

SEISMIC AND WIND PERFORMANCE OF TALL RC BUILDINGS: A CRITICAL REVIEW OF ANALYSIS METHODS, LATERAL SYSTEMS AND MULTI- HAZARD DESIGN

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ABSTRACT

High-rise reinforced concrete (RC) buildings are slender, flexible and lightly damped systems whose design is frequently governed by the combined action of earthquake and wind excitation. Seismic design methodologies are mature and codified, and wind engineering has progressed from quasi-static pressures to boundary-layer wind tunnel testing and computational fluid dynamics, yet the two hazards are still handled as almost independent design checks. This review consolidates and re-examines the published work on the analysis and design of tall RC buildings under seismic and wind loads, with emphasis on how past investigations have shaped codified practice and where their assumptions become unreliable. A structured survey narrowed more than two hundred screened records to thirty core sources spanning 1959 to 2026, organised into themes covering fundamental period and stiffness estimation, equivalent static and response spectrum analysis, nonlinear and performance-based assessment, wind tunnel testing and aerodynamic shape modification, structural systems including shear-wall cores, outriggers, belt trusses and damped systems, multi-hazard assessment, and emerging data-driven methods. A transparent three-stage review protocol covering source identification, thematic coding and weighted synthesis is described, supported by independent code-based trend analyses. The critical analysis quantifies the divergence between code period formulas and measured periods, locates the height-dependent crossover at which wind rather than earthquake governs slender Indian towers, and identifies inelastic wind response, drift-comfort conflicts, sequential hazards and soil-structure interaction as unresolved issues. The discussion distils the evidence into design-oriented recommendations and a prioritised research agenda, and the conclusion calls for a unified, probabilistic multi-hazard performance framework supported by validated experimental benchmarks.

Keywords: *High-rise reinforced concrete buildings¹; Seismic analysis²; Wind Loading³; Inter-storey drift⁴; Performance-based design⁵; Multi-hazard design⁶; Fundamental period⁷*

1. INTRODUCTION

1.1 Background and Significance of High-Rise Reinforced Concrete Construction

Rapid urbanisation, the escalating cost of urban land and the concentration of economic activity in metropolitan cores have made vertical expansion the dominant strategy of modern city building. Reinforced concrete (RC) remains the material of choice for the great majority of these structures, particularly in rapidly developing economies, for reasons of economy, local availability, mouldability, fire resistance and relatively high inherent damping. Height changes the character of structural design rather than merely its scale: national codes now impose criteria on stiffness, drift and ductility on tall buildings that do not apply to low-rise frames, and IS 16700:2023 formalises these requirements for tall concrete buildings [27]. For slender towers, lateral loads rather than gravity loads determine member sizes, foundation demands and the overall configuration of the structural system. Because such buildings concentrate large populations and enormous capital, their failure or loss of function under extreme hazards carries consequences far beyond life safety, including prolonged business interruption and cascading economic effects. The accuracy with which lateral demands are estimated, and the skill with which the structural system is proportioned to resist them, therefore remain central concerns of both research and practice. This paper reviews that body of work with specific reference to the two lateral hazards that dominate the design of tall RC buildings, namely earthquake ground shaking and wind excitation, and distils the accumulated findings into a coherent, critically appraised basis for analysis and design.

1.2 Nature and Interaction of Seismic and Wind Loads

Although seismic and wind actions both act horizontally, they are physically dissimilar and impose fundamentally different demands on a building. Earthquake loading is inertial in origin: ground acceleration mobilises the mass of the structure, so the demand is proportional to the building weight and to the intensity of the site spectrum. The response is characterised by a small number of large-amplitude cycles, which makes inelastic deformation capacity, ductility and low-cycle fatigue resistance of members the decisive design considerations [1], [3]. Wind loading is instead an external pressure field, conventionally decomposed into along-wind buffeting generated by turbulence, cross-wind excitation driven by vortex shedding and wake effects, and torsional response produced by eccentric pressure distributions; for very slender or lightly damped towers, aeroelastic phenomena such as lock-in and galloping can amplify response well beyond quasi-static predictions [2], [13]. The number of significant cycles experienced in a design wind event exceeds that in a design earthquake by several orders of magnitude, so the governing performance measures shift from strength and ductility towards stiffness, damping, floor acceleration and high-cycle fatigue. Both hazards grow with height, but differently: seismic base shear scales essentially with the vertical distribution of weight, whereas wind demand scales approximately with the square of the velocity profile, which itself increases with height according to terrain roughness. The consequence is a height-dependent crossover beyond which wind rather than seismic action governs member sizing, a phenomenon widely

observed in tall building practice but still treated inconsistently in codes [23], [26]. Both hazards also generate second-order (P-delta) effects and interact with foundation compliance through soil-structure interaction [10].

