Shape Memory Alloy Dampers for Response Modification of Light-Frame Wood Buildings

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SUMMARY:
Superelastic shape memory alloys (SMA's) have been used as energy dissipation devices and have been shown to greatly improve a structure's response to an earthquake by significantly reducing peak response and limiting damage. This type of seismic response modification has been tested at the wall level but has never been investigated at the system level either numerically or experimentally for wood frame structures. In this study a hysteresis was developed for a SMA wire using existing data. The hysteresis was combined with a wood shear wall hysteresis to form a model of a SMA damped shear wall and a database of walls developed for later use. A series of analyses at increasing levels of seismic intensity were performed for both the wall and building level. It is concluded that including SMA's in wood frame buildings subjected to large ground motions can significantly improve the structure's seismic performance.

Keywords: Shear walls; Shape Memory Alloys; Dampers; Lateral Loads; Hysteresis.

1. INTRODUCTION

Despite significant improvement in designing structures to resist strong earthquakes failure and damage to buildings has continued. The state of the art research has focused on shifting from a strength-based approach to performance-based design (PBD) methodology, primarily to control losses in buildings. Using shape memory alloys (SMA) as passive damping devices is one such PBD method that is being explored in civil engineering structures recently. Shape memory alloys possess one of two key features that make them very suitable for such application: shape memory and superelasticity. There exists various types of SMAs; the type felt to have the most potential for civil engineering applications are superelastic wires consisting of near equiatomic parts of Nickel and Titanium. Upon mechanical loading to the SMA superelastic wire, a stress-induced martensite phase transformation occurs. Upon unloading of the wire, an imperfect reverse martensite transformation occurs thus always resulting in a small amount of residual deformation. The Titanium provides significant strength to the wire, while the amount of residual deformation depends mostly on the Nickel content and temperature at which the loading occurs. This combination of properties and superelastic behaviour is ideal for providing additional lateral resistance in wood frame shear walls.

As part of the MANSIDE project, Dolce and Cardone (2006) developed SMA bracing dampers, SMA isolation dampers , and SMA smart ties to be used in reinforced concrete framed structures, concrete buildings, bridges, arches, and vaults. McCormick et al. (2007), Motahari et al. (2007) and Asgarian and Moradi (2011) analysed and tested various SMA-damped braces implemented in steel framing systems. In all cases, the SMA dampers significantly reduced the peak interstory drift and the residual deformations on the structures after very high ground motions through excellent energy dissipation properties and high fatigue resistance. Recently, Dong et al. (2011) provided an extensive review of SMA applications in bridges ranging from base isolation dampers to post-tensioned reinforcing bars (the reader is referred there for additional information).

Limited studies have been conducted on implementing SMA damping devices into wood frame structures. Despite the fact that wood frame buildings represent a large percentage of North American residential and low-rise commercial structures built in seismic regions. This consistency is generally due to their high strength/stiffness to weight ratio and construction convention. Architectural features and the ever-increasing demand for larger windows reduce the strength and stiffness of these structures hence a need to investigate other means to reduce seismic response, including various seismic response modification devices. Within wood frame structures, shear walls are generally responsible for providing the lateral resistance. After supplying significant energy dissipation, the shear wall is able to effectively transfer the lateral forces down into the foundation. Van de Lindt (2004) provides a thorough review on the evolution of shear wall testing, modelling, and reliability analyses that have been conducted two decades prior to the publishing date. Henceforth, due to the combined efforts from the CUREE-Caltech and NEESWood projects, significant progress has been made in the testing and development of PBD for wood frame buildings in seismically active regions.

Numerous full-scale experimental tests have been carried out providing for a mechanism to calibrate new software capable of accurate numerical analysis. In a two part study conducted by Folz and Filiatrault (2004), a numerical model was developed and incorporated into the software program SAWS (Seismic Analysis of Woodframe Structures) to predict the time history response of wood frame buildings. The second part of the project conducted full-scale two-story shake table tests, confirming the results from the previous numerical study. In Filiatrault et al. (2010), the authors confirmed the efficacy of wall sheathing in a full-scale, two-story, light-frame wood townhouse building and determined the addition of both interior and exterior wall sheathing significantly adds to the structure's successful response. The data from this test is used to validate a numerical study conducted by van de Lindt et al. (2010) in the novel software package, SAPWood. In 2010, van de Lindt et al. conducted tri-axial shake table tests on a full-scale six-story wood frame building to provide validation of a performance-based seismic design developed as part of the same project. Considering interstory drifts and shear wall deformations for an array of ground motions, good agreement was found between the experimental test and developed numerical models.

