are in a good agreement. The maximum hinge opening in the cases of both restrainer types was approximately 84 mm which corresponds to 7.8% strain in the restrainers. The similarity in the effect of both types of restrainers on the hinge opening response is also demonstrated in Figure 15 which presents the force–displacement relationship of the two restrainer types. The figure shows a significant difference in the hysteretic energy dissipated in each case. The amount of hysteretic energy dissipated in the case of the restrainers with narrow hysteresis was approximately 13.4% of that which was dissipated by the wider hysteresis. Despite this large difference, the figure shows that the maximum displacement, which represents the maximum hinge opening was not affected. This behaviour shows that the hinge opening problem in bridges is primarily a recentring problem rather than a problem of energy dissipation.

Effect of hysteretic slope

This study was focused on investigating the effect of variability in the SMAs hysteretic slope on their effectiveness as seismic restrainers for bridges. Shape memory alloy restrainers with two

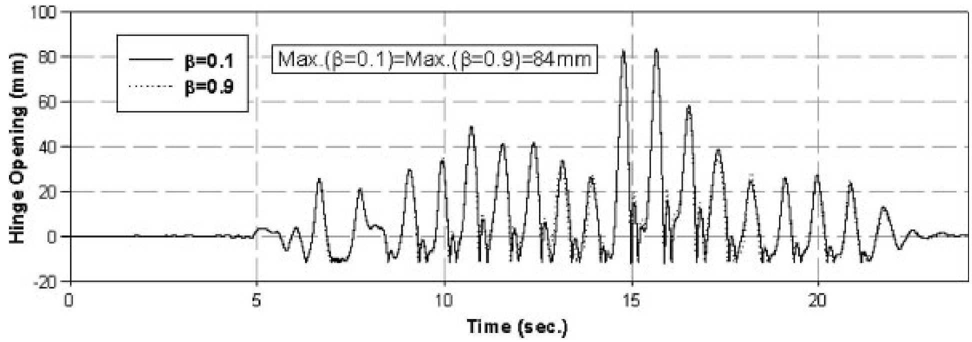

Figure 14. Comparison between the time histories of the hinge opening when using SMA hysteresis with thick hysteresis ($\beta = 0.1$) and narrow hysteresis ($\beta = 0.9$) under the scaled 1989 Loma Prieta, WAHO record.

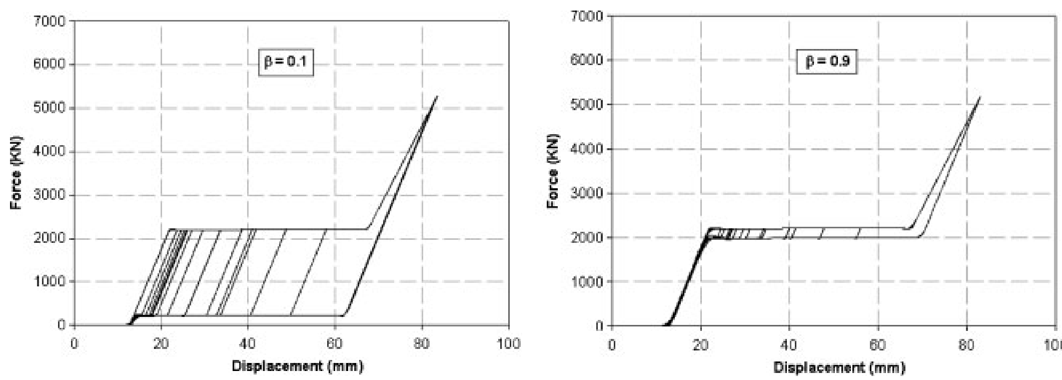

Figure 15. Force–displacement relationships for the two SMA restrainers with different hysteresis height under the scaled 1989 Loma Prieta, WAHO record.

different hysteretic shapes were implemented at the hinge of the bridge model. Figure 16 shows a schematic of the stress–strain relationship of the two shapes considered for the SMA hysteresis. As shown in the figure, Shape A represents the family of SMAs that is characterized by a flat plateau and a steep martensitic strain hardening, while Shape B represents SMAs with relatively steep plateau and a moderate martensitic strain hardening. The initial stiffness and the transformation force of the two SMA restrainer types were assumed to be identical. The strain hardening during phase transformation was assumed to be 1 and 10% for Shapes A and B, respectively, while the martensitic strain hardening was taken as 80 and 40% in the cases of Shape A and Shape B, respectively. Both shapes were assumed to have identical hysteretic height, where the unloading stress was assumed to be half of the transformation stress. The bridge properties and ground motion record used in this study were identical with the ones used in the case study presented in the previous section.

