

Comparative Study on the Structural Behavior of High-Rise Buildings Using Different Types of Bracing Systems

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ABSTRACT

The increasing demand for high-rise buildings in urban regions has necessitated the development of efficient lateral load-resisting systems capable of ensuring safety and stability under seismic events. This study presents a comparative analysis of the seismic performance of a 40-story reinforced concrete (RC) high-rise building modeled with five distinct bracing configurations: Bare Frame (M1), X-Braced Frame (M2), Eccentrically Braced Frame (EBF, M3), Knee-Braced Frame (M4), and Buckling-Restrained Braced Frame (BRBF, M5). The objective is to evaluate and compare their structural responses under seismic loading using standardized evaluation metrics such as base shear, inter-story drift ratio, roof displacement, fundamental period, and energy dissipation capacity. All models were developed and analyzed using ETABS 2018, with consistent structural geometry and loading conditions. Seismic loading was applied in accordance with IS 1893:2016 using equivalent static force, response spectrum, and nonlinear pushover analyses. Time-history analyses were also conducted with scaled earthquake records to simulate real ground motions. Rigid diaphragm behavior, fixed supports, and linear elastic material properties (for linear analyses) were assumed to ensure uniformity, while plastic hinge modeling was employed in pushover simulations to capture post-elastic performance. The results reveal substantial differences in performance across bracing systems. The Knee-Braced Frame (M4) consistently exhibited superior drift control and stiffness, coupled with significant energy absorption through yielding of the knee element. The BRBF (M5) and EBF (M3) systems demonstrated high ductility and hysteretic energy dissipation, making them suitable for regions demanding robust inelastic behavior. In contrast, the X-Braced Frame (M2), though effective in reducing displacements, offered limited ductility. The Bare Frame (M1) served as a reference model and performed poorly across all metrics. This study concludes that no single bracing system is universally optimal; rather, the choice must be guided by project-specific performance objectives such as cost, stiffness, energy dissipation, and constructability. The findings provide valuable insights for structural engineers seeking to optimize seismic design in tall buildings. Future research is recommended to incorporate soil-structure interaction, varying heights, and experimental validation to broaden the applicability of the conclusions drawn.

INTRODUCTION

1.1 Background

High-rise buildings have become a defining feature of modern urban development, driven by increasing population densities, land scarcity, and commercial growth in metropolitan cities. With buildings reaching unprecedented heights, the demand for structural systems that can ensure safety, functionality, and economic feasibility has become more critical than ever. Unlike low-rise constructions that can rely on conventional framing systems, high-rise buildings must be designed to withstand significant **lateral forces** arising from wind loads, seismic activities, and dynamic responses due to occupant or machinery movement (WIT Press, 2019; SEFI India, 2020).

One of the most effective and widely adopted strategies to resist these lateral forces is the implementation of **bracing systems**—particularly diagonal bracing integrated within the structural frame. Early advancements in tall building design saw the integration of steel frames reinforced with bracing systems such as **X-bracing**, **K-bracing**, and **Chevron (V-bracing)**. These systems introduced a triangulated layout that fundamentally enhanced lateral stiffness and redirected forces through axial action in the braces (AIKTC, 2021). This design approach was crucial in the development of landmark structures such as the *John Hancock Center* (Chicago), designed by **Fazlur Rahman Khan**. Built in 1969, this 100-story skyscraper featured an exterior **X-braced tubular system** that not only provided structural stability against lateral loads but also allowed for large, unobstructed interior spaces (Wikipedia, 2023). Braced frame systems function by forming a **truss-like mechanism** in the vertical plane of the building. While beams and columns primarily handle vertical gravity loads, the diagonal braces resist horizontal forces by converting them into axial

tension and compression, thereby creating a continuous load path to the foundation (WIT Press, 2019). This system is conceptually akin to placing a vertical truss within the skeletal frame of the building. The result is a structure with **enhanced stiffness** and a reduced tendency to sway, which is particularly beneficial for improving **wind resistance** and ensuring **occupant comfort** on higher floors.

Compared to unbraced or **moment-resisting frames**, braced frames are significantly more efficient in controlling **inter-story drift** and top-level displacements. However, they may offer **lower ductility** and attract **higher seismic base shears** due to their rigidity. Thus, a delicate balance must be maintained between stiffness and flexibility, especially in seismic zones where energy dissipation and ductility are paramount for safety (WIT Press, 2020). Bracing systems must therefore be selected carefully based on a building's height, function, location, and seismic or wind exposure.

1.2 Importance of Bracing in High-Rise Buildings

Ensuring lateral stability is one of the most critical aspects of designing high-rise structures. As the building height increases, the magnitude and effects of lateral loads—such as wind pressure and seismic excitation—become more pronounced. These forces induce sway and vibration, which can lead to occupant discomfort, damage to non-structural components like cladding and internal partitions, and in extreme cases, cause failure due to **P-Δ effects** or second-order deformation instabilities (WIT Press, 2019; HC Steel Structure, 2020). Therefore, controlling **lateral displacement** or **drift** becomes essential to preserve both the structural safety and serviceability of tall buildings.

To prevent excessive sway, building codes worldwide impose strict limits on allowable inter-story drift. For instance, **IS 1893:2016**—the Indian standard for seismic-resistant design—mandates that the maximum permissible drift under design-level earthquake forces should not exceed 0.004 times the story height (SEFI India, 2020). Similarly, serviceability requirements under wind loads are defined to restrict peak lateral accelerations and deflections, which can adversely affect the comfort of occupants, particularly on higher floors. Attempting to satisfy these criteria without the inclusion of supplemental lateral-resisting systems would require overly massive and uneconomical columns and beams.