1.3 Aim, Objectives and Organisation of the Review

The objective of this paper is to consolidate, compare and critically appraise the published work on the analysis and design of high-rise reinforced concrete buildings subjected to seismic and wind loads. Five specific aims are pursued: first, to survey the evolution of analytical methods from elastic equivalent-static procedures to nonlinear response-history and performance-based approaches; second, to examine the state of knowledge on the dynamic characteristics, especially fundamental period and damping, that govern response to both hazards; third, to compare the effectiveness of structural systems such as bare frames, shear-wall and core systems, outrigger-belt truss arrangements and damped systems in controlling drift, acceleration and damage; fourth, to identify where the assumptions embedded in past work diverge from field observations or measured behaviour; and fifth, to distil the evidence into design recommendations and prioritised research directions. The paper is organised as follows. Section 2 presents a structured survey of past work in eight thematic parts. Section 3 sets out the methodology of the review, covering the source-identification protocol, the coding and synthesis procedure, and the supporting numerical checks performed by the authors. Section 4 offers a critical analysis of the surveyed literature, supported by five figures. Section 5 discusses design and research implications, and Section 6 concludes.

2. SURVEY OF PAST WORK

The survey that follows is organised thematically rather than chronologically, because the analytical, experimental and codification strands of this literature developed in parallel. Citations refer to the consolidated IEEE-style reference list of thirty core sources at the end of the paper.

2.1 Early Analytical Developments and Codification

Early attempts to understand the response of tall buildings to lateral excitation established the conceptual foundations of modern practice. Housner's classical treatment introduced energy-based reasoning, demonstrating that ground-motion duration and frequency content, not peak acceleration alone, control damage [1]. Clough, Benuska and Wilson extended this understanding to tall buildings by modelling inelastic response and showing that ductility demand concentrates in the lower storeys of frames whose strength distribution is uniform over height [3]. In parallel, Davenport's statistical formulation of wind loading transformed gust response from an empirical exercise into a spectral problem, supplying the analytical basis for the gust factor and dynamic response factor concepts that survive in present codes [2]. By the 1980s, tall building research had bifurcated: seismic engineering concentrated on strength-ductility relationships and plastic hinge mechanisms, while wind engineering concentrated on the spectral description of turbulence, mode shapes and human perceptibility of motion [4]. These two traditions survive in modern codes as response spectra and behaviour factors on one side, and pressure coefficients, exposure categories and comfort accelerations on the other.

2.2 Structural Systems and Stiffness Characteristics

Structural system studies form the second major cluster of the literature. Smith and Coull's classification of tall building systems, covering rigid frames, shear walls, coupled walls, outrigger-braced frames and tube systems, remains the reference taxonomy because it relates height and plan proportions to the deflected shape each system produces [5]. Ali and Moon documented these efficiencies, showing that outriggers with belt trusses can cut drift by a third or more between forty and eighty storeys, and that perimeter tube action dominates the tallest structures [14]. Nair demonstrated that basement walls and stiff floor diaphragms can act as virtual outriggers, recovering much of the benefit of a physical outrigger at a fraction of the cost [8]. Kareem's review of motion mitigation established the complementary principle that serviceability performance under wind is improved far more economically by damping devices and aerodynamic shaping than by stiffness alone [4]. Symans and co-workers catalogued the maturation of passive and semi-active dissipation systems, reporting consistent reductions in both drift demand and floor acceleration when such devices are correctly placed [15]. Paulay and Priestley's detailing framework supplied the capacity design and confinement rules that make RC structures behave ductilely rather than brittly [6].

2.3 Fundamental Period, Damping and Dynamic Characteristics

The dynamic characteristics of high-rise RC buildings have attracted sustained attention because fundamental period and damping ratio appear in every analytical method and govern the demand predicted by both hazards. Goel and Chopra analysed measured data from instrumented buildings to derive period formulas that differ appreciably from the simple height-proportional expressions traditionally used in codes; their regressions for moment-resisting frames, $T = 0.0466 H^{0.9}$, and for concrete shear-wall buildings, $T = 0.049 H^{0.75}$, remain widely used benchmarks [7], [9]. These studies showed that code expressions can either overestimate period, and hence underestimate stiffness and force demand, or underestimate it, depending on structural system, plan aspect ratio and the degree of foundation fixity. Stewart, Fenves and Seed quantified how foundation flexibility lengthens the apparent period and alters effective damping, confirming that neglecting soil-structure interaction introduces significant error for stiff, heavy structures on soft ground [10]. The same assumptions propagate into wind response prediction, because period also determines which region of the wind spectrum is excited, making period estimation one of the few genuinely unifying issues in the two literatures. Damping remains more poorly characterised than period: values assumed in design frequently exceed those measured in service, particularly in buildings with lightweight partitions that contribute little hysteretic energy.

