International Journal of Earth, Energy and Environmental Sciences
ISSN: 2517-942X
Vol:5, No:11, 2011

Analytical Prediction of Seismic Response of Steel Frames with Superelastic Shape Memory Alloy

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Abstract**—**Superelastic Shape Memory Alloy (SMA) is accepted when it used as connection in steel structures. The seismic behaviour of steel frames with SMA is being assessed in this study. Three eight-storey steel frames with different SMA systems are suggested, the first one of which is braced with diagonal bracing system, the second one is braced with nee bracing system while the last one is which the SMA is used as connection at the plastic hinge regions of beams. Nonlinear time history analyses of steel frames with SMA subjected to two different ground motion records have been performed using Seismostruct software. To evaluate the efficiency of suggested systems, the dynamic responses of the frames were compared. From the comparison results, it can be concluded that using SMA element is an effective way to improve the dynamic response of structures subjected to earthquake excitations. Implementing the SMA braces can lead to a reduction in residual roof displacement. The shape memory alloy is effective in reducing the maximum displacement at the frame top and it provides a large elastic deformation range. SMA connections are very effective in dissipating energy and reducing the total input energy of the whole frame under severe seismic ground motion. Using of the SMA connection system is more effective in controlling the reaction forces at the base frame than other bracing systems. Using SMA as bracing is more effective in reducing the displacements. The efficiency of SMA is dependant on the input wave motions and the construction system as well.

Keywords**—**Finite element analysis, seismic response, shapes memory alloy, steel frame, superelasticity

I. Introduction

DEVASTATION including permanent damage and failure of many buildings and structures have been caused by many earthquake events. Steel structures are mostly designed for safety conditions, where the earthquake energy is mainly dissipated through yielding of its inelastic deformation. Structures are allowed to undergo severe damage – this means saving lives at the expense of structures incurring excessive economic losses. Recently, the seismic design of structures has evolved towards a performance-based approach in which there is need for new structural members and systems that possess enhanced deformation capacity and ductility, higher damage tolerance, and recovered and/or reduced permanent deformations.

Under great earthquake ground motions, the flexibility of steel moment-resisting frames may result in great lateral drift induced nonstructural damage. In steel frames, the inter-story drift ratio should be limited in design due to the weak seismic performance to resist earthquake related to geometric nonlinearities and brittle failure of beam-to-column connections [1]-[3]. Therefore, the inter-story drift ratio should be limited in design, and hence larger bracing member sizes are required. [4]-[7]. Limited ductility and low energy dissipation capacity due to braces buckling is one of several reasons for the weak performance of steel braced frames.

The inelastic behavior of steel frames is strongly dependent on the behavior of connection members; so an alternative strategy can be pursued by using superelastic Shape Memory Alloy (SMA) in bracing and connection systems. By using supplemental energy dissipation capabilities of SMA materials, the displacement of the structure could be decreased. The objective of this paper is to study the effectiveness of different systems utilizing such materials in steel frames, as innovative seismic devices for the protection of buildings.

Shape Memory Alloy (SMA) is unique material that has the ability to undergo large deformation and return to a predetermined shape upon unloading or by heating. The distinct and unique properties of SMA have been used in a wide variety of applications in different fields and industries such as aviation, medical equipment and implants. SMA are gradually gaining recognition and finding new applications in various engineering fields.

Recently, utilizing SMA in civil engineering has been investigated analytically and expermently [8]-[11]. Various investigations have been carried out into use the SMA as bracings [12],[17],[20], beam connections [11],[23], anchorage systems [13], [14], restrainers [15], isolation devices [24], and energy dissipating devices [16], [25]-[26].

Although the number of analytical and experimental studies on the use of SMA in several components of steel structures, a comparison study to show how the best system to use SMA in steel structures has not been carried out. Thus, this paper presents a comparison study on the different systems of use SMA in steel frame structures. Eight story frame equipped with SMA with three different systems is presented. First system is to use SMA as diagonal bracings, second one is to use SMA as nee bracings and the last one is to use of superelastic SMA in the plastic hinge areas of beam-column joints. Nonlinear finite element analysis has been implemented to investigate and compare the performances of steel frame structures with SMA in different three systems under seismic loads. The finite element program (SeismoStruct 5.2.1, 2011 [27]) has been validated at the element level for steel frames. Dynamic time history analyses were performed for three

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frames to determine the characteristic differences in terms of top displacements, base shear force and total vertical reactions at frame base.

