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Seismic Response of Braced Steel Frames with Shape Memory Alloy and Mega Bracing Systems

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***Abstract*—**Steel bracing members are widely used in steel structures to reduce lateral displacement and dissipate energy during earthquake motions. Concentric steel bracing provide an excellent approach for strengthening and stiffening steel buildings. Using these braces the designer can hardly adjust the stiffness together with ductility as needed because of buckling of braces in compression. In this study the use of SMA bracing and steel bracing (Mega) utilized in steel frames are investigated. The effectiveness of these two systems in rehabilitating a mid-rise eight-storey steel frames were examined using time-history nonlinear analysis utilizing seismostruct software. Results show that both systems improve the strength and stiffness of the original structure but due to excellent behavior of SMA in nonlinear phase and under compressive forces this system shows much better performance than the rehabilitation system of Mega bracing.

***Keywords*—**Finite element analysis, seismic response, shapes memory alloy, steel frame, mega bracing.

I. INTRODUCTION

EARTHQUAKE events cause destructions including permanent damage and failure of many buildings. Steel structures are mostly designed for safety conditions, where the earthquake energy is mainly dissipated through yielding of their nonlinear 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 nonlinear 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 [8].

Innovative topics in structures subjected to sever earthquakes have been considered after studying the behaviors of these structures. In high seismic areas, braced steel frames are used to resist the lateral loads. High ductility, enhanced energy dissipations and symmetrical hysteric response in tension and compression are the main characteristics of braced systems.

The present study assesses the nonlinear seismic performance of braced steel frames with two different bracing systems. These include SMA braced steel frame system SMABS and mega-braced steel frame system MBS. Comprehensive nonlinear time-history analysis was carried out for analyzing the frames compared to unbraced frame. Two different input earthquake motions were selected and employed to perform nonlinear time-history analysis. The nonlinear seismic response has been demonstrated in terms of both frame top displacement and member deformations (rotations) parameters derived by means of nonlinear time history analyses.

II. STEEL BRACING

Braced system is considered as an effective system in enhancing the stiffness and strength of steel frames [1]-[7]. It can exhibit high lateral stiffness. The capacity of a steel frame can be greatly strength under moderate-to-large magnitude earthquakes by increasing the energy absorption of structures and decreasing the demand imposed by earthquake loads. On the other hand, the connections and foundations which need to be strengthened are affected by using braces. Also, changing of the original building architectural by using braces is not preferable.

Due to the high efficiency and economically, braced steel frame systems are widely used. Braced steel frame system is effective if the braces in linear stage. The asymmetrical response is developed when at the nonlinear stage starts whereas, the lateral stiffness starts to decrees. Previous studies have shown the limited redundancy of the braced steel frames due to seismic load concentration in a specific floor where the large story force and interstory drift are developed. The plastic hinges start to be formed in this floor and becomes a vulnerable leading the structure to collapse in sideway. The beams of frames should be strengthened enough to resist the shear vertical forces developed from the concentric braces. To resist seismic loads, braced steel frames have many bracing systems, such as concentric bracing system, eccentric bracing system, knee bracing system and mega bracing system.

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Bracing is concentric when the center lines of the bracing members intersect. The concentric braced steel frames used in structures include X, Chevron and Knee bracing. X bracing is the most common type of bracing. The diagonal members of X and Chevron bracing go into tension and compression. Connections for X bracing are located at beam to column joints. While Chevron bracing members are connected to the beam at the top and converge to a common point. The frame lateral stiffness is increased resulting in natural frequency increasing and lateral drift decreasing. A larger inertia force in seismic region is attracted due to stiffness increasing. While the axial compression in the braced connected columns is increased with decreasing the bending moments and shear forces in columns.

