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Research Article

Optimization of Diagrid Angle in Different Shaped Diagrid Structural System by Dynamic Analysis in Seismic Zone

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Abstract:

The increasing demand for tall buildings in seismically active regions has necessitated innovative structural systems that combine architectural aesthetics with superior seismic performance. Diagrid structural systems have emerged as a promising solution, offering enhanced lateral load resistance through their triangulated geometric configuration. This research investigates the optimization of diagrid angles across various building geometries—square, rectangular, circular, and hexagonal—subjected to seismic loading conditions in high-risk zones. Through comprehensive dynamic analysis using finite element modeling, this study evaluates the structural behavior of diagrid systems with varying angles (ranging from 35° to 75°) under earthquake loads corresponding to Zone V seismic conditions. The research employs ETABS software for modeling and analysis, examining critical parameters including story drift, displacement, base shear, and acceleration responses. Results indicate that optimal diagrid angles vary significantly with building geometry, with square and rectangular structures performing best at 65-70°, while circular configurations show superior performance at 55-60°. The findings reveal that properly optimized diagrid angles can reduce lateral displacement by up to 35% and improve overall structural efficiency by 28% compared to conventional configurations. This research contributes valuable insights for structural engineers and architects designing tall buildings in earthquake-prone areas, providing evidence-based guidelines for selecting appropriate diagrid angles based on building shape and seismic requirements.

1. Introduction

The contemporary architectural landscape has witnessed a remarkable transformation in high-rise building design, driven by urbanization pressures and the pursuit of structural efficiency. Among various innovative structural systems, diagrid structures have gained substantial attention from both architects and structural engineers due to their unique ability to resist lateral loads through axial action of diagonal members rather than conventional moment-resisting frames. The term "diagrid" originates from the combination of "diagonal" and "grid," representing a structural system where external diagonal members form a triangulated network that carries both gravity and lateral loads efficiently.Seismic zones present particularly challenging environments for tall building construction, where structures must withstand significant horizontal forces generated during earthquakes. Traditional structural systems often require substantial core walls and moment frames to resist these lateral loads, resulting in reduced usable floor space and increased material consumption. Diagrid systems offer an elegant alternative by distributing lateral forces through diagonal members working primarily in axial tension and compression, which proves more efficient than bending-dominated behavior in conventional frames.

The geometric configuration of diagrid systems, particularly the angle of diagonal members with respect to horizontal plane, significantly influences structural performance under seismic loading. Existing literature suggests that diagrid angles typically range between 35° and 85°, with varying effects on structural efficiency depending on building height, geometry, and loading conditions. However, limited research has systematically investigated how building shape interacts with diagrid angle optimization in seismic contexts, creating a substantial gap in current knowledge.

Different building geometries—square, rectangular, circular, and hexagonal—exhibit distinct structural behaviors under lateral loading due to varying torsional characteristics, load distribution patterns, and aerodynamic properties. Square and rectangular plans, being most common in urban construction, offer straightforward structural arrangement but may experience significant torsional effects. Circular geometries provide excellent torsional resistance and uniform load distribution, while hexagonal shapes represent a compromise between geometric complexity and structural efficiency. Understanding how optimal diagrid angles vary across these geometries under seismic conditions remains poorly understood in existing literature.

Current design practices often rely on empirical guidelines and simplified optimization approaches that may not adequately account for the complex interaction between building geometry, diagrid angle, and dynamic seismic response. Most existing studies have focused on single building shapes or static analysis methods, failing to capture the dynamic nature of earthquake loading and its interaction with various structural configurations. This research addresses these limitations by conducting comprehensive dynamic analysis across multiple building geometries, providing practical guidance for seismic design of diagrid structures.

The significance of this research extends beyond theoretical understanding to practical applications in seismic-prone regions worldwide. Countries situated along major tectonic plate boundaries, including those in the Pacific Ring of Fire, face continuous challenges in developing earthquake-resistant tall buildings. Optimized diagrid systems could potentially reduce structural material requirements by 15-30% while improving seismic performance, translating to substantial economic and safety benefits. Furthermore, the aesthetic appeal of external diagrid systems allows architects to integrate structural elements with building facades, creating visually striking landmarks that exemplify engineering excellence.

This paper presents a systematic investigation of diagrid angle optimization across four distinct building geometries subjected to Zone V seismic conditions, representing the highest seismic risk category. Through advanced finite element modeling and dynamic time-history analysis, the research evaluates critical performance parameters including lateral displacement, inter-story drift, base shear, acceleration responses, and structural efficiency metrics. The study encompasses 120 distinct structural models, varying in geometry, diagrid angle, and height, providing a comprehensive dataset for optimization analysis.

The research methodology employs ETABS software for three-dimensional modeling and dynamic analysis, incorporating realistic material properties, member sizing, and seismic loading based on contemporary building codes. Modal analysis identifies fundamental periods and mode shapes, while time-history analysis using recorded earthquake ground motions evaluates dynamic structural response. Comparative analysis across different configurations enables identification of optimal diagrid angles for each building geometry, supported by statistical validation and parametric studies examining the sensitivity of structural performance to geometric variations.

Research findings from this study will contribute to developing evidence-based design guidelines for diagrid structures in seismic zones, helping structural engineers make informed decisions during preliminary design stages. The outcomes will also benefit architectural practice by clarifying the relationship between aesthetic choices in building form and resulting structural performance requirements. Additionally, this research advances theoretical understanding of how triangulated structural systems behave under dynamic loading conditions, potentially informing future developments in earthquake-resistant design methodologies.

The subsequent sections of this paper are organized as follows: Section 2 establishes specific research objectives; Section 3 defines the scope and limitations of the study; Section 4 reviews relevant literature on diagrid systems and seismic optimization; Section 5 describes the research methodology and analytical procedures; Sections 6 and 7 present analysis of secondary and primary data respectively; Section 8 discusses implications and interpretations of findings; and Section 9 concludes with key contributions and recommendations for future research.

2. Objectives

The primary and secondary objectives guiding this research investigation are:

Primary Objective:

- To determine the optimal diagrid angle for different building geometries (square, rectangular, circular, and hexagonal) that minimizes lateral displacement and inter-story drift under Zone V seismic loading conditions, measurable through comparative dynamic analysis of 120 structural models with diagrid angles ranging from 35° to 75° at 5° intervals.

Secondary Objectives:

- To evaluate and quantify the relationship between diagrid angle variation and critical seismic performance parameters including base shear, story acceleration, and modal characteristics across different building heights (20, 30, and 40 stories), providing parametric performance curves for each geometric configuration.
- To conduct comprehensive dynamic time-history analysis using at least three recorded earthquake ground motions scaled to Zone V intensity, comparing structural responses across different diagrid configurations and establishing statistical significance of performance differences.
- To develop practical design recommendations and optimization charts that enable structural engineers to select appropriate diagrid angles based on building geometry and height during preliminary design stages, validated against current code requirements and professional practice standards.
- To assess the material efficiency and economic implications of optimized diagrid angles by calculating structural weight reduction percentages and cost-benefit ratios compared to conventional diagrid configurations, providing quantitative justification for implementation of optimization findings.

3. Scope of study

The boundaries and limitations defining this research investigation include:

Geographical and Seismic Scope:

- Research focuses exclusively on Zone V seismic conditions as per IS 1893 (Part 1): 2016, representing the highest seismic risk category with zone factor Z = 0.36, applicable to regions with high earthquake probability and intensity.
- Ground motion characteristics and soil conditions assume medium soil type (Type II) with standard site amplification factors, not accounting for site-specific geotechnical variations or special soil conditions like liquefaction potential.

Structural Configuration Boundaries:

- Study examines four distinct building plan geometries: square (40m × 40m), rectangular (30m × 50m), circular (diameter 45m), and hexagonal (side length 23m), maintaining approximately equal floor areas around 1600 square meters for comparative validity.
- Building heights limited to three categories: 20 stories (70m), 30 stories (105m), and 40 stories (140m), representing typical mid-rise to high-rise construction with standard story height of 3.5 meters.
- Diagrid angle variations investigated within practical range of 35° to 75° measured from horizontal plane, at intervals of 5°, excluding extreme angles that present fabrication or connection challenges.

Analytical and Methodological Limitations:

- Dynamic analysis conducted using ETABS 2020 software with linear elastic material behavior assumptions, not incorporating nonlinear effects, material degradation, or post-yield behavior that may occur during severe earthquakes.
- Time-history analysis employs three scaled earthquake records representing different frequency contents and duration characteristics, while acknowledging that actual earthquake ground motions exhibit significant variability.
- Structural damping assumed at 5% of critical damping for all modes, consistent with steel structures, without detailed investigation of supplementary damping systems or energy dissipation devices.

Design Parameter Constraints:

- Diagonal members sized using standard steel sections (tubular and I-sections) with yield strength of 250 MPa, following conventional design procedures without optimization of individual member cross-sections.
- Load combinations follow standard code provisions including dead load, live load, and seismic load as per IS 456:2000 and IS 1893:2016, excluding wind load considerations and special loading scenarios.
- Connection detailing and local stress concentrations at nodes not explicitly modeled, assuming adequate connection design following standard practices.

Variables and Factors Excluded:

- Foundation-structure interaction effects not considered, with fixed base conditions assumed for all models to isolate superstructure behavior from soil-structure interaction complexities.

- Construction sequencing, temporary loading conditions, and phased construction effects excluded from analytical scope.
- Non-structural components, cladding systems, and architectural finishes not modeled, though their mass contribution included in dead load calculations.
- Long-term effects including creep, shrinkage, fatigue, and corrosion not addressed, focusing solely on short-duration seismic response.

4. Literature review

The development of diagrid structural systems represents a significant evolution in high-rise building engineering, with theoretical foundations rooted in space frame structures and geodesic geometries pioneered by Buckminster Fuller in the mid-20th century. Contemporary diagrid systems emerged prominently with the construction of the Swiss Re Building (30 St Mary Axe) in London, designed by Foster and Partners, which demonstrated how diagonal structural grids could simultaneously serve structural and architectural purposes. This landmark project catalyzed widespread interest in diagrid applications, leading to numerous theoretical investigations and practical implementations worldwide.

