ENERGY-BASED SEISMIC DESIGN OF SMABF USING HYSTERETIC ENERGY SPECTRUM

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Abstract - *Superelastic shape memory alloy has an amazing property of retaining its original initial Shape after removing the stress on it. It is due to the intrinsic property to undergo large deformation due to hysteretic behavior and hence does not induce plastic deformation. This property can be exploited in many passive control schemes. When exposed to cyclic loading, SMA shows very good energy dissipation and hence shows very good energy absorption capacity. The property which is very useful in earthquake resistance systems such as dampers, isolation systems. Nowadays bracing is very effective way to make a structure seismic resistance if only figured out the way to hide them so as to its appearance so as not to affect the structures aesthetics. And introducing this SMA into bracing purely enhances its performance further. This paper presents the study of different types of SMA bracing frame and comparing them for the better optimization of the structure. Also the energy Based method which uses hysteretic behavior and ductility demands as a governing properties to determine the damage in the structure. Then investigating and comparing different types of bracing systems to check for various parameters such as economic aspects, weight of the structure, maximum story displacements under seismic loading.*

***Key Words*: Shape memory alloy, energy based seismic design, bracing systems, hysteretic energy spectrum, ductility, seismic design.**

1. INTRODUCTION

1.1. GENERAL

During earthquake every structure is often designed to sustain seismic loads without collapsing. But excessive residual deformation directly reduces seismic resilience because of long downtime, high repair cost which can further result into finally demolished buildings. Hence an effective way for prompt post-earthquake recovery of structures is reducing residual deformation. Shape memory alloy shows excellent self-centering capacity, stable hysteretic behavior, satisfactory energy dissipation capacity due to its two distinct properties of shape memory effect and superelasticity. This makes SMA a promising material for SC structures. This makes SMA a promising material for SC structures. As SC structures emerge as a new lateral resisting system the corresponding seismic design parameter should properly reflect the dynamic characteristics of flag shaped hysteresis, which are not available in existing codes. It is therefore widely recognized for the need to develop efficient seismic design methods for SC structures to directly utilize the deformation targets in the design procedure. Despite promising results from all the attempted methodologies, there are pressing needs for new seismic design methodologies of SMABFs to account for the hysteretic nature of earthquake induced non-linear responses.

In seismic design, displacement is usually the noteworthy response. The damage of the structures is often not contributed by maximum displacements but is contributed by total cumulative plastic deformation. Hence in this study a new seismic design method using hysteretic energy spectrum is presented for SMABFs. The main idea behind the proposed design method is to make sure that the hysteretic behavior of the critical seismic-resisting components primarily dissipates the input energy from earthquake. The main structure should remain safe with limited or no damage after earthquake so the SMABFs are designed to significantly dissipate energy through fundamental superelastic behavior and hence maintain the rest of the structure to respond within deformation limits under seismic excitation.

1.2 SHAPE MEMORY ALLOY

The basic aspects of the SMA-based passive control devices for the seismic protection of structures are great adaptability, i.e., the possibility to obtain a wide range of cyclic behaviours, from fully recentering to highly dissipating, just by changing the properties and/or the number of the SMA components, thus allowing to attune the shape of the force-displacement loops according to any particular individual need, and to have a simple functioning mechanism, even though they are behaviourally sophisticated.