Figure 17 presents a comparison between the hinge opening time histories using SMA restrainers with Shapes A and B under the scaled WAHO record from the 1989 Loma Prieta earthquake. The two time histories were in a good agreement for most of the record. The

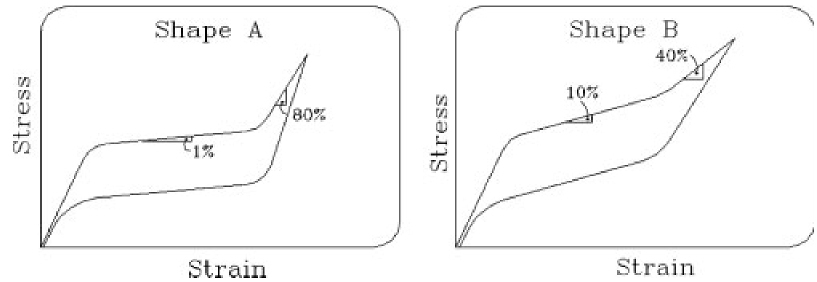

Figure 16. Schematic of the stress–strain relationships of the two SMA restrainer types used in the case study.

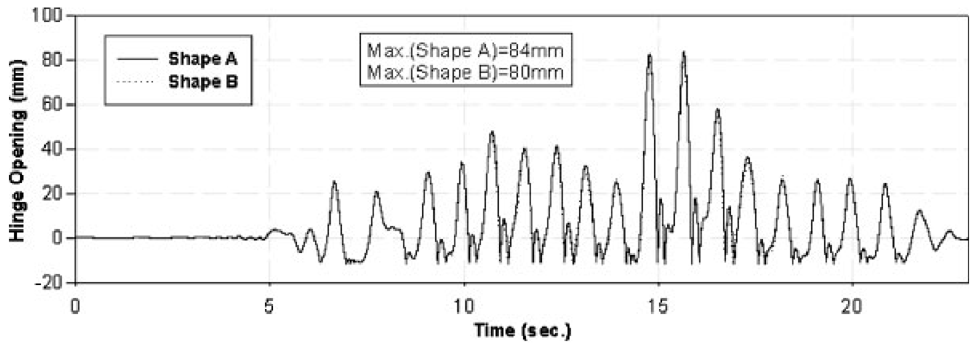

Figure 17. Comparison between the time histories of the hinge opening when using SMA hysteresis with different shapes (slopes) under the scaled 1989 Loma Prieta, WAHO record.

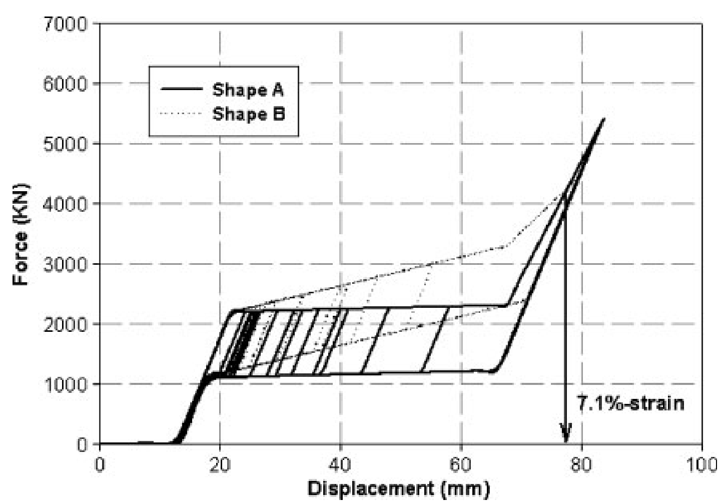

Figure 18. Force–displacement relationships for the two SMA restrainers with different hysteretic shapes (slopes) under the scaled 1989 Loma Prieta, WAHO record.

