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Structural Frame Analysis under Earthquakes with Various Base Flexibility: A Review

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ABSTRACT

This literature review investigates the seismic behavior of low-rise steel structural frames with fixed, pinned, and base-isolated column bases under single and successive earthquake excitations. Experimental shaking table tests and Abaqus finite element models are utilized to evaluate the impact of base flexibility on structural performance measures, including inter-story drift, base shear, and acceleration response. Base-isolated systems, including elastomeric, lead-rubber, and friction pendulum bearings, demonstrate superior energy dissipation capacity and reduced seismic demand compared to traditional fixed and pinned bases. While pinned bases offer rotational flexibility that reduces moment concentration, they are susceptible to excessive lateral displacement in multi-story configurations. Fixed bases provide stiffness but transmit higher forces directly to the structural frame. Current research underestimates the seismic loading capability of base isolation and bracing systems, despite significant advances in isolation technology. This review identifies a critical research gap in evaluating hybrid seismic protection strategies, especially for structures subjected to multi-event ground motions. Future directions are proposed to address these challenges through integrated experimental and numerical investigations, aiming to enhance the resilience of modern buildings in earthquake-prone regions.

Keywords: Frame analysis, Earthquakes, Shaking table, Column base, Low-rise buildings.

1. INTRODUCTION

In earthquake-prone areas, construction sites are especially susceptible. Seismic forces may shake, damage, and collapse buildings. Understanding earthquake impacts may improve building resilience and reduce property damage. Most construction's structural frames are subject to ground motion-induced lateral stresses. Material qualities, geometric arrangement, and column base flexibility affect these structures. Structure seismic

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performance depends on base flexibility, which affects energy transfer and dissipation **(Chanda and Debbarma, 2021)**. The three main column bases are isolated, pinned, and fastened. A permanent foundation provides the most stiffness and direct load transmission. When seismic pressures are applied on pinned bases, rotational flexibility reduces bending moments but increases lateral displacement **(De Angelis and Pecce, 2020)**. However, base isolation creates a flexible interface that isolates the structure from ground motion, reducing seismic energy transfer and increasing stability **(Peng et al., 2021)**. The foundation condition determines the building's reaction to seismic stresses in seismic design. Base-isolated systems have gained attention for their capacity to boost structural resilience, particularly in low-rise structures where fixed-base systems may not work as well. Many studies have examined seismic performance and base flexibility, but there are still gaps, notably in how buildings respond after numerous earthquakes. Many studies only look at seismic reactions to individual shocks, although many earthquakes cause significant harm. The techniques of base isolation have been extensively investigated, but not their effects on bracing systems.

This study analyzes base flexibility to compute the seismic resilience of one- to three-story low-rise structures, aiming to address these issues. Abaqus finite element simulations will verify numerical accuracy, and shaking table testing will verify empirical validity. We will also test elastomeric, lead-rubber, and friction pendulum base isolators for seismic force mitigation. This study analyzes base flexibility and fills the research gap in designing earthquake-resistant buildings.

2. SEISMIC BEHAVIOR OF STRUCTURAL FRAMES

2.1 Fundamental Concepts of Seismic Response

Seismic dynamic loading affects structural performance and stability. Shifting, unexpected earthquake stresses differ from static strains. Inertial forces cause structures to swing, vibrate, and experience stress. Earthquake damage depends on ground acceleration, frequency content, length, and soil-structure interaction **(Chanda and Debbarma, 2025)**. Engineers study building response and create seismic-resistant designs to maintain structures robust to dynamic stress.

Important elements affect a building's seismic response. Structures have intrinsic disturbance oscillation frequencies **(De Angelis and Pecce, 2020)**. If an earthquake's major frequencies match a building's inherent frequency, resonance may increase vibrations and cause structural collapse. Structures diffuse energy and minimize oscillation via damping. Higher damping ratios reduce vibrations and increase stability **(Peng et al., 2021)**. Energy-absorbing dampening devices, base isolation, and inelastic material deformation may lessen earthquake forces **(Jangid, 2022)**. These qualities allow a building to endure seismic pressures and prevent deformation-induced collapse. These key concepts are necessary to assess structural frame seismic behavior and develop appropriate mitigation methods.

