International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 09 , September - 2026

Analysis of the Effectiveness of Base Isolation using Single Friction Pendulum Bearings in Plan Irregular Structures

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Abstract - Base isolation using Single Friction Pendulum Bearings (SFPB) is an effective technique to reduce seismic demands on buildings. This study evaluates the effectiveness of SFPB in improving the seismic response of G+7 storey reinforced concrete moment-resisting frame buildings with regular, L-shaped and C-shaped plan configurations located in Seismic Zone III. Three-dimensional models of fixed-base and SFPB-isolated buildings were developed in ETABS. Modal analysis and nonlinear time history analysis were performed using seven selected PEER ground motion records. The key response parameters examined are fundamental time period, base shear ratio and top storey acceleration. Results show that the fundamental time period increased by 78.0%, 74.5% and 72.5% for regular, L-shaped and C-shaped buildings respectively after isolation. Base shear ratio reduced by up to 78.6% in regular buildings, 75.2% in L-shaped buildings and 78.2% in C-shaped buildings, depending on the ground motion. Top storey acceleration reduced by up to 82.1% (regular), 80.8% (L-shaped) and 78.9% (C-shaped). Although plan irregularity introduces some residual torsional effects, SFPB isolation consistently reduced seismic demands in all three configurations. The study confirms that Single Friction Pendulum Bearings are effective in enhancing the seismic performance of both regular and plan-irregular mid-rise RC buildings.

Keywords: Base isolation; Friction pendulum bearing; Nonlinear time history analysis; Nonlinear link element; Seismic Performance evaluation.

INTRODUCTION

Earthquake-induced ground motion continues to pose a major threat to building structures, particularly in seismically active regions. Conventional fixed-base design primarily relies on strength, stiffness and ductility of the structural system. Although this approach can prevent collapse, it often results in significant structural and non-structural damage during strong earthquakes, leading to high economic losses and prolonged functional downtime [1, 2]. Base isolation has emerged as an effective passive seismic protection technique that decouples the superstructure from the ground motion. Among various isolation devices, Single Friction Pendulum Bearings (SFPB) are widely preferred due to their simple configuration, stable energy dissipation characteristics and inherent self-centering capability [3, 4]. By lengthening the fundamental period of the structure and dissipating energy through friction, SFPB systems significantly reduce base shear, inter-storey drift and floor accelerations. Most previous studies on SFPB have focused primarily on regular-plan buildings. In actual practice, many buildings are plan-irregular (L-shaped or C-shaped) due to architectural and functional requirements. Such irregularities introduce torsional effects and uneven distribution of seismic demands, which may influence the efficiency of the isolation system [5, 6]. Systematic comparative evaluation of SFPB performance for both regular and plan-irregular mid-rise RC buildings under identical seismic inputs remains limited. Therefore, the present study investigates the effectiveness of Single Friction Pendulum Bearings in G+7 storey reinforced concrete moment-resisting frame buildings with regular, L-shaped and C-shaped plan configurations. The key seismic response parameters considered are fundamental time period, base shear ratio and top storey acceleration. Both fixed-base and SFPB-isolated models are analysed using modal analysis and nonlinear time history analysis with seven selected ground motion records.

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DESCRIPTION OF BUILDING AND MODELLING APPROACH

Three G+7 storey reinforced concrete moment-resisting frame (RC-MRF) buildings with different plan configurations-regular, L-shaped and C-shaped-were considered in the present study. All buildings were assumed to be located in Seismic Zone III as per IS 1893 (Part 1): 2016 with medium soil conditions. The total height of each building was 24 m, with a bottom storey height of 1.0 m and typical storey height of 3.0 m. The buildings were designed for residential use.

The geometric details of the three plan configurations are as follows:

- Regular shape: 25 m × 25 m
- L-shape: 20 m × 20 m
- C-shape: 15 m × 20 m

Uniform member sizes were adopted for all models: columns of 450 mm × 450 mm, beams of 230 mm × 450 mm and slabs of 150 mm thickness. Material properties of M25 grade concrete and Fe500 steel were assigned. Dead loads were calculated by the program, while floor finish of 1.0 kN/m², live load of 2.0 kN/m² and wall load of 13.8 kN/m were applied. A rigid diaphragm was assigned at each floor level.

Two support conditions were modelled for each plan configuration:

1. Conventional fixed-base condition
2. Base-isolated condition using Single Friction Pendulum Bearings (SFPB)

The SFPB isolators were modelled as nonlinear friction isolator link elements in ETABS with appropriate radius of curvature, friction coefficients and high vertical stiffness to represent the actual behaviour of the bearings. Modal analysis was performed to obtain the natural time periods and mode shapes. Nonlinear time history analysis was carried out using seven selected ground motion records obtained from the PEER Ground Motion Database. The selected records covered a magnitude range of 6.2 to 7.3 and included both near-fault and far-fault motions with varying frequency content. The ground motions were applied simultaneously in both principal directions of the buildings. Key response parameters fundamental time period, base shear ratio and top storey acceleration were extracted and compared between the fixed-base and isolated models for all three plan configurations.