Thus far, only a single study has been conducted related to incorporating a SMA bracing device in a wood frame structure. In van de Lindt and Potts (2008) a single, full-scale (2.44 m x 2.44 m) wood shear wall was strengthened with the SMA bracing damping device developed by Dolce et al. (2000). The shear wall was tested on a shake table before and after strengthening. Results of the test showed the interstory drift was reduced by 40% at high intensity level ground motions by adding the SMA damping device. The physical damage to the wood shear wall was essentially eliminated upon incorporating the SMA device.

2. SMA SHEAR WALL DATABASE DEVELOPMENT

The SMA damping device analysed in this study was modelled after the same device developed by Dolce et al. (2000) and also employed in van de Lindt and Potts (2008). This device requires pure tensile action of the SMA wires. Within the device, a prescribed number of 1 mm diameter NiTi SMA wires are installed. On either side of the device there are two wires, each wire is wrapped the prescribed number of times around an outside stud and then around a shared connecting stud. The outer studs are allowed to displace up to 25.4 mm in either direction. All studs are attached to an inner and outer tube running throughout the length of the device. This device was incorporated diagonally into the shear wall by a threaded 25.4 mm diameter steel rod running into the inner and outer tubes. The device requires pure tensile action of the SMA wires which is accomplished by initial prestraining of the wires to 4%. As the shear wall laterally displaces, one wire set elongates creating a higher internal tensile stress which the other wire set contracts exhibiting a lower internal tensile stress, therefore never allowing either wire set to enter into the compression state. The elongation of the wires in the device is then simply a function of geometry. A schematic of the device is provided in Fig.1 (taken with permission from van de Lindt and Potts (2008)).