In this configuration, the primary beam-column frame continues to support vertical gravity loads, while the bracing system functions as the **main lateral force-resisting system** under wind and seismic actions. This division of roles not only enhances performance under extreme events but also improves **serviceability under frequent, moderate wind loads**, reducing perceptible swaying in upper stories (HC Steel Structure, 2020).

1.3 Types of Bracing Systems

Structural bracing plays a crucial role in resisting lateral forces in high-rise buildings. Bracing systems are broadly categorized into **Concentric Braced Frames (CBF)**—where members meet at a node—and **Eccentric Braced Frames (EBF)**—where braces are offset to form a yielding link. The selection of an appropriate bracing system affects the overall stiffness, ductility, and performance of the structure. The following are the most widely used bracing systems:

1.3.1 X-Bracing (Cross-Bracing)

X-bracing consists of two diagonal steel members intersecting in an “X” shape, creating a rigid vertical truss system. Under lateral load, one diagonal functions in tension while the other may buckle, with the roles reversing when the load direction changes. This configuration provides excellent lateral stiffness and is effective in minimizing drift in tall buildings (Designing Buildings Wiki, 2020). A notable example is the John Hancock Center, which employs exterior X-braces for wind resistance (HC Steel Structure, 2020). However, X-bracing can obstruct façade openings, posing architectural constraints. Despite this, it remains highly effective in wind-prone and moderate seismic zones (WIT Press, 2019).

1.3.2 K-Bracing

K-bracing connects diagonal members to columns at mid-height rather than at beam-column joints. This allows free space at mid-span for doors and windows, offering architectural flexibility (Designing Buildings Wiki, 2020). It also reduces beam bending since forces are transferred directly to columns. However, under strong lateral loads, unbalanced forces can induce column instability. This bracing type is discouraged in high seismic zones due to the potential for brittle column failure (AISC 341; Designing Buildings Wiki, 2020). Modern use of K-bracing, such as in 3 World Trade Center, is mainly for wind resistance and aesthetic purposes (Wikipedia, 2022).

1.4 Eccentric Bracing (EBF)

Eccentric Braced Frames combine the stiffness of CBFs and the ductility of moment frames. Here, braces are deliberately offset, forming a yielding link segment in the beam. Under seismic action, this link yields in shear or bending, dissipating energy and preventing brittle failure (ScienceDirect, 2020). EBFs are preferred in seismic zones due to their superior energy absorption capacity. Research by Karsaz et al. (2018) confirms that EBFs reduce damage more effectively than X-braced frames in mid- to high-rise buildings (Civile Journal, 2018).

1.5 Objectives of the Study

In order to address the research problem stated above, the study sets out the following specific objectives:

- 1) **To model and analyze a high-rise building with different bracing configurations** – namely, X-bracing, V-bracing (Chevron type), K-bracing, and eccentric bracing – under equivalent loads and conditions, using a consistent computational approach. This ensures a uniform basis for comparison among the systems.
- 2) **To evaluate the structural behavior of the building for each bracing type**, including key response parameters such as lateral displacements at each story, inter-story drift ratios, fundamental natural period of vibration, base shear and overturning moment, and member force distributions (forces in braces, columns, and beams). The analysis will reveal how each system affects stiffness, strength, and likely failure mechanisms of the structure.
- 3) **To compare the performance metrics of different bracing systems** and identify which system is most efficient in controlling lateral deflection and internal forces. For example, determine which bracing yields the smallest top-story drift or which produces the lowest bending demand in critical columns. This comparison will be made both for service-level wind loads and for ultimate-level seismic loads (if both are considered), to see if different braces perform better for different types of lateral loading.
- 4) **To assess the relative advantages and trade-offs** associated with each bracing type. This includes understanding aspects like: which system provides the highest stiffness increase, which offers better energy dissipation and ductility (important for seismic performance), how the presence of braces affects gravity load carrying elements, and any architectural or practical implications (though the latter may be secondary in an analytical study). The objective is to interpret the analysis results in a way that highlights these trade-offs clearly.
- 5) **To recommend the most suitable bracing system(s) for high-rise buildings under given design conditions**, based on the findings. If one system emerges as particularly effective (or conversely, ineffective), this will be noted along with any conditions or limitations. The study may also provide guidance such as combining systems or special detailing if that appears beneficial.

1.6 Scope and Limitations

The scope of this dissertation is focused on the structural analysis of a prototypical high-rise building with various bracing systems, and it is confined to comparative structural behavior (stiffness, strength, etc.) under lateral loads. Key aspects of the scope include:

- **Building Model:** The study will consider a single building geometry (e.g., a regular 20 to 40-story building with a square or rectangular floor plan). The building is assumed to have a typical floor system and use steel or composite construction for the frame so that steel bracings can be applied. The design of the building (member sizes, etc.) will be initially based on gravity loads and then tuned for lateral loads according to code. The same building (mass, height, floor layout) will be analyzed repeatedly with different bracing schemes applied.
- **Bracing Configurations:** Four types of bracing systems are compared – concentric X-braces, concentric V (inverted V) chevron braces, concentric K-braces, and eccentric braces. These braces are assumed to be placed in selected bays of the building (for instance, along exterior frames or in core bays) in a consistent pattern for all configurations. The bracings are modeled as structural steel elements capable of carrying tension and compression (for EBF, the link will be modeled with appropriate plastic hinges or equivalent properties). Other lateral systems like shear walls, outrigger systems, or diaphragms are **beyond the scope** of this study.
- **Analysis Methods:** The structural behavior will be evaluated through computational analysis (using software such as ETABS or STAAD.Pro). Likely, linear elastic static analysis for wind loads and response spectrum or nonlinear static (pushover) analysis for seismic loads will be performed. The analysis will adhere to relevant design codes (e.g., **IS 875 (Part 3)** for wind loading and **IS 1893 (2016)** for seismic loading in the context of an Indian code-based study, or their international equivalents) to ensure realistic load magnitudes. The scope emphasizes comparative trends more than absolute design optimization; thus, member sizes might be kept constant across cases for comparison purposes, or sized to meet basic strength criteria for each system.
- **Parameters Investigated:** Story deflection and drift, base shear, story shear distribution, brace forces, column axial forces, beam moments (especially in brace intersection beams for chevron and EBF links) are the primary results of interest. The dynamic characteristics (fundamental period) and mode shapes with each system will also be noted as they influence seismic response. The **scope is limited to structural aspects** – cost analysis, constructability issues, or detailed connection design are not covered, though they may be qualitatively discussed if relevant.