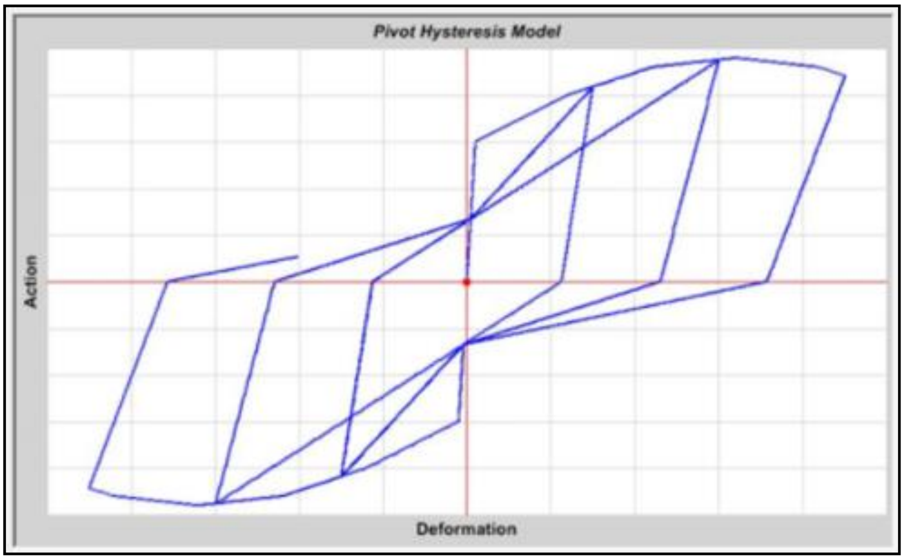

Figure.1 Hysteresis behaviour of SMA bracing

By properly calibrating their design parameters, a mechanical behaviour characterized by double flag-shaped hysteresis loops can be obtained. In this case, the seismic devices provides three affirming features:

1.2.1 Recentering capability, with the possibility to provide a supplemental recentering force to bring back the structural system at its initial configuration, even when non conservative forces external to the devices are acting,

1.2.2 High stiffness for small displacements, to avoid the structure to move under wind or service actions, and

1.2.3 Good energy dissipation capability, to reduce accelerations and displacements caused by an earthquake.

1.3. SHAPE MEMORY ALLOY BRACING

Self-centering concentrically braced frames (SCCBFs) are emerging as high performance seismically resistant framing systems, known for the capability to control peak seismic demands and eliminating residual deformation.
In the technique of growing SCCBFs, form reminiscence alloys are deemed because the capacity candidate for the important thing issue of SCCBFs, because of the extremely good superelastic capability and proper flag-form hysteresis.

For the SCCBFs the usage of SMA braces (SMABs), a cheap and powerful layout method primarily based totally at the performance-primarily based totally plastic layout turned into these days derived. This alloy is capable of show off a 'yielding' plateau as much as a stress of 6–8% and right away get better deformation because the elimination of implemented stress, which is basically due to the section transformation among austenite and martensite.[1]

1.4. ENERGY BASED SEISMIC DESIGN

Energy primarily based totally seismic layout considers that a shape can live on below intense earthquake if the structural electricity deliver is extra than the electricity demand. The enter power to an normal shape subjected to sturdy floor motions may be resolved into kinetic power, elastic stress power, damping power and the hysteretic power. In the power primarily based totally seismic design, the he call for performs an crucial function as it's far associated with the cumulative structural harm that resulted from seismic activity. Hysteretic energy demand is considered to be the best means for quantifying structural damage. Probabilistic seismic threat evaluation is accomplished via way of means of building uniform threat spectra for hysteretic strength call for at a particular web website online the use of simulated floor motions. an equal unmarried degree of freedom system-primarily based totally technique is followed for the use of the uniform threat spectra records in call for evaluation of multi-diploma of freedom structures. Finally, a deterministic equation is established for checking the target probabilistic performance criterion for the building. The proposed technique lets in a designer to test a layout for a goal probabilistic criterion without acting any nonlinear time-records evaluation or any uncertainty evaluation.

1.5 EARTHQUAKE GROUND MOTIONS

A suite of 20 earthquake ground motion records are selected in this study and scaled to the design basis earthquake (DBE) and maximum considered earthquake (MCE) hazard levels. These ground motions were generated by Somerville et al. (1997) for Los Angeles with an exceedance probability of 10% and 2% in 50 years.[3]