2.2 Structural Behavior under Earthquakes

Columns and beams that can withstand vertical and lateral stresses may behave differently during earthquakes. The rigidity and pliability of a frame affect its seismic response. Rigid structures have higher stress concentrations, yet flexible structures can sustain bigger displacements without internal forces **(De Angelis and Pecce, 2020)**. Engineers must

balance rigidity and pliability while assessing seismic performance. Lateral forces during an earthquake cause axial stresses, shear pressures, and bending moments. Due to its rigidity, fixed-base frames stress foundations seismically **(Jangid, 2022)**. High-column internal stresses may degrade the foundation. Pinned-base frames allow base rotation, reducing bending strains but increasing lateral sway. Pinched connections are versatile but might damage buildings after strong earthquakes **(Chen et al., 2022)**. Base-isolated systems provide a flexible structure-foundation interface for complicated solutions. These seismic energy absorbers and dissipators improve stability and lateral displacements.
Base conditions affect earthquake damage mechanisms. Plastic hinges at beam-column connections cause localized failure in fixed-base constructions. Pinched-base buildings swing more, making taller structures unstable **(Du et al., 2023)**. Buildings with split bases may concentrate seismic pressures on top stories. Effectiveness depends on isolator type, ground motion, and building location **(Jangid, 2022)**. Engineers may increase earthquake resilience by analyzing how buildings respond to various foundations, as shown in **Fig. 1.**

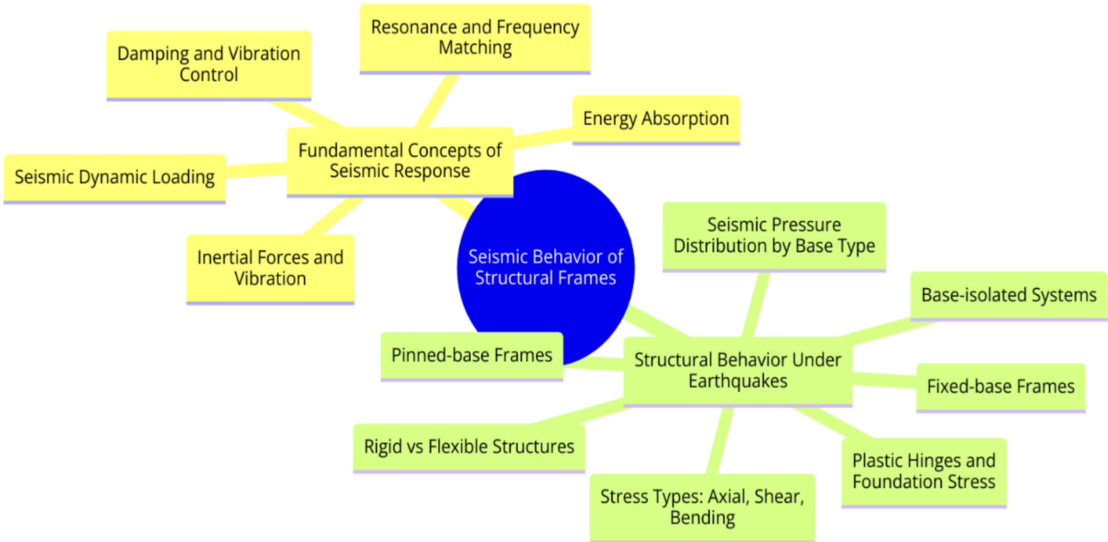

Figure 1. Seismic behaviour of structures. Source: Authors (This study), based on **(De Angelis and Pecce, 2020; Chanda and Debbarma, 2021; Jangid, 2022)**

2.3 Role of Column Base Conditions in Structural Stability

2.3.1 Fixed Base vs. Pinned Base vs. Base-Isolated Structures

Traditional designs employ solid fixed-base constructions to restrict lateral movement. Through the structure-foundation interaction, all seismic pressures affect the ground **(Butenweg et al., 2021)**. This design enhances stability in mild to moderate earthquakes but worsens column and foundation damage in severe earthquakes since the structure absorbs the stress. Pinched columns may rotate at the base without bending **(Du et al., 2023)**. This design decreases stress concentrations and allows some lateral displacement, making it excellent for controlled movement in buildings **(Rama Rao et al., 2021)**. However, flexibility may produce excessive sway in multi-story constructions **(Du et al., 2021)**. Thus, pinned bases are more common in constructions that value ductility and controlled deformation above stiffness.

Modern base-isolated structures use elastomeric, lead-rubber, or friction pendulum systems to separate the foundation and superstructure. These isolators isolate the structure from the ground to reduce seismic damage **(Butenweg et al., 2021)**. Reduced structural stress improves occupant safety. Stability requires reduced peak acceleration; hence, base isolation is useful in low-rise structures **(Rama Rao et al., 2021)**. Cost, maintenance, and seismic performance must be addressed while designing and implementing base isolators. Therefore, in summary, the base types' effect is:

- Fixed Base: Provides maximum stiffness but transfers seismic forces directly to the structure, increasing internal stresses.
- Pinned Base: Reduces bending moments but increases lateral displacement, making taller structures vulnerable.
- Base-Isolated Systems: Absorb seismic forces through isolators, reducing stress concentrations and enhancing stability in low-rise buildings.