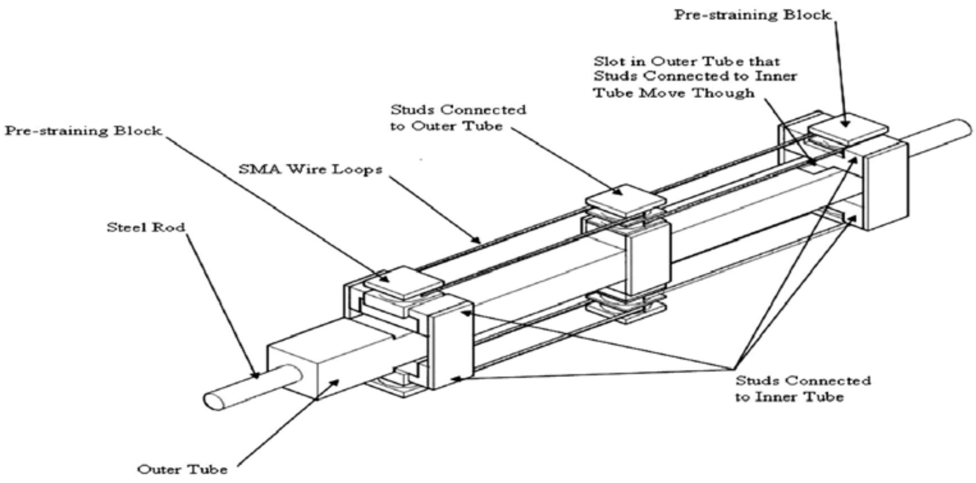


Figure 1. SMA-based device with clamp-based wire retention system

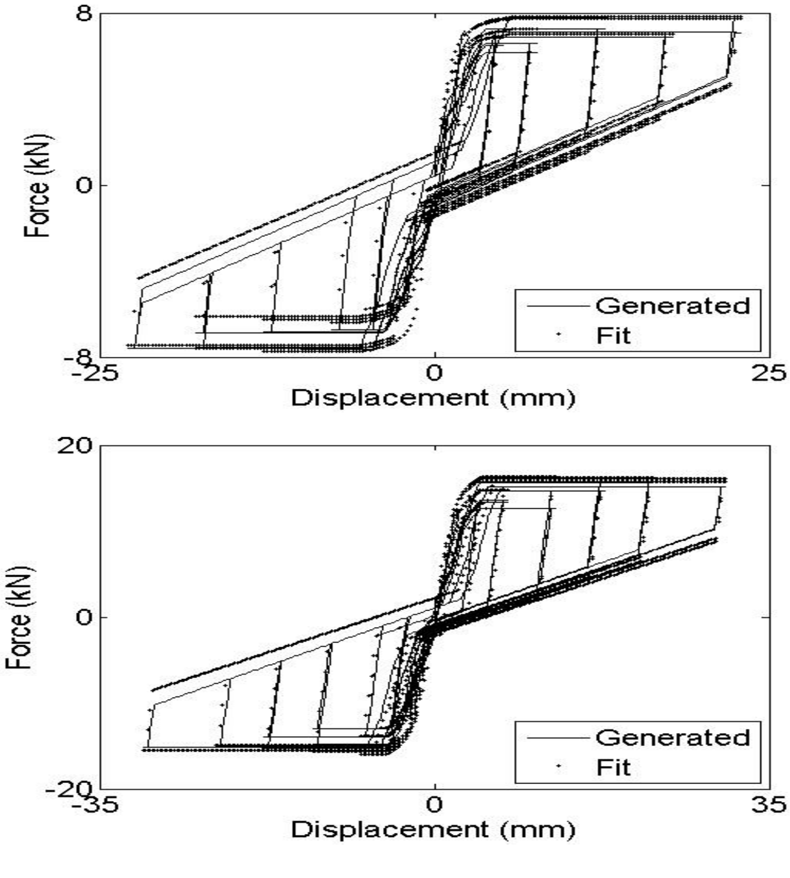


Figure 2. Fitted 10 parameter hysteresis for SMA damping device

A numerical database was developed and consisted of six shear wall dimensions and six SMA wire wrap options (2, 4, 6, 8, 10, and 12 wraps which increases the cross sectional area proportionally). The database development initiated through the reproduction of the SMA stress-strain hysteresis produced for a 1.8 mm diameter NiTi wire from cyclic testing in DesRoches et al. (2004). Considering the cross sectional area of a 1 mm diameter wire and the gage length within the device, a new force-displacement hysteresis was developed. The initial hysteresis consisted of four cycles and was fit with a 10 parameter hysteretic model via the software program SAPWood. A standard cyclic protocol, xd, initiating at zero displacement and ending at 76.2 mm was used to create two specific protocols to develop the SMA device hysteresis. All wires were assumed to be prestrained to 4%.

When the device is subjected to lateral motion, one set of wires extends in additional tension; therefore the first protocol becomes 4.0% + xd. This subtracts from the remaining set of wires' tension, and the second protocol becomes 4.0% - xd. The initial 10 parameters fit to the single wire hysteresis are installed in a single wall uniaxial model that is subjected to the two displacement protocols. The force array from the second protocol (4.0% - xd) is subtracted from the force array of the first protocol (4.0% + xd). To account for the restriction of wire compression, all force values are set to be greater than or equal to zero. The new force vector is plotted with the original displacement protocol, xd, to represent the SMA device hysteresis, and fit with a 10 parameter hysteretic model. Four examples from the database of the hysteretic model of the SMA damping device are shown in Fig. 2, where the line is the generated hysteresis from SAPWood as described above, and the curve consisting of a marker is the fitted 10 parameter hysteretic model. Fig.2a models a SMA damper using 2 wire wraps and angled for a 1.83 m x 2.44 m wall. The hysteresis in Fig. 2b uses 6 wire wraps within the device and is angled for a 2.44 m x 2.44 m wall.