Eccentrically braced frames look similar to frames with Chevron bracing. The difference between Chevron bracing and eccentric bracing is the space between the bracing members at the top gusset connection. In an eccentrically braced frame bracing members connect to separate points on the beam. The energy from seismic activity through plastic deformation is absorbed by the beam segment between the bracing members. The lateral stiffness of the system is reduced by eccentric bracings which improve the energy dissipation capacity. Due to eccentric connection of the braces to beams, the lateral stiffness of the system depends upon the flexural stiffness of the beams and columns, thus reducing the lateral stiffness of the frame. The vertical component of the bracing forces due to earthquake causes lateral concentrated load on the beams at the point of connection of the eccentric bracings.

The steel frame lateral displacement can be reduced by using of knee braces [8]-[10]. If knee bracings are provided to replace the moment connections, overall deflection of the structure may increase under the effect of lateral loads. Knee bracing is provided to avoid moment connection at the beam-column connection by shifting the maximum stress point at the beam-column connections.

The mega bracing system MBS is considered as viable solution to augment both global lateral stiffness and strength of steel frames. MBS is most cost-effective than other types of bracing. Mega-braces can be installed without business interruption within the building thus preventing loss of use (downtime) caused by the structural retrofitting strategy [11].

III. SHAPE MEMORY ALLOY

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 experimentally [8], [12]-[16]. Various investigations have been carried out into use the SMA as bracings [20], [21], [24], beam connections [11]-[23], anchorage systems [17], [18], restrainers [19], isolation devices [28], and energy dissipating devices [20], [29], [30].

Although the number of analytical and experimental studies on the use of SMA [25]-[27], 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 [31]) has been validated at the element level for steel frames. Dynamic time history analyses were performed for three frames to determine the characteristic differences in terms of top displacements, base shear force and total vertical reactions at frame base.

IV. 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.

V. 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 steel frames have been considered in this study. The first system is un-braced frame (a); the second system is a braced steel frame with concentric X-bracings using shape memory alloy SMA at beam-bracing connection (b) while the last one is braced frame with mega bracing (c).

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.

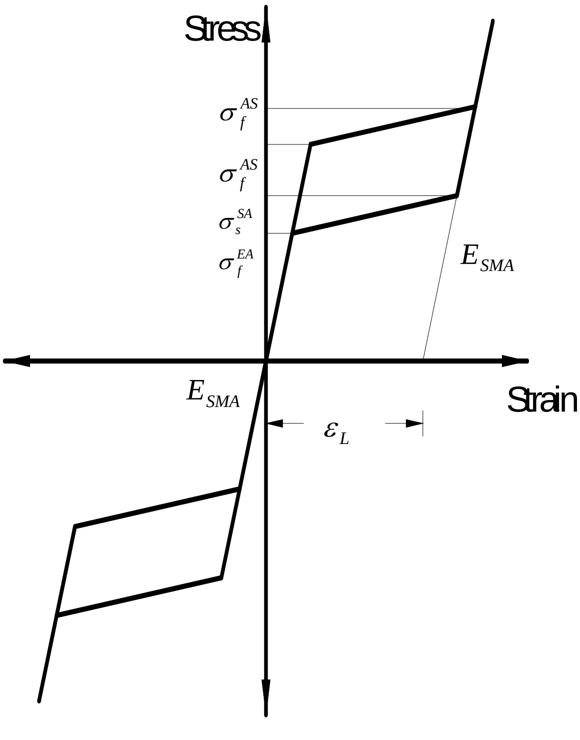
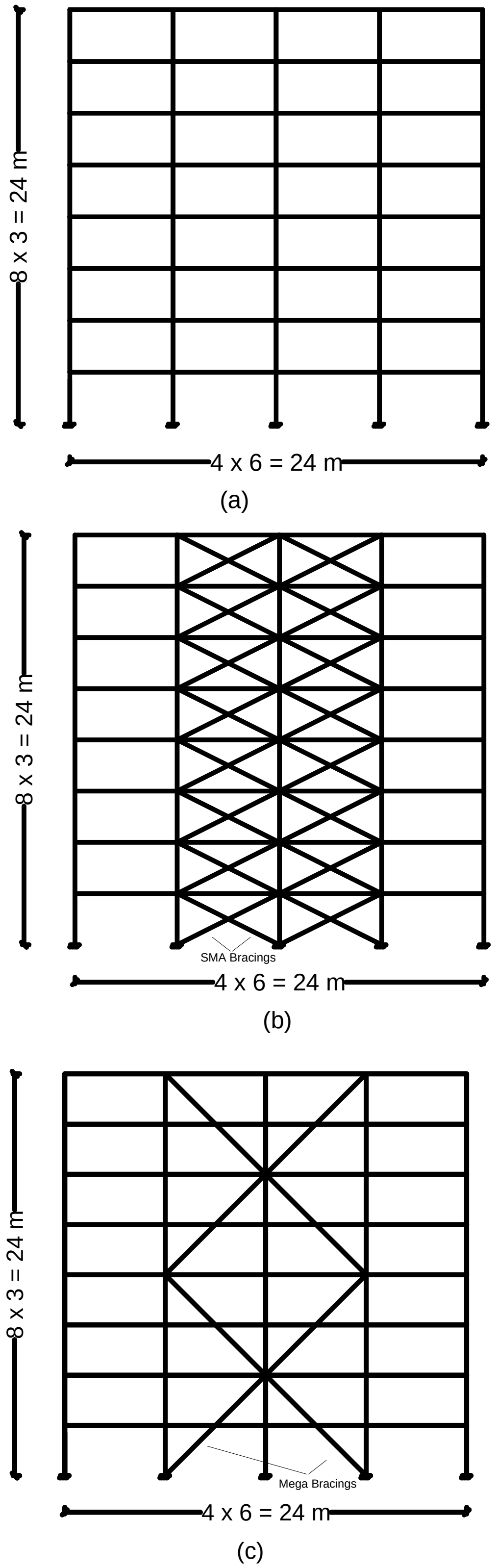