2.3.2 Practical Implications in Low-Rise Construction

The condition of column bases affects low-rise building design and construction. Low-rise buildings react differently to earthquakes due to their lighter construction and lower center of gravity. Earthquake lateral forces may induce beam-column fractures and collapse in low-rise structures with permanent foundations **(Cruz et al., 2024)**. Even while pinched bases lower stress concentrations, severe lateral displacements may jeopardize structural integrity. Base isolation may reduce seismic stresses in low-rise structures **(Mohammadzadeh Osalu and Shakib, 2020)**. Engineers may improve structural safety and usefulness by controlling acceleration and displacement using isolators. When selecting to isolate the foundation, soil conditions, construction mass, and economic feasibility must be considered **(Cruz et al., 2024)**. Damage from several earthquakes may undermine base-isolated structures' capacity to resist future earthquakes.
Seismic performance, construction feasibility, cost, and maintenance depend on column base specifications **(Ruggieri and Vukobratović, 2023)**. A fixed structure may require reinforcement in a large earthquake. Flexible pinned base designs require displacement control **(Du et al., 2021)**. Base-isolated structures reduce seismic stresses but cost more and need more technical design. Engineers and academics are building hybrid systems with diverse base conditions to balance flexibility, stability, and cost. The improved knowledge of seismic behavior drives this strategy.

3. COLUMN BASE FLEXIBILITY AND ITS IMPACT ON SEISMIC RESPONSE

Column-to-base connections fundamentally influence the seismic performance of structures by dictating how forces are transferred from the foundation to the superstructure. Fixed, pinned, and base-isolated systems provide distinct modes of force transmission, each impacting structural stability and resilience differently. For low-rise structures, where mass and height amplify base influences, selecting an appropriate base type is critical to mitigate seismic effects.

3.1 Fixed Base Systems

Many structural engineers employ fixed-base systems. A fixed base system prevents column base rotation by securely anchoring it. The structure is rigid because all vertical and lateral forces are transmitted to the ground **(El Hoseny et al., 2022)**. Fixed base connections stiffen reinforced concrete and steel-framed structures, decreasing lateral displacements. Fixed base systems reduce lateral strains and stabilize buildings **(Ruggieri and Vukobratović, 2023)**. These devices reduce foundation movement in earthquakes, keeping the building straight and eliminating swaying **(Emamikoupaei et al., 2023)**. Fixed bases disperse seismic loads and stiffen the structure. Helpful in towering structures when uncontrolled lateral movement threatens stability and occupant safety.

Major earthquakes may also limit permanent foundations. Due to the stiff foundation, seismic forces transfer completely to the structural frame, causing substantial internal stresses and beam-column damage **(El Hoseny et al., 2022).** Non-ductile materials may shatter brittlely with high deformations. Base shear forces may damage or fail poorly designed fixed basis constructions **(Emamikoupaei et al., 2023)**. Though stable in normal circumstances, permanent base systems may not give the best seismic protection in seismically active places.

3.2 Pinned Base Systems

Pin-based systems enable column bases to rotate, unlike permanent base connections. The base connection only allows rotation; thus, the column may tilt in response to lateral loads but not slide or move horizontally **(Falborski et al., 2020)**. Its pliability minimizes base bending moments, which distributes loads and reduces structural frame stress. Pin-based structures respond to seismic stress differently from fixed-base structures **(Scarfone et al., 2020).** Pinched connections minimize beam and column internal stresses and prevent damage at important connection locations by permitting rotation **(Falcone et al., 2020)**. This makes pinned base systems appropriate for bridges and industrial structures with controlled movement. Pinned bases absorb and distribute seismic load energy due to their elastic nature.

Despite their efficiency, pin-based systems are seismically fragile. Extreme lateral movement, which might compromise higher-level structures, is the main issue. Pinned foundations swing more than permanent foundations, making them more prone to collapse in an earthquake without sufficient planning **(Sheikh et al., 2022)**. Lateral forces may impair low-rise structures. Pinned bases minimize base bending moments but do not eliminate them; therefore, additional supports are needed to manage internal stress **(Tian et al., 2020)**. Damping devices and bracing are utilized with pinned base systems to improve seismic performance **(Gholhaki et al., 2021)**. Anchored bases, energy-dissipating mechanisms, and balanced stability and flexibility increase earthquake resistance **(Falborski et al., 2020)**. These systems operate best when structural organization, connecting details, and material choices are considered.

3.3 Base-Isolated Systems

Isolating the base is a cutting-edge and effective earthquake mitigation method. In contrast to fixed and pinned base systems, base-isolated systems enable continuous structure-ground mobility **(Song et al., 2020).** Specially designed isolators disperse and absorb seismic energy, reducing superstructure stress and structural damage **(Gholhaki et al., 2021).** The base separates in ground motion from the building. The structure moves independently of the ground during an earthquake because base isolators distort and absorb energy. **(Formisano et al., 2021)** found that building acceleration, internal forces, and damage decrease. Whenever Elastomeric, lead-rubber, or frictional pendulum seismic base isolators are available. Each flexible isolator dissipates energy to support the structure during strong earthquakes.