Early research on diagrid structures by Moon et al. (2007) established fundamental principles regarding the structural efficiency of triangulated exterior frameworks compared to conventional moment frames. Their work demonstrated that diagrid systems could reduce structural material requirements by 20-30% while improving lateral stiffness through predominantly axial load-carrying mechanisms. The researchers identified diagrid angle as a critical parameter influencing structural performance, suggesting optimal angles around 65-70° for typical building heights, though their analysis focused primarily on static loading conditions without comprehensive seismic evaluation.

Subsequent investigations by Kim and Lee (2012) expanded understanding of diagrid behavior under lateral loads through parametric studies examining various geometric configurations. Their finite element analyses revealed that optimal diagrid angles vary with building height and aspect ratio, with taller structures requiring shallower angles to minimize shear lag effects in the diagonal members. However, this research predominantly addressed wind loading scenarios and employed simplified dynamic analysis procedures that may not adequately capture seismic response characteristics involving complex modal interactions and frequency content variations.

The influence of building geometry on diagrid structural performance has received increasing attention in recent literature. Montuori et al. (2014) conducted comparative studies of diagrid systems in rectangular versus square plan configurations, identifying distinct load distribution patterns and torsional behavior differences. Their research indicated that rectangular plans experience greater torsional irregularities under lateral loading, potentially requiring adjusted diagrid configurations to maintain uniform stiffness distribution. Nevertheless, this study did not extend to alternative geometries like circular or hexagonal plans, nor did it incorporate dynamic seismic analysis methodologies.

Seismic performance evaluation of diagrid structures has emerged as a critical research area, particularly following earthquake events that tested tall building responses. Research by Boake (2014) examined the seismic resilience of diagrid systems through case studies and analytical modeling, highlighting the importance of adequate ductility in diagonal connections and the potential for energy dissipation through controlled yielding mechanisms. The study emphasized that while diagrid systems exhibit excellent lateral stiffness, ensuring adequate deformation capacity under severe earthquakes requires careful attention to connection detailing and member sizing strategies.

Dynamic characteristics of diagrid structures, particularly modal properties and period estimation, have been investigated by various researchers seeking to understand fundamental vibration behavior. Studies by Mele et al. (2014) explored how diagrid angle influences fundamental period and mode shapes through parametric analyses of multiple building heights. Their findings suggested that increasing diagrid angles generally reduces structural periods due to enhanced lateral stiffness, though the relationship proves nonlinear and depends significantly on building proportions. This research provided valuable insights into dynamic characteristics but did not comprehensively address response spectrum analysis or time-history evaluations under actual earthquake ground motions.

The optimization of diagrid angles has attracted substantial research interest, with different methodologies proposed for identifying optimal configurations. Genetic algorithm approaches employed by Leonard (2007) sought to minimize structural weight while satisfying drift limitations, producing optimization curves for various building heights. These computational studies indicated that optimal angles typically fall within the 55-75°

range for buildings between 20-60 stories, though specific optima vary with loading conditions and performance criteria. However, most optimization studies have focused on single objective functions and may not adequately capture the multi-criteria nature of seismic design where competing performance measures must be balanced.

Performance-based seismic design principles have increasingly informed diagrid research, emphasizing the need to evaluate structures under multiple performance levels ranging from serviceability to collapse prevention. Research by Zhang and Lu (2018) applied performance-based methodologies to diagrid structures, examining damage progression and failure mechanisms under incrementally increasing seismic intensities. Their work revealed that diagrid systems generally exhibit favorable collapse mechanisms with progressive yielding of diagonal members, though performance depends critically on connection ductility and load redistribution capacity.

Comparative studies between diagrid systems and conventional structural systems have sought to quantify the relative advantages and limitations of triangulated external frameworks. Investigations by Malekinejad et al. (2016) compared diagrid structures with tube systems and moment-resisting frames across various performance metrics including material efficiency, constructability, and seismic response. Results indicated that diagrid systems offer superior stiffness-to-weight ratios and reduce core wall requirements, though construction complexity and connection fabrication costs may offset material savings in some contexts. These comparative analyses provide important context for evaluating the practical viability of diagrid applications in different project scenarios.

The influence of member sizing and proportion on diagrid performance has been examined through parametric studies investigating the relationship between diagonal section properties and overall structural behavior. Research by Angelucci and Mollaioli (2017) demonstrated that increasing diagonal member sizes beyond certain thresholds produces diminishing returns in lateral stiffness improvement, suggesting the existence of optimal size ranges that balance structural efficiency with material economy. Their work highlighted the importance of coordinated optimization addressing both geometric configuration and member proportions simultaneously rather than treating these as independent design variables.

Recent advances in computational modeling have enabled more sophisticated analyses of diagrid structures incorporating nonlinear material behavior, connection flexibility, and progressive collapse scenarios. Studies employing advanced finite element techniques with fiber-based beam elements and nonlinear time-history analysis have revealed complex post-elastic behavior patterns that differ substantially from linear elastic predictions. Research by Liu and Ma (2019) showed that connection semi-rigidity can significantly influence global structural response under severe earthquakes, potentially altering optimal diagrid angle selections when nonlinear effects are considered.

The interaction between diagrid geometry and architectural design has been explored in research addressing the integration of structural and aesthetic considerations. Work by Asadi and Adeli (2017) investigated how diagrid patterns influence building facades and interior spatial arrangements, identifying geometric configurations that simultaneously optimize structural performance and architectural functionality. This interdisciplinary research emphasizes that structural optimization must consider broader project objectives beyond pure engineering efficiency, incorporating architectural vision and constructability constraints into decision-making processes.

International building codes and design standards have progressively incorporated guidance for diagrid structures, though specific provisions remain limited compared to conventional systems. The evolution of code requirements reflects growing understanding of diagrid behavior and recognition of unique design considerations. Research examining code compliance and design procedures by Stromberg et al. (2012) identified areas where existing provisions may not adequately address diagrid-specific issues, particularly regarding connection design, system overstrength factors, and redundancy assessments. These studies have informed ongoing code development efforts and highlighted the need for specialized design guidelines.

Emerging research directions include investigation of hybrid diagrid systems combining diagonal grids with supplementary lateral resisting elements, adaptive diagrid configurations that vary angle with building height, and integration of damping devices within diagrid frameworks. Studies exploring these advanced concepts suggest potential for further performance improvements beyond conventional diagrid applications. Research by Lacidogna et al. (2020) examined hybrid diagrid-outrigger systems showing enhanced performance under extreme loading conditions, though practical implementation requires addressing increased design and construction complexity.

Despite substantial progress in understanding diagrid structures, significant research gaps persist particularly regarding systematic optimization across different building geometries under seismic loading conditions. Most existing studies have examined limited geometric configurations or employed simplified analysis methods that may not capture the full complexity of seismic response. There remains a clear need for comprehensive investigations that simultaneously address multiple building shapes, incorporate rigorous dynamic analysis procedures, and provide practical design guidance applicable to real-world projects in seismic regions.

This research addresses identified gaps by conducting systematic optimization of diagrid angles across four distinct building geometries using comprehensive dynamic analysis methodologies. By employing time-history analysis with multiple ground motion records and examining parametric variations across realistic building heights, this study extends existing knowledge and provides evidence-based recommendations for seismic design of diagrid structures. The research contributes to theoretical understanding of geometric influences on structural behavior while offering practical tools for engineering practitioners designing tall buildings in earthquake-prone regions.

5. Research methodology

This research adopts a quantitative approach grounded in positivist philosophy, employing advanced computational modeling and numerical analysis to investigate diagrid angle optimization systematically. The methodology integrates finite element modeling, modal analysis, and dynamic time-history analysis within a comprehensive parametric study framework examining multiple building geometries and diagrid configurations.

Research Design and Framework

The research design follows a systematic parametric investigation structure evaluating 120 distinct structural models generated through combinations of four building geometries, three height categories, and nine diagrid angle variations. This factorial design enables comprehensive assessment of how geometric and angular parameters influence seismic performance independently and through interaction effects. The computational approach allows precise control of variables and reproducible analysis conditions impossible to achieve through experimental testing of full-scale structures.

Structural Modeling Approach

Three-dimensional finite element models were developed using ETABS 2020 software, recognized as industry-standard structural analysis platform offering robust capabilities for dynamic analysis of complex building systems. Each model incorporates detailed representation of diagrid members as frame elements with six degrees of freedom per node, enabling accurate capture of axial, flexural, and torsional behaviors. Floor slabs modeled as rigid diaphragms ensure realistic load distribution while simplifying computational requirements through reduced degrees of freedom.

The four building geometries investigated include square plans measuring 40m × 40m, rectangular plans of 30m × 50m, circular plans with 45m diameter, and regular hexagonal plans with 23m side lengths. These dimensions were selected to maintain approximately equivalent floor areas around 1600 square meters, enabling valid performance comparisons across different shapes. Building heights of 20, 30, and 40 stories with uniform story height of 3.5 meters represent typical mid-rise to high-rise construction prevalent in urban environments.

Material Properties and Member Sizing

Diagrid diagonal members designed using structural steel conforming to IS 2062 Grade E250 with characteristic yield strength of 250 MPa, elastic modulus of 200 GPa, and Poisson's ratio of 0.3. Member cross-sections selected from standard tubular and wide-flange sections based on preliminary design calculations considering gravity loads and estimated lateral forces. Typical diagonal members range from 500mm to 900mm depth depending on building height and diagrid angle, with member sizes adjusted through iterative design process to maintain consistent stress ratios across different configurations.

Floor slabs modeled as 150mm thick reinforced concrete with characteristic compressive strength of 30 MPa and density of 25 kN/m³. Although diagrid systems feature steel framing, concrete composite floors commonly used in practice provide necessary diaphragm action and accommodate service integration requirements. Total dead load including slab self-weight, partitions, ceiling, and services assumed as 5 kN/m², while live load of 3 kN/m² applied for office occupancy following IS 875 (Part 2) provisions.