Fig. 1 Shape memory alloy properties



(a)

(b)

(c)

Fig. 2 Frame geometry with three cases, (a) un-braced frame, (b) SMA-braced frame and (c) mega-braced frame

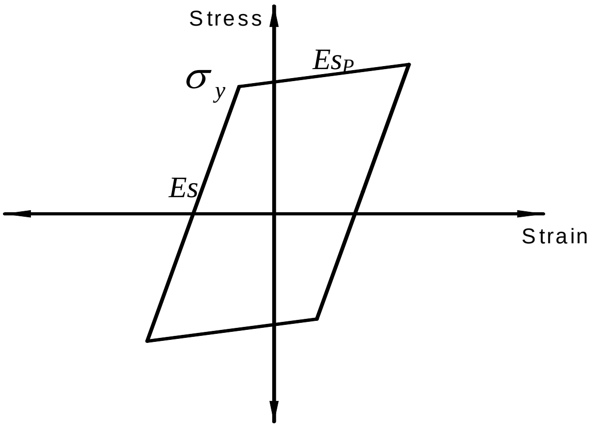


Fig. 3 Steel model

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%

TABLE II
STEEL PROPERTIES

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

VI. 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).

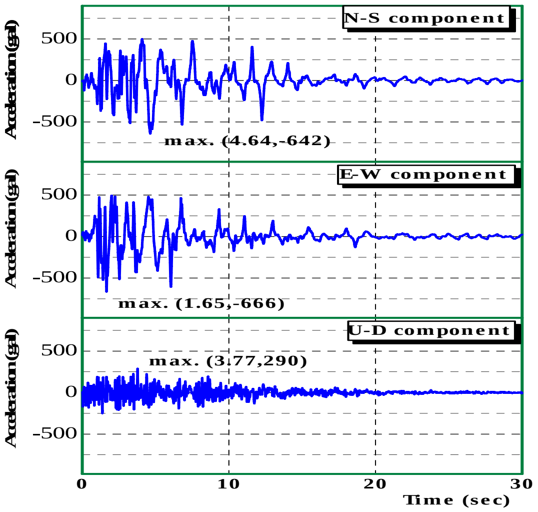


Fig. 4 Strong ground motion measured at JR Takatori

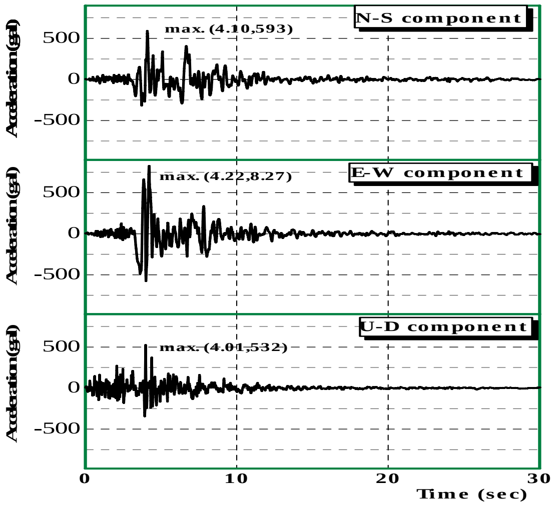


Fig. 5 Ground motion measured at Sylmar STA

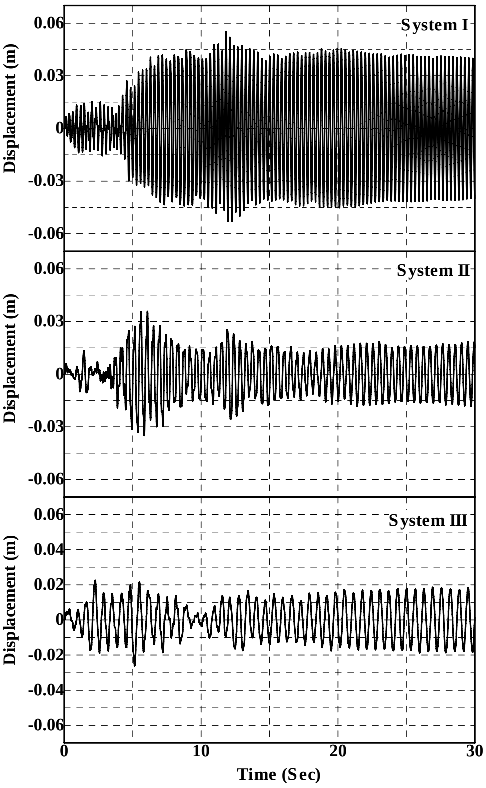
VII. RESULTS AND DISCUSSION

In order to study in detail the nonlinear seismic behavior of different systems of steel frames, nonlinear time history analyses were performed. All the frame models were analyzed as two-dimensional (2D) models. Eight story steel frames braced and unbraced with MBS and SMAS are presented. Nonlinear finite element analysis has been implemented to investigate and compare the performances of the three different models of steel frame structures 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:

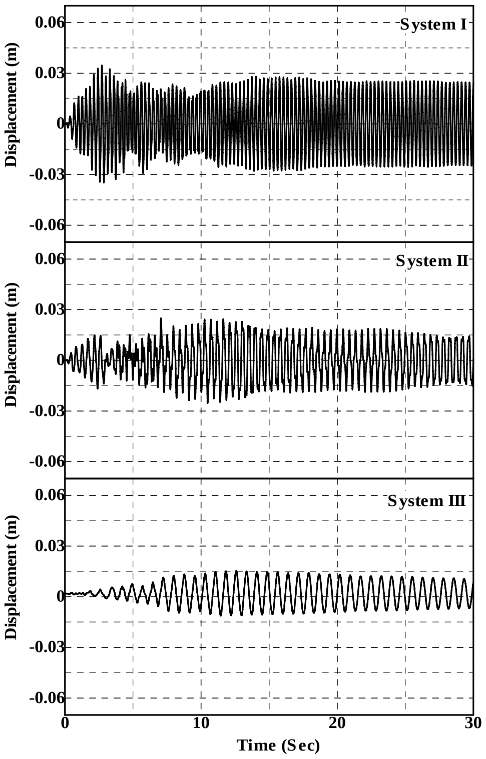
System I: the steel frame is unbraced,
System II: the steel frame is braced with MBS bracings,
System III: the steel frame is braced with concentric X-bracing system using SMA at the beam-braces connections.