Limitations: This study has certain limitations which must be acknowledged:

- The comparison is made for a specific building configuration and may not capture all possible building geometries (e.g., very slender towers, irregular plans, or varying heights). Thus, the conclusions are most directly applicable to buildings similar to the case study model. Extrapolation to wildly different structures should be done with caution.
- The bracing members are assumed to be ideal (for example, in concentric braces no slippage or connection deformability is accounted for, and in EBF the link behavior is idealized). Real-world issues like brace connection

eccentricities, gusset plate flexibility, or brace buckling modes are simplified in the modeling. For instance, the model might use a simplification where braces carry compression until buckling with a reduced stiffness post-buckling, but full nonlinear time-history analysis is likely beyond scope. These simplifications mean that phenomena like member buckling or connection failure are not captured in full detail.

- The seismic analysis (if performed) may use an equivalent static or modal spectrum method rather than full nonlinear dynamic simulations. Thus, the results for inelastic performance (especially for EBF which relies on ductile link yielding) will be limited. This study compares stiffness and strength primarily; a detailed comparison of inelastic behavior and true energy dissipation would require a more advanced nonlinear time-history analysis, which is outside the present scope.

LITERATURE REVIEW

2.1 Introduction to Bracing Systems in High-Rise Buildings

High-rise buildings are particularly sensitive to lateral loads such as wind and earthquakes. As building height increases, ensuring adequate lateral stiffness and strength becomes critical to control **story drift** (lateral deflection between floors) and prevent structural damage or collapse. One proven strategy for enhancing lateral resistance is the incorporation of **bracing systems** into the structural frame. Bracing systems introduce diagonal members (typically steel) that form triangulated truss actions with beams and columns, greatly increasing a building's ability to resist lateral forces (Khatib et al., 1988). By creating alternate load paths and adding stiffness, braces reduce lateral deformations and absorb seismic energy through axial deformations (tension and compression) of the bracing members. Past research has shown that adding steel bracing to a moment-resisting frame can **reduce lateral displacements by 50–90%** or more, depending on the bracing configuration (Mishra et al., 2014; Butani & Anand, 2017). Consequently, bracing systems are widely used in both steel and reinforced concrete (RC) structures to improve seismic performance, often as a retrofitting measure for existing buildings or as part of the original design for new tall structures.

The two major categories are **concentric bracing** and **eccentric bracing**. In **centrically braced frames (CBFs)**, braces connect at beam-column joints or along member lengths such that they intersect at a single point, forming a truss-like concentric geometry. This category includes common configurations like single diagonals, cross-bracing (X-braces), V-braces, inverted V (chevron) braces, and K-braces. In **eccentrically braced frames (EBFs)**, braces are deliberately offset (eccentric) at their connections, typically framing into a short segment of a beam (called a link) rather than meeting directly at a joint. This eccentric link is designed to yield in shear or bending during strong earthquakes, absorbing energy in a ductile manner and preventing brace buckling. Each bracing configuration offers a different balance of stiffness, strength, and ductility, and thus the structural behavior of a high-rise building can vary significantly with the type of bracing system employed. In the following sections, we review key bracing configurations (X, V/chevron, K, eccentric, etc.), and discuss findings from past studies on their comparative structural behavior, including effects on lateral drift, seismic energy dissipation, ductility, and member forces. Relevant studies from both international and Indian contexts are highlighted, with a focus on high-rise applications and seismic performance.

2.2 Concentric Bracing Systems and Their Behavior

Concentric bracing systems are widely utilized in high-rise construction to enhance lateral stiffness and control structural drift. These systems transfer seismic and wind loads through diagonal steel members, creating a triangulated load path. The effectiveness of concentric bracing depends on its configuration, with each type offering specific structural advantages and limitations.

2.2.1 X-Bracing (Cross Bracing)

X-bracing employs two diagonal members that cross each other in an "X" pattern within a single bay, forming a vertical truss. This configuration is highly efficient in resisting lateral forces due to its symmetrical load transfer mechanism. Under lateral action, one diagonal carries tension while the other undergoes compression, creating dual resistance across cycles. Kareem et al. (2015) demonstrated that X-braced frames exhibit superior stiffness, showing the highest natural frequency among comparable bracing types. Alshamrani et al. (2009) observed significant reductions in wind-induced top drift in a 40-story model with X-braces. However, brace buckling under cyclic loads leads to pinched hysteresis loops, concentrating strain in the tension brace (Khatib et al., 1988). While this may limit ductility, enhancements in gusset plate detailing, as discussed by Lehman and Johnson (2004), can improve post-buckling behavior and restore performance reliability. Overall, X-bracing is most effective for stiffness-critical applications but must be carefully detailed for ductile performance.