Table 1

Mechanical characteristics of the materials

Concrete Type: M25	Steel Type: HYSD 500	Concrete compressive strength fc (MPa)	Elasticity modulus of concrete Ec (MPa)	Poisson's ratio of concrete, µc	Yield strength of steel, fy (MPa)	Ultimate stress capacity of steel, fsu (MPa)	Ultimate strain capacity of steel, εsu	Elasticity modulus of steel, Es (MPa)	Poisson's ratio of steel, µs
25	-	25	25000	0.20	500	545	0.12	200000	0.30

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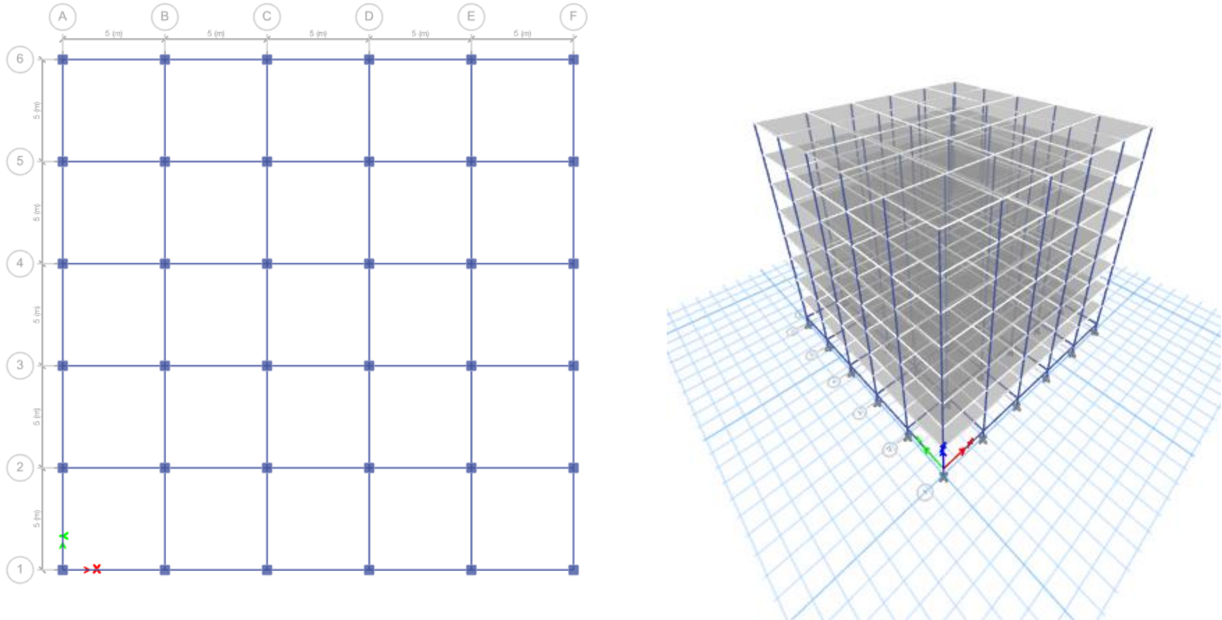