maximum hinge opening in the case of Shape A was 84 mm, while in the case of Shape B it was 80 mm. This 5% difference in the maximum hinge opening between the two cases lies within the range that was observed earlier in the sensitivity study. To get a better understanding on the behaviour of the restrainers in each case, the force–displacement relationships for both SMA restrainers are presented in Figure 18. As shown in the figure, SMA restrainers with Shape B were slightly more efficient in reducing the maximum hinge opening. This is due to two primary reasons. The first reason is the fact that most of the cycles occurred in the region of the martensitic transformation and before reaching the martensitic strain hardening level. In this region, Shape B has more stiffness compared to Shape A. The second is associated to the level of the force transmitted to the bridge through the restrainers. As illustrated in the figure, although both restrainers had different hysteretic shape they reached the same level of force at a hinge opening of approximately 78 mm which corresponds to a strain in the restrainers equal to 7.1% and a force equal to 4250 kN. The two types had the same effective stiffness at 7.1%-strain. This played an important role in producing close results in both cases.

CASE STUDIES ON BUILDINGS

In order to expand the investigation to other SMA structural applications, two case studies are presented in this section to briefly explore the effect of variability in the SMAs hysteretic behaviour on their performance as structural bracings for buildings. A single degree of freedom (SDOF) system representing a one-storey shear frame with SMA cross-bracings was used in the study. Figure 19 presents a schematic of the braced frame and the SDOF model which represent the focus of this study. The weight of the beam was assumed to be approximately 90 kN. The natural period of the unbraced frame was assumed to be 0.5 s. The frame was assumed to remain elastic during the analysis. Two identical superelastic SMA cables were used as cross-bracings for the analysed frame. The initial stiffness and yield strength of the SMA bracings were chosen to be 17.5 kN/mm and 31.5 kN. These values were selected such that when the frame is subjected to the WAHO record from the 1989 Loma Prieta earthquake the maximum drift of the frame would reduce by approximately 60% when the bracings are used compared to the case with no bracings.

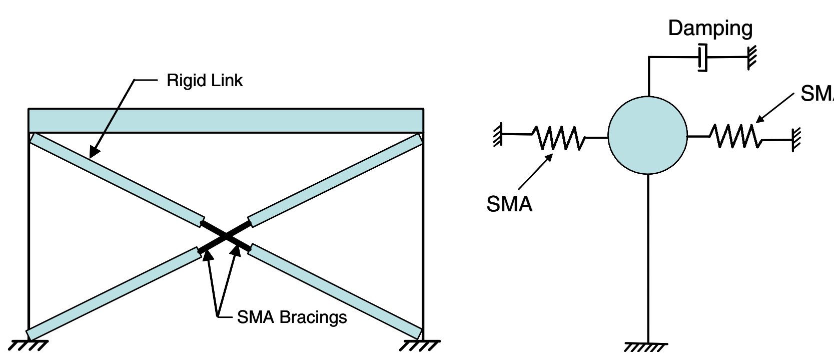

Figure 19. Schematic of the braced frame and the SDOF model used in the case studies.

Effect of hysteretic height

In this study, two types of SMA bracings with different hysteretic height were analysed and compared. The first type represents the SMAs with thick hysteresis ($\beta = 0.1$), while the second type represents SMAs with narrow hysteresis ($\beta = 0.9$). The slope of the hysteresis in both types was assumed to be constant ($\alpha = 0$ and $\gamma = 0.9$). Figure 20 presents a comparison between the lateral drift time histories of the frame when using both types of SMA bracings. The force–deformation relationship of the SMA bracings in both cases is also presented in Figure 21. As demonstrated by the figures, the SMA bracings with thick hysteresis were more efficient in reducing the maximum drift compared to the SMA bracings with narrow hysteresis. The difference in the maximum drift in both cases was approximately 12%. The damping capability of the SMAs with thick hysteresis played an important role in controlling the frame drift. This is illustrated by the fact that the frame came to rest more rapidly in the case of SMA bracings with thick hysteresis. This behaviour was not observed in the case of applying SMAs as bridge restrainers since the main effectiveness if the restrainers lie in their recentring capability and not their damping capability. Thus the results presented in this study show that the SMA hysteretic height might have a significant effect on the structural response depending on the specific application.

