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Seismic Response of Timber Braced Frames with Shape Memory Alloy Dampers

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ABSTRACT

Braced frames are often used to enhance lateral load capacity and stiffness of timber structures, especially in tall buildings subjected to significant lateral loads. This paper examines applicability of Shape Memory Alloy (SMA) dampers within braces in timber buildings. With significant energy dissipation capacity, the concept is of considerable interest for tall timber structures in seismic regions. The superelastic nature of SMA contributes to self-centering performance of the system. A robust numerical model of timber frames incorporating SMA dampers is developed. Seismic responses of the system with different arrangements and configurations of braces are examined through extensive numerical investigations. Results indicate frames with V-braces exhibit superior performance compared to other brace configurations.

Keywords: Timber Frame; Braced Frame, Seismic Performance, Energy Damper, Shape Memory Alloy.

INTRODUCTION

The conventional timber brace is a popular and cost-effective lateral resisting system construction method. The inherent stiffness of timber is utilized when loaded parallel to its grain, and it can provide adequate initial stiffness during low to moderate seismic events. However, the brittle nature of timber may limit the ductility and energy dissipation capabilities of timber braces or structures in seismically active areas. In such cases, steel connections are critical for providing strength and flexibility for effective seismic performance [1].

Consequently, new bracing systems and connections for timber structures have been proposed and investigated. Chan et al. [2] investigated and tested a novel tension-only connection that effectively eliminates pinching while achieving complete load-plateau behaviour in both the first and third quadrants of the hysteresis curve. Blomgren et al. [3] proposed a new Buckling-Restrained Brace (BRB) with a timber sleeve for use in timber structures. This new design replaces the brace's traditional connection with resilient slip friction joints, resulting in less damage during seismic events. Gilbert and Erochko [4] developed a novel braced frame for use in heavy timber frame applications that is made of steel and wood. This design employs a steel brace with a friction connection as the primary lateral load resistance system, with glued-in end connections. Although the above attempts meet some of the requirements for resilience structures, they still need to meet the requirements for self-centering and re-occupation after major earthquakes.

Shape Memory Alloy's (SMA) remarkable centering ability has sparked interest in structural applications. Extensive research has demonstrated the material's exceptional seismic performance in Reinforced Concrete (RC) structures. Abdulridha [5] conducted experiments on a concrete wall reinforced with longitudinal SMA bars along the plastic hinge region and discovered that the material could recover up to 85% of its drift after load removal. In addition, the SMA bars improved the ductility of the wall and significantly reduced residual displacements. Abraik and Youssef [6] investigated the seismic performance and re-centering capability of RC walls with SMA bars positioned at various locations and discovered that the location of reinforcement SMA bars influenced seismic performance and re-centering capability. Furthermore, the material improved significantly in RC frames reinforced with it SMA rebars in their plastic hinges. Alam et al. [7] conducted analytical studies on the use of SE-SMA bars in RC frames of various heights and details. SMA RC frames had lower seismic demand than steel-reinforced frames, according to their findings. Because SMA has distinct mechanical properties that alter structural response under earthquake loading, seismic design factors must be calculated for it, unlike conventional steel reinforcements.

Several research studies have been undertaken to investigate its seismic performance in employing SMA material within the brace system. Abraik and Asif [8] investigated the seismic performance of the design utilization ratio on the seismic performance of SMA with different configurations. Results of their study indicated that using a design utilization of 50% or higher led to economical use while maintaining the unique properties of SMA. Abraik [9] also investigated the influence of torsional amplification on the seismic response of SMA braces, indicating the ability of the material to reduce the torsional effect. None of the previous works had investigated the use of novel two-stage SMA in braces in timber buildings.

The objective of this paper to conduct a comparative analysis of the seismic performance of timber structures with varying brace configurations. A time history analysis was carried out using a numerical model. Firstly, the structural capacity of the chosen building is compared, and then a nonlinear analysis is presented.

