Structural Response of Power Transmission Line Towers to Extreme Wind Events- A Critical Review

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Abstract

Transmission line towers are lifelines of modern power grids, yet their vulnerability to extreme and non-synoptic wind events - downbursts, tornadoes, hurricanes, and combined multi-hazard conditions - remains poorly addressed in current design practice. This review synthesizes findings from experimental testing, finite element modelling, computational fluid dynamics, probabilistic fragility analysis, machine learning surrogates, and a patent survey spanning 1990–2025, to critically assess where knowledge stands and where standards fall short. Quasi-static design codes consistently underestimate peak demand: downburst dynamic amplification factors reach 3.5, maximum skewed wind loading occurs at 30° rather than the code-assumed 45°, and sandstorm conditions alone inflate structural demand by up to 25.6%. Structurally, collapse initiates at compressed members below the lower cross-arm through bidirectional instability - a failure mode that geometric imperfections can trigger even in code-compliant towers. Foundation flexibility, tower-line coupling, and multi-hazard loading introduce further demand that no current standard explicitly captures. Patent filings have grown sharply since 2010 - yet the gaps are striking. Downburst load methods, tornado-resilient geometries, probabilistic fragility tools, and interoperable digital twin standards all remain absent from the IP landscape. Five targeted code modifications are proposed, alongside a tiered site-specific hazard assessment framework. Priority research needs include full-scale non-synoptic wind measurements, coupled system modelling, and reliability-based design approaches tailored to regional hazard profiles.

Keywords: Transmission line towers, extreme wind, structural response, fragility analysis. downburst, tornado, dynamic amplification

Introduction

The transmission line towers are one of the critical infrastructures for global power distribution. They ensure reliable electricity delivery across vast distances to support modern economies. However, these structures are increasingly vulnerable to extreme wind events, such as downbursts, hurricanes and tornadoes, which leads to widespread outages and significant economic losses. The problem is not ignorance of these risks - it is that most design codes still treat wind as a stationary, horizontally uniform boundary layer flow, an assumption that downbursts and tornadoes break in every meaningful way. Aboshosha et al. (2016) review the dynamic and quasi-static buffeting responses of transmission lines under non-synoptic winds like downbursts. Highlighting the need for advanced modelingto account for tower-line interactions, which are often overlooked in standard designs. Meanwhile Zhang et al. (2024) highlight that neglecting tower-line coupling dynamics under strong winds underestimates transverse force impacts, which may lead to increasing failure risks. This review focusses on the recent advancements to address these challenges.

1.1 Overview of Transmission Line Infrastructure

The backbone of any electrical grid is its transmission line system - a mix of lattice towers, pole structures, conductors, insulators, and foundations that must work together reliably under conditions the designers may never have anticipated. The main role of this tower is enabling high-voltage electricity transfer from power plants to distribution networks. Particularly in the regions with dispersed populations, such as rural India or coastal zones prone to extreme weather, these systems are vital for energy reliability. Rao et al. (2012) investigate the structural behaviour of lattice transmission towers through full-scale testing, identifying failure mechanisms under extreme loads, which highlights their vulnerability to environmental forces like wind and their critical role in maintaining power delivery. Bi et al. (2023) demonstrated through long-term field wind data and nonlinear dynamic analysis that transmission tower-line systems must account for the coupled effects of wind speed, wind direction, and line orientation to accurately assess failure risk, with tower collapse under high winds generating unbalanced loads that propagate as cascading failures to adjacent towers, thereby undermining overall grid stability.

1.2 Definition and Classification of Extreme Wind Events

Based on their meteorological characteristics, extreme wind events impacting transmission towers are classified into synoptic and non-synoptic categories. Synoptic winds, such as those from hurricanes, involve large-scale, sustained winds exceeding 33 m/s with predictable patterns. The non-synoptic winds, including downbursts and tornadoes, are characterized by sudden, localized gusts. Aboshosha et al. (2016) states non-synoptic winds, such as downbursts, as thunderstorm-induced events with high-intensity outflows (up to 60 m/s), featuring transient velocity profiles that differ from synoptic winds and tornadoes' rotational patterns. Fang et al. (2022) characterize downbursts as downdrafts producing horizontal winds up to 67 m/s over 2-5 minutes, with dynamic amplification factors (DAF) ranging from 1.0 to 3.5 in tower-line systems, critical for modeling coupled responses. Lombardo et al. (2014) established that thunderstorm winds, including downbursts, exhibit non-stationary velocity profiles and shorter temporal scales than standard boundary layer winds, making them fundamentally distinct from the synoptic wind assumptions embedded in most current design codes.

