

PARAMETRIC STUDY OF VERTICALLY ISOLATED STEEL BRACED FRAMES CONTROLLED BY SHAPE MEMORY ALLOYS

S. Babaei ^a, F. Karimi Ghaleh Jough ^{a,*}

^a Faculty of Engineering, Department of Civil Engineering, Final International University, Via Mersin 10, AS 128, Kyrenia, North Cyprus, Turkey, E-mails: sasan.babaei@final.edu.tr, * fooad.karimi@final.edu.tr

Received: 12.06.2024 / Accepted: 22.08.2024 / Revised: 08.10.2024 / Available online: 15.12.2024

DOI: [10.2478/jaes-2024-0024](https://doi.org/10.2478/jaes-2024-0024)

KEY WORDS: Vertical isolation, Shape memory alloy, Parametric study, Finite element analysis, Incremental dynamic analysis.

ABSTRACT:

Vertical isolation has gained interest in recent years by incorporating the damping mechanism within the height and evading the concentration of isolation elements in the base. However, dividing the building into separate systems may be less practical in regular buildings. This study used a conventional steel-braced lateral load-resisting system inherently made up of two soft and stiff portions to compare the efficiency of the isolation technique. Shape memory alloys (SMAs) with flag-shaped hysteresis damping mechanisms are assigned among the two subsystems to elaborate the damping mechanism. Parametric coding in OpenSees investigates a large set of frames with altered stiffness of the stiff subsystem subjected to time histories of 40 records with 2 and 10 % probability of exceedance. Increasing the stiffness of the stiff subsystem reduces the interstory and roof drift by more than 30%. SMA employment is shown to be effective in reducing the interstory, and roof drift at the soft- subsystem. The maximum reduction happens on the 1st floor by 32% and the least on the roof by 8%. There was a mild rise in the stiff subsystem's responses, however, this increase may be neglected as the performance level is governed by the soft- subsystem's response. The SMA-equipped frame is then further assessed by incremental dynamic analysis. Fragility curves of the system damage states delineate a promising response from the system.

1. INTRODUCTION

Base isolation is known as one of the effective methods to keep from the principal frequency content of the expected seismic hazard in the region. This technique can be implemented either globally or locally within the lateral load-resisting system, to both control structural or targeted non-structural components. High-period substructure at the base, on the other hand, demands huge gaps at the base due to the accumulation of displacement. Formerly to address this issue, the damping mechanisms were introduced in the isolation layer at the base, which may become less practical due to the activation of higher modes in strong seismic events. As a result, mid-story and multi-story isolation have been assessed and were effective in decentralizing the damping mechanism and drift arising from the high period isolation layer.

Multi-layer isolation by shifting the displacement at the base to the upper stories facilitates the construction of isolated high-rise buildings close to a low rise in a densely populated area. Becker and Ezazi's investigation showed that two layers of isolation decrease almost half of the 1st floor's displacement while increasing the upper-story ones by 19% (Becker and Ezazi 2016). Skandalos et al. benefiting meta-heuristic optimization reported multiple layers of isolation are effective and isolation layers should be installed at the lower story level (Skandalos, Afshari et al. 2020).

Isolation bearing also may fail due to the uplift or high gravitational loads imposed on them, especially in high-rise buildings. To address this drawback vertical isolation is suggested to apply both isolation and damping mechanisms within the height. In this system, the structure system is divided into two individual skeletons, one stiff with less system mass and the other ductile with more system mass (Ziyaeifar and Noguchi 1998, Ziyaeifar 2000). This system is effective in evading the resonance like its horizontal counterparts and also corresponds to the prevailing construction design. In fact, the stiff substructure can be located on one side of the building or be accommodated at the core of a lateral load-resisting system such as at the elevator shaft (Babaei and Hosseini 2023). A dual isolation system comprising horizontal isolation at the base and vertical isolation at the upper portion is another manipulation of conventional design. Babaei et al. showed dual isolation system with the help of the tuning effect reduces the relative and absolute lower story drift by 10% compared to traditional base isolation (Babaei, Zarfam et al. 2023).

Moeinadini et al. decoupled the frame of a massive building façade from the main structure, demonstrating a 66% reduction in lateral drift at the façade and a 14% reduction in the main building (Moeinadini et al., 2023). Milanchian and Hosseini showed the efficiency of the model in reducing the engineering demand parameters is mostly attributed to the mass and stiffness ratio of its subsystems rather than to the nonlinearity of the damping mechanism (Milanchian and Hosseini 2019). Babaei

* Corresponding author: Foad. Karimi Ghaleh Jough, Associate professor, Faculty of Engineering, Department of Civil Engineering, Final International University, Via Mersin 10, AS 128, Kyrenia, North Cyprus, Turkey. Email: fooad.karimi@final.edu.tr.

and Karimi compared the response of a linear-shear-type model of tuned vertical isolation controlled by the viscous damper. Dividing the ductile substructure with more mass into two subcomponents and tuning the period of the upper portion were reported to be effective in reducing lower subsystem response by 45% (Babaei and Karimi Ghaleh Jough 2024). Previous research on vertical isolation, mostly considers the structure to be linear and the damping system used is either a linear or nonlinear viscous damper (Karimi Ghaleh Jough and Şensoy 2020, Jough et al. 2021, Ghaleh Jough 2024, Karimi Ghaleh Jough and Ghasemzadeh 2024).