SELECTED BUILDINGS

A four-story building is supported 2.0 kN/m^2 and 1.5 kN/m^2 live and dead load, respectively. The lateral resistance system of the building comprises of two bays of SMA braces in each direction, illustrated in Figure 1. The building is assumed to be in Vancouver, BC on site class D. The topical story height is 3.5 m and the bay width is 3.86 m. The building is designed using equivalent lateral load and the cross-section details are listed in Table 1. Three different brace configurations are selected to investigate the difference in their seismic performance, as shown in Figure 2. The gravity columns and beams are designed as per CSA 086 [14] while S-16 [15] is used to design the lateral braced system.

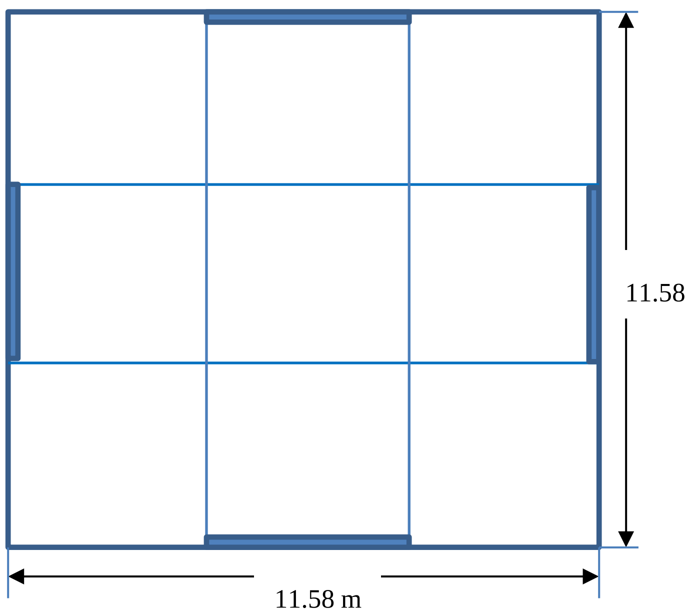

Figure 1. Timber building layout

Table 1. Cross-section details for each floor

Level	Inverted-V		M-X-braced		V-braced	
	Beam	Column	Beam	Column	Beam	Column
Roof	241 mm by 140 mm	292 mm by 292 mm	394 mm by 292 mm	292 mm by 292 mm	394 mm by 292 mm	292 mm by 292 mm
3rd	241 mm by 140 mm	292 mm by 292 mm	241 mm by 140 mm	292 mm by 292 mm	394 mm by 292 mm	292 mm by 292 mm
2nd	241 mm by 140 mm	292 mm by 292 mm	394 mm by 292 mm	292 mm by 292 mm	394 mm by 292 mm	292 mm by 292 mm
1st	241 mm by 140 mm	292 mm by 292 mm	241 mm by 140 mm	292 mm by 292 mm	394 mm by 292 mm	292 mm by 292 mm