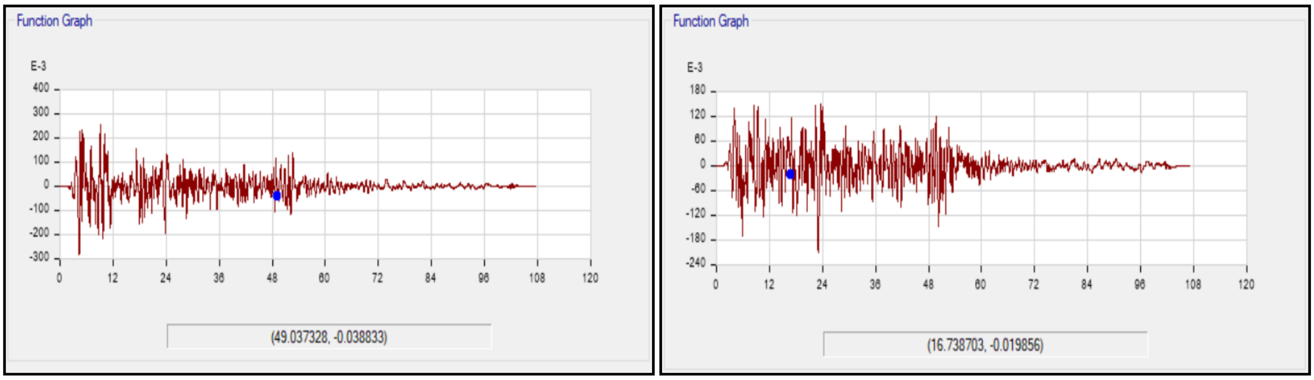

Figure.2 Ground motions of Imperial Valley : In X-direction(left) & In Y-direction(right)

They were derived from 10 historical records with frequency domain adjusted and amplitude scaled, and the soil type was modified from SB–SC to SD. The records are designated as LA01–LA20 and LA21–LA40 for the DBE and MCE hazard levels, respectively. The ground motions supplementary with DBE hazard level are used for constructing seismic response spectra of SDOF systems in the projected design methodology. Both DBE and MCE hazard levels are considered in this study as seismic inputs to the multistory concentrically-braced frames (CBFs).

2. LITERATURE REVIEW

A detailed literature review was carried out prior to the commencement of the project. This literature survey includes the energy based seismic design, Shape Memory Alloy and its application in the bracing and its effects on the structure.

Canxing Qiu, et.al,2020 Low to medium rise building structure are studied by designing two models of SMABF. These models are then exposed to suite of earthquake ground motions scaled from design basis earthquake (DBE) and maximum considered earthquake (MCE) seismic hazard levels. Results showed that the designed SMABFs satisfy the performance target very well.

Canxing Qiu, et.al,2017 The seismic performance of four SCCBFs with various story numbers was evaluated by exposing them to ground motion records analogous to design-basis earthquake. The analysis results show that all the resulting frames were proficient of coinciding well with the approved targets of peak interstory drift ratios and ductility demands. In addition, the structures returned to at-rest positions without generating residual deformation after earthquake events.

Can-Xing Qiu, et.al,2017a proposed a performance-based seismic design (PBSD) method for steel braced frames with novel self-centering (SC) braces that utilize shape memory alloys (SMA) as a kernel component. The seismic performance of the designed frames is scrutinized at various seismic intensity levels. Results of nonlinear time-history analyses specify that the four SMABFs can efficaciously achieve the prescribed performance objectives at three seismic hazard levels. The contrasts among the designed frames divulge that the SMABs with greater hysteretic parameters consequence in a more efficient design in terms of the consumption of steel and SMA materials.

Canxing Qiu, et.al,2017b conducted shake table tests of self-centering steel frame with novel shape memory alloy braces (SMAB) and systematically investigated seismic performance of SMAB frame (SMABF) at different seismic intensity levels through incremental dynamic tests and analyses. In this paper they experimentally validated the salient features of SMABF, including large recoverable interstory drift ratio, reusability of SMAB for numerous earthquakes, and a nearly damage-free state of the frame under strong earthquakes.

Hyunhoon Choi, et.al,2006 adopted an energy-based seismic design procedure for framed structures with buckling-restrained braces are proposed using hysteretic energy spectra and accumulated ductility spectra. The design procedure was applied to three- and eight-story framed structures with buckling-restrained braces. According to analysis results, the mean values for the top story displacement resemble well with the given performance target displacements. The inter-story drifts evicted to be quite uniform over the structure height, which is desirable because uniform inter-story drifts specify uniform damage distribution.

Wen-Shao Chang, et.al,2016 provided an synopsis of the impending and restrictions of shape memory alloys in construction.

Cameron R. Bradley, et.al, 2017 demonstrated overall hysteretic behaviors that are highly dependent on two underlying design parameters: system type and system configuration.

Kazuhiko Kawashima, et.al, 1989 analyzed many single degree-of-freedom bilinear oscillators, with different natural periods, damping ratios, ductility factors, bilinear factors, and input ground motions. A residual displacement response spectrum is presented for design of a single degree-of-freedom structures and a design application is also provided.

