Smart Material Application in Moment Resisting and Eccentric Braced Frames

Zahra Roshanfekr Rad, Mohammad Soheil Ghobadi, Mansoor Yakhchalian

Abstract**—**shape memory alloys (SMAs) as smart materials, have been found increasing application in seismic engineering. These materials have ability to recover their original shape by heating (shape memory effect) or unloading (superelastic effect) after experiencing large deformations. This paper evaluates seismic performance of steel moment resisting frames and eccentrically braced frames using superelastic NiTi shape memory alloy (SMA) bolts in connections. The main concept of using SMA bolts is to localize deformation into the connection such that superelastic hinges form via elongation of bolts. Therefore, residual drifts are minimized and structure shows flag shape behavior. The numerical modeling of connections in both systems is verified through comparisons with previous studies. Incremental dynamic analysis were conducted on four- and eight-story moment resisting frames and eccentrically braced frames selected from NIST projects, that their connections are redesigned with superelastic bolts. The effects of SMA bolts on structural performance in connections of aforementioned two different frames are compared to evaluate the best application of smart materials in current framing systems.

Keywords**—** Shape memory alloy, moment resisting frame, eccentrically braced frame, incremental dynamic analysis, self-centering material.

I. INTRODUCTION

Since Northridge earthquake in 1994, that most of the moment frames experienced brittle fracture in their welded connections, structures have been designed to resist seismic loads while having enough ductility to undergo large deformations. In other worlds, structures must be designed to have enough stiffness (to control drifts), ductility (to control fracture), and energy dissipation (by nonlinear mechanism) to show proper performance. Consequently, after a severe earthquake occurrence, large permanent residual deformation may occur in structural component due to extensive yielding, then make the building unsafe for residents and increase repairing costs. Therefore, researches proposed an innovative system could return to its initial position called 'self-centering' system. Afterwards, some type of connections utilizing smart materials were promoted to cause recentering behavior in structures. Among these smart materials, shape memory alloys (SMAs) have attracted so many attentions due to their self-centering capability and energy dissipating [1]. These materials have two main unique characteristic properties named shape memory effect (SME) and superelasticity (SE). SME behavior refers to the property when residual deformation of material can be recovered through heating. Superelastic effect refers to the state when material returns to its initial shape by unloading. Both properties have so many application due to their unique behavior; but SE performance has promising usage and wild variety of civil engineering applications, due to its hysteretic damping and recentering characteristics. The other features of SMAs can be mentioned as high strength, fatigue and corrosion resistance (which overcome ageing, durability and maintenance of passive control devises), undergoing large strain up to 6-8 percentage and large damping capacity [2].

There are numbers of studies investigating utilization of SMA in frames connections. For example, Ocel et al. [3] designed a partially restrained connection equipped with four martensite nickel-titanium (NiTi) rods. High-energy dissipation and large ductility was observed after processing of loading, unloading and heating the connection and it was able to recover 76% of the experienced drift. Ma et al. [4] investigated a self-centering connection consisting of long superelastic NiTi bars, continuity plates, beam flange ribs and web stiffeners. They made a comparison with equal connection using high strength steel bars, through a 3D finite element model. Their result showed high ductility capacity of both connections, former due to superelastic bars, whereas latter because of formation of plastic hinge on beam. Moreover, no local buckling was observed in NiTi connection. Speicher et al. [5] tested four beam-column connection equipped with superelastic NiTi tendons, steel tendons, martensite NiTi tendons and combination of NiTi tendons and Aluminum tendons. Martensitic connection could recover its deformation up to 75% by heating. Two other NiTi connections had high self-centering capacity and their residual deformation was reported between 0.5% and 1% after a maximum drift of 5%. Desroches et al. [6] evaluated seismic performance of three- and nine-story buildings with moment resisting system, which martensite and superelastic bolts were used in their beam-column connections. Through a nonlinear time history analysis, martensite connection showed having more effect on decreasing maximum drift while superelastic connection had better controlling on residual drift. In the following of aforementioned study, Elingwood et al. [7] conducted a probabilistic seismic demand assessment. The results showed

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that the effect of using SMA connection in the structures depends on seismic demand level. A probabilistic seismic demand assessment. The results showed that the effect of using SMA connection in the structures, depends on seismic demand level. Fang et al. [8] tested an experimental extended end-plate connection with superelastic bolts in a moment-resisting frame. Seven specimens were designed with different end-plate size and different SMA bolt diameter and cyclic loading was applied to all specimens. SMA connections demonstrated high self-centering ability and moderate energy dissipating. Long and small diameter (i.e. slender) bolts presented more ductility to connections.