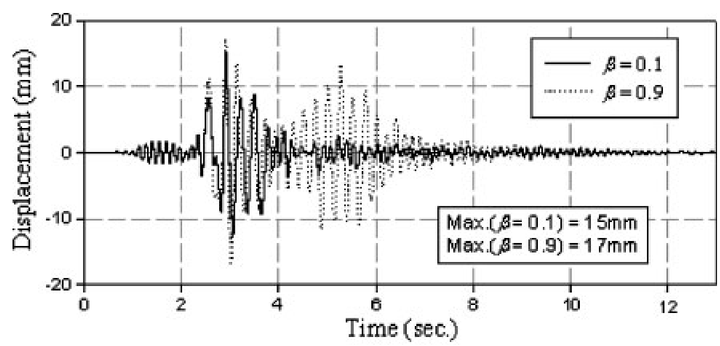

Figure 20. Comparison between the lateral frame drift time histories when using SMA hysteresis with thick hysteresis ($\beta = 0.1$) and narrow hysteresis ($\beta = 0.9$) under the 1989 Loma Prieta, WAHO record.

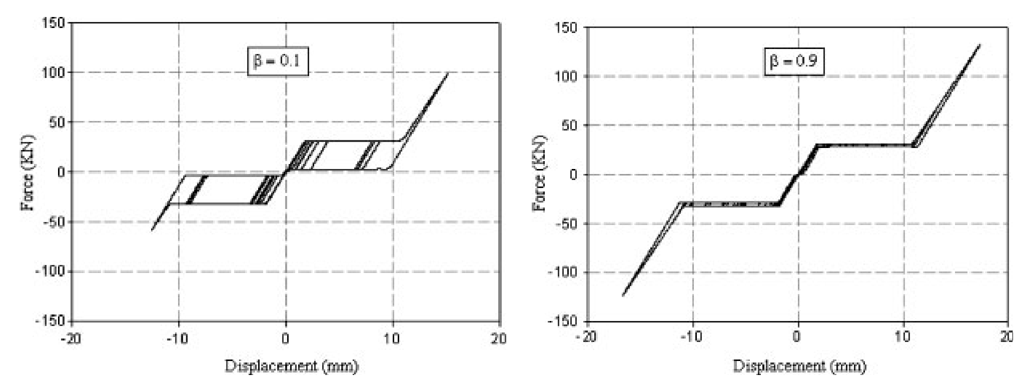

Figure 21. Force–displacement relationships for the two types of SMA bracings with different hysteresis height under the 1989 Loma Prieta, WAHO record.

Effect of hysteretic slope

Two types of SMA bracing were analysed and compared in this study. The two types of bracings had hysteretic properties which match the properties of Shape A and Shape B that were previously presented in Figure 16. Both shapes have identical hysteretic height ($\beta = 0.5$) and different hysteretic slopes. The braced frame was subjected to the WAHO record from the 1989 Loma Prieta earthquake and the results obtained for the drift time history are presented in Figure 22. The force–deformation responses of the two bracing types are also presented in Figure 23. The difference between the maximum drifts in both cases was less than 6%. This is typical with the range of results obtained in the case of using the SMAs as bridge restrainers.

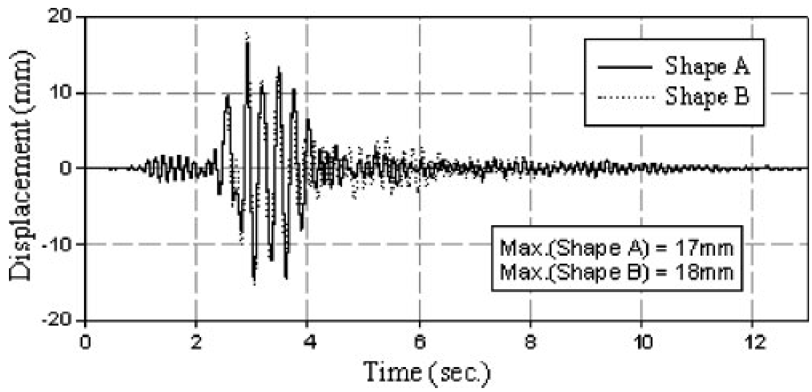

Figure 22. Comparison between the time histories of the lateral frame drift when using SMA hysteresis with different shapes (slopes) under the 1989 Loma Prieta, WAHO record.