II. Superelasticity of SMA and its Modeling

One of the distinct properties that make SMA a smart material is its superelasticity. A superelastic SMA can restore its initial shape spontaneously, even from its inelastic range, upon unloading. Among various composites, Ni-Ti has been found to be the most appropriate SMA for structural applications because of its large recoverable strain, superelasticity and exceptionally good resistance to corrosion. In this study, SMA is mainly referred to Ni-Ti SMA (commonly known as Nitinol). When an SMA specimen is subjected to a cycle of axial deformation within its superelastic strain range, it dissipates a certain amount of energy without permanent deformation. This results from the phase transformation from austenite to martensite during loading and the reverse transformation during unloading ensuring a net release of energy. SMA with superelasticity has an advantage over other common metals alloys in the sense that besides dissipating a considerable amount of energy under repeated load cycles, it has a negligible residual strain. Since most civil engineering applications of shape memory alloys are related to the use of bars and wires, one-dimensional phenomenological models are often considered suitable. Several researchers have proposed uniaxial phenomenological models for SMA. The superelastic behaviour of SMA has been incorporated in a number of finite element packages, e.g. ANSYS 10.0 (2005), and Seismostruct (http://www.seismosoft.com/SeismoStruct/index.htm). Fig. 1 shows the 1D-superelastic model used in FE packages (SeismoStruct and ANSYS 2005) where shape memory alloy has been subjected to multiple stress cycles at a constant temperature and undergoes stress induced austenite-martensite transformation. The parameters used to define the material model are σ_f^{AS} (austenite to martensite starting stress); σ_f^{AS} (austenite to martensite finishing stress); σ_s^{SA} (martensite to austenite starting stress); σ_f^{EA} (martensite to austenite finishing stress); ε_L superelastic plateau strain length or maximum residual strain; and modulus of elasticity, E_{SMA}. The material properties are presented in Table I.

III. Characteristics and Modeling

An eight-storey steel frame has been selected in this study. The geometry of the building is shown in Fig. 2. Three different systems of using SMA in steel frames have been considered in this study. The first system is braced with diagonal bracings (Frame-1); the second system is a steel frame braced with nee bracings (Frame-2) while the last one is using shape memory alloy SMA as connection at plastic hinge region at the beam-column connection (Frame-3). The length of the plastic hinge of a typical beam (Paulay and Priestley 1992) is taken as 900 mm from the face of the column, while the SMA was taken as 20 mm bars.

Fig. 3 shows the steel material model used is uniaxial bilinear stress-strain model with kinematic strain hardening, whereby the elastic range remains constant throughout the various loading stages, and the kinematic hardening rule for the yield surface is assumed as a linear function of the increment of plastic strain. The model calibrating parameters to fully describe the mechanical characteristics of the material are: Modulus of elasticity *Es*, yield strength σ_y, strain hardening parameter μ which correspond the ratio between the post-yield stiffness (*Esp*) and the initial elastic stiffness (*Es*) of the material and finally the fracture strain ε_{ult} the strain at which fracture occurs. These steel parameter values are shown in Table II.

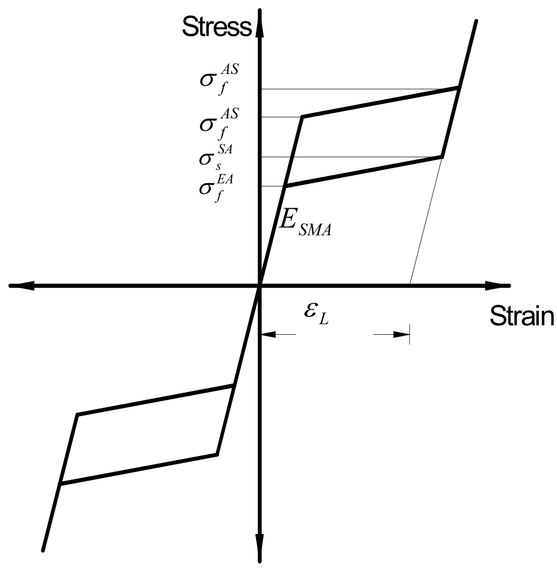

Fig. 1 Shape Memory Alloy Properties

TABLE I
SMA PROPERTIES

Parameter	Value
E_{SMA}	27579 MPa
σ_f^{EA}	414 MPa
σ_s^{SA}	550 MPa
σ_s^{AS}	390 MPa
σ_f^{AS}	200 MPa
ε_L	3.5%