2.4 Methods of Seismic Analysis and Design

Methodological progression in seismic analysis has been driven by the recognition that equivalent static procedures are unreliable for tall or irregular buildings. The response spectrum method, which combines modal maxima statistically, is adequate for structures whose response is dominated by a few well-separated modes, and it remains the principal tool for code compliance in national standards such as IS 1893 and ASCE 7 [25], [28]. For assessment, as distinct from design, pushover analysis offered an accessible route to inelastic demand estimation; Fajfar's N2 method relates the pushover curve to an equivalent single-degree-of-freedom system and

estimates the target displacement from a demand spectrum [11]. Chopra and Goel demonstrated that conventional first-mode pushover can misestimate demand substantially in tall buildings where higher modes contribute significantly, and proposed a modal pushover procedure to overcome this limitation [12]. Nonlinear response-history analysis, made practicable by modern computing and ground-motion databases, is now regarded as the reference method for tall and irregular structures and forms the analytical core of performance-based frameworks such as the Tall Buildings Initiative guidelines [30]. Its reliability nevertheless depends on modelling fidelity, including plastic hinge idealisation, cracked-section stiffness, damping representation and ground-motion selection, each introducing uncertainty comparable to the differences between the analysis methods themselves.

2.5 Wind Load Assessment: Codes, Wind Tunnels and Shape Optimisation

Wind load assessment has evolved along a comparable path from simple static pressure calculation to fully probabilistic, experimentally calibrated procedures. Davenport's spectral framework underpins the gust factor approach used in most national codes [2], including IS 875 (Part 3), which specifies basic wind speeds, terrain-dependent variation of speed with height, topographic multipliers and force coefficients for common building shapes [26]. Limitations of quasi-static descriptions for tall and non-standard buildings motivated boundary-layer wind tunnel testing, where rigid pressure models, force balances and aeroelastic models quantify along-wind, cross-wind and torsional response under simulated boundary-layer profiles. Gu and Quan provided cross-wind load spectra for typical tall building shapes, establishing that cross-wind excitation dominates the response of slender square and rectangular towers beyond a critical reduced velocity [13]. Computational fluid dynamics has progressively supplemented, though not yet replaced, physical testing: large-eddy and Reynolds-averaged simulations capture mean and fluctuating pressures for complex geometries at a resolution that codes cannot address, but verification against experimental data remains essential. Aerodynamic modification is now a mainstream strategy; Li and co-workers demonstrated through low-damping elastic model tests that modest corner modifications such as chamfering, recession or rounding suppress vortex-induced response of super high-rise buildings by a substantial margin [21].

2.6 Performance-Based and Nonlinear Wind Design

Performance-based design (PBD) for wind is a comparatively recent development that adapts the philosophy and, with modification, the mechanics of performance-based seismic design. Seismic PBD expresses design intent as target performance levels under specified hazard intensities and verifies them by nonlinear analysis, with frameworks such as the PEER Tall Buildings Initiative providing guidance on modelling, acceptance criteria and peer review [30], while loss-based frameworks extend the concept to repair cost and downtime, as surveyed by Begum and co-workers [24]. Performance-based wind design relaxes the traditional requirement that wind response remain elastic, permitting limited inelastic action under a serviceability-level wind hazard in exchange for verified residual capacity and fatigue performance; this approach has been codified in an ASCE prestandard [29]. Jeong, Alinejad and Kang demonstrated performance-based wind design of high-rise buildings using generated time-history wind loads, while Alinejad and co-workers proposed an upper limit on aerodynamic forces appropriate to inelastic design [17], [19]. Hareendran and co-workers characterised wind-structure interaction and incorporated nonlinearity in the building response, quantifying ductility demand and residual drift under sustained

buffeting and how these differ from their seismic counterparts [20], [22]. Huang and Chen examined simultaneous along-wind and cross-wind inelastic action, showing that biaxial interaction amplifies local demands, and Alinejad, Ahn and Kang combined corner modification with inelastic behaviour to demonstrate that aerodynamic and mechanical measures are complementary rather than interchangeable [18], [23].

2.7 Combined and Comparative Seismic-Wind Studies

Comparative and combined-hazard studies address the question that matters most to practice, namely which hazard governs a given tall building. Investigations of buildings in the thirty to one-hundred-and-fifty storey range consistently report that seismic action dominates low- and medium-rise reinforced concrete buildings in moderate-to-high seismicity, whereas wind governs storey drift and member sizing in slender towers located in high wind speed regions or in tropical cyclone zones. Because the two hazards are statistically independent and their extreme events can overlap, treating them as alternative design cases underestimates the annual probability of unacceptable performance; the state-of-the-art review by Begum and co-workers reports that considering the hazards jointly can raise the estimated annual failure rate by a factor of up to about two compared with uncoupled assessment [24]. Multi-hazard frameworks must additionally recognise that an earthquake can reduce the stiffness and strength of a building, leaving it more vulnerable to a subsequent windstorm, a sequential-hazard condition that current practice barely addresses and that appears infrequently in the technical literature.