Despite of steel moment connections, there are finite studies about eccentrically braced frame (EBF) connection using SMA material. Just like steel moment frames, which have large deformation in severe earthquakes due to yielding, link beams in an eccentric braced frame is designed to absorb energy, while other structural components remain in elastic range, so this elements are in danger of failing because of yielding and large deformation. Therefore, it is essential to limit link beams deformation and increase frame performance. Cheng et al. [9] were first ones who bring concept of self-centering in an eccentric braced frame by means of using post-tension tendons so that these tendons produce a self-centering mechanism at beam-link beam connection and all other component behave in their elastic range. Xu et al. [10] represented an analytical study on link beam connection using post-tensioned SMA tendons to create self-centering and energy dissipating in the connection. Parametric study demonstrated flag shape hysteretic curve and moderate energy dissipation of connection. Also Xu et al. [11] investigated an eccentric braced frame equipped with post-tensioned tendons and SMA bolts. Analytical study was performed on specimens with zero to four tendons and results illustrated self-centering behavior even with no post-tensioned tendons. More ductility was observed by increasing number of tendons.

Since the performance of structures with SMA bolts in comparison to convenient structures have been investigated by many researches, for better understanding of influence of SMA bolts on performance of different structural systems, in this paper, two lateral resisting system i.e. moment resisting system and eccentric braced system equipped with SMA bolts, are chosen and modeled by Opensees finite element program. Also in order to realize the effect of height on performance of structures, two height levels of low rise (four story) and medium rise (eight story) are considered for both systems. Incremental dynamic analysis is performed using suitable ground motion records and results are investigated to compare both structural systems.

II. SHAPE MEMORY ALLOYS

SMAs have two main phases with different crystal structures known as martensite and austenite. Martensite is stable at low temperature and high stresses and has disordered crystal structure whereas austenite is stable at high temperature and low stresses and has cubic crystal structure. Martensite phase could be stable in two crystal forms (twinned or detwinned), depending on crystal orientation direction. Unique properties of SMA (SME and SE) are result of its phase transformation. There are different alloys have been studied that show SMA properties, among which nickel-titanium (NiTi) alloys have found the most application. If NiTi is deformed in the temperature below the austenite finish temperature Af, residual deformation will remain upon unloading. When temperature increases to Af or more, most of the residual deformation can be recovered and SMA will return to its original shape. This phenomenon is known as shape memory effect (SME). When NiTi is deformed above the austenite finish temperature Af, martensite phase is induced. This phase will become unstable while unloading and hence, SMA will return to its original shape (austenite phase) at the end of unloading. Energy dissipation can be attained by martensite interface motion during inelastic deformation. This is called superelastic effect that has found so many seismic application due to its hysteretic damping and resentering. Fig. 1 and Fig. 2 shows stress-strain diagrams of shape memory behavior and superelasticity behavior of SMA, respectively.

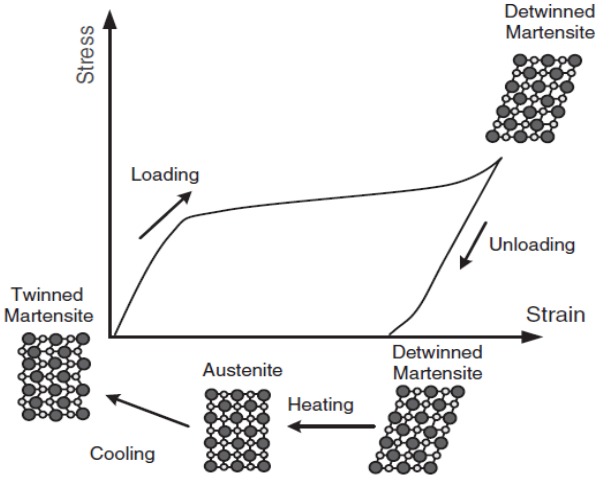

Fig. 1: Stress-strain curve and crystallographic changes of SMAs in shape memory behavior. [2]