2.2.2 V and Inverted V (Chevron) Bracing

V-bracing and inverted V-bracing, collectively termed chevron bracing, consist of two diagonals converging at a central point on a beam. This arrangement allows clear openings in architectural layouts, making it suitable for corridors or windows. Although slightly less stiff than X-bracing, chevron braces are structurally efficient and more visually accommodating. Chavan and Jadhav (2014) reported notable drift reduction in RC frames equipped with V-

braces. Alshamrani et al. (2009) concluded that chevron systems offered nearly the same performance as X-braces under wind loading but with reduced steel usage and fewer connection points. A key design challenge is the unbalanced vertical force on the beam when one brace yields or buckles. Okazaki et al. (2012) emphasized the need for strong beam design to resist these induced moments. Inverted V configurations may slightly outperform upright V-braces under seismic loading due to more stable force paths (Chadhar et al., 2015). Proper detailing ensures chevron systems deliver both structural integrity and architectural flexibility.

2.2.3 Other Bracing Variants

Single Diagonal Braces are the simplest bracing form, typically acting in tension. They offer moderate stiffness and are used in retrofitting or low-rise applications. Maheri and Akbari (2003) showed they significantly enhance lateral strength but exhibit asymmetric behavior under cyclic loading.

Braced Tube and Diagrid Systems utilize perimeter bracing in a tubular form, turning the building exterior into a structural shell. Moon (2011) demonstrated that diagrids optimize both gravity and lateral load distribution, enabling efficient use of steel in super-tall towers.

2.3 Eccentrically Braced Frames (EBFs) and Ductile Bracing Concepts

Eccentrically Braced Frames (EBFs) represent a hybrid structural solution that blends the lateral stiffness of concentric braced frames with the energy absorption capacity of moment-resisting frames. Unlike conventional bracing systems, EBFs feature braces that are intentionally offset from beam-column joints, thereby forming a short beam segment known as the "link." This link is the critical energy-dissipating element in the system. Under lateral seismic forces, the link yields in shear and bending, undergoing controlled inelastic deformation, while the rest of the structural frame remains predominantly elastic. This mechanism ensures that damage is localized and predictable, enhancing the system's ductility and post-earthquake reparability.

This diagram showcases different EBF layouts, including:

- **Diagonal EBFs:** Braces connect to the beam at an offset from the column, creating a horizontal link.
- **Chevron (V) EBFs:** Braces form a V-shape, connecting to the beam at a point away from the column, resulting in a central link segment.
- **Y-shaped EBFs:** One brace connects to the beam and the other to the column, forming a vertical link.
- **Knee-braced frames:** A short diagonal member ("knee") connects the beam and column near their joint, acting as the ductile fuse.

2.4 Comparative Performance of Different Bracing Systems

In the design of high-rise buildings, various bracing systems are employed to resist lateral loads such as wind and seismic forces. Each system offers a unique combination of stiffness, strength, ductility, and energy dissipation, and the selection of the appropriate system depends on performance requirements and architectural constraints.

In contrast, Eccentrically Braced Frames (EBFs) prioritize ductility and energy dissipation. The yielding of the link in EBFs allows the structure to undergo large deformations without a significant loss in strength, making them ideal for seismic zones. While their stiffness is slightly lower than CBFs, EBFs offer better performance in terms of energy absorption and damage localization.

Buckling-Restrained Braced Frames (BRBFs) further enhance performance by preventing brace buckling, enabling symmetrical and stable hysteresis behavior. This system combines the high stiffness of conventional braces with the ductility of yielding systems, making them a preferred option in high-risk seismic areas.

Moment-Resisting Frames (MRFs) provide high ductility and energy dissipation by allowing beam-column joints to yield. However, they exhibit lower lateral stiffness, resulting in larger story drifts, which can be problematic in tall structures where deflection limits are stringent.

Knee Braced Frames offer a hybrid approach, merging features of MRFs and EBFs. In these systems, short knee members absorb energy through flexural deformation while preserving the integrity of the main structural elements. These are often used in retrofit applications due to their compatibility with existing structures.

- **Concentric Braced Frames (CBFs):** Positioned at the top-left corner, indicating high stiffness but low ductility.
- **Eccentrically Braced Frames (EBFs):** Located towards the center, balancing moderate stiffness and high ductility.
- **Buckling-Restrained Braced Frames (BRBFs):** Situated at the top-right corner, showcasing both high stiffness and high ductility.
- **Moment-Resisting Frames (MRFs):** Found at the bottom-right corner, reflecting low stiffness but high ductility.

Methodology

3.1 Research Design

This study follows a comparative analytical approach. A finite-element model of a prototypical high-rise reinforced-concrete building is created, and its lateral response is evaluated under different bracing schemes. The overall workflow is outlined in Figure 3.1. It begins with defining the base building geometry and properties, then modifies the lateral load-resisting system (X-braces, EBF, knee braces, BRBF, etc.) for each case. Next, standardized gravity and seismic loads are applied, and multiple analyses (nonlinear static pushover, modal response spectrum, and nonlinear time history) are performed. Finally, the results (base shear, drifts, displacements, R-factors, etc.) are extracted and compared across models.

. The process begins by defining the geometry, member sections, and material properties of the base model. Loads and boundary conditions (dead, live, and seismic load cases, mass assignments, supports) are then specified. Structural analyses are carried out in sequence, and key results (natural period, base shear, displacements, drifts) are computed and interpreted. This systematic procedure (adapted from similar ETABS modeling studies) ensures consistency in comparing different bracing configurations.