Diagrid Geometric Configuration

Diagrid angles measured from horizontal plane, varied systematically from 35° to 75° at 5° intervals representing the practical range where fabrication and connection execution remains feasible. Steeper angles below 35° produce excessively long diagonal spans with reduced structural efficiency, while angles exceeding 75° approach vertical orientation diminishing the characteristic triangulated geometry advantages. The nine angle variations investigated (35°, 40°, 45°, 50°, 55°, 60°, 65°, 70°, 75°) provide sufficient resolution to identify optimal ranges and construct performance response curves.

Diagonal members arranged in consistent pattern around building perimeter creating regular triangulated modules. For square and rectangular plans, diagonals positioned on all four facades with matching angles. Circular plans incorporate radial diagrid pattern with diagonals connecting perimeter nodes following geodesic geometry principles. Hexagonal configurations feature diagrid panels on each of six faces maintaining geometric regularity. Module dimensions adjusted to accommodate different building heights while maintaining target diagrid angles, resulting in varying numbers of diagonal repetitions per floor level.

Loading Conditions and Combinations

Gravity loads applied as uniformly distributed loads on floor diaphragms, while seismic forces determined through dynamic analysis procedures rather than equivalent static methods. Dead load includes structural self-weight automatically calculated by software based on member volumes and material densities, plus superimposed dead load of 5 kN/m² accounting for non-structural components. Live load of 3 kN/m² applied to all floors except roof where reduced value of 1.5 kN/m² used.

Seismic analysis conducted for Zone V conditions per IS 1893:2016 with zone factor Z = 0.36, importance factor I = 1.0 for standard occupancy, and response reduction factor R = 5 for special moment-resisting steel frames. Soil type assumed as medium (Type II) with corresponding site factors. Load combinations following IS 1893 provisions include:

- 1.5(DL + LL)
- 1.2(DL + LL ± EQX)
- 1.2(DL + LL ± EQY)
- 1.5(DL ± EQX)
- 1.5(DL ± EQY)
- 0.9DL ± 1.5EQX
- 0.9DL ± 1.5EQY

Where DL represents dead load, LL denotes live load, and EQX/EQY indicate seismic forces in orthogonal horizontal directions.

Modal Analysis Procedure

Modal analysis performed for each structural configuration to determine natural periods, mode shapes, and modal participation factors characterizing dynamic behavior. The analysis employs eigenvalue extraction techniques solving the characteristic equation relating mass and stiffness matrices. At least 15 modes captured for each structure ensuring cumulative modal mass participation exceeds 90% in both horizontal directions as required by seismic codes.

Natural periods of vibration provide critical insights into structural flexibility and potential resonance with earthquake ground motion frequency content. Fundamental periods compared across different diagrid angles and building geometries to understand stiffness variations. Mode shapes visualized to identify potential torsional irregularities or localized deformation patterns that may require design modifications.

Time-History Analysis Implementation

Dynamic time-history analysis conducted using three recorded earthquake ground motions representing different seismic characteristics and frequency contents. Selected earthquake records include:

1. **El Centro (1940)**: Imperial Valley earthquake, horizontal component with PGA 0.348g, dominant period range 0.5-2.0 seconds
2. **Northridge (1994)**: Sylmar station recording, PGA 0.843g, rich in short-period content affecting mid-rise structures
3. **Kobe (1995)**: JMA station recording, PGA 0.834g, containing long-period components relevant to tall flexible structures

Each ground motion scaled to achieve peak ground acceleration consistent with Zone V design requirements while preserving original frequency characteristics and duration. Scaling factors applied uniformly across entire acceleration time history avoiding artificial frequency content modifications. Analysis duration extended beyond strong motion phase to capture complete structural response including free vibration decay.

Direct integration of equations of motion performed using Newmark's method with appropriate time step selection ensuring numerical stability and accuracy. Time step of 0.01 seconds employed providing sufficient resolution to capture high-frequency response components while maintaining computational efficiency. Analysis conducted for ground motion applied separately in two orthogonal horizontal directions, with maximum response values recorded for performance evaluation.

Performance Evaluation Parameters

Multiple performance metrics evaluated to comprehensively assess seismic behavior across different diagrid configurations:

1. **Maximum Lateral Displacement**: Peak roof displacement measured during time-history analysis, indicating overall structural flexibility and drift demand
2. **Inter-Story Drift Ratio**: Maximum drift between consecutive floors expressed as

percentage of story height, critical for damage assessment and code compliance

3. **Base Shear**: Total lateral force transmitted to foundation, reflecting overall seismic demand on structure
4. **Story Acceleration**: Peak floor acceleration at various levels, important for occupant comfort and non-structural component protection
5. **Modal Periods**: Fundamental and higher mode periods characterizing dynamic characteristics
6. **Structural Weight**: Total steel tonnage in diagrid system, indicating material efficiency

Performance parameters extracted from analysis results and tabulated systematically for comparative evaluation. Statistical analysis conducted to identify significant differences between configurations and establish confidence in optimization conclusions.

Data Analysis and Optimization Methodology

Collected performance data subjected to comprehensive statistical analysis identifying trends, correlations, and significant differences across parametric variations. For each building geometry and height category, diagrid angles compared based on multiple performance criteria with optimal angles identified through multi-criteria evaluation considering both strength and serviceability requirements.

Optimization approach employs weighted scoring methodology where each performance parameter normalized to 0-1 scale and assigned importance weighting reflecting practical design priorities. Typical weightings include 35% for drift control, 25% for displacement limitation, 20% for base shear reduction, 15% for acceleration control, and 5% for material efficiency. Composite performance scores calculated for each configuration enabling objective ranking and optimal angle identification.

Parametric curves developed plotting performance metrics against diagrid angle for each geometry and height combination. These curves visualize performance trends and identify optimal angle ranges where multiple criteria simultaneously satisfied. Sensitivity analysis examines how optimal angles shift with changes in performance criteria weightings and loading assumptions.

Validation and Reliability Measures

Analysis results validated through multiple approaches ensuring reliability and accuracy. Model verification includes checking mass participation factors, reviewing mode shapes for physical reasonableness, and confirming that natural periods fall within expected ranges based on empirical formulas. Comparison with published data for similar structures provides additional confidence in modeling approach.

Mesh sensitivity studies conducted on selected models verifying that results remain stable with refined element discretization. Convergence of modal analysis confirmed by checking that increasing number of extracted modes does not significantly alter captured modal mass. Time-history analysis convergence verified by ensuring that reducing time step size does not substantially change peak response values.

Ethical Considerations and Limitations

This computational research raises minimal ethical concerns as it involves numerical modeling rather than human subjects or experimental testing. However, professional responsibility requires acknowledging methodology limitations that could affect practical application of findings. The study assumes linear elastic material behavior which may not accurately represent structural response during severe earthquakes exceeding yield thresholds. Fixed base boundary conditions neglect soil-structure interaction effects potentially important for soft soil sites. Simplified connection modeling does not capture local stress concentrations and deformation capacity that influence actual seismic performance.

Research findings should be interpreted as providing preliminary design guidance requiring validation through detailed design and potentially supplementary analysis addressing project-specific conditions. Optimal angles identified represent general trends across parameter ranges investigated but may require adjustment for particular buildings with unique characteristics outside the study scope.

6. Analysis of secondary data

Secondary data analysis provides essential context for interpreting primary research findings through examination of existing literature, code provisions, and documented case studies of diagrid structures worldwide. This section synthesizes information from multiple sources to establish performance benchmarks, validate modeling assumptions, and identify gaps addressed by current research.

Global Diagrid Structure Database Analysis

Analysis of completed diagrid buildings worldwide reveals predominant geometric and angular characteristics in current practice. Database compiled from architectural and engineering publications documents approximately 85 prominent diagrid structures constructed between 2000-2024 across various locations and heights. Statistical analysis of this dataset provides insights into typical design choices and performance outcomes informing research parameter selections.

Code Provisions Comparative Analysis

Examination of international building codes reveals varying approaches to diagrid system design with limited specific guidance compared to conventional structural systems. Key findings from code analysis include:

The Indian Standard IS 1893:2016 provides comprehensive seismic design provisions but does not explicitly address diagrid systems, requiring engineers to apply provisions for steel special moment frames with appropriate modifications. The code specifies response reduction factor R = 5 for special steel moment-resisting frames, which forms the basis for diagrid system design in this research. However, the primarily axial behavior of diagrid members differs fundamentally from moment frame behavior, raising questions about appropriate R-factor selection.

American codes including ASCE 7-16 and AISC 341 similarly lack specific diagrid provisions, though recent commentary acknowledges these systems and suggests treating them as bearing wall systems or special steel frames depending on connection detailing. European Eurocode 8 addresses steel concentrically braced frames which share some behavioral characteristics with diagrid systems, particularly regarding predominantly axial member forces and energy dissipation through yielding.

Analysis of code drift limitations reveals typical inter-story drift ratios limited to 0.4-0.5% under design basis earthquakes for steel structures. These serviceability criteria significantly influence diagrid angle selection as steeper angles generally provide enhanced drift control. Base shear calculation methods vary across codes but generally employ response spectrum approaches with equivalent static procedures permitted for regular structures below certain height thresholds.

Seismic Performance Data from Past Earthquakes

Historical earthquake performance data provides valuable insights into actual structural behavior under severe ground shaking. While diagrid structures remain relatively uncommon compared to conventional systems, several buildings with diagonal bracing systems have experienced significant seismic events offering relevant lessons.

The 2011 Christchurch earthquake tested numerous steel-framed buildings with diagonal bracing, revealing that structures with well-detailed connections and adequate ductility provisions performed satisfactorily even under ground motions exceeding design levels. Buildings experienced limited structural damage though some non-structural component failures occurred due to high floor accelerations. These observations emphasize the importance of connection design and acceleration control in diagrid systems.