International Journal of Earth, Energy and Environmental Sciences
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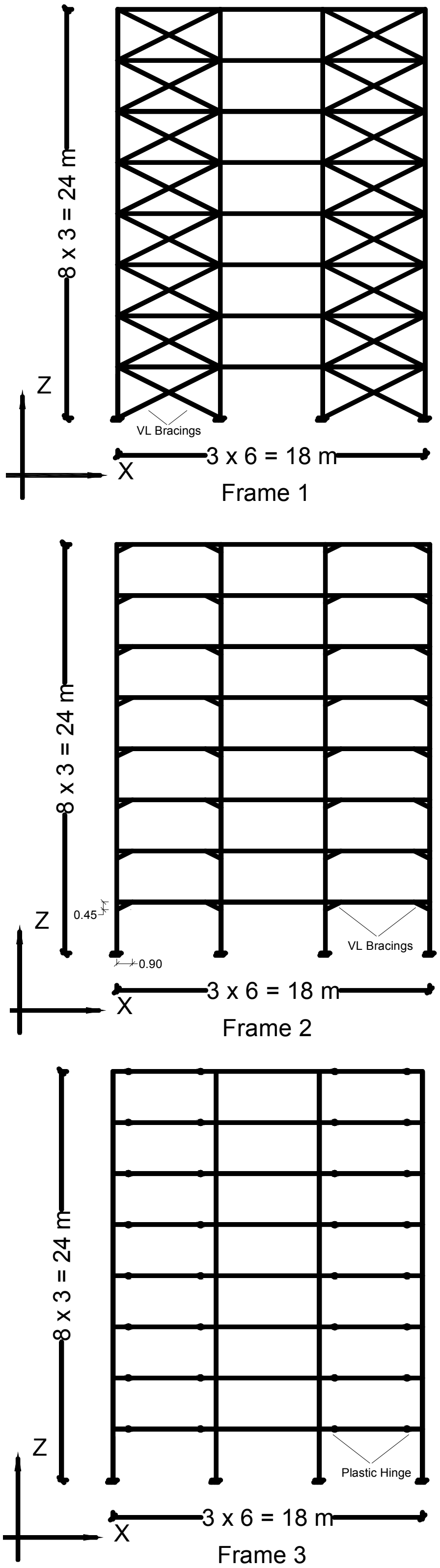


Fig. 2 Frame Geometry with Three Cases

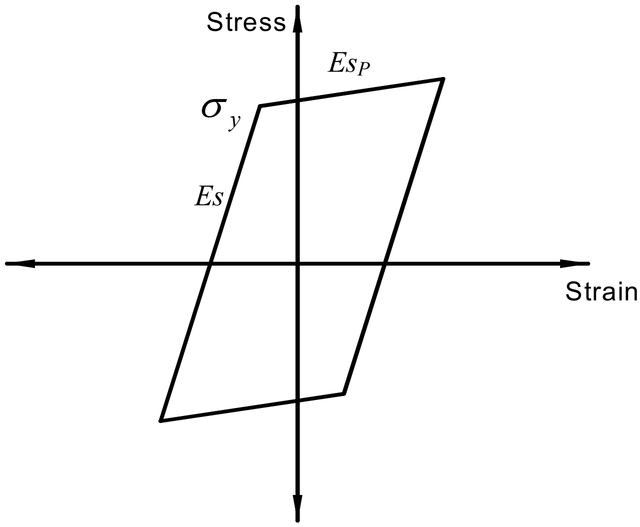


Fig. 3 Steel Model

TABLE II
STEEL PROPERTIES

Parameter	Value
E_S	200 GPa
σ_y	500 MPa
μ	0.005
ε_{ult}	0.06

IV. Selection of Earthquake Ground Motion

Following the 1995 Hyogoken Nanbu earthquake, Japan Society of Civil Engineers issued "Proposal on Earthquake Resistance for Civil Engineering Structures". According to the proposal, two types of earthquake ground motions should be taken into account in earthquake resistant design of the structures. One of the most important decisions in carrying out proper is to select a design earthquake that adequately represents the ground motion expected at a particular site and in particular the motion that would drive the frame structure to its critical response, resulting in the highest damage potential. A wide range of peak ground accelerations, frequency contents and energy or duration for the records, vertical ground motion; and near source ground motion is potentially important to frame facilities design.

A suite of recorded and simulated standard ground motion records are used for the nonlinear time history analysis: Two near-fault ground motion records obtained during the 1995 Hyogoken-Nanbu earthquake (M7.2) and the 1994 Northridge Earthquake (M6.7), including three-components acceleration time histories recorded at JR Takatori and Sylmar-Converter STA. The calculated responses for different records are compared. The horizontal and the vertical accelerations of ground motions for improved analysis are given in Figs. 4 and 5. The ground motion measured at JR Takatori has maximum acceleration of its components equal to 642 gal (N-S), 666 gal

(E-W) and 290 gal (U-D) while ground motion measured at Sylmar Converter STA has maximum acceleration of its components equal to 593 gal (N-S), 827 gal (E-W) and 532 gal (U-D). The earthquake force of E-W wave is put into the frame axis direction (out-plane), and N-S wave to the right angle to the frame axis (in-plane).