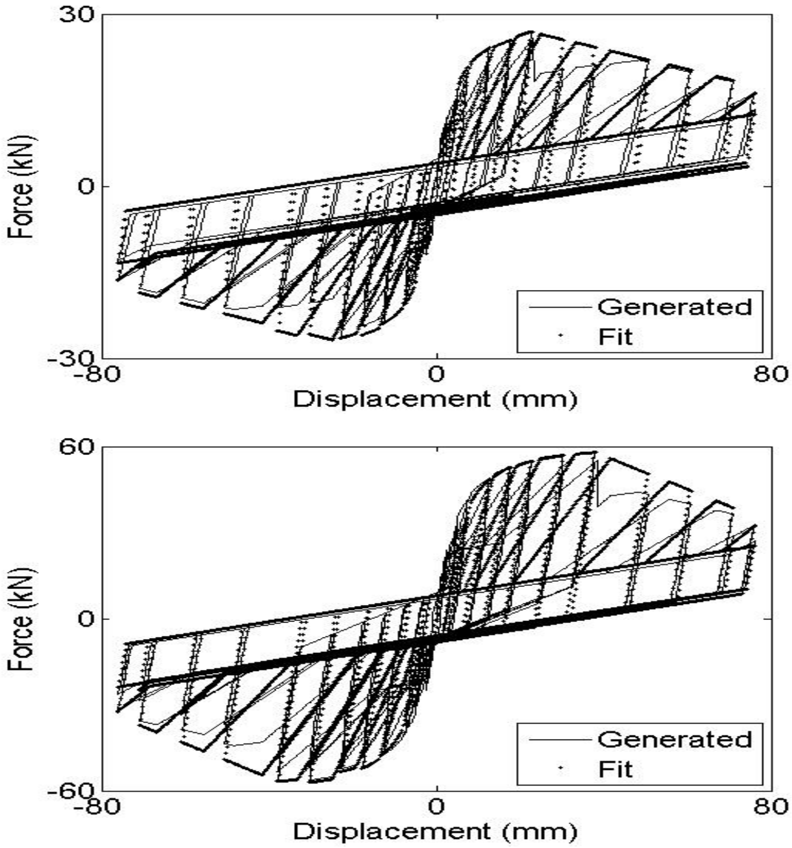


Figure 3. Fitted 10 parameter hysteresis for SMA damped shear walls

The SMA device and undamped wood shear wall were given identical coordinates within the wall model. This model is then subjected to a cyclic displacement protocol to obtain a combined force vector for developing a combined single hysteretic spring model. The outputted force vector is plotted with the displacement protocol and fit with a 10 parameter hysteretic model representing the model for the SMA damped shear wall. Fig. 3 shows example fits for two damped shear walls from the database. The damped shear wall hysteresis shown in Fig.3a and Fig. 3b correspond to the devices shown in Fig. 2a and Fig. 2b, respectively. It is evident from Fig. 2 that the angles of the device, along with the provided cross sectional area of the SMA wire, simultaneously play major roles in increasing the provided lateral resistance. It can also be noted that the 10 parameter hysteretic models from SAPWood provide excellent fits to the generated hysteresis.

The procedure described above is followed for all 36 combinations of SMA damped wood shear walls within the database. It should be noted that the Nickel and Titanium content, along with the individual wire diameter, are held constant throughout the database. Table 1 provides the parameters for all wire wrap combinations for the 2.44 m x 2.44 m SMA damped shear wall combinations within the database. As the number of wire wraps increases, the initial stiffness and resisting force increase; this trend is seen for all wall lengths. The number of wraps is not the only factor affecting these two parameters; the angle the device is positioned reduces the elongation in the wires by the cosine of the angle. Therefore, 4 wire wraps positioned at a lower angle provides more resistance than 4 wire wraps positioned at a steep angle, as one would expect from basic geometry.

The shear walls were modelled in SAPWood (Pei and van de Lindt, 2007). All shear wall models were 2.44 m in height with varying length. Nominal 2 x 6 (50.8 mm x 101.6 mm) Hem-Fir lumber was used throughout the frame. The model consisted of a single top and bottom plate, with double side plates. All studs were spaced at 406.4 mm on centre. All sheathing panels had 1.22 m x 2.44 m maximum overall dimensions and were fastened with 152.4 mm on centre edge spacing and spaced at 304.8 mm on centre at intermediate supports. Closer nail spacing for the panel edge nailing would provide stiffer and stronger wood shear walls in general, but edge nailing was kept constant to investigate the effect of the SMA damped walls.

Table 1. 10 Parameter Database for 2.44m x 2.44m SMA Damped Shear Wall Model

# wraps	k0 (kN/mm)	F0 (kN)	F1 (kN)	r1	r2	r3	r4	Xu (mm)	alpha	beta
2	5.43	31.58	4.89	0.04	-0.08	1.00	0.03	37.08	0.80	1.10
4	8.58	36.47	4.89	0.04	-0.07	1.00	0.02	35.31	0.80	1.10
6	10.16	46.70	4.89	0.03	-0.07	1.00	0.01	30.48	0.80	1.10
8	13.31	52.49	4.89	0.02	-0.07	1.00	0.01	36.32	0.80	1.10
10	15.24	58.27	4.89	0.02	-0.07	1.00	0.01	34.80	0.80	1.10
12	17.34	62.72	4.89	0.02	-0.06	1.00	0.01	30.48	0.80	1.10

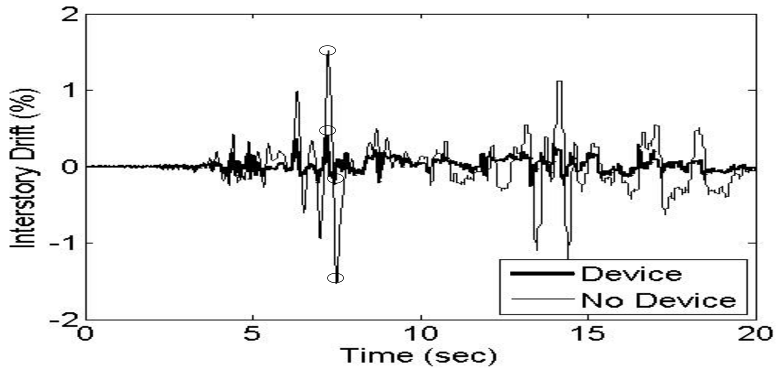
3. NUMERICAL EXAMPLES

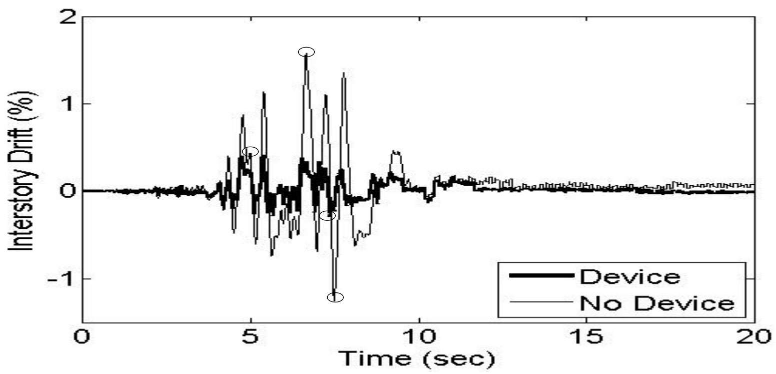
Three examples are provided with increasing levels of complexity, beginning at the single wall level and extending to a three-story building. Various wire wraps and wall lengths are used throughout the examples to demonstrate the SMA device's potential, but it should be noted that no specific design methodology was employed. The damped and undamped structure's performance is quantified using incremental dynamic analysis for a suite of 22 earthquakes at 20 different spectral values.