Fig.1. Views of regular-shape building (a) Plan view, (b) 3D linear appearance

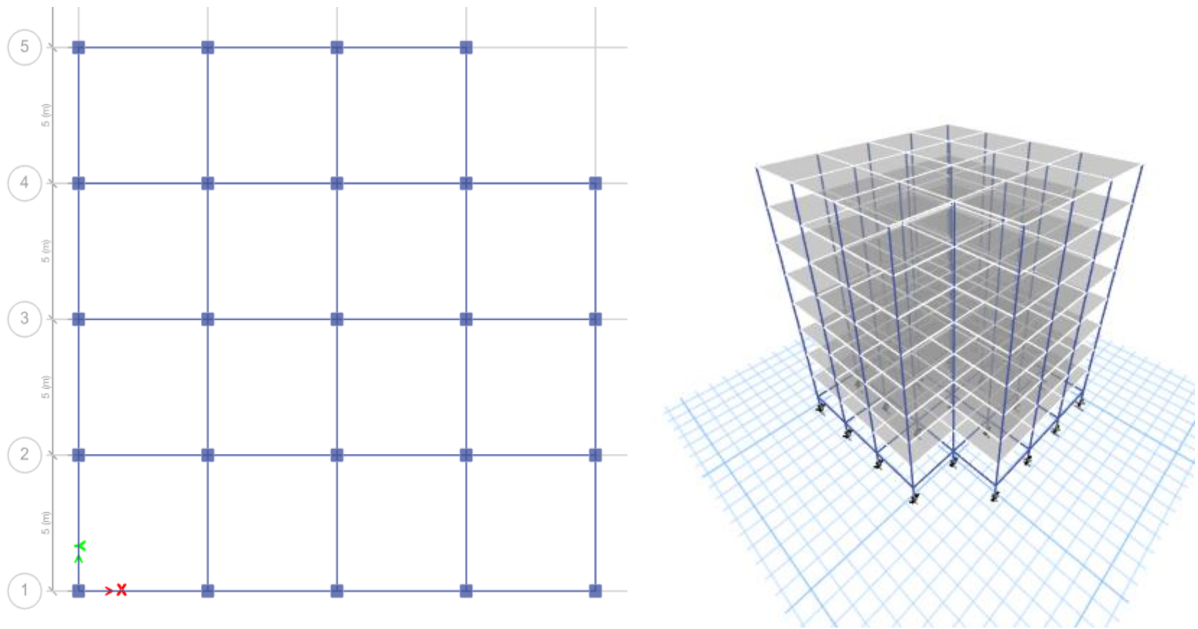

Fig.2. Views of L-shape building (a) Plan view, (b) 3D linear appearance

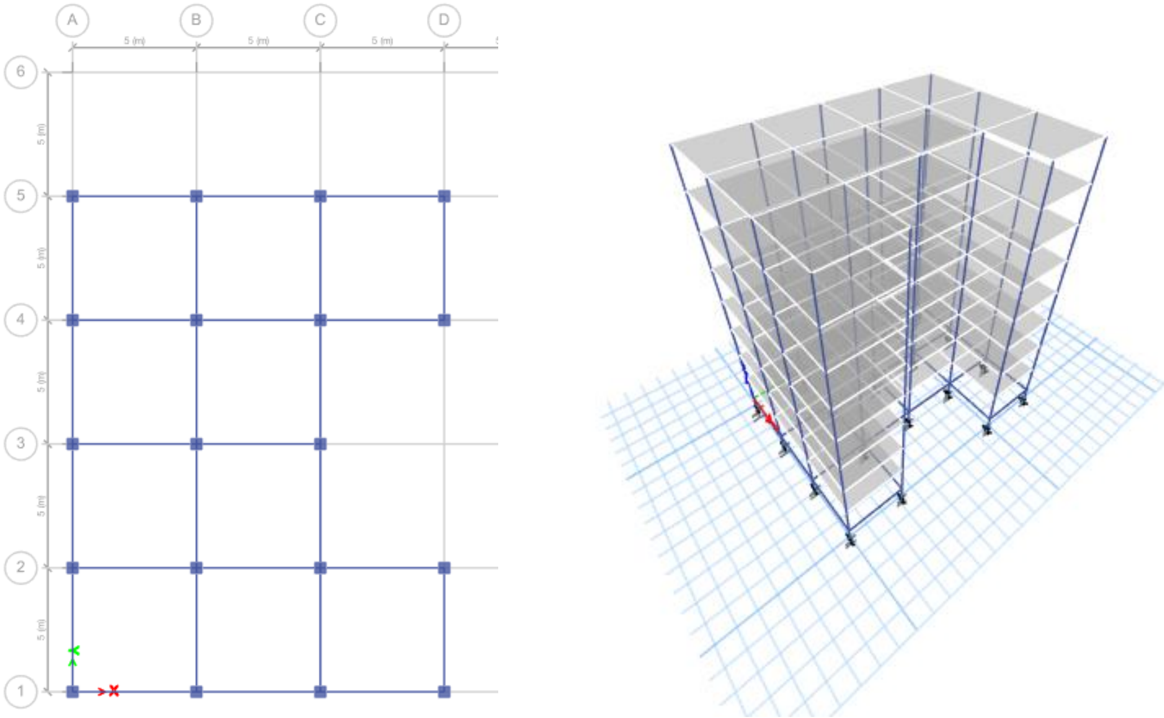

Fig.3. Views of C-shape building (a) Plan view, (b) 3D linear appearance

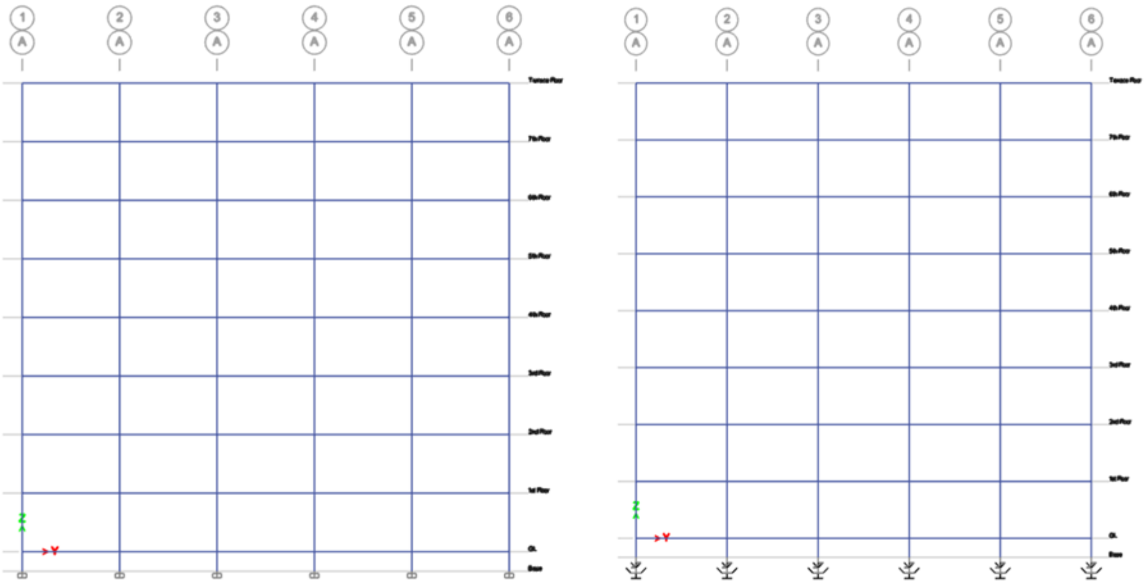

Fig.4. Elevation views of buildings (a) Fixed base, (b) Isolated base.