The seismic response of the structure is greatly affected by the input ground motion characteristic. To check the volubility of the proposed three different steel frame systems, two different input ground motion has been used to affect on the frame. Fig. 6 shows the nonlinear time response 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 in the bracing system can provide more effective than MBS in order to limit the frame top displacement. Using of the SMA in bracing system can be designed to provide sufficient stiffness and damping to limit the frame top displacement below a re-determined value. The SMA bracing system, system III, is more effective in reducing the displacement at frame top than that of MBS system II. Using of either MBS or SMABS is effective in reducing the total top displacement. In case of using Taktori input wave, the maximum displacement of approximately 5.5cm was found in unbraced frame. The maximum displacement reaches 3.6cm in case of use MBS while it reaches 2.6cm when SMABS is used. In case of using Sylamr input wave, the maximum displacement of approximately 2.45cm occurs in the MBS braced frame while it reaches 1.5cm in case of use SMABS. In that case, the maximum displacement at frame top was 3.4cm. The use of SMABS reduces the maximum displacement to a reduction more 50% than that of using MBS.

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 low amplitude displacement and low accelerations. Using of shape memory alloy at beam-bracing connections SMABS is more affect than that of using MBS. Thus, the SMABS has a longer natural period that lead to more efficiency in dissipating energy of the input seismic waves than that of MBS.