3. PROPOSED DESIGN METHOD

3.1. DESIGN PROCEDURE

3.1.1 DESIGN OF SMAB

This section presents the step by step procedure for the proposed energy based method. The procedure is derived on the basis of a assumption that the main frame would carry all the dead loads and gravity loads whereas the lateral loads will be resisted by Shape Memory Bracings. It must be noted, however, that the primary body additionally contributes to seismic resistance in practice. Ignoring the contribution of the main frame may result in conservative design of SMABFs.

Based on the capacity design philosophy, the main frame should remain elastic during earthquakes and the braces develop inelastic hysteretic behavior for energy dissipation. Therefore, this proposed design technique specializes in the design of SMAB.

Step 1: Determination of Target Ductility Ratio

Since minimal deformation is established within the rigid segments of SMABs, the design of SMABs decreases to the determination of SMA cables. The yield displacement of SMAB can be computed from yield strain of the SMA and the effective length of the brace as follow:

$$\mathrm{Uby} = \frac{\mathrm{Lb}}{\varepsilon\mathrm{by}} = \mathrm{Lb}\frac{\sigma\mathrm{by}}{\mathrm{Eb}} \quad (1)$$

$$Usy = \frac{Uby}{\cos\theta} \quad (2)$$

$$Ust = \frac{Ubt}{\cos\theta} \quad (3)$$

Where E_b and σ_{by} = elastic modulus and yield stress of SMA, respectively; θ and L_b = inclination angle and effective length of the SMAB, respectively; Usy = interstory drift corresponding to the yield displacement of SMAB, Uby; and Ubt and Ust = target displacements of brace and the associated story, respectively. Once the yield and target displacements are determined, the target ductility can be calculated as;

$$\mu\mathrm{s} = \frac{\mathrm{ust}}{\mathrm{usy}} = \frac{\mathrm{ubt}}{\mathrm{uby}} \quad (4)$$

Where μs and μb = the ductility demands of the story and the corresponding braces, respectively. It should be noted that the ductility demands in different stories are deemed equivalent to each other, based on the assumption that the structural response is dominated by the fundamental mode.

Step 2: Estimation of Fundamental Period

The fundamental period of the structure desires to be valued in the earliest design. BRBFs and SCCBFs or SMABFs often have different fundamental periods, although they would exhibit comparable seismic demands. Thus the period equation suggested by existing provisions for BRBFs is not necessarily applicable.

In this study, the following simple method is adopted to estimate the fundamental period for SMABFs:

$$\Delta r = Sd\Gamma\phi r = \frac{\mu}{R}\ Sde\Gamma\phi r \quad (5)$$

$$\Gamma = \frac{L}{M} \quad L = \sum_{j=1}^{n} mj\phi j \quad M = \sum_{j=1}^{n} mj\phi 2\ j \quad (6)$$

$$\Delta r = \theta t\ H \quad (7)$$

where S_d and S_{de} = maximum deformation of the nonlinear flag shape model and the corresponding linear model, respectively; Γ, ϕ_r, and ϕ = modal participation factor, modal coordinate at roof level, and modal coordinate over building height, analogous to the fundamental vibration mode, correspondingly;

H = total building height; and θ_t = target roof drift ratio, which equals the target interstory drift ratio if the structure has a uniform height-wise deformation. Eqs. (5) and (6) are based on the assumption that by assuming the SMABs at different stories yield simultaneously, the structural vibration is dominated by its first mode.. Combining Eqs. (5), (6), and (7) with the R-μ-T relationship for the flag-shape model, the fundamental period can be readily estimated for SMABFs.

Step 3: Required Size of SMAB

The cross-sectional area of the SMA cable used in SMABs is acquired by equating the hysteretic energy demand to the energy dissipated by the nonlinear behavior of SMABs. For the flag-shape hysteresis, the loading process contributes to positive work, while the unloading process contributes to negative work. The cross-sectional area of SMAB in the jth story, Abj, follows the story-wise distribution ratio, DRj. To obtain DRj, the lateral force pattern coefficient, Cj, reported by a prior study [4], is introduced to allocate the design base shear to each floor, and defined as :

$$Cj = (pj - pj1)\ (\frac{Wnhn}{\sum_{i=1}^{n} wihi})^{qT-0.2} \quad (8)$$

when j = n; $p_{j+1} = 0$

$$pj = \left(\frac{\sum_{i=j}^{n} wihi}{wnhn}\right)^{qT-0.2} \quad (9)$$

where w_i and w_n = seismic weight at the i^{th} floor and roof, respectively; h_i and h_n = height of the ith floor and roof measured from the ground level, respectively; and q = a parameter related to the high mode effect, which was currently set to be 0.75 based on prior suggestions (Qiu and Zhu 2017a). For convenience, the lateral force distribution coefficients are normalized for P_n j=1 C_j = 1. With C_j obtained, the values of DR_j can be calculated as

