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Original Research Article

INVESTIGATION OF RESILIENCE OF ECCENTRICALLY BRACED FRAMES EQUIPPED WITH SHAPE MEMORY ALLOYS

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Abstract

Nowadays, the use of smart materials in structures is a major concern to structural engineers. The act of benefiting from numerous advantages of these materials is the main objective of researches and studies focused on seismic and structural engineering. In the present study, in addition to the development of finite element models of several steel frames using *ABAQUS* software, the effect of shape memory alloys (*SMAs*) on superelastic behavior and the various types of eccentric braces will be checked. Moreover, it was observed that the use of *SMAs* within various types of bracing systems of steel frames leads to a decrease in the reduction factor of the frames. Also, the eccentric bracing in which *SMAs* are utilized in the middle of bracing led to the highest effect on reduction of lateral drift of the frames and decrease of reduction factor. The obtained results indicated

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that the application of smart materials led to increasing of strain energy and base shear of the first plastic hinge, which is followed by a decrease in the reduction factor of the frame.

Keywords: shape memory alloy (*SMA*), superelastic behavior, response modification factor, shape memory effect, reduction factor, seismic resilience

1. INTRODUCTION

The idea behind traditional approaches for designing structures to survive natural disasters has undergone significant alterations in recent years. Shape memory alloys (*SMAs*) are distinguished by their superelastic characteristic, which allows them to revert to their original shape after massive deformations. This property gives an optimum reversibility capacity that can be exploited in the passive control of earthquake-prone buildings. The purpose of this paper was to investigate the impact of modifying the hysteretic properties of *SMA* materials when they are utilized as passive control systems in eccentric bracing frames. *SMAs* have gained extensive and various uses and applications in various fields of structural engineering like active, semi-active and passive control systems due to their unique features, including high damping capacity, durability, resistance to fatigue and erosion, shape memory and superelasticity [1-3]. In the following, the research background is presented below:

Chung conducted research with a main focus on the structural seismic behavior by shaking table experiments and applying various earthquake records. He evaluated two single-story concrete frames, and in the first specimen, the brace was made of steel, while in the second sample, a portion of the brace was made of *SMAs* attached to the braces by bolted connections. For measuring the horizontal drift and axial length variation of *SMA*, *LVDTS* sensors were used. In this experiment, the seismic parameters of structures were studied, and after applying earthquake load, parameters like displacement and base shear were investigated and compared, and it was deduced that by applying various earthquake records on the structure possessing *SMA* braces, the reduction in displacement was observed in all cases [4]. Ozbulut et al. investigated the control of the seismic response of *20*-story building using a hybrid controlling device based on *SMA*. They evaluated *20*-story structure by applying various magnitudes of earthquake and they concluded that the use of *SMAs* leads to a significant reduction in peak displacement, enhancement of structure acceleration response and reduction of permanent deformations [5]. Araki et al. conducted a series of researches with a main focus on the application feasibility of flexible memory bars of copper-aluminum-manganese in tensile bracings. They compared steel tensile braces, and this experiment revealed its effects on available braces exposed to quasi-static periodic loading and dynamic loading originating from ground motion with a frequency of *6 Hz*. By performing time-history analysis and plotting hysteresis loop, they construed that the application of *SMAs* leads to higher ductility, greater recoverable strains within structure, reduction in the cost of materials, etc. [6]. Eatherton et al. investigated the self-centering buckling restrained brace (*SC-BRB*) computationally and experimentally *SC-BRB*. It can be used in real-world buildings to increase seismic performance. The results showed that *SC-BRB* outperformed *BRB* in terms of seismic performance [7]. Abou-Elfath examined the ductility properties of short-segment *SMA* braces in order to determine their safety levels against failures in seismic recordings. The results demonstrated that short-segment *SMA* designs were unable to add appropriate ductility to lateral-resisting systems [8]. Shi et al. and Nazarimofrad and Shokrgozar considered various design parameters for *SMA* braces installed in steel frame buildings, and then used incremental dynamic analyses (*IDA*) to evaluate the seismic responses of the structures at different seismic intensity levels based on earthquake records [9, 10]. Mirzai et al. proposed using a shear re-centering polyurethane friction damper in the shear link of an inverted *Y*-shaped braced frame to minimize residual structural deformation and limit seismic damage to the structure [11]. Kari et al. suggested an energy-dissipative self-centering brace for usage in structural frames. The brace can provide sufficient energy dissipation capacity in the structure [12]. Hashemi et al. conduct research about sensitivity analyses to determine how each design option affects the performance of an *SC-BRB* and the corresponding *BRB* without *SMA* rods. In addition, reliability assessments of *BRB* and *SC-BRB* are carried out in this study. Given the high computing cost of the simulation methodologies, the surrogate models are built using three Meta-models: Kriging, radial basis function (*RBF*), and polynomial response surface (*PRSM*). Nonlinear dynamic analyses on both *BRB* and *SC-BRB* are performed for this purpose using the *OpenSees* program. According to the findings, the *SMA* area, *SMA* length ratio, and *BRB* core area have the greatest influence on the failure likelihood of *SC-BRB* [13]. Hashemi et al. presented a two-objective optimum design technique of *SC-BRB*s subjected to pulse-like near-field seismic excitations using a multi-objective cuckoo search (*MOCS*) optimization algorithm. The best geometric specifications of *SMA* and *BRB*, including the length of *SMA* bars, *BRB* core, area of *SMA*, and *BRB* core, are designed with the goal of reducing the maximum displacement and acceleration of structural floors at the same time. The results demonstrated that the modified *SC-BRB* is capable of significantly decreasing the dangers caused by residual drifts and deformations [14].