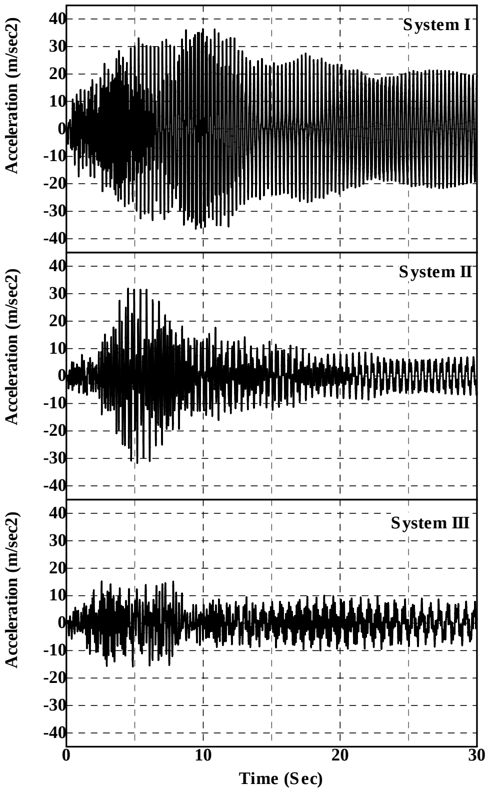


(a) Takatori input wave

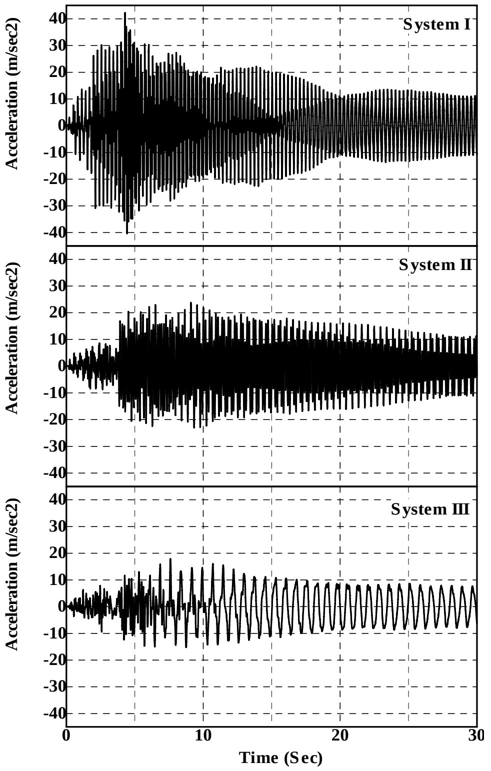


(b) Sylmar input wave

Fig. 6 Displacement time history at frame top

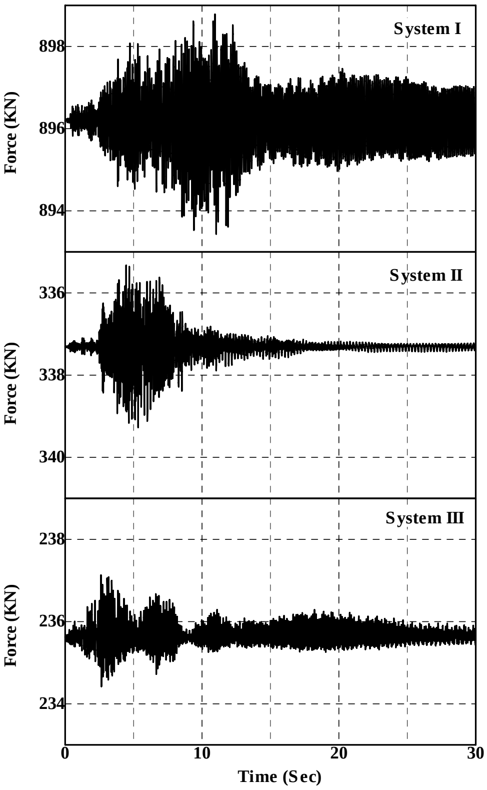


(a) Takatori input wave