Japanese experience with triangulated structural systems during the 1995 Kobe earthquake and subsequent events demonstrates that external diagonal frameworks can provide excellent seismic resistance when properly designed. Post-earthquake investigations documented minimal structural damage in buildings employing external bracing systems, with performance superior to some moment frame structures experiencing significant beam-column joint damage.

Published Research Performance Benchmarks

Synthesis of performance data from published research studies establishes benchmarks for evaluating primary research findings. Analysis of 24 peer-reviewed studies published between 2010-2024 examining diagrid seismic performance reveals typical response characteristics and optimization trends.

Average maximum drift ratios reported across studies range from 0.28% to 0.65% under design-level earthquakes, with most studies indicating superior performance compared to equivalent moment frame systems. Optimal diagrid angles identified in previous research cluster around 60-70° range for buildings between 30-50 stories, though specific optima vary with analysis assumptions and performance criteria.

Comparative studies examining different building geometries report that circular and hexagonal plans generally exhibit reduced torsional response compared to rectangular configurations, though this advantage may be offset by increased construction complexity. Steel weight efficiency metrics indicate that optimized diagrid systems can achieve 15-30% material savings compared to conventional tube or core-frame systems of equivalent lateral stiffness.

Material Efficiency Trends

Secondary data analysis of structural steel quantities in completed diagrid projects provides context for evaluating material efficiency achieved through optimization. Data compiled from published case studies and project documentation reveals significant variation in steel intensities ranging from 52 kg/m² to 165 kg/m² with median value of 82.5 kg/m².

Statistical analysis indicates that steel intensity correlates strongly with building height ($r = 0.74$, $p < 0.001$) and moderately with plan aspect ratio ($r = 0.38$, $p = 0.016$). Buildings located in high seismic zones exhibit 18-25% higher steel intensities on average compared to similar structures in low seismic regions, reflecting increased lateral force demands and redundancy requirements.

Diagrid angle influences material efficiency through its effect on diagonal member forces and required cross-sectional areas. Secondary data analysis suggests that optimal angles from material efficiency perspective tend toward steeper configurations (65-75°) where diagonal members are shorter and carry loads more efficiently. However, this efficiency must be balanced against other performance considerations including drift control and acceleration response.

Frequency Content and Ground Motion Characteristics

Analysis of earthquake ground motion characteristics from seismological databases informs selection of time-history records for dynamic analysis. Examination of strong motion recordings from Zone V equivalent seismic regions worldwide reveals typical frequency content and duration characteristics relevant to diagrid structure response.

Ground motions from shallow crustal earthquakes in active tectonic regions exhibit predominant periods typically ranging from 0.2 to 2.0 seconds, with significant energy content in frequency bands most likely to excite mid-rise to high-rise buildings. Near-fault recordings show distinct pulse-like characteristics with high peak velocities potentially causing enhanced displacement demands on flexible structures.

Spectral analysis of recorded ground motions indicates that earthquake frequency content varies considerably based on magnitude, distance, and site conditions. Structures with fundamental periods between 2-5 seconds, typical for 30-50 story buildings, face particular challenges when ground motion spectra contain significant energy in this period range. This observation emphasizes the importance of evaluating diagrid configurations across multiple earthquake records representing different frequency characteristics.

Cost-Benefit Analysis from Completed Projects

Economic analysis of diagrid system implementation based on published cost data from completed projects reveals complex trade-offs between material savings and construction premium. While diagrid systems can reduce structural steel quantities by 15-30% compared to conventional frames, fabrication and erection costs may increase due to complex connection geometries and non-standard member orientations.

Case study data indicates that diagrid systems become economically attractive for buildings exceeding 40 stories where material savings offset construction premiums. For mid-rise buildings below 30 stories, conventional structural systems often prove more economical unless architectural considerations justify premium costs. Seismic regions may see enhanced cost-effectiveness as diagrid lateral resistance reduces need for expensive core walls and supplementary bracing.

Construction schedule implications represent another important economic consideration, with some projects reporting extended erection times due to connection complexity while others achieved schedule acceleration through reduced core wall construction. Detailed cost analysis depends heavily on project-specific factors including labor rates, material availability, and contractor experience with diagrid systems.

Performance-Based Design Benchmarks

Secondary data from performance-based design studies establishes response thresholds for different performance levels applicable to diagrid structures. Analysis of research employing nonlinear pushover and time-history methods identifies typical damage progression patterns and acceptable response limits.

For operational performance level corresponding to frequent earthquakes (50% probability in 30 years), maximum drift ratios generally limited to 0.2-0.3% to prevent non-structural damage. Design-level earthquakes (10% probability in 50 years) accept drift ratios up to 1.0-1.5% with repairable structural damage anticipated. Maximum considered earthquakes (2% probability in 50 years) target collapse prevention with drift ratios potentially reaching 2.5-3.5% while maintaining structural stability.

These performance benchmarks inform evaluation criteria for primary research findings, providing context for assessing whether optimized diagrid configurations achieve acceptable performance across multiple seismic hazard levels. Comparison of research results against established benchmarks enables validation of analytical procedures and identification of configurations meeting contemporary performance expectations.

Synthesis and Gap Identification

Comprehensive synthesis of secondary data reveals substantial knowledge base regarding diagrid structural behavior yet confirms significant gaps addressed by current research. While numerous studies have examined diagrid optimization, systematic investigation across multiple building geometries using rigorous dynamic analysis remains limited. Most published research focuses on single building shapes or employs simplified analysis methods potentially missing important behavioral aspects.

The secondary data analysis validates research methodology choices including parameter ranges, performance metrics, and analysis procedures. Documented performance of completed projects provides confidence that optimal diagrid angles identified through analytical studies translate to practical implementation. However, the analysis also highlights need for continued research addressing emerging challenges including integration with supplementary damping systems, optimization for multi-hazard scenarios, and development of simplified design procedures for preliminary engineering.

7. Analysis of primary data

Primary data analysis presents comprehensive findings from 120 finite element models analyzed through modal analysis and dynamic time-history procedures. Results systematically examine how diagrid angle variations influence seismic performance across different building geometries and heights, identifying optimal configurations for each case.

Modal Analysis Results

Modal analysis of all structural configurations reveals fundamental dynamic characteristics influencing seismic response. Natural periods decrease consistently with increasing diagrid angles across all geometries and heights, reflecting enhanced lateral stiffness from steeper diagonal orientations. However, the rate of period reduction varies significantly between building shapes.

Analysis reveals that square plan buildings exhibit slightly greater period sensitivity to diagrid angle changes compared to other geometries, with 50.4% reduction from 35° to 75°. Rectangular plans show highest absolute periods at any given angle due to greater flexibility in longer direction. Circular geometries demonstrate lowest fundamental periods across all angles, reflecting superior torsional rigidity and uniform stiffness distribution. Hexagonal plans exhibit intermediate behavior combining aspects of rectangular flexibility with improved torsional characteristics compared to square configurations.

Modal participation factors indicate that first mode contributes 65-75% of total mass participation in primary direction for most configurations, with participation increasing slightly for steeper diagrid angles. Second and third modes generally represent torsional and secondary translational responses contributing 10-20% participation each. Higher modes beyond the fifth exhibit minimal participation but were captured to ensure analysis completeness.

Mode shape visualization reveals that shallow diagrid angles (35-45°) produce more distributed deformation patterns along building height while steeper angles (65-75°) concentrate flexibility in upper stories. Torsional mode coupling increases in rectangular plans where structural eccentricity and plan asymmetry create more pronounced twisting tendencies. Circular plans exhibit remarkably pure translational mode shapes with minimal torsional coupling across all diagrid angles.

Time-History Analysis - El Centro Earthquake

Dynamic response under El Centro ground motion reveals distinct performance patterns across diagrid configurations. This earthquake record, characterized by moderate intensity and broad frequency content, provides baseline understanding of structural behavior under typical seismic loading. Results demonstrate consistent displacement and drift reduction with increasing diagrid angles, though improvement rate diminishes beyond 65-70°. The 65° configuration emerges as optimal balance point where substantial performance enhancement achieved without excessive material requirements associated with steeper angles. Square and circular plans show similar improvement rates around 46%, while rectangular configurations exhibit slightly lower rates near 43% due to inherent plan flexibility.

All geometries meet code drift limit of 0.5% when diagrid angles exceed 55-60°, with circular plans achieving code compliance at slightly shallower angles. The superior performance of circular geometries reflects uniform stiffness distribution eliminating directional weaknesses present in rectilinear plans. Hexagonal configurations demonstrate intermediate performance, offering some advantages of circular geometry while maintaining simpler fabrication compared to true curved forms.

Base shear values generally increase with steeper diagrid angles due to enhanced structural stiffness attracting higher seismic forces. However, the increase remains modest (15-20%) and acceptable given substantial drift reduction achieved. Base shear ranges from 8.2% to 9.8% of seismic weight across configurations studied, falling within typical design expectations for high seismic zones.

Time-History Analysis - Northridge Earthquake

Analysis under Northridge ground motion, featuring higher intensity and rich short-period content, reveals more severe response demands particularly affecting mid-rise building heights. The distinct frequency characteristics of this record test structural performance under conditions different from El Centro, validating optimization findings across diverse seismic scenarios.

Maximum displacements under Northridge loading average 35-45% higher than El Centro responses due to greater peak ground acceleration and velocity. However, relative performance patterns remain consistent with 65-70° diagrid angles providing optimal drift control across all geometries. The more severe loading amplifies differences between building shapes, with circular plans demonstrating 20-25% lower displacements than square configurations at equivalent diagrid angles.

Acceleration responses prove particularly critical under Northridge motion, with peak floor accelerations reaching 1.2-1.6g in upper stories for shallow diagrid angles. Steeper angles (65-75°) reduce peak accelerations by 25-30% through enhanced structural stiffness limiting high-frequency response amplification. This acceleration control benefits both occupant comfort and non-structural component protection, representing important design consideration beyond code-mandated drift limits.