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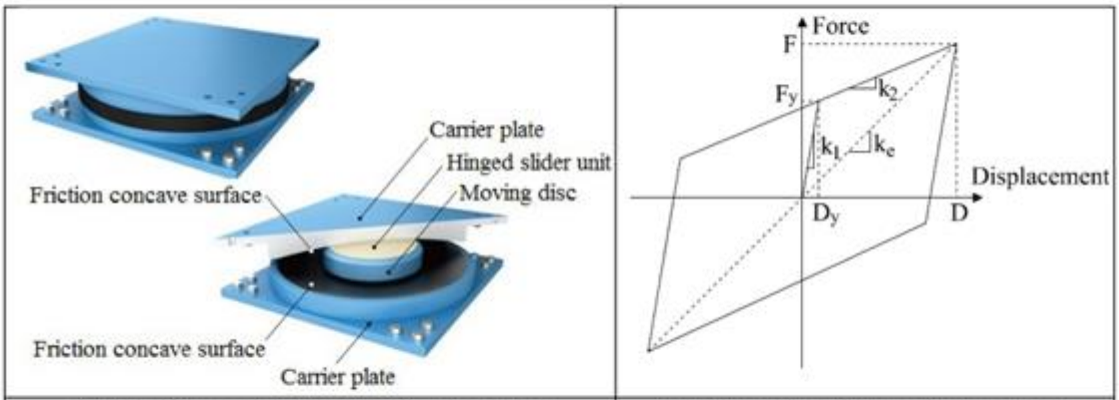

(a) Section and elements of an isolator	(b) Simplified force-displacement curve (load cycle)

Fig.5. Support details and idealized cylindrical behavior of FPB.

Table 2

Features of design parameters of FPS with periods of isolated and non-isolated buildings

Model	**Unit**	**Regular**	**L-shape**	**C-shape**
Parameters				
W	kN	28450	19870	15240
mt	kN·s²/m	2901	2025	1554
me (non-isolated)	kN·s²/m	2410	1680	1290
T (non-isolated)	s	0.82	0.91	0.97
Te (isolated)	s	2.45	2.68	2.82
T_{ETABS} (isolated)	s	2.61	2.85	2.98
R	m	1.49	1.78	1.97
k1	kN/m	1422500	993500	762000
k2	kN/m	19090	11 160	7 735
ke	kN/m	22 180	13 420	9 480
βe	-	0.10	0.11	0.12
η	-	1.40	1.40	1.40
Sae (Te)	g	0.175	0.158	0.149
DD	m	0.38	0.46	0.52

The parameters of the friction pendulum system and the buildings are presented in Table 2. The table includes vertical load (W), total mass (mt), effective mass (me), and natural vibration periods (T) of the non-isolated buildings, effective vibration periods (Te), vibration periods obtained from ETABS (T_{ETABS}) and the remaining isolator design parameters for the isolated buildings. It is clear that the periods of the isolated-base buildings are substantially higher than those of the corresponding fixed-base buildings. The period values obtained from ETABS are approximately 0.15-0.16 s higher than the target effective periods (Te) for all three models. When the periods of both isolated and non-isolated buildings are compared with the regular configuration, an increase of about 11% and 18% is observed for the L-shaped and C-shaped buildings, respectively. Regarding the design

International Journal of Engineering Research & Technology (IJERT)
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displacement capacities (DD), the regular building shows the lowest value while the highest value is obtained for the C-shaped building, consistent with the differences in effective period and spectral acceleration.

Characteristics of ground motion records used in analysis

The seismic response of the buildings is evaluated using nonlinear time-history analysis. Seven real earthquake records are selected from the PEER Ground Motion Database to represent the design earthquake level corresponding to a 10% probability of exceedance in 50 years, as specified in IS 1893 (Part 1): 2016 for Seismic Zone III on medium soil (Type II). The selected records have magnitudes ranging from 6.2 to 7.3 and rupture distances between approximately 6 km and 21 km. Both near-fault and far-fault motions are included to cover a realistic range of frequency content and duration. The basic properties of the records are summarized in Table 3. The accelerograms are scaled by spectral matching so that the mean of the resultant horizontal spectra does not fall below 1.3 times the design response spectrum in the period range of interest. The SRSS combination of the two horizontal components is used, and the same scale factor is applied to both components of each record. The scaling factors range from 0.84 to 1.89, which is within the recommended limits. All building models (regular, L-shaped and C-shaped, fixed-base and isolated) are analysed under bidirectional excitation. Rayleigh damping of 5% is assigned to the first two modes, and P-Delta effects are considered.

