Evaluation of Wind and Seismic Load Modelling in High-Rise Concrete Structures: A Literature Review

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Abstract

The dynamic interaction between high-rise structures and environmental actions-particularly wind and seismic actions has remained a fundamental challenge in structural engineering for decades. This review critically examines the evaluation of modeling approaches, design standards, and analytical tools related to lateral load prediction and structural response in reinforced concrete high-rise buildings from 2000 to 2025. Drawing on over two decades of peer reviewed publications, Eurocode developments, and advancements in computer-aided structural analysis, the study traces the conceptual and practical shifts in how wind and seismic forces are understood static models toword performance-based and dynamic analysis using tools such as SAP2000, ETABS and TOWER. Key developments covered include the refinement of wind tunnel simulation data, probabilistic seismic hazard assessments, coupling of soil-structure interaction model, and the integration of damping mechanisms into design. The review also evaluates how modern guidelines (e.g., EN 1998, EN 1991-1-4, EUROCODE, ASCE 7, JUS) have evolved in response to empirical findings and catastrophic events (e.g., earthquakes in Turkey, Chile, Japan; extreme windstorms in Europe and Asia). This paper concludes by identifying future research directions, including the role of AI-assisted optimization, climate-adaptive design, and the integration of resilience-based frameworks for urban high-rise development. The review serves as a comprehensive resource for researchers and practicing engineers seeking to understand the trajectory of structural design methodologies for tall buildings in the face of increasing environmental uncertainty.

Keywords: *Structural Modeling; Performance-Based design; Structural Dynamics; High-Rise Structures; Seismic load; Wind load; Eurocode, ETABS.*

1. Introduction

Due to their popularity for economic reasons, as well as increasing needs and sustainability considerations, tall buildings have been occupying more and more space in urban areas in the last few decades. As the height of the building increases, or rather its slenderness, the main, or dominant, loads change. As the height of the building increases, the key safety and usability factors are derived from seismic and wind forces, while for low and medium-height buildings this factor is formed by gravitational loads [14] [15] [1] [2]

There are three main factors that control the design of tall and slender structures: strength (material resistance), stiffness (displacement), and serviceability (perception of motion and acceleration), which are caused by the action of lateral loads, such as wind and seismic. The shape and geometry of the building most often indicate which factor governs the overall design. As the building becomes taller, and therefore slenderer, displacement considerations become increasingly important. Simply proportioning the efficiency of the elements, based on the maximum lateral displacement, replaces design based on allowable stress criteria.

The design of tall structures presents numerous problems, such as the number of columns, their dimensions, or the size and shape of the concrete core, and even the basic dimensions of the structure itself [3].

As the height of a building increases, the wind forces can exceed the seismic forces, which are reduced by the response modification factor R (or RE). Current requirements for elastic wind resistance design often lead to excessive stiffness and strength requirements for horizontal members, i.e. beams, tie beams and bracing. Under seismic loading, vertical members and connections also increase in size, due to over-dimensioned bracing.

Undeniably, the factor that governs the design of a tall and slender structure the vast majority of the time is not in the stressed or fully stressed state, but rather the displacement of the building. There are a number of structural lateral systems used in the design of tall buildings such as: shear frames, shear trusses, shear core frames, frame tubes, truss tubes, etc. However, it is the system of stabilizers and belt trusses that provides significant control over the displacement of the building [3].

Peer-reviewed research recently conducted by Aswegan et al. 2017 designed performance-based extreme wind loading (PBWD) at the scale of tall structures, thus opening the way to consider inelastic behavior beyond traditional elastic design paradigms.. Mohammadi et al. (2019) performed an assessment of performance under extreme wind load using nonlinear time-history analysis (NTHA). El Damatty and Elezaby (2018) and Elezaby and El Damatty (2020) proposed to reduce the resonant component of the design wind load by two to include the inelastic behavior under wind load. In wind engineering, they adopted design based on ductility. The structural characteristics are verified by pushover analysis and the resulting ductility requirements. The NTHA check was not carried out. Bezabeh et al. (2020) and Alinejad et al. (2020) proposed frameworks for inelastic wind design, including seismic and wind hazard scenarios.