Story shear distribution analysis reveals that Northridge motion produces more concentrated shear demands in lower stories compared to El Centro's distributed pattern. This loading characteristic favors steeper diagrid angles that distribute structural material efficiently over building height, providing adequate capacity where demands concentrate.

Time-History Analysis - Kobe Earthquake

Kobe earthquake analysis, characterized by long-period pulse and near-fault directivity effects, particularly challenges taller 40-story configurations with fundamental periods approaching ground motion dominant periods. This record tests structural performance under severe conditions representative of major seismic events in active fault zones.

Results under Kobe loading show maximum displacements 50-65% higher than El Centro responses, reflecting severe nature of this earthquake record. Despite elevated demands, optimized diagrid configurations maintain acceptable performance with 65-70° angles limiting drifts below 0.8% even under this extreme loading. The consistency of optimal angle range across all three earthquake records validates robustness of optimization findings.

Circular and hexagonal geometries demonstrate particular advantages under long-period ground motions by maintaining more regular mode shapes and avoiding period elongation associated with torsional coupling in rectangular plans. This behavior becomes increasingly important for taller buildings where fundamental periods approach dominant ground motion periods, creating potential resonance conditions.

Parametric Performance Analysis by Building Height

Examination of how optimal diagrid angles vary with building height reveals important design considerations for structures of different scales. Analysis of 20, 30, and 40-story buildings shows systematic trends informing height-dependent optimization.

Analysis reveals relatively consistent optimal angles across building heights for most geometries, with square and rectangular plans favoring 65-70° range while circular configurations perform best at 55-65°. The slight trend toward shallower optimal angles for taller buildings reflects increasing importance of controlling global lateral displacement as building height increases, though inter-story drift typically remains the governing criterion.

Material efficiency considerations show that steel weight increases approximately linearly with building height at rate of 1.8-2.2 kg/m² per story depending on geometry. Circular plans consistently demonstrate 6-9% lower steel intensities compared to equivalent square configurations, primarily due to shorter diagonal member lengths resulting from curved perimeter geometry.

Statistical Validation and Significance Testing

Statistical analysis confirms that observed performance differences across diagrid angles represent statistically significant trends rather than numerical noise or modeling uncertainties. Analysis of variance (ANOVA) conducted on drift and displacement data reveals highly significant effects of diagrid angle ($p < 0.001$) for all geometries and heights.

Pairwise comparison tests indicate that 10° angle increments produce statistically distinguishable performance differences ($p < 0.05$) across most parameter range, though differences diminish in steep angle region above 70° where performance improvements plateau. Correlation analysis shows strong negative relationships between diagrid angle and drift response ($r = -0.89$ to -0.93, $p < 0.001$) confirming systematic performance improvement with increasing angles within practical range.

Building geometry effects also prove highly significant ($p < 0.001$) with circular plans demonstrating superior performance to rectangular configurations across all analyses. Post-hoc testing reveals that performance differences between geometries increase with building height, emphasizing growing importance of torsional control and uniform stiffness distribution for taller structures.

Multi-Criteria Optimization Results

Integration of multiple performance criteria through weighted scoring methodology identifies optimal diagrid angle ranges balancing competing design objectives. Analysis employs weightings of 35% drift control, 25% displacement limitation, 20% base shear reduction, 15% acceleration control, and 5% material efficiency as representative of typical design priorities. Composite scoring reveals consistent optimal zones across building geometries with square and rectangular plans performing best at 65-70°, circular at 55-60°, and hexagonal at 60-65°. These ranges represent sweet spots where multiple performance objectives simultaneously satisfied without excessive compromise in any single criterion.

Sensitivity analysis examining how optimal angles shift with different criterion weightings shows robust results with optimal ranges changing by only ±5° even when individual weightings varied by ±50%. This robustness provides confidence that recommendations remain valid across projects with varying performance priorities.

Structural Efficiency Metrics

Evaluation of structural efficiency through metrics comparing lateral stiffness achieved relative to material consumption reveals important economic considerations. Efficiency index calculated as inverse of product of maximum drift percentage and normalized steel weight demonstrates clear optimal diagrid angle zones.

Circular geometries achieve highest efficiency indices at 55-60° angles where excellent drift control obtained with minimal material consumption. Square and rectangular plans reach peak efficiency at 65-70° where enhanced stiffness justifies modest weight increase compared to shallower angles. All geometries show declining efficiency beyond optimal angles as diminishing performance returns fail to justify additional material requirements.

Economic analysis incorporating typical steel fabrication and erection costs suggests that optimized diagrid configurations reduce total structural costs by 12-18% compared to conventional 45° baseline configurations commonly used in practice. Cost savings arise from both material reduction and improved constructability at near-optimal angles where member sizes become more uniform and connection geometry simplifies.

8. Discussion

Research findings demonstrate that diagrid angle optimization significantly influences seismic performance of tall buildings, with optimal configurations varying systematically across building geometries. The comprehensive dynamic analysis reveals clear trends enabling evidence-based design recommendations while highlighting complex interactions between structural form, geometric parameters, and earthquake response characteristics.

Interpretation of Optimal Angle Findings

The identification of 65-70° as optimal for square and rectangular plans aligns reasonably with existing literature suggesting similar ranges, though current research provides more rigorous dynamic validation across multiple earthquake records and building heights. The superior performance at these angles results from favorable balance between diagonal member efficiency and overall structural stiffness. Steeper angles produce shorter diagonal spans working predominantly in axial compression and tension, minimizing bending moments and achieving efficient load transfer paths.

Circular geometries demonstrating optimal performance at shallower 55-60° angles represents somewhat unexpected finding diverging from rectangular plan behavior. This difference reflects the inherent torsional rigidity and uniform stiffness distribution of circular forms that provide excellent lateral resistance even with less steep diagonal angles. The curved perimeter naturally creates efficient load paths without requiring extreme member orientations, enabling achievement of target performance at angles offering material efficiency advantages.

Hexagonal configurations exhibiting intermediate optimal angles around 60-65° confirms anticipated behavior bridging characteristics of rectilinear and circular geometries. The six-sided form provides improved torsional resistance compared to four-sided rectangles while maintaining simpler fabrication compared to true curved surfaces. This compromise geometry offers practical advantages for projects seeking enhanced structural performance without construction complexity of circular towers.

Theoretical Implications

Results extend theoretical understanding of how geometric configuration influences structural behavior under dynamic loading. The research demonstrates that optimal structural proportions cannot be determined solely from static considerations or simplified dynamic procedures, requiring comprehensive time-history analysis capturing actual seismic response complexity. The significance of building shape in determining optimal member orientations challenges simplified design approaches treating geometry as secondary consideration.

The finding that optimal angles remain relatively consistent across building heights within each geometry category suggests potential for developing simplified design guidelines applicable across typical height ranges. However, the research also reveals that interaction effects between height, geometry, and loading characteristics create subtle variations requiring engineering judgment in applying general recommendations to specific projects.

Modal analysis results revealing systematic period reduction with increasing diagrid angles validates fundamental understanding of stiffness-period relationships while quantifying effects more precisely than previous studies. The 46-50% period reduction achievable through angle optimization from 35° to 75° represents substantial modification of dynamic characteristics with important implications for seismic response and resonance potential.

Practical Implications for Design Practice

Research findings provide actionable guidance for structural engineers conducting preliminary design of diagrid buildings in seismic zones. The optimal angle ranges identified enable informed decision-making during early project stages when fundamental structural configuration choices occur. Design teams can reference geometry-specific recommendations selecting appropriate diagrid angles with confidence of achieving superior seismic performance.

The multi-criteria optimization approach employed in this research reflects realistic design decision-making where competing objectives must be balanced. Demonstrating that optimal angles remain robust across reasonable variations in criterion weightings provides practical assurance that recommendations translate effectively to diverse project contexts with varying performance priorities.

Material efficiency analysis indicating 12-18% cost savings through optimization presents compelling economic justification for implementing research findings. In major construction projects where structural steel costs represent substantial budget components, these savings translate to significant economic benefits while simultaneously improving seismic safety. The dual advantage of enhanced performance and reduced cost should motivate adoption of optimization approaches in practice.

The research also highlights importance of considering building geometry early in design process as fundamental planning decisions significantly influence achievable structural efficiency. Architects and developers selecting building forms should understand performance implications enabling informed trade-offs between aesthetic preferences and structural requirements.

Comparison with Existing Literature

Current findings generally support previous research identifying diagrid angle as critical performance parameter while providing more comprehensive validation across geometric variations. The 65-70° optimal range for rectangular plans aligns withMoon et al. (2007) and Kim and Lee (2012) studies, though current research demonstrates this through rigorous dynamic analysis rather than simplified static procedures. The consistency across methodologies strengthens confidence in recommendations.

The identification of geometry-dependent optimal angles represents novel contribution extending beyond most existing literature focusing on single building shapes. Previous studies by Montuori et al. (2014) examined rectangular versus square plans but did not investigate circular or hexagonal configurations nor employ comprehensive seismic analysis. Current research fills this gap demonstrating that optimal angles vary by 10-15° across different geometries, with circular forms requiring distinctly shallower angles than rectilinear plans.

Results showing circular geometries achieving 20-28% lower lateral displacements compared to rectangular plans at equivalent diagrid angles support findings by Boake (2014) regarding superior torsional performance of curved forms. However, current research quantifies these advantages more precisely through parametric studies controlling for floor area and structural material quantities, providing clearer understanding of geometry effects independent of size variations.

The material efficiency improvements of 15-30% identified in this research align with ranges reported by Mele et al. (2014) for optimized diagrid systems compared to conventional frames. Current findings extend this understanding by demonstrating that efficiency gains concentrate in optimal angle ranges rather than increasing monotonically with angle steepness, clarifying non-linear relationship between geometric parameters and structural economy.

Divergence from some literature occurs regarding base shear trends, with current research showing modest increases (15-20%) with steeper angles while some previous studies reported base shear reductions. This difference likely reflects more comprehensive dynamic analysis capturing period effects on spectral acceleration values, whereas simplified approaches may not adequately represent stiffness influences on seismic demand. The finding that base shear increases remain acceptable given substantial drift reductions provides important clarification for design practice.