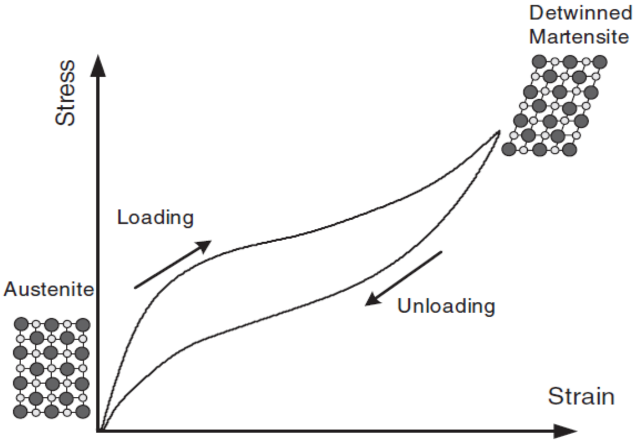

Fig. 2: Stress-strain curve and crystallographic changes of SMAs in superelastic behavior. [2]

III. FINITE ELEMENT MODELING OF STRUCTURES

A. *Verification*

In this study, the extended end-plate connection proposed by [8] was used in the moment-resisting frames. This connection consisted of eight long superelastic NiTi bolts and the end-plate was designed in order to ensure thick-plate behavior so no inelastic deformation was formed in it. Geometric configuration of the connection is illustrated in Fig.3. For eccentric braced frames, configuration proposed by [11] was used, in which four superelastic NiTi bolts and post-tensioned tendons were used at the link beam-beam connection of a single frame. In this study, post-tensioned tendons are eliminated due to set equal condition for both systems. Fig.4 shows proposed geometric configuration for this connection.

First, verification of both SMA connections was done to ensure accurate modeling. This task was achieved by comparing results of numerical modeling and experimental tests. Opensees finite element program was employed to simulate behavior of connections in both systems.

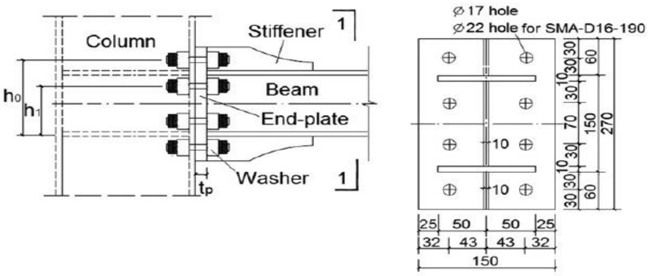

Fig. 3: Description of experimental model of moment-resisting connection. [8]

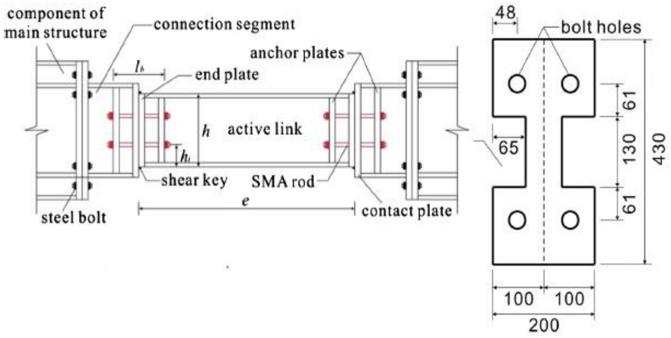

Fig. 4: Description of analytical model of eccentric braced frame.[11]

The moment-resisting connection was idealized as two stiff component connected by assembly of nonlinear springs. Self-centering material was chosen from opensees library to simulate superelastic behavior of SMA bolts. Main properties of SMA material used in moment-resisting connection are presented in TABLE I according to [8]. Due to post-tensioning of bolts, an elastic multi linear material was employed in parallel to self-centering material to simulate behavior of connection with prestressed bolts. A fiber section was constructed with eight fibers, represented SMA bolts and was allocated to a zerolength section. Two zerolength elements were used at the top and bottom of connection (compressive center) and ENT material was allocated to these elements in order to modeling of gap opening/closing behavior of connection. This material works in compression only.