Earthquake-resistant base-isolated systems provide design benefits. The structure benefits from reduced lateral forces and displacement **(Ghosh et al., 2021)**. This is an ideal alternative to fixed and pinned foundation systems for low-rise buildings without seismic protection **(Tiwari and Lam, 2021).** Limiting ground motion using base isolation increases structural resilience and occupant safety. Base-isolated systems prevent seismic damage and prolong building life **(Formisano et al., 2021)**. Seismic pressure deteriorates fixed-base structures, increasing maintenance costs and instability **(Wang et al., 2023)**. Base isolation absorbs energy at the foundation, reducing structural component wear. Invest in base-isolated systems, particularly in earthquake-prone locations.

The type of base connection greatly influences the structural response of frames under seismic excitation. Following the classification into fixed, pinned, and isolation bases, a comparative overview is presented in **Table 1** to synthesize their essential features and functional implications during earthquake applications.

Table 1. Comparative Features of Seismic Isolation Systems.

System Type	Key Features	Authors
Fixed Systems	Rigid connection, no isolation, high structural stiffness	**(Sabiha et al., 2023)**
Pinned Systems	Allows rotation, limited seismic performance	**(Sabiha et al., 2023)**
Base Isolation Systems	Decouples structure from ground, reduces acceleration and force, improves resilience	**(Deshmukh and Parekar, 2023; Song and Jeong, 2024; Zhan et al., 2024)**

4. BASE ISOLATION SYSTEMS FOR LOW-RISE STRUCTURES

4.1 Types of Base Isolators

Base isolators are engineered to deliver a balance of damping, energy dissipation, and lateral flexibility tailored to seismic demands **(Torres-Rodas et al., 2021)**. Among the most widely applied types in low-rise structures are elastomeric bearings, friction pendulum systems, and hybrid configurations. Elastomeric bearings, constructed with layered rubber materials, provide both vertical load-bearing capacity and horizontal flexibility. Lead-rubber bearings (LRBs), combining elastomeric layers with lead cores, offer enhanced damping and energy absorption, enabling lateral movement without compromising superstructure integrity **(Harirchian et al., 2021; Gioffrè et al., 2022).** Friction pendulum bearings utilize sliding mechanisms to allow controlled movement under seismic loads while ensuring re-centering capabilities after displacement **(Xie et al., 2020a)**. These isolators are particularly efficient in applications requiring high mobility and minimal residual drift. Hybrid isolators merge the properties of elastomeric and sliding systems to achieve higher flexibility, customized damping behavior, and enhanced seismic performance **(Wang et al., 2021; Gioffrè et al., 2022)**. The schematic representation of these types is shown in **Fig. 2**

