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Comparative Response of Mid-Rise Base-Isolated and Conventional Steel Moment Resisting Frame

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Abstract
Base isolation systems are preferably applied in low-rise buildings since the vibration period of the structure can be shorter, so that it performs more rigidly to maximize the benefit from the isolation system. Mid-rise and high-rise base-isolated buildings are expected to have different and variable response characteristics compared to low-rise base-isolated buildings, and may not perform as well as low-rise or relatively stiffer base-isolated buildings. However, in this study, the benefit of seismic isolation in a 9-story is comparable better than a conventional building that was investigated thoroughly in a previous study with respect to peak floor displacement and peak story drifts. 9-story building were designed to satisfactorily meet the current building code standards. SAP 2000 were used to develop analytical models of the 9-story buildings for independent purposes. The SAP model was used for nonlinear pushover analysis and nonlinear response history analysis to suites of ground motions representing various probability of occurrence events. Pushover analysis of the model was carried out under an inverted triangle load pattern to determine the base shear capacity and post-yield behavior. The responses of the 9-story isolated building were also compared to investigate the influence of height as the isolation system designs are comparable in the two buildings. The total displacement, which is a function of the fundamental period of the system, was observed to be about the same in the 9-story isolated building. Thus, the drift demands were much lower in the 9-story building as they were distributed over the height more effectively.

Keywords: *SAP2000, peak story drifts, isolation system, displacement, base shear capacity, post-yield behavior.*

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I. INTRODUCTION

There have been a lot of studies conducted to compare the reaction of low-rise isolated structures with conventional buildings (e.g. Thakare and Jaiswal, 2011; Shenton and Lin, 1992; Lin and Shenton, 1992). Despite widespread acceptance of the concept that low-rise isolated buildings provide significantly superior performance to conventional buildings in a design-level earthquake, owners' desires to reduce the initial cost of isolated buildings have prevented widespread implementation of seismic isolation in practice. Fortunately, new Performance-Based Earthquake Engineering (PBEE) processes are being developed that will allow building owners to bring in life cycle cost factors into their decision-making process, allowing for a realistic estimate of probabilistic earthquake losses. Various methodologies, such as those used for economic analysis and life cycle performance assessment (ATC, 2009), have been developed to assess the cost and performance of conventional and base-isolated buildings. As a result, a multi-level response review will be necessary. The intuitive notion that improved performance of an isolated building in a design event will automatically translate into higher performance in other earthquake situations has to be questioned.

Ryan and colleagues (2008) set out to complete a comparison of the life cycle performance and cost evaluation of realistic case study conventional and base-isolated buildings as part of the NEES TIPS project (National Energy Efficiency Standards and Technologies for Performance and Cost Evaluation). Performance-Based Earthquake Engineering (PBEE) loss estimating framework established by the Pacific Earthquake Engineering Research Center (PEER) was to be used to evaluate the buildings. PEER was responsible for developing the framework (Miranda, 2003). Performance metrics, or decision variables, such as maintenance costs and downtime, are determined in this framework by the application of a consequence analysis technique. Four basic stages are identified while deconstructing the assessment problem. Hazard analysis, response analysis, damage analysis, and loss analysis are all types of risk analysis. In hazard analysis, discrete occurrences along the hazard curve are represented by ground motions that have been selected. Response analysis entails the production of high-fidelity structural models of the buildings, as well as the prediction of the relevant structural demands resulting from each ground motion through the use of response history analysis techniques. A fragility function is created for each structural component in the damage analysis, and this function is used to relate the structural response values to the physical damage in the structural and nonstructural components. Repair actions and associated costs, as well as repair timeframes and durations, are finally described in the loss analysis. Under the total probability theory, the four stages are merged via integration to determine the expected losses in a specific incident or over the course of the building's lifetime. The results of a rigorous cost analysis are expected to show that the initial investment in a protective system is statistically likely to be recouped through a reduction in earthquake-related losses (repair and reconstruction costs, business interruption losses, and profit losses) over the building's lifetime.

