Seismic Performance Assessment of Framed Building with Base Isolators of Special Configurations

A thesis submitted in partial fulfilment for the

Award of Degree of

DOCTOR OF PHILOSOPHY

by

DHIRENDRA PATEL

DEPARTMENT OF CIVIL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY

(BANARAS HINDU UNIVERSITY)

VARANASI-221005

17061504 **2025**

CERTIFICATE

It is certified that the work contained in the thesis titled "**Seismic Performance Assessment of Framed Building with Base Isolators of Special Configurations**" by ***Mr. DHIRENDRA PATEL*** (Registration No. 17061504) has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

It is further certified that the student has fulfilled all the requirements of Comprehensive Examination, Candidacy, and SOTA for the award of Ph.D. Degree.

Dr. Rajesh Kumar

(Supervisor)
Professor
Department of Civil Engineering
Indian Institute of Technology (Banaras Hindu University) Varanasi

DECLARATION BY THE CANDIDATE

I, ***DHIRENDRA PATEL***, certify that the work embodied in this thesis is my own bonafide work carried out by me under the supervision of ***PROF. RAJESH KUMAR*** from 27 Dec. 2017 to March 2025 at the Department of Civil Engineering of the Indian Institute of Technology (Banaras Hindu University) Varanasi. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma. I also declare that I have faithfully acknowledged and given credits to the research workers wherever their works have been cited in my work in this thesis. I further declare that I have not willfully lifted any other's work, paragraphs, text, data, results, etc., reported in journals, books, magazines, reports dissertations, thesis, etc., or available at websites and included them in this thesis and cited as my own work.

Date: 02/04/2025

Place: IIT (BHU) Varanasi

DHIRENDRA PATEL

CERTIFICATE BY THE SUPERVISOR

It is certified that the above statement made by the student is correct to the best of my knowledge.

Dr. RAJESH KUMAR
Professor
Department of Civil Engineering
Indian Institute of Technology (BHU), Varanasi

02.04.25

Signature of Head of Department

विभागाध्यक्ष/HEAD
जानपद अभियांत्रिकी विभाग
Department of Civil Engineering
भारतीय प्रौद्योगिकी संस्थान (बी.एच.यू.)
Indian Institute of Technology (B.H.U.)
वाराणसी-221005/Varanasi-221005

COPYRIGHT TRANSFER CERTIFICATE

Title of the Thesis: **"Seismic Performance Assessment of Framed Building with Base Isolators of Special Configurations"**

Name of the Student: **Mr. Dhirendra Patel**

Copyright Transfer

The undersigned hereby assigns to the Indian Institute of Technology (Banaras Hindu University) Varanasi all rights under copyright that may exist in and for the above thesis submitted for the award of the **Doctor of Philosophy** degree.

Date: 02/04/2025

Place: IIT (BHU), Varanasi

(Dhirendra Patel)

Note: However, the author may reproduce or authorize others to reproduce material extracted verbatim from the thesis or derivative of the thesis for author's personal use provided that the source and the Institute's copyright notice are indicated.

Dedicated

To

My parents

Shri. Bhai Lal & Shrimati. Ratnesh Kumari

Acknowledgement

Varanasi, revered as the spiritual capital of India, holds a special place on any pilgrim's itinerary. With the majestic Ganges River flowing through its heart and adorned by numerous temples, including the revered Vishwanath Temple housing one of the twelve Jyotirlingas, Varanasi is a city steeped in spirituality and cultural richness.

I owe a profound debt of gratitude to several individuals who have been instrumental in my academic journey. First and foremost, my esteemed supervisor, Prof. Rajesh Kumar, deserves special recognition. His constant support, insightful guidance, and constant encouragement were pivotal in the successful completion of this thesis. His deep expertise in engineering field not only shaped my research journey but also significantly contributed to my professional growth.

I extend my heartfelt thanks to Prof. K.K. Pathak, a respected member of my research progress evaluation committee, for his invaluable guidance, expertise, and insightful contributions throughout my academic journey. His support has been crucial in shaping my research and academic achievements. Additionally, I am deeply grateful to Prof. L.P. Singh from the Department of Mathematical Sciences, serving as my external research progress evaluation committee member. His expertise and constructive feedback enriched my research and added depth to my thesis.

I gratefully acknowledge the significant contributions of Professor S.S. Mandal, Head of the Department of Civil Engineering. His visionary leadership, support, and encouragement fostered an atmosphere conducive to academic excellence and research innovation. The department's faculty and staff at the Indian Institute of Technology, Varanasi, provided a nurturing research environment and essential resources that proved invaluable throughout my PhD program. Their academic and administrative support played a pivotal role in facilitating my research endeavors. I am deeply grateful to Dr. Mahendra Kumar Pal and Dr. Kshitij Kumar Yadav for their support during the progress of my experimental research.