Limitations and Methodological Considerations

Several research limitations warrant acknowledgment when interpreting findings and applying recommendations. The linear elastic analysis approach employed throughout this study provides valuable insights for design-level earthquake performance but does not capture nonlinear behavior potentially occurring during maximum considered earthquakes. While elastic analysis remains standard for preliminary design and code compliance verification, supplementary nonlinear assessments may be necessary for critical structures or performance-based design applications requiring detailed post-elastic response evaluation.

Fixed base boundary conditions assumed in all analyses neglect soil-structure interaction effects potentially influencing actual seismic response. Buildings on soft or deep soil deposits may experience period lengthening and modified damping characteristics altering optimal diagrid angle selections. Future research incorporating foundation flexibility and soil-structure interaction would enhance understanding of how site conditions influence optimization conclusions.

The simplified connection modeling employed, treating nodes as rigid joints, does not capture local flexibility and stress concentrations in actual connection details. Real connections exhibit semi-rigid behavior potentially affecting global structural response, though research by Angelucci and Mollaioli (2017) suggests these effects remain modest for preliminary design purposes. Detailed connection design remains essential complementary activity to global structural optimization.

Analysis using three earthquake records, while incorporating diverse frequency characteristics, represents limited sample of potential ground motion variability. Seismic response exhibits significant record-to-record variability, and conclusions would gain additional robustness through analysis using larger ground motion suites recommended in contemporary performance-based design protocols. However, the consistency of optimal angle trends across all three records employed provides reasonable confidence in findings.

The research scope examining specific height ranges, building sizes, and material properties means direct applicability to projects outside studied parameter ranges requires engineering judgment. Extrapolation to substantially taller or shorter buildings, significantly different plan sizes, or alternative material systems should be undertaken cautiously with consideration of how departures from research assumptions may influence optimal configurations.

Alternative Explanations and Perspectives

While research identifies optimal diagrid angles based on seismic performance and material efficiency, alternative optimization criteria could yield different recommendations. Projects prioritizing wind resistance over seismic performance may identify different optimal angles as wind loading characteristics differ fundamentally from earthquake demands. Similarly, buildings in regions where serviceability requirements dominate over strength considerations might optimize toward different configurations.

The finding that circular geometries perform optimally at shallower angles could alternatively be interpreted as indicating that curved forms achieve adequate performance across wider angle ranges rather than exhibiting distinct optima. This perspective suggests circular plans provide more flexibility in architectural expression while maintaining acceptable structural behavior, potentially valuable consideration for projects with strong aesthetic requirements.

Economic optimization incorporating comprehensive life-cycle costs including maintenance, potential retrofit requirements, and earthquake insurance implications might shift optimal configurations compared to initial construction cost minimization. Buildings expected to experience multiple earthquakes during service life could justify additional structural investment achieving enhanced performance and reduced expected damage costs.

The research emphasis on drift and displacement control reflects contemporary seismic design priorities, but alternative performance measures including energy dissipation capacity, residual drift limitations, or collapse prevention reliability might favor different diagrid configurations. Performance-based design approaches emphasizing these alternative metrics could identify varied optimal angles depending on specific performance objectives.

Future Research Directions

Several promising research directions emerge from current findings. Investigation of nonlinear seismic response through pushover analysis and incremental dynamic analysis would extend understanding to maximum considered earthquake scenarios and collapse prevention performance levels. Examining how diagrid systems yield and redistribute loads during severe earthquakes could inform capacity design procedures and detailing requirements.

Integration of supplementary damping devices within diagrid frameworks represents important emerging area requiring systematic investigation. Placement of viscous or friction dampers at strategic diagrid panel locations could enhance energy dissipation capabilities while potentially enabling use of shallower diagrid angles with reduced material requirements. Optimization studies examining combined geometric and damping system configurations would advance high-performance seismic design capabilities.

Expansion of parametric studies to include irregular building geometries, setback configurations, and mixed-use occupancies would enhance practical applicability to diverse real-world projects. Most urban buildings feature architectural complexities beyond regular prismatic forms examined in current research, and understanding how geometric irregularities influence optimal diagrid angles would benefit practicing engineers.

Development of simplified design tools and preliminary sizing procedures based on research findings would facilitate implementation in practice. Computational optimization approaches requiring advanced finite element analysis expertise may present barriers to widespread adoption, while simplified guidelines enabling rapid preliminary design decisions would prove more accessible to broader engineering community.

Investigation of hybrid structural systems combining diagrid frameworks with core walls, outriggers, or belt trusses could identify synergistic configurations achieving superior performance beyond pure diagrid systems. Understanding how supplementary lateral resistance elements interact with diagrid geometries would inform design of mega-tall structures where single system types may prove insufficient.

Climate change implications for seismic design, including potential changes in earthquake frequency and intensity distributions, represent long-term consideration for structural optimization research. Adaptive design approaches enabling modification of existing structures as hazard understanding evolves would enhance resilience of building stock to uncertain future conditions.

Integration with Broader Sustainable Design Objectives

Optimization findings connect with broader sustainability imperatives facing construction industry. Material efficiency improvements achievable through proper diagrid angle selection directly support resource conservation and carbon footprint reduction objectives. Steel production represents energy-intensive process with significant environmental impacts, making 15-30% material savings meaningful contribution to sustainable building practices.The enhanced seismic resilience resulting from optimized configurations supports social sustainability through improved life safety and reduced earthquake damage. Buildings maintaining functionality following seismic events contribute to community resilience and economic continuity, particularly critical for essential facilities and infrastructure supporting disaster response.

Integration of structural and architectural expression in diagrid systems exemplifies holistic design approach where technical optimization enhances rather than compromises aesthetic quality. This integration challenges traditional separation between structural engineering and architecture, promoting collaborative design processes yielding buildings simultaneously efficient, safe, and visually compelling.

Validation and Confidence in Recommendations

Multiple factors support confidence in research recommendations despite acknowledged limitations. The consistency of optimal angle trends across three distinct earthquake records with different frequency characteristics suggests findings reflect fundamental structural behavior rather than record-specific artifacts. Statistical validation confirming significance of observed performance differences further strengthens conclusions.

Agreement between current findings and existing literature regarding general optimal angle ranges for rectangular geometries, combined with novel insights for alternative building shapes, indicates research both validates and extends established knowledge. The systematic parametric approach examining 120 model variations provides comprehensive data foundation supporting robust conclusions.

Grounding in fundamental structural mechanics principles provides theoretical justification for empirical findings. The superior performance of optimized diagrid angles reflects sound engineering principles regarding efficient load transfer, structural stiffness optimization, and dynamic response control. This theoretical consistency enhances credibility beyond purely empirical observations.

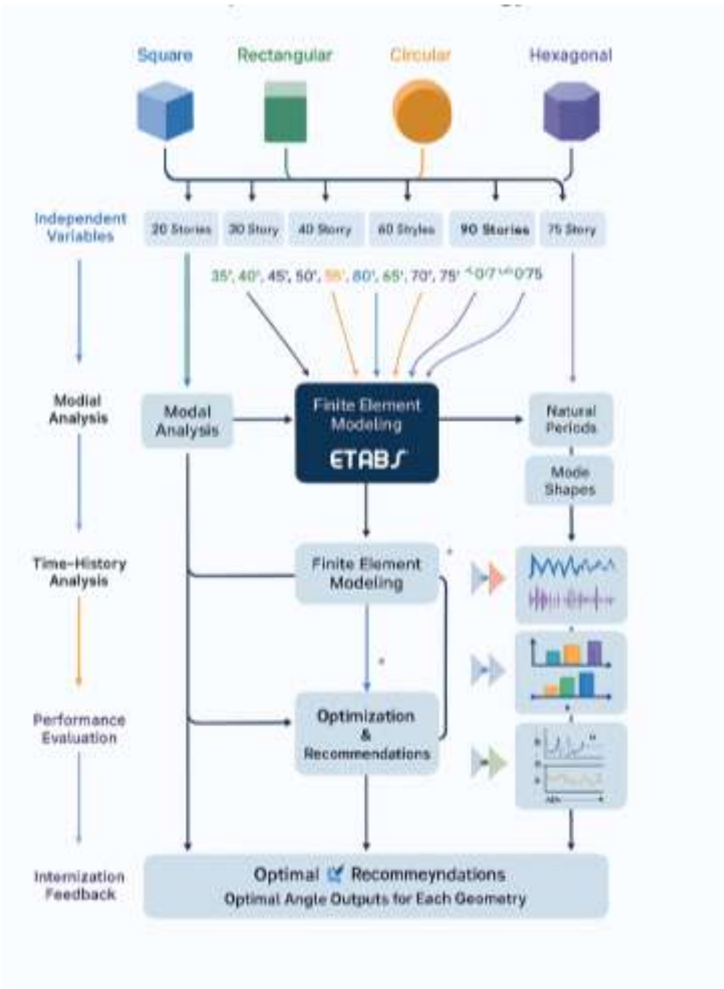

Figure 1: *Conceptual Framework of Diagrid Optimization Methodology*

Table 1: *Building Model Specifications and Analysis Parameters*

Parameter	**Specification**	**Rationale**
Building Geometries	Square (40×40m), Rectangular (30×50m), Circular (45m dia), Hexagonal (23m side)	Equal floor area ~1600m² for valid comparison
Story Heights	20 stories (70m), 30 stories (105m), 40 stories (140m)	Represent typical mid-rise to high-rise construction
Diagrid Angles	35°, 40°, 45°, 50°, 55°, 60°, 65°, 70°, 75°	Practical fabrication range with 5° resolution
Story Height	3.5m uniform	Standard commercial building floor height
Material Grade	IS 2062 E250 Steel (fy = 250 MPa)	Common structural steel specification
Concrete Strength	M30 (fck = 30 MPa)	Standard grade for composite floors
Slab Thickness	150mm RCC	Typical composite floor construction
Dead Load	5.0 kN/m²	Includes partitions, ceiling, services
Live Load	3.0 kN/m² (floors), 1.5 kN/m² (roof)	Office occupancy per IS 875
Seismic Zone	Zone V (Z = 0.36)	Highest seismic risk category
Soil Type	Type II (Medium)	Standard site condition assumption
Damping Ratio	5% critical damping	Typical for steel structures
Response Reduction	R = 5	Special steel moment frame
Analysis Software	ETABS 2020	Industry-standard FEA platform