II. STRUCTURAL SYSTEMS

Two buildings that were used in this study is as; Model A: Conventional 9-story moment resisting frame and Model B: Base-isolated 9-story moment resisting frame. For the sake of completeness, the design information for the nine-story buildings is duplicated here. Designed for site class D, all of the buildings were subjected to the same design spectrum accelerations, with Ss=2.2 g for short intervals and SI=0.74 g for 1 second periods (g=gravitational acceleration). Buildings with occupancy category II and importance factor I=1.0 were designed using the Equivalent Lateral Force Method (ELF) and Linear Response Spectrum (LRS) for 9-story conventional buildings and 9-story isolated buildings respectively to meet the requirements of the 2020 International Building Code (IBC, 2020), ASCE 7-16 (ASCE, 2016), and AISC 341-16 (American Institute of Steel Construction, 2016). (AISC, 2016). The three-story structures, on the other hand, were designed by ELF. Because of the gap in design requirements between conventional and isolated structures, different member sizes and details were required for each kind of structure.

Design drifts were 2.5% for the conventional buildings and 1.5% for the isolated buildings, according to the study. A specific moment resistant frame was designed for the standard structures (9-story), allowing for great ductility in the frames (SMRF). Because seismic isolation technologies significantly minimise seismic force input, they do not impose a ductility requirement on the superstructures, whereas traditional buildings accommodate the design force through inelastic reaction to the seismic force (Nagarajaiah, 1991). In order to do this, the isolated structures were designed as an intermediate moment resistant frame (IMRF) (Sayani et al., 2011). The design force reduction factors for the conventional structures were R = 8 and RI = 1.69 for the isolated buildings, respectively, based on a structural steel design yield strength of 380 MPa.

They are symmetrical and have the same plan dimensions of 46 m x 46 m, with storey heights of 4.5 m and column spacing of 9.0 m in each direction. Both in the X and Y directions, two 4-bay perimeter moment frames and two 2-bay interior moment frames are used to give lateral resistance to the frame structure. The designs for the nine-story structures included a complicated schedule of gravity and moment resisting beams and columns, with regular variations in height throughout the structure. These buildings' complete schedule of section sizes is shown in Tables 1.1 to 1.3 with reference to the plan drawing shown in Fig. 1.1, and 1.2 as well as in the appendices.

Table 1.1. Column Sizes for the 9-story Conventional and Isolated Buildings

Story Level	Conventional Buildings					Isolated Buildings				
	C1	C2	C3	C4	C5	C1	C2	C3	C4	C5
0-1	W24×306	W24×229	W24×250	W24×306	W14×145	W24×306	W24×306	W24×370	W24×370	W14×211
1-2	W24×306	W24×229	W24×250	W24×306	W14×145	W24×306	W24×306	W24×370	W24×370	W14×211
2-3	W24×250	W24×207	W24×229	W24×250	W14×109	W24×207	W24×176	W24×229	W24×250	W14×109
3-4	W24×250	W24×207	W24×229	W24×250	W14×109	W24×207	W24×176	W24×229	W24×250	W14×109
4-5	W24×229	W24×176	W24×207	W24×229	W14×90	W24×146	W24×146	W24×162	W24×162	W14×90
5-6	W24×229	W24×176	W24×207	W24×229	W14×90	W24×146	W24×146	W24×162	W24×162	W14×90
6-7	W24×192	W24×162	W24×176	W24×192	W14×61	W24×131	W24×103	W24×103	W24×131	W14×61
7-8	W24×192	W24×162	W24×176	W24×192	W14×61	W24×131	W24×103	W24×103	W24×131	W14×61
8-9	W24×162	W24×162	W24×176	W24×192	W14×48	W24×131	W24×103	W24×103	W24×131	W14×48

Table 1.2. Beam & Girder Sizes for the 9-story Conventional and Isolated Buildings

Storey Level	Conventional Buildings						Isolated Buildings					
	A	B	C	D	E	F	A	B	C	D	E	F
0-1	W27×194	W16×26	W16×31	W24×55	W16×31	W24×55	W27×146	W16×26	W18×35	W24×55	W24×68	W24×68
1-2	W27×194	W16×26	W16×31	W24×55	W16×31	W24×55	W27×146	W16×26	W18×35	W24×55	W24×68	W24×68
2-3	W27×178	W16×26	W16×31	W24×55	W16×31	W24×55	W27×114	W16×26	W18×35	W24×55	W24×68	W24×68
3-4	W27×178	W16×26	W16×31	W24×55	W16×31	W24×55	W27×114	W16×26	W18×35	W24×55	W24×68	W24×68
4-5	W27×161	W16×26	W16×31	W24×55	W16×31	W24×55	W27×114	W16×26	W18×35	W24×55	W24×68	W24×68
5-6	W27×146	W16×26	W16×31	W24×55	W16×31	W24×55	W27×94	W16×26	W18×35	W24×55	W24×68	W24×68
6-7	W27×146	W16×26	W16×31	W24×55	W16×31	W24×55	W24×84	W16×26	W18×35	W24×55	W24×68	W24×68
7-8	W27×146	W16×26	W16×31	W24×55	W16×31	W24×55	W24×55	W16×26	W18×35	W24×55	W24×68	W24×68
8-9	W24×68	W16×26	W16×26	W21×55	W16×26	W21×55	W24×55	W16×26	W16×26	W21×55	W24×55	W24×55

Table 1.3. Design Parameter Comparison for the Isolation Systems

Isolator properties	DBE	MCE
	LRB-1/LRB-2	**LRB-1/LRB-2**
Effective period	2.84 sec	2.95 sec
Effective stiffness	1215 - 1410 kN/m	1125 – 1315 kN/m
Effective damping	15% - 13%	12% - 10%
Isolator displacement	DD = 400 mm	DM = 625 mm
Total displacement	TD = 450 mm	TM = 730 mm

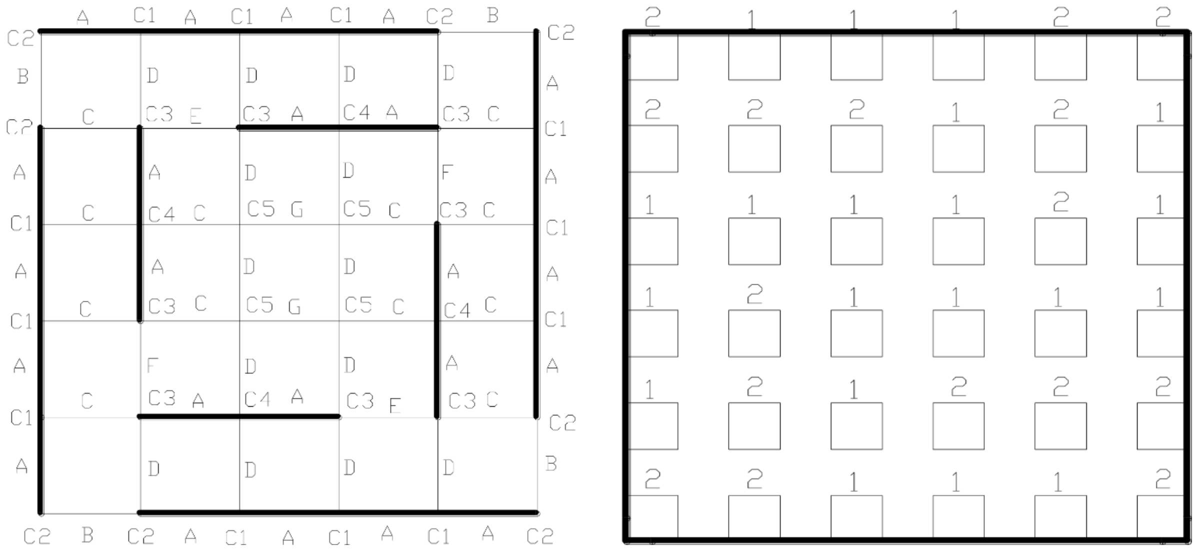

Figure 1.1. (a) Plan view of 9-story buildings, (b) Plan view of isolators for 9-story buildings

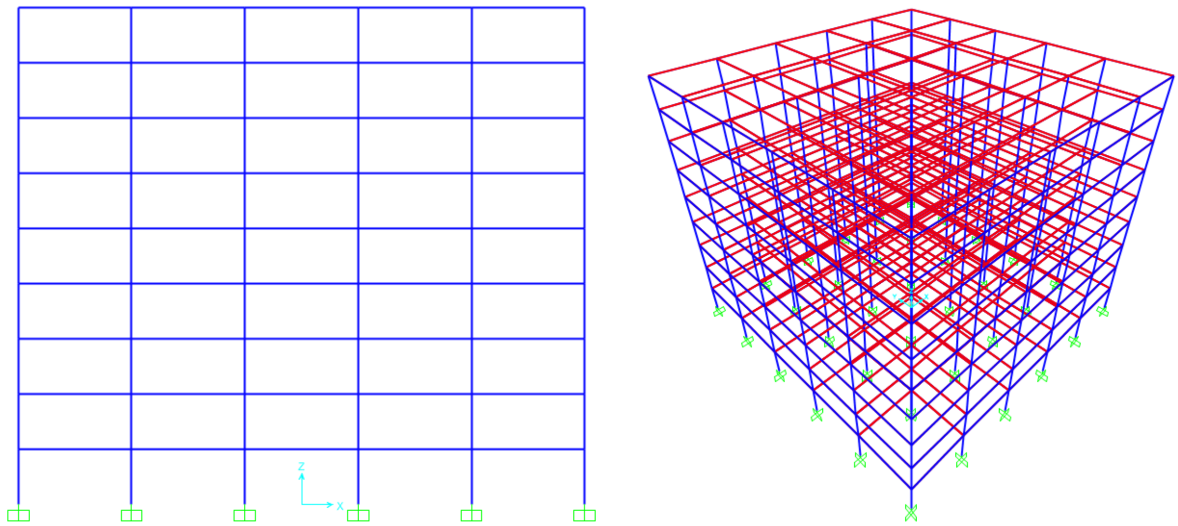

Figure 1.2. Elevation and 3D view of 9-story buildings in SAP 2000

III. NONLINEAR STATIC PUSHOVER ANALYSIS

Pushover is a nonlinear static analysis method that can be used to predict the reaction of a building or a non-building structure when subjected to nonlinear loads such as earthquakes. In this approach to structural analysis, a series of forces are applied to the structure in order to demonstrate the influence of earthquake ground motion on the structure. The lateral load pattern is expected to increase continually as a result of inelastic and elastic behaviour until the critical condition has been reached. Pushover analysis has become increasingly popular in recent years, owing to the simplicity of its computer-based technique for representing the various base shear ranges subjected to earthquake stress. Pushover analysis is presented in this study, along with the various applications in shear walls and moment resistant frames that can be found using these methodologies. Regular response spectra analysis for elastic high-rise buildings can be reformulated as modal pushover analysis in order to account for the elastic nature of the structure (MPA). Capacity curves for the 9-story conventional building and the superstructure of the isolated building (fixed without isolators) are plotted in Fig. 1.3.

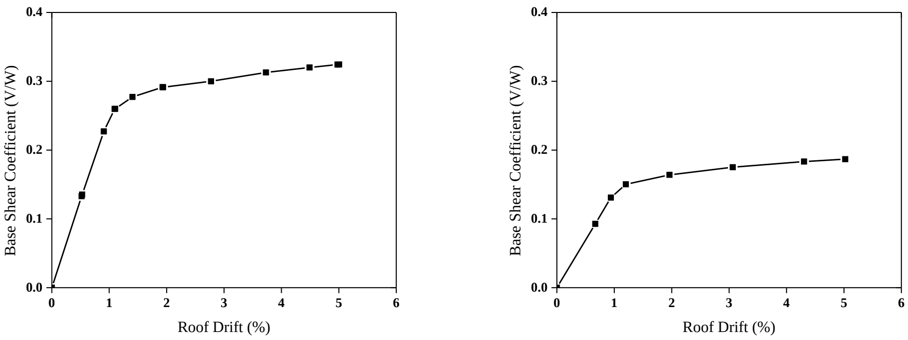

Figure 1.3. Capacity curves for the 9-story conventional building (Model A) and with isolators (Model B)

The predicted base shear capacities at first yield for the 2 building models are approximately: V=0.23W (9-story conventional), V=0.13W (M3 model for 9story isolated. The base shear capacity of the 9-story conventional building is 1.8 times that of the isolated building. This means that the performance of the 9-story isolated building compared to the conventional building. For 9story buildings, the conventional model has positive incremental stiffness over the entire post-yield range, while the isolated building capacity curve essentially flattens once it is fully yielded. Thus, the isolated building may be more prone to large inelastic excursions in yielding events.

IV. RESULT & DISCUSSION

Nonlinear time history analysis (RHA) were carried out to comparatively evaluate the structural response of the 9-story conventional and isolated buildings under the four ground motion scenarios above. Story drift was defined as the ratio of maximum (or residual) displacement to the story height; this measure indicates damage to structural elements and drift-sensitive nonstructural components. Peak drifts and residual drifts of each story were calculated from the maximum peak drifts of four corners in the same plane, because maximum drifts will be observed at the corner nodes in a rigid diagram if torsion is included. Floor acceleration, expressed in g, was evaluated to study the damage in acceleration sensitive nonstructural components and contents. The peak floor accelerations were calculated from the centers of mass in each story, as an average measure of the shaking intensity. Plastic rotation demands of individual elements can more precisely indicate local damage and verify yielding. Displacements of all isolators were recorded to evaluate the isolator demands under different levels of ground motions.

Table 1.4: Set of Ground Motion records

Earthquake	Year	Station	$\emptyset^{*1}$	M^{*2}	R^{*3} (Km)	$V_{S\,30}$ (m/s)	PGA
Superstition Hills (CC)	1987	Parachute Test Site	225	6.54	0.95	348.69	0.25g
Northridge (NR)	1984	Jensen Filter Plant	22	6.69	5.43	373.07	0.2g
Kobe, Japan (KO)	1995	Takatori	0	6.9	1.46	256	0.105g
Imperial Valley (IV)	1979	El Centro	140	6.53	0.56	210.51	0.89g

The selected response quantities include peak story drift and displacement, peak total floor acceleration, and peak isolator deformations (lateral and vertical). Fig. 4.1 anf Fig. 4.2 shows the median and peak displacement distribution in the x and y directions under selected earthquake, respectively, while Fig. 4.3 and Fig. 4.4 presents story drift demands in the same format. Peak displacements for all the events increased with height and increased as ground motions become severe. The median roof displacements ± standard deviation in the 9-story isolated building are comparable with the conventional building in the four events, which means the period of both buildings has shifted to the same degree for ground motion intensity within the design level intensity (Fig. and Fig. 4.6). The difference is that the period shift in the isolated building is due to the isolation system while the period shift in the conventional building is due to inelastic behaviors. The median peak roof displacement of 9-story conventional and isolated buildings is around 0.954 m, 1.324 m, 1.570 m and 1.833 m under selected events respectively. Since base displacement is significant in the isolated building and zero in the conventional building, the slope or rate of change of displacement in the conventional building is greater than the isolated building in lower stories as shown in Fig. 1.4. As a result, the drift demands are smaller than the conventional building in the lower stories. Basically, the benefit of the isolation system is that the overall structural displacement is reduced by an amount equal to the isolator displacement. The dispersion of the displacement demands is larger in the MCE event than the design event due to the large variation of isolator displacement, and leads to the peak displacement in Fig 1.4 with dispersion two times greater than conventional building.

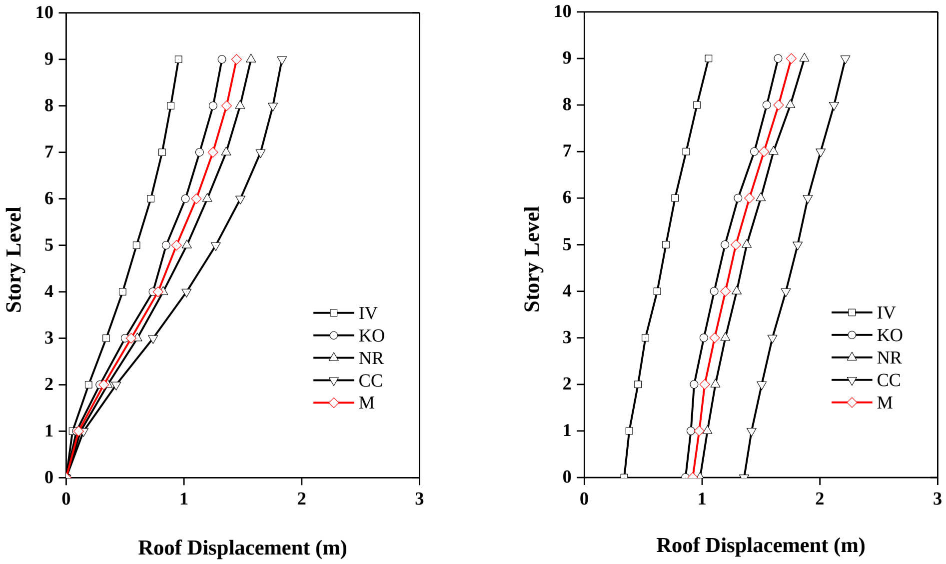

Figure 1.4. Median (M) and peak displacement distribution in the x directions under selected earthquake for Model A and Model B

The median story drifts of the 9-story buildings are below 2 % in the frequent event [Fig. 1.5]. Both buildings respond within the elastic range, and the median story drifts of the isolated building are not significantly smaller than conventional building since the substantial flexibility of the superstructure makes it hard to isolate for low drifts. For the design events, the story demands in 9-story isolated building are on the verge of yielding, with median roof drifts around 1.95 %. The 9-story conventional building more certainly yields in the design event, with median story drift demands being highest at drift of 2.15 % around stories 4 and 5 [Fig. 1.5)]. Drift demands and dispersions of the 9-story buildings increased a lot in the MCE event relative to the design event, and the median story drift mostly exceeds yield limits of 1.5% and 2.5% of the isolated and conventional buildings, respectively [Fig. 1.6].

With respect to accelerations, the median peak ground acceleration (PGA) for selected earthquake were 0.28g, 0.61g and 1.0g respectively in Fig. 4.19. Acceleration demands of the 9-story isolated building are essentially uniform with the height except the base level for all the events. The 9-story conventional building responded in a third mode shape in design events because of the higher modes effects. This can be expected because the first two modes mass participation factor is only 77% for the conventional building rather than 90% for the isolated building. For the design events, the median roof acceleration of the 9-story isolated building is reduced to 0.4g while the median roof acceleration in the 9-story conventional building is amplified to 0.8g [Fig. 1.6]. For the MCE event, high confidence in acceleration demands still can be observed in isolated building, but this is not true for the drift demand. Dispersion in acceleration remains small because period lengthening causes the system to be shifted to the smooth part of the spectral acceleration curve, while the yielding of the building in MCE events increases the dispersion in drift slightly relative to the design events.

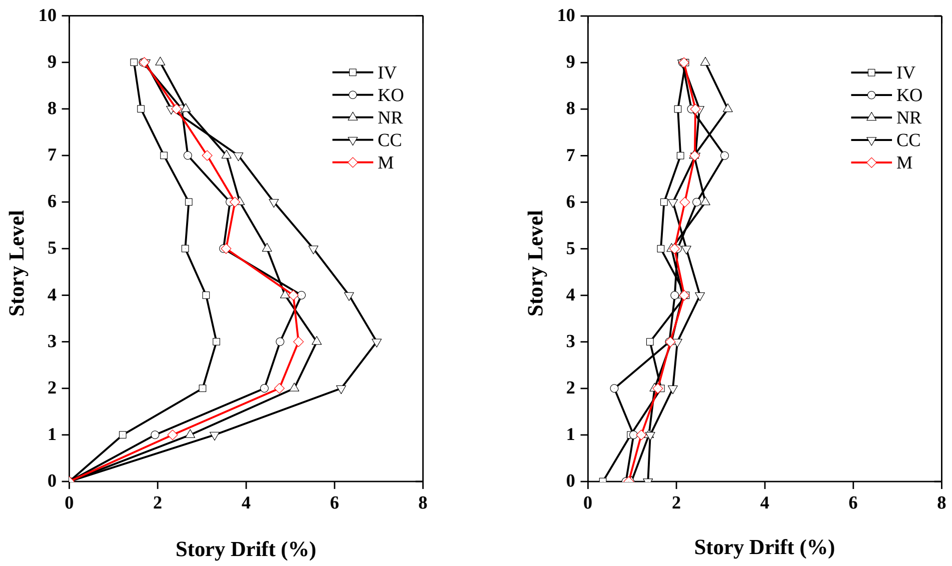

Figure 1.5. Median (M) and story drift distribution in the x directions under selected earthquake for Model A and Model B

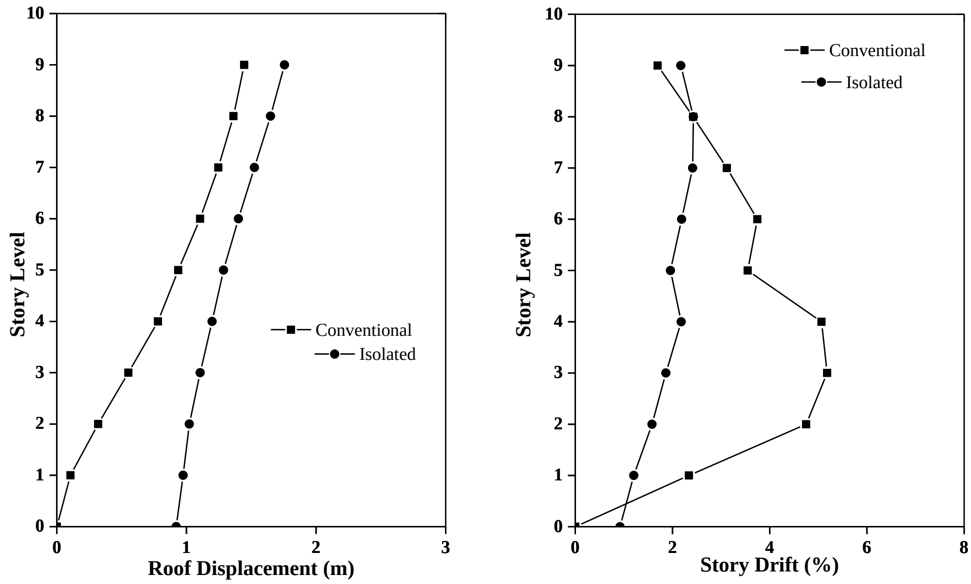

Figure No. 1.6. The median story displacement of 9-story conventional building (Model A) isolated building (Model B) in the four events

V. CONCLUSION

In the study, the multi-level seismic response of minimally code compliant 9-story conventional and isolated steel moment resisting frame buildings was evaluated and the influence of height on the response of an isolated moment frame was assessed. The design of the 9-story conventional and base-isolated steel moment frame buildings was verified separately in SAP. Eigenvalue analysis was carried out on the various building models to evaluate their elastic dynamic properties. Nonlinear static analysis (or pushover analysis) of the models was carried out under an inverted triangle load pattern to determine the base shear capacity and post-yield behavior based on the various building models. Nonlinear response history analysis (RHA) was carried out to comparatively evaluate the structural response of the 9-story conventional and isolated buildings under three ground motion scenarios. Synthesis of the study presented has led to the following conclusions:

1. The design objectives for the 9-story isolated and conventional buildings have been met. The 9-story isolated building performs much better than the 9-story conventional building with respect to peak floor acceleration, peak story drifts, and peak plastic rotation.
2. The isolated buildings do not have as much overstrength as the conventional buildings from the pushover analysis.
3. The flexibility of the moment frame leads to non-negligible structural participation in the structural modes of the 9-story isolated building. This can be observed from the peak displacement distribution, which varies from a first mode distribution, and larger relative story drifts compared to an idealized application of seismic isolation. This phenomenon could be exacerbated in a frequent earthquake event where the isolation system is not fully activated.
4. Drifts demands are lower in taller buildings as the total displacement, which is a function of the fundamental period of the system, is distributed over the height more effectively in a taller building. Displacement demands are essentially the same for 9-story isolated buildings in MCE level.

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