The utilization of *SMAs* in braces is considered as the most important and effective application of *SMA* in the field of structural engineering, as these materials possess unique features, including super vibrational characteristic, shape memory feature, ability to recover the structure to its primary state (re-centering) and high capability of energy damping. However, a large portion of conducted researchers regarding the applications of *SMAs* in structural engineering is in the theoretical phase, and a very few number of studies was tested in real-world, and none of these researches are implemented in real structures. Since the studies on the use of *SMA* in structures are in the early stages, so in this paper, as a novelty, we will try and highlight to change the modification factor of various eccentric braced steel frames using *SMA* segment under cyclic loading. The nonlinear static analysis is conducted, and the parameters of the modification factor in these frames, such as displacement responses and their base shear with each other, should be investigated, and the effect of using these alloys on the rate of change of ductility, strength coefficients, and the modification factor of these structures are evaluated.

2. MODELLING PROCEDURE

2.1. Modeling verification

The present research has used the geometrical, material, and cyclic loading details of a study carried out by Zahrai et al. [15]. This prototype is *3*-story steel frames with a total height and frame bay of *9 m* and *5 m*, respectively. In the modelling procedure, the horizontal link beam and vertical link beam are equal to *0.6 m* and *0.3 m*, respectively. The columns, beams, and link beams are designed by using *2IPE220*, *IPE220*, and *2UNP80*, respectively.

The properties of the study model and its assumptions and analyses are based on reference [15], and modeled in *ABAQUS* software. The obtained results indicate that the high accuracy of the base shear versus displacement curve. Fig. 1 (a) shows the finite element model developed in *ABAQUS* software, and Fig. 1 (b) and (c) indicate the comparison of base shear-displacement curve between the finite element model and reference [15] and plastic strain counter, respectively. The comparison is evident that the difference is average *5%*, while this amount of error rate is desirable in the numerical analyses. This rate of error can be attributed to the difference between the number of elements and the nonlinear properties of the used materials.