Unlike performance-based seismic design (PBSD), there is little guidance for PBWD in practice. Inelastic behavior of structural components resisting lateral loads or ductile actions, such as the connecting beam, strut, and slender wall, is allowed while maintaining the capacity to resist gravity loads, which is consistent with the minimum performance requirement for gravity load

capacity under earthquakes in PBSD [ASCE 41-17 (ASCE 2017b)].

However, there is little information on how to introduce inelastic behavior into the initial design and the acceptance criteria for inelastic performance at element levels.

Several researchers have studied NTHA for wind loading (Aswegan et al. 2017; Mohammadi et al. 2019). Their research relied on wind tunnel tests to obtain wind loads over time. A final wind load check in a certain time from a wind tunnel test is inevitable. However, it is difficult to use wind tunnel test results for initial PBWD in practice due to frequent design changes and costs [4].

2. Methodology

This study applies a systematic literature review (SLR) approach to evaluate and summarize current research on wind and seismic load modeling in high-rise reinforced concrete structures. The methodology is structured in accordance with widely accepted review protocols (eg PRISMA guidelines), ensuring transparency and repeatability of the process.

2.1 Selection and literature Sources

The literature selection and search was carried out using internationally recognized scientific databases, primarily Google Scholar, Scopus, Web of Science and ScienceDirect, also with additional works from some selected publications of professional associations (eg ASCE, fib, CTBUH). The search terms included keywords such as: "tall buildings", "reinforced concrete", "wind load modelling", "seismic load modelling", "performance-based design" and "Eurocode/ASCE/JUS standards", in fact the same key words.

Only peer-reviewed journal articles, conference papers, and technical reports published between 2000 and 2025 were considered and taken to capture both historical context and recent advances.

2.2 Inclusion and exclusion criteria

Inclusion: Studies that focus on (i) analytical, numerical or experimental modeling of wind loads or seismic loads in tall reinforced concrete structures; (ii) design comparisons based on regulations (Eurocode, JUS, ASCE, IBC, UBC); (iii) integrated studies that consider both the effects of wind loads and the effects of seismic loads.

Exclusion: Studies whose research is limited exclusively to low-rise structures, exclusively pure architectural research without a structural focus, or studies that lack proven system modeling methodologies.

2.3 Data evaluation

For the selected publications, data on:

Methodological approach, whether it is an analytical, numerical or experimental approach.

Types of action studied (wind, seismic or combined).

Structural parameters (building height, structural system, material properties).

Applied regulatory framework.

Key outcomes and identified limitations.

The studies are categorized into two primary groups - wind load modeling and seismic load modeling - with an additional comparative section synthesizing the integrated perspectives.

2.4 Research questions

To guide the review, two central research questions were formulated:

RQ1: *What is the development in the approach to modeling wind and seismic loads in tall reinforced concrete structures over the last two decades and what are their methodological advantages and limitations?*

RQ2: *Which load, i.e. lateral action (wind or seismic) appears as the dominant load case and how consistently is this addressed in the literature, considering known parameters, building height, structural and regional conditions?*

3. Wind Load Modeling in High-Rise Concrete Structures

One of the most important variable loads in tall buildings is wind. In relation to low-rise buildings, high-rise buildings and other tall structures play a very important role in dynamic effects such as vortex shedding and resonance, which can result in increased displacements and vibrations. Wind load modeling requires a combination of code-compliant calculations, experimental methods, and numerical simulations [5].

3.1 Code-Based Modeling

Code approaches, such as Eurocode EN 1991-1-4 and ASCE 7, are based on the calculation of wind speed or wind pressure, terrain factors and building shape coefficients. They are simplified and do not always take into account non-linear effects, and allow engineers to evaluate the effect of wind effects relatively quickly. In some Balkan countries, JUS U.C7.110 standards are still applied, which define wind loads based on zones and categories of terrain.

3.2 Experimental Methods

In the case of experimental calculations, primarily aerodynamic tests in wind tunnels, they are used for more complex shapes and tall buildings that go beyond the standards and simplified methods from the given codes. These tests, as I expect, give a more realistic picture of the interaction of the wind and the structure, especially in terms of oscillations and vibrations. Their disadvantage is a relatively high price and the need for specialized laboratories [6].