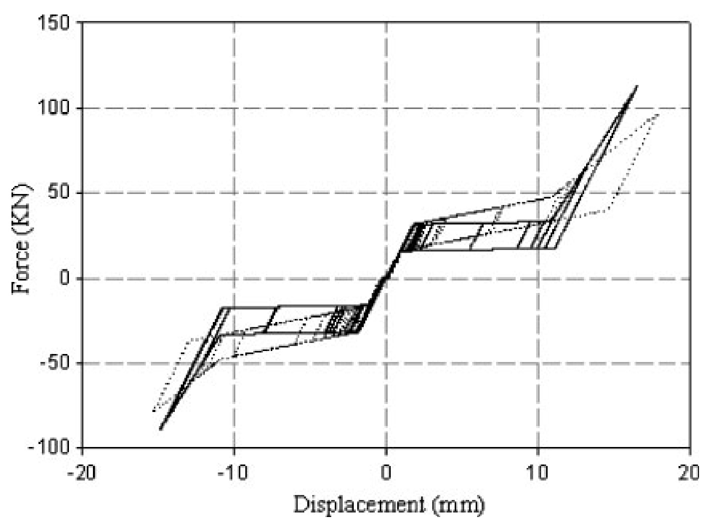

Figure 23. Force–displacement relationships for the two types of SMA bracings with different hysteretic shapes (slopes) under the 1989 Loma Prieta, WAHO record.

From Figure 23, it is noticed that the small difference in the responses of the frame in the two cases is possibly referred to the fact that at some point on the curve, both bracings reach the same level of force at the same level of strain, i.e. they have similar effective stiffness. This shows that the hysteretic slope in superelastic SMAs has similar effect on the structural response regardless of the type of SMA application.

CONCLUSIONS

The hysteretic properties of SMAs are known to be highly sensitive to factors such as the alloy's chemical composition, the manufacturing processing of the alloy, and the loading strain rate. The effect of variability in the SMAs hysteretic properties on the structural response need to be addressed before using them in structural applications. This paper is focused on exploring the effect of variability in SMAs hysteretic properties on their effectiveness as potential seismic restrainers for bridges and bracings for buildings. A sensitivity analysis and four case studies were conducted using a simplified 2-DOF bridge model, a SDOF frame model, and a one-dimensional tension-only SMA model. The superelastic SMA's hysteretic shape was assumed to be defined using three parameters, a parameter controlling the strain hardening during phase transformation, a parameter controlling the strain hardening beyond phase transformation and a parameter controlling the hysteresis height.

The results showed that the hysteretic height of the SMAs affects the structural response in a manner that depends on the type of application. In the case of using the SMAs as bridge restrainers, the hysteretic height had the least effect on the hinge opening value compared to other hysteretic parameters. This is due to the fact that the hinge opening problem is most affected by the recentring capability as opposed to the energy dissipation. However, when the same types of SMAs were examined as bracings for frames, their hysteretic height showed an impact on the frame drift, with differences as large as 12%. This illustrates the importance of the damping properties of SMAs when used as bracings elements in buildings.

On the other hand, the sensitivity study conducted on MF bridges showed that for the ranges considered for the strain hardening ratios (0–20% during phase transformation and 30–90% beyond phase transformation) the variability in the hinge opening value was below 10% in average. These results were also confirmed by a case study. The same result was observed when the SMAs were analysed as cross-bracings for frames. The case studies further showed that two SMA devices with various hysteretic slope would result in a close structural response should they have similar effective stiffness at a point beyond the completion of phase transformation. In general, this research has shown that superelastic SMAs are relatively stable in their effectiveness as bridge restrainers and bracing cables despite slight variations in the SMAs hysteretic properties which might be associated with the variability in the strain rate, the alloy composition, or the alloy's manufacturing process.

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