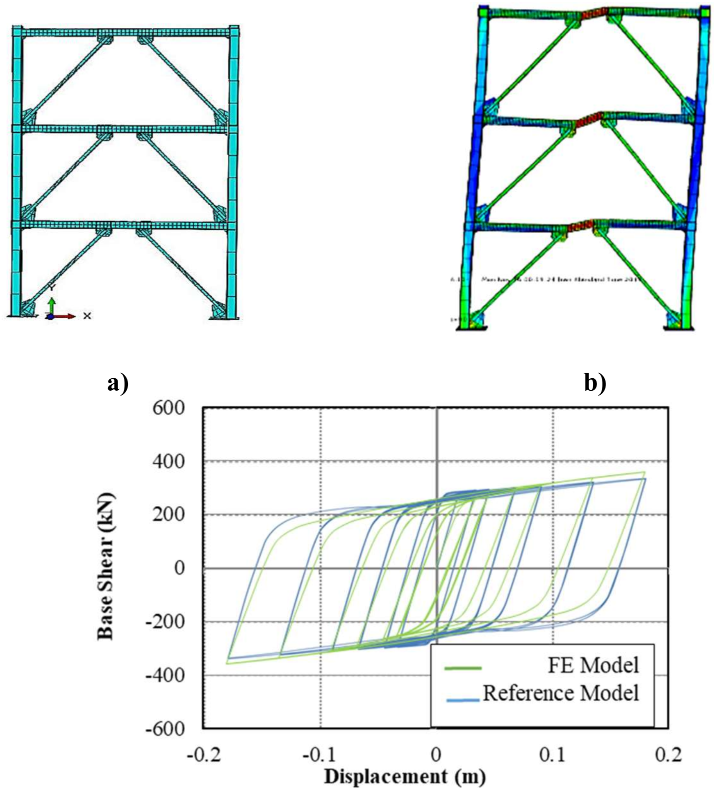


Fig. 1. a) Finite element model in *ABAQUS* software. b) Plastic counter of the modelled prototype. c) Comparison between base shear-displacement curves of Finite element model and model proposed in Ref. [15]

2.2. The studied models

In this paper, nine steel frames whose various segments are equipped with *SMAs*, were modeled in *ABAQUS* software. Fig. 2 shows the shape of the models employed in the present paper. The location of the *SMAs* is indicated with red lines. In the notations, *F* refers to the eccentrically inverted-*V* braced steel frame, and s refers to the use of shape memory alloys. *V* represents a vertical link. *P1*, *P2* and *P3* denote one-third of below, middle, and above of the brace, respectively. The horizontal link beam is represented by *B*. The single and paired vertical links are denoted by *L1* and *L2*. For investigating the effect of *SMAs* on modification factor and comparing the ductility during the insertion of *SMA* on the bracing system, *F-V*, *F-SP2*, *F-SPA* and *F-7SP2* models were selected for the steel frame. For the realization of the study objective, the difference between reduction factor of steel frame with eccentric inverted-*V* brace possessing vertical link with insertion of *SMA* in the vertical link, models named, *F-SL1* and *F-SL2* were fabricated, respectively, and these samples exhibited the highest amount of reduction factor in the counterpart frames. For investigation of the influence of *SMAs* on modification factor of steel frame with eccentric inverted-*V* braces including insertion of *SMA* within link beam, *F-SB2* model was studied. Meanwhile, in the modeling phase, the *C3D8R* element was used for all elements of the steel frame. The *Tie* constraint is used in the steel and *SMAs* connection.