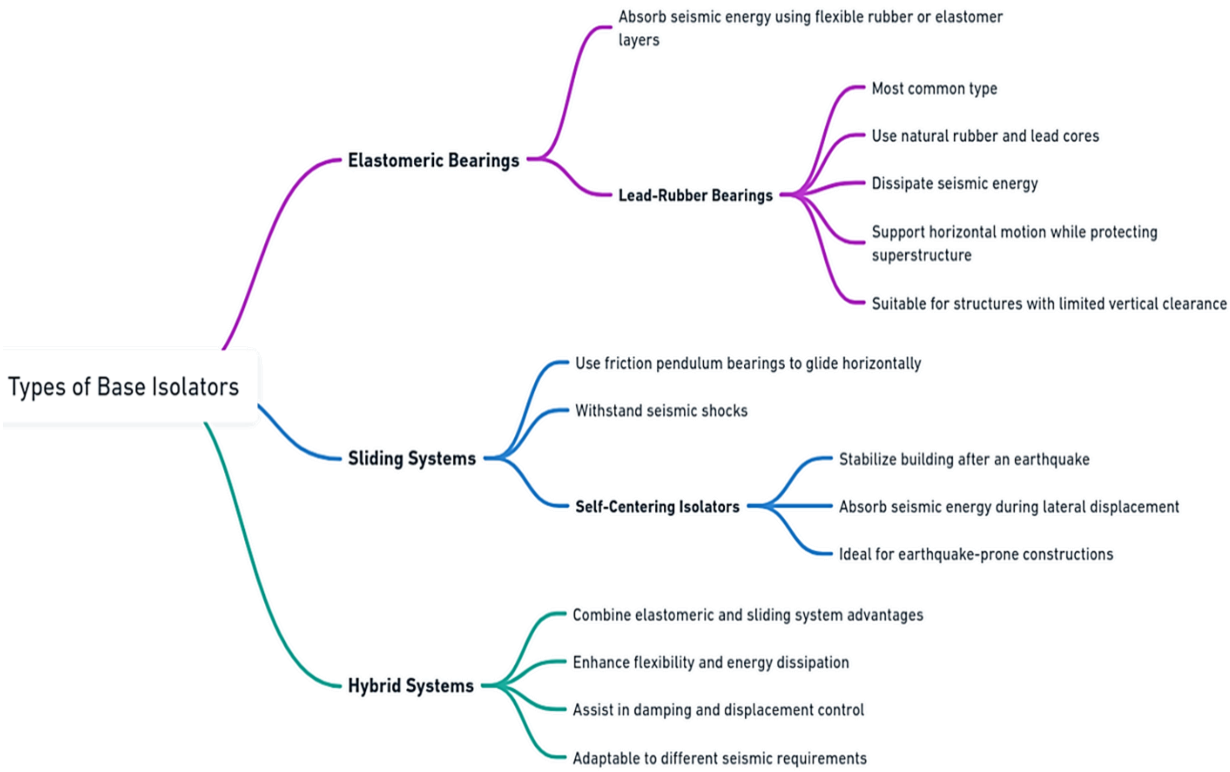

Figure 2. Base Isolator Types in this study based on **(Xie et al., 2020a; Harirchian et al., 2021; Gioffrè et al., 2022; Wang et al., 2023)**

4.2 Performance of Base Isolators in Earthquakes

The **(Inamasu and Lignos, 2022)** suggests that foundation isolators lessen earthquake stress. Commercial and residential structures benefit from earthquake protection **(Xie et al., 2020b).** Science in earthquake-prone areas in Japan and California shows foundation isolators may minimize lateral displacements, expedite earthquake recovery, and protect superstructures **(Hernandez-Hernandez et al., 2021)**. Lead-rubber bearings reduced lateral vibrations in buildings during the 1989 California Loma Prieta earthquake, averting collapse and saving maintenance costs **(Krzywanski et al., 2024).** Shaking table and numerical computations verify base isolators. Earthquake tests assess base isolators' building force reduction. Buildings separated from their bases have lower accelerations and lateral displacements, preserving structural integrity and reducing maintenance costs **(Hu et al., 2021).** Experimental data enhances base isolation technology for different structural systems.

4.3 Comparative Efficiency of Different Isolators

Structure, seismic risk, and performance affect base isolators' efficiency. Lower-floor constructions with mild to moderate seismic zones benefit from elastomeric bearings, especially lead-rubber bearings **(Krzywanski et al., 2024)**. Buildings need dampening and flexibility to absorb and spread seismic energy without over-displacement **(Ya et al., 2021)**. Their low cost and ease of use make them popular in earthquake-resistant buildings.

Friction pendulum bearings can withstand significant lateral displacements, making them useful for earthquake-prone structures. These isolators can transfer more energy and withstand bigger earthquakes because they can endure massive horizontal vibrations **(Huang et al., 2022)**. Higher prices and installation issues may limit certain projects. Sliding systems lower seismic pressure, although soil and earthquake frequency may hinder them **(Xu et al., 2020)**. Hybrid systems with elastomeric and sliding isolators perform better seismically. These systems may be tailored to the building's energy dissipation, displacement control, and budget **(Hu et al., 2021).** Single-component isolators are cheaper and simpler than hybrids. The seismic environment and structural performance dictate hybrid system use. A comparative overview of seismic isolation techniques relevant to low-rise structures is provided in **Table 2**, highlighting key characteristics and performance benefits of fixed, pinned, and advanced isolation systems such as LRB, HDRB, and FPS.

Table 2. Comparative Summary of Seismic Isolation Techniques.

Isolation Technique	Key Characteristics	Reference
Fixed-Pinned-Base Isolation	Reduces seismic forces and displacements; suitable for masonry and low-rise buildings.	**(Ali et al., 2023; Ali et al., 2024)**
Lead Rubber Bearings (LRB)	Simple and reliable; effective in reducing story shear forces.	**(Ghafooripour, 2012; Rajput and Mishra, 2022)**
High Damping Rubber Bearings	Superior energy dissipation reduces accelerations and story drifts.	**(Ghafooripour, 2012; Belbachir et al., 2023)**
Friction Pendulum Systems	Excellent re-centering capabilities; reduces base shear and inter-story drifts.	**(Sabiha et al., 2023; Rajput and Mishra, 2022)**
Sliding-Based Isolation	Balances stiffness and friction; effective in mitigating seismic impacts.	**(Karad and Murnal, 2024; Ali et al., 2024)**
Elastomeric Rolling Spheres	Low-cost; protects against both seismic and ambient vibrations.	**(Reyes et al., 2023)**
Viscous Dampers and Stiff Core	Reduces lateral displacements; enhances stability in low-rise buildings.	**(Talebi Jouneghani et al., 2023)**

5. EXPERIMENTAL STUDIES ON BASE FLEXIBILITY IN EARTHQUAKE ANALYSIS

5.1 Shaking Table Tests: Methodology and Importance

Shaking table tests may show how a fixed, pinned, or isolated foundation structure reacts to earthquake forces **(Kohler et al., 2022)**. Engineers test design assumptions and structural response to dynamic stresses in controlled earthquake tests. Shaking tables simulate seismic events to assess building models' foundation flexibility **(Bandyopadhyay et al., 2021).** Understanding seismic performance and developing earthquake-resistant constructions requires these experiments. Shaking table testing simulates earthquakes by shaking a tiny building model on a large platform **(Zheng and Yue, 2020)**. Platform movements are precisely controlled to simulate earthquake power, length, and frequency. Accelerometers and displacement sensors measure building forces. Shaking table experiments examine seismic energy absorption and structural weaknesses that may be addressed during design **(Huergo et al., 2020)**.