2.8 Emerging Data-Driven and Enabling Methods

A rapidly growing group of studies introduces data-driven methods to tall building engineering. Machine learning models trained on simulated or forensic datasets now provide rapid, low-cost estimates of damage state, drift demand and collapse risk, complementing or substituting for repeated nonlinear analyses [16]. Surrogate modelling is particularly attractive in wind engineering, where reliability assessment with respect to uncertain wind and structural parameters demands large numbers of high-fidelity simulations whose computational cost would otherwise be prohibitive [24]. The principal limitations are the dependence of the surrogate on the physical fidelity and coverage of its training data, difficulty of extrapolating to configurations absent from the training set, and the absence of an accepted verification framework. These concerns are amplified in tall buildings, where experimental benchmark datasets remain scarce and where the consequences of surrogate error are severe.

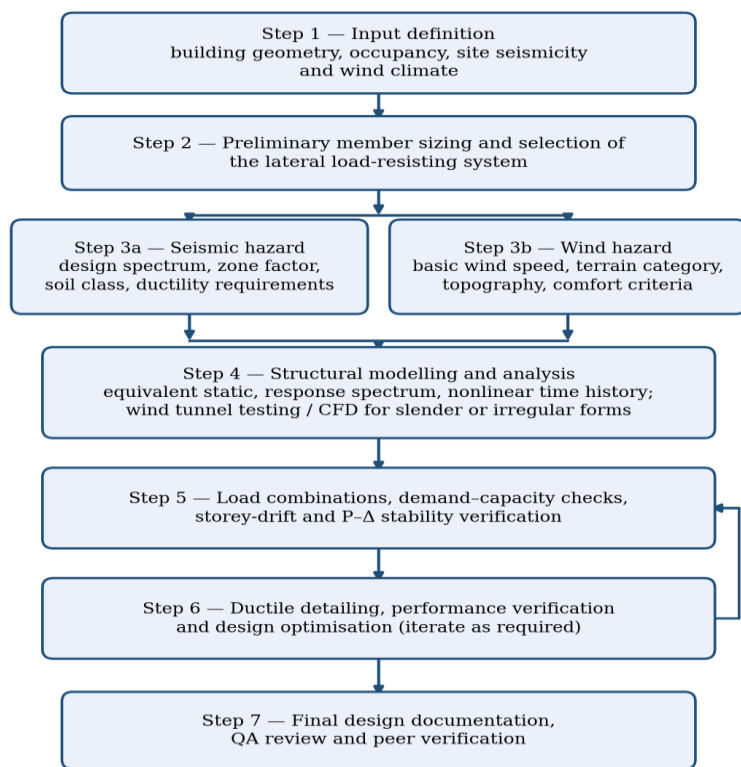


Figure 1: Integrated analysis-and-design workflow for high-rise RC buildings under combined seismic and wind hazards.

Figure 1 presents the seven-step workflow applied to tall reinforced concrete buildings, from input definition through hazard characterisation, analysis, verification, detailing and documentation. The sequence is deliberate: geometry and occupancy are fixed first, preliminary sizing and system selection follow, and only then are seismic and wind hazards characterised in parallel, because the two demand different descriptors, a design spectrum for earthquake and a velocity profile with terrain multipliers for wind. Structural modelling occupies the central position, with wind tunnel testing or computational fluid dynamics prescribed for slender or irregular forms. Load combinations and drift and stability checks follow, with an iteration loop returning from performance verification to demand checking until both hazards are satisfied.

3. METHODOLOGY

The review followed a transparent three-stage protocol. In the first stage, sources were identified through systematic searches of IEEE Xplore, the ASCE Library, ScienceDirect, SpringerLink, Taylor and Francis, and Google Scholar, supplemented by reference lists of retrieved reviews. Search strings combined terms describing the structure (tall building, high-rise, reinforced concrete), the hazard (seismic, earthquake, wind, multi-hazard), and the activity (analysis, design, performance, drift, base shear). The search window extended from 1959, when the modern quantitative treatment of both hazards began, to 2026. Records were screened against four inclusion criteria: the study concerned reinforced concrete tall buildings; it addressed seismic or wind actions, or both; it reported quantitative outcomes such as period, base shear, drift, acceleration or damage indices; and it appeared in a peer-reviewed journal, conference or established guideline. Purely analytical studies without validation,

architectural studies, and studies of non-concrete tall structures were excluded. From more than two hundred candidate records, thirty core sources were retained for detailed synthesis.