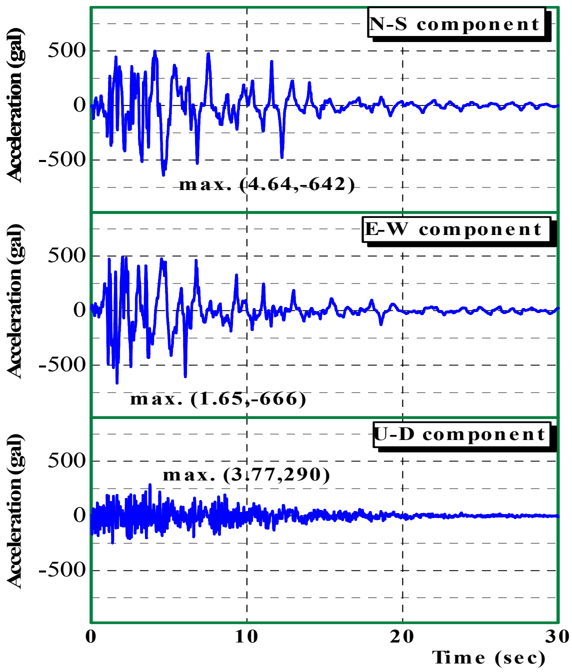


Fig. 4 Strong ground motion measured at JR Takatori

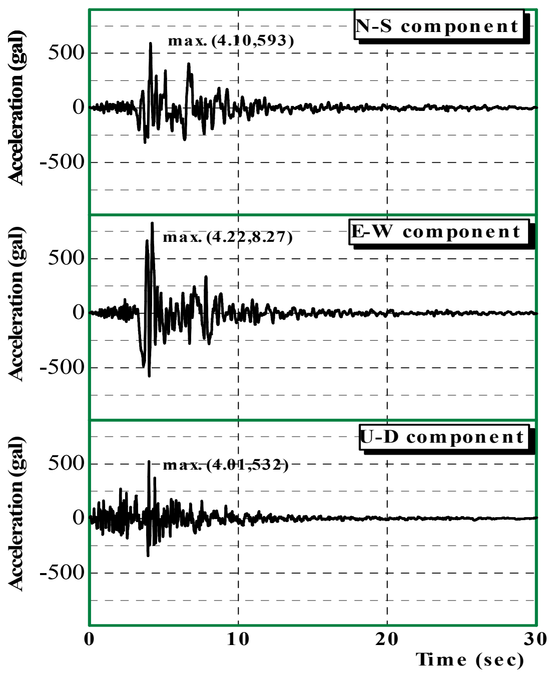


Fig. 5 Ground motion measured at Sylmar STA

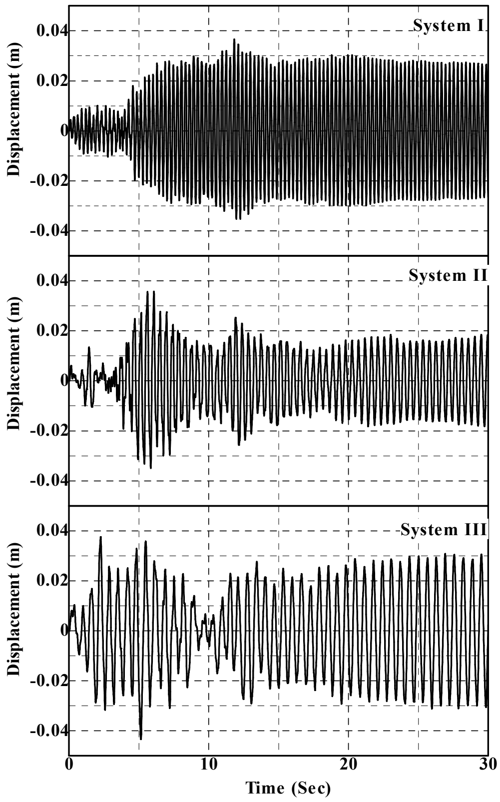
V. Results and Discussion

In order to study in detail the dynamic behavior of steel frames with SMA systems, nonlinear time history analyses were performed. All the frame models were analyzed as two-dimensional (2D) models. Eight story frame equipped with SMA with three different systems is presented. Nonlinear finite element analysis has been implemented to investigate and compare the performances of steel frame structures with SMA in different three systems under seismic loads. The finite element program (SeismoStruct) has been validated at the element level for steel frames. The following three different systems of steel frame with SMA are analyzed:

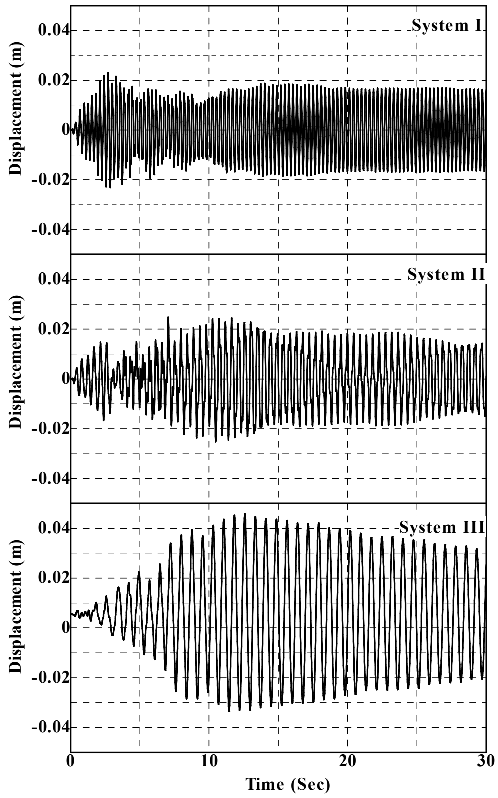
System I: the frame is braced with diagonal bracings,
System II: the frame is braced with nee bracings,
System III: the frame is using SMA as connections at the plastic hinge regions of beams.