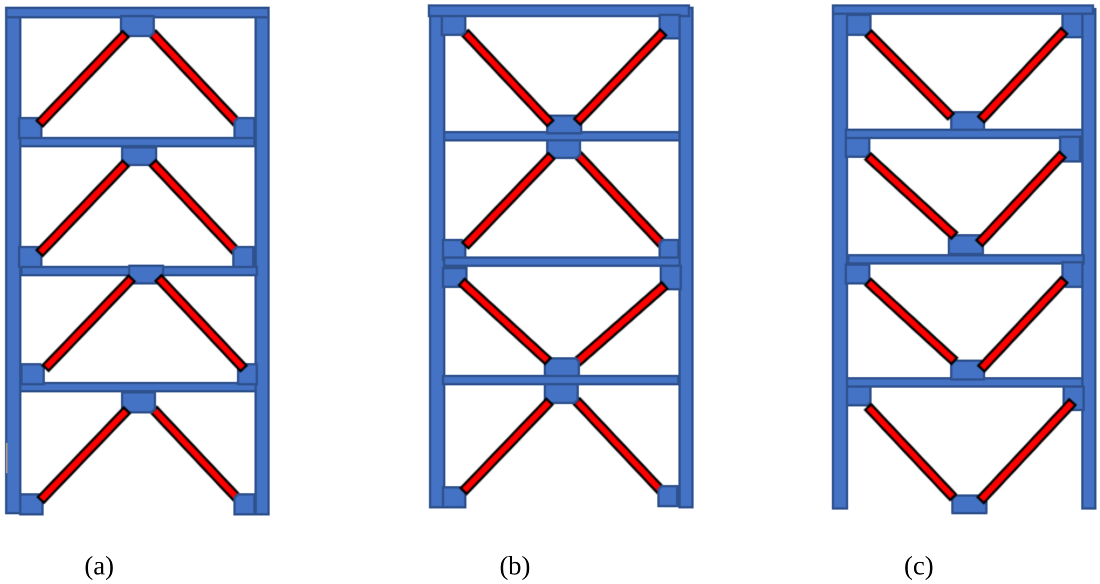

Figure 2. Timber SMA brace configurations: (a) inverted V-braced; (b)M-X-braced; (c) V-braced.

NUMERICAL MODEL AND GROUND MOTIONS

The timber beams and columns are modeled as elastic elements in OpenSees software [10]. The SMA braces, shown in Figure 3, are modeled using the self-centering material to model the short segment SMA brace, whereas a rigid element is used to connect between the SE-SMA segment and the gusset plate.

Table 2. Structure period of timber SMA building.

Building	IV-braces	M-X-braces	V-braces
T_1 (sec)	1.70	1.48	0.95
T_2 (sec)	0.54	0.49	0.32

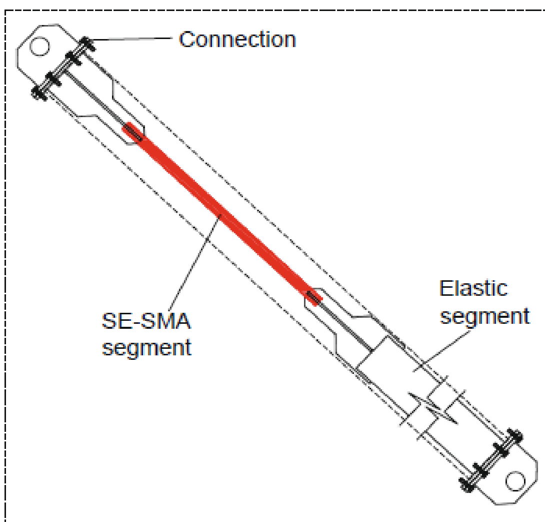

Figure 3. Details of SE-SMA brace segment [11]

Natural Resources Canada (NRC) (2020) provided 5% damped spectra for the site that have a probability of 2% exceeding in 50 years (2/50). The PEER NGA database [12] is used to select ground motions. In the range from 0.15 T_{min} to 2.0 T_{max}, the mean spectrum for the scaled ground motions does not fall below the target spectrum by 10%. The scale factors were limited between 0.5 and 5. Table 3 summarizes the selected ground motions used in this study.

Table 3. Ground motion details.

Name	Station	M_w	Scale
Imperial Valley-06	El Centro Array #1	6.53	2.547
Imperial Valley-06	El Centro Array #13	6.53	2.0296
Landers	Desert Hot Springs	7.28	1.4402
Landers	Mission Creek Fault	7.28	2.3182
Northridge-01	LA - Baldwin Hills	6.69	1.3512
Northridge-01	LA - W 15th St	6.69	1.8688
Kobe_ Japan	Abeno	6.9	1.4316
Chuetsu-oki_ Japan	Sanjo Shinbori	6.8	0.7869
Chuetsu-oki_ Japan	Hinodecho Yoshida Tsubame City	6.8	1.6573
Chuetsu-oki_ Japan	Nagaoka Kouiti Town	6.8	1.7178
Chuetsu-oki_ Japan	Niigata Nishi Kaba District	6.8	1.4893
El Mayor-Cucapah_ Mexico	Chihuahua	7.2	0.9312
El Mayor-Cucapah_ Mexico	MICHOACAN DE OCAMPO	7.2	0.5323
El Mayor-Cucapah_ Mexico	RIITO	7.2	0.6089
El Mayor-Cucapah_ Mexico	El Centro - Meloland Geot. Array	7.2	0.9581
El Mayor-Cucapah_ Mexico	Calexico Fire Station	7.2	0.8061
El Mayor-Cucapah_ Mexico	El Centro Array #7	7.2	1.1076