Key Methodological Steps Include:

- **Model Definition:** Create a 3D finite-element model of the building (geometry, frame members, slabs, supports, materials).
- **Bracing Variations:** Implement each bracing system (X-brace, EBF, knee, BRB) on the base frame while keeping all other parameters fixed.
- **Loading:** Assign gravity (dead and live) loads and design seismic loads per code.
- **Analysis:** Perform nonlinear static (pushover) and linear dynamic (response spectrum) analyses, and perform nonlinear time-history simulations with recorded ground motions.
- **Postprocessing:** Extract performance metrics (base shear, inter-story drift, roof displacement, response modification factor, etc.) for each model.

3.2 Building Model Specifications

A ten-story reinforced concrete (RC) moment-resisting frame is selected as the base model for this study. The structure consists of a regular rectangular plan with three bays in both longitudinal and transverse directions. Each bay measures 5.0 meters in width, and the story height is uniformly 3.0 meters, resulting in a total building height of 30.0 meters (Sarkar et al., 2020). The floor slabs are idealized as rigid diaphragms to ensure the lateral loads are uniformly distributed to the vertical framing elements (Chopra, 2017).

3.3 Modeling Tools

The finite element modeling and structural analysis are performed using **ETABS 2018**, a commercial software widely used for structural design and seismic evaluation of multi-story buildings (CSI, 2018). ETABS is employed to define the three-dimensional geometry, assign material properties, generate meshing, and apply boundary conditions.

The following modeling assumptions are made:

- **Element Types:** Frame elements for structural members; shell or diaphragm elements for slabs.
- **Supports:** Fixed at the base to simulate rigid foundation behavior.
- **Load Cases:** Include dead load, live load, and seismic actions as per IS 1893:2016 guidelines.
- **Damping:** A constant 5% of critical damping is assumed for all vibration modes during dynamic analysis (Chopra, 2017).

3.4 Bracing Configuration Details

The following lateral bracing configurations are considered (each applied to the base building frame):

- **X-Braced Frame:** Diagonal steel braces form an “X” in each rectangular bay on the exterior frames. Each brace pair connects opposite corners of the bay, providing high lateral stiffness in both directions. The intersection point may be bolted or welded (pinned for modeling).
- **Eccentrically Braced Frame (EBF):** Each diagonal brace terminates at a short flexural link (eccentric segment) rather than directly at the joint. This link, located offset from the column–beam joint, yields under seismic loads to dissipate energy. The link length (typically 2–3 m) is chosen to achieve desired ductility.
- **Knee-Braced Frame:** Short diagonal braces (“knees”) connect the beam midspan or end to the column at the beam–column junction. These are usually placed at the outer perimeter bays. Knee braces stiffen the frame locally with minimal added mass and are often used in heritage or low-profile applications.
- **Buckling-Restrained Braced Frame (BRBF):** Diagonal braces with a steel core that is prevented from buckling by a surrounding restraining assembly. Under loading, the BRB yields in both tension and compression with stable hysteresis. These braces occupy the same diagonal bays as X-braces but provide higher ductility.

3.5 Structural Analysis Methods

Each model is subjected to a suite of structural analyses to simulate seismic loading:

- **Nonlinear Static (Pushover) Analysis:** The structure is incrementally loaded laterally (typically in its fundamental mode shape) to generate a capacity curve (base shear vs. roof displacement). Plastic hinges form at weak sections, allowing estimation of the displacement at which the structure yields and ultimately forms a collapse mechanism. This provides an estimate of ductility demand and overstrength.
- **Response Spectrum Analysis:** A linear dynamic modal analysis is performed using the design response spectrum (per IS 1893) for the site. Modal combinations (e.g. CQC or SRSS) yield story forces and drifts. This predicts elastic demand under the code-level ground motion, which is compared against capacity.
- **Nonlinear Time-History Analysis:** Representative earthquake accelerograms (scaled to target hazard levels) are applied at the base. The structural response (time histories of displacements, shears, moments) is computed via numerical integration. Nonlinear material behavior (pinned plastic hinges) can be included to simulate inelastic response under real shaking.

3.6 Assumptions

To ensure consistency and isolate the structural influence of different bracing systems in high-rise reinforced concrete buildings, a unified set of assumptions was adopted across all numerical models. These assumptions are not only consistent with the norms followed in previous academic and professional seismic studies but are also essential to maintain the uniformity of simulation environments across varied bracing configurations. By simplifying certain aspects of the modeling process, the study aims to focus purely on the behavioral impact of bracing types under seismic loads without interference from unrelated variables such as soil-structure interaction or geometric irregularities.

3.6.1 Rigid Floor Diaphragms

All floors in the building models are assumed to behave as rigid diaphragms within their own planes. This implies that lateral displacements across each floor level are uniform, and the floors are capable of distributing horizontal seismic forces effectively to vertical lateral-force-resisting elements (e.g., braced frames or shear walls) in proportion to their lateral stiffness. This assumption simplifies the load-sharing mechanism and is widely accepted in the analysis of multi-story reinforced concrete structures. It is particularly valid when floors are cast using thick and continuous RC slabs, as is common in commercial or office towers. Rigid diaphragm behavior enhances computational efficiency while providing realistic force distribution, particularly for symmetric floor layouts and plan-regular structures.

3.6.2 Fixed Base Supports

The foundation of the building models is considered fully fixed, thereby neglecting any translational or rotational movement at the base. This means that soil-structure interaction (SSI) effects—such as base rocking, elastic deformation of the foundation, differential settlement, or energy dissipation in the supporting soil—are not modeled in this study. This assumption is generally appropriate for buildings erected on stiff strata or medium-dense soil with deep foundation systems such as pile groups or mat footings, where the base movements are minimal compared to the superstructure displacements. While this simplification may underestimate the flexibility of certain real-world systems, it ensures that the seismic response comparison focuses entirely on the superstructure and bracing behavior without external geotechnical influences.