The input ground motion characteristic has a great influence on the seismic response of the structure. To check the volubility of the proposed three different systems with the shape memory alloy material. Two different input ground motion has been used to affect on the frame. Fig. 6 shows the response history of the displacement at the frame top subjected to the Hyogoken-Nanbu ground motion record and Sylmar station input motions. The displacement at top of the frame can result in collapse of the building if it exceeds the allowable displacement. The use of the SMA as nee bracing system can provide more effective in order to limit the frame top displacement than that one used as diagonal bracings. The SMA bracing can be designed to provide sufficient stiffness and damping to limit the frame top displacement below a re-determined value. The nee bracing system, system II, is more effective in reducing the displacement at frame top than that of SMA connection at plastic hinge. In case of using Taktori input wave, the maximum displacement of approximately 3.5 cm occurs in the braced frame while it reaches 4.5 cm in case of use SMA at plastic hinge connection. In case of using Sylamr input wave, the maximum displacement of approximately 2.2 cm occurs in the braced frame while it reaches 4.5 cm in case of use SMA at plastic hinge connection. The use of SMA as nee bracing for the frame reduces the maximum displacement to a reduction around 50 % than that of plastic hinge connection system.

It can be observed that the frame top acceleration and displacement responses are significantly affected according to the chosen system. The frame seismic response in case system III has longer natural vibration, Fig. 7, with significantly high amplitude displacement and low accelerations. Inserting shape memory alloy as nee bracing system as in case system II is more affect than that of system III where the SMAs are inserted at plastic regions of the beams. Though, the System III has a longer natural period that lead to more efficiency in dissipating energy of the input seismic waves than that of bracing systems.