NUMERICAL RESULTS

Figure 4 shows the drift ratio obtained from nonlinear time history analysis. The results indicate that the I-V-braced building exhibits the maximum inter-story drift ratio (IDR) on the second floor. The I-V-braced and M-X-braced buildings exceed the code drift limit of 2%, while the V-braced building presents a favorable seismic response. Most seismic design codes do not formally incorporate residual deformations or drift ratios. However, they are becoming more widely recognized as an essential seismic performance indicator. The FEMA P-58-1 guideline [13] defines four damage states (DS1-DS4) that span the spectrum from non-structural damage initiation to almost complete collapse and are associated with residual drift ratios. The guideline specifies a 0.5% (DS2) residual story drift limit, allowing for repairs to non-structural and mechanical components while avoiding decreased structural stability (collapse safety). Figure 5 shows the residual inter-story drift ratio (RIDR). Comparing the results with FEMA P-58-1 [13] limit, both M-X-braced and V-braced exhibit lower RIDR than the I-V-braced building, which has RIDR exceeds the FEMA P-58-1 [13] limit.

The braced axial deformation response for the studied buildings is plotted in Figure 6. Among the studied buildings, the V-braced building has lower axial brace deformation and is below the critical deformation (Δ_{cr}), calculated from the allowable IDR. In this case, 2% IDR is considered as the upper drift limit.

The forces in the brace elements along the building height are illustrated in Figure 7. The V-braced building shows a higher ratio on the first floor (i.e., 30%), reducing from 30% to 10% at the roof level. Due to the lower IDR and RIDR of the V-braced building, the force concentrated in the brace at the first level.

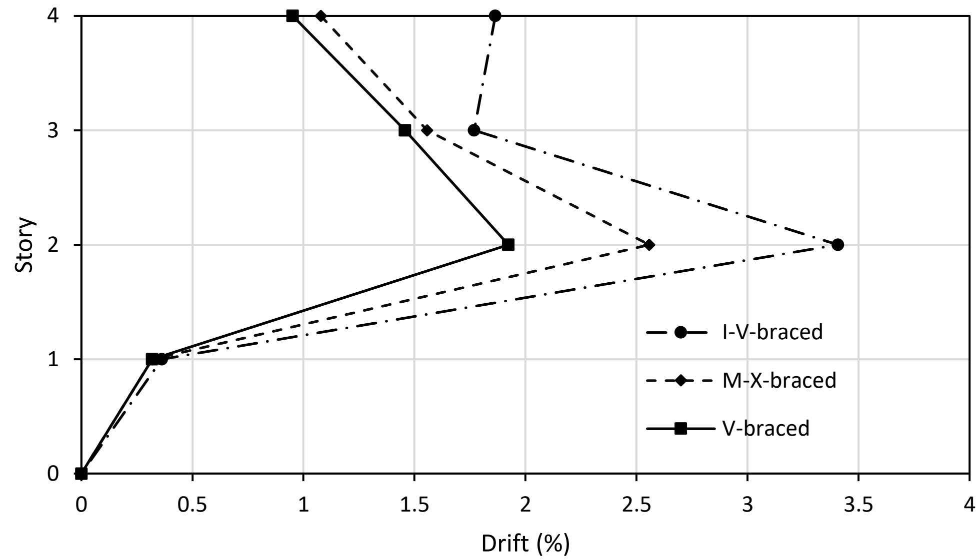

Figure 4. Inter-story drift ratio (IDR)