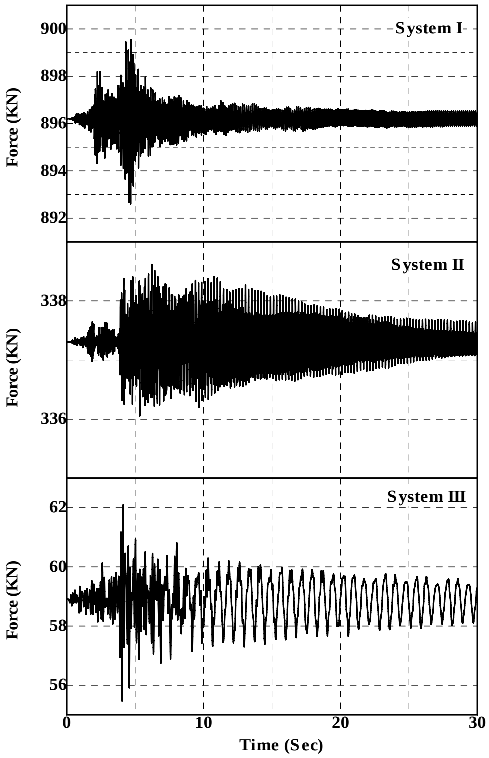


(b) Sylmar input wave

Fig. 7 Acceleration time history at frame top



(a) Takatori input wave



(b) Sylmar input wave

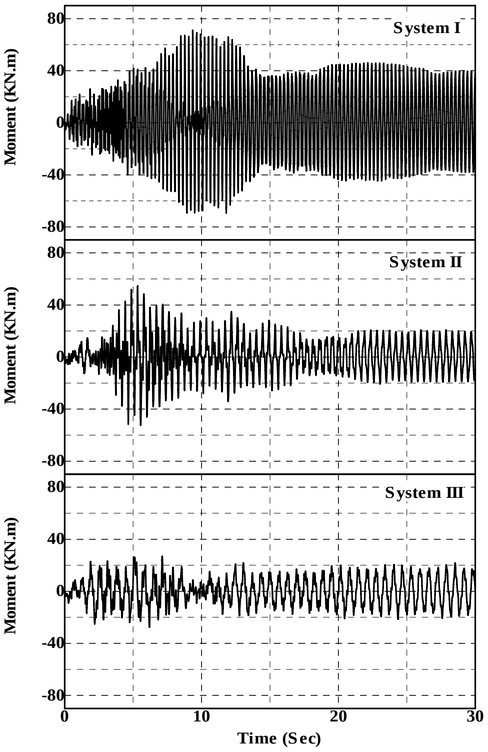
Fig. 8 Vertical force time history at tower base