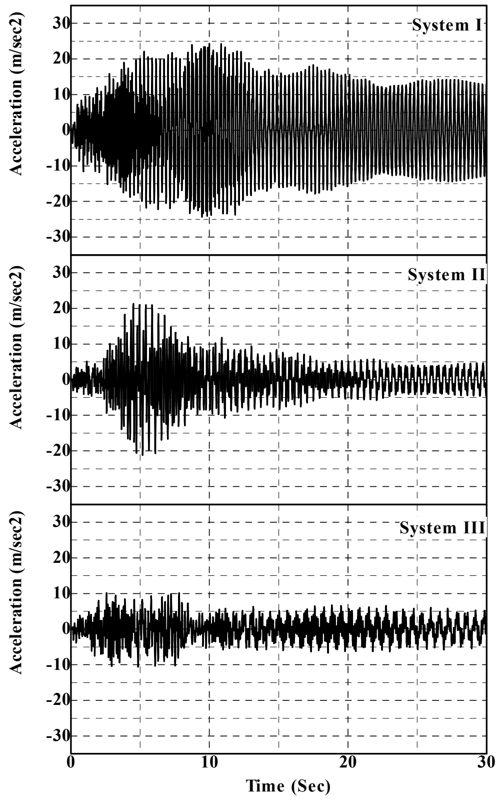


(a) Takatori input wave

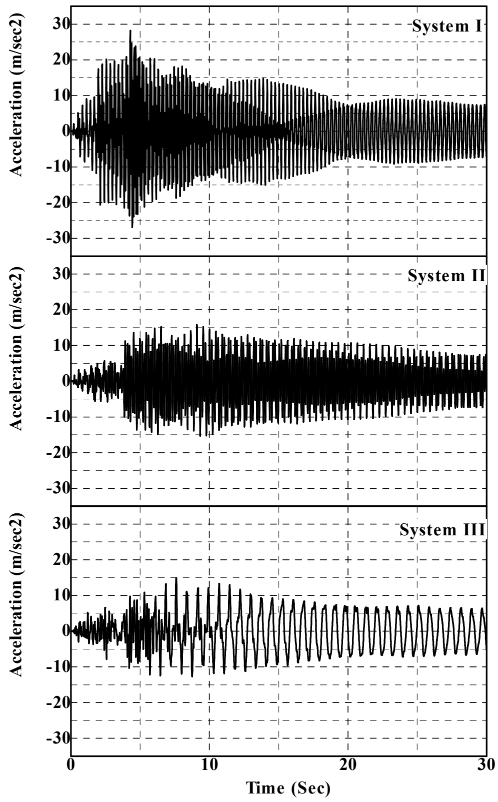


(b) Sylmar input wave

Fig. 6 Displacement time history at frame top



(a) Takatori input wave

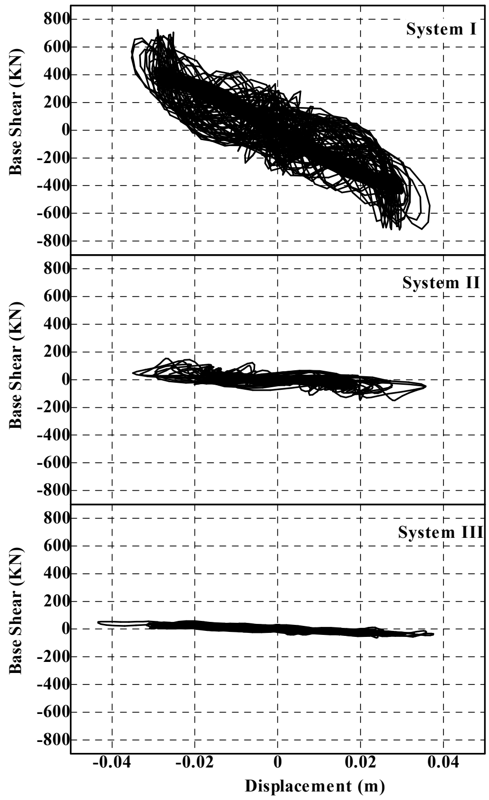


(b) Sylmar input wave

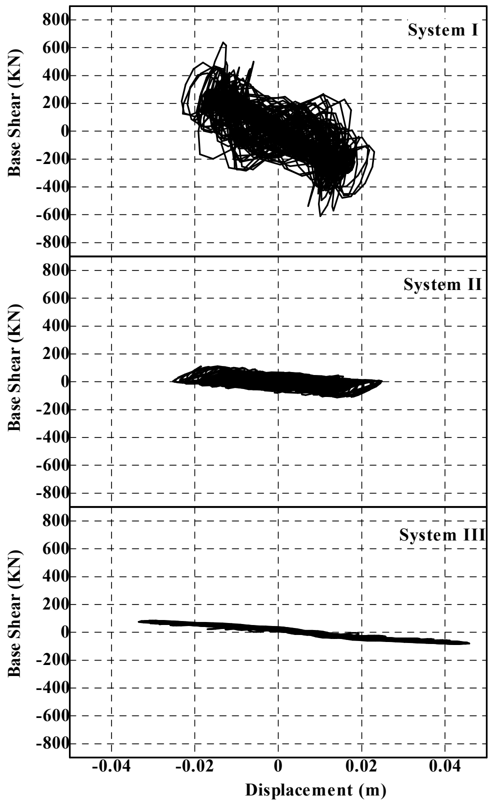
Fig. 7 Accelerationt time history at frame top

There are many reasons for the effectiveness of the SMA connections compared to the steel connections. First, since the SMA connections are superelastic, they have the ability to maintain their effective stiffness for repeated cycles. Reviewing the response history plot, it is observed that the SMA bracings are effective in limiting the displacement. When Takatori station input wave was used, the maximum base shear and the displacement, Fig. 8, were predicted as 680 kN and 38 mm in the first system and 170 KN and 36 mm in the second system that compared to third system values of 77 kN and 43 mm. whereas the Sylmer input wave was used, the maximum base shear and the displacement, were predicted as 600 kN and 22 mm in the first system and 100 KN and 25 mm in the second system that compared to third system values of 70 kN and 50 mm. The results show more advantages of the third case in reducing the base shear, though the displacement of third system is still more than that of the other cases. The total difference of third case displacement is little which present less than 5 % and can be neglected. The cumulative energy dissipation is more in the third system that use SMA as connection at plastic hinge regions.

By comparing the reaction force and time histories at the frame base for three cases, Fig. 9, it is observed that the third system when SMA used at plastic hinge region provides pronounced reduction in the reaction force responses compared to that for braces frame systems. This may be attributed to the larger amount of energy which absorbed at the SMA put at the plastic hinge regions. When Takatori Station input wave is used, the vertical base force reaches around 599 KN for the first system and reaches around 226 KN for the second system while it reaches 197.5 KN for the last third system. Using of shape memory alloy as nee bracing system leads to a reduction in the amount of vertical force at frame base by 62% of that when shape memory alloy is used as braced system. Also, there is a reduction of the about of vertical force at frame base of around 67% when shape memory alloy is used as connection in the plastic hinge region than that braced frame system. When Sylmar Station input wave is used, the vertical base force reaches around 599.5 KN for the first system and reaches around 225.7 KN for the second system while it reaches 207 KN for the last third system. Using of shape memory alloy as nee bracing system leads to a reduction in the amount of vertical force at frame base by 60% of that when shape memory alloy is used as braced system. Also, there is a reduction of the about of vertical force at frame base of around 63% when shape memory alloy is used as connection in the plastic hinge region than that braced frame system. Hence using of the shape memory alloy as connections is more effective in controlling the reaction force at the frame and stresses as well than that using shape memory alloy as bracing. On the other hand the need bracing system reduces the vertical force effectively compared with diagonal bracing.

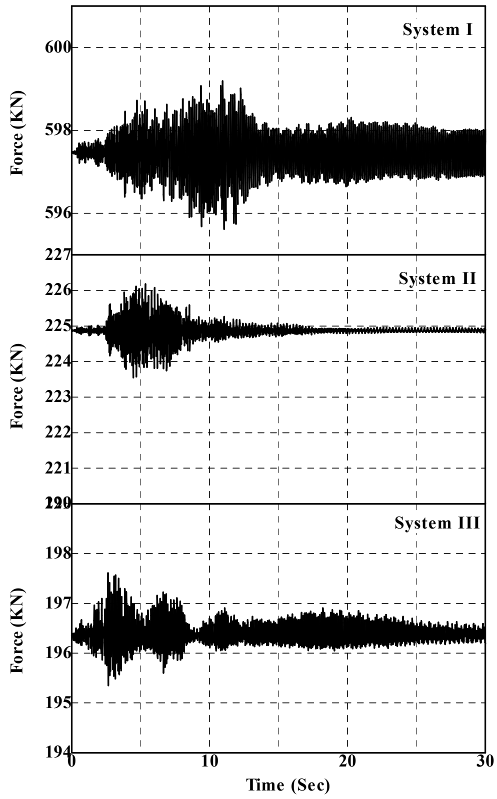


(a) Takatori input wave

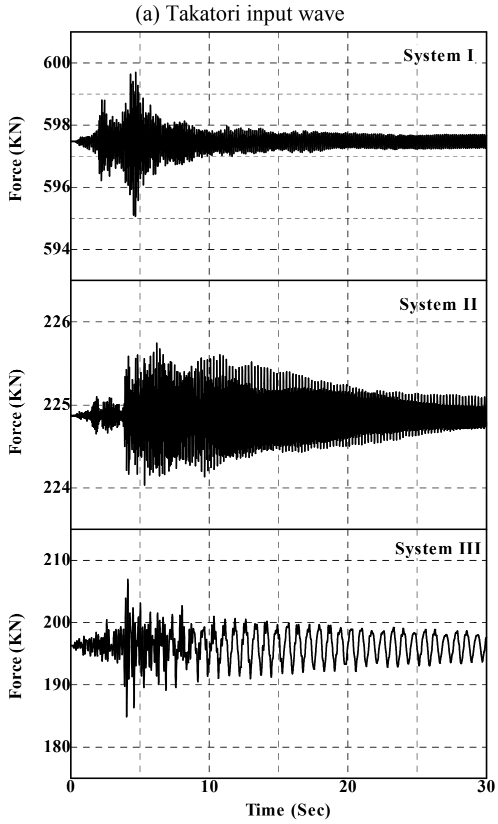


(b) Sylmar input wave

Fig. 8 Base Shear versus Displacement

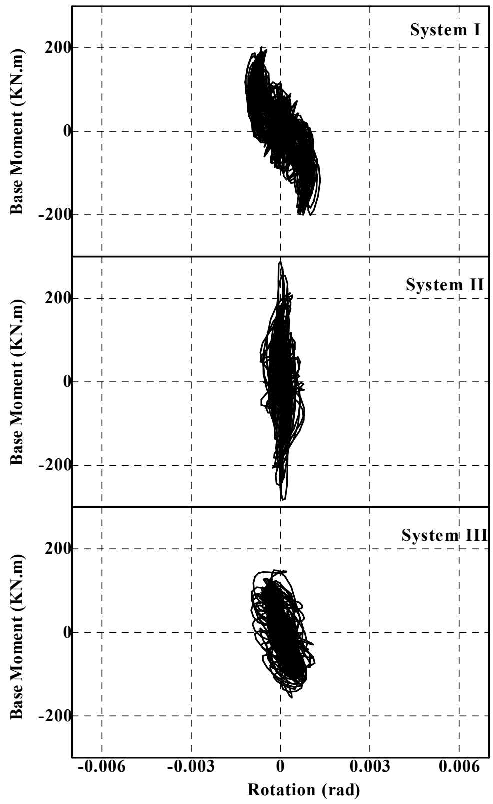


(a) Takatori input wave

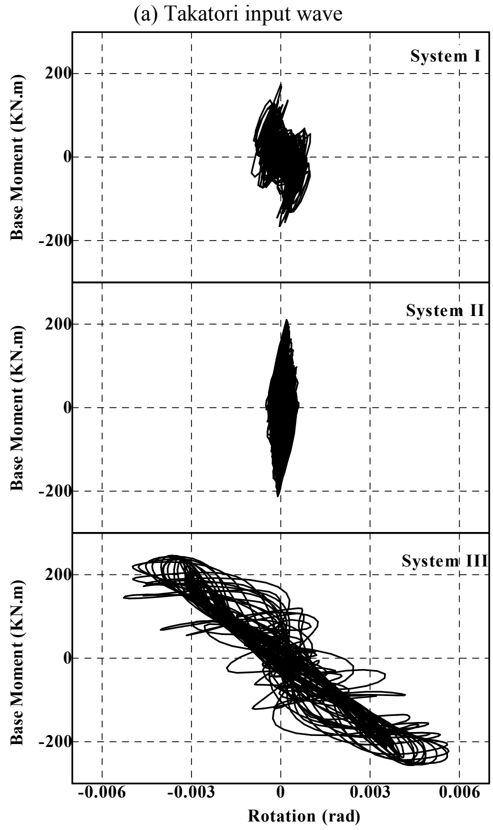


(b) Sylmar input wave

Fig. 9 Vertical force time history at tower base



(a) Takatori input wave



(b) Sylmar input wave

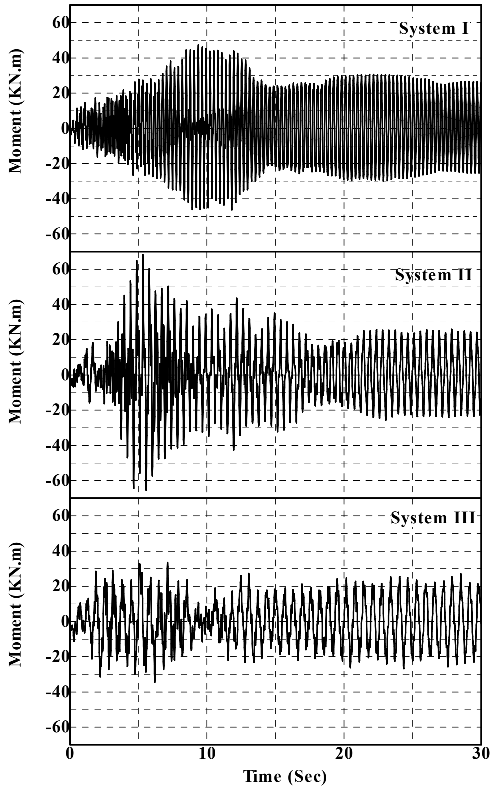
Fig. 10 Moment versus Rotation

The moment versus rotation is plotted as shown in Fig. 10. It is observed that in case of using Takatori input wave, there is a slight change in the moment and rotation between all three different systems. The moment in the two braced systems is around 200 KN.m. while it reached about 170 KN.m. in the third system. On the other hand, when Sylmar Station input wave was used, there is a significant increase in rotation at the third system compared to that other two braced systems. The moment in the first two braced system is around 200 KN.m. and the rotation is around 0.001 rad. For the third system where the SMA is put at the plastic hinge, the rotation reached 0.058 rad with a 250 KN.m. of maximum moment. It can be concluded that the second system of nee bracing is more effective in reducing the moment and rotation more than that using SMA as connection where the rotation is highly increase with a slight different in the moment compared to braced systems.

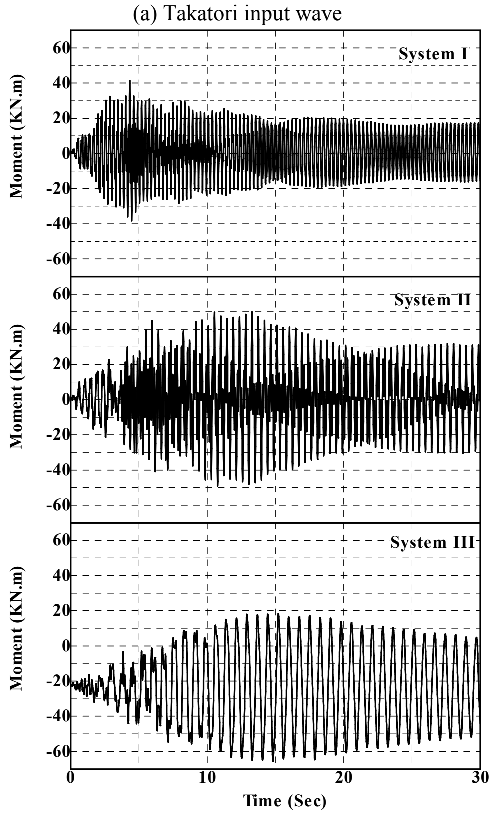
The moment time history at the frame base, Fig. 11, is compared between the three different systems. In case of using Taka input wave, the better performance of the proposed system is that when SMA is used as connection in the plastic hinge. There is a reduction of the