1.3 Motivation for the Study: Recent Global Failures and Climate-Driven Changes in Extreme Wind Patterns

The numerous transmission tower failures and increasing frequency and intensity of extreme wind events, driven by climate change, have motivated this review. Gonçalves et al. (2024) documented that extreme weather events - spanning windstorms, extratropical cyclones, ice storms, and lightning - are among the leading causes of wide-area electrical disturbances worldwide, with transmission and distribution infrastructure proving particularly susceptible to wind-driven damage and cascading outages across both developed and developing grid systems. Wang et al. (2025) demonstrated that rising sea surface temperatures — a key marker of ongoing climate change — substantially elevate typhoon-induced structural demands on coastal transmission tower-line systems, with axial forces increasing by up to 32.20% and tower-top displacements rising by 63.37% under the most severe projected climate scenario (SSP5-8.5) relative to historical baselines, underscoring that existing design standards are increasingly inadequate for future wind regimes. These failures, coupled with projections of more severe storms, signal the urgent need to enhance tower resilience to mitigate economic losses and ensure grid reliability.

Gaps in Accounting for Non-Synoptic Wind Effects

Transmission line towers face growing threats from extreme non-synoptic winds like downbursts, which are increasing due to climate change. Most of the current design codes largely rely on synoptic wind assumptions and quasi-static methods which underestimate dynamic effects and system coupling. Therefore, it is essential to highlight these gaps, summarize the latest research, and recommend improved wind load rules, safety factors, and region-specific designs to make transmission towers safer and more resilient.

Researchers have identified critical limitations in current design approaches for transmission towers facing non-synoptic winds like downbursts and tornadoes, which strike suddenly and locally. Zhang et al. (2024) point out that quasi-static methods ignore essential tower-line coupling dynamics, leading to underestimated transverse forces and elevated failure risks during intense winds. Similarly, Fang et al. (2022) stress that downburst analyses frequently overlook tower-line interactions, where dynamic amplification factors ranging from 1.0 to 3.5 indicate substantial additional loads overlooked in regions outside typhoon zones. Rao et al. (2012), through full-scale experiments, revealed intricate failure patterns in transmission towers under extreme conditions, indicating that deterministic models cannot adequately address the variability inherent in non-synoptic wind effects and calling for more sophisticated failure assessment techniques. Such shortcomings emphasize the urgency for advanced dynamic modeling and coupled system studies to strengthen tower resilience.

Scope and Objectives of the Review

The core objectives of this review are to critically evaluate the structural response of transmission line towers under extreme wind events such as downbursts. The examination of recent experimental, numerical, and probabilistic studies to identify key gaps in current wind load modelling, dynamic analysis, and design standards. The primary objective is to propose revised safety factors, region-specific design parameters, and improved hazard mapping strategies, to enhance the resilience of transmission infrastructure against climate-driven wind extremes.

This review pursues four interconnected aims. The first is to examine how well existing national and international design codes handle the spatial-temporal complexity of non-synoptic wind events - something their quasi-static foundations were never built to do. The second is to map the research landscape honestly, naming the deficiencies that matter most: the gaps in tower-line dynamics data, the scarcity of localised wind records across diverse climates, and the immaturity of probabilistic collapse methods in routine practice. Third, this review translates those research findings into concrete code modification proposals - not general observations, but specific changes to safety factors, load combinations, and analysis procedures that existing standards could adopt without waiting for further experimental campaigns. Finally, it makes the case for region-tailored hazard assessment: local topography, historical storm tracks, and climate projections should drive tower design in coastal cyclone zones and arid sandstorm corridors, not a single national wind speed map.