By comparing the reaction force and time histories at the frame base for three cases, Fig. 8, it is observed that the third system when SMA used at beam-brace connections provides pronounced reduction in the reaction force responses compared to that for MBS. This may be attributed to the larger amount of energy which absorbed at the SMA provided in eccentric braces. When Takatori Station input wave is used, the vertical base force reaches around 899 KN for the unbraced frame system and reaches around 335 KN for the MBS system while it reaches 237 KN for the SMABS. Using of shape memory alloy at beam-brace connection leads to a reduction in the amount of vertical force at frame base by 76% of that when original unbraced frame is used. Also, there is a reduction of the about of vertical force at frame base of around 63% MBS is used. When Sylmar Station input wave is used, the vertical base force reaches around 899 KN for the unbraced frame system and reaches around 339 KN for the MBS while it reaches 62 KN for the SMABS. Using of MBS leads to a reduction in the amount of vertical force at frame base by 64% of that when unbraced frame system is used. Also, there is a reduction of the about of vertical force at frame base of around 99% when shape memory alloy is used at beam-brace connection, SMABS. Hence using of both either mega bracing system MBS or the shape memory alloy as connections SMABS is effective in controlling the reaction force at the frame and stresses. On the other hand, the SMABS reduces the vertical force more effectively compared with mega bracing system MBS. It can be observed that when SMABS is used, the vertical forces at frame base can be vanished.

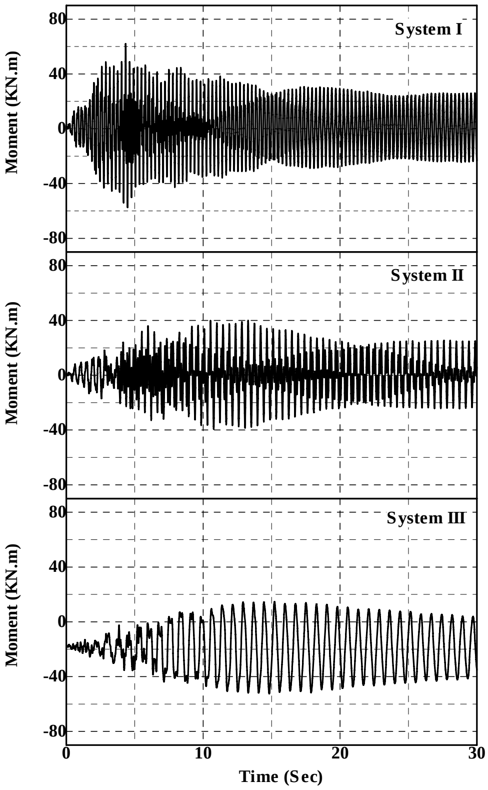
The moment time history at the frame base, Fig. 9, is compared between the three different systems. There is a reduction of the moment amplitude at frame base around 10 % and 20% of MBS and SMABS respectively.

VIII. CONCLUSIONS

The paper presents an analytical study of concentric bracing in steel frame structures provided with SMA bars, in order to enhance their seismic behavior. Eight story steel frames with different bracing system are studied. In this study, in addition to the unbraced frame, two of bracing systems were assessed: concentric bracing with SMA system (SMABS) and mega-bracing system (MBS). Results show that both systems improve the strength and stiffness of the original structure but due to excellent behavior of SMA in nonlinear phase and under compressive forces this system shows much better performance than the rehabilitation system of Mega bracing. The reduction of top displacement with respect to the original unbrced frame is around 70%. Maximum lateral displacement in MBS is 45%–55% lower than SMABS. The SMABS is more effective in reducing shear force, moment at frame base and axial forces. Further works still are necessary to compare the other SMA systems used in structures.



(a) Takatori input wave



(b) Sylmar input wave

Fig. 9 Moment time history at frame base

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