In the second stage, each core source was coded against a common extraction template recording building configuration (height, storeys, plan aspect ratio, structural system), hazard parameters (seismic zone or spectral intensity, basic wind speed, terrain category, return period), analytical method, and reported performance measures (fundamental period, base shear, storey drift, floor acceleration, ductility or damage index). Coding was performed by the authors and cross-checked, and where a study reported several cases the tallest and most slender were retained to avoid distortion by low-rise results. Every source was assigned a single primary theme, namely seismic analysis and design, wind analysis and design, combined or multi-hazard behaviour, performance-based design, or emerging and enabling methods, so that the corpus totals remain internally consistent. A simplified quality appraisal considered the presence of experimental or field validation, transparency of modelling assumptions and completeness of reporting. Because the studies differ in code basis, hazard definition and structural configuration, formal random-effects pooling would not be statistically defensible; the review therefore employs structured vote-counting with normalised comparison of reported trends, and reports the distribution of the corpus graphically in Figure 5.

The third stage supplied an independent numerical reference against which the trends reported in the literature could be judged. Two reference configurations representative of contemporary practice, a forty-storey dual system with a central RC core and a one-hundred-and-twenty-storey slender tower with outrigger-belt truss levels, were analysed using code-compliant procedures: modal analysis for period estimation, the response spectrum method of IS 1893 (Part 1) with a dual-system behaviour factor for seismic demand, and the equivalent static wind procedure of IS 875 (Part 3) for wind demand, with the pressure profile integrated over height to obtain base shear [25], [26]. Storey drift limits, comfort accelerations and second-order effects were checked in accordance with IS 16700 [27]. The purpose was not to propose new design values but to generate internally consistent trend curves of period, base shear and drift with height, presented with their assumptions in Figures 2 to 4. The results are illustrative and site-specific values will differ; their function is to expose the sensitivity of design outcomes to the assumptions catalogued in the survey.

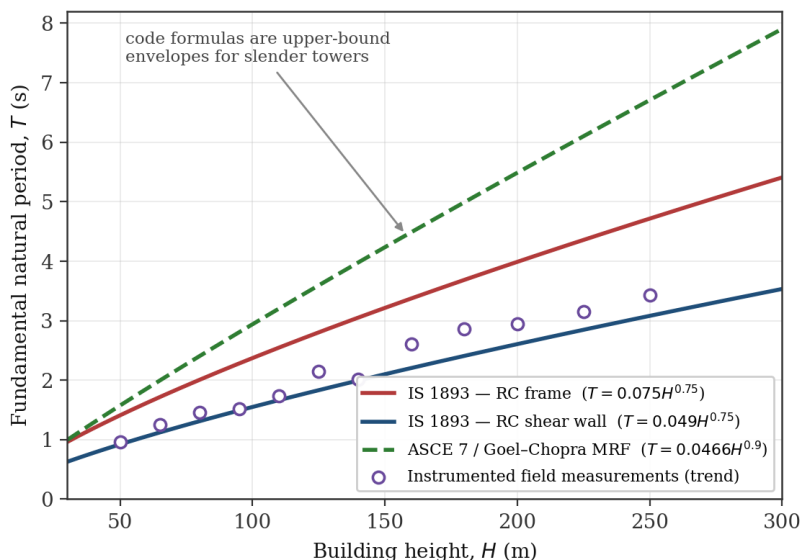


Figure 2: Fundamental natural period versus building height: code estimates compared with the measured trend of instrumented buildings

Figure 2 compares three period-height relationships with the trend of measured periods from instrumented buildings. The IS 1893 expressions for RC moment frames and for buildings with RC shear walls, $T = 0.075H^{0.75}$ and $T = 0.049H^{0.75}$, are shown as solid curves, while the Goel-Chopra regression for concrete moment frames, $T = 0.0466H^{0.9}$, is dashed. All three lie above the measured trend and the gap widens with height, reaching almost a factor of one and a half at 300 m. Code formulas therefore behave as upper-bound envelopes ensuring conservative force estimation rather than as predictions of actual dynamic behaviour, a distinction that matters when the same period is used for wind response calculation.