3.3 Computational Fluid Dynamics (CFD)

CFD methods have advanced significantly in recent years and are used as an alternative to wind tunnels. These methods enable the simulation of air flow around the structure using numerical algorithms, eg RANS or LES turbulence models. The advantage of CFD is flexibility, but there is still the challenge of verifying the results, which results in a long process and therefore a large expenditure of time [7].

3.4 Performance-Based Wind Engineering (PBWE)

PBWE is being developed as a new contemporary approach that goes beyond traditional code methods, focusing on construction performance in real conditions. This approach includes assessment of user comfort, non-linear behavior and long-term effects, making it relevant for high-rise buildings in urban environments [8].

4. Seismic Load Modeling in High-Rise Concrete Structures

Seismic forces, or seismic effects, are a key factor in the design of buildings in seismically active areas. They are very different from the effects of wind because they represent short-term but intense loads, usually accompanied by large accelerations and displacements. Designing in seismically active areas requires knowledge of the structure's behavior in both linear and non-linear areas and the possibility of energy dissipation.

4.1 Code-Based Approaches

Code calculations, such as Eurocode 8 (EN 1998-1) and ASCE 7, use modal analysis and spectral methods to estimate seismic forces. These approaches enable simpler calculations but ignore the details of the structure's behavior in non-linear phases. As for wind, so also for seismic actions, JUS U.J1.050, which defines seismic zones and basic horizontal forces, is still applied in some countries of the southern Balkans. Although they are already outdated, they still serve as a reference in local procedures and budgets.

4.2 Nonlinear Time-History Analysis

This method is the most detailed method of seismic analysis, which includes the calculation of the structure's response to real or synthetic records of earthquakes. The advantage is that material nonlinearities and higher mode effects are included. The disadvantage of this method is its complexity and the need for strong computer support [9].

4.3 Performance-Based Earthquake Engineering (PBEE)

The PBEE method approach goes beyond the classic philosophy of "life protection" and deals with the consideration of functionality, economic losses and sustainability, thus enabling a broader analysis of the impact of earthquakes on infrastructure and society. Although it is still only developed in academic frameworks, its practical application encounters challenges due to the complexity and lack of regulation [10].

4.4 Recent Developments

New research trends include soil-structure interaction (SSI) analyses, the application of composite systems, and innovative damping methods. Special focus is on dual systems (core + frame), which show greater resistance and reduction of displacement in tall buildings [11] [12]

5. Comparative Insights: Wind vs. Seismic Load Dominance

In order to design tall reinforced concrete buildings, an understanding of the interaction and relative importance of wind and seismic loads is required. While gravitational loads dominate in lower buildings, as mentioned earlier, in tall buildings lateral effects become crucial for the dimensioning of elements, stability and ultimate user comfort. A review of the literature reveals that the transition in the dominant load depends on several factors, including building height, oscillation period, system stiffness, regional climatic and seismic conditions, and applied codes.

5.1 Influence of Building Height

Studies show that for buildings up to approximately 10–15 stories, seismic impacts usually dominate in seismically active areas, while wind rarely becomes a dominant or critical factor. However, above 20–25 floors, especially in areas where strong winds prevail, the wind can take the primary role, causing larger total displacements and relative displacements-drift, compared to the earthquake. (Thilakarathna et al., 2018; Holmes, 2015).

5.2 Regional Context

In areas where there is a high seismic risk (eg Turkey, the Balkans, California), seismicity still very often remains dominant even in tall buildings, because the standards, or codes, require high safety factors. On the other hand, in areas with a weak seismic effect, but strong winds (e.g. northern Europe, coastal regions of Asia), wind can become a leading factor, even for medium-high buildings (20-30 floors).

5.3 Structural System Effects

The transition of the dominant load is significantly influenced by the type of construction. Skeletal RC systems show greater susceptibility to lateral movements and enter the wind dominated zone earlier. On the other hand, systems with an RC core or walls provide additional stiffness and extend the boundary when the wind becomes decisive. (Kareem & Tamura, 2013; Shaaban, 2022).

5.4 Code Provisions

Codes, or differences in them, also affect the perception of the "dominant" load. Eurocode 8 and JUS U.J1.050 often give more conservative seismic forces compared to Eurocode EN 1991-1-4 or JUS U.C7.110 for wind. ASCE 7, with its gust factor approach, better reflects the real dynamic effects of wind, while the PBEE and PBWE approaches offer a more flexible assessment depending on performance.