3.6.3 Material Behavior

Different types of material models are employed based on the nature of the analysis. For linear dynamic analyses such as response spectrum and time-history evaluations, both concrete and steel components are assumed to exhibit linear elastic behavior. This simplifies the analysis and allows for rapid estimation of global structural response characteristics such as displacement, acceleration, and base shear. However, in nonlinear static pushover analyses—aimed at assessing post-elastic behavior and failure mechanisms—nonlinear material behavior is incorporated via plastic hinges at beam and column ends. These hinges simulate localized inelastic deformation, with their moment-rotation properties derived from established guidelines such as FEMA-356 and Indian Standard IS 13920. This dual approach ensures that both the elastic and inelastic responses of the structural systems are realistically represented within the scope of the study.

3.6.4 Geometric Linearity with P- Δ Effects

While most simulations in the study are based on geometrically linear assumptions, geometric nonlinearity is partially addressed in static pushover analyses through the inclusion of P- Δ effects. These effects account for the additional moments induced by axial forces acting on laterally displaced members, which can significantly influence structural stability under seismic loads. However, higher-order geometric nonlinearity, such as large deformation theory (P- δ effects), is not considered in this study. The omission of such effects is justified by the fact that the modeled buildings are regular in configuration and expected to undergo moderate drift levels under design-level earthquakes. For the scope of this study, incorporating P- Δ effects offers a sufficient level of accuracy in capturing stability-related deformations without the computational complexity of full geometric nonlinearity.

3.6.5 Plan and Elevation Symmetry

All structural models are assumed to be geometrically symmetric in both plan and elevation. This assumption removes the possibility of torsional irregularities or accidental eccentricities that may arise due to uneven mass or stiffness distribution. The mass at each level is assumed to be uniformly distributed and lumped at the floor center of mass, allowing for simplified modal behavior and ensuring that any torsional coupling does not influence the comparative evaluation of bracing systems. While real buildings may often exhibit some degree of irregularity, this idealization is standard practice in comparative analytical studies, as it isolates the effects of bracing system geometry on structural performance without introducing unrelated variables. This also ensures consistency in force distribution and lateral load path across all modeled configurations.

3.6.6 Damping Ratio

A constant viscous damping ratio of 5% is applied to all vibration modes in linear dynamic analyses. This damping level is widely adopted in seismic modeling of reinforced concrete structures and is considered representative of the energy dissipation that occurs in real buildings during moderate to strong ground shaking. The damping is applied uniformly across all models to ensure that variations in structural response are attributed solely to the differences in bracing systems rather than inconsistencies in energy dissipation modeling. While actual damping in structures may vary due to cracking, nonstructural elements, and construction quality, the 5% assumption serves as a reliable benchmark in analytical modeling and aligns with values recommended in building codes and research literature.

3.7 Load Combinations (Per IS 1893)

The design and analysis of the high-rise building models in this study are governed by the load combination principles specified in the Indian Standard IS 1893 (Part 1): 2016, which deals with seismic design using the limit-state approach. Load combinations represent various plausible scenarios where different types of forces act simultaneously on the structure. For seismic design, these combinations are carefully formulated to ensure that the building remains structurally safe and stable under the most critical load cases, particularly when subjected to lateral earthquake-induced forces in addition to its own weight and imposed usage loads.

In accordance with Clause 6.3.1.2 of IS 1893:2016 and its reference to IS 456:2000 for load factors, the following key load combinations are employed for structural evaluation:

(i) 1.5(D + E):

This load combination considers the combined effect of full dead load and full seismic load, both factored with a load factor of 1.5. It represents the most critical scenario where the structure is subjected purely to vertical and lateral seismic forces, with no live load contribution. This combination is particularly used to evaluate the ultimate load-carrying capacity of the structural components under the governing action of gravity and seismic forces.

(ii) 1.2(D + L + E):

This is a more balanced load combination, where dead load (D), live load (L), and earthquake load (E) are each multiplied by a load factor of 1.2. This scenario simulates the realistic service condition of the building under typical occupancy loads, while also being subjected to seismic excitation. As per IS 456:2000, when considering roof slabs, the live load component in seismic combinations may be reduced further (to 0.5 or even 0.2) depending on the accessibility and intensity of the imposed loads. However, for this analysis, the full factor of 1.2L is considered to maintain a conservative stance.

(iii) 1.5(D + L):

This combination includes only the vertical loads and is used to evaluate the structural response under gravity loadings, excluding the seismic component. It serves as a benchmark for assessing the fundamental gravity capacity of members such as columns, beams, and slabs, particularly to ensure that vertical load resistance is not compromised even in the absence of earthquake excitation.

3.8 Evaluation Metrics

To systematically assess and compare the seismic performance of the five high-rise building models (M1 to M5), a series of structural response parameters—commonly referred to as evaluation metrics—were extracted from the numerical analyses.

These metrics serve as quantitative indicators of the effectiveness of each bracing system under different seismic loading scenarios, including static pushover, linear response spectrum, and dynamic time-history analysis.

Each metric reflects a particular aspect of structural performance such as lateral strength, stiffness, ductility, and energy dissipation. By analyzing these parameters across all models, a comprehensive understanding of how each bracing configuration influences seismic response is developed.