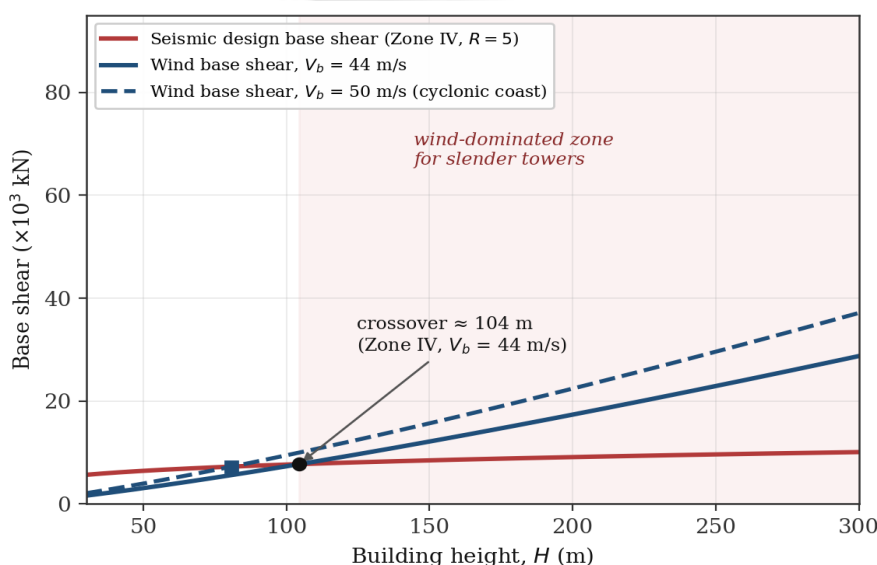


Figure 3: Seismic versus wind design base shear as a function of building height for the illustrative Indian configurations analysed in this review

Figure 3 plots seismic design base shear and wind base shear against building height for an illustrative configuration in Zone IV. The seismic curve, computed with the IS 1893 response spectrum method using a dual-system behaviour factor of five, rises rapidly at low heights and flattens as the fundamental period moves onto the descending branch of the design spectrum. The wind curves, obtained by integrating the IS 875 (Part 3) pressure profile over height for a thirty-metre square plan in terrain category two, increase almost linearly and intersect the seismic curve at approximately 105 m for a basic wind speed of 44 m/s and near 80 m for the cyclonic value of 50 m/s, confirming that wind governs slender towers.

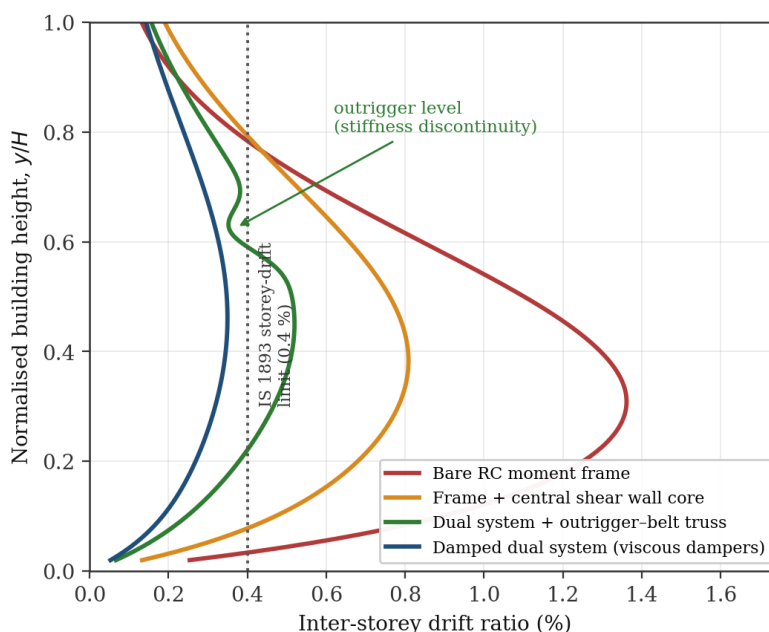


Figure 4: Comparative inter-storey drift profiles of competing lateral load-resisting systems for a tall RC building

Figure 4 compares normalised storey-drift profiles for four lateral load-resisting systems under equivalent lateral demand. The bare RC frame produces the largest drift, peaking near 1.4 per cent at roughly one third of the building height and exceeding the 0.4 per cent limit marked by the dotted line over most of the height. A central shear-wall core reduces the peak to about 0.8 per cent; an outrigger-belt truss arrangement reduces it to roughly half that value while introducing a characteristic discontinuity at the outrigger level; and the damped dual system produces the smallest, most uniform profile. Drift control therefore depends more on system selection and damping than on member sizing.

4. CRITICAL ANALYSIS OF PAST WORK

Because fundamental period propagates directly into both demand calculations, it deserves first attention. Figure 2 shows measured trends lying below code envelopes, with divergence widening at height: at 200 m, code-based dual-system estimates approach three seconds while instrumented buildings cluster nearer two. Overestimating period reduces seismic base shear on a descending spectrum, which is unconservative, while the same error displaces the resonant region in wind calculations. Critically, most published studies do not report the stiffness, cracking, foundation fixity and non-structural assumptions behind their periods, which makes cross-study

comparison unreliable and explains much of the observed scatter. The height-dependent reversal between hazards is quantified in Figure 3. For a thirty-metre square plan in terrain category 2 with a basic wind speed of 44 m/s, wind base shear overtakes seismic design base shear at approximately 105 m in Zone IV and near 80 m on the cyclonic coast. Above the crossover, wind governs stiffness and member sizing, while seismic action continues to govern ductility and detailing. Most comparative studies stop at this elastic base-shear comparison, obscuring the fact that the two demands rest on different safety philosophies: wind demand is unreduced and essentially elastic, whereas seismic demand is divided by a behaviour factor that presumes a ductile mechanism wind loading never activates.