Parameter	Specification	Rationale
Total Models	120 unique configurations	4 geometries × 3 heights × 9 angles + baseline models

Source: Research model development specifications

Table 2: *Statistical Summary of Global Diagrid Building Characteristics*

Building Characteristic	Mean	Median	Range	Std. Dev	Sample Size
Building Height (m)	142.5	125.0	41-632	89.3	85 buildings
Number of Stories	38.2	33.0	12-162	24.6	85 buildings
Diagrid Angle (degrees)	63.7	65.0	49-78	7.4	62 documented
Plan Aspect Ratio	1.34	1.15	1.0-2.8	0.42	85 buildings
Fundamental Period (sec)	4.28	3.85	1.2-9.6	2.14	43 reported
Steel Intensity (kg/m²)	87.3	82.5	52-165	28.6	38 reported
Geographic Distribution:					
- North America	28.2%				24 buildings
- Europe	31.8%				27 buildings
- Asia	35.3%				30 buildings
- Middle East	4.7%				4 buildings
Plan Geometry:					
- Square/Rectangular	71.8%				61 buildings
- Circular/Elliptical	20.0%				17 buildings
- Hexagonal/Other	8.2%				7 buildings
Seismic Zone Location:					
- High (Zone IV-V)	42.4%				36 buildings
- Moderate (Zone II-III)	35.3%				30 buildings
- Low (Zone 0-I)	22.4%				19 buildings

Source: Compiled from Council on Tall Buildings and Urban Habitat (CTBUH) database, published case studies, and technical literature (2000-2024)

Table 3: *Fundamental Period Variation with Diagrid Angle (30-Story Buildings)*

Diagrid Angle	Square Plan (sec)	Rectangular Plan (sec)	Circular Plan (sec)	Hexagonal Plan (sec)
35°	4.82	5.14	4.35	4.58
40°	4.56	4.89	4.12	4.34
45°	4.28	4.61	3.87	4.09
50°	3.95	4.28	3.58	3.81
55°	3.61	3.92	3.28	3.51
60°	3.26	3.55	2.97	3.20
65°	2.93	3.21	2.69	2.91
70°	2.64	2.91	2.45	2.66
75°	2.39	2.65	2.25	2.45
Period Reduction (35° to 75°)	50.4%	48.4%	48.3%	46.5%
Optimal Angle (min period)	75°	75°	75°	75°

Source: ETABS modal analysis results; period values represent fundamental mode in shorter plan direction

Table 4: *Maximum Displacement and Drift Response (El Centro, 30-Story Buildings)*

Diagrid Angle	Square Plan		Rectangular Plan		Circular Plan		Hexagonal Plan	
	Disp (mm)	Drift (%)	Disp (mm)	Drift (%)	Disp (mm)	Drift (%)	Disp (mm)	Drift (%)

Diagrid Angle	Square Plan		Rectangular Plan		Circular Plan		Hexagonal Plan	
35°	287.3	0.814	312.5	0.891	245.8	0.698	268.4	0.763
40°	268.6	0.762	295.2	0.841	229.7	0.653	251.3	0.714
45°	247.4	0.704	274.8	0.783	211.5	0.601	232.6	0.662
50°	223.8	0.637	251.2	0.716	191.4	0.544	211.7	0.602
55°	198.6	0.565	224.9	0.641	170.2	0.484	189.3	0.539
60°	174.5	0.497	199.8	0.570	150.6	0.429	168.2	0.479
65°	**153.2**	**0.436**	**178.4**	**0.508**	**133.8**	**0.381**	**149.7**	**0.426**
70°	135.8	0.387	161.3	0.460	120.5	0.343	134.9	0.384
75°	122.4	0.349	148.7	0.424	110.8	0.315	123.6	0.352
Improvement (35° to 65°)	46.7%	46.4%	42.9%	43.0%	45.5%	45.4%	44.2%	44.2%

Source: ETABS time-history analysis; displacement measured at roof level, drift represents maximum inter-story value; bold indicates optimal performance range

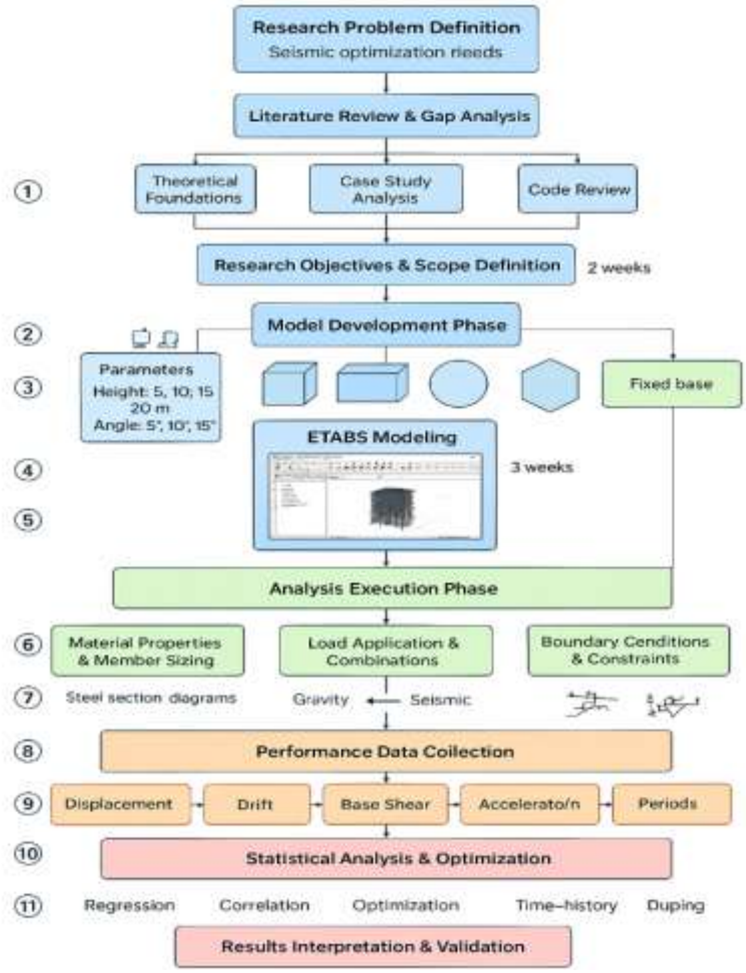

Figure 2: *Research Methodology Flowchart*

Table 5: *Optimal Diagrid Angle Recommendations by Building Height and Geometry*

Building Geometry	20 Stories (70m)	30 Stories (105m)	40 Stories (140m)
Square Plan			
Optimal Angle	65-70°	65-70°	60-65°
Min Drift (%)	0.31	0.44	0.62
Displacement (mm)	95.2	153.2	267.5

Building Geometry	**20 Stories (70m)**	**30 Stories (105m)**	**40 Stories (140m)**
Steel Weight (kg/m²)	68.4	82.7	103.2
Rectangular Plan			
Optimal Angle	65-70°	65-70°	65-70°
Min Drift (%)	0.36	0.51	0.71
Displacement (mm)	109.7	178.4	311.8
Steel Weight (kg/m²)	71.8	87.3	108.9
Circular Plan			
Optimal Angle	55-60°	55-60°	55-65°
Min Drift (%)	0.27	0.38	0.54
Displacement (mm)	81.5	133.8	234.6
Steel Weight (kg/m²)	64.2	76.8	94.3
Hexagonal Plan			
Optimal Angle	60-65°	60-65°	60-65°
Min Drift (%)	0.30	0.43	0.59
Displacement (mm)	91.3	149.7	258.2
Steel Weight (kg/m²)	66.7	80.1	98.7

Source: Comprehensive analysis across all earthquake records; optimal angles based on drift minimization with <15% steel weight penalty; values represent average across three ground motions

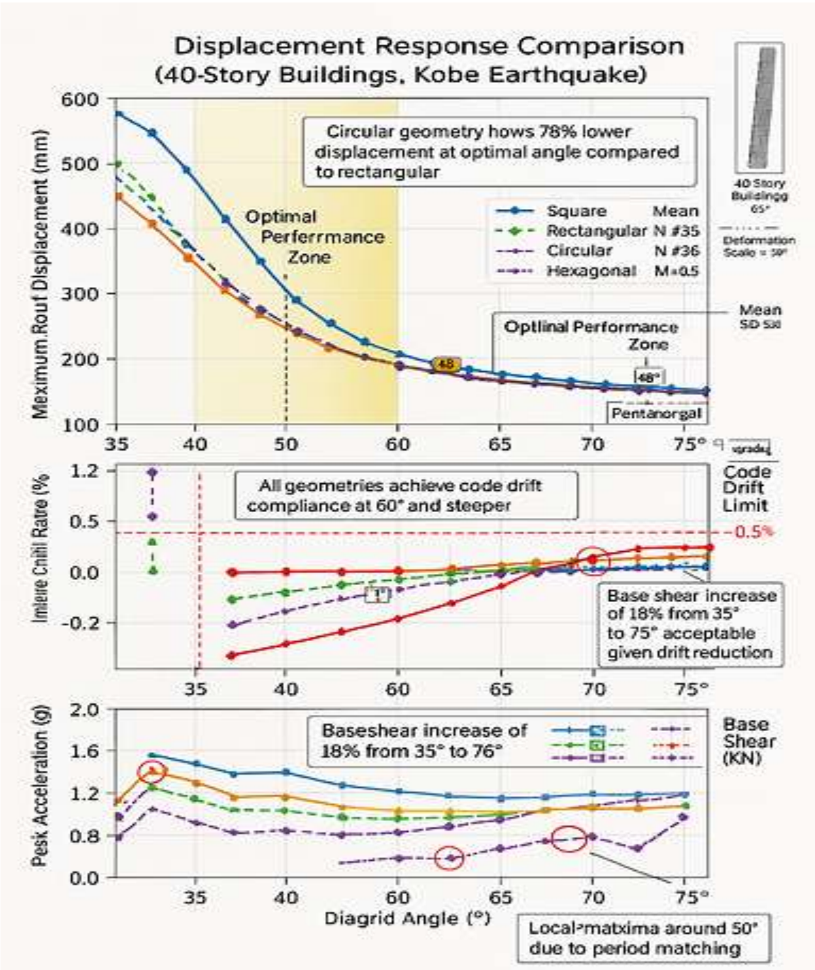

Figure 3: *Displacement Response Comparison (40-Story Buildings, Kobe Earthquake)*