Table 3

Properties of ground motion records used in this study.

Sr.No.	Earthquake Event	Date	Recording Station	Magnitude (Mw)	Rupture Distance (Rrup) (km)	PGV (cm/s)	PGA (g)
1	Chalfant Valley	21 July 1986	Bishop-LADWP South	6.2	6.09	35.89	0.45
2	Chuetsu	16 July 2007	Shiura Nagaoka	6.8	17.17	41.13	0.40
3	Darfield	04 Sept 2010	Dfhs	7.0	13.03	39.30	0.46
4	Superstition Hills	24 Nov 1987	Westmorland Fire Sta	6.5	11.86	41.42	0.27
5	Iwate	14 June 2008	Iwadeyama	6.9	20.17	38.67	0.37
6	Landers	28 Jun 1992	Landers	7.3	20.78	40.16	0.12
7	Northridge	17 Jan 1994	Sun Valley-Rosco Blvd	6.7	13.71	30.13	0.33

Evaluation of seismic demands from analyses results

Seismic demand estimates obtained from the time-history analyses are examined in this section to evaluate the influence of single friction pendulum isolation on the response of regular and plan-irregular mid-rise reinforced concrete buildings. The behavior of the fixed-base and isolated-base models is compared through the principal demand parameters expressed in normalized form. Base shear forces are divided by the total seismic weight of the building and reported as base shear ratio (BSR). Top-storey accelerations are likewise examined in absolute and relative terms. These normalized quantities permit a direct comparison among buildings of different plan geometry.

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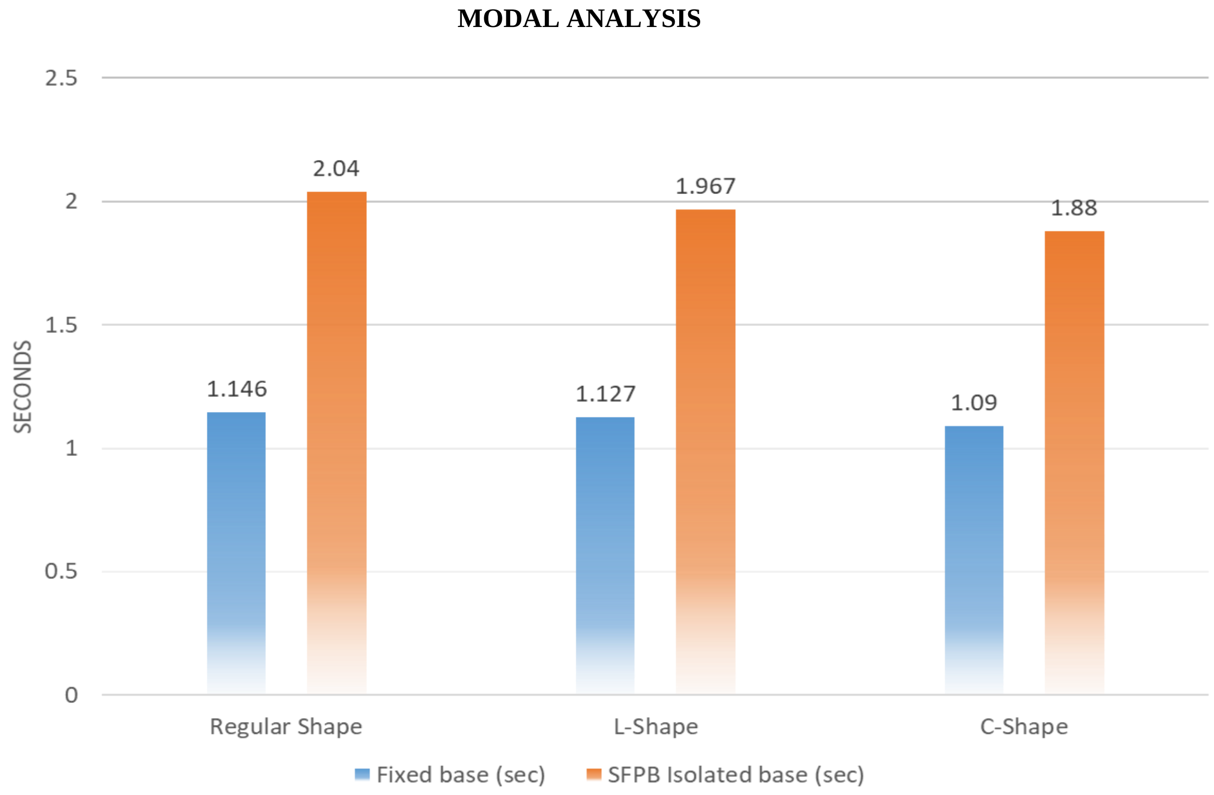

Fig.6. Variation in natural time period for isolated and non-isolated building models.