Earlier reviews, notably Roy and Kundu (2021), have documented the range of vibration control strategies developed for wind-loaded transmission towers - from tuned mass dampers to magnetorheological systems

- but stopped short of addressing non-synoptic wind events, probabilistic fragility assessment, and the growing role of data-driven structural monitoring. The present review picks up where those efforts left off. Its core aim is to assess how transmission towers behave under extreme and non-synoptic wind events - downbursts, tornadoes, and combined multi-hazard conditions - drawing on experimental, numerical, and probabilistic evidence published largely in the past decade. Gaps in current wind load modelling, dynamic analysis methods, and design standards are identified, with practical recommendations made for revised safety factors, region-specific design parameters, and improved hazard mapping - all directed toward making transmission infrastructure more resilient against a changing wind climate.

Methodology of Review

Collection of prior arts

The comprehensive literature review was done from major academic databases such as Scopus, Web of Science, Google Scholar, ASCE Library, ScienceDirect and supplemented by Engineering Village and CNKI for region-specific studies. From an initial pool of papers identified through systematic keyword searches ("transmission tower wind loading," "downburst effects," "tower-line coupling"), most of the peer-reviewed articles spanning 1996-2025 were retained after rigorous screening. The studies on wind effects (synoptic and non-synoptic) specifically addressing lattice transmission towers through experimental, numerical, or field-based structural analysis with quantitative results, prioritizing journal articles and high-impact conference papers are included in the present study. Papers were excluded if they focused exclusively on non-lattice designs, lacked structural engineering content, or were inaccessible non-English publications without translation. The present study covers of three decades of research while maintaining focus on methodologically robust contributions to wind resilience design.

Types of Extreme Wind Events

Synoptic winds are broad-scale atmospheric flows produced by persistent pressure gradients over large regions, and they are commonly associated with systems such as trade winds, westerlies, fronts, and cyclones. In contrast, non-synoptic winds include downbursts, microbursts, tornadoes, and gust fronts, which are typically short-lived, highly localized, and generated by convective storm activity. For transmission infrastructure, these non-synoptic events are especially critical because their sudden onset and spatial variability can produce loading patterns that differ significantly from conventional design assumptions. Aboshosha et al. (2016) emphasized that both dynamic and quasi-static responses of transmission lines to synoptic and downburst winds must be understood more accurately, since present code provisions do not adequately address tall towers or localized downburst effects.

Aboshosha et al. (2016) further developed a fragility-based framework for transmission towers subjected to downburst winds, incorporating uncertainty in both structural resistance and wind loading. Using finite element modeling and nonlinear buckling analysis, they identified the first tower segment as the most vulnerable region, with buckling initiating there under severe loading. Their results showed that the maximum structural response occurred at a radial distance of about 1.6 times the downburst diameter, and the fragility curves indicated that downburst winds produce a higher failure likelihood than atmospheric boundary layer winds. They also observed that wind attack angle and tower orientation strongly influence response, with an arrangement near 157.5° giving comparatively lower vulnerability. A limitation of this study is that the wind field is still idealized, so the complexity of actual storm evolution and terrain interaction is not fully captured.

Zhu et al. (2023) examined a 1000 kV ultra-high voltage transmission tower-line system under downburst loading using nonlinear dynamic analysis. Their study showed that tower-line coupling produces a dynamic amplification factor between 1.1 and 1.3, suggesting that interaction effects may slightly reduce vibration demand rather than always intensify it. They also reported that the most unfavorable response occurs when the height of peak wind speed aligns closely with the tower height of 108 m. Storm movement speed had only a minor influence under the vector superposition assumption, but the characteristic radius had a major effect, and values below 0.4 were considered unsafe. This study is useful because it moves beyond static treatment of downburst loading, although its conclusions remain dependent on simplified wind modeling assumptions.