I extend my sincere thanks to the Ministry of Education for providing the scholarship that made this research possible, and to Indian Institute of Technology, Varanasi, for their support and resources throughout my academic journey.

I am deeply grateful for the blessings and guidance of my late grandfather, Shri Ram Naresh, and my grandmother, Shrimati Kalawati Devi. Their wisdom, love, and blessings have been a guiding force throughout my life's journey, shaping my character and inspiring me in all my endeavors.

To my beloved parents, Shri Bhai Lal and Shrimati Ratnesh Kumari, I owe immense gratitude for their unwavering support and encouragement. My father, provided steadfast guidance, wisdom, and sacrifices that inspired my determination to excel in my studies. My mother, offered boundless love, patience, and staunch encouragement, nurturing my growth and achievements. Together, their sacrifices and values of perseverance, integrity, and compassion continue to inspire me daily.

I extend my heartfelt thanks to my elder brother, Dr. Devendra Pratap, and my sister-in-law, Shrimati Pooja Singh, whose encouragement, motivation and understanding have been constant pillars of support throughout my PhD journey. Their belief in my abilities and constant inspiration have been sources of strength and motivation. To my nephews, Viraj Pratap Singh and Vedant Pratap Singh, I extend heartfelt thanks for bringing joy and inspiration into my life.

I express my deepest gratitude to my sister, Shreya Singh, and brother-in-law, Raju Singh, for their support and motivation. I am also deeply thankful to my younger sister, Shivangi Singh, for her support and cheer. Her understanding and encouragement have been invaluable in navigating challenges and celebrating successes.

I sincerely thank my late maternal grandfather, Shri Brahma Shankar Singh, for his enlightening guidance and encouragement towards achieving academic excellence. I also extend my gratitude to my maternal uncle, Shri Uday Pratap Singh, for his constant support and motivation. Additionally, I am thankful to my cousins Ajit, Pankaj, Neeraj, Rohit, Rohan, Rahul, and Riyam, for their invaluable support and companionship.

I am sincerely thankful to my PhD friends, Dr. Gaurav and Vishal, for their support and encouragement. I deeply cherish their friendship and am profoundly grateful for their unwavering presence in my life.

I extend my heartfelt thanks to my PhD colleagues, Abhay, Dr. Abhilash, Kirti, Sheela, Akanksha, Sher Bahadur, Neeraj, Abhijit, Anoop, Vijay, Abhishek, and Vivek for their support and camaraderie throughout my doctoral journey. Their friendship, collaboration, and dedication to academic excellence have been invaluable sources of encouragement and inspiration.

I am deeply grateful to my PhD seniors, Dr. Rahul Singh, Dr. Dheeresh Kumar Nayak, and Dr. Ravinder Kumar Agrahari, for their support throughout my doctoral journey. Their willingness to share their knowledge were instrumental in my research endeavors.

I am also grateful to everyone who has played a part, big or small, in my academic journey. Your support, encouragement, and belief in my abilities have been instrumental in reaching this milestone. I am forever indebted to each of you for enriching my experience and shaping my path forward. Thank you all for your unwavering support and encouragement.

Abstract

Earthquakes, one of the oldest natural hazards, pose unpredictable threats to buildings and infrastructure, often resulting in significant damage and requiring extensive retrofitting to maintain structural integrity. Despite advances in structural designs, structures remain vulnerable during the hazardous seismic events. Seismic isolation, especially through passive base isolation systems, has emerged as an effective method to enhance flexibility by decoupling a structure's response from ground shaking.

The present study has been divided into six Chapters. In the introductory Chapter, the importance of seismic isolation in structural engineering is highlighted. Seismic isolation serves as the literal and metaphorical safeguard of any structure, ensuring stability and safety during earthquakes. Further, the Chapter 2, review literature sets the stage for the comprehensive understanding of the various seismic base isolation and its effectiveness in mitigating seismic forces. The Chapter 3 investigates the performance of two prominent passive isolators, High Damping Rubber Bearing (HDRB) and Lead Rubber Bearing (LRB), under near-fault and far-fault ground motion conditions. Using ABAQUS CAE for validation, this study provides a comprehensive finite element assessment of HDRB and LRB behavior under various seismic conditions. Initially, each isolator's response is validated against static analysis results from established literature. Subsequently, dynamic simulations under historical earthquake records, including those from Imperial Valley, Northridge, Loma Prieta, Kobe, and ChiChi, events, reveal key insights into each isolator's effectiveness. LRBs demonstrated notable efficiency, with top-of-bearing acceleration reductions reaching 68.42% during the Kocaeli earthquake, while HDRBs provided a 61.80% reduction for the Northridge event. Across various seismic intensities, LRBs consistently showed higher damping capacity, indicating robust performance in minimizing acceleration and deformation.