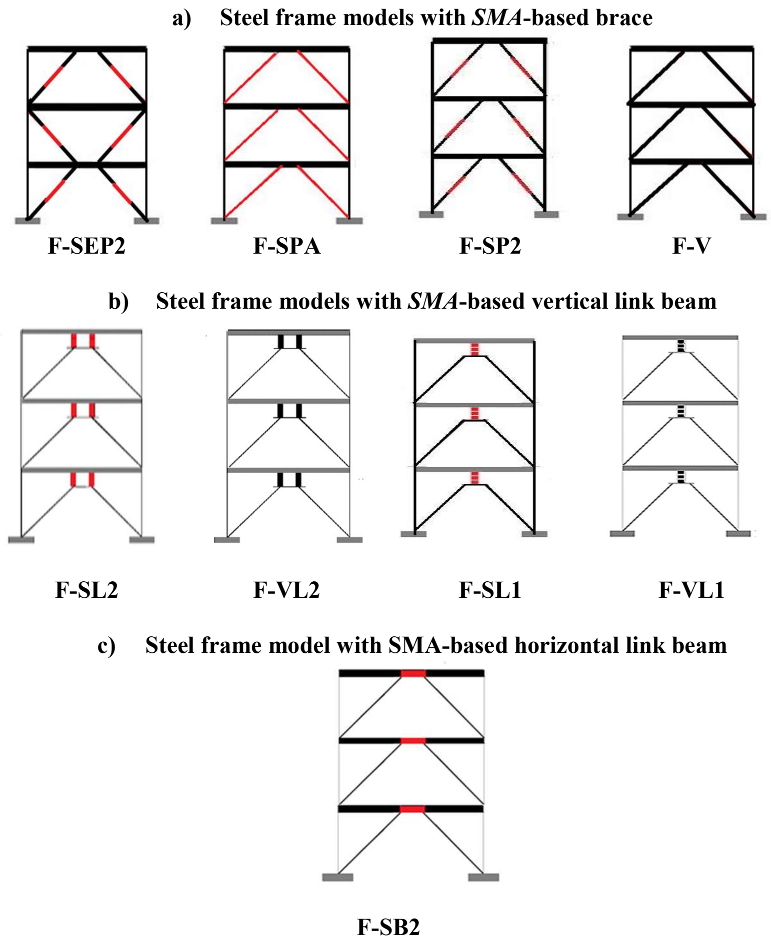


Fig. 2. Configuration of the studied frames

SMAs are used in these samples are of *Ni-Ti* type (*Nickel-Titanium*) with an ultra-resilient feature known with commercial name of *Nitinol*. Table 1 shows the mechanical properties of *SMA* utilized in the present research [16].

Table 1. Mechanical features of *SMA* [16]

Maximum strain recovery	**8%**
Young's modulus	30-83 GPa
Yield strength	140-410 MPa
Ultimate tensile strength	3400 MPa
Poisson ratio	17.50%

As *ABAQUS* software doesn't include *SMAs* in its library, so it is necessary to introduce *SMA* via another application by coding. Therefore, in the present study, a sub-procedure of the *FORTRAN* programming language developed by Lagudas was introduced to the model. In this behavior model proposed by Lagudas, *24* parameters are introduced to the software, which is related to the temperature of each phase (Austenite and Martensite), the mechanical features of the materials, coefficients related to the stress and strain components, and other variables. The introduced sub-routine which is related to the *Nitinol* Alloy (*Nickel-Titanium*) is among the most applicable materials in the structures.

3. RESULTS

3.1. Effect of sma on steel frame with eccentrically inverted-v brace

In this phase, *F-SP2*, *F-SPA*, and *F-SEP2* models in which *SMA* in their bracing system is studied, then these models were compared with *F-V* model. Based on Fig. 3, by investigation of pushover curves of models in which *SMA* was used within their braces and making a comparison between them, it can be claimed that the existence of *SMAs* leads to an increase of base shear and the enhancing of base shear related to a model with totally *SMA*-based brace was so significant.

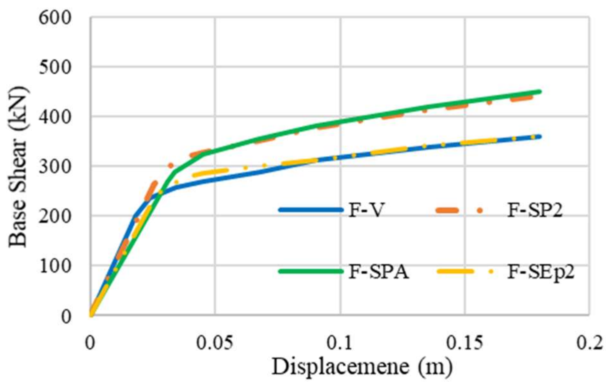


Fig. 3. Effect of *SMA* on eccentrically inverted-*v* braced steel frames based on pushover curve

Based on Fig. 4, as the *SMA* is used in the brace, the origin point displacement of pulp mode of the bilinear curve increases, which is followed by a decrease of ductility factor. Moreover, it leads to a decrease in the ratio of the first plastic point force of the bilinear curve to the force developed by the first plastic hinge in the structure, which is followed by a slight reduction in the over-strength factor.

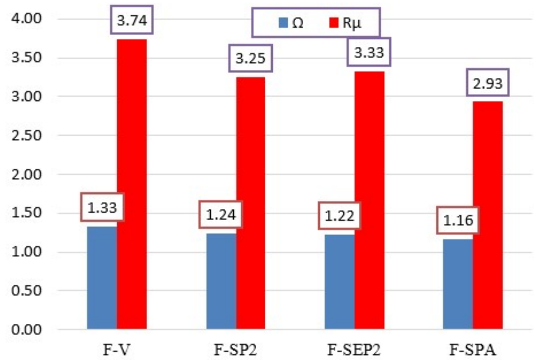


Fig. 4. Effect of *SMA* on eccentrically inverted-*v* braced steel frames based on Rμ and Ω

By investigating the pushover curves of models in which *SMA* was used within their braces and making a comparison between them, it can be claimed that the existence of *SMAs* leads to an increase of base shear and the increase of base shear related to a model with totally *SMA*-based brace was so significant.