5.2 Model Scaling

Models of structures are often tested on shaking tables in this way to represent actual earthquake activity. The scale factors are based on similitude laws, so that the model responds like the prototype to the experiments. For instance, bedside experiments and numerical simulations investigated the seismic behavior of a steel frame structure at 1/12.5 scale **(Kalyanshetti et al., 2022)**.

5.3 Sensor Placement

Sensors are located at points in the model for sensing acceleration, displacement, stress, and force. This offers valuable information on the structural response under different seismic events **(Han et al., 2023; Zhan et al., 2024).**

5.4 Ground Motion Input

The shaking table experiments employ a set of pre-recorded earthquake time histories (or artificial ground motions) to model a range of seismic conditions. These motions are scaled to the level of the design earthquake and are imposed on the model in order to compute its response **(Kalyanshetti et al., 2022).**

5.5 Data Analysis

Shaking table testing data are processed to investigate the seismic behavior of the structure. The isolation system's effectiveness is evaluated on the basis of various parameters, including maximum displacement, acceleration, and force **(Han et al., 2023; Zhan et al., 2024).**

5.6 Results from Experimental Studies

Shaking table tests show that base conditions affect seismic performance. **(Ansari et al., 2021)** found that earthquake frames absorb shocks differently. Seismic stress is concentrated on the rigid fixed-base construction's foundation and frame **(Hussain et al., 2022).** Shaking table testing may show lateral displacement and internal stresses in fixed-base buildings, especially at higher stories **(Bai et al., 2021)**. If the structure cannot withstand these forces, the column and beam junctions may be damaged or collapse. Since fixed-base systems are less earthquake-resistant, they cause greater damage.

Pinned base systems that rotate enhance seismic flexibility and reduce frame bending stresses. Even while pinned bases move less than fixed bases during shaking table testing, they nevertheless move **(Li et al., 2023)**. Though buildings absorb seismic energy, structures with lower levels are more susceptible to instability induced by severe lateral displacement **(Bai et al., 2021)**. Internal tensions may cause fixed-base buildings to sway even with pinned bases.

(McCallen et al., 2021) show that systems without fixed or pinned bases work better. Base isolation reduces seismic stresses on the building's superstructure. Shaking table testing showed lower lateral displacements and accelerations due to base structural isolation **(Domadzra et al., 2024)**. To prevent structural frame damage, isolators effectively absorb a significant amount of seismic energy **(Li et al., 2023**). Segregated buildings are better able to resist big earthquakes since they do not collapse or lose structural integrity.

6. ANALYTICAL EVALUATION USING ABAQUS

6.1 Earthquake Engineering Numerical Modelling

In earthquake engineering research, numerical modeling has become a crucial tool due to the limitations of physical testing, such as high costs, scale restrictions, and the inability to capture complex nonlinear behavior. Although useful, shaking table tests only provide information about a structure's response in specific situations and cannot easily account for variations in base flexibility or a range of earthquake scenarios. Computer simulations, however, offer a more comprehensive analysis of how a structure behaves under different input parameters, material properties, and boundary conditions. Engineers can evaluate the effects of base conditions, structural configurations, and seismic intensity levels efficiently and cost-effectively by using parametric studies with numerical models.**(Zakian and Kaveh, 2023)**. By bridging the gap between theoretical formulations and empirical observations, these simulations offer a more comprehensive understanding of how structural systems perform under seismic stresses.

6.2 Finite Element Analysis using Abaqus

Models due to its strong nonlinear analytical ability and flexibility in simulating complex base conditions, Abaqus is one of the standout finite element modeling (FEM) tools available today to simulate the seismic response of structures. Columns, beams, and foundations are some structural elements that can be modeled in depth. Depending on the situation, fixed, pinned, or base-isolated base constraints can be created **(Stanikzai et al., 2020)**. While material models capture nonlinear stress-strain relationships, stiffness degradation, and damping effects, mesh discretization allows for accurate modeling of member connections. Complete fixation, partial flexibility, or isolation mechanisms like friction pendulum systems or elastomeric materials can all be represented by boundary conditions **(Lu et al., 2022).** Researchers can measure the redistribution of internal forces, lateral drift, and energy dissipation using Abaqus, which is especially well-suited for examining how structural response changes with variations in base flexibility.