TABLE I:
MECHANICAL PROPERTIES OF SMA BOLTS USED IN OPENSEES FOR MODELING OF MOMENT-RESISTING FRAME (MRF) CONNECTION

Material properties	***value***
Modulus of elasticity EA (GPa)	40
Modulus of elasticity EM (GPa)	40
Austenite to martensite starting stress σMS (MPa)	360
Austenite to martensite finishing stress σMf (MPa)	450
Martensite to austenit starting stress σAs (MPa)	280
Martensite to austenite finishing stress σAf (Mpa)	130
Transformation strain εL (%)	5

Same strategy was used to simulate EBF connection except that the fiber section included four fibers, represented SMA bolts with properties presented in TABLE II according to [11]. For modeling of beam, columns and braces, elasticbeamcolumn elements were used with the sizes presented in analytical study and module of elasticity of 200GPa. Fig. 5 and 6 show schematic configuration used for modeling of connections.

TABLE II:
MECHANICAL PROPERTIES OF SMA BOLTS USED IN OPENSEES FOR MODELING OF ECCENTRIC BRACED FRAME (EBF) CONNECTION

Material properties	***value***
Modulus of elasticity E_A (GPa)	50
Modulus of elasticity E_M (GPa)	50
Austenite to martensite starting stress σ_{MS} (MPa)	380
Austenite to martensite finishing stress σ_{Mf} (MPa)	490
Martensite to austenit starting stress σ_{As} (MPa)	220
Martensite to austenite finishing stress σ_{Af} (Mpa)	120
Transformation strain ε_L (%)	5

Fig. 7, presented verification curve of moment-plastic rotation, for moment-resisting connection subjected to cyclic displacements control loads, done by [8]. Also Fig 8, shows lateral force-drift ratio curve of EBF frame subjected to displacement control load, and its verification to numerical result of [11]. Good agreement was observed between previous results and FEM results for both systems.

B. *Structural Modeling*

The four- eight-story buildings were selected form NIST project [12], to model the 2D structural systems. All beams and columns were modeled using forceBramColumn element

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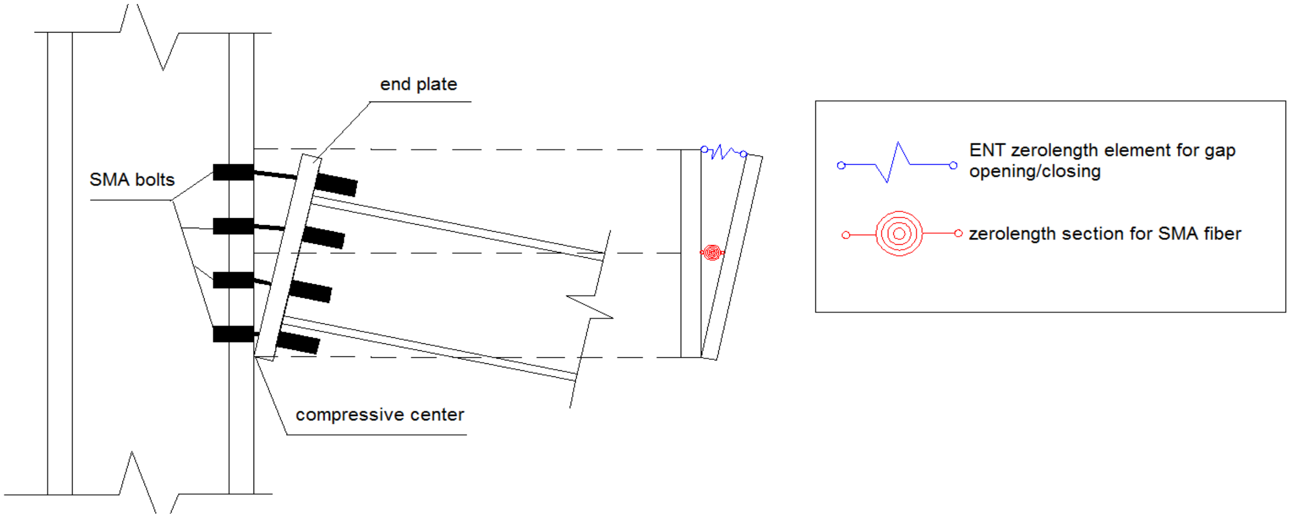