3.1. Single Shear Wall

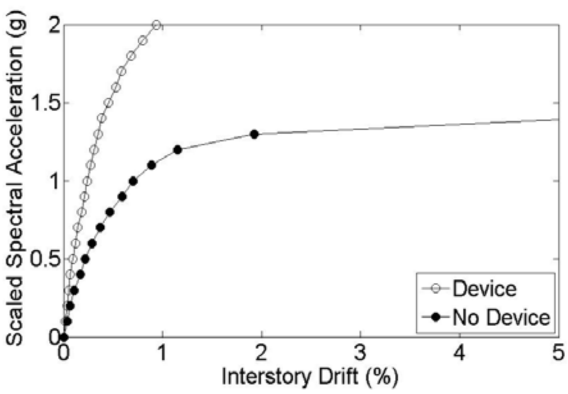
The SMA damped shear wall numerical database consists of 36 combinations by varying the angle of the device (i.e. the width of the wall) and the cross sectional area provided by the wire (i.e. the number of wraps within the device). Two of the 36 combinations are tested and compared here with undamped wood shear walls of equivalent length. The objective of this example is to demonstrate the effect the SMA damper has on a single undamped wall, even when a minimum amount of SMA wire is provided. First a 2.44 m x 2.44 m wall is presented with 4 wire wraps installed in the SMA device, and secondly a 3.66 m x 2.44 m wall is presented with only 2 wire wraps installed within the SMA device. The time series is provided for the ground motion record closest to the mean value of the peak response at a spectral scaling of 1g.

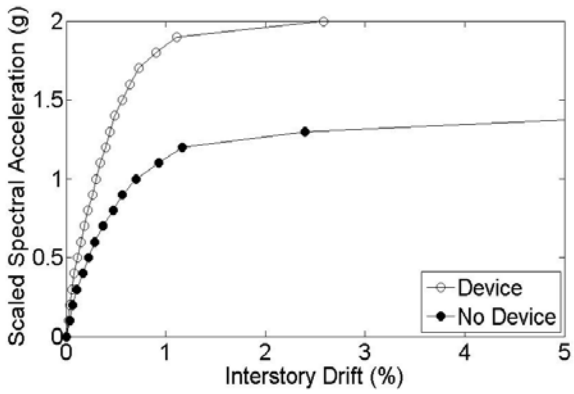
Figs. 4a and 4c compare a 2.44 m width wall. The damped shear wall model uses 4 wire wraps within the device. Fig. 4a provides a comparison on the time-history analysis for the damped and undamped 2.44 m shear wall upon being subjected to the 1987 Superstition Hills ground motion at 1g spectral scaling. One can clearly observe the difference in the peak response as a result of the SMA damper. The peak interstory drift of the wall is reduced by as much as 67%. Fig. 4c shows the mean response of the damped and undamped 2.44 m wall subjected to a multi-record IDA at 20 spectral scalings. The addition of the device keeps the interstory drift of the shear wall within an acceptable range, never exceeding 1% drift even at high intensity levels. Upon subjection to intensity approaching 1.5g, the undamped shear wall begins to fail. Figs. 4b and 4d compare a damped and undamped 3.66 m wall. The damped shear wall in this analysis used 6 wire wraps within the device. Fig. 4b presents the time-history for both 3.66 m walls being subjected to the 1994 Northridge ground motion at a spectral scaling of 1g. The addition of the seismic damper significantly reduces peak response, never exceeding more than 0.5% drift. The mean IDA response is shown in Fig. 4d for the two 3.66 m walls. The damped shear wall approaches 3% interstory drift upon experiencing very high intensity ground motions. The undamped shear wall begins to fail upon approaching intensity levels of 1.5g. Supposing a performance design criteria for the wall with a maximum of 2% interstory drift, in both cases, the addition of the SMA dampers increases the wall's capacity from approximately 1.2g to approximately 2g.