Fig. 6 presents the fundamental time periods of the regular, L-shaped and C-shaped buildings for both fixed-base and SFPB-isolated conditions. The time period of the regular building increases from 1.146 s to 2.04 s, the L-shaped building from 1.127 s to 1.967 s, and the C-shaped building from 1.09 s to 1.88 s after isolation. This significant increase in the natural period shifts the structure away from the dominant frequency range of earthquake ground motions. As a result, the spectral acceleration demand reduces considerably, leading to lower forces transmitted to the superstructure. The elongation of the time period is one of the primary reasons for the improved seismic performance observed in the isolated buildings.

Base shear ratio

Table 4

Base shear ratio (BSR) demands for isolated and non-isolated building models

Earthquakes	Fixed Base Regular	Fixed Base L-shape	Fixed Base C-shape	Isolated Base Regular	Isolated Base L-shape	Isolated Base C-shape
Chalfant Valley	0.14	0.145	0.138	0.03	0.036	0.039
Chuetsu	0.28	0.27	0.267	0.07	0.09	0.116
Darfield	0.34	0.39	0.456	0.14	0.14	0.193
Superstition Hills	0.30	0.30	0.293	0.16	0.17	0.189
Iwate	0.35	0.38	0.386	0.18	0.30	0.262
Landers	0.39	0.36	0.352	0.12	0.13	0.145
Northridge	0.25	0.28	0.308	0.07	0.07	0.067
Maximum	0.39	0.39	0.456	0.18	0.30	0.262

Earthquakes	Fixed Base Regular	Fixed Base L-shape	Fixed Base C-shape	Isolated Base Regular	Isolated Base L-shape	Isolated Base C-shape
Minimum	0.14	0.145	0.138	0.03	0.036	0.039
Mean	0.29	0.30	0.31	0.11	0.13	0.14