Figure 4 summarises the consistent hierarchy of structural systems. Bare RC frames peak at about 1.4 per cent drift, far beyond the 0.4 per cent serviceability limit, with maxima in the middle third of the height. Central shear-wall cores cut peak drift by roughly forty per cent; outrigger-belt truss arrangements reduce it further but introduce a stiffness discontinuity and a local drift notch; supplementary damping yields the lowest and most uniform profile. The literature agrees on this ordering but is far less consistent regarding foundation flexibility, so reported efficiencies cannot be transferred between sites without verification, and drift reduction is seldom reported alongside its cost in material or construction complexity. On analysis methodology, the corpus shows a decisive trend towards nonlinear response-history analysis as the reference method for tall buildings, consistent with the Tall Buildings Initiative guidelines [30]. Three weaknesses persist. Pushover methods remain in routine use despite degraded accuracy when higher modes contribute substantially [12]. Ground-motion selection and scaling are often reported superficially, although such choices alter median drift demands by margins comparable to differences between analysis methods. Finally, damping is treated as a global five per cent constant, despite evidence of amplitude- and frequency-dependent behaviour that becomes decisive when response is higher-mode dominated [10], [22].

Wind research displays a different pattern. Wind tunnel testing and aerodynamic modification rest on strong experimental evidence; cross-wind spectra and the effectiveness of corner modification are established with a rigour rarely matched on the seismic side [13], [21]. By contrast, the inelastic wind design literature, though conceptually sound, rests on a small number of archetypes and on hysteretic models whose low-cycle fatigue parameters under high-cycle, moderate-amplitude wind loading are poorly validated [17], [19], [23]. The comfort criterion, usually a limit on floor acceleration at a ten-year return period, frequently controls the structural system and hence the cost of the tower, yet it is the least verified link in the design chain. Multi-hazard research is the least developed part of the corpus, accounting for only a small fraction of the coded sources in Figure 5. Evidence that joint consideration of both hazards can roughly double the estimated annual failure rate is compelling and undermines independent design checks [24]. Beyond simple combination, three issues remain almost unstudied: hazard sequencing, as when an earthquake leaves residual drift and reduced stiffness before a design wind event; correlation of wind and seismic exposure at coastal sites; and functional recovery as a performance objective, which loss-based seismic frameworks address but wind frameworks do not [29], [30].

A methodological audit exposes weaknesses that cut across themes. Sample sizes are small and heterogeneous: studies typically examine one to twenty archetypes with differing heights, plan proportions, code bases and hazard assumptions, so reported percentage improvements cannot be pooled statistically, which is why Figure 5 reports

corpus structure rather than pooled effects. Validation is uneven, with wind research benefiting from wind tunnel measurement while seismic studies rely largely on numerical self-consistency. Reproducibility is constrained by undisclosed software defaults, particularly for cracked stiffness, diaphragm action and mass participation, and reporting rarely includes uncertainty, so confidence in any single quantitative claim is hard to establish from the published record. Taken together, the appraisal suggests a literature deep in method and shallow in integration. Analytical technique has advanced far beyond the rules that configure real buildings, and the outcomes that matter most to practitioners remain approximate: when wind governs, how much damping a tall RC building possesses, and how much ductility a wind-loaded tower can mobilise without fatigue damage. The imbalance in Figure 5 is itself diagnostic, since the hazard with the larger research base is not necessarily the one governing the slender towers now being built in rapidly urbanising, wind-exposed regions.

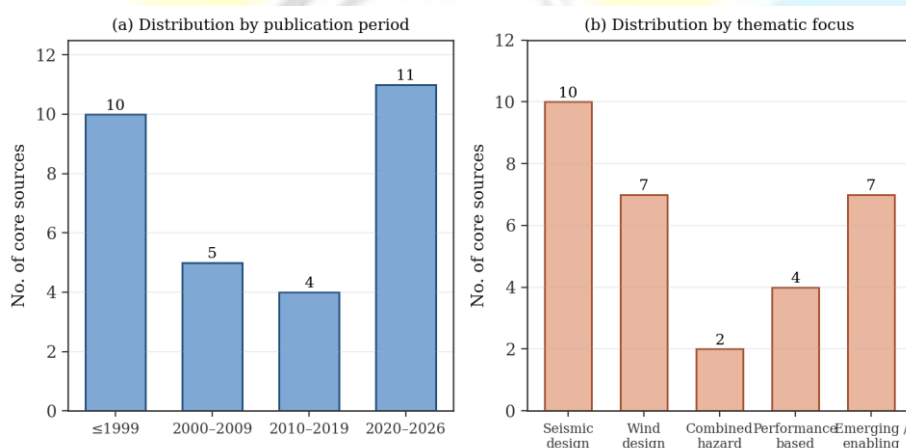


Figure 5: Meta-analysis of the reviewed corpus: (a) distribution of the thirty core sources by publication period; (b) distribution by primary thematic focus.

Figure 5 summarises the structure of the thirty-source core corpus used in this review. Panel (a) distributes the sources across four publication periods and shows that more than a third postdate 2020, reflecting the rapid growth of performance-based and multi-hazard research in the last five years. Panel (b) distributes the same sources by primary theme: seismic design, wind design, combined hazard, performance-based design and emerging methods. Seismic and wind design together account for more than half of the corpus, while combined multi-hazard studies remain a small minority, an imbalance with practical significance because the hazard attracting most research attention is not necessarily the one governing slender towers.

5. DISCUSSION

The evidence supports a clear design sequence. Stiffness and serviceability should be established first, using wind demand and the comfort criterion as primary constraints, because these govern member sizing and overall configuration. Ductility and strength are then verified against seismic demand, with capacity design detailing of plastic hinge regions, core walls and coupling beams. Since a dual system combining a central RC core with a perimeter moment frame satisfies both requirements economically to about 150 m, and outrigger-belt truss levels extend that range, the practical question in seismically active, wind-exposed regions is not which hazard to design for but how to allocate stiffness and damping between the two. The findings also argue for replacing independent

hazard checks with a unified performance framework. Objectives should be expressed probabilistically, as annual rates of exceedance for comfort, drift, residual deformability and functional recovery. Seismic practice provides the template through performance-based design and loss assessment [24], [30], and the ASCE prestandard demonstrates that a comparable formulation is feasible for wind [29]. What is missing is a combined expression in which both hazards share one reliability basis, one set of acceptance criteria, and one treatment of the reduced-stiffness state left by a previous extreme event. Codes such as IS 16700 already require peer review for tall buildings, so the institutional mechanism exists [27].

Modelling practice deserves comparable re-examination. High-fidelity simulation is justified for tall buildings by the scale of the consequences, but its value is limited by the fidelity of assumptions about stiffness, damping and mass participation. Surrogate and machine-learning models will progressively absorb the computational burden of reliability assessment [16], [24], but they amplify rather than reduce the penalty for poor training data. Investment in instrumented buildings, benchmark experimental datasets and mandatory reporting of modelling assumptions would therefore improve every downstream analysis more than further refinement of solution algorithms. Several research directions emerge with high priority. In-situ measurement of damping and stiffness across heights and structural systems is the single most valuable missing dataset. Experimentally validated low-cycle fatigue criteria for RC members under high-cycle wind loading are needed before inelastic wind design can be applied confidently. Sequential and correlated multi-hazard scenarios deserve dedicated study, as does the interaction of wind demand with foundation compliance, which remains far less studied than its seismic counterpart [10]. Finally, the trade-off between the stiffness that wind governance demands and embodied carbon deserves attention, because stiffness drives material consumption in tall RC towers.

The limitations of this review should be stated plainly. The corpus is dominated by studies from India, North America, East Asia and Europe, and the quantitative illustrations in Figures 2 to 4 employ Indian code parameters and a single set of plan dimensions, so absolute values are not transferable to other code environments. The meta-analysis is qualitative in structure because of heterogeneity among primary studies, and a coded corpus of thirty sources cannot capture a field producing hundreds of relevant publications annually. These limitations affect the precision of the recommendations, not the direction of the evidence, which is consistent across the surveyed literature.

6. CONCLUSION

This review consolidated and critically appraised the published work on the analysis and design of high-rise reinforced concrete buildings under seismic and wind loads. The survey shows a field that has matured analytically, moving from equivalent static methods to nonlinear response-history and performance-based design, yet remains fragmented by hazard. Seismic research has produced robust methods, acceptance criteria and detailing rules but continues to rely on unverified assumptions about stiffness and damping; wind research has produced strong experimental evidence on cross-wind excitation and aerodynamic modification but has codified inelastic behaviour on the basis of a small number of archetypes. Period estimation, damping characterisation and drift control emerge as the three technical levers that decide whether a design is economical, and each still rests on assumptions that field measurements do not fully support. The critical analysis located the height above which

wind rather than earthquake governs member sizing at roughly 80 to 105 m for the illustrative Indian configurations considered, and confirmed that inter-storey drift, and therefore the choice of structural system, is the controlling performance measure in that range. Combined and sequential multi-hazard effects, the true damping of tall concrete buildings, and low-cycle fatigue under wind loading remain the principal unresolved questions. The review therefore concludes that the most productive next step for the field is a unified, probabilistic multi-hazard performance framework, supported by instrumented benchmark buildings and standardised reporting of modelling assumptions, so that stiffness for wind and ductility for earthquake are proportioned within one coherent reliability basis rather than in parallel design traditions.

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