a.) Time-history for 2.44m wall b.) Time-history for 3.66m wall





c.) Mean MIDA response for 2.44m wall d.) Mean MIDA response for 3.66m wall

Figure 4. Comparison of two damped and undamped single shear walls

3.2. Single Story Building

A single story building was modeled and analysed in SAPWood for validation of the SMA dampers at the system level. The floor plan for the test building is shown in Fig. 5a. The model used is consistent with a typical single family dwelling in the United States with a large two car garage opening on the bottom right side. The garage opening and number of windows creates a difficult task in lateral strengthening. The objective of this example is to demonstrate that when SMA damping devices are used the total number of shear walls may be reduced enabling architecture of this type. The single story building consists of 20 shear walls of varying length identified in Fig. 5a. The dampers in the SMA damped building model all consisted of 2 wire wraps, the minimum within the developed database. The undamped building's period is 0.188 seconds, and the SMA damped building model has a period of 0.132 seconds. Fig. 6 illustrates a comparison between the interstory drift time-histories when SMA damping devices are modeled in the building's shear walls. These time-histories are obtained from the numerical simulations using the 1994 Northridge ground motion at a spectral scaling of 1.0g at the building's period. The wall experiencing the greatest amount of deformation in the building plan is shown for both axes directions. Fig. 6a is the interstory drift time-history for an external shear wall in the x direction for both buildings. The location of this wall is shown in the upper right corner of the plot. A maximum interstory drift of approximately 1.3% is seen without the addition of any SMA dampers. Fig. 6b displays the time-history for the limiting wall in the y direction for both building models. Similarly as in the x direction, a maximum interstory drift just over 1.5% is seen in the y direction for the undamped building. In both directions, the SMA damped building maintains a maximum interstory drift less than 0.5%.

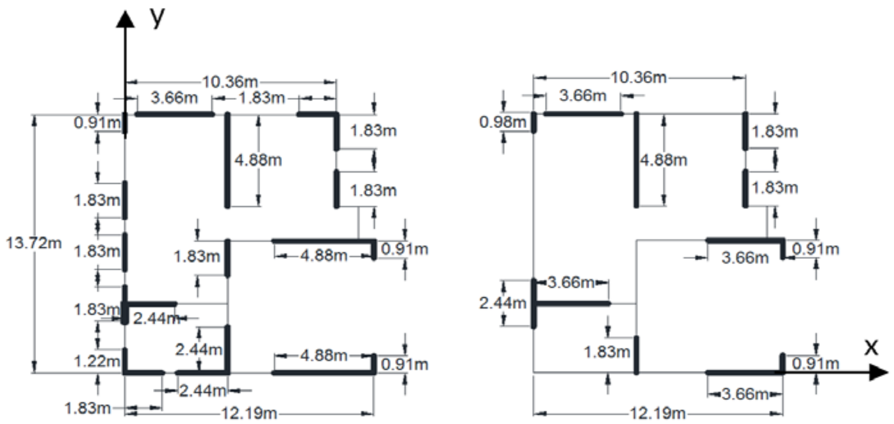


Figure 5. Single story building model floor plan, layout 1 and layout 2

To further demonstrate the benefit of using seismic dampers within a structure, eight of the shear walls from the previous example were removed, and the number of wire wraps within the SMA device for the damped building was increased to 10. A multi-record IDA plot is shown in Fig. 7. Layout 1 refers to the single story building models consisting of 20 shear walls, and layout 2 refers to the single story building models with only 12 shear walls, shown in Fig. 5b. For layout 2, the undamped building model's period is 0.258 seconds and the damped building model's period is 0.128 seconds. From Fig. 7, it is seen, that the undamped single story building model from the previous example, layout 1, maintains satisfactory performance levels until being subjected to spectral accelerations exceeding 1.7g. When the 2 wire wrap SMA dampers are added, the building's response improves, never exceeding 1% interstory drift. When the number of shear walls is decreased (i.e. layout 2), the undamped single story building model loses its integrity around 1g spectral scaling. The addition of 12 SMA dampers significantly improves the structure's response and limits the interstory drift to less than 1% even after exposure to spectral accelerations equating to 2g. Consider an arbitrary location in Northern California with a MCE level of 1.5g, for layout 1, the interstory drift is limited to less than 0.4% for the SMA damped building. At 1.5g, the undamped building drifts to 0.9%. For layout 2, the building using SMA dampers is limited to less than 0.6% interstory drift; however the building without any dampers fails at 1g. At 0.4% and 0.6% interstory drift, limited nonstructural damage will be seen without any structural damage. The high performance of these dampers indicates that fewer wraps could have been used to still achieve satisfactory performance.