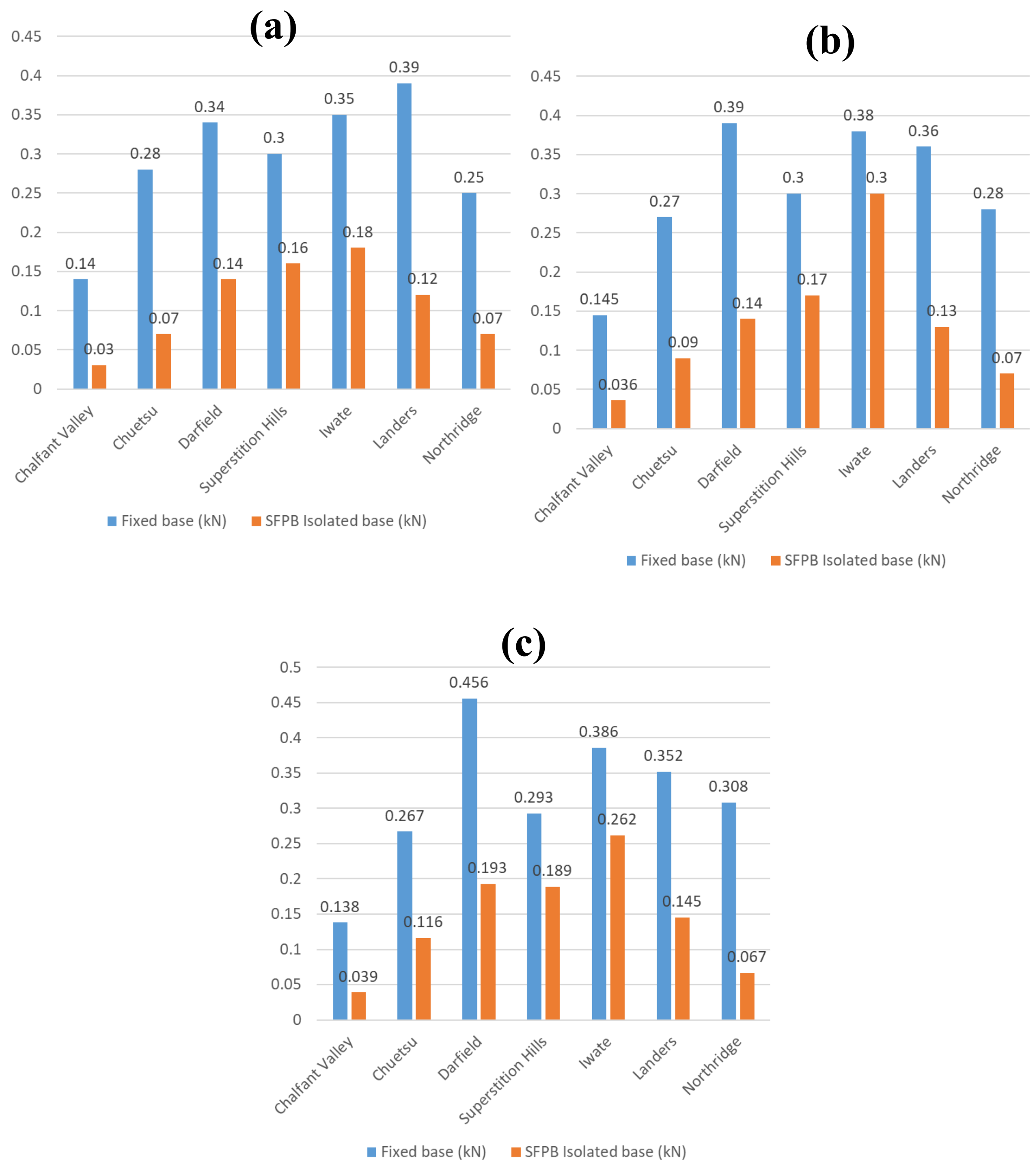

Fig.7. Base shear ratio (BSR) demands for isolated and non-isolated building models, (a) Regular-shape, (b) L-shape, and (c) C-shape

Table 4 presents the base shear ratio (BSR) values obtained for regular, L-shaped and C-shaped buildings under the seven selected ground motions for both fixed-base and isolated conditions. Due to the low lateral stiffness of the isolators, the fundamental period of the isolated buildings increases significantly, resulting in lower spectral

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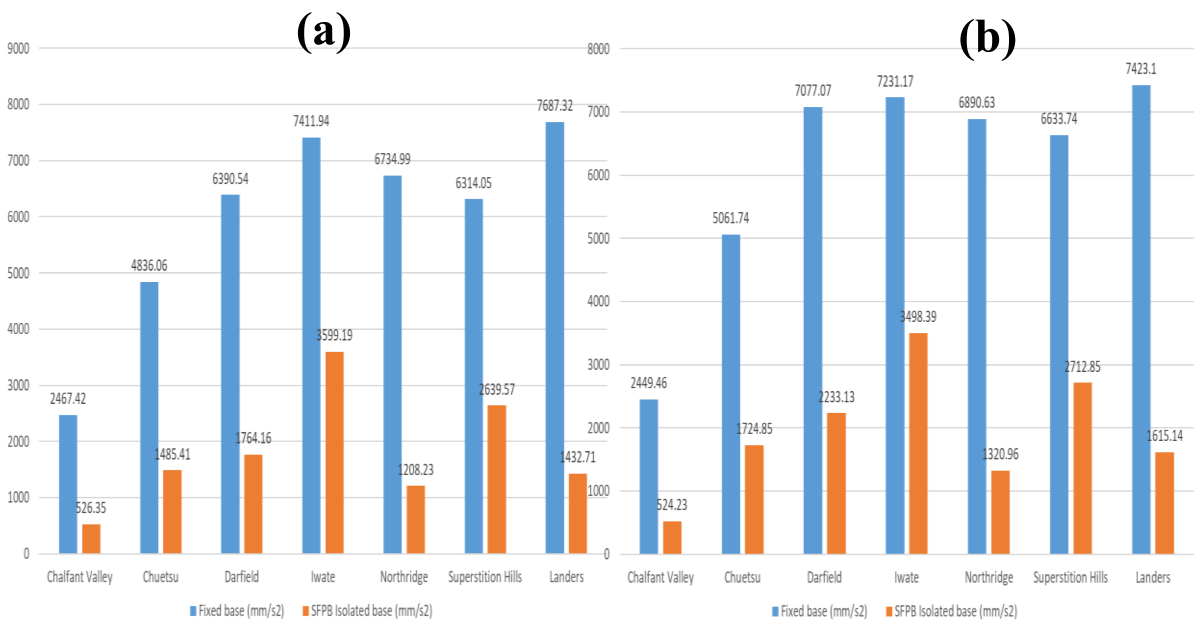
accelerations and reduced base shear demand. For the regular building, the isolated models show 47% to 76% lower BSR compared to the fixed-base models. The corresponding reductions range from 25% to 75% for the L-shaped building and from 32% to 78% for the C-shaped building. The largest reductions are observed under the Chalfant Valley and Northridge records, while the smallest reductions occur under the Iwate and Superstition Hills records. the percentage reduction achieved by isolation remains comparable across all three plan configurations. The mean BSR of the fixed-base models lies between 0.29 and 0.31, whereas that of the isolated models reduces to the range of 0.11-0.14. In addition, the variation in BSR values among the seven records is smaller for the isolated buildings, indicating more consistent response. Overall, the results confirm that Single Friction Pendulum Bearings effectively reduce the base shear ratio in both regular and plan-irregular G+7 RC buildings.