$$DRj = \sum_{i=j}^{n} Ci \quad (10)$$

The cross-sectional area of the first-story SMAB is defined to be Ab_1, and the A_{bj} in the other stories can be obtained by multiplying the DR_j

$$Ab_j = DRjAb_1 \quad (11)$$

Based on Eqs. (8)–(10), the cross-sectional area of SMAB at the first story, Ab1, can be expressed as

$$Abj = \frac{Eh\sum_{i=1}^{N} mi}{[(\mu aP - 1) - (\mu aN - 1)\times(1-\beta)^2]\times\sum_{j=1}^{N} DRj\sigma by\frac{Lbj\sigma by}{Eb}} \quad (12)$$

Once the size of SMAB in the first story is determined, those in the other stories can be readily obtained.

Step 4: Finalization of the SMAB

Size Based on the sizes of SMABs in the initial trial, eigenvalue analysis can be carried out to compute the natural period for the structure. This process is repeated until the fundamental natural period converges within an error of 5%, if necessary. In this study, the final periods of the 3- and 6-story frames are 0.6 and 1.3 s, respectively, according to the eigenvalue analysis. The design results are summarized in Table 1 for both the 3- and 6-story SMABFs.[4] It is worth noting that the SMABFs are designed based on the DBE spectrum and are required to meet the targets of θt =1.5% and μ = 5. Regarding the structural performance at the MCE hazard level, the target is set to be θt = 4% and μ = 12.

SMAB			
Story No.	6-story frame		
	DRj	Abj (mm²)	Lbj (m)
1	1	2,213.10	1.05
2	0.96	1,799.80	0.89
3	0.88	1,649.80	0.89
4	0.77	1,443.60	0.89
5	0.61	1,143.60	0.89
6	0.39	731.2	0.89

TABLE 1: Design results of the SMABs [1]

Seismic analysis is conducted for the 6-story framed structures with V-shaped SMABs, as shown in Fig. 3. The bay length of the model structures is 9.14 m (30 ft). The 3-story frame has equal story height of 3.96 m (13 ft). For the 6-story frame, the height of the first story is 5.49 m (18 ft) and 3.96 m (13 ft) in the other stories. The mass of each floor is 151 metric tons. Assuming the installed SMABs at different stories yield simultaneously the target deformation are calculated by the internal forces of beams and columns. According to capacity design, beams and columns are sized to make sure that they remain elastic upon this deformation demand. The final design of the member sizes is presented in Fig. 3.