Fig. 5: Modeling of SMA connection section for moment-resisting frame in opensees

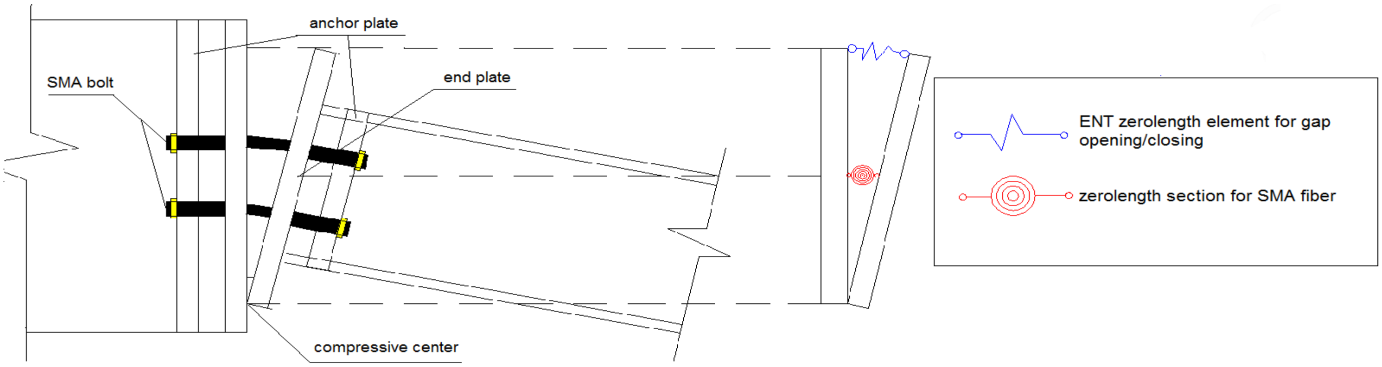

Fig. 6: Modeling of SMA connection section for EBF frame in opensees

With their actual size in opensees. For transferring the location of plastic hinges from beams to connections in order to prevent forming nonlinearity on all components but SMA bolts, lower values were selected for bolts moment capacity. The bolts diameter at the connections of the steel moment-resisting frames were redesigned according to [13] as follows:

$$d=\sqrt{\frac{2Mu}{\Pi\phi Ft(h0+h1)}} \qquad (1)$$

Where Mu is moment at the face of connection, Ft is bolt tensile strength and h0 and h1 are distances from the centerline of the beam compression flange to the centerline of upper and lower bolts, respectively.

The bolts diameter at the connection of EBF frames were designed as proposed by [10] as follows:

$$pb=\sum Ab\,\sigma bi(\varepsilon bi) \qquad (2)$$

$$peq=\int \sigma dAc=pb \qquad (3)$$

$$V=\frac{2}{e}(dcpb+Mb) \qquad (4)$$

Where Pb and σb are tension force and stresses of SMA bolts, Peq is integration of the normal stresses over the contact region, V is shear force in the link, dc is distance from Peq to middle depth line of link end-plate and Mb is defined as moment about middle depth line of link end-plate generated by tension forces in SMA bolts.