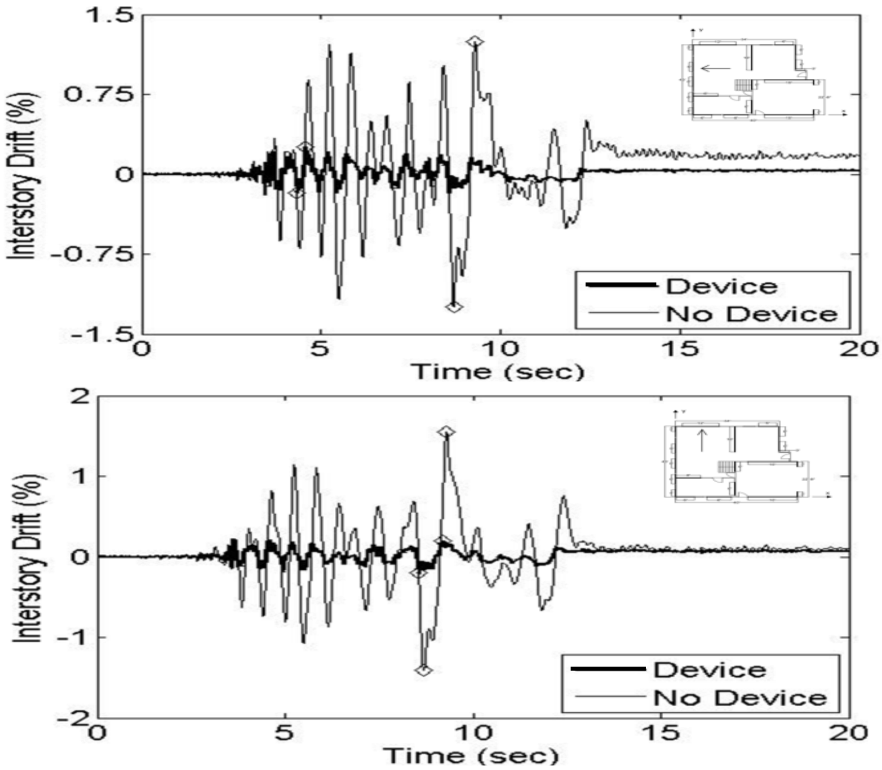


Figure 6. Comparison of interstory drift time history in the x and y directions for the single story building

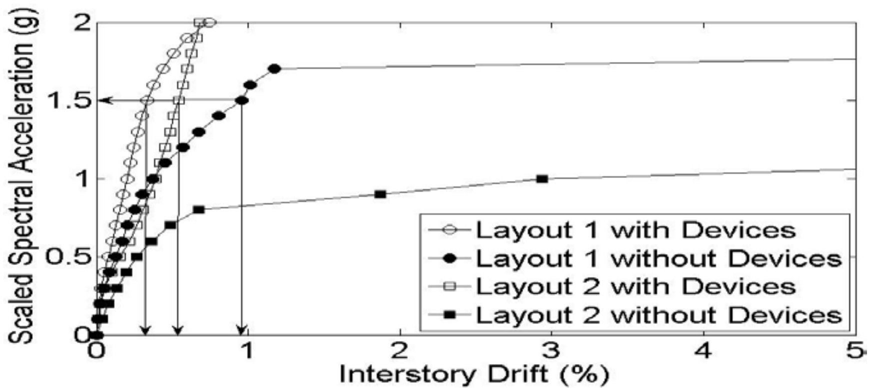


Figure 7. Mean IDA response for single story building models

3.3. Three Story Building

As a final example, a three-story building was modeled in SAPWood and analysed using incremental dynamic analysis to show the capabilities of the SMA dampers. The floor plan is shown in Fig. 8, where the second and third levels are architecturally identical. The shear walls are indicated by bold lines with dimensions. Architectural constraints for this building include the large openings on the first level creating a softer story. A damped and an undamped building model are compared where both models consist of 20 shear walls on all three levels. The undamped building model has a period of 0.53 seconds. The damped building model uses an SMA damping device in all 20 shear walls, where each device utilizes 6 wire wraps. The damped building model has a period of 0.36 seconds.

Fig. 9 presents the IDA results for the multi-story buildings in the x and y directions. Considering a location in Northern California where the DBE is 0.8g, the difference the SMA dampers make is significant. Referring to Fig. 9a, the x direction, it can be seen that the addition of SMA dampers limits the interstory drift to 1.2%, indicating only nonstructural damage (i.e. drywall damage). The building without dampers experiences just over 3.5% interstory drift, indicating significant structural damage similar to what was observed in Filiatrault et al (2010). If the performance constraint is set to an interstory drift of 2%, the damped building raises the structure's intensity tolerance by nearly a factor of 2, thus significantly reducing the risk of damage. The undamped building experiences 2% interstory drift at 0.6g, and the damped building experiences 2% drift at 1g. Considering the same DBE of 0.8g in Northern California, and referring to Fig. 9b, the y direction, for the first story the interstory drift is reduced by the SMA dampers from 1.5% to 1.1%, a 27% reduction. Considering the same performance design constraint of 2% interstory drift, the SMA dampers allow the structure to withstand just over 1g, whereas the undamped building withstands just less than 1g. The second story of the SMA damped building performs significantly better, limiting the drift to 1.5%, whereas the second story of the undamped building drifts to 2.5%. The third stories of each building perform approximately the same; however the damped building's interstory drift is slightly less than the undamped building's. The less significant difference seen in the first story is due to the extra walls provided in the y direction of the building. In the x direction, there are specific architectural features that make the building difficult to laterally strengthen. The SMA dampers have no problem overcoming this obstacle providing significant lateral resistance and maintaining building erection up to 1g in both directions.

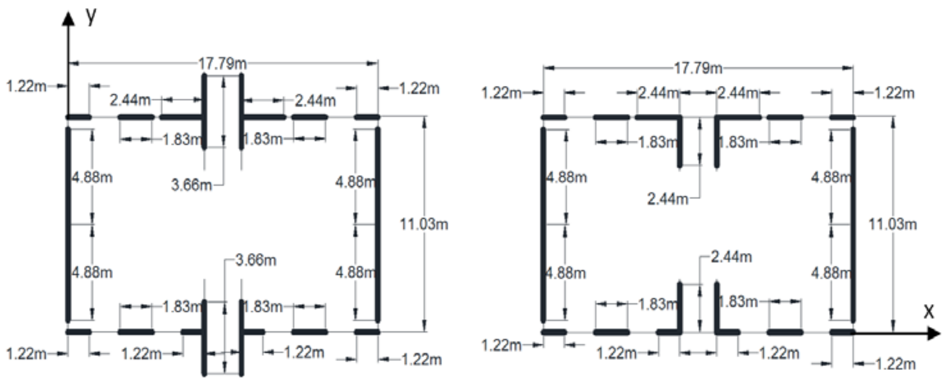


Figure 8. Three story building model floor plan

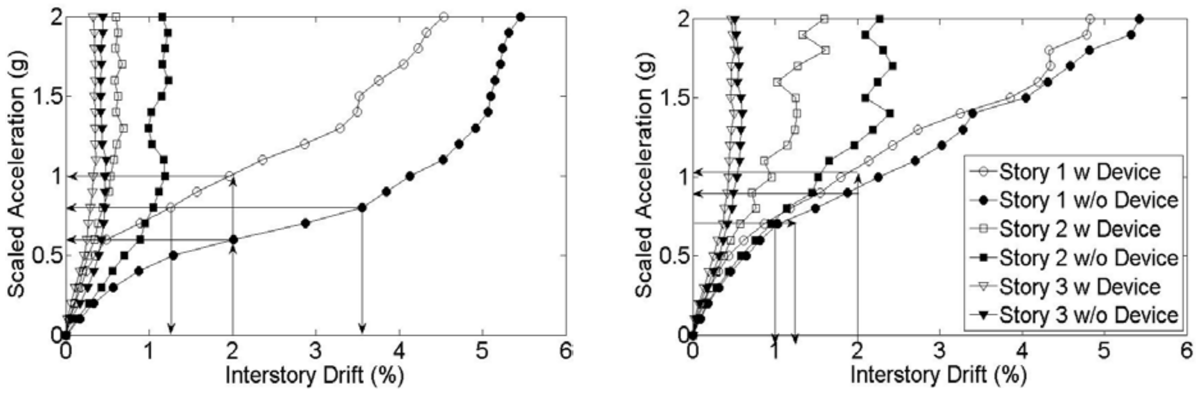


Figure 9. Mean IDA response for multi-story building models

4. SUMMARY AND CONCLUSIONS

Using shape memory alloys as supplemental damping provides drift reduction for a building and improves the response to ground motions. A database comprised of 36 combinations of SMA damped shear walls, various length walls, and varying cross sectional area of the wire, is presented. Multiple examples were provided ranging from the single wall level to a three-story building. It was shown that the SMA's included in wood frame buildings subjected to large ground motions can significantly improve the structure's seismic performance. Increasing the number of wire wraps within the device always increases the level of damping and resistance; however an optimum performance level must also consider economics. The angle at which the device is positioned also affects the amount of resistance provided to the structure. Three examples were conducted, one at the single wall level, one at the single story level, and one at a three-story level. In all cases the addition of SMA dampers significantly improved the structure's performance. For the single wall example, the maximum interstory drift was reduced by approximately 67%. For the single story building model example, the maximum interstory drift, on average, was reduced by approximately 50%. Furthermore, for the single building model example, both MCE and DBE performance levels were met for the damped building for a typical U.S. west coast seismic intensity. Considering the multi-story building example, the SMA dampers allow for the building to withstand up to 1g before structural damage would likely occur. When considering a DBE of 0.8g, the SMA dampers limit the deformation to levels associated with only non-structural damage, thus making them considerably attractive. To further increase the building's performance, additional wire wraps can be used within the device. From the three examples provided, it has been shown that the SMA dampers can not only replace, but also decrease the required number of shear walls throughout the structure.

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