The research extends to evaluating the dynamic responses of a 10-story reinforced concrete building equipped with HDRB and LRB using SAP2000 in Chapter 4. Parametric variations are introduced to assess the isolators' effectiveness in real-world building applications. Near-fault and far-fault earthquake scenarios are simulated, with ground motions scaled to match the IS 1893 Zone V, medium soil condition, response spectrum using SeismoMatch software. Under both NF and FF earthquake simulations, base isolation systems reduced base shear, peak displacements, and peak acceleration responses, enhancing stability across all floors. These results confirm that base-isolated structures reduce responses significantly, thus protecting both structural and non-structural components.

In Chapter 5, the analysis for sliding isolators with spring combinations has been performed. As accurate dynamic characterization is a cornerstone of effective seismic analysis. This study employs Impact Hammer testing and numerical modeling using Abaqus software to ensure the compatibility of computational models with physical systems. This study conducted the experimental tests on a quarter-scaled by length steel moment-resisting frame using shake table tests compatible with the Pulse Labshop software package. The experimental study examined five configurations: Fixed Base (FB), Sliding Base (SB), Sliding Base with Conical Spring (SB+CS), Sliding Base with Low-Stiffness Linear Spring (SB+LS), and Sliding Base with High-Stiffness Linear Spring (SB+HS), are tested to evaluate the impact of restoring devices on seismic isolation performance.

To verify the mechanical properties of the spring combinations, numerical and experimental force-deformation curves were generated using SOLIDWORKS and a Universal Testing Machine (UTM). The close agreement between these results confirms the reliability of the numerical model. A quarter-scaled three-story moment-resisting frame was analyzed to compare responses under fixed-base and sliding-base springs combinations, focusing on peak top acceleration response and maximum inter-story drift ratio (IDR). The analysis demonstrates that the sliding base isolation system effectively reduces seismic demands compared to the fixed-base structure. Further, numerical analyses were performed using ABAQUS to verify the experimental results. The close agreement between experimental and simulation data further reinforces the reliability of the developed model. The findings emphasize that while sliding base isolators with spring combinations effectively reduce seismic responses, particularly at high amplitudes and frequencies.

In Conclusion, this study offers a comprehensive assessment of various seismic isolators, affirming the effectiveness of HDRBs and LRBs in mitigating seismic impacts and enhancing structural ability. The numerical and experimental analyses underline the advantages of base isolation, while sliding isolation system with spring combinations present promising avenues for further optimization. Future research could focus on investigating the long-term performance and durability of HDRB, LRB, and sliding bearing hybrid isolators, exploring real life larger structures and varying seismic intensities, and developing advanced computational models to simulate complex interactions in hybrid isolation systems.

Table of Contents

List of Tables

List of Figures

List of Symbols

U	Strain Energy Function
I_1	First Deviatoric Strain Invariant of the Green Deformation Tensor
I_2	Second Deviatoric Strain Invariant of the Green Deformation Tensor
I_3	Third Deviatoric Strain Invariant of the Green Deformation Tensor
$\lambda_1, \lambda_2, \lambda_3$	Principal Stretches (Stretch Ratios)
C_{10}, C_{20}, C_{30}	Material Constants in The Yeoh Hyper-Elastic Model
D_1, D_2, D_3	Compressibility Parameters in the Yeoh Model
N	Material Constant (Positive Numbers $N = 1,2,3$)
μ	Shear Modulus
λ_m	Material Constant
D	Temperature-Dependent Parameter
λ_i	Principal Stretch
J	Jacobian Determinant (Volume Change)
J^{el}	Elastic Volume Ratio
K	Bulk Modulus
G_i	Prony Series Modulus Coefficients
t_i	Prony Series Time Constants
T_r	Total Thickness of Rubber
t_r	Thickness of a Single Rubber Layer
t_s	Thickness of a Single Steel Shim Layer
h	Total Height of the Elastomeric Rubber Bearing
A	Bonded Rubber Area
D_0	Outer Diameter of the Bearing