To this end, finite element analysis of a vertical isolation system accommodating shape memory alloy (SMA) as a damping mechanism was analyzed in OpenSees. An SMA performs two macroscopic behaviors namely, super-elasticity (SE) and a shape memory effect (SME) through a flag-shaped stress-strain hysteresis diagram. These behaviors contribute to stiffness in linear areas and to ductility and energy dissipation in nonlinear regions. In addition to the self-centering and high damping capacity, this material provides for the lateral load-resisting system, in comparison with traditional viscous and metal dampers, they have a greater resistance toward fatigue, and corrosion, and require less maintenance (Menna, Auricchio et al. 2015, Babaei and Zarfam 2019).

SME and SE have introduced numerous new applications for improving the seismic resistance of steel structures, such as smart braced frames, SMA cable-restrained bearings, and SMA reinforcements in concrete structures (Karmakar et al., 2024, Liu et al., 2024, Baidya & Roy, 2024). Rele et al. equipped the piers of a rocking-controlled isolated bridge with SMA, demonstrating a 25% reduction in the demand moment for the pier section (Rele et al., 2021). Zhang et al. investigated a novel SMA-friction isolator enhanced with an inertia pendulum for vibration control in bridges. Their study revealed reductions in both deck drift and pier base shear (Zhang et al., 2022). Li et al. explored the shear performance of seawater sea-sand concrete beams reinforced with SMA longitudinal bars and stirrups, showing an 89% increase in shear ductility alongside effective self-centering behavior (Li et al., 2024).

In this study, a conventional three-story four-bay steel-braced building was initially designed in ETABS. A braced frame of the designed building is then parametrically modeled in OpenSees. Braced portion of the building was designated as a stiff subsystem and the moment frame was labeled as a ductile one. Shape memory alloy was then assigned at the two ends of the mid-beam connecting the two subsystems. Floors interstory drift of the steel-braced and frame with SMA were subjected to 40 ground motions of 2 and 10% probability of exceedance in 50 years. To assess the sensitivity of the response to the subsystem's period, the stiffness of the stiff- subsystem changed in the low to high range for the two steel and SMA-equipped frame, to generate the spectra of the engineering demand parameters, namely, residual interstory, interstory, and roof drifts. The results indicate increasing the stiffness of the stiff subsystem leads to a response reduction for all the investigated parameters and for all floors of the stiff and soft subsystems. Utilization of shape memory alloy proved to be effective in reducing the soft-subsystem's response, especially on the first floor. Depicted spectral interstory drift response, for instance, shows that SMA-equipped frames on average for the 1st, 2nd, and 3rd floors have a reduction of 32, 19, and 8%. Stiff subsystem may witness a mild rise, however, as the building's performance level is governed by the soft subsystem response this increase can be ignored. After portraying the

efficacy of the SMA-equipped frame the incremental dynamic analysis of 22 far-field records was conducted, and lower, mean, and upper fractile curves were generated. The fragility curve for slight moderate, and extensive damage states is finally estimated. The sequential procedure of design and assessment of vertical isolation is introduced in Figure. 1.

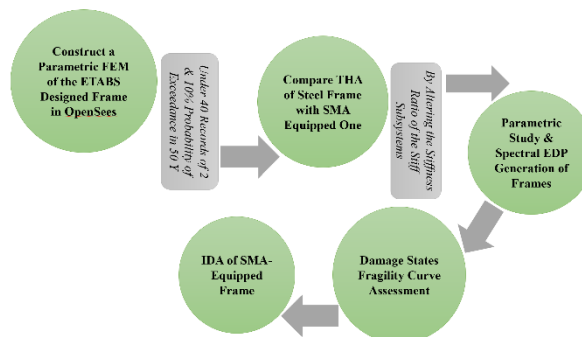


Figure 1. The sequential procedure of design and assessment of vertical isolation

2. ANALYTICAL MODEL

A three-story steel-braced buildings were designed in ETABS for a site in downtown Seattle (47.6 longitude and-122.34 latitude) with a soil class D. X-braced bays allocated in the perimeters are assigned to represent the lateral load resistance of the building. Each orthogonal direction is braced at two bays, four bays at two corners. The span length and the story height at the frame are equal to six and three meters. The base connections are rigid. Columns, beams, and braces are HE260A, IPE300, and HSS 180X180X10 respectively. Assigned sections, the bay's dimensions, and the plan view of the building are portrayed in Figure 2. a and b.

Two-dimensional modeling was conducted hence the building is symmetric in both directions. The lateral load-resisting system is mainly made up of the braced bays contributions. As a result, the mass assigned to the story level of the modeled frame is also attained by dividing the whole mass of each story level by the braces in each orthogonal direction. The analysis takes the P-delta effect and 5% of Rayleigh into consideration.

The fiber-section command was used to define the sections in OpenSEES. All beam-column connections were modeled as rigid. The Steel01 bilinear command was utilized to characterize the steel behavior in the columns, whereas the steel in the beams and braces was represented using a uniaxial hysteretic command that captures strength and stiffness degradation as well as pinching behavior. To account for the global buckling of the brace frames, an imperfection of 0.001 was introduced. Additionally, the gusset plates at the braces, as illustrated in Figure. 2b, were incorporated into the system using the Steel02 command.

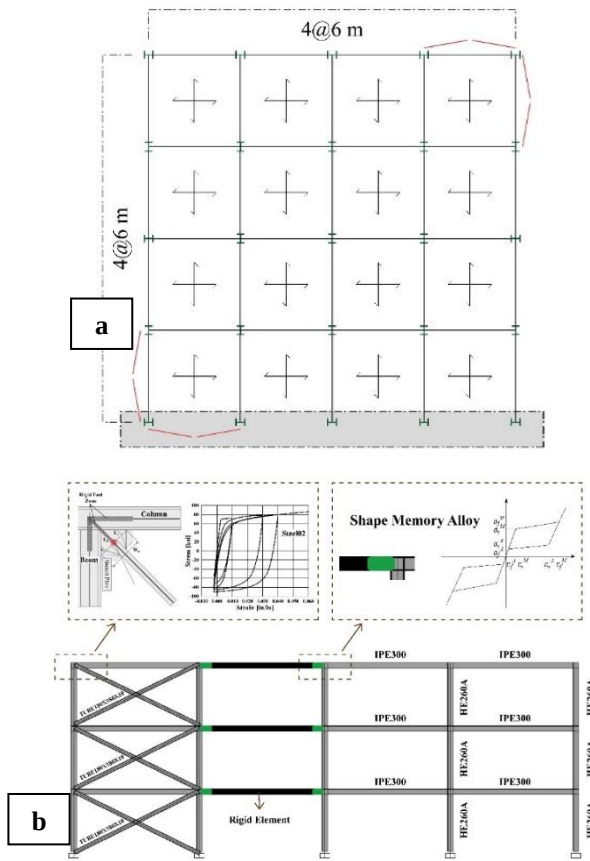


Figure 2. a) Plan view, b) Elevated view of the three-story frame

The beams, columns, and braces in both the steel and smart frames are identical, except for the beams in the second span, which connects the two substructures replaced and contains SMA. For an equitable comparison, both the steel and smart frames possess identical natural periods, and the material within the beams should yield at similar strength. To make the use of high-cost SMA economically feasible, the entire beams in the second span of the smart frame are not made of SMA. Instead, a rigid segment is connected to a specific length of SMA to construct these beams (see Figure 2b). This rigid segment ensures that all the deformation occurs in the SMA portion. The required length of the SMA segments for a constant-period section can be determined using the following equations.

$$\frac{1}{m} = \frac{1}{k} + \frac{1}{10k} + \frac{1}{k} \quad (1)$$

$$k = 2.1m \quad (2)$$

$$\frac{E_{sma}A_{sma}}{L_{sma}} = 2.1 \frac{E_s A_s}{L_s} \quad (3)$$

$$A_{sma} = 2.1A_s \frac{E_s L_{sma}}{E_{sma} L_s} \quad (4)$$

Where m and k are the stiffness of the conventional beam and stiffness of each SMA segment, E_s , E_{sma} , A_s , A_{sma} , L_s , and L_{sma} are the modules of elasticity, area, and length of the regular beam and SMA element.

The self-centering command in OpenSEES was utilized to include SMA. Elements were assigned by the nonlinear beam-

column command and have five integral points. The SMA-equipped beam segments were linked using zero-length elements, which exhibited high stiffness at the SMA-steel connections. The material characteristics used for numerical modelling are detailed in Table 1.

Young's modulus (MPa)		Steel yielding stress (MPa)	
Steel	SMA		
200000	27579		
		345	
Transformation stress level (MPa)			
Austenite-martensite		Martensite-austenite	
Start	Finish	Start	Finish
414	550	390	200

Table 1. Material characteristics of steel and shape memory alloy

3. TIME HISTORY ANALYSIS OF STEEL AND SMA-EQUIPPED FRAME

The time history analysis of the two substructures of the steel-braced and SMA-equipped frame subjected to LA16 (1994 Northridge) and LA30 (1974 Tabas) ground motions are compared in Figure 3. The analysis expatiates that the stiff subsystem experiences a lower roof drift in comparison to the soft one which is expected as inherits lower period. Shape memory alloy for LA16 and LA30 reduced the maximum roof drift from 28.4, and 23.4 cm to 19.7, and 19.5 cm respectively. In addition to that, the application of SMA speeds up the energy dissipation process. Stiff subsystem equipped with SMA on the other hand, has a greater value in LA16, while reduced under LA30. Residual roof drift with two records may not lead to conclusive results as SMA was quite effective while the frame was subjected to LA30 (record with 2% probability of exceedance). Residual drift on the contrary increased under LA16, especially for the soft-subsystem.

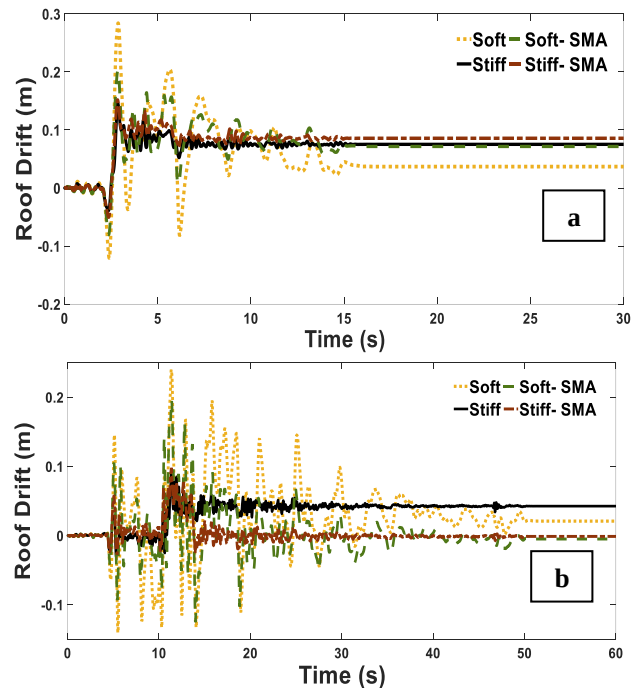


Figure 3. Time history analysis subjected to LA16 (1994 Northridge) and LA30 (1974 Tabas)

In this regard, the two conventional and SMA-equipped buildings were subjected to a time history analysis of 40 ground motions. The average maximum interstory drift of these buildings concerning the story level is depicted in Figure 4. Soft substructures by their higher periods entail the maximum interstory drift in comparison to the stiff ones.

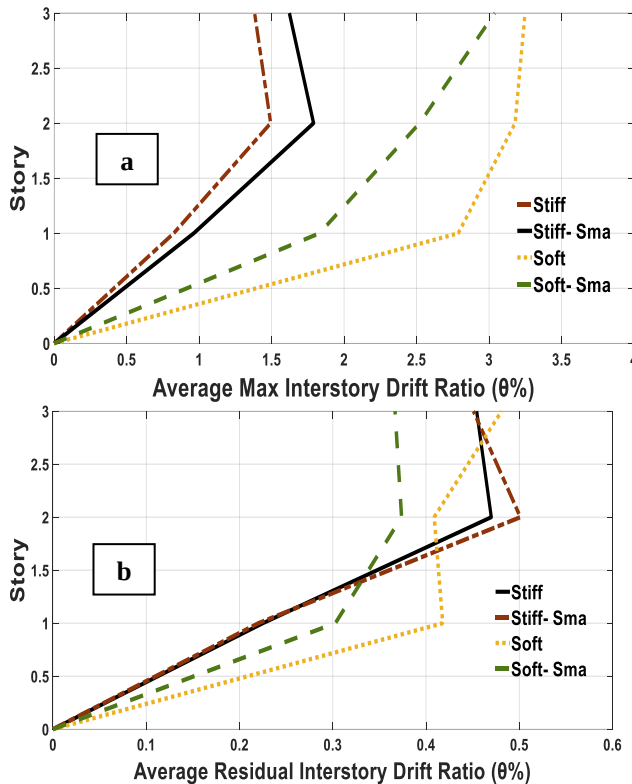


Figure 4. Average maximum, a) Interstory drift ratio, b) Residual interstory drift ratio

The substructures comprise the least interstory drift at the lower floors, and the soft sub-structures inherit their maximum interstory drift on the 3rd floor equal to 3.24 and 3.04 percent rotation for the conventional and SMA -equipped frame respectively. It also can be seen the SMA presence led to a more uniform behavior. On the contrary, in conventional steel frames, the stiff sub-structures have less drift while the soft- subsystem witnesses a higher amount of rotation, especially in the 1st and 2nd stories. Figure 4 also portrays the average residual interstory drift

as less dispersed and stiff subsystem experience the most, particularly on the 2nd and 3rd floors.

4. EFFECT OF STIFFNESS RATIO OF STIFF SUB-SYSTEM ON FRAMES SEISMIC BEHAVIOR

As the frame response is mostly affected by its sub-components period (stiff and soft substructures). The stiffness of the stiff substructures altered in the range of 0.7 to 1.8 times the initially designed frame to generate a set of frames. The stiffness ratio of these frames to the initial one is called SR. The spectral seismic demand parameters of these frames were then obtained regarding this evolutionary parameter (SR). The generated frames once with SMA and once without it are subjected to time history analysis of two sets of records with a 2 and 10 percent probability of exceedance in 50 years. Figure 5 delineates increasing the stiff's substructure stiffness reduces the maximum interstory drift for all sets of ground motions at two frames at all floors. Interstory drift on the 1st floor is less than the upper ones, this value is even much less for the SMA-equipped frame. In fact, utilizing SMA reduced the 1st floor's drift by 32%. This trend is also evident on the second floor, shape memory alloy reduced this story response almost by 19%. 3rd floor however is less sensitive to the SMA by capacity of reducing the interstory drift by 8%. SMA capacity to reduce the response for the first floor is not sensitive to the stiffness of the stiff subsystem. However, by increasing the stiffness of the stiff subsystem, the SMA contribution decreases especially on the 3rd floor.

Although SMA reduces the interstory drift at the soft sub-system, Figure 6 reveals that SMA leads to higher interstory drifts at the stiff sub-structure. This increase in response is more considerable in the upper story, and it may reach to 14%. However, the overall interstory drift of the building as is controlled by the soft sub-structure, SMA-equipped frame represents a better occupancy.

The residual interstory drift of the system is portrayed in Figure 7. Both SMA-equipped and conventional frames experience higher residual drift at the stiff subsystems at upper stories, while residual interstory drift for this subsystem is the least on the first floor. SMA was also effective in reducing the response on the 2nd floor. Soft- subsystems, on the other hand, contain similar residual drifts. A comparison of the two figures also reveals the usage of the SMA leads to a 20% reduction of the soft subsystem's residual interstory drift.

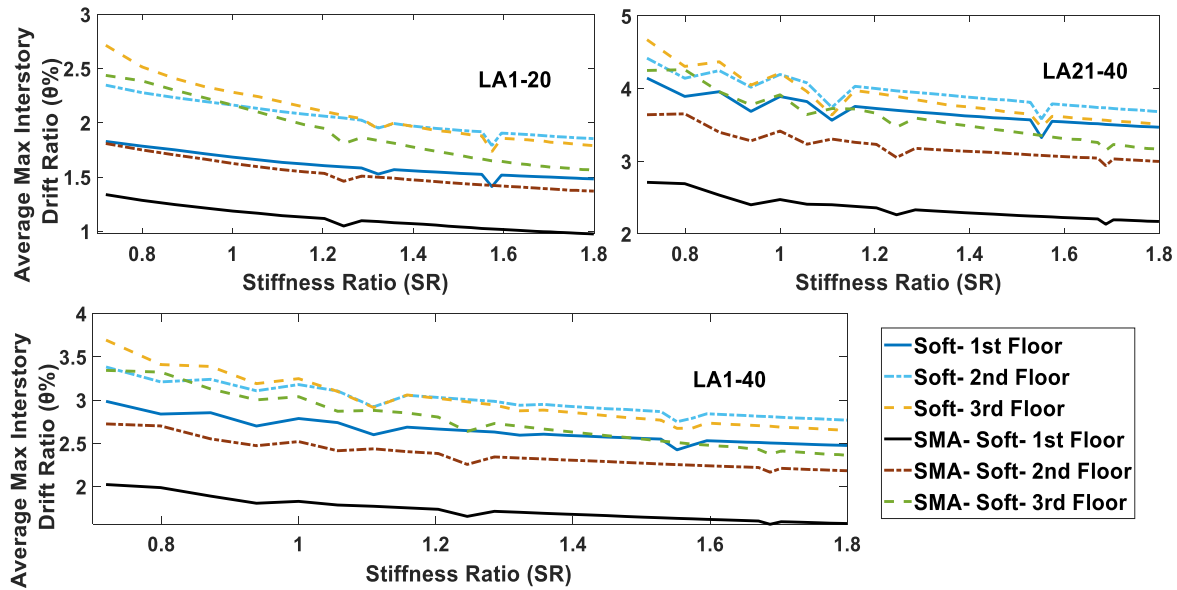


Figure 5. The soft- subsystem' maximum average interstory drift corresponds to a series of records (a) 20 records with 10% probabilities of exceedance in 50 years (b) 20 records with 2% probabilities of exceedance in 50 years (c) 40 investigated records

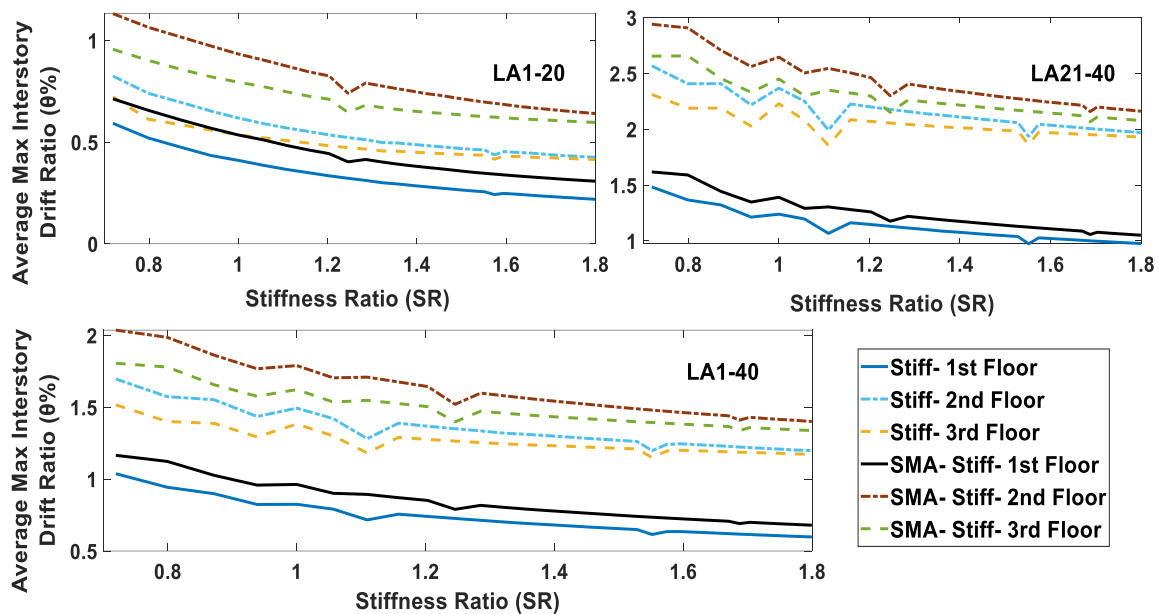


Figure 6. The stiff - subsystem' maximum average interstory drift corresponds to a series of records (a) 20 records with 10% probabilities of exceedance in 50 years (b) 20 records with 2% probabilities of exceedance in 50 years (c) 40 investigated records

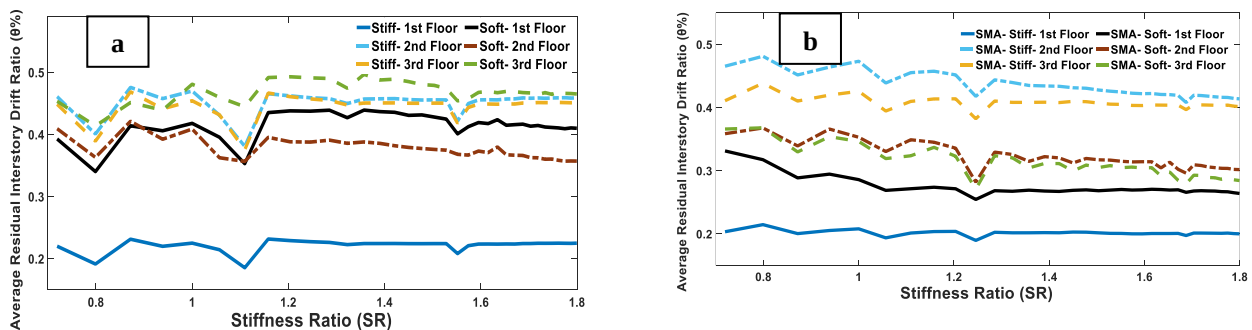


Figure 7. Average residual interstory drift of the a) Steel braced frame; b) SMA-equipped frame when subjected to 40 records with 2 and 10% probabilities of exceedance in 50 years

The maximum roof drift of the frames subjected to 40 ground motions delineates increasing the stiff sub-system's stiffness to 2.5 times of its initial ones leads to a 32% reduction of drift for the stiff subsystem and a 27% reduction of the soft ones (Figure 8). SMA's contribution to the stiff subsystem's response is almost negligible. However, SMA-embedded frames have

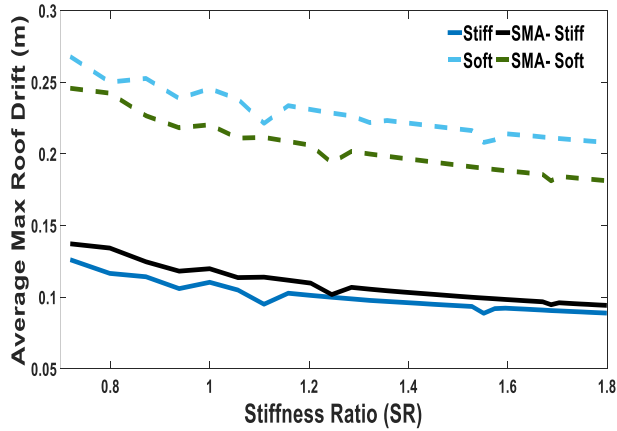


Figure 8. Average maximum roof drift of the a) Steel braced frame; b) SMA-equipped frame when subjected to 40 records with 2 and 10% probabilities of exceedance in 50 years

almost 8% lower spectral roof drift in comparison with conventional steel frames.

5. INCREMENTAL DYNAMIC ANALYSIS

To gain an in-depth understanding of the seismic behavior of the analyzed frame, Incremental Dynamic Analysis (IDA) was performed using 22 far-field records recommended by FEMA P695. The input acceleration was incremented by 0.5 m/s^2 at each step. Figure 9 depicts the maximum interstory drift for each step of the stiff and soft subsystems, respectively. The mean, lower, and upper fractiles were also calculated and shown in the graph. Stiffness resurgences visible in the graph may be attributed to initial plastic deformations caused by the yielding of the Shape Memory Alloy (SMA) with lower stiffness.

A comparison of the subsystems reveals that the soft subsystem experiences significant yielding at a drift ratio that is 25% higher than the stiff subsystem. The lower fractile of the IDA results indicates that the stiff subsystem exhibits brittle behavior, while the soft subsystem shows a more ductile failure mode. Initially, the three fractile results for both subsystems are almost identical, but they diverge significantly towards the end of the analysis.

This divergence is likely due to the formation of plastic hinges during nonlinear analysis and differences in the frequency content and duration of the ground motion records.

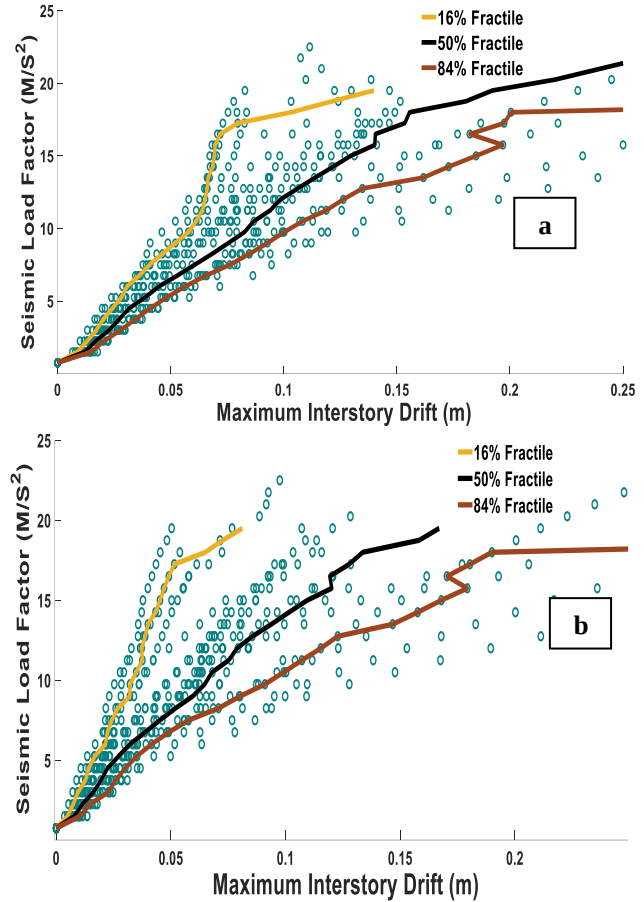


Figure 9. Incremental dynamic analysis of a) Soft subsystem, b) Stiff subsystem

The fragility curve of the SMA-equipped frame corresponding to the slight, moderate, and extensive damage states was obtained subjected to 22 far-field records. The log-normal distribution of the damage states is portrayed in the Figure 10. The threshold of the average peak acceleration for the slight, moderate, and extensive damage states are 1.6, 4, and 10.4 m/s^2 respectively.

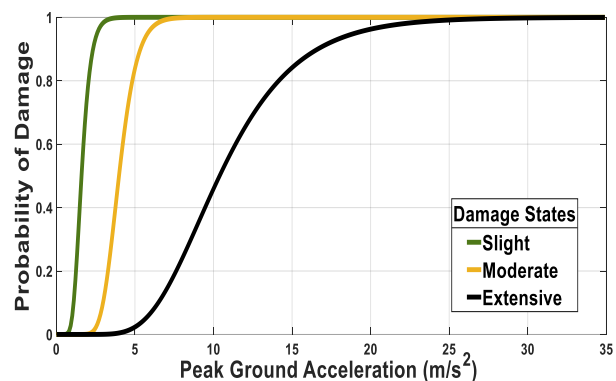


Figure 10. Incremental dynamic analysis of a) Soft subsystem, b) Stiff subsystem

6. CONCLUSION

The current study assessed the sensitivity of a three-story SMA-equipped vertically isolated frame to its subsystem's stiffness. The stiffness of the stiff substructures altered in the range of 0.7 to 1.8 times the initially designed frame to generate a set of frames. The generated frames once with SMA and once without it are subjected to time history analysis of two sets of records with a 2 and 10 percent probability of exceedance in 50 years.

The results reveal, that increasing the stiff- subsystem's stiffness to 2.5 times reduces interstory, and roof drifts by more than 30 percent for both sets. On the contrary residual interstory drift is less sensitive to the stiffness of the stiff subsystem.

SMA-equipped frames, compared to conventional steel ones, comprise on average 32, 19, and 8% interstory drift for the soft subsystem's 1st, 2nd, and 3rd stories.

Nonetheless, the stiff subsystem experienced a rise in interstory drift by 14% on the 3rd floor. However, as the response is controlled by the soft -subsystem this rise does not affect the performance level of the frame. Spectra of the average maximum roof drifts also indicate the stiff subsystem experiences negligible increased drifts, whereas the soft subsystem within the SMA-equipped frame experiences drifts that are 8 percent lower.

In order to conduct a more comprehensive seismic evaluation of the SMA-equipped frame, Incremental Dynamic Analysis was performed. Fragility curves were then derived for the system's damage states, revealing a promising response for the overall system.

References

- Baidya, S., & Roy, B. K. (2024). Seismic reliability analysis of base isolated building supplemented with shape memory alloy rubber bearing using support vector regression metamodel. *Structures*, 65, 106773. <https://doi.org/https://doi.org/10.1016/j.istruc.2024.106773>.
- Babaei, S. and M. Hosseini (2023). Semi-active Control of 3D-Vertically Isolated Buildings with Divided Skeleton into Inner and Outer Interactive Subsystems Equipped with MR Dampers. *Canadian Conference - Pacific Conference on Earthquake Engineering 2023*.
- Babaei, S. and F. Karimi Ghaleh Jough (2024). "A Comprehensive Evaluation of Tuned Vertical Isolation System for Seismic Risk Mitigation." *Journal of Applied Engineering Sciences* 14(1): 27-34.
- Babaei, S. and P. Zarfam (2019). "Optimization of shape memory alloy braces for concentrically braced steel braced frames." 9(1): 697-708.
- Babaei, S., P. Zarfam, A. Sarvghad Moghadam and S. M. Zahrai (2023). "Assessment of a dual isolation system with base and vertical isolation of the upper portion." *Structural Engineering and Mechanics* 88(3): 263-271.
- Becker, T. C. and A. Ezazi (2016). "Enhanced performance through a dual isolation seismic protection system." *The Structural Design of Tall and Special Buildings* 25(1): 72-89.
- Jough, Foad Karimi Ghaleh (2024). "Fuzzy Logic-Based Fragility Curve Development for Steel Moment-Resisting Frames Considering Uncertainties in Seismic Response." *Journal of Earthquake and Tsunami*, 18(05): 2450014.
- Jough, F. K. G., Veghar, M., & Beheshti-Aval, S. B. (2021). Epistemic Uncertainty Treatment Using Group Method of Data Handling Algorithm in Seismic Collapse Fragility. *Latin American Journal of Solids and Structures*, 18(3), e355. <https://doi.org/10.1590/1679-78256254>.
- Karmakar, S., Kumar, A., & Kolay, C. (2024). Development, characterization, and seismic application of a shape memory alloy-based self-centering damper. *Soil Dynamics and Earthquake Engineering*, 183, 108797. <https://doi.org/https://doi.org/10.1016/j.soildyn.2024.108797>.
- Karimi Ghaleh Jough, F. and B. Ghasemzadeh (2024). "Uncertainty Interval Analysis of Steel Moment Frame by Development of 3D-Fragility Curves Towards Optimized Fuzzy Method." *Arabian Journal for Science and Engineering* 49(4): 4813-4830.
- Karimi Ghaleh Jough, F. and S. Şensoy (2020). "Steel Moment-Resisting Frame Reliability via the Interval Analysis by FCM-PSO Approach considering Various Uncertainties." *Journal of Earthquake Engineering* 24(1): 109-128.
- Li, Z., Dong, F., Qian, H., Qiu, P., & Shi, Y. (2024). Shear performance of seawater sea-sand concrete beams reinforced with shape memory alloy longitudinal and stirrup bars. *Construction and Building Materials*, 421, 135685. <https://doi.org/https://doi.org/10.1016/j.conbuildmat.2024.135685>.
- Liu, X., Wang, W., Hu, D., Qu, J., & Cao, C. (2024). Test, design, and parametric analysis of a prefabricated industrial building with shape memory alloy (SMA) cable-restrained bearings for seismic resilience. *Engineering Structures*, 313, 118288. <https://doi.org/https://doi.org/10.1016/j.engstruct.2024.118288>.
- Menna, C., F. Auricchio and D. Asprone (2015). Chapter 13 - Applications of Shape Memory Alloys in Structural Engineering. *Shape Memory Alloy Engineering*. L. Lecce and A. Concilio. Boston, Butterworth-Heinemann: 369-403.
- Milanchian, R. and M. Hosseini (2019). "Study of vertical seismic isolation technique with nonlinear viscous dampers for lateral response reduction." *Journal of Building Engineering* 23: 144-154.
- Moeinadini, A., Ziyaeifar, M., & Nekooei, M. (2023). Facade isolation in seismic design of tall buildings. *Structures*, 58, 105416.
- Rele, R., Balmukund, R., Bhattacharya, S., Cui, L., & Mitoulis, S. A. (2021). Application of controlled-rocking isolation with shape memory alloys for an overpass bridge. *Soil Dynamics and Earthquake Engineering*, 149, 106827. <https://doi.org/https://doi.org/10.1016/j.soildyn.2021.106827>.
- Skandalos, K., H. Afshari, W. Hare and S. Tesfamariam (2020). "Multi-objective optimization of inter-story isolated buildings using metaheuristic and derivative-free algorithms." *Soil Dynamics and Earthquake Engineering* 132: 106058.

Ziyeifar, M. (2000). Method of mass isolation in seismic design of structures. Twelfth world conference on earthquake engineering, Auckland, New Zealand.

Ziyeifar, M. and H. Noguchi (1998). "Partial mass isolation in tall buildings." *Earthquake Engineering & Structural Dynamics* 27(1): 49-65.

Zhang, Z., Zhou, H., Qian, H., & Wang, L. (2022). Shape-memory alloy-friction isolator enhanced with inertia pendulum for seismic mitigation of bridges. *Structures*, 45, 243-256. <https://doi.org/https://doi.org/10.1016/j.istruc.2022.08.123>.