

Lateral Load Resisting Systems in Tall Buildings: A Comprehensive Review with Emphasis on Diagrid and Hexagrid Structural Configurations

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Abstract - The relentless vertical growth of urban skylines has made the selection of an appropriate lateral load resisting system one of the most consequential decisions in the structural design of tall buildings. Wind pressure and seismic ground motion introduce overturning moments, storey drifts, and floor accelerations that, beyond a certain height threshold, govern structural material consumption far more decisively than gravity loading. Classical interior systems such as moment frames, braced cores, and shear wall-frame combinations served the industry adequately through the mid-twentieth century, but the emergence of exterior tube-type systems and, subsequently, of geometry-driven perimeter grids has transformed contemporary high-rise practice. This paper presents a structured and critical review of the evolution of lateral load resisting systems, from the pioneering rigid frame and shear wall concepts of Fazlur Khan through to the tube-in-tube, bundled-tube, diagrid, and hexagrid configurations that now define the frontier of tall building structural engineering. Special attention is directed toward the diagrid system, whose triangulated perimeter members carry both gravity and lateral forces through axial action, and the hexagrid system, whose honeycomb geometry offers architecturally richer facades, higher ductility sensitivity, and compelling prospects for supertall construction. Parametric studies on diagonal member inclination, module height, material choice, and plan geometry are synthesised from over thirty-five peer-reviewed sources indexed in Scopus, Web of Science, and ASCE databases. The review identifies the continued absence of a unified design standard for these geometry-based systems in the Indian subcontinent, suggests avenues for future investigation including machine-learning-assisted optimal pattern selection and hybrid diagrid-outrigger configurations, and proposes a comparative performance index framework that could underpin next-generation design guidelines.

Keywords: lateral load resisting systems; diagrid; hexagrid; tall buildings; wind load; seismic performance; tube structures; structural optimisation; storey drift; IS 800:2007

1. INTRODUCTION

Urbanisation at an unprecedented pace, combined with the scarcity and rising cost of developable land in metropolitan centres, has made vertical construction an inescapable response to the demands of the twenty-first century. Tall buildings are no longer simply engineering artefacts; they represent the intersection of architectural ambition, structural ingenuity, and civic identity. Yet every metre of additional height carries a disproportionately large structural penalty. The overturning moment at the base of a cantilever column grows with the square of its height under uniform lateral pressure; floor accelerations perceived by occupants worsen as fundamental periods lengthen; and material consumption climbs steeply unless structurally efficient systems are deployed.

The lateral loads imposed by wind and seismic excitation have historically been the controlling design criterion for any building slender enough that its height-to-width ratio exceeds approximately five. This threshold was well understood by the early twentieth-century designers of Chicago and New York steel frames, and it drove the systematic development of progressively more efficient lateral load resisting strategies throughout the decades that followed. Fazlur Khan of Skidmore, Owings and Merrill articulated the now-canonical "structural systems for tall buildings" framework in the 1970s, classifying systems by their economical height ranges and thereby equipping the profession with a language for discussing structural efficiency at the building scale.

The subsequent decades witnessed the proliferation of tubular concepts, outrigger-braced cores, and bundled tubes, each addressing the shear lag deficiency of its predecessor. By the early 2000s, structural designers began exploiting the entire building envelope as a load-carrying skin, giving rise to the diagrid, a system in which closely spaced perimeter diagonals eliminate the need for vertical exterior columns while redistributing both gravity and lateral forces entirely through axial member action. The diagrid found its first iconic large-scale application in the Swiss Re Building in London (2003) and the CCTV Headquarters in Beijing (2008), and it has since been adopted for dozens of supertall projects worldwide.

The hexagrid, introduced formally in the structural engineering literature by Mashhadiali and Kheyroddin in 2012, represents a logical evolution of the diagrid concept. By replacing the triangulated diamond module with a honeycomb hexagonal module, the system achieves a more uniform stress distribution, greater ductility sensitivity, and a markedly different architectural character. Research into hexagrid structural behaviour has grown steadily since its introduction, though it remains considerably less developed than the diagrid body of knowledge.

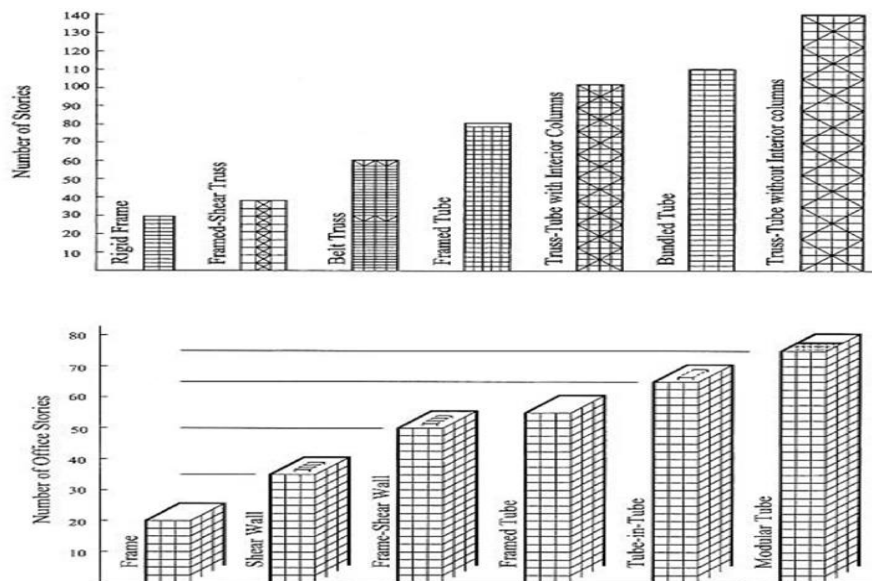


Figure 1: Different Lateral Load resisting Structural Systems by Fazlur Rahman Khan

Despite the considerable volume of research available on these systems internationally, their adoption within the Indian structural engineering practice has been slow, partly because IS 800:2007 and associated codes do not provide explicit design provisions for geometry-driven perimeter grid systems, and partly because design engineers lack consolidated guidance on optimum diagonal inclinations, module configurations, and hybrid system combinations suitable for the Indian seismic and wind environment. This paper attempts to bridge that gap by synthesising the international literature into a coherent narrative organised around system typology, design methodology, performance under wind and seismic loading, material considerations, and emerging computational optimisation techniques. The review aims to serve both as a scholarly consolidation of existing knowledge and as a practical reference for structural engineers and researchers engaged in the design and study of tall buildings in seismic zones.

2. CLASSIFICATION OF LATERAL LOAD RESISTING SYSTEMS

A rational classification of lateral load resisting systems must acknowledge that no single taxonomy is universally accepted. Systems are variously categorised by their structural typology, by the location of the primary resisting elements relative to the building plan, or by the dominant internal force mechanism. For the purposes of this review, systems are grouped into interior systems, exterior systems, and combined or hybrid systems, following the widely used framework discussed by Ali and Moon and subsequently elaborated by researchers including Mele et al. and Faiella et al.

2.1 Interior Systems

Interior systems resist lateral loads through elements placed within the building footprint, typically at or near its centroid. The moment-resisting frame (MRF), the shear wall, the braced frame, and the core-outrigger arrangement all belong to this family.

2.1.1 Moment-Resisting Frames

The steel and reinforced concrete moment-resisting frame was the dominant lateral system for the first eight decades of tall building construction. Its appeal lies in the complete absence of diagonal members within the structural bay, which maximises architectural planning flexibility and unobstructed facade openings. Beam-column connections are designed to transfer moment, and the frame resists lateral loads through the combined bending resistance of its members. The efficiency of the MRF is nevertheless limited; inter-storey drift accumulates rapidly with height, and the lateral stiffness of a regular MRF diminishes as the fourth power of storey height for an idealised continuum model. Economic application is generally considered viable only below approximately fifteen to twenty storeys, though composite MRF systems incorporating concrete encasement or concrete-filled steel tubes extend this range modestly.