moment amplitude at frame base around 70 % of the first system of bracing SMA while about 50% of that system II as nee bracings. Whereas the Sylmar wave is used, the reduction of moment occur in the first system compared to the two other systems II and III. It is obviously the increasing of moment at the system III in the opposite direction. Hence, the amount of moment at frame base is mainly affected by the input ground motion rather than the construction system.

VI. Conclusions

In this paper, a numerical parametric study of the steel frames with SMA has been conducted to investigate the efficiency of the different shape memory alloy systems in order to determine the best way to use SMA at steel frames to enhance its seismic behavior. Eight story frame equipped with SMA with three different systems, first system is use SMA as diagonal bracings, second one is to use SMA as nee bracings and the last one is to use of superelastic SMA at the plastic hinge areas of beam-column joints. Dynamic time history analyses were performed for three types of frames to determine the characteristic differences in terms of top displacements, base shear force and total vertical reactions at frame base. The results of this comparative study showed that using of SMA as connections at plastic hinge regions is more effective than that use of SMA as bracings. Shape memory alloy at plastic hinge is more effectively reduced maximum reactions while the bracing systems are more effective in reducting the displacement at the frame top. Further works still are necessary to compare the other SMA systems used in structures.



(a) Takatori input wave



(b) Sylmar input wave

Fig. 11 Moment time history at frame base

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