Based on Fig. 5, for obtaining the modification factor, the simplifying technique should be used. Indeed, the nonlinear behavior of structure representing the relation between base shear and control point drift should be replaced by a simple bilinear behavior model in order to calculate the effective lateral stiffness and effective yield shear. With regard to *FEMA 356* code [17], the allowable displacement referring to the target displacement of nonlinear static analysis was set to *0.02h,* and h denotes the total height. In this study, the Young's coefficient of ductility is used in accordance with the *UBC* Regulations [18], the National Canadian Building Regulations [19], to calculate the modification factor in which a nonlinear static analysis of the curve is drawn and by acquiring the area under this graph and performing computational, the modification factor of the models was obtained. The result of the calculation of the modification factor shows that the use of *SMA* in braces reduces the modification factor, which means that the structures with braces of *SMAs* should be designed for larger forces compared to structures with steel braces.

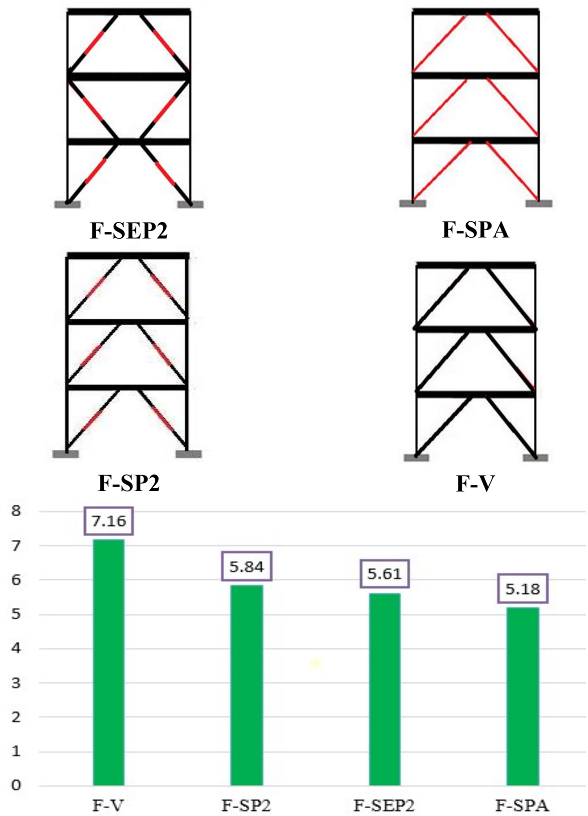


Fig. 5. Modification factor of samples containing *SMA* in the associated bracing system

3.2. Effect of SMA on steel frame with eccentrically inverted-v brace incorporating single and paired vertical link beam

In Fig. 6, the pushover curve of samples, including *F-VL1*, *F-SL1*, *F-VL2* and *F-SL2* are presented. This curve indicates the effect of *SMAs* on the vertical link of these samples. As it is obvious, the use of *SMA* in single and paired vertical links leads to an increase in the value of base shear.

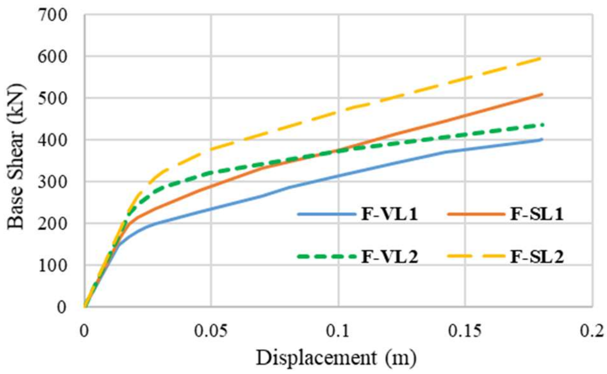


Fig. 6. Effect of *SMA* on eccentrically inverted-v braced steel frames incorporating single and paired vertical link beam based on pushover curve

Fig. 7 shows that utilization of *SMAs* in single and paired vertical link beam of eccentrically inverted-*V* braced steel frame leads to a reduction in factor resulting from ductility, which refers to the ratio of maximum relative lateral displacement quotient to relative lateral yield displacement. This finding indicates that *SMAs* do not have a significant effect on making the frame more ductile. For over strength factor, which refers to the ratio of base shear of first development point of the plastic hinge of the bilinear curve to base shear of first development point of the plastic hinge of pushover curve related to frames with the single and paired vertical link, it can be stated that this factor was stable and constant, compared to that of samples based on the use of *SMAs* in their vertical links.