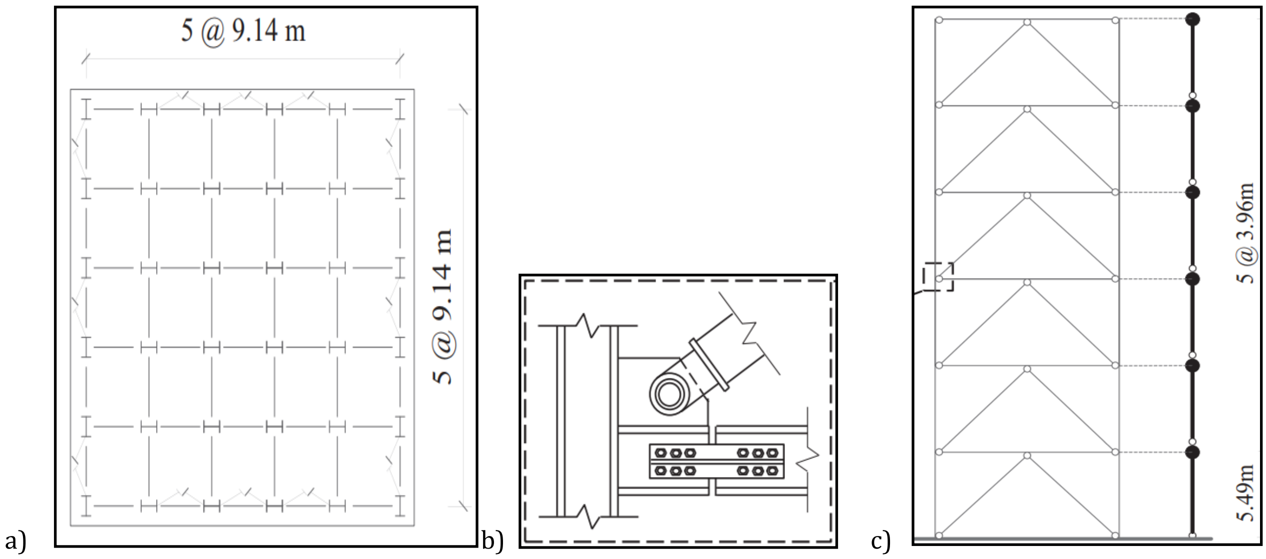

Figure 3. 6-story frame building with SMAB: (a) plan layout; (b) beam-bracing-column connections;

(c) elevation view [5]

The overall performance of the two frames is first evaluated by performing a monotonic pushover analysis, of which the lateral force that conforms to the first mode is applied and maintained throughout the pushover analysis. Gravity loads are gradually placed on the numerical model to produce a P-Δ effect before the lateral force is applied. It can be observed that frames exhibit bilinear elastoplastic behavior within the considered deformation range. The reduction in global stiffness can be attributed to the yield behavior of the SMABs, which is actually the beginning of the forward phase transformation of the SMA cables.

4. RESULT AND DISCUSSION

4.1. MONOTONIC PUSHOVER ANALYSIS

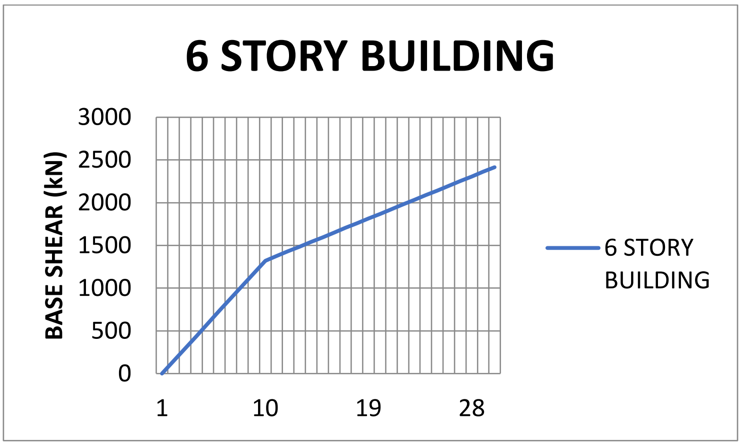

Figure 4. Monotonic Pushover Curve (Base shear vs story drift)

The 3- and 6-story frames begin to yield on the 11.2 cm roof drift, respectively, which correspond to the base shear of 1,644 kN. After yielding, the structures maintain their load carrying capacity without strength deterioration, which is primarily attributed to the positive postyield stiffness ratio of the SMA cables. The target displacement was stopped at 30 cm, which is sufficiently large to allow the two frames to develop considerable nonlinear behavior and to activate the P-Δ effect on the building.

4.2 MAXIMUM STORY DRIFT

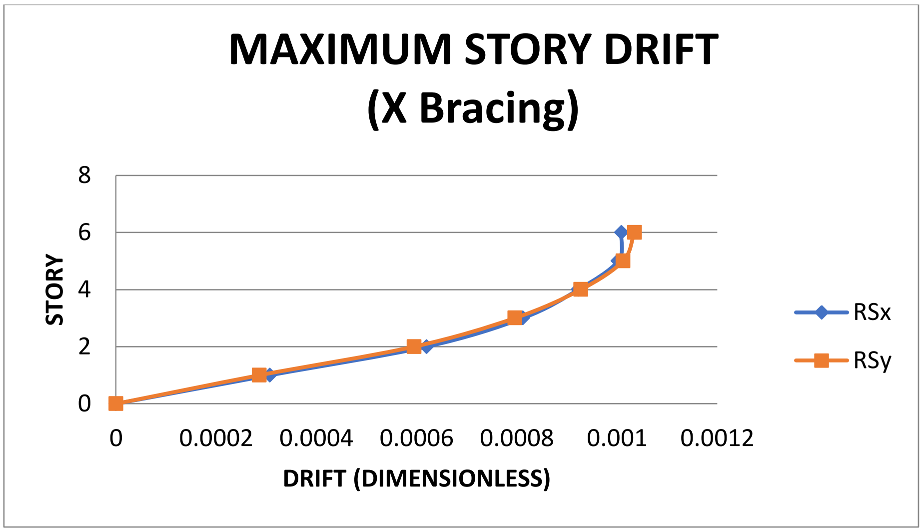

Figure.5 Maximum Story Drift (X-Bracing)

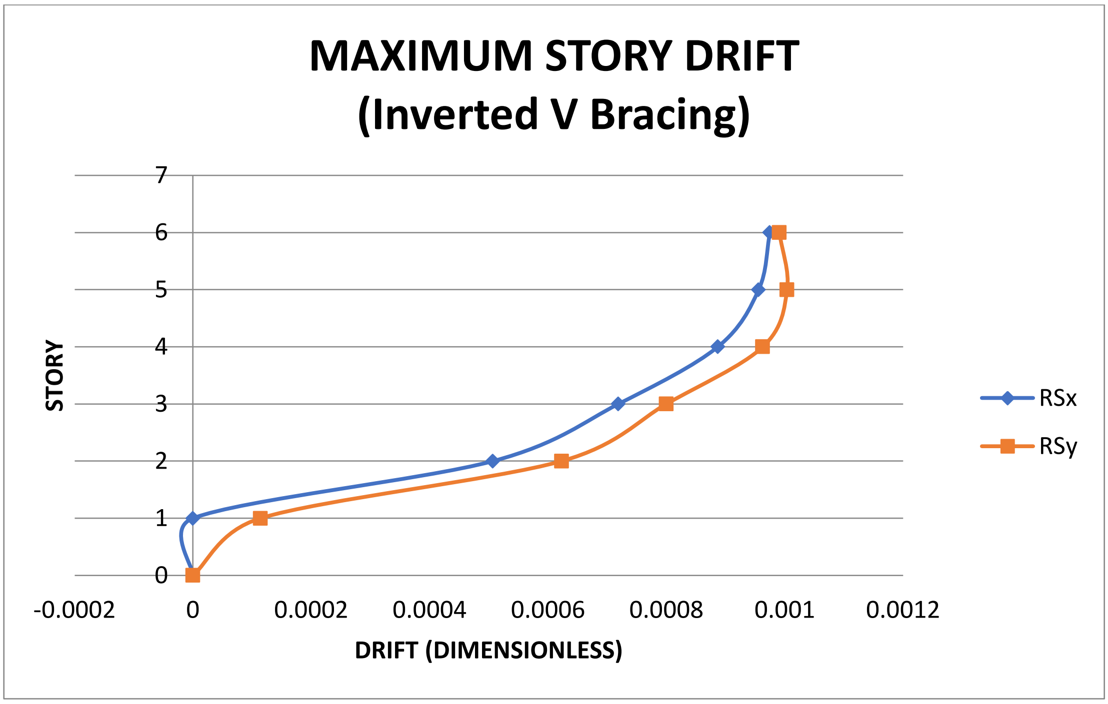

Figure.6 Maximum Story Drift (Inverted V Bracing)

The maximum storey drifts are obtained and compared amongst the building models. The drift changes when the orientation of the bracing is changed. Also the drift is minimized by 16% after the application of SMAB on the structure. This shows that the designed SMAB is working effectively.

4.3. MAXIMUM STORY DISPLACEMENT

The maximum storey displacement are obtained and compared amongst the building models. From the graphs, we can see that the displacement has been drastically reduced to 16.77% after the application of SMAB in the structure.

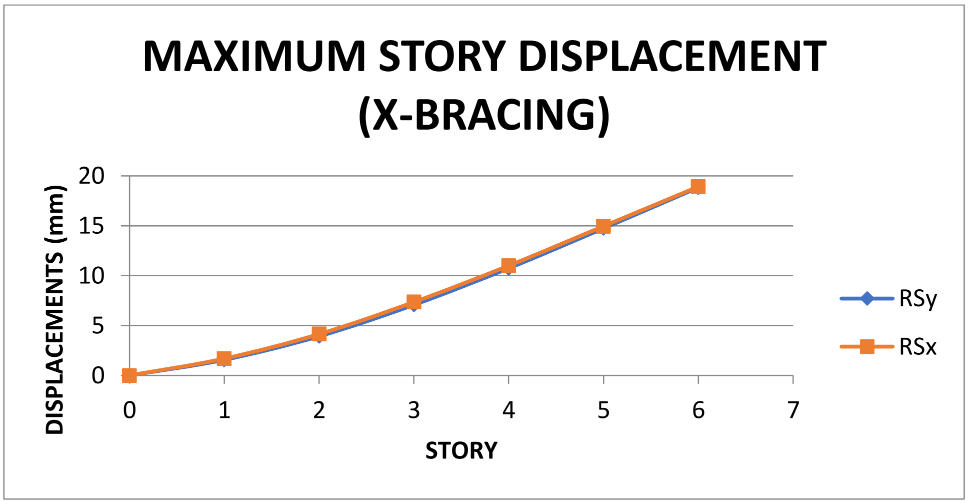

Figure.7 Maximum Story Displacements (X-Bracing)

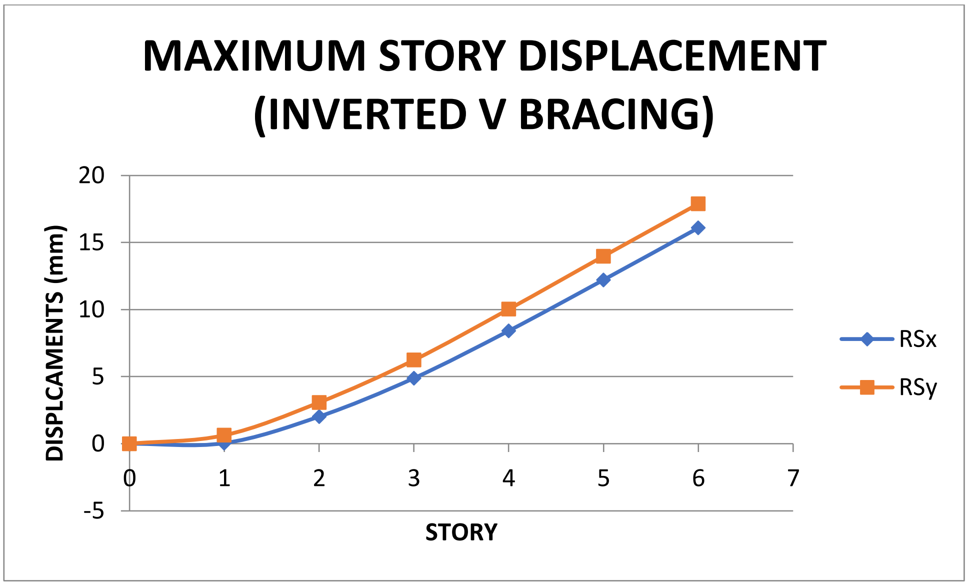

Figure 8. Maximum Story Displacement (Inverted V Bracing)

5. CONCLUSIONS

This study proposed an energy-based seismic design methodology for SMABFs. In this method, the construction of the spectra of hysteretic energy and accumulated ductility are the essential steps. Two low-to-medium rise multistory SMABFs were designed to demonstrate the efficacy of the proposed design method. The following conclusions are obtained from the seismic analysis of the SMABFs under the selected suite of ground motions associated with the DBE and MCE hazard levels:

1. At the DBE level, the properly designed SMABFs demonstrate satisfactory seismic performance, where the peak interstory drift meets the prescribed target very well, the floor acceleration is controlled within safe region, and the residual deformation is almost eliminated.

2. Both the peak demands of deformation and acceleration of the designed SMABFs are almost uniformly distributed along the building height, indicating that the design effectively avoids damage concentration for the structures.

3. The hysteretic energy generated in the SMABs generally matches the accumulated ductility demand on these components, implying that the nonlinear behavior of SMABs enables the SMABFs to perform up to expectations.

4. For the SMABFs designed based on the DBE spectrum, the earthquakes associated with MCE hazard level might cause unrecoverable deformation in the structures. The residual deformation is, however, mostly smaller than the repairing threshold due to the SC capability of SMABs.

5. The spectra of hysteretic energy and accumulated ductility are constructed and can be extended to other structures characterized by flag-shape behavior.

6. Further work is being done to examine the generalization of the proposed methodology to account for various hysteretic behaviors of SMAs, the high mode effect in high-rise buildings, and the effect of varying span length or story height of SMABs.

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