6.3 Simulation-Based Verification and Design Insights

It is common practice to validate simulations based on Abaqus by contrasting their results with experimental shaking table testing. These comparisons ensure that the numerical model accurately represents the behavior of real-world structures under seismic loads **(Alam et al., 2022)**. Validation makes simulation results more reliable and encourages their use in design decisions. After being verified, these models can be used to predict the effects of different foundation configurations on the dynamic response of structures, such as isolated, pinned, or fixed systems. For example, studies using numerical simulations have demonstrated that base-isolated systems perform better in reducing inter-story acceleration and drift **(Yu et al., 2023)**. The ability to test various earthquake configurations and scenarios in a controlled digital environment aids engineers in creating structural designs and assessing how resilient they are to future earthquakes, which ultimately results in safer and more effective seismic mitigation strategies. **Fig. 3**, which shows the structural reaction under various base flexibility conditions, is an example of such simulation output.

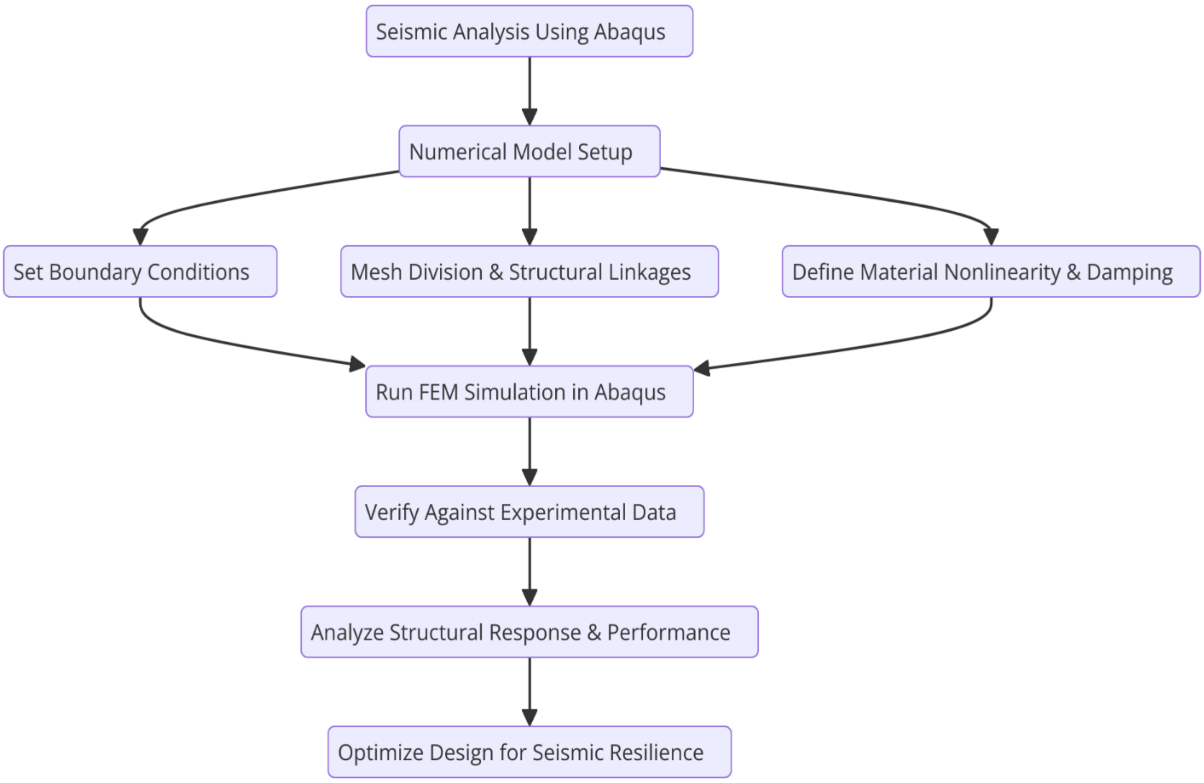

Figure 3. The Seismic Analysis Procedure in this study based on **(Liu et al., 2020; Alam et al., 2022; Zakian and Kaveh, 2023)**

6.4 Emerging Challenges in Seismic Engineering

Extensive research on bracing systems, including concentric, eccentric, and buckling-restrained braces, has been carried out with the aim of improving lateral seismic stability and controlling structural deformation. Concentric braces provide lateral stiffness, eccentric ones can increase energy dissipation due to their offset connections, but buckling-restrained braces (BRBs) are designed specifically to limit yield offsets and thereby help achieve hysteretic behaviors **(Patel et al., 2024; Akbari et al., 2024)** . These systems are effective in resisting damage during single seismic events by reducing inter-story drift and enhancing energy absorption. However, most investigations are limited to individual earthquake scenarios and do not sufficiently address performance under repeated seismic loading.
Although the importance of nonlinear degradation in materials and systems due to repeated stress cycles is recognized, there remains a lack of comprehensive studies on the cumulative deterioration of bracing systems during consecutive earthquakes **(Yazdandoust et al., 2022; Liu et al., 2024)**. Such degradation may significantly reduce the structural effectiveness and energy dissipation capabilities of these systems over time. In regions subjected to seismic sequences or aftershocks, this performance decay is particularly concerning and yet underrepresented in current experimental and numerical frameworks. Additionally, the experimental evaluation of braced frames under sequential seismic excitations remains underdeveloped due to the complexity of replicating realistic multi-event shaking in laboratory environments **(Ocak et al., 2022)**. Existing shaking table studies often simulate only single-event ground motion, limiting our understanding of how bracing components interact dynamically across repeated load cycles. Moreover, while base-isolated