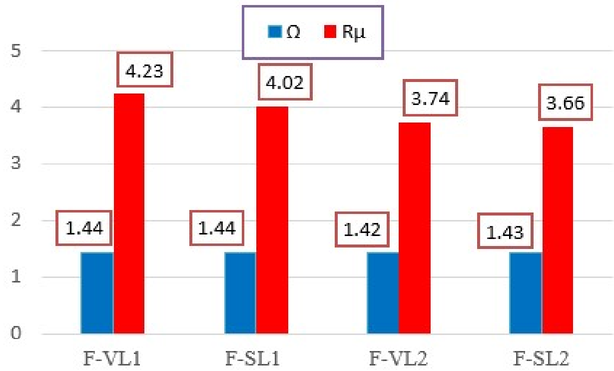


Fig. 7. Effect of SMA on eccentrically inverted-v braced steel frames based on incorporating single and paired vertical link beam based on Rμ and Ω

The modification factor is obtained from the multiplication of the two parameters of ductility and strength. According to Fig. 8, the modification factor of models of eccentrically inverted-v braced steel frame that holds *SMA* in a single and paired vertical link and a slight decrease in the modification factor was observable.

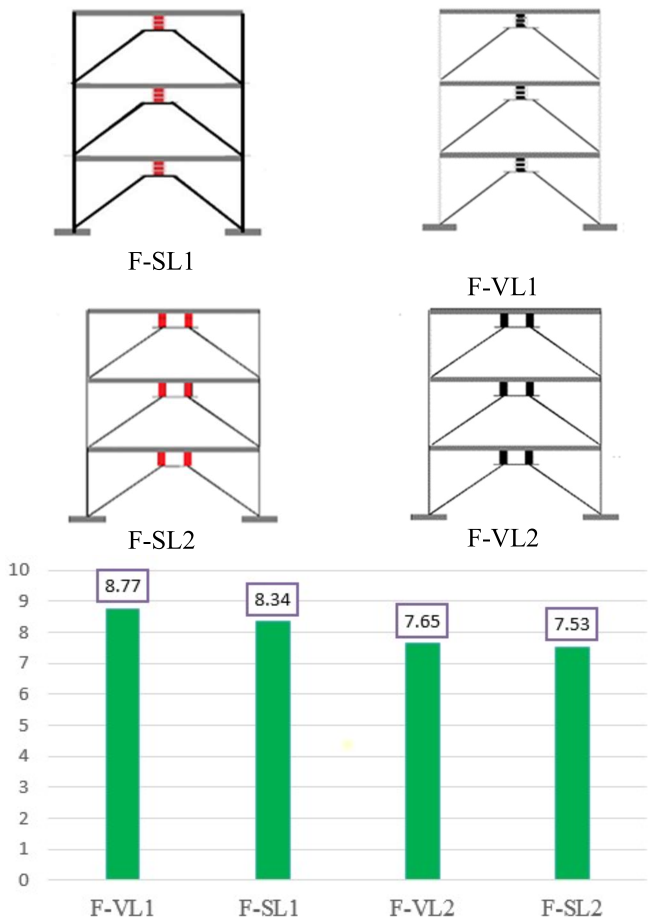


Fig. 8. Modification factor of eccentrically inverted-v braced steel frames equipped with single and paired vertical link beam

3.3. Effect of SMA on steel frame with eccentrically inverted-v brace incorporating horizontal link beam

The comparison made between two pushover curves of eccentrically inverted-*v* braced steel frame with and without *SMA* indicates that the use of *SMA* in the horizontal link beam leads to an increase in the values of base shear, according to Fig. 9.

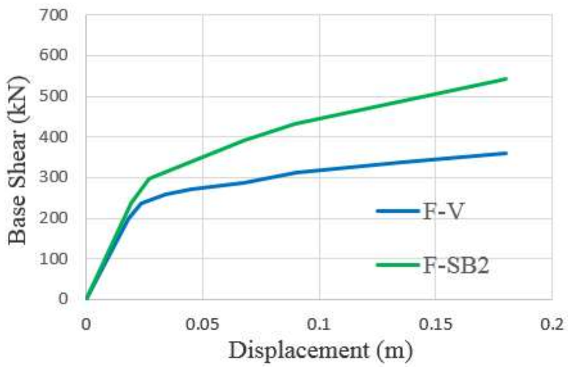


Fig. 9. Effect of *SMA* on eccentrically inverted-v braced steel frames incorporating horizontal link beam based on pushover curve

Fig. 10 shows that the use of *SMA* alloys in the horizontal link beam for the eccentrically inverted-*v* braced steel frame leads to a reduction in the factor resulting from ductility and over-strength factor.