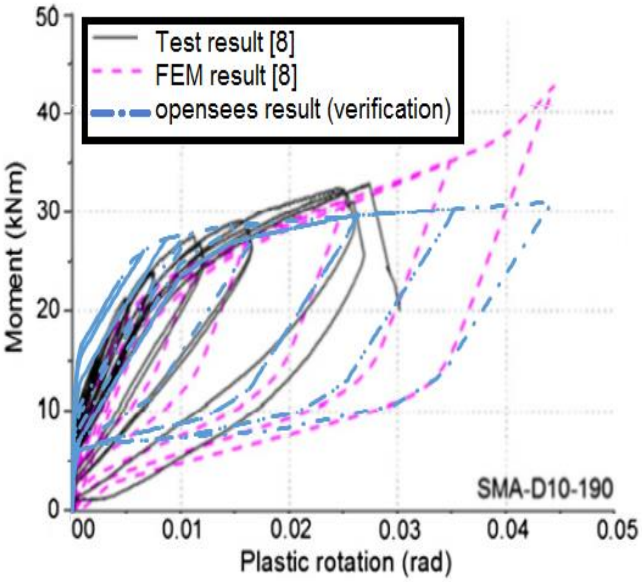

Fig. 7: Verification of moment-resisting connection

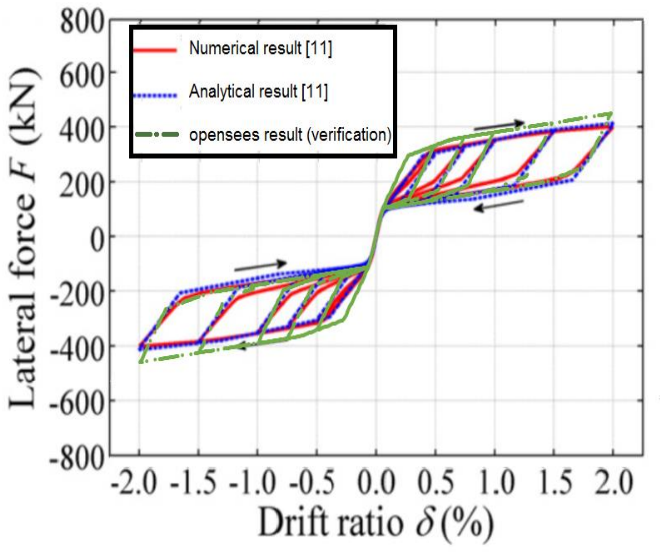

Fig. 8: Verification of EBF connection

C. Incremental Dynamic Analysis

IDA analysis was conducted to all four models for two ground motion acceleration records given in TABLE III. 5% damped first mode spectral acceleration (Sa(T1, 5%)) and maximum inter-story drift ratio (θmax) were chosen as IM and EDP. Results are presented in Fig. 10 to 13. Median of Sa collapse values calculated by IDA processor is presented in TABLE IV.

TABLE III:
DETAILS OF SELECTED GROUND MOTIONS

ID	***Magnitude***	***Year***	***Name***	***Station***	***Site to source epicentral distance***	***PGA***
1	6.7	1994	Northridge	Beverly hills-14145 Mulhol	13.3	0.52
2	6.7	1994	Northridge	Canyon country-W Lost Cany	26.5	0.48

As shown in IDAs curves, for a constant EDP value, story frames with higher height levels have higher IM values. This may illustrate the effect of using SMA bolts at high building connections. No smoothing was observed in all IDA curves. Also, there is no specific difference between IM values at lower story level of MRF and EBF frames but huge difference could be observed in higher story level. Eight-story EBF frame has higher IM value in comparison to MRF frame about 1.17%.