D_i	Inner Thickness or Lead Core Diameter (For LRB, $D_i = 0$ For HDRB)
t_c	Rubber Cover Thickness
Q_d	Zero-Displacement Force Intercept in LRB (Characteristics Strength)
σ_L	Shear Yield Strength of the Lead
A_L	Area Of the Cross-Section of the Lead Plug
K_d	Second-Slope Stiffness (Elastomeric Stiffness)
d	Specific Horizontal Displacement
K_{eff}	Effective Or Secant Stiffness of the LRB
S	Shape Factor
E_c	Compression Modulus of the Elastomeric Layer
G	Shear Modulus of Rubber
K_{bulk}	Bulk Modulus of Rubber
F	Central Hole Factor
r_d	Diameter Ratio D_0/D_i
K_v	Vertical Stiffness
K_h	Horizontal Stiffness
K_t	Torsional Stiffness
T_{eff}	Effective Period of the System
W	Seismic Weight of the Structure
g	Gravitational Acceleration
β	Damping Ratio
W_D	Energy Dissipation Per Cycle
E_{loop}	Energy Dissipated Per Loading Cycle
Δ^+	Peak Positive Displacement

Δ^-	Peak Negative Displacement
F^+	Positive Force at Maximum Positive Displacement
F^-	Negative Force at Minimum Negative Displacement
β_{eff}	Effective Damping Ratio
B	Damping Reduction Factor
S_a	Spectral Acceleration
D_D	Design Displacement
Q_{ISO}	Shear Force
$\mathrm{Q_j}$	Portion Of Q_S that is Assigned to Level i
$\mathrm{M_i}$	Portion Of *M* that is Located at or Assigned to Level i
$\mathrm{M_j}$	Portion Of *M* that is Located at or Assigned to Level *j*
$\mathrm{H_i}$	Height Above the Base of Level i
$\mathrm{H_j}$	Height Above the Base of Level *j*
Q_b	Minimum Lateral Force
$K_{e,max}$	Maximum Effective Stiffness
$K_{e,min}$	Minimum Effective Stiffness
D_M	Maximum Design Displacement
D_{TD}	Total Design Displacement
Z	Seismic Hazard Zone Factor
G_S	Soil Amplification Factor
e	Actual Eccentricity
b	Shortest Plan Dimension of the Structure
d	Longest Plan Dimension of the Structure
T_L	Lead Core Temperature Rises at Time t

u	Motion of the Lead-Rubber Bearing
σ_{YL_0}	Initial Effective Yield Stress of Lead
ρ_L	Density of the Lead Core
c_L	Specific Heat of the Lead
a	Radius of the Lead Core
k_s	Thermal Conductivity of the Steel
α_s	Thermal Diffusivity of the Steel

Abbreviations

BI	Base Isolation
HDRB	High Damping Rubber Bearing
LRB	Lead Rubber Bearing
LDRB	Low Damping Rubber Bearing
FPS	Friction Pendulum Bearing
DCFP	Double Concave Friction Pendulum Bearing
TFPS	Triple Concave Friction Pendulum System
FREB	Fibre Reinforced Elastomeric Bearing
EDF	Electricite-de-France
SR-F	Sliding Resilient-Friction
EPB	Elastomeric Polymer Bearing
NF	Near-Field
FF	Far-Field
RC	Reinforced Concrete
MRF	Moment Resisting Frame
NLTH	Non-Linear Time History Analysis
NLSA	Non-Linear Static Analysis
IDA	Incremental Dynamic Analysis
MSDA	Multiple-Stripe Dynamic Analysis
FEA	Finite Element Analysis
FEM	Finite Element Modelling
IM	Intensity Measures
PEER	Pacific Engineering Earthquake Records

MRE	Magnetorheological Elastomeric Bearing
NLVD	Non-Linear Viscous Dampers
UHMWPE	Ultra-High Molecular Weight Polyethylene
PTFE	PolyTetraFluroEthylene
RIS	Rolling Isolation System
VFPB	Variable Friction Pendulum Bearing
GWO	Grey Wolf Optimization
CSA	Crow Search Optimizer
WOA	Whale Optimization Algorithm
FDEVM	Fuzzy Differential Evolution with Virtual Mutant
CFRP	Carbon Fiber-Reinforced Polymer
SSI	Soil-Structure Interaction
SDOF	Single Degree of Freedom
NPP	Nuclear Power Plants
LVIVS	Long-Period Vertical Isolation Device Featuring Variable Stiffness
NRC	Nuclear Regulatory Commission
ICBO	International Conference of Building Officials
IABI	Inertial Amplifier Coupled Base Isolator
CSI	Core-Suspended Isolation
SB	Sliding Base
FB	Fixed Base
SB+CS	Sliding Base with Conical Spring
SB+HS	Sliding Base with High Stiffness Linear Spring
SB+LS	Sliding Base with Low Stiffness Linear Spring