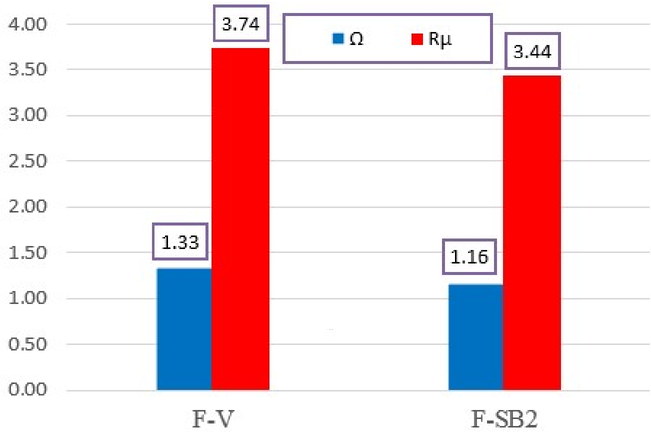
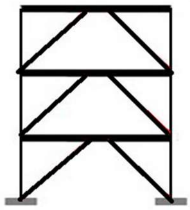
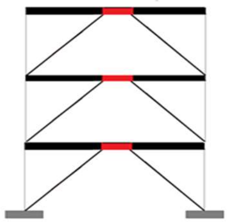


Fig. 10. Effect of SMA on eccentrically inverted-v braced steel frames based on incorporating horizontal link beam based on Rμ and Ω

Fig. 11 indicates that the modification factor of studied models developed for eccentrically inverted-*v* braced incorporating *SMA* in the horizontal link beam, where *2%* reduction in the modification factor was noticed.



F-V



F-SB2

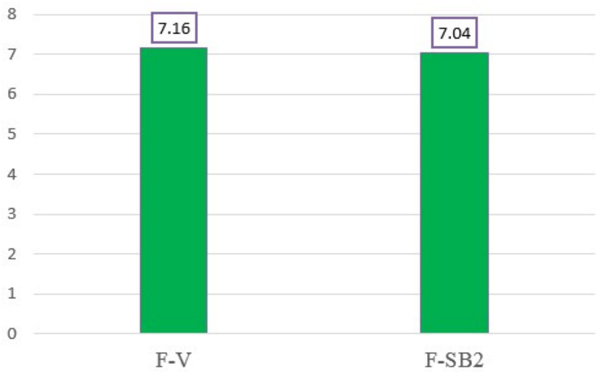


Fig. 11. Modification factor of eccentrically inverted-v braced steel frames equipped with horizontal link beam

4. CONCLUSIONS

One of the most important and effective applications of *SMAs* in structural engineering is the use of these materials in bracing systems; Because of their unique properties, such as ultra-elastic properties and shape memory, they provide the ability to re-centering the structure and the ability to consume high energy. However, many studies on the use of *SMAs* in structural engineering are in the theoretical stage, and a small number of them have been laboratory and have not been used in any real structure. In this study, nine samples of the eccentric brace are modeled and compared with each other in order to specify the effect of *SMAs* with considering the nonlinear static analyses. In the following, the general results are summarized and highlighted below:

- The obtained results showed that the braced structures with *SMAs* have a very low reduction factor, compared to that of braced structures without *SMAs*. It can be deduced that the structures with *SMA*-based braces should be designed for greater forces, compared to the structures without smart materials.
- Seemingly, with regard to the low rate of modification factor and limitations related to the application of *SMAs*, the use of them as the main lateral load-bearing members is not suggested, while the use of *SMAs* as re-centering devices with a aim of reducing post-deformation after the earthquake is highly recommended. Hence, it is essential to conduct studies with the main focus on use of *SMA* as a re-centering system.
- There exists a logical relation between base shear force and lateral displacement linked to all models possessing *SMAs*, so that these two values have an inverse relation with each other and any reduction in any of them leads to an increase in the other one.
- The highest rate of decrease in modification factor has corresponded to the samples in which *SMAs* were inserted in their brace, and the amount of this reduction of the sample in which *SMAs* were inserted in one-third of brace middle is equal to *20*%.

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