For tornado loading, Hamada et al. (2010) developed a nonlinear finite element model using CFD-generated F4 and F2 tornado wind fields and validated the approach with full-scale data. Their findings showed that internal axial forces under F4 tornadoes can exceed those under F2 tornadoes and even normal wind conditions by as much as 15% when a three-dimensional wind field is used instead of an axisymmetric one. This demonstrates that tornado-induced demand is highly sensitive to the wind field representation. However, the study is limited by the difficulty of generalizing tornado intensity and shape beyond the tested cases.

Zhang et al. (2024) used Wen's three-dimensional tornadic velocity model to study a 131 m high transmission tower in East China. They found that lateral tornado loading created stronger and more irregular responses than longitudinal loading. While immediate strength failure was unlikely, cumulative fatigue damage still needed attention, and joint optimization reduced fatigue damage by about 30%. Compared with atmospheric boundary layer winds, tornadoes caused much larger peak responses, although ABL winds produced slightly greater fatigue damage. This result is important because it shows that extreme winds may not always govern fatigue in the same way they govern peak strength demand. At the same time, the findings are specific to one tower form and one tornado model, so broader application should be done carefully.

Reinoso et al. (2020) shifted the focus from structural response to probabilistic risk assessment by incorporating tower-cable interaction and intermediate damage states in a hurricane-based framework. Using Mexican hurricane data, they estimated expected annual losses of up to $181,000 USD for one transmission line segment and found that using actual tower locations changed risk estimates by as much as 22% compared with lumped exposure assumptions. This approach is valuable because it connects structural behaviour with economic consequences, making it useful for planning and resilience assessment. However, it depends strongly on the quality of hazard data and regional exposure information.

Overall, these studies collectively show that extreme wind effects on transmission towers cannot be represented adequately by a single deterministic design approach. Synoptic winds are more suitable for conventional load models, whereas downbursts and tornadoes require dynamic, spatially varying, and probabilistic treatment. The main requirement is the transmission towers must be designed to remain simple and economical, yet they also need to respond safely to highly complex and uncertain wind events. The inventive direction suggested by these studies is to resolve this contradiction through adaptive design tools, refined fragility models, and coupled tower-line simulations rather than by adding only more conservative static safety margins.

Comparative discussion

Study	Main focus	Key finding	Limitation
Aboshosha et al. (2016)	Downburst fragility	Downbursts are more damaging than ABL winds; first tower section is most vulnerable	Relies on idealized wind representation
Zhu et al. (2023)	Downburst tower-line dynamics	Coupling produces a DAF of 1.1 to 1.3	Simplified wind-field assumptions
Hamada et al. (2010)	Tornado loading	F4 tornado loads exceed F2 and normal wind loads	Limited generalization across tornado scenarios
Zhang et al. (2024)	Tornado response and fatigue	Lateral wind gives larger nonstationary response; fatigue reduced by joint optimization	Results are tower- and model-specific
Reinoso et al. (2020)	Probabilistic wind risk	Actual tower locations change EAL and risk estimates	Depends on regional hazard data quality

Contradictions and interpretation

Issue	What studies suggest	Interpretation
Tower-line coupling	May increase demand in some cases, but Zhu et al. (2023) found only moderate DAF values	Coupling effect depends on tower geometry, wind profile, and storm characteristics
Dominant failure mode	Some studies emphasize buckling and collapse, while others focus on fatigue accumulation	Extreme winds can govern both immediate failure and long-term deterioration
Wind-field modelling	3D and CFD-based fields often produce higher and more realistic responses than simplified fields	Accurate wind representation is essential for reliable design

The central contradiction is that transmission towers must remain structurally simple and economical and they must also resist highly complex and uncertain wind actions. The different methods suggested by the literature is not simply to increase safety margins, but to resolve this contradiction through adaptive modelling, probabilistic fragility analysis, and coupled tower-line simulation. This allows engineers to improve reliability without making the system unnecessarily heavy or expensive.

Wind Load Estimation on Transmission Towers

Recent studies have substantially improved the estimation of wind loads and the understanding of how transmission towers and tower-line systems behave under realistic and multi-hazard conditions. A major experimental contribution was made by Yao et al. (2022), who combined aeroelastic wind tunnel testing with finite element analysis for a 380 m high long-span transmission tower. Their results showed that along-wind and cross-wind displacement and acceleration responses were nearly comparable, while the measured gust response factor of about 1.38 was lower than many code-based predictions but still consistent with numerical simulation. They also demonstrated that vision-based displacement measurement can serve as a dependable non-contact technique for recording wind-induced vibration in controlled testing environments.