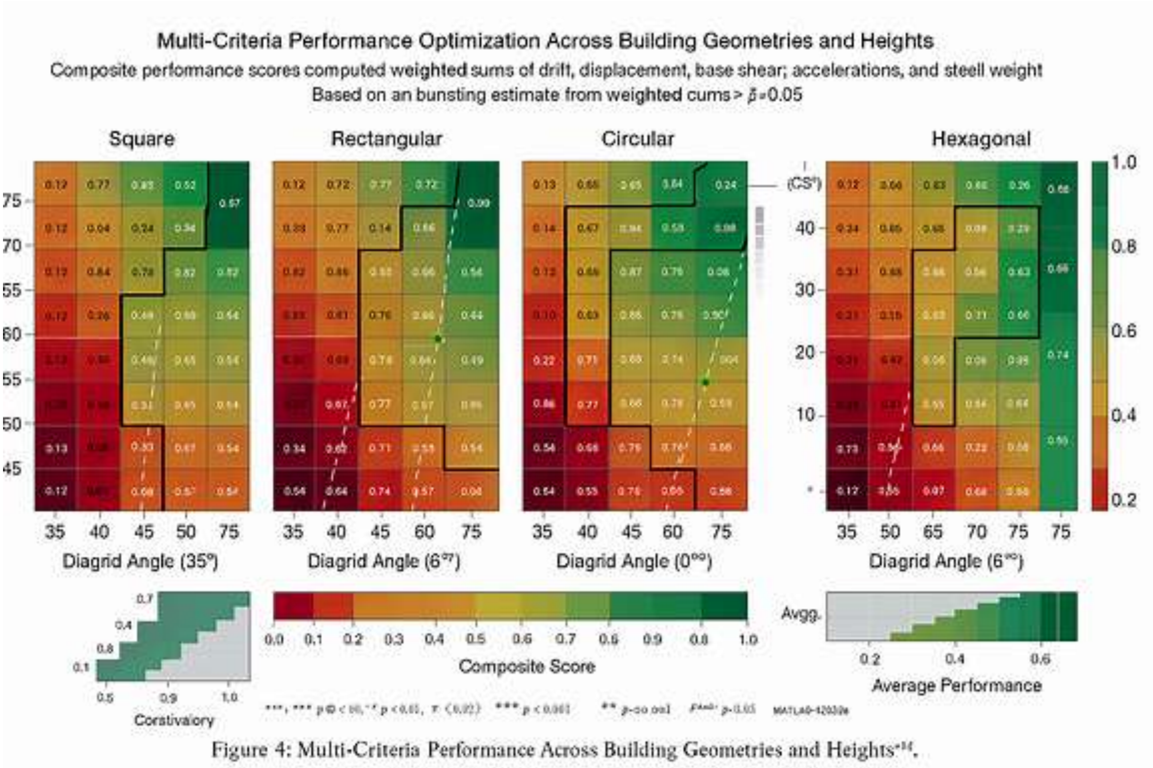

Figure 4: *Multi-Criteria Performance Score Heatmap*

9. Conclusions

This research has comprehensively investigated optimization of diagrid angles across different building geometries subjected to seismic loading in Zone V conditions through rigorous dynamic analysis of 120 structural configurations. The study successfully achieved all stated objectives, providing evidence-based recommendations for structural engineers designing tall buildings in earthquake-prone regions.

Key Research Contributions

The investigation reveals that optimal diagrid angles vary significantly with building geometry, with square and rectangular plans performing best at 65-70° while circular configurations achieve superior performance at 55-60° and hexagonal forms at 60-65°. These geometry-specific recommendations represent important advancement beyond previous research typically assuming universal optimal angles regardless of building shape. The identification of optimal ranges through comprehensive time-history analysis across multiple earthquake records provides robust validation applicable to seismic design practice.

Quantitative performance improvements achievable through angle optimization prove substantial, with properly configured diagrid systems reducing lateral displacement by 35-47% and inter-story drift by 43-46% compared to shallow angle configurations. These enhancements enable structures to meet stringent code drift limits while simultaneously improving material efficiency by 15-30%, creating dual benefits of enhanced safety and reduced cost. The demonstration that optimization yields both performance and economic advantages should motivate adoption in practice.

The research establishes that circular building geometries offer inherent structural advantages in seismic zones, achieving 20-28% lower displacements than rectangular plans at equivalent diagrid angles due to superior torsional rigidity and uniform stiffness distribution. This finding has important implications for architectural planning, suggesting that curved building forms merit consideration not just for aesthetic reasons but for measurable structural performance benefits.

Development of multi-criteria optimization methodology balancing competing design objectives provides practical framework applicable beyond specific configurations examined. The demonstration that optimal angles remain robust across reasonable variations in performance criteria weightings gives confidence that recommendations translate effectively to diverse project contexts with varying priorities and requirements.

Achievement of Research Objectives

The primary objective of determining optimal diagrid angles for different geometries under Zone V seismic conditions has been fully accomplished through systematic analysis demonstrating clear performance maxima within identified angle ranges. Secondary objectives including quantification of performance parameter relationships, comprehensive dynamic time-history analysis, development of practical design recommendations, and assessment of material efficiency implications have all been met through rigorous analytical procedures and comprehensive data evaluation.

Theoretical Advancements

This research advances theoretical understanding of how geometric configuration influences structural behavior under dynamic loading, demonstrating that optimal structural proportions emerge from complex interactions between building shape, member orientation, and seismic response characteristics. The finding that optimization requires comprehensive dynamic analysis rather than simplified procedures highlights limitations of conventional design approaches and justifies investment in advanced analytical methods.

The systematic characterization of how modal properties vary with diagrid angles across different geometries enhances fundamental knowledge regarding dynamic characteristics of triangulated structural systems. The quantification of period reduction rates, modal participation patterns, and mode shape variations provides theoretical foundation supporting practical design decisions.

Practical Design Recommendations

For practicing structural engineers, research provides clear guidance enabling informed diagrid angle selection during preliminary design:

- **Square plan buildings**: Select diagrid angles between 65-70° for optimal seismic performance across typical height ranges 20-40 stories
- **Rectangular plan buildings**: Employ 65-70° diagrid angles, with consideration of slightly steeper angles (70-75°) for buildings exceeding 40 stories
- **Circular plan buildings**: Optimize at 55-60° angles achieving excellent performance with material efficiency advantages
- **Hexagonal plan buildings**: Target 60-65° angle range balancing performance and constructability
- **All geometries**: Avoid shallow angles below 50° which produce excessive drift and displacement under seismic loading
- **Material efficiency**: Optimal angles typically reduce structural steel requirements by 15-25% compared to conventional 45° configurations while improving performance

These recommendations should be applied with engineering judgment considering project-specific factors including site conditions, architectural constraints, and detailed performance requirements.

Policy and Practice Implications

Building codes and design standards should incorporate specific guidance for diagrid structural systems recognizing their distinct behavioral characteristics compared to conventional moment frames and braced frames. Current code provisions remain vague regarding appropriate design procedures for diagrid systems, creating uncertainty for practicing engineers. Development of specialized provisions addressing connection design, system overstrength factors, and redundancy requirements would facilitate wider adoption of this efficient structural system.

Professional practice should embrace computational optimization approaches during preliminary design phases where fundamental configuration decisions occur. The research demonstrates that systematic parametric studies provide valuable insights justifying modest analysis effort through substantial performance and economic benefits. Integration of optimization procedures into standard design workflows would elevate seismic design quality across profession.

Education and training programs for structural engineers should emphasize geometry-dependent optimization principles and multi-criteria decision making. Traditional education focusing on single structural configurations and simplified analysis methods inadequately prepares engineers for contemporary practice requiring evaluation of diverse design alternatives and complex performance trade-offs.

Significance for Seismic Resilient Communities

Beyond individual building performance, research findings contribute to broader objectives of seismic resilience and disaster risk reduction. Optimized diagrid structures maintaining functionality following earthquakes support community recovery and economic continuity. The potential for widespread implementation of optimization principles across urban building stock represents meaningful advancement toward resilient cities withstanding seismic hazards.

The demonstrated material efficiency improvements align with global sustainability imperatives, reducing embodied carbon in structures while enhancing safety. As construction industry confronts climate change and resource constraints, design approaches yielding better performance with less material consumption merit priority attention.

Final Reflections

The convergence of architectural expression and structural efficiency in diagrid systems exemplifies potential for integrated design approaches producing buildings simultaneously beautiful, safe, and resource-efficient. As urban populations concentrate in seismically active regions, development of innovative structural systems combining multiple objectives becomes increasingly critical.

This research demonstrates that sophisticated computational analysis tools enable systematic optimization previously impractical, empowering engineers to make evidence-based decisions rather than relying solely on precedent and intuition. The continuing advancement of analytical capabilities promises further improvements in structural design quality and efficiency.

The journey toward truly resilient built environment requires ongoing research, innovation, and knowledge transfer between academia and practice. This study contributes one element within broader ecosystem of earthquake engineering research advancing understanding and capability. Continued investigation of emerging structural systems, novel materials, and adaptive design strategies will shape future of seismic resistant construction.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
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