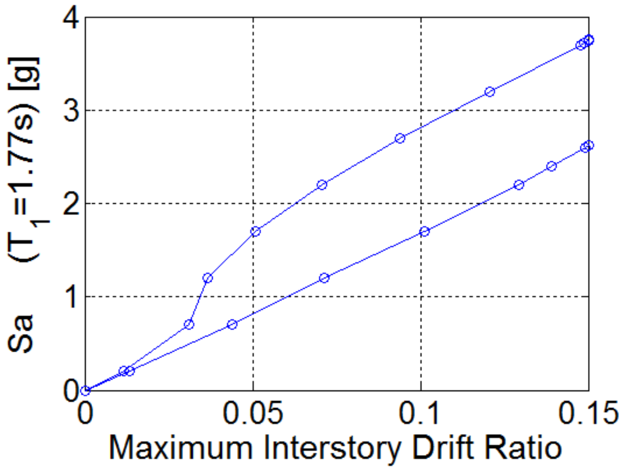

Fig. 10: IDA curve for 4 story moment-resisting frame

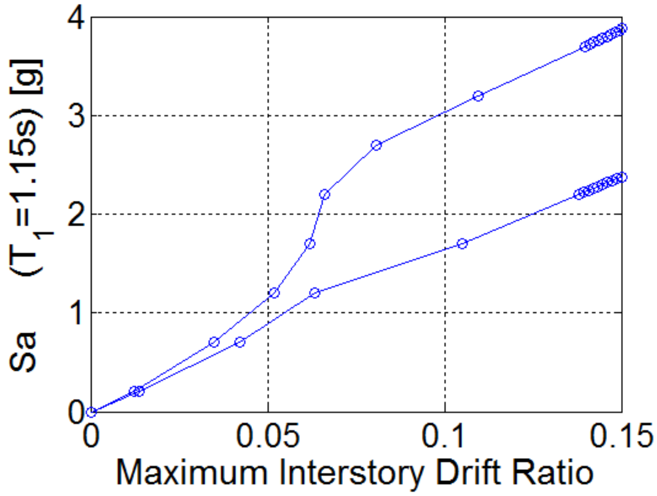

Fig. 11: IDA curve for 4 story eccentric braced frame

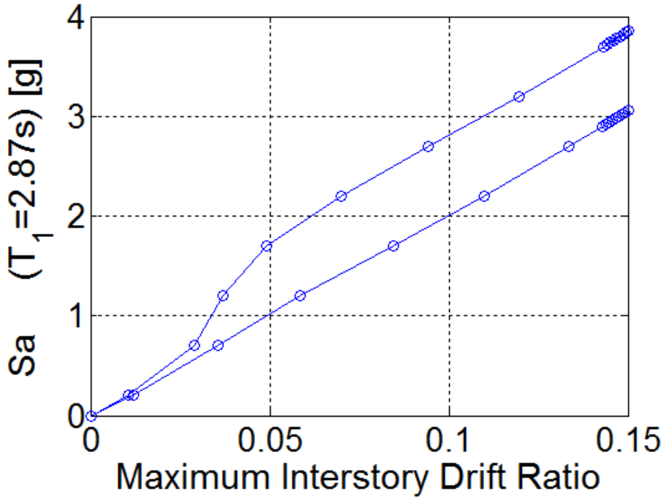

Fig. 12: IDA curve for 8 story moment-resisting frame

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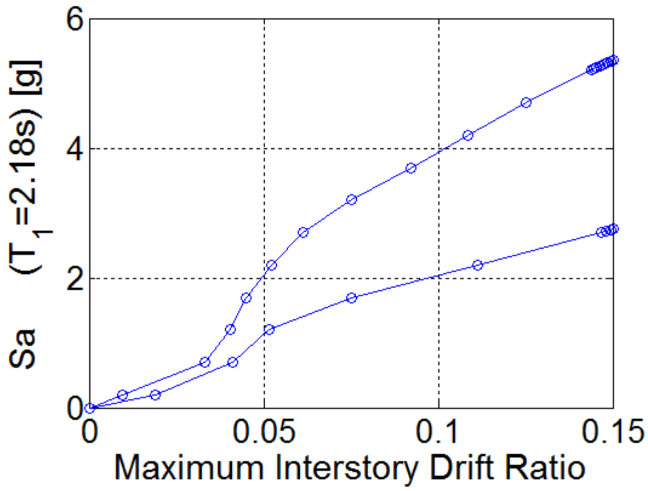

Fig. 13: IDA curve for 8 story eccentric braced frame

TABLE IV:
MEDIAN OF SA COLLAPSE VALUES OF FRAMES

frames	***Sa2***	***Sa2***	***Median***
4 story MRF	3.73	2.61	3.17
4 story EBF	3.87	2.37	3.12
8 story MRF	3.85	3.05	3.45
8 story EBF	5.35	2.75	4.05

IV. CONCLUSION

In this study, two connections using SMA bolts were established and verified versus experimental and finite element results according to [8] and [11]. These connections were redesigned and employed in four- and eigth-story moment-resisting frames and eccentric braced frames using opensees finite element program. Incremental dynamic analysis was performed with two ground motion acceleration records and 5% damped first mode spectral acceleration versus maximum drift story curves were derived. Results evidenced advantage of using SMA bolts in high story level structures. Eight-story EBF frame curve showed highest IM value and so it may be chosen as better lateral resisting system using SMA bolts beside moment-resisting system.

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[14] Keywords: Self-centering; Seismic resistant structures; Shape memory alloys; Pseudoelasticity; Energy dissipation