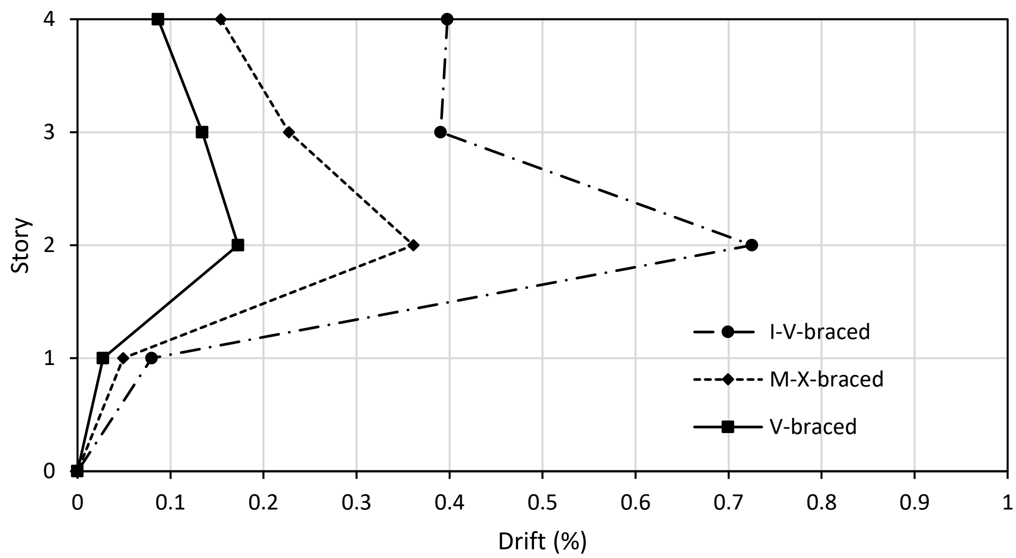

Figure 5. Residual inter-story drift ratio (RIDR)

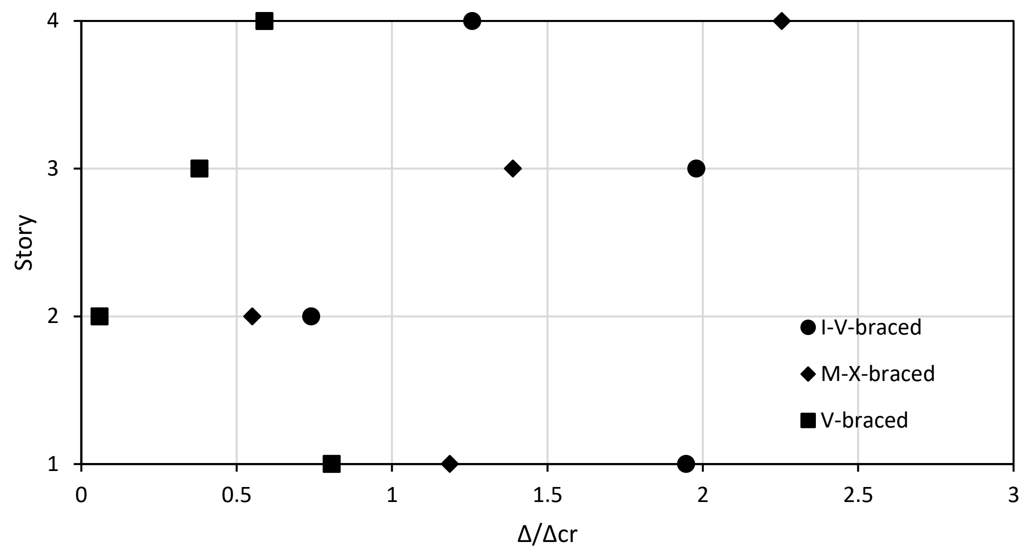

Figure 6. Braced axial deformation.