systems have been widely applied and analyzed for their efficiency in decoupling ground motion **(Yu et al., 2023).** Limited attention has been given to the interaction between base isolation and bracing mechanisms in hybrid structural systems. **(Qu et al., 2021; Pan et al., 2022)** pointed to the benefits of base isolators in reducing seismic demands; however, the synergistic or competitive behaviors when combined with bracing remain largely unexplored in the literature.
Therefore, a critical research gap exists in assessing the hybrid application of base isolators and bracing systems under successive earthquake events, especially in low- to mid-rise structures. Understanding how these systems behave together, considering degradation, energy dissipation, and re-centering capacities, would significantly advance the development of resilient design strategies. Future studies should aim to develop experimental frameworks and high-fidelity simulations to replicate real-world consecutive seismic events, enabling engineers to optimize the design of structural systems for enhanced performance under multi-event earthquake scenarios.

7. CONCLUSIONS

The study has shown that the flexibility of the column is very important in controlling the seismic behavior of short steel frames. By combining experimental shaking table tests and computer simulations, we show how different base conditions affect the way structures respond to repeated earthquakes. The summaries below pick out the main results and suggest directions for future work.

- Fixed-base systems are stiff, but high internal stresses are transferred. At beam-point connections, this can lead to damage concentration at the junction between columns and beams.
- Because stress is redistributed into torque-hinging in pinned-base structures, they do not work as well in multi-floor configurations, but are also susceptible to overall deflection.
- When the bottom hangs loose on Base-isolated structures, inter-story drift and accelerations will unfailingly abate. This is especially beneficial for buildings of lower heights.
- Successive earthquake loading shows how bracing systems may fail over time and how hybrid solutions that combine isolation with energy-dissipating bracing might be more useful.
- Future research should concentrate on combined experimental and numerical investigations, utilizing biaxial shaking tables and nonlinear finite element modeling, to develop hybrid mitigation systems that can sustain functioning and reparability during significant earthquakes.

Credit Authorship Contribution Statement

Taha Adeeb Alshammary: Conceptualization, Literature review, Methodology, Writing – original draft, Visualization, Validation. Adel A. Al-Azzawi: Supervision, Writing – review & editing, Validation, Guidance on methodology.

Declaration of Competing 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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تحليل الإطار الهيكلي تحت تأثير الزلازل مع مرونة قاعدة متنوعة: مراجعة

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الخلاصة

تبحث هذه المراجعة الأدبية في السلوك الزلزالي للإطارات الهيكلية الفولاذية منخفضة الارتفاع ذات القواعد الثابتة والمثبتة والمعزولة عن القاعدة تحت تأثيرات زلزالية مفردة ومتتالية. يتم استخدام اختبارات الطاولة الاهتزازية التجريبية ونماذج العناصر المحدودة Abaqus لتقييم تأثير مرونة القاعدة على مقاييس الأداء الهيكلي، بما في ذلك الانجراف بين الطوابق، وقص القاعدة، واستجابة التسارع. تُظهر الأنظمة المعزولة القاعدة، بما في ذلك المحامل المرنة والمطاطية والرصاصية والبندول الاحتكاكية، قدرة فائقة على تبديد الطاقة وتقليل الطلب الزلزالي مقارنة بالقاعدة الثابتة والمثبتة التقليدية. في حين أن القاعدة المثبتة توفر مرونة دورانية تقلل من تركيز العزم، إلا أنها عرضة للإزاحة الجانبية المفرطة في التكوينات متعددة الطوابق. توفر القاعدة الثابتة الصلابة ولكنها تنقل قوى أعلى مباشرة إلى الهيكل الإنشائي. تقلل الأبحاث الحالية من قدرة تحميل الزلازل لأنظمة عزل القاعدة وتدعيمها، على الرغم من التقدم الكبير في تكنولوجيا العزل. تحدد هذه المراجعة فجوة بحثية حاسمة في تقييم استراتيجيات الحماية الزلزالية الهجينة، خاصة بالنسبة للهياكل المعرضة لحركات أرضية متعددة الأحداث. يتم اقتراح اتجاهات مستقبلية لمعالجة هذه التحديات من خلال تحقيقات تجريبية ورقمية متكاملة، بهدف تعزيز مرونة المباني الحديثة في المناطق المعرضة للزلازل.

الكلمات المفتاحية: تحليل الإطار، الزلازل، منضدة الاهتزاز، قاعدة الأعمدة، الأبنية منخفضة الارتفاع.