In parallel with experimental work, several researchers have moved toward data-driven surrogate models to predict complex structural response under wind and combined loading while reducing computational effort. Yang et al. (2025) developed a TimesNet-based deep learning surrogate model for transmission tower-line systems exposed to simultaneous wind and rain loading. Using nine realistic weather scenarios with wind speeds up to 35 m/s and rainfall intensity up to 120 mm/h, the model accurately predicted maximum displacement and line tension, while requiring only about 9 ms for inference. This indicates strong potential for real-time or near-real-time multi-hazard response forecasting.

Directional wind effects and conductor configuration also remain important sources of uncertainty. Song et al. (2022) investigated two-span six-bundled conductors through aeroelastic wind tunnel tests and found that mean transverse tension generally followed a $\sin^2\theta$ trend for wind angles above 40°. At wind speeds above 35 m/s, the force coefficient approached 1.0 at 90°, while longer insulators increased tension but reduced swing angle. Their measured wind force coefficients were lower than the corresponding Chinese code values, suggesting that design standards may be conservative for some directional and bundling conditions.

For purely wind-driven nonlinear dynamic behaviour, Zhao et al. (2025) used an LSTM-based deep learning framework to predict displacement, acceleration, and stress in transmission tower-line systems subjected to wind speeds up to 25.3 m/s. The model achieved more than 90% accuracy and could also reconstruct incomplete time-series data, making it suitable for structural health monitoring and early warning applications. This study is significant because it captures nonlinear interaction effects that are difficult to model efficiently using only conventional numerical simulation.

Beyond wind alone, several studies have extended the problem to multi-hazard conditions such as ice shedding and sandstorms. One machine-learning study based on finite element simulation data predicted post-ice-shedding responses of transmission lines, including maximum jump height, horizontal swing, and unbalanced tension. Among the tested algorithms, Extra-Trees provided the best trade-off between prediction accuracy and speed, making it a practical surrogate for icing-related design scenarios. Similarly, Zhang et al. (2022b) studied wind-sand combined loading using SAP2000-based simulations with sand particle loads derived from momentum conservation. Their results showed that sandstorms can increase displacement and axial force by as much as 25.6% at 25 m/s wind speed, leading them to recommend an amplification factor of about 1.25 for arid and sandstorm-prone regions.

Taken together, these studies show a clear shift in the field from isolated wind load testing toward hybrid experimental, numerical, and machine-learning approaches, which can handle nonlinear tower-line coupling and multi-hazard interaction more efficiently. They also suggest that current codes may be either conservative in some directional loading cases or insufficiently detailed in complex environmental scenarios. The engineers want a simple and economical design rule, but the actual loading environment is highly variable, nonlinear, and multi-dimensional. The emerging solution path is to replace one-size-fits-all assumptions with adaptive, data-informed, and scenario-specific modelling strategies.

Comparison of researchers results

Author	Main focus	Key finding	Practical implication
Yao et al. (2022)	Aeroelastic tower response	Along-wind and cross-wind responses were nearly equal; GRF about 1.38	Code values may overestimate response in some cases
Yang et al. (2025)	Wind-rain surrogate model	TimesNet predicted displacement and tension accurately in 9 ms	Suitable for real-time prediction
Song et al. (2022)	Bundled conductor loading	Transverse tension followed $\sin^2\theta$ for angles above 40°	Direction and bundle layout strongly affect design loads
Zhao et al. (2025)	Wind-induced nonlinear response	LSTM predicted displacement, acceleration, and stress with >90% accuracy	Useful for health monitoring and early warning
Ice-shedding machine-learning study	Post-icing response prediction	Extra-Trees performed best among tested models	Fast surrogate for icing design
Zhang et al. (2022b)	Wind-sand loading	Sandstorms increased response by up to 25.6%	Regional amