International Journal on
“Technical and Physical Problems of Engineering”
(IJTPE)
Published by International Organization of IOTPE

ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com

June 2024 | Issue 59 | Volume 16 | Number 2 | Pages 231-239

COMPERATIVE RESEARCH BETWEEN A CORE-WALLED FIXED BASE AND A BASE ISOLATED TALL BUILDINGS

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Abstract- This study seeks to evaluate and compare the effectiveness of the two predominant seismic protection methodologies employed for safeguarding tall buildings against seismic forces in regions prone to high seismic activity. One such approach that is widely used to resist lateral loads caused by seismic loads is the earthquake-resistant method. In this design approach, the structure is made rigid usually by applying a concrete core wall to resist lateral loads. This method is widely used in USA. Another design approach is the structure response control method which focuses on increasing the damping and/or period of the structure in most cases making the structure flexible while dissipating energy. This method is widely used in countries like Japan to protect buildings. The two conventional methods of seismic protection are presented in this research to compare the seismic behavior of the structures under seismic demand. Numerous seismic isolation devices with periods of up to 4 seconds have been developed and are extensively utilized in seismic-prone regions, including but not limited to Japan, China, New Zealand, and Turkey. These devices are commonly applied to a variety of buildings for enhanced seismic protection. A tall building with a concrete core wall was selected and used. The dynamic performance of a high-rise RC building with a shear wall core is compared to a redesigned model of the same building with base isolators inserted between the mat foundation and the foundation slab. A redesign of the sections of the building with base isolators was then carried and compare to a core-walled fixed base building with the original section properties. The design and seismic performance of the two buildings under seismic demands is presented. The thickness of the core wall was reduced by 37.78% and shear wall reinforcement by 34.10% due to the addition of base isolation. This translated to a cost reduction $1300641 that is almost equal to the estimates cost of procuring lead core rubber isolators which is $1306800. The peak floor accelerations at the roof and base shear responses of the Base isolated building structure were 78% and 58% on average lower than the core-walled fixed base structure respectively. The story drift ratios are well within the limits prescribed by the code. i.e. seismic (1/50) and wind design loading (1/400) respectively for both cases. Fundamental period of the base isolated structure was larger (6.95sec) when compared to the core-walled fixed base building (4.6sec).

Keywords: Base Isolation; Shear Core-Wall Building, Long-period Earthquake; FE Modelling, Reinforced Concrete-RC.

1. INTRODUCTION

The performance of a building under seismic stress is also related to its height and structural system. According to the American code of building a high-rise building is any building that is 160 ft (about 50 m) and above. In Japan, however, any building that is 60m and above is considered as a high-rise building. Research into both cost-effective and practical seismic design solutions for the protection of both people and property in seismic regions is necessary. Response controlled structures focus on lateral resistance through addition of damping devices to the superstructure and/or substructure in order to resist lateral loads. Rigid structures focus is the stiffening of the superstructure using structural systems that resist lateral loads.

Structural systems used in high rise RC buildings are rigid frames, braced frame systems, shear-walled frame systems, framed Tube-Tube, bundled system, braced tube system, outrigger system, buttressed core, diagrid, super frames, space Truss Structures. The most commonly used structural systems in active seismic regions such as the United States of America (USA) for resisting lateral loads are core shear walls [1, 2]. Shear walls resist the shear and thus reduce shear deformation, the effects of drift and overturning moment. High-rise reinforced concrete (RC) buildings employ a variety of structural systems to ensure stability and resilience. These systems include rigid frames, braced frame systems, shear-walled frame systems, framed tube-tube structures, bundled systems, braced tube systems, outrigger systems, buttressed core configurations, diagrid structures, super frames, and space truss structures. Each of these systems offers distinct advantages in addressing the unique challenges posed by tall structures and seismic considerations.

Registered: 231129 | Article Info: 1802 | Accepted: 240522
Reserved: 240215 | | Available: 240630

The most commonly used structural systems in active seismic regions such as the United States of America (USA) for resisting lateral loads are core shear walls [1, 2]. Shear walls resist the shear and thus reduce shear deformation, the effects of drift and overturning moment. Seismic isolation separates the structure from the harmful motions of the ground by providing the flexibility and energy dissipation capability through the insertion of isolation devices, called isolators, between the foundation and the superstructure. This leads to the shifting of the superstructure's dominant period. Therefore, the acceleration of the superstructure is significantly reduced in comparison to the earthquake acceleration [3].

After the 2011 Tohoku earthquake in Japan 129426 buildings totally collapsed, 265240 buildings partially collapsed, and another 727054 buildings were partially damaged. The earthquake and subsequent tsunami caused US$200 billion worth of damage in Japan [4]. Response control methods such as base isolation devices and dampers came under scrutiny. The Japan Society of Seismic Isolation JSSI conducted survey of the damage and performance of 327 base isolated buildings and 130 vibration-controlled buildings.

Displacement of the seismic isolation layer was about 0.100 to 0.200 m, on average, and 0.400 m maximum in the Tohoku area; in the Kanto area it was 0.050 m to 0.080 m and 0.150 m, respectively. The average maximum displacements of the seismic isolation layer were around 50-100 mm in the Kanto district (400 km from the epicenter), 0.100-0.200 m, in Miyagi prefecture (170 km from the epicenter), 0.150 m in Fukushima, 0.415 m in Miyagi, 0.150 m in Tokyo. In other regions the maximum displacement was around 0.029 m to 0.180 m. The maximum residual displacement was around 0.020 m. In summary response devices installed on Tall RC buildings in the Tokyo metropolitan area performed fairly well during the 2011 Tohoku Earthquake but tall buildings were mostly affected by the strong long duration motion of the earthquake [4, 5].

There are several studies on enhancing the performance of seismic base-isolated structures against near-fault and far-source long-period earthquakes. Kasimzade, et al. [3, 6, 7] proposed and developed new Structural Seismic Isolation Method (SSIM) for protection of structures against strong and long-period ground motions. This method aims to eliminate the limitation and vulnerability of the conventional elastomeric (lead rubber or laminated rubber bearing) base-isolated structures. In this approach using currently existing conventional elastomeric isolators that have a period of up to 4 seconds the structure is converted to a Structural Seismic Isolation System (SSIS) and exhibits inverse pendulum behavior thus keeping the natural-period of the structure in a larger interval, which is greater than the predominant-period of most earthquakes (including near-fault pulse). Detailed applications and performance of the new Structural Seismic Isolation Method (SSIM) for the high-rise building structures (SSIS-Bg), for the nuclear containment structures (SSIS-NC) and for tower structures (SSIS-Ts) was researched by Kasimzade, et al. [3, 8, 9, 20, 21, 22]. Results indicate that the base and top accelerations, base shear, and base moment responses of the SSIS-Bg structure is 23.21, 75.47 and 85.74 on average lower than the structures that use the Conventional Application Method of Seismic Base Isolation Devices for Building (CAMSBID-Bg) respectively [6, 7].

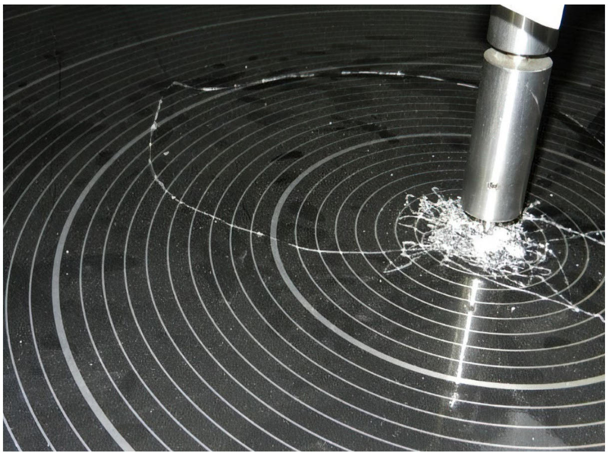


Figure 1. Scratch plate indicating maximum isolation system displacement of 0.23 m [4, 5]

The 40% or more of the base isolated buildings had scratch plates (Figure 1) to show trajectories during the shaking.

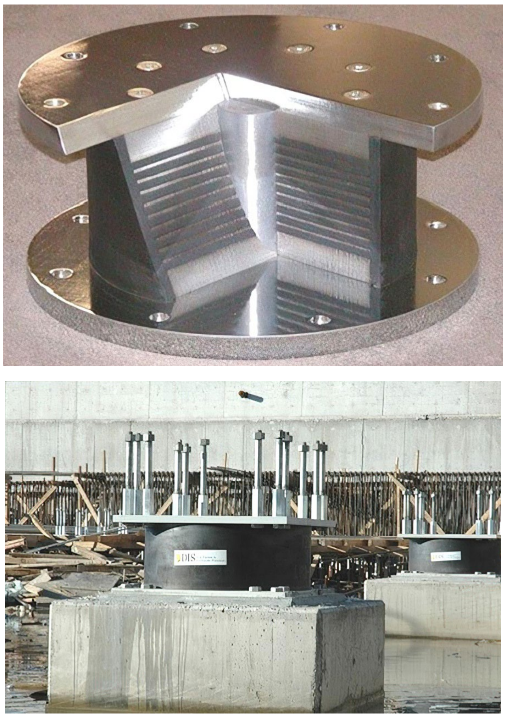


Figure 2. Elastomeric base isolation devices [4, 5]

When compared with predominately core-walled s6tructures and other fixed base structures base isolated buildings have an initial construction cost that is between 1-10% more than the initial construction cost of other conventional buildings [10]. In general, base isolation and installation cost is 5% of the total initial construction cost.

Base isolation results in reduced seismic demands on the structure thus after an earthquake the financial loss from business interruption (cost of temporary relocation, retrofitting costs, cost of demolition (CD) and reconstructing the building) are minimal when compared to the fixed base alternative [13, 14]. Despite the benefits of base isolation and its relatively low cost according to Eriksen, Mohammed [16] there are less than 5 tall base-isolated building projects a year in America. Research into both cost-effective and practical seismic design solutions for the protection of both people and property becomes necessary and urgent.

2. PROBLEM IDENTIFICATION

This study aims to compare the two most popular seismic protection approaches to protecting tall buildings against seismic forces in highly seismic regions. One such approach that is widely used to resist lateral loads such as wind and seismic demands is the earthquake-resistant method. In this design approach, the structure is made rigid usually by applying a concrete core wall to resist lateral loads. Another design approach is the structure response control method which focuses on increasing the damping and/or period of the structure in most cases making the structure flexible while dissipating energy.

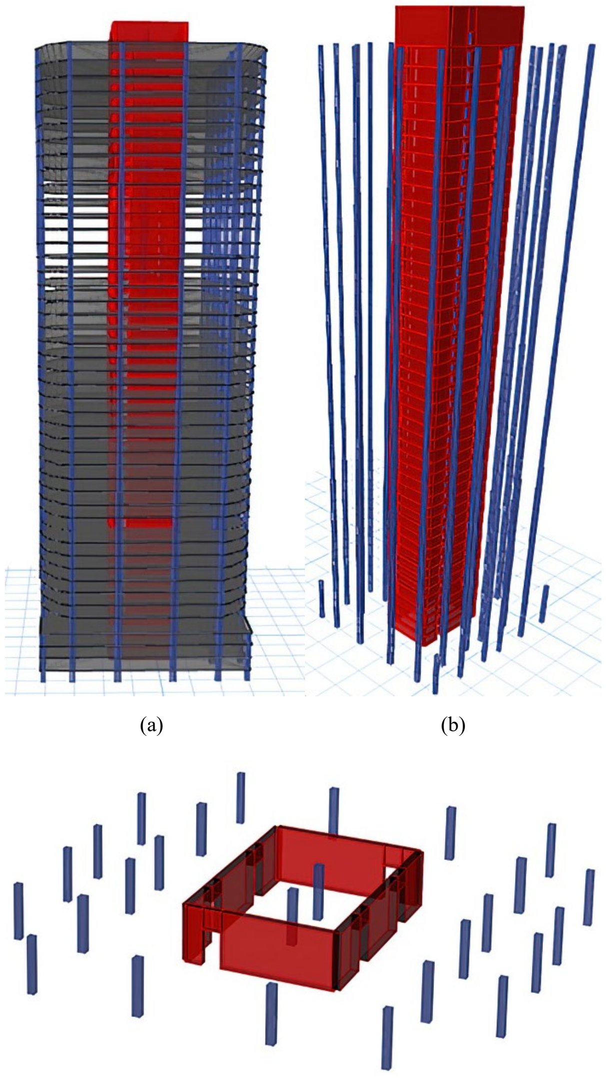
The two conventional methods of seismic protection are presented in this research to compare the seismic behavior of the structures under seismic demand.

A tall building with a concrete core wall was selected and used in this research. The tall building was then designed with a base isolated inserted between the mat foundation and the foundation slab. A redesign of the sections of building with base isolators was then carried out and compared to a core-walled fixed base building with the original section properties.

The isolation devices chosen for this research are lead core rubber bearings (LCRB).

3. DESCRIPTION OF BUILDING, CODE REQUIREMENTS AND FINITE ELEMENT MODELLING

To assess and enhance performance-based seismic designs for tall buildings, the Tall Buildings Initiative (TBI) research program was initiated by PEER. As a component of the TBI program, a case study project focusing on tall buildings was undertaken. One such building, designated as building 1A, features a reinforced concrete (RC) core wall structure and serves as a representative benchmark for the study [1, 2]. The building to be modelled is a 42-story (131.01 m) reinforced concrete residential building located in Los Angeles, California with four stories below ground. his building type was selected as a representative model for residential buildings in seismic regions what use the rigid structure design approach. The building was altered from the original design provided by PEER research institute [1, 2].



(a)

(b)

(c)

Figure 3. Representative model, a) 3D view, b) Lateral resisting system 3D story floor view

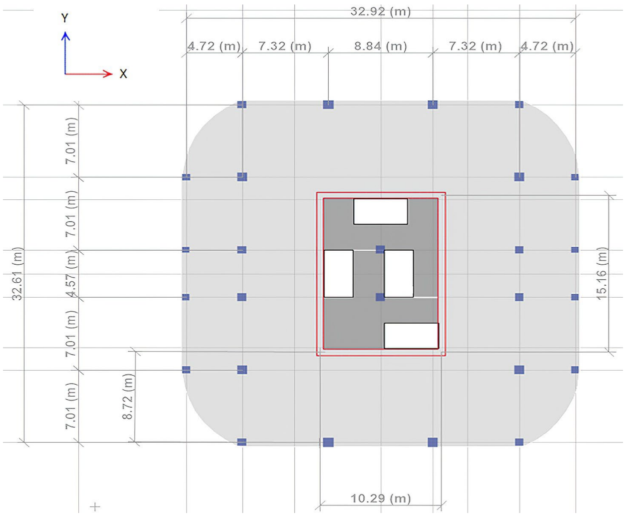


Figure 4. Typical floor plan [1, 2]

Table 1. Geometric properties of the structure [1, 2]

item	Property	Value
1	Height (Hs)	131.01 m
2	Typical story height	2.95 m
3	Core Top height	6.096 m
4	Roof height	3.2512 m
5	First floor height	3.81 m
6	Building stories above ground	44
7	Basement height	3.08 m
8	Building stories below ground	4
9	Dir: *X*	32.92 m
10	Dir: *Y*	32.62 m

The gravity loads listed are in addition to the self-weight of the structure. Th5e minimum loading requirements ASCE 7.

Table 2. Design loads [1, 2]

Area	Live Loading (kN/m^2)	Superimposed (kN/m^2)
Ground story	4.788	5.26
Exit Areas	4.788	1.34
Residential Area	1.915	1.34
Residential/Hotel	1.915	1.34
Roof	1.197	1.34
Mechanical/Electrical	0	4.788 at roof level

The load combinations follow the strength design load combinations listed in ASCE 7. Load Combinations: 2006 International Building Code (2006 IBC). Seismic loads are in accordance with the ASCE 7. Reinforced Concrete: Building Code Requirements for Structural Concrete and Commentary by the American Concrete Institute, 2008 Edition (ACI 318). The following building and material codes were used for the design.

Table 3. Concrete properties

	Structural member	Specified strength of concrete (×10^6 N/m^2)	Modulus of Elasticity (×10^6 N/m^2)	Dimensions	
1	Non-Post-Tensioned Slab	50	30302.46	Basement level slabs, roof level	Thickness= 0.254 m
				Ground level slab	Thickness= 0.304 m
2	Post-Tensioned Slabs	50	30302.46	Rest of slabs	Thickness= 0.203 m
3	Columns	55.15	31577.99	Varies 0.863.6×0.863.6 m ~ 0.457.2×0.457.2 m	
4	Shear Walls	55.15	31577.99	Story B4-25 (thickness =0.609.6m) Story 25-Roof (thickness =0.533.4 m)	

The site is situated in close proximity to several active faults, including:

Puente Hills fault: 1.5 km away
Hollywood fault: 7.3 km away
Raymond fault: 8.8 km away
Santa Monica fault: 11.5 km away
Elsinore fault: 24.5 km away
Sierra Madre fault system: 40 km away
San Andreas fault: 56 km away

The building in question was designed by Magnusson Klemencic Associates for the PEER research institute. Slabs were modelled as rigid diaphragms. Shear wall was modelled as thin shell finite element. The coupling beam were modelled as shell finite elements assigned spandrel labels in Etabs. The theoretical values of stiffness were used for dynamic analysis without including any stiffness modifiers.

4. PRELEMANARY DESIGN OF LCRB TYPE SEISMIC ISOLATORS

The initial dimensions and analytical parameters for the seismic isolators have been computed following the guidelines provided in ASCE 7-16 [18] and ASCE 41-13 [19] codes. Key analytical parameters for finite element modeling of the seismic isolators include yield force (F_y), yield displacement (D_y), damping ratio, and vertical stiffness (K_v).

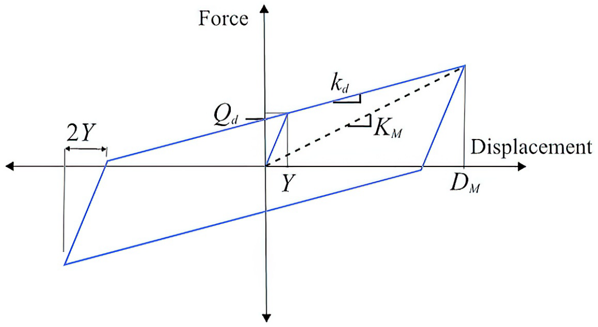


Figure 5. Bilinear characteristics on an LCRB seismic isolator [4, 5]

Table 4. Rubber properties for LCRB (Bridgestone)

Item		Symbol	Unit
1	Shear modulus (rubber)	G	0.385 ×10^6 N/m^2
2	Bulk modulus	K	1176 ×10^6 N/m^2
3	Shear yield strength of lead	f_{py}	8 (×10^6 N/m^2)
4	Allowable compressive stress range	σ_C	3×10^6 N/m^2-15×10^6 N/m^2
5	Percentage of shear strain range	γ	100%-150%
6	Yield Stiffness Ratio	K_2/K_1	13
7	Elongation at break Min.		600%
8	Compressive stress (Axial stress)		5×10^6 N/m^2-15×10^6 N/m^2

Minimum horizontal stiffness and the design displacement of the isolator are calculated using Equations (1) and (2), respectively:

$$K_{eff}=\frac{W}{g}\times\left(\frac{2\pi}{T_D}\right) \tag{1}$$

$$D_D=\frac{g}{4\pi^2}\times\left(\frac{S_D T_D}{Bd}\right) \tag{2}$$

Let Design period: $T_D=4\,\text{sec}$; $S_D=0.521$; $B_{eff}=1.7$; $\xi=0.3$, Seismic LCRB isolators with the characteristics (Table 5) were used in finite element modeling as link finite element, the layout and quantities are presented in Figure 6 and Table 6, respectively.

Table 5. Selected LCRB (Bridgestone) for analysis

Item	Parameter	Evaluation	LCRB-1 LT140G4	LCRB-2 LT120G4	LCRB-3 LT110G4	LCRB-4 LT100G4
1	Bearing diameter	m	1.4	1.20	1.10	1.00
3	Nominal long-term column load	kN	21800	13800	11000	7940
4	Rotational Inertia1	$I=\pi D^4/64$	0.1886	0.1018	0.0719	0.0491
5	U_1Vertical Stiffness KN/m	K_v	7320000	5390000	4450000	3740000
6	U_2 and U_3 Effective Stiffness KN/m	K_{eff}	5230	3930	2690	2590
7	For U_2 and U_3 Effective Damping	B_{eff}	0.305	0.310	0.287	0.299
8	Yield Displacement (Distance from End-J), (m)	$D_y=Q/(K_1-K_2)$	0.023	0.024	0.0201	0.0219
9	U_2 and U_3 Stiffness (KN/m)	K_1	32100	23500	19400	16300
10	Characteristic strength	Q	681	526	360	330
11	Post-yield stiffness	K_2	2470	1810	1490	1250
12	Total weight	kN	57.0	28.4	24.4	21.0

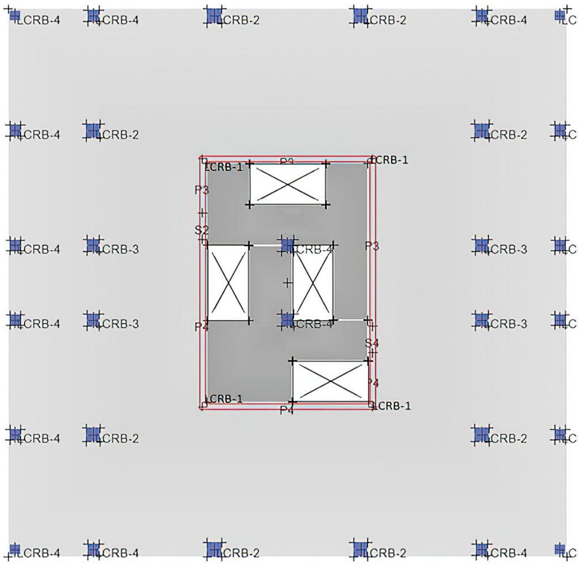


Figure 6. Isolation layer layout

Table 6. LCRB sizes

Item	ID	Diameter	Number
1	LCRB-1	0.140	4
2	LCRB-2	0.120	8
3	LCRB-3	0.110	4
4	LCRB-4	0.100	18
Total			34

The conclusive design of the elastomeric isolator's parameters is validated in each iteration through the evaluation of the hysteresis loop of elastomeric isolators.

5. EIGENVALUE AND MODAL ANALYSIS EVALUATION OF THE FINITE ELEMENT MODELS

Ritz vectors were used to calculate the modes (Target mass participation ratio 90%). Non iterative P-delta effects where considered. Seismic weight of the building was set to $DL+SDL+0.25LL$ (DL=dead load, SDL=super dead load, LL=live load). Modal damping assumed was assumed to be 5%. The summation of the mass participation ratios was above 90% for the number of modes considered. Eigenvalue analysis performed using the Equation (3) MATLAB and results are presented in Table 7.

$$\left\{[k]-\omega i^2[m]\right\}\varphi i=0 \tag{3}$$

Table 7. Natural periods of models for the first five mode shapes

Period (sec)		Pure-Core wall building (Fixed-base)	Base Isolated core walled building
Mode 1	X	4.568	6.952
Mode 2	Y	3.762	6.077
Mode 3	T	1.357	3.676
Mode 4	X	0.993	2.159
Mode 5	Y	0.789	1.964

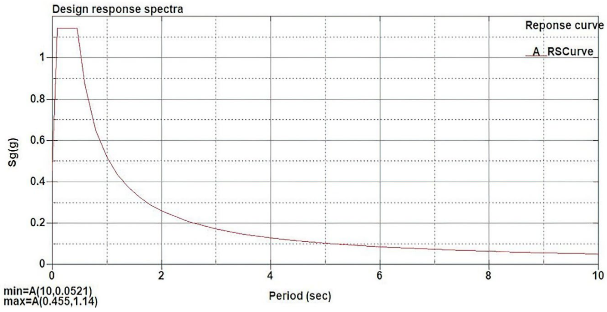


Figure 7. Site response spectrum [1, 2]

Table 8. Seismic design properties for isolated structure

Design Coefficients and Factors Obtained from ASCE	Design Coefficients and Factors Obtained from ASCE table 12.2.1
Ω_0	2.5
Cd	5
I	1
R (fixed base)	6 (ASCE)
R (base isolated)	2 (ASCE)

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The response modification factor for a base isolated building is 2. Redesign of core wall for base isolated building based on ASCE 7-05 and ACI 318-08. Designed as an uncracked section. The target displacement for the shear wall (IBC2006). From IBC If $T\geq 0.7$ sec, then;

$$\Delta \leq 0.020\,H_{sx}$$

Wind load (WL) load case was also defined for the model. Using MATLAB, excel and Etabs a series of shear wall thicknesses were selected 0.3048 m, 0.356 m, 0.4064 m and 0. 4572 m. The design of the shear wall was performed Etabs and the following checks were performed. Taking 0.7 as wall stiffness modifier as per ACI uncracked section;

- Flexural shear stress (Wall Pier Demand/Capacity Ratio) check
- Moment Capacity Check
- Shear Capacity Check
- Axial load check

The section which was designed was for is a 0.3556m.

6. RESULTS AND DISCUSSION

For comparison of the two different approach a site-specific response spectra analysis was used to evaluate the following parameters at design stages; the displacement, inter-story drift ratio, floor accelerations, overturning moments, story shear forces, reduction in core-wall sections, section properties reduction, cost estimates are presented in Figures 8-9 and Tables 9-11, respectively.

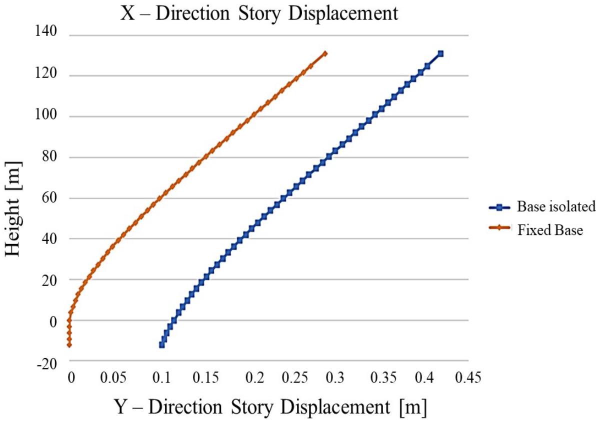

Figure 8. Story displacement (m)

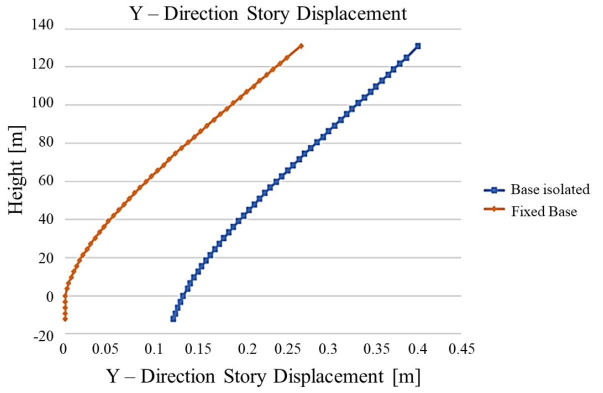

Figure 9. Story displacement

The maximum displacement under the site response spectra is shown in Figures 8 and 9. The base displacement of the base-isolated building is 0.1158 m and 0.1228 m in the direction of *X* and *Y*, respectively. The impact of using the LRB (Lead Rubber Bearing) support system is evident in the reduction of roof drift demand for the building. The maximum story drift ratio for the core-walled fixed base building is 0.003128 in the *X* direction and 0.002655 in the *Y* direction. In comparison, for the base-isolated building, these values are 0.003 in the *X* direction and 0.002429 in the *Y* direction, both of which are smaller than the acceptance limit of 0.02 specified for the inelastic inter-story drift ratio in ASCE 7-05. This indicates that the base-isolated building, particularly with LRB support, meets the specified criteria for inelastic inter-story drift.

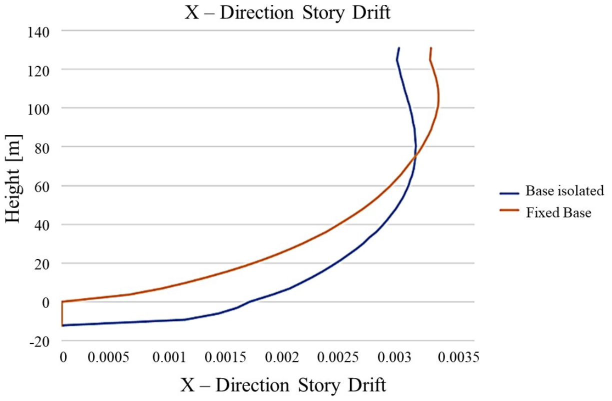

Figure 10. Story drift ratio

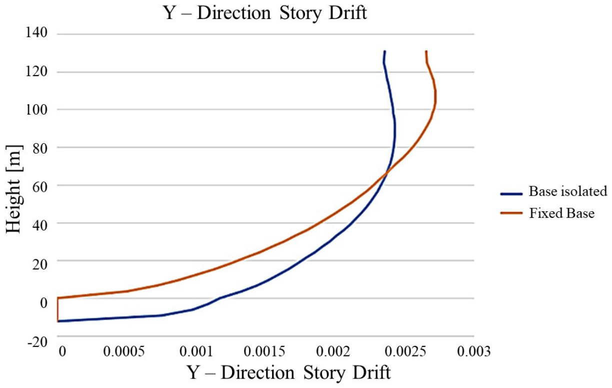

Figure 11. Story drift ratio

It can be clearly seen that the building supported with the LRB has generally reduced the roof drift demand.

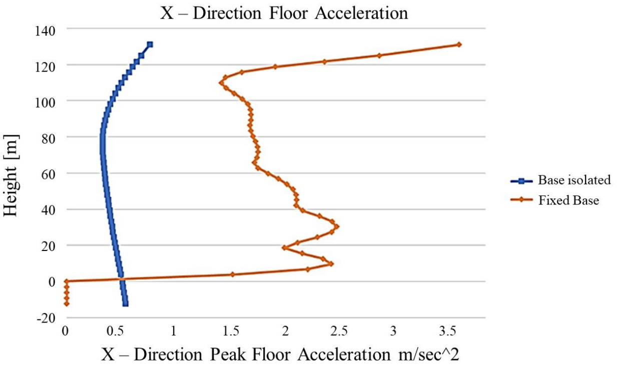

Figure 12. Floor acceleration

Maximum floor acceleration for the base isolated structure is 0.69 m/sec^2 in the *X* and *Y* direction compared to 3.28 m/sec^2 and 3.31 m/sec^2 for the core-walled fixed base building in the direction of *X* and *Y*, respectively. They are a 78% and 79.15% reduction in the peak floor acceleration in the direction of *X* and *Y*, respectively at the roof level.

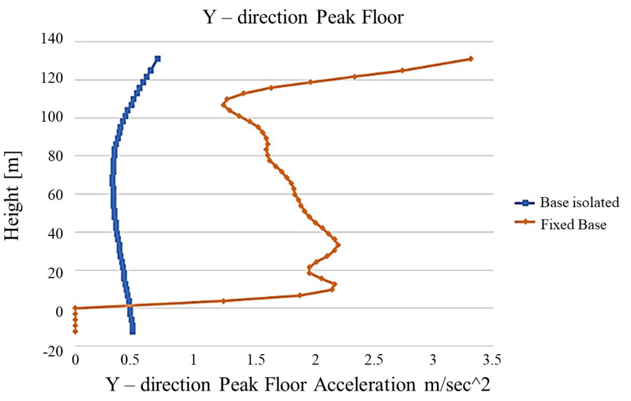

Figure 13. Floor acceleration

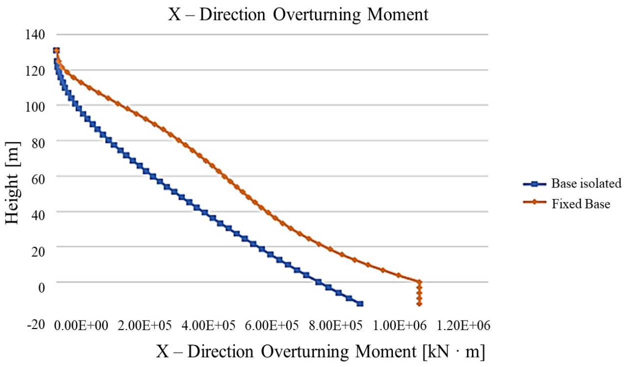

Figure 14. Overturning moment

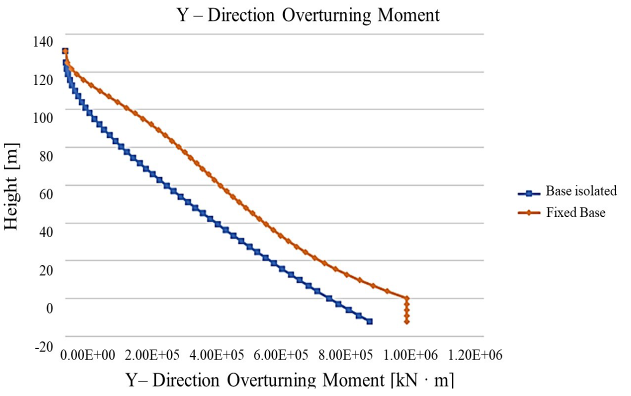

Figure 15. Overturning moment

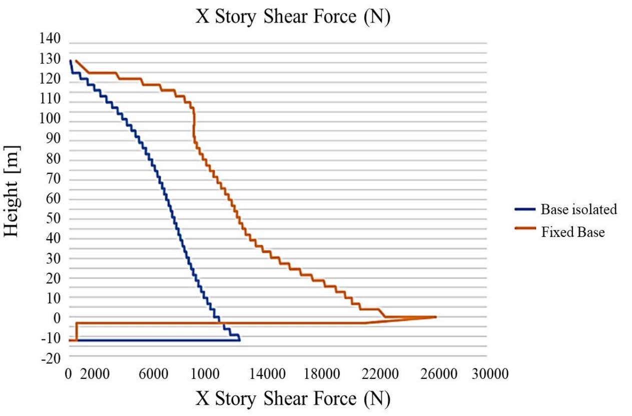

Figure 16. Story Shear forces

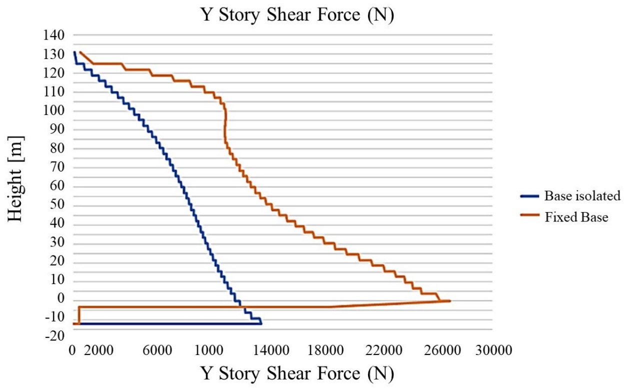

Figure 17. Story shear forces

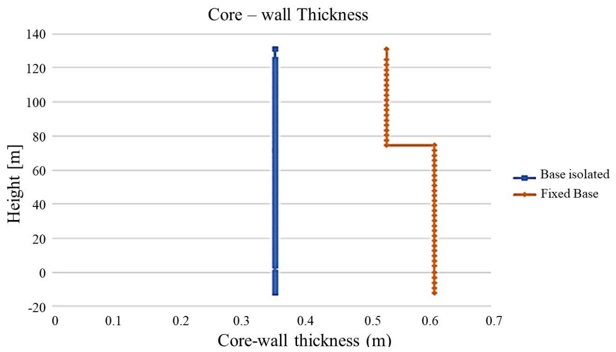

Figure 18. Reduction in core-wall section

Table 9. Section properties reduction

	Element /Property	Description	Old	New	% reduction
1	Shear wall	Shear wall section thickness	0.5715 m	0.3556 m	37.78
		Shear-wall Reinforced concrete	4440.535 m^3	2763 m^3	37.78
2		Shear wall reinforcement	531457.397 kg	350217 kg	34.10

Table 10. Cost estimates of LCRB

Item	Isolator ID	Diameter	Number	$Price
1	LCRB-1	1400	4	69 400
2	LCRB-2	1200	8	45 300
3	LCRB-3	1100	4	35 300
4	LCRB-4	1000	18	29 200
Total			34	1306800

Table 11. Base isolated building cost impact

Item	Element /Property	Shear wall building	Base isolated building
1	Isolator cost	-	$1306800
2	Concrete (1677.54m^3* $457.8)	-$767975	
3	Reinforcement rebar (181240kg* $2.939)	-$532666	

The use of base isolation results in reduced cost as shown on Tables 8 and 9. The reduction costs can be utilized to procure LCRB

7. CONCLUSIONS

For the two buildings design and seismic performance which are seismically protected by the fore-mentioned conventional methods from seismic demands, the following conclusions are reached:

A building designed using the response control methods such as a base isolator has reduced structural element cross-sections and building mass when compared to structures built using the rigid structure approach. This results in the design of an even lighter structure. The thickness of the core wall was reduced by 37.78% and a reduction in shear wall reinforcement of 34.10%. A base isolated building allows for a reduction in base shear. The peak floor accelerations and base shear responses of the Base isolated building structure were 78 and 58 on average lower than the core-walled fixed base structure, respectively.

The use base isolation allows for the reduction in floor accelerations thus during earthquake a base isolated structure can be used to protect buildings with sensitive equipment. The story drifts and displacement are well within the limits prescribed by the code thus the design is safe under both seismic (1/50) and wind design loading (1/400). The use of base isolation is thus far more attractive when compared to the use of a core-wall as a lateral resisting system during earthquake. Isolated designs are less sensitive to uncertainties in ground motion. Seismic isolation leads to a simpler structure with much less complicated seismic analysis as compared with conventional structures.

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