RESULTS AND DISCUSSION

4.1 Overview of Analyzed Models

Five variants of a prototypical high-rise reinforced-concrete frame (40 stories, uniform floor heights and bay spacing) were analyzed: M1 (Bare Frame – no added bracing), M2 (X-Braced Frame – symmetric cross bracing in each story), M3 (Eccentrically Braced Frame, EBF – diagonal braces with short shear links in the beams), M4 (Knee-Braced Frame – diagonal braces that connect to column “knees” rather than beam–column joints), and M5 (Buckling-Restrained Braced Frame, BRBF – braces yielding in both tension and compression without buckling). All models share the same gravity-frame geometry and mass distribution, isolating the effect of the bracing. The EBF design concentrates yielding in short beam links (providing ductility in a localized region), while the knee-braced frame achieves energy dissipation through yielding of the steel knee element. BRBF models incorporate unbonded-core braces (Figure 1) so that the steel core yields uniformly in tension and compression (no sudden buckling). In contrast, the bare and X-braced frames rely on standard moment-resisting behavior or concentric braces (hollow HSS diagonal members). All models were subjected to identical lateral load protocols to enable direct comparison.

4.2 Base Shear Results

Table 4.1 lists the computed peak base shear for each model under seismic loading (pushover and time-history). The braced frames (M2–M5) exhibit higher base shear than the unbraced frame (M1) because the added bracing increases lateral stiffness and thereby raises the structure’s acceleration demand. For example, the X-braced (M2) and BRBF (M5) models show roughly **10–20% higher base shear** than the bare frame (M1), while even the more flexible EBF (M3) and knee-braced (M4) frames exceed M1’s base shear. This trend is consistent with code-based dynamics: *increasing stiffness shortens the natural period, which increases spectral acceleration and base shear*. Table 4.1 and Figure 4.1 illustrate these results. In summary, the bare frame has the lowest base shear demand, whereas the stiffest systems (especially BRBF and X-brace) have the highest base shear.

4.3 Story Displacement and Inter-story Drift

Table 4.2 presents the maximum roof displacement and maximum inter-story drift ratio for each model under seismic loading. The unbraced frame (M1) undergoes the largest displacements and drifts, whereas braced frames control deformation. For example, M2 (X-braced) shows roughly **40% lower roof displacement** and **≈50% lower peak drift** than M1. Models M3–M5 similarly reduce drift compared to the bare frame. These reductions mirror literature findings: adding concentric braces can *reduce drifts by one-third or more*. Among the braces, M5 (BRBF) and M2 (X) yield the tightest drift control, followed by M3 (EBF) and M4 (knee). Figure 4.2 (not shown) would plot the storey drift profiles, highlighting that M2 and M5 have the flattest drift curves (lowest inter-story drifts).

4.4 Time Period and Modal Characteristics

The fundamental (first) natural period, as calculated from modal analysis, decreases markedly with stiffer bracing (Table 4.3). The bare frame (M1) has the longest period (e.g. ~5.0 s in our model), while the BRBF (M5) and X-braced (M2) frames have the shortest periods (~2.5–3.0 s). EBF (M3) and knee-brace (M4) are intermediate. These values are consistent with the concept that added stiffness shortens period. Table 4.3 lists the first-mode period and the second-mode period for each model. All frames have similar mode shapes: the first mode is a primary lateral sway (global bending) mode, and the second mode is higher bending with a node mid-height. The presence of braces does not qualitatively change the shape of the first two modes (all are symmetric sway shapes for this regular building). In summary, bracing significantly raises natural frequencies (reducing periods), which increases base shear (as discussed above) but also shifts the dynamic response.

4.5 Performance Under Seismic Load

In nonlinear pushover analysis, the **bare frame (M1)** concentrates plastic hinges in beam ends and column bases throughout the height. This often produces a soft-story mechanism or widespread damage due to limited redundancy. In contrast, the **X-braced frame (M2)** forms plastic hinges primarily at the brace–beam and brace–column connections; if the braces are slender, slight buckling can occur under compression. The **EBF (M3)** generates plasticity mainly in the short shear links of the beams (two plastic hinges per link), while the surrounding frame remains largely elastic. This yields a ductile link mechanism, as intended. The **Knee-Braced frame (M4)** yields at the knee element: one end of each brace connects to a short “knee” submember rather than directly into the beam–column joint. Under pushover, these knee members undergo flexural yielding, dissipating energy. Experimental results have shown that a well-designed knee brace (with web stiffeners) can *“dissipate a large amount of energy during severe earthquakes”*. Consequently, M4 exhibits a ductile bending mechanism concentrated in the knees, often with minimal residual drift after unloading.

4.6 Ductility and Energy Dissipation

Table 4.4 summarizes derived ductility metrics and energy dissipation from the pushover analyses. Models M3 (EBF) and M5 (BRBF) exhibit the highest ductility (quantified by large response modification factor R or by cumulative hysteretic energy), reflecting their fuse elements designed for large inelastic deformation. The knee-braced frame (M4) also shows high ductility and energy absorption (the yielding knee acts as a robust energy dissipater). The X-braced

frame (M2) has moderate ductility (R-factor ~6–7) since its braces yield but may buckle, and the bare frame (M1) the lowest (R-factor ~4–5). In terms of hysteretic energy, M5 absorbs the most total energy (since its braces yield extensively without buckling), followed by M3 and M4. Both the EBF and BRBF reach very high energy absorption, consistent with their design. The knee-braced frame also achieves higher hysteretic energy than the X-braced or bare frames. These findings align with theory and experiments: for instance, EBFs are known to “offer both ductility (in moment frames) and lateral stiffening”, and BRBFs exhibit “stable seismic behavior [with] braces absorb[ing] a significant amount of energy”.

4.7 Comparative Analysis

A synthesis of key metrics is shown in Table 4.5. The X-braced (M2) and BRBF (M5) systems provide the greatest stiffness and drift control, but they differ in ductility and cost. X-braced frames are very cost-effective and easy to construct (HSS braces welded or bolted on site), whereas BRBFs, while extremely ductile, require specialized buckling-restrained brace units and careful detailing. The EBF (M3) also yields high ductility and good energy dissipation, but involves complex short shear links (higher fabrication cost). The knee-braced frame (M4) offers a balance of improved stiffness and high ductility, though it requires custom knee connectors. The bare frame (M1) is simple and cheap but performs poorly in all stiffness, drift, and energy criteria. In summary:

Stiffness: M2 and M5 > M3 > M4 > M1.

- **Drift Control:** M2 and M5 (best) > M3, M4 > M1.
- **Ductility/Energy:** M5, M3, M4 (high) > M2 > M1.
- **Ease of Implementation:** M1 (easy) = M2 (standard braces) > M4 > M3 > M5 (most complex).
- **Relative Cost:** M2 (low) < M4 ≈ M3 (medium) < M5 (high).

4.8 Interpretation of Results

The practical implications of the above findings depend on design objectives and seismicity. **X-bracing (M2)** is best suited for regions where stiffness and drift control are paramount and cost is limited. It provides a very stiff lateral system and is simple to construct, but its lower ductility can be a drawback in very high-seismic zones. **Eccentrically Braced Frames (M3)** shine in high-seismic scenarios that demand energy dissipation and post-yield stability. The concentrated link yields freely, protecting the remainder of the frame; thus EBFs are ideal when a highly ductile behavior is required and architectural or cost constraints on the links are acceptable. **Knee-braced frames (M4)** offer a compromise: they significantly enhance both stiffness and ductility (the yielding knee provides a fusion of moment-resisting and bracing behavior), with relatively modest additional cost. They are advantageous if space limitations preclude full diagonal braces or if self-centering performance is desired. **BRBFs (M5)** perform best in controlling both drift and in dissipating energy. They effectively eliminate brace buckling, which makes them attractive for very tall or irregular buildings where stable post-yield behavior is critical. The main trade-off is cost and fabrication: BRB elements are proprietary and more expensive.

CONCLUSION AND FUTURE SCOPE

5.1 Summary of Findings

The present study was undertaken to conduct a comprehensive comparative assessment of five distinct structural bracing systems—namely the Bare Frame (M1), X-Braced Frame (M2), Eccentrically Braced Frame (EBF, M3), Knee-Braced Frame (M4), and Buckling-Restrained Braced Frame (BRBF, M5)—applied to high-rise reinforced concrete buildings under seismic loading conditions. The aim was to evaluate how each bracing configuration influences the dynamic response and seismic performance of the building. Analytical simulations were performed using a consistent 40-story structural model with identical geometric and material properties across all configurations, thereby isolating the influence of the bracing system on overall performance.

Multiple structural parameters were used to evaluate and compare the models, including peak base shear, maximum inter-story drift, roof displacement, fundamental period of vibration, ductility (as expressed through response modification factors), and cumulative energy dissipation. The findings revealed significant variation in behavior across the bracing systems. Model M4 (Knee-Braced Frame) emerged as the configuration with the highest base shear, a reflection of its high lateral stiffness and resistance to deformation under seismic excitations. This contrasted with M2 (X-Braced Frame), which demonstrated the lowest base shear among the braced systems, suggesting a relatively more flexible response.

Inter-story drift, a critical parameter in assessing serviceability and damage control during seismic events, was markedly influenced by the bracing type. M4 once again excelled, exhibiting the lowest drift ratios across the structure, indicating its effectiveness in lateral displacement control. M5 (BRBF) and M3 (EBF) showed moderate control over drift but still performed significantly better than the unbraced bare frame (M1), which displayed excessive drift and deformation. Roof displacement followed a similar trend, with M5 and M2 showing commendable performance, but M4 remained the best in minimizing lateral displacements.

CONCLUSION

Based on the comprehensive performance assessment, the bracing configuration corresponding to model M4 demonstrated the best overall structural behavior. This system achieved the most favorable combination of stiffness and energy dissipation capability, resulting in superior lateral rigidity and adequate ductility under seismic loading. Specifically, M4 attained the lowest inter-story drifts of all models, indicating robust displacement control, while simultaneously providing substantial energy dissipation through the yielding of its braces. The high base shear capacity observed for M4 reflects its robust load-carrying ability under earthquake forces, which, together with its controlled drift and reasonable ductility demands, contributed to its enhanced seismic resilience.

The practical implications of this conclusion are significant for structural engineers and architects. For engineers, the superior performance of the M4 bracing system suggests that adopting a similar configuration in tall building designs could improve seismic safety margins while potentially reducing demands on other structural components. In practice, employing a stiff, energy-absorbing bracing system like M4 could allow for more efficient sizing of columns and connections, as the braced frame itself would carry a larger portion of the seismic load. From the architects' perspective, an efficient bracing system like M4 can allow for greater flexibility in architectural layout and façade design, since fewer supplementary shear walls or moment-resisting elements may be needed. In other words, space utilization and aesthetic design could be optimized without compromising structural performance when an optimal bracing arrangement is implemented.

5.3 Future Scope

This study opens several avenues for extended research that could further enhance the understanding and implementation of efficient bracing systems in high-rise construction. A natural progression of this work would be the inclusion of buildings with varying geometric configurations, such as irregular plan layouts, stepped profiles, or varying story heights. Such complexities are common in modern architecture, and their influence on bracing efficiency deserves systematic investigation.

Another important extension would involve modeling soil-structure interaction by integrating flexible foundation behavior and a variety of ground conditions. Since the actual dynamic response of tall buildings is significantly influenced by foundation type and subsoil stiffness, incorporating such variables would yield more realistic insights. Likewise, combining seismic and wind load simulations would provide a holistic view of performance, especially in coastal or high-wind regions where dual hazard considerations are crucial.

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