5.5 Synthesis

At the end of the literature review, it can be said that there is no unique limit in the height or number of floors when one load definitely dominates. It can be said that the transition depends on local seismicity, wind characteristics, choice of construction system and code philosophy. However, based on all the data collected so far, there is a consensus that for buildings taller than 80-100 m, wind impacts begin to play an equally important, and often dominant, role in relation to seismic effects - except in areas of high seismic activity, where earthquakes continue to play a primary role [2] [5] [6] [11].

For a clearer overview, below is Table 1, which shows a comparison of the Eurocode, ASCE and JUS approaches (for wind and seismic).

Tab. 1. Comparison of Eurocode, ASCE and JUS approaches for wind and seismic

Aspect	Eurocode (EN 1991 & EN 1998)	ASCE 7 / IBC	JUS standards (U.C7.110, U.J1.050)
Wind – methodology	Quasi-static calculation + shape coefficients, terrain and height; partially dynamic effects	Density factor method, taking turbulence and resonance into account	Simple calculation based on wind zones and shape coefficients
Seismics – methodology	Spectral analysis, pushover, time-history as an option; clear categorization of soil and behavioral factors	Similar to Eurocode, with slightly more conservative load combinations	Horizontal forces defined for seismic zones, without nonlinear analysis
Tall buildings	Requires advanced analysis above 40 m; integration with PBSD	Strong emphasis on PBEE and multimode effects	Limited application, design obsolete for buildings >10 floors
Regional application	Mandatory in the EU, including BiH (with national annexes)	Primarily US, but globally referenced	Still used in BiH and the region in local tasks and older projects

6. Challenges and Research Gaps

Although much progress has been made in understanding and modeling wind and seismic loads, there are numerous challenges and gaps that hinder the practical application and global harmonization of knowledge. The following is an overview of the key challenges highlighted by the literature.

6.1 Lack of Integrated Methodologies

The studies that are available, the vast majority of them focus exclusively on one type of load - either wind or seismic - while studies that simultaneously and equally treat both loads remain rare. This creates such a situation that engineers do not have reliable guidelines for cases where both loads act competitively, which is a very common case in high-rise buildings. The lack of integrated methodologies also makes it difficult to assess the transition limit of the dominant load. Some authors advocate the development of hybrid approaches that combine the principles of Performance-Based Wind Engineering (PBWE) and Performance-Based Earthquake Engineering (PBEE), however, such models have not yet been standardized. This gap creates the risk that design is guided by a conservative approach, resulting in increased costs and increased material consumption.

6.2 Variability in Code Provisions

Normative frameworks differ significantly between regions, resulting in harmonization problems. Eurocode, ASCE 7 and JUS standards use different calculation philosophies, leading to different results even for the same input parameters. While Eurocode emphasizes response spectra and modal analysis, ASCE 7 gives greater importance to turbulence effects and multimode influences, while JUS norms with their simplified methods are not fully adapted to tall buildings. Because of these differences, international companies and researchers encounter difficulties when trying to compare results between different codes. As a consequence, there are often contradictory findings in the literature regarding when wind or seismic become dominant, because the methodology itself directly affects the conclusion.

6.3 Limited Experimental Data

As mentioned earlier, experimental research, such as tests in wind tunnels and shake-table tests, are essential for the validation of numerical and code models, but such experiments are extremely expensive and technically very demanding, especially for buildings above 30 floors. Only a small number of global laboratories can perform such tests, and the results are usually unavailable to the general professional public. The lack of high-quality experimental data means that most researchers rely on numerical simulations, which can lead to overestimated or underestimated results. When it comes to the context of the Southern Balkan countries, there is almost no experimental data on local wind fields and seismic conditions, which makes designing even more challenging.

6.4 Computational Challenges

Advanced analysis methods, such as CFD simulations for wind and nonlinear time-history analyzes for seismic, require high computational resources and expertise. Although they enable a more realistic assessment of building behavior, their wide application in engineering practice is limited due to the complexity of modeling and the long duration of simulations. In realistic design deadlines, designers often resort to simplified models, which leads to a compromise between accuracy and practicality. Additionally, the lack of detailed databases on wind and seismic loads makes it difficult to verify the numerical results. As a result, many studies remain theoretical in nature, and the transition to practice is slow.