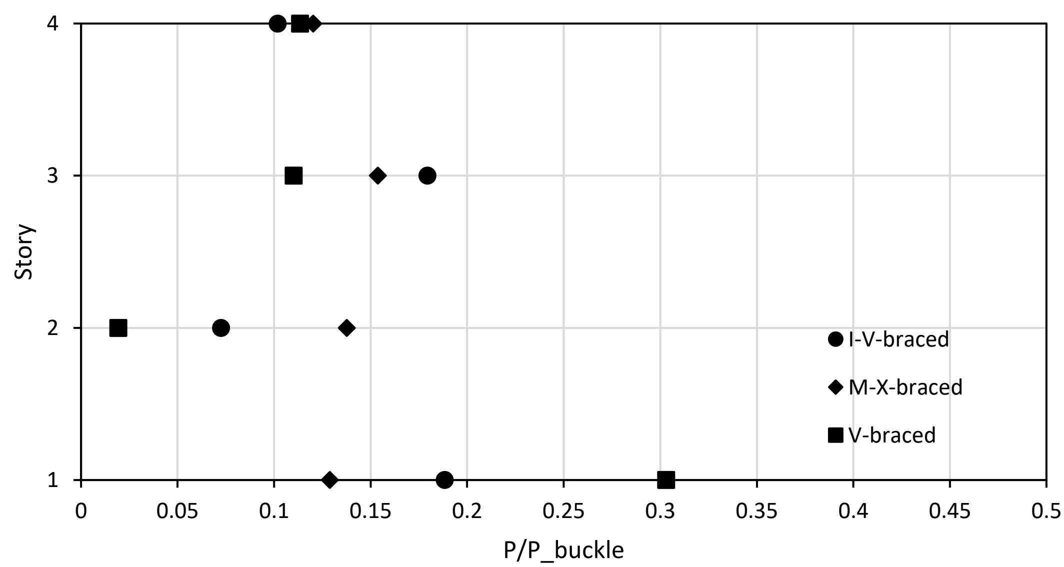

Figure 7. Braced axial forces.

Figure 8 depicts the Peak Floor Acceleration (PFA) to Peak Ground Acceleration (PGA) ratio in timber Shape Memory Alloy (SMA) braced structures. The analysis reveals that the floor acceleration response of the I-V-braced and M-X-braced timber SMA buildings is comparable across their heights. The V-braced timber SMA building, on the other hand, exhibits higher floor acceleration, indicating that the design of non-structural components must take this into account.

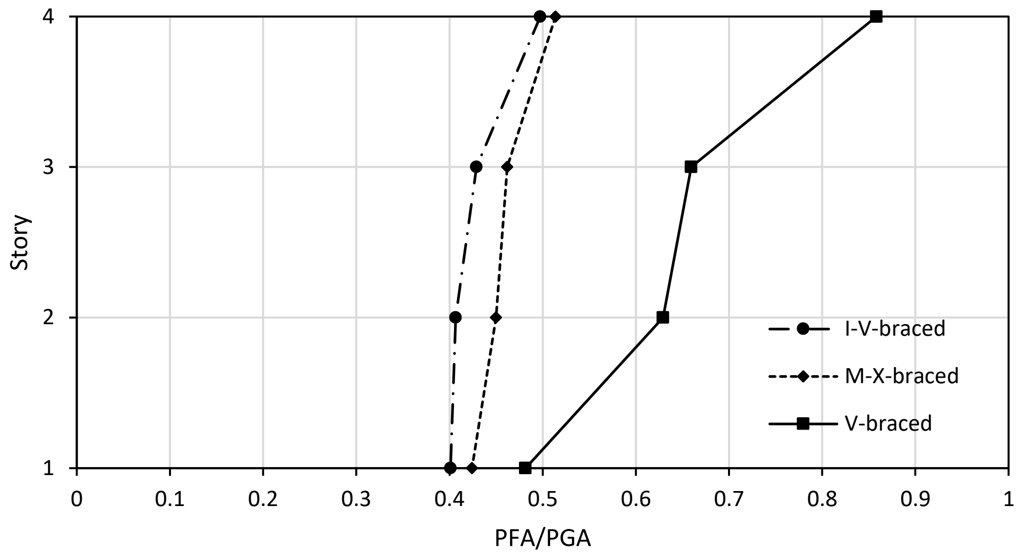

Figure 8. Floor acceleration along the building height

CONCLUSIONS

The seismic performance of four-story timber SMA buildings with various brace configurations was compared. The following conclusions have been drawn from a synthesis of the seismic response of the studied buildings:

1- Compared to the other buildings studied, the V-braced building had a lower inter-story drift ratio (IDR), indicating better seismic performance.
2- Both M-X-braced and V-braced buildings met the FEMA P-58-1 drift limit.
3- The axial deformation of the brace elements reflected the transfer of forces from the IDR to the brace elements. The V-braced building had lower braced deformation than the other configurations studied.
4- Due to a decrease in IDR and RIDR, the first story of the V-braced building experienced higher forces in the brace members. At higher levels, however, all members had nearly identical force level ratios.
5- The floor acceleration of the V-braced timber Shape Memory Alloy (SMA) building is greater than that of other timber SMA buildings.

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