Top storey acceleration

Table 5

Top storey acceleration (mm/s²) demands of non-isolated and isolated building models

Earthquakes	Fixed Base Regular	Fixed Base L-shape	Fixed Base C-shape	Isolated Base Regular	Isolated Base L-shape	Isolated Base C-shape
Chalfant Valley	2467.42	2449.46	2413.44	526.35	524.23	602.03
Chuetsu	4836.06	5061.74	5361.73	1485.41	1724.85	1868.74
Darfield	6390.54	7077.07	7617.81	1764.16	2233.13	2690.35
Iwate	7411.94	7231.17	6998.95	3599.19	3498.39	3148.06
Northridge	6734.99	6890.63	6967.35	1208.23	1320.96	1473.75
Superstition Hills	6314.05	6633.74	7167.49	2639.57	2712.85	2695.45
Landers	7687.32	7423.10	6625.95	1432.71	1615.14	1823.91
Maximum	7687.32	7423.10	7617.81	3599.19	3498.39	3148.06
Minimum	2467.42	2449.46	2413.44	526.35	524.23	602.03
Mean	5977.47	6110.99	6164.67	1808.09	1947.08	2043.18



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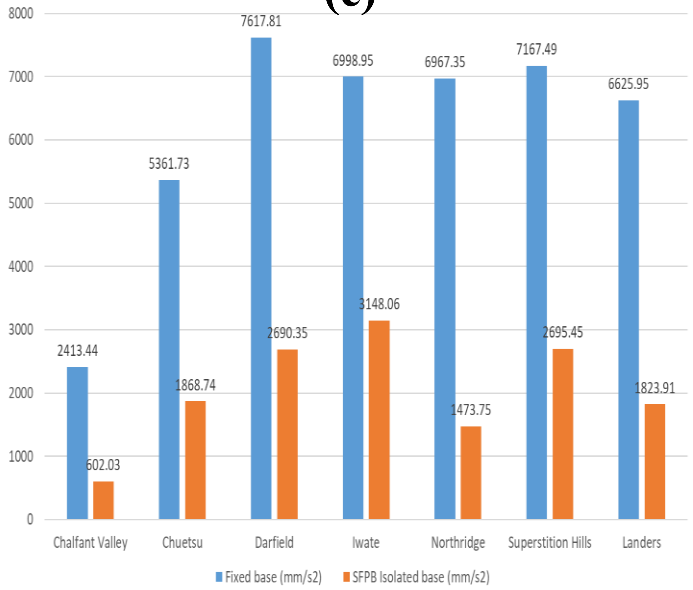

Fig.8. Top storey acceleration (mm/s²) demands of non-isolated and isolated building models, (a) Regular-shape, (b) L-shape, and (c) C-shape

Table 5 shows the top storey acceleration values for regular, L-shaped and C-shaped buildings under the seven ground motions for both fixed-base and isolated conditions. High floor accelerations can damage non-structural components and building contents. The results indicate a clear reduction in top storey acceleration after the introduction of Single Friction Pendulum Bearings in all three plan configurations. For the regular building, the reduction ranges from 51% to 82%, with an average of about 70%. The L-shaped building shows reductions between 52% and 81% (average ≈ 69%), while the C-shaped building records reductions of 55% to 79% (average 68%). The largest reductions occur under the Northridge and Landers records, and the smallest under the Iwate record. The mean top storey acceleration of the fixed-base models lies between 5977 and 6165 mm/s². After isolation, these values reduce to the range of 1808–2043 mm/s². Although the irregular buildings show slightly higher absolute accelerations due to residual torsion, the percentage reduction achieved by isolation remains substantial and consistent across all configurations. The results confirm that Single Friction Pendulum Bearings effectively limit the acceleration demand transmitted to the upper floors of both regular and plan-irregular G+7 RC buildings.

SUMMARY AND DISCUSSION OF CONCLUSIONS

The present study evaluated the effectiveness of Single Friction Pendulum Bearings (SFPB) in improving the seismic performance of G+7 storey RC buildings with regular, L-shaped and C-shaped plan configurations. The key response parameters examined were fundamental time period, base shear ratio and top storey acceleration. The results show that the introduction of SFPB significantly lengthens the fundamental time period of all three buildings. The period increased by 78.0% for the regular building, 74.5% for the L-shaped building and 72.5% for the C-shaped building. This period elongation shifts the structure away from the predominant frequencies of earthquake ground motions and reduces the seismic forces transmitted to the superstructure. Base shear ratio decreased substantially in the isolated models. Reductions of up to 76% were observed for the regular building, up to 75% for the L-shaped building and up to 78% for the C-shaped building, depending on the ground motion. The mean base shear ratio of the fixed-base models (0.29-0.31) reduced to 0.11-0.14 after isolation. Top storey acceleration also showed consistent reduction. Maximum reductions of approximately 82% were recorded for the regular building, while average reductions of about 69% and 68% were obtained for the L-shaped and C-shaped buildings, respectively. This reduction is beneficial for limiting damage to non-structural components and building contents. Although plan irregularity introduces residual torsional effects, the percentage improvements achieved by isolation remain comparable across all three configurations. Overall, the study confirms that Single Friction

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Pendulum Bearings are effective in reducing seismic demands for both regular and plan-irregular mid-rise RC buildings located in Seismic Zone III.

Author Contributions

Mateen M. Pakhali conceptualized the study, conducted the literature review, prepared the figures and tables, and wrote the original draft of the manuscript. Sachin P. Patil contributed to the methodology, critically reviewed the manuscript, and provided supervision throughout the work. All authors have read, discussed, and approved the final version of the manuscript. Each author has made substantial intellectual contributions to the research.

Funding: The authors did not receive any funding or financial support from any organization for conducting this research.

Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of Interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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