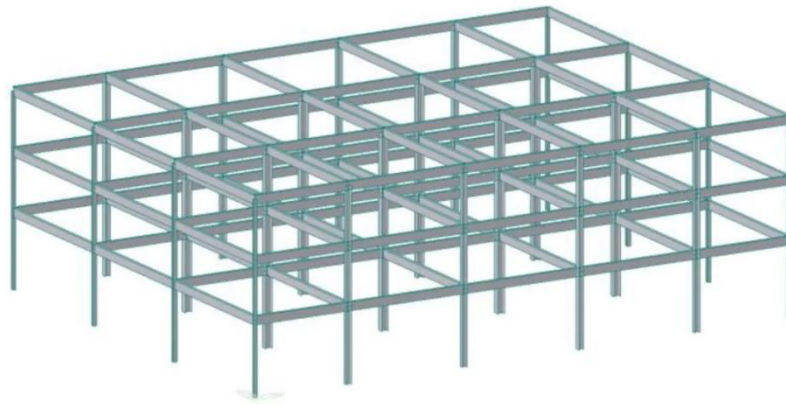


Figure 2: Special moment resisting frame

2.1.2 Shear Wall Systems

Reinforced concrete shear walls offer a substantial step-change in lateral stiffness relative to moment frames because they resist horizontal forces primarily through in-plane shear and flexure over a large effective depth. A study by Krishnan and Sivakumar published in *Materials Today: Proceedings* in 2023 confirmed that the strategic placement and sizing of shear walls has a profound impact on the dynamic stability of both regular and irregular building configurations. When shear walls are coupled by link beams, they develop a coupled-wall action that effectively deepens the resisting cross-section and reduces both overturning moment and lateral deflection. However, shear walls impose planning constraints, are difficult to accommodate in architecturally open facades, and, above approximately fifty to sixty storeys in pure form, require cross-sections that consume excessive rentable floor area.

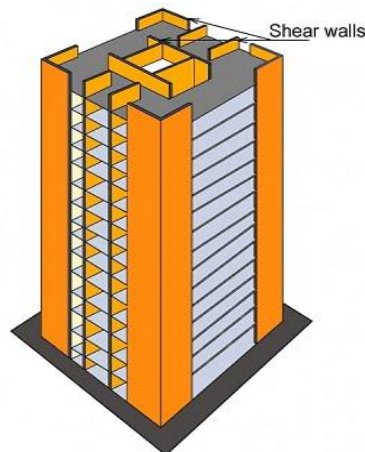


Figure 3: Special moment resisting frame

2.1.3 Braced Frame Systems

Concentrically and eccentrically braced frames transfer lateral forces largely through the axial action of diagonal members, rendering them considerably stiffer per unit weight of steel than moment frames of equivalent bay geometry. Concentrically braced frames (CBF) are characterised by diagonal members whose centrelines intersect at structural nodes, generating a truss action that is highly efficient under wind loads. Eccentrically braced frames (EBF) introduce a deliberately offset "link" element designed to yield in shear under seismic demand, providing ductility without sacrificing the elastic stiffness of the CBF. The research by Sinaga et al. and subsequent work reviewed by Nassani and Ali demonstrated that the storey shear distribution in X-braced, V-braced, and inverted-V-braced configurations differs significantly, with implications for the design of floor diaphragms and foundation systems. A comparative study published in the *Asian Journal of Civil Engineering* in 2024 quantified storey displacement, base shear, and inter-storey drift for eight different lateral resisting configurations on a G+20 building using Indian standard codes, confirming that braced frame systems offer approximately thirty to forty percent reduction in top displacement relative to unbraced moment frames of equivalent column sizing.

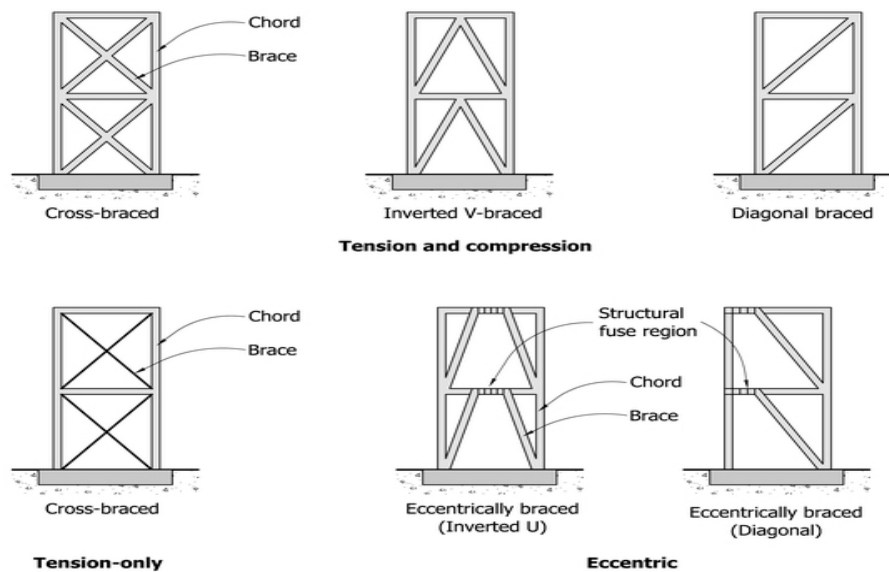


Figure 4: Braced frame system

2.1.4 Core-Outrigger Systems

The core-outrigger system emerged as the dominant structural choice for the building height range between forty and one hundred and twenty storeys during the 1990s and 2000s, partly because it decouples the lateral resisting function from the facade design, allowing architects full freedom over the external envelope. The system consists of a stiff central core, typically a reinforced concrete shear wall box or a braced steel frame, from which stiff outrigger trusses or walls extend at one or more levels to engage perimeter mega-columns. When the building deflects under lateral load, the outriggers impose a restoring couple between the core and the perimeter columns, reducing both core base moment and top drift. A study by Rao, Remakanth, and Karve published in 2023 demonstrated across six different building heights that outrigger systems consistently outperform wall-frame systems in controlling inter-storey drift as slenderness increases, and that the optimum outrigger level migrates upward as building height grows. Belt trusses, circumscribing the perimeter at outrigger levels, distribute the outrigger-induced column forces more uniformly around the plan and further reduce differential column shortening, a serviceability concern of particular importance in composite construction. The ScienceDirect publication on the effect of outrigger systems confirmed that triple-outrigger configurations at optimised levels can reduce lateral deflection by up to sixteen percent relative to unbraced core buildings.

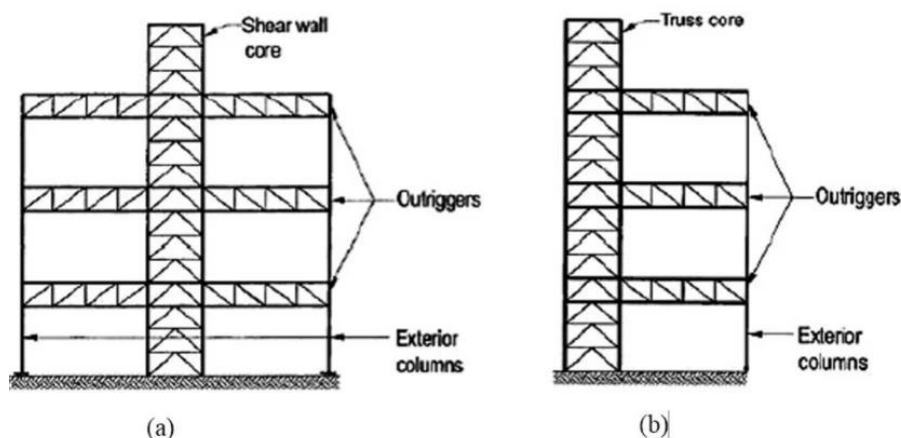


Figure 5: Outrigger system with core (a) in the centre and (b) at one side

2.2 Exterior Systems

Exterior systems exploit the full depth of the building plan by locating the primary lateral resisting elements on the perimeter, engaging the largest possible moment arm to resist overturning. This philosophy was first articulated at the structural scale by Fazlur

Khan through the framed tube concept and subsequently refined through a succession of innovations including the braced tube, the bundled tube, and eventually the diagrid and hexagrid.

2.2.1 Framed Tube Structures

The framed tube, first realised in the 42-storey Dewitt-Chestnut Apartment Building in Chicago in 1965, places closely spaced columns connected by deep spandrel beams around the entire perimeter of the building, creating a hollow perimeter box that resists lateral load as a tube cantilever from the ground. The system mobilises all four facade frames simultaneously, including the two frames parallel to the lateral load direction as flanges in compression and tension. Its principal weakness is shear lag: the in-plane flexibility of the spandrel beams allows the stress in the flange columns to vary parabolically across the plan width rather than remaining uniform as in an ideal thin-walled tube. This shear lag effect reduces the effective width of the tube and penalises the system structurally compared to its theoretical ideal. Numerous analytical and experimental investigations into shear lag in framed tubes were published through the 1980s and 1990s, and the topic remains of research interest; Hafner, Vlastic, and Kisicek in 2021 presented a parametric finite element study that quantified shear lag correction factors for framed tubes of varying width-to-height ratios.

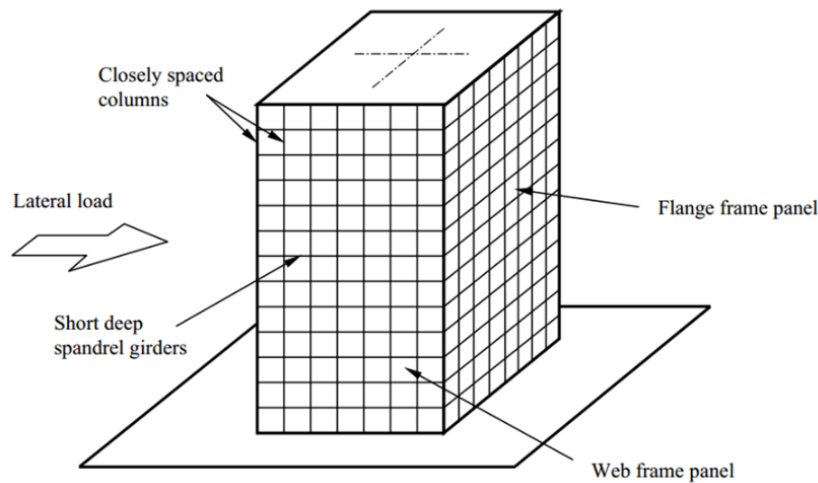


Figure 6: Typical Framed Tube structure

2.2.2 Braced Tube Structures

The braced tube overcomes the shear lag weakness of the framed tube by introducing large-scale diagonal members on the facade, spanning multiple storeys. The diagonals, in combination with the perimeter columns and spandrels, form a triangulated exterior shell that approximates the stress distribution of a true thin-walled tube far more closely than a spandrel-only frame. The 100-storey John Hancock Center in Chicago (1970), designed by Fazlur Khan, is the canonical example; its giant X-bracings span nine storeys and intersect at panel points to which the gravity loads of the facade columns are transferred, largely eliminating the need for internal columns. The structural efficiency of the braced tube is substantially higher than that of the framed tube, and the system remains economically viable well above one hundred storeys when designed in steel.

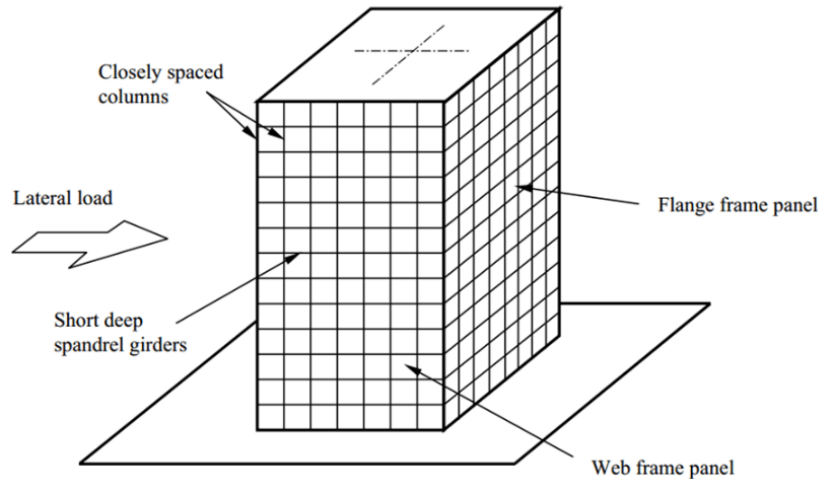


Figure 7: Braced Tube Structure

2.2.3 Bundled Tube Structures

The bundled tube system, exemplified by the 110-storey Willis Tower (formerly Sears Tower, 1974) in Chicago, addresses shear lag at the building scale by grouping several framed tubes together into a bundled cluster, in which internal walls shared between adjacent tubes act as effective diaphragms that suppress the differential shear displacement between interior and exterior columns. The bundled configuration also permits tubes to be terminated at different heights, creating the stacked setback silhouette characteristic of many supertall buildings of the 1970s. The Structural Design of Tall and Special Buildings published several important analyses of bundled tube behaviour during the 1990s; more recent contributions have revisited the concept in the context of composite construction and sustainability.

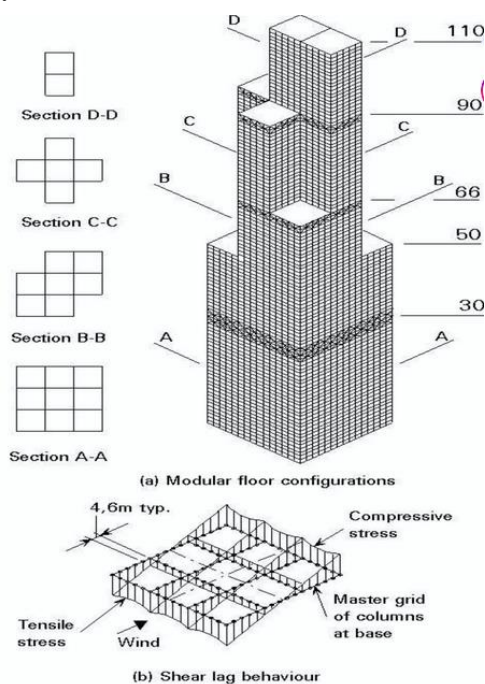


Figure 8: Bundled Tube Structure

2.3 Combined Systems

In practice, most tall buildings above sixty storeys employ hybrid configurations that draw on more than one system typology. Core-outrigger systems with belt trusses are the most common combination, but diagrid facades have been combined with internal shear wall cores, outrigger trusses, and concrete-filled steel tube (CFST) members to produce systems whose overall efficiency exceeds any single-system configuration. Ali and Moon in their comprehensive MDPI review published in July 2022 traced the evolution of

combined systems from the early shear wall-frame interaction models through to the composite mega-structures and mega-subcontrol systems of recent decades, concluding that the boundary between "system types" is increasingly fluid in contemporary supertall design.

3. DIAGRID STRUCTURAL SYSTEM

3.1 Concept and Geometry

The word "diagrid" is a contraction of "diagonal grid," and the system is constituted by a dense triangulated network of inclined members that cover the entire building facade. Unlike a braced tube, in which diagonals are superimposed on a separate frame of columns and beams, the diagrid eliminates vertical exterior columns entirely; all gravity loads and lateral forces are resolved into axial forces in the diagonal members, which then carry these forces to the foundation through triangulated action. The absence of vertical perimeter columns not only reduces the total number of structural elements but also provides architects with unrestricted transparency between the building envelope and the interior, opening possibilities for visually striking facades of the type associated with, for example, the Swiss Re Tower in London and the CCTV Headquarters in Beijing.

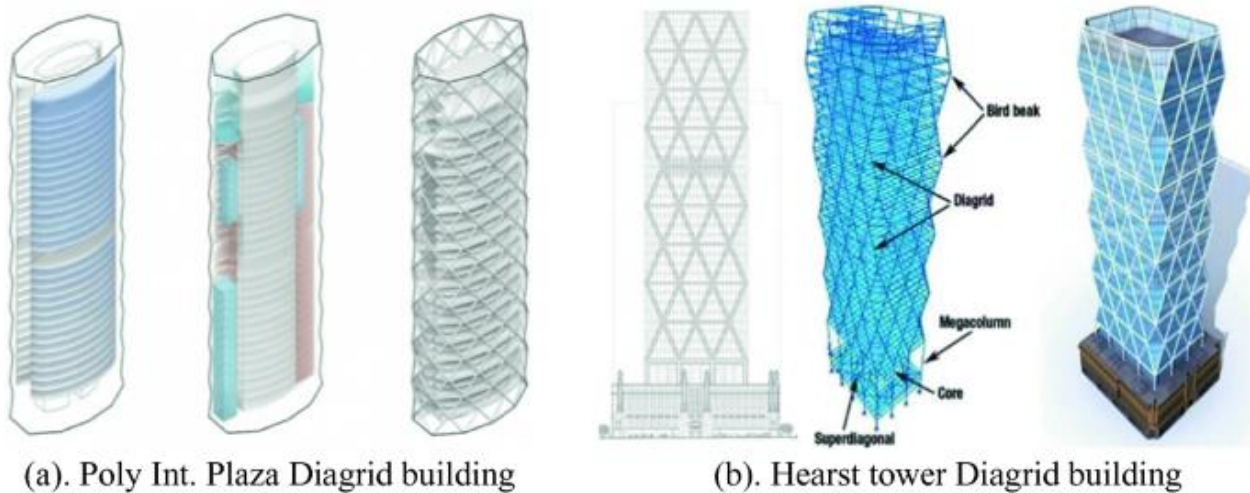


Figure 9: Diagrid Structural System

The geometry of a diagrid module is characterized primarily by the inclination angle of the diagonal members to the horizontal, conventionally denoted θ . The seminal parametric study by Moon, Connor, and Fernandez published in the *Structural Design of Tall and Special Buildings* in 2007 established the stiffness-based design framework for steel diagrids and showed that the optimum diagonal inclination is approximately sixty degrees for buildings in the forty to seventy storey range, where lateral stiffness typically governs, rising modestly toward seventy degrees for shorter buildings whose design may be controlled by gravity load combinations. This finding has been corroborated and refined by numerous subsequent investigations.

3.2 Structural Behaviour

In a diagrid system, the diagonal members forming the triangulated facade panels carry gravity and lateral loads together. Under wind or seismic lateral loading, the windward face of the diagrid experiences net tension in the diagonals, while the leeward face experiences net compression, generating the global overturning resistance in a manner analogous to the flange forces in a beam. Shear is resisted locally within each triangular panel by the axial forces in the crossing diagonals, which is structurally far more efficient than the bending mechanism by which shear is carried in conventional moment-frame or shear wall-frame systems. This dual-mode load-carrying capacity means that the diagrid system simultaneously addresses the two principal design criteria for tall buildings, namely stiffness against sway and resistance to overturning, without the need for any supplementary interior lateral system beyond a central service core.

Jani and Patel in their widely cited analysis of diagrid structural systems for high-rise steel buildings as per Indian Standard codes, published through ASCE proceedings in 2013, confirmed that the consumption of steel in a diagrid building is approximately fifteen to twenty percent lower than in an equivalent moment-resisting frame, owing to the efficient axial utilisation of the diagonal members. The analysis revealed that storey displacement, time period, and inter-storey drift under IS 1893 seismic loads were all substantially reduced relative to the MRF baseline, a finding consistent with the parametric findings of Moon et al.

3.3 Optimum Diagonal Inclination

The choice of diagonal inclination angle is the single most influential geometric parameter in diagrid design. An inclination close to ninety degrees approaches the geometry of a conventional column and loses the triangulated shear-resisting efficiency of the diagrid. An inclination close to zero degrees approaches a horizontal floor beam, also losing diagrid action. Between these extremes, the optimal angle represents a balance between the bending stiffness contribution, which favours lower inclinations producing longer horizontal projections of each diagonal, and the shear stiffness contribution, which favours higher inclinations.

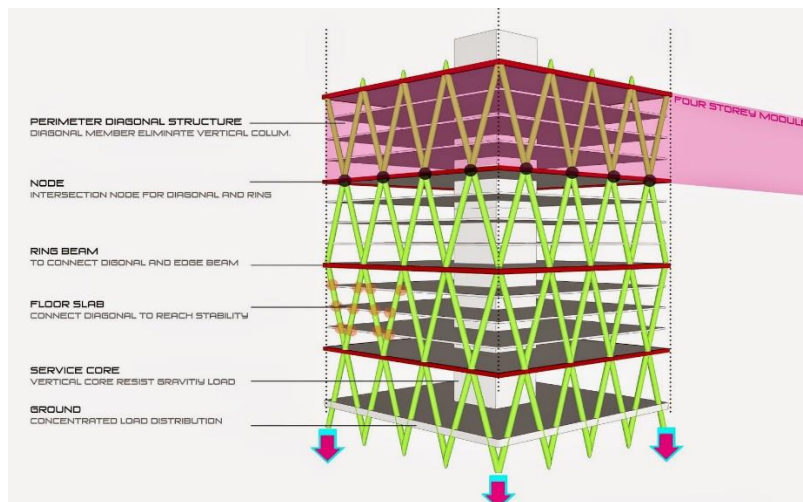


Figure 10: Diagrid Structural System parts

The selection of optimal diagrid patterns was studied in depth by Tomei, Imbimbo, and Mele in Engineering Structures (2018), using a Pareto-front optimisation that simultaneously minimised structural weight and lateral drift. The authors found that uniform-angle geometries with inclinations in the 55 to 65 degree range consistently dominated the Pareto front for buildings between forty and eighty storeys. More recently, Kazemi, Ghisi, and Mariani published a study in 2022 using machine-learning classification to categorise the structural behaviour of 36 parametrically generated diagrid tall buildings, demonstrating that floor plan geometry and diagonal span interact in complex non-linear ways that simple analytical formulae cannot fully capture. The 2022 ScienceDirect paper in the Structures journal by the same group further established that varying-angle diagrids, in which inclination changes with building height to reflect the variation in shear and bending demand up the structure, generally do not outperform uniform-angle geometries when construction complexity is included as a fourth objective in the optimisation.

Shakiba and Heshmatia, in their study of seismic performance assessment of tubular diagrid structures with varying angles in tall steel buildings published in Structures in 2020, evaluated five diagrid buildings with diagonal inclinations ranging from 51 to 76 degrees, subjected to far-field and near-field ground motion records. Their results showed that the 63-degree configuration offered the most balanced performance across displacement ductility, energy dissipation, and residual drift metrics. The 2025 paper by Kazemi, Ghisi, and Mariani in the Structural Design of Tall and Special Buildings extended the parametric investigation to non-prismatic plan forms, finding that tapering the plan area between base and roof significantly alters the critical inclination, with tapered buildings performing best at slightly lower inclinations than prismatic counterparts of equal height.

3.4 Seismic Performance

The seismic performance of diagrid structures has been studied through a range of analytical approaches including equivalent static force method, response spectrum analysis, pushover analysis, and nonlinear time history analysis. Kamath, Divya, and Rao conducted a pushover analysis of a diagrid structure and compared the performance point, plastic hinge formation pattern, and inter-storey drift profile against a conventional MRF, reporting in an Elsevier publication that the diagrid system exhibits a significantly higher base shear capacity and delayed onset of plastic hinge formation due to the distributed nature of its axial yielding mechanism. The study by Mugale and Londhe published in the Journal of Structural Engineering and Management in 2024 employed response spectrum analysis on ETABS for G+3, G+7, and G+11 building models, demonstrating that diagrid systems outperform conventional structures across all three height categories by reducing storey displacement and inter-storey drift by margins of twenty to forty percent, while simultaneously lowering the fundamental period, which reduces seismic base shear in high-period spectral regimes.

Progressive collapse resistance is an additional dimension of diagrid seismic performance that has received growing attention in the wake of post-earthquake reconnaissance findings. A study on the optimum geometry of diagrid systems to resist progressive collapse conducted by Saied and Hazaa employed UFC provisions to impose sudden member removal scenarios at the base, mid-height, and top of the diagrid. The findings indicated that corner diagonal removal at low storey levels produces the lowest robustness index and is therefore the most critical scenario for design; interior column removal similarly triggered progressive collapse in all plan configurations studied.

The seismic performance factors for steel diagrid systems were rigorously quantified by Rofooei and Seyedkazemi in a 2020 Bulletin of Earthquake Engineering study using the FEMA P-695 methodology. Response modification factors, overstrength factors, and deflection amplification factors were extracted from a suite of twenty-two archetype buildings subjected to forty-four far-field ground motion records. The results revealed that the response modification factor for steel diagrid systems is lower than that commonly assumed for special moment frames, a finding with direct implications for the design of diagrid buildings in high-seismicity regions. Padashpour and Mohsenian complemented this work in 2020 by conducting a seismic reliability analysis and estimating multilevel response modification factors for steel diagrid systems, published in the Journal of Building Engineering, concluding that conventional single-value R factors inadequately characterise the probabilistic performance of these systems at the serviceability, life-safety, and collapse-prevention performance levels.

3.5 Wind Performance

Wind loading in tall buildings is characterised by both the mean component, which produces a quasi-static deflection, and the dynamic fluctuating component, which produces accelerations that govern occupant comfort. For diagrid buildings, the aerodynamic response is additionally influenced by the triangulated surface texture of the facade, which modifies the wind pressure coefficients relative to smooth curtain-wall buildings. Abu-Zidan, Mendis, and Gunawardena reviewed the state of the art in wind design of tall buildings in the Electronic Journal of Structural Engineering in 2022, noting that geometry-driven facades such as diagrids introduce local pressure concentration at nodal junctions and require wind tunnel testing for reliable pressure coefficient estimation.

Alizadegan, Ardekani, and Golabchi investigated the effect of plan curvature on diagrid tall buildings subjected to wind loads in a 2024 paper in the Structural Design of Tall and Special Buildings, finding that circular and elliptical plan forms reduce wind-induced lateral displacement by twelve to twenty-two percent relative to rectangular plans, with the diagrid module geometry interacting with plan curvature to produce response variations that require explicit aerodynamic assessment. The 2022 ScienceDirect paper on the selection of optimal diagrid patterns within a multi-response framework employed a desirability function approach to simultaneously minimise wind-induced lateral displacement, torsional rotation, structural weight, and construction complexity, confirming that a 60-degree diagonal inclination in a uniform-angle pattern represents the best compromise across all four objectives for a range of building heights from thirty to ninety storeys.

3.6 Material Aspects and CFST Diagrids

The original diagrid concept was developed and applied predominantly in structural steel, but the growing preference for concrete-encased and concrete-filled sections in fire-resistant, high-stiffness applications has motivated considerable research into CFST diagrid systems. Han, Huang, Ji, and Wu conducted early experimental work on the axial behaviour of CFST connections in diagrid structures, establishing that the concrete infill substantially improves the compressive resistance and deformation capacity of diagonal-to-node joints. Liu et al. in their review of CFST diagrid structural behaviour confirmed in 2018 that concrete-filled diagonal members exhibit superior energy dissipation in cyclic loading relative to hollow steel sections, making CFST diagrids particularly appropriate for high-seismicity applications. The analytical study published in Engineering Structures by Chen and colleagues on the stability of slender CFST X-columns under axial compression in 2021 extended this database to slenderness ratios representative of actual supertall diagrid proportions, establishing interaction curves for combined axial-bending loading.

Ying, Shi, and Wang conducted experimental investigations of the seismic performance of CFST joints in diagrid structures, publishing the results in Elsevier Structures in 2021. Cyclic loading tests on six full-scale specimens showed that the joints exhibit stable hysteretic loops without significant strength degradation up to four percent interstorey drift, suggesting that CFST diagrid joints can meet the ductility demands imposed by near-fault ground motions without the need for supplementary energy dissipation devices.

4. HEXAGRID STRUCTURAL SYSTEM

4.1 Origin and Geometric Definition

The hexagrid system was formally introduced to the structural engineering literature by Mashhadiali and Kheyroddin in a 2012 CTBUH conference paper and subsequently developed through a series of journal publications in the Structural Design of Tall and Special Buildings. The system replaces the triangulated diamond module of the diagrid with a hexagonal module, whose geometry mirrors the honeycomb cell geometry exploited by natural organisms for efficient load distribution at minimal material cost. In a hexagonal module, the six edges of each hexagon are oriented at zero, sixty, and one hundred and twenty degrees to the vertical, creating a pattern in which diagonal and horizontal members alternate continuously around the building perimeter without any vertical columns. The result is a facade that is visually denser and more architecturally intricate than the diagrid, offering a distinctive aesthetic quality that has attracted interest from designers seeking to differentiate supertall projects from the now-numerous diagrid buildings.

The stiffness and strength properties of the hexagrid depend on the inclination of the diagonal members, the ratio of horizontal to diagonal member dimensions, and the number of floors spanned by each hexagonal module. Lee and Kim in a ScienceDirect paper published as a Procedia Engineering article in 2017 proposed a stiffness-based preliminary design formula for hexagrid tubular buildings, analysing sixty-storey buildings to extract size-pattern relationships analogous to those Moon et al. established for diagrids.

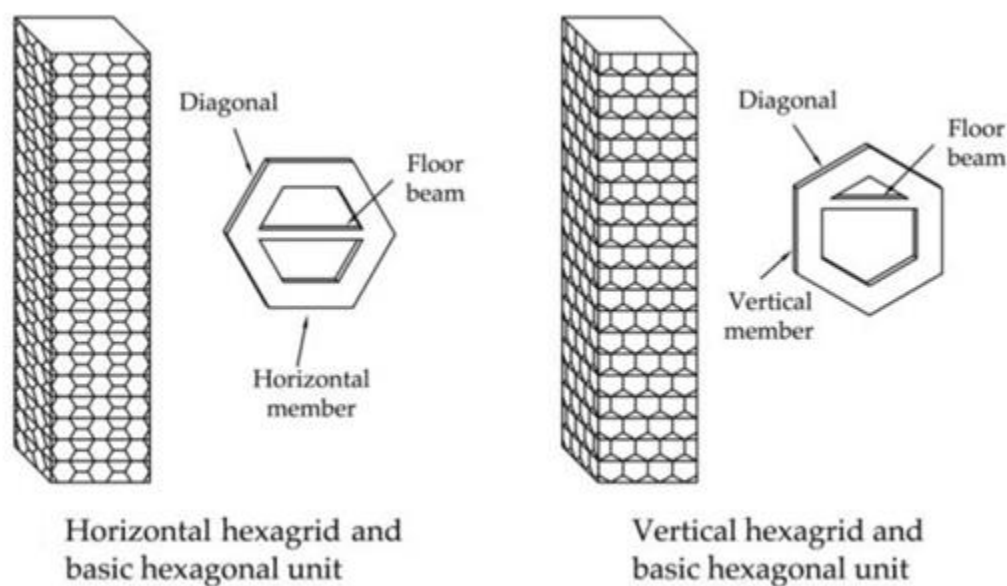


Figure 10: Hexagrid Structural System

4.2 Structural Performance Compared to Diagrid

The comparative structural performance of hexagrid and diagrid systems was rigorously examined in the landmark study by Mashhadiali and Kheyroddin published in the Structural Design of Tall and Special Buildings in 2013. Using strength and stiffness-based design for buildings of 30, 50, 70, and 90 storeys subjected to wind loading, the authors found that the hexagrid system exhibits ductility sensitivity approximately three times that of the diagrid, meaning that small changes in member sizing produce larger changes in system stiffness in the hexagrid, a property that is both a limitation in preliminary design and an asset in optimisation. The hexagrid system also showed lower maximum lateral displacement than the diagrid for the same total structural steel weight in the taller building configurations, suggesting a more favourable stiffness-to-weight ratio at supertall heights.

Mashhadiali and Kheyroddin further conducted nonlinear static and dynamic analyses on a thirty-storey comparison pair in 2014, examining progressive collapse assessment through sudden member removal. The hexagrid system showed superior robustness in that the load redistribution after member loss was more diffuse, reflecting the multiple alternative load paths inherent in the hexagonal topology. However, the lower ductility of the hexagrid relative to the diagrid at comparable member proportions poses a design challenge in high-seismicity zones.

The recent ScienceDirect comparative study on architectural design and structural performance of diagrid and hexagrid systems in high-rise steel buildings, published in 2024, designed three 36-floor, 144-metre steel building models using Turkish seismic code provisions. A 69-degree diagrid model was compared against both a small-module hexagrid (41 degrees) and a large-module hexagrid (60 degrees). The results indicated that both hexagrid configurations produced lower maximum storey displacement and

lower inter-storey drift than the diagrid under equivalent seismic loading, with the large-module hexagrid additionally consuming less steel per unit floor area. The study concluded that the hexagrid system, particularly at larger module sizes, offers compelling advantages in terms of material efficiency, seismic performance, and natural daylighting through its wider structural bays.

4.3 Seismic Assessment of Hexagrid Structures

The seismic performance of hexagrid buildings has been assessed through both linear and nonlinear dynamic analyses. The study published in Earthquake Engineering and Engineering Vibration journal investigating the seismic assessment of the nature-inspired hexagrid lateral load resisting system subjected to near-field ground motions is particularly significant. Two twenty-storey buildings with bundled-tube and hexagrid skeletons were analysed using three-dimensional nonlinear time history analyses with seven three-component near-field ground motion records. The replacement of the bundled tube exterior columns with inclined hexagonal members significantly increased the lateral stiffness of the building, and the distributed nature of nonlinear demand in the hexagrid meant that local nonlinearities concentrated in ring beams rather than in primary columns, a more desirable failure mode from a life-safety perspective.

Mashhadiali and Kheyroddin quantified the seismic performance factors for steel hexagrid structures using the methodology of Journal of Constructional Steel Research (2019). The R factor, ductility-related force modification factor, and overstrength-related force modification factor were derived from incremental dynamic analyses, and the results showed that the hexagrid performance factors are comparable to those of braced tube and diagrid systems, confirming the system as a viable alternative in the seismic design domain.

A study comparing conventional, hexagrid, and octagrid steel structural systems for G+10, G+15, and G+20 buildings in seismic zone V, published in the Journal of Structural Engineering and Management in 2024, employed the response spectrum method and found that the hexagrid configuration consistently demonstrated superior performance in reducing storey drift and storey displacement relative to both the conventional frame and the octagrid alternative. The octagrid system, which uses octagonal perimeter modules, was found to perform intermediately between the hexagrid and the conventional frame, suggesting a general trend in which higher polygon order in the perimeter module correlates with improved lateral performance up to the hexagonal optimum.

Isaac and Ipe conducted a comparative study of hexagrid, diagrid, and octagrid systems under dynamic loading for high-rise buildings, reporting in an IRJET publication that the hexagrid exhibited the best performance in terms of storey displacement and base shear reduction across all building heights considered. The fundamental time period of the hexagrid was found to be shorter than that of the diagrid, which implies higher seismic base shear but lower displacement, a trade-off that must be managed through careful selection of member proportions and damping strategies.

Deepika conducted comparative studies of thirty-storey diagrid and hexagrid structural systems using ETABS in 2021 and 2022, finding that the diagrid exhibited a first-mode time period of 3.268 seconds while the hexagrid recorded 3.69 seconds, a modest difference that nevertheless shifts the location of the two systems on the design response spectrum and affects the seismic demand imposed by the code. The inter-storey drift profile was found to be more uniform over the height in the hexagrid relative to the diagrid, which tends to concentrate drift demand in the lower third of the building.

4.4 Progressive Collapse and Robustness

Mashhadiali and Kheyroddin examined the progressive collapse assessment of the hexagrid structural system in a 2014 publication in the Structural Design of Tall and Special Buildings. Member removal scenarios following UFC guidelines were imposed at the ground, mid-height, and roof levels. The hexagrid exhibited noticeably better redistribution of load after member loss than the diagrid, attributable to the multiple horizontal members in the hexagonal module that provide alternative load paths not present in the purely triangulated diagrid. The authors concluded that the hexagrid offers superior robustness against accidental local failure, a quality of increasing importance as progressive collapse design requirements are codified in building regulations worldwide.

4.5 Evaluation in the Context of Bionic Structures

The conceptual parallel between the hexagrid structural system and the geometry of natural honeycomb structures has inspired a research thread that examines hexagrid performance from a bio-inspired structural optimisation perspective. An analytical study evaluating the new hexagrid structural system in bionic high-rise buildings, comparing tube, diagrid, and hexagrid configurations for 30-storey steel buildings modelled in ABAQUS and SAP2000, found that the hexagrid exhibits higher lateral stiffness than both the tube and diagrid alternatives. However, the plasticity of the hexagrid system was lower than that of the other two systems,

confirming the ductility limitation identified by Mashhadiali and Kheyroddin and suggesting that hexagrid systems are best deployed in moderate-to-low seismicity regions unless supplemented by energy dissipation devices.

The preliminary design study for tall buildings with a hexagrid system published by Lee and Kim through Procedia Engineering in 2017 proposed stiffness-based sizing formulae for hexagrid members analogous to those Moon et al. developed for diagrids, filling an important methodological gap in the hexagrid design toolkit. The formulae express the required moment of inertia of hexagonal members as a function of building height, diagonal inclination, module height, and target drift limit, enabling designers to size members at the schematic stage without recourse to full three-dimensional finite element analysis.

5. COMPARATIVE ANALYSIS OF DIAGRID AND HEXAGRID SYSTEMS

5.1 Structural Efficiency

Both the diagrid and hexagrid derive their lateral efficiency from the concentration of structural material at the building perimeter and the exploitation of axial member action for both gravity and lateral load transfer. The key metric of structural efficiency is the steel weight per unit floor area required to achieve a specified drift limit under code-prescribed lateral loading. Published studies consistently show that both systems require less structural steel than moment-resisting frames, shear wall-frame systems, and framed tubes of comparable height, with savings in the range of fifteen to thirty percent depending on building height, diagonal inclination, and seismic zone. The diagrid tends to be more material-efficient at building heights between thirty and sixty storeys, where the triangulated geometry aligns well with the shear-dominant lateral load pattern, while the hexagrid shows a relative advantage at greater heights where the bending-dominant load pattern favours the wider horizontal members of the hexagonal module.

5.2 Summary Table

Parameter	Diagrid	Hexagrid	Conventional MRF
Lateral mechanism	Axial (diagonal)	Axial (diag + horiz)	Flexure (col + beam)
Optimum inclination	60 to 70 deg	41 to 60 deg	N/A
Column elimination	Yes (exterior)	Yes (exterior)	No
Relative ductility	Moderate	Lower	High
Shear resistance	High (axial)	High (axial)	Low (bending)
Progressive collapse	Moderate	Superior	Moderate
Steel savings vs MRF	15 to 20%	10 to 15%	Baseline
Architectural freedom	Moderate	High	High
Code support (India)	Limited (IS 800)	Absent	Full

Table 1: Comparative attributes of diagrid, hexagrid, and conventional moment-resisting frame systems

5.3 Facade Integration and Architectural Implications

The choice between diagrid and hexagrid is not purely structural; it carries significant architectural consequences. The diamond pattern of the diagrid creates a strong directional visual rhythm that reads clearly at the urban scale and has become associated with a particular brand of high-tech architectural expression. The hexagonal pattern is visually denser, more isotropic, and carries associative references to natural forms that may be more appropriate for certain programmatic or contextual settings. The larger structural bays of the large-module hexagrid admit more daylight per unit facade area than the finer-grained diagrid, an increasingly important sustainability metric. The 2024 ScienceDirect study confirmed that hexagrid buildings exhibit measurably better daylighting performance than diagrid buildings of equivalent dimensions.

5.4 Hybrid Configurations

Hybrid systems that combine a diagrid or hexagrid exterior tube with an internal shear wall core, an outrigger system, or both represent a promising area of current research. Faiella, Argenziano, and Mele published a study in the Open Construction and Building Technology Journal in 2022 on improving the seismic response of tall buildings through the combination of diagrid and

mega-substructure control systems, demonstrating that the addition of viscous dampers at outrigger connections on a diagrid building reduced floor acceleration by approximately twenty percent relative to the pure diagrid configuration. The concept of a diagrid-outrigger hybrid is particularly appealing for buildings in high-seismicity zones, where the diagrid provides elastic stiffness and the outrigger dampers reduce response in the inelastic range. The structural design of hybrid tall buildings: from diagrid to megastructures and mega-subcontrol systems was identified as a major research frontier by Faiella et al., and several research groups are currently developing performance-based design frameworks for such configurations.

6. OTHER ADVANCED LATERAL LOAD RESISTING SYSTEMS

6.1 Tube-in-Tube and Core-Wall Systems

The tube-in-tube system, first employed in the DeWitt-Chestnut building and later developed to greater structural maturity in the late 1960s and 1970s, places a framed inner tube (typically formed by the elevator and service core walls) concentrically within an outer framed tube. The two tubes act in parallel to resist lateral load, with the inner tube carrying a greater proportion of shear and the outer tube carrying a greater proportion of overturning moment. The system is efficient in combined wind and seismic loading because the inner tube provides damping through hysteretic action in its link beams while the outer tube maintains global stiffness. The seismic performance of a G+20 building with a concrete core wall lateral resisting system was evaluated and compared to diagrid, braced frame, and shear wall configurations in the 2024 Asian Journal of Civil Engineering study, confirming that core wall buildings achieve substantially lower drift than unbraced frames but cannot match the combined stiffness-ductility balance of well-designed diagrid or hexagrid configurations.

6.2 Super Frame and Mega-Frame Systems

The super frame system, sometimes also called the mega-frame, organises the primary lateral resisting structure at the macro-scale of the building by creating a small number of very large composite columns at the building corners, connected by equally large belt trusses or deep transfer beams at mechanical floor levels. Between mega-floors, lighter subframes carry gravity loads from the intervening stories and deliver them to the mega-columns through the belt trusses. The system is particularly well-suited to supertall buildings above three hundred metres, where the gravity loads are large enough to pre-stress the mega-columns to acceptable compression levels even under large overturning moments.

6.3 Diagrid Evolved: Space Truss and Belt Truss Systems

The space truss structural system extends the three-dimensional triangulation principle of the braced tube to a fully three-dimensional perimeter grid, creating a spatial lattice that resists both lateral and torsional loads through axial forces in all three directions. Belt truss systems, as noted in the outrigger discussion above, supplement core-outrigger configurations by distributing the concentrated outrigger column forces around the full building perimeter, improving uniformity of column shortening and reducing torsional response to asymmetric loading.

6.4 Core Outrigger-Structural Wall Systems

The core outrigger system combined with structural walls forms a composite resisting mechanism in which the wall panels of the core, the outrigger trusses, and the perimeter mega-columns act together to limit drift and base moment simultaneously. Evaluation of lateral load resisting systems in high-rise buildings presented in the International Journal of Current Science Research and Review in 2024 confirmed, through response spectrum analysis of a forty-storey building, that the outrigger system with a central shear wall core achieves the lowest maximum lateral displacement of the three systems studied, outperforming both corner shear wall and perimeter shear wall configurations.

7. DESIGN METHODOLOGY AND CODE PROVISIONS

7.1 Stiffness-Based Preliminary Design

The stiffness-based preliminary design methodology for diagrid structures, formalised by Moon et al. in 2007, provides closed-form expressions for the cross-sectional areas of diagonal members required to satisfy a prescribed lateral drift limit under idealised triangular wind pressure distribution. The methodology separates the total lateral stiffness into a bending stiffness component, controlled by the column-like action of the windward and leeward facade panels, and a shear stiffness component, controlled by the web-like action of the panels perpendicular to the wind direction. This decomposition enables independent sizing of member areas for each stiffness contribution, providing a rational and computationally inexpensive starting point for full three-dimensional

analysis. Lee and Kim extended this methodology to hexagrid buildings in 2017, deriving analogous formulae for hexagonal module geometry and validating them against ETABS finite element models of sixty-storey buildings.

7.2 Optimisation Approaches

Structural optimisation of diagrid and hexagrid buildings has progressed from simple parametric sweeps over diagonal inclination to multi-objective optimisation using genetic algorithms, particle swarm methods, and, most recently, machine learning surrogate models. Angelucci and Mollaioli investigated diagrid structural systems for tall buildings with varying pattern configurations through topological assessments in the Structural Design of Tall and Special Buildings in 2017, demonstrating that topology optimisation methods can identify non-uniform pattern geometries whose performance is superior to that of any single uniform-angle alternative. Tomei, Imbimbo, and Mele in Engineering Structures in 2018 extended this work to include material weight explicitly in the objective function, deriving Pareto fronts that quantify the trade-off between structural efficiency and architectural simplicity. Kazemi, Ghisi, and Mariani in 2022 showed that machine learning classifiers trained on simulation data from 36 parametric buildings could predict the optimal diagonal pattern with high accuracy, opening the prospect of real-time design recommendation tools that could materially accelerate the schematic design process for geometry-driven facades.

7.3 Indian Code Framework

The design of diagrid and hexagrid buildings in India must currently navigate a code landscape that does not explicitly address these systems. IS 800:2007, the general construction standard for structural steel, provides provisions for member design under combined axial and bending loading that are applicable to diagonal members, but it does not address the specific connectivity requirements, the stiffness decomposition methodology, or the ductility classification criteria that these systems require. IS 875 Part 3:2015 provides wind pressure coefficients for buildings with smooth facades; the modification factors applicable to triangulated or hexagonal facade textures must currently be determined through wind tunnel testing or computational fluid dynamics simulation. IS 1893 Part 1:2016 provides the seismic zone factor, response reduction factor R, and importance factor for buildings classified by their structural system; the absence of a specific classification for diagrid and hexagrid systems forces designers to adopt conservative R values from the "special concentrically braced frame" or "special moment frame" categories, which may either over- or under-estimate the actual seismic performance of the perimeter grid system. IS 16700:2017 provides additional guidance on structural safety criteria for tall concrete buildings, but its application to steel geometry-driven systems requires interpretative judgement. The development of an Indian design standard or an IS code amendment specifically addressing perimeter grid structural systems is an identified research and standardisation priority.

8. RECENT ADVANCES AND EMERGING RESEARCH DIRECTIONS

8.1 Machine Learning in Structural Form-Finding

The application of machine learning and artificial intelligence to the design of tall buildings is accelerating, driven by the availability of large parametric simulation datasets and the maturation of neural network architectures capable of handling high-dimensional structural response data. Kazemi, Ghisi, and Mariani demonstrated in 2022 that random forest classifiers trained on finite element simulation results could classify the structural behaviour of diagrid tall buildings with high accuracy, and their 2025 paper in the Wiley Structural Design of Tall and Special Buildings extended this approach to non-prismatic plan geometries. The prospect of real-time AI-assisted pattern selection for diagrid and hexagrid facades, integrated into parametric design environments such as Grasshopper and Karamba3D, is now technically feasible and could eliminate the need for iterative full-scale finite element analysis during the schematic design phase.

8.2 Sustainable and Timber Diagrid Systems

The growing imperative to reduce the embodied carbon of tall buildings has prompted research into diagrid and hexagrid systems constructed from low-carbon materials including engineered timber and high-strength aluminium. Cross-laminated timber (CLT) and glue-laminated timber (Glulam) diagrid panels have been studied for medium-height applications; the lower stiffness and higher susceptibility to creep and moisture variation of timber relative to steel require modified design criteria, but the significantly lower embodied carbon can justify the additional complexity in sustainability-conscious projects. Composite diagrids combining timber infill panels with steel node connectors represent a promising intermediate approach that retains the structural efficiency of steel diagrids while achieving a substantially reduced carbon footprint.

8.3 Seismic Isolation and Supplemental Damping Integration

Singh and Tiwary demonstrated in 2023 that the combination of a diagrid structural system with base isolation improves seismic performance substantially relative to either the fixed-base diagrid or the isolated conventional frame, because the base isolation reduces the spectral acceleration imposed on the structure while the diagrid provides the stiffness needed to prevent excessive isolator displacement under service wind loading. The study by Chen and Xiong on seismic resilient design with friction pendulum bearings and viscous dampers published in 2022 provides a complementary perspective, showing that supplemental viscous dampers installed within diagrid nodal connections can reduce peak inter-storey drift by up to twenty-five percent under design-level seismic excitation without compromising the gravity load-carrying function of the system.

8.4 Voronoi and Bio-Inspired Mesh Geometries

Research is increasingly exploring the possibility of generalising beyond the regular repeating modules of the diagrid and hexagrid to irregular biomorphic mesh geometries derived from Voronoi tessellations and topology optimisation. The approach, discussed by several research groups in the context of supertall structural skins, allows the mesh geometry to adapt continuously to the varying stress state within the tube, concentrating material where it is most effective and reducing it where demand is low. While the computational and constructional challenges of such geometries are considerable, advances in parametric modelling software and digital fabrication are progressively lowering the barriers to their practical implementation.

9. RESEARCH GAPS AND FUTURE SCOPE

Despite the substantial volume of research reviewed in this paper, several important gaps in knowledge and practice remain.

First, the absence of dedicated Indian code provisions for diagrid and hexagrid structural systems is a significant impediment to their wider adoption in the Indian tall building market. A systematic programme of research calibrating the response modification factor R , overstrength factor, and ductility factor for these systems against IS 1893 performance objectives would provide the technical basis for a code amendment. Studies specifically calibrated to Indian seismic zones II through V, Indian wind zones, and the concrete and steel grades specified in Indian standards are largely absent from the current literature, which is dominated by research conducted under American, European, and Turkish design standards.

Second, the performance of hexagrid systems has been studied far less extensively than that of diagrid systems. There is a particular paucity of experimental research involving physical testing of hexagrid nodal joints and facade panels under combined gravity, wind, and seismic loading. Without experimental data, the finite element models used in parametric studies rest on material and connection constitutive assumptions that have not been independently validated for the hexagonal geometry.

Third, the emerging class of hybrid diagrid-outrigger and hexagrid-damper systems identified by Faiella et al. requires the development of integrated analysis and design frameworks. The interaction between the perimeter grid system and the internal outrigger or damper system introduces coupling that current simplified design methods do not capture. Performance-based design procedures for these hybrid systems, calibrated to multiple seismic hazard levels, represent an important research frontier.

Fourth, the environmental and life-cycle cost implications of diagrid and hexagrid systems have received very limited attention. While the structural efficiency of these systems reduces steel tonnage, the complexity of node fabrication and erection increases construction cost; a comprehensive lifecycle assessment balancing embodied carbon against operational energy savings and adaptive reuse potential is needed to support informed decision-making by owners and developers.

Fifth, the response of diagrid and hexagrid buildings to long-period ground motions, of the type that have caused severe damage to flexible structures in Mexico City, Christchurch, and other cities with soft-soil conditions, has not been systematically investigated. The long fundamental periods of supertall diagrid buildings may bring them into resonance with near-fault long-period ground motions in a way that current design code provisions do not adequately address.

10. CONCLUSIONS

This paper has traced the evolution of lateral load resisting systems for tall buildings from the classical moment-resisting frame and shear wall configurations through to the contemporary diagrid and hexagrid structural geometries. The following principal conclusions are drawn from the review.

The diagrid structural system, through its triangulated perimeter configuration, achieves a highly efficient coupling of gravity and lateral load resistance through axial member action, reducing structural steel consumption by fifteen to twenty percent relative to equivalent moment-resisting frames while substantially reducing storey displacement and inter-storey drift. The optimum diagonal inclination of sixty degrees has been consistently confirmed across multiple studies for buildings in the thirty to seventy storey range.

The hexagrid structural system extends the diagrid concept by replacing the triangular module with a hexagonal module, offering higher ductility sensitivity, superior robustness against progressive collapse, and improved daylighting performance, particularly at larger module sizes. Its relative seismic performance advantage over the diagrid becomes more pronounced at greater building heights, suggesting that hexagrid systems are particularly well-suited for supertall applications above one hundred storeys.

Both systems currently lack explicit design provisions in Indian codes IS 800:2007 and IS 1893:2016, representing a critical gap that constrains their adoption in the growing Indian tall building sector. Developing calibrated response modification factors and design guidelines for these systems in the Indian code framework is an urgent priority for the structural engineering research community.

Emerging research directions including machine-learning-assisted optimal pattern selection, hybrid diagrid-outrigger-damper configurations, sustainable timber diagrids, and bio-inspired Voronoi mesh geometries suggest that the field is far from mature and that significant performance improvements are achievable beyond current best-practice configurations.

It is anticipated that this review will serve as a consolidated reference for researchers and practising structural engineers engaged in the design and analysis of laterally loaded tall buildings, and that it will stimulate targeted investigations into the areas identified as future research priorities.

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