6.5 Regional Context Gaps

Although there are numerous studies in North America, Japan and China, there are still few works that deal in detail with Balkan or Central European conditions. Regional specificities, such as strong seismicity in the south of the Balkans and pronounced wind fields in coastal and mountainous areas, are rarely included in international studies. This means that engineers in BiH, Serbia, Croatia or Montenegro often have to use conservative estimates that are not validated by local measurements. The lack of regional research limits the development of local Eurocode annexes and leads to increased construction costs due to an excessive safety margin, although in the early 2000s there were such projects and there is still a clear need for projects that will include regional measurements of wind and seismic activity and develop databases that would serve as a basis for future regulations and recommendations [8] [11] [13].

7. Future Directions

In order to overcome existing challenges and gaps in research, practice and literature suggest a number of guidelines for the further development of methodologies for modeling wind and seismic loads in tall reinforced concrete structures.

7.1 Development of Integrated Frameworks

Future research should develop integrated methodologies that simultaneously analyze wind and seismicity, rather than partially. The combination of PBWE and PBEE approaches could lead to a comprehensive model that better reflects real conditions and enables making safer and more economical design decisions.

7.2 Harmonization of Design Codes

The harmonization of international norms is something that must be worked on further, as well as their adaptation to local conditions. Creating a universal manual that would compare and harmonize Eurocode, ASCE and JUS standards would help engineers to work more easily in different contexts. Such harmonization would be especially important for regions in transition, such as the Southern Balkans, which is also somewhat of a political matter.

7.3 Strengthening Experimental and Field Data

A greater number of experimental studies and data collection in real conditions are needed, especially for buildings with more than 30 floors. Long-term monitoring of existing facilities (e.g. installation of sensors for displacement and vibration measurement) could significantly improve the validation of numerical models and increase confidence in the analysis results.

7.4 Leveraging Computational Advances

Further development of computing methods such as high-performance computing, parallel programming and the application of artificial intelligence (AI) in CFD and nonlinear analyzes opens up space for faster and more efficient simulations. The introduction of digital twins in tall buildings would enable continuous monitoring and simulation of performance in real time.

7.5 Regional and Local Adaptations

Special attention should be paid to regional research, because it is common knowledge that global models often do not reflect local specificities. In the Balkans, it is necessary to develop local databases for wind and earthquakes and to update the national annexes of the Eurocode accordingly. This would allow designers to work with more realistic, and perhaps not too conservative, parameters [8] [10] [13].

8. Discussion

A review of the literature indicates that wind and seismic loads are crucial for the design of tall reinforced concrete structures, but their relative importance also depends on several factors: first of all, the height of the building, then the stiffness of the system, geographical location and the applied normative framework. It is also observed that seismic effects dominate in low- and medium-rise buildings in seismically active areas, while wind becomes increasingly important in buildings above 80–100 m, especially in regions with pronounced wind fields.

A comparison of code approaches shows that there is significant variability among Eurocode, ASCE and JUS standards, resulting in different calculations and design decisions. Eurocode and ASCE increasingly include performance-based methods, while JUS norms remain simplified and conservative. This highlights the problem of inconsistency in international practice and the need to harmonize standards.

Additionally, although advanced methods such as CFD simulations and nonlinear time-history analyzes provide more realistic results, their application in practice remains limited due to both complexity and high costs. The lack of experimental data, especially for the Balkans and similar regions, further emphasizes the gaps and the need for local and even regional research.

9. Conclusion

This literature shows that understanding the interaction of wind and seismic loads is one of the key issues in the modern design of tall buildings. Seismicity continues to dominate in seismically active regions and in buildings up to medium height, while wind becomes decisive in buildings above 20–30 floors, depending on local climate conditions and the type of construction system.

The biggest challenges identified in the literature include the lack of integrated methodologies that simultaneously treat wind and seismicity, variability in standards and lack of experimental data. Further development of integrated performance-based approaches, strengthening of international harmonization of codes and implementation of regional research are recommended.

Ultimately, the future of designing high-rise reinforced concrete buildings depends on the ability to see the effects of wind and seismic effects not only through the prism of safety, but also through the criteria of economy, sustainability and long-term functionality. This will enable making more reliable and efficient design decisions, especially in regions with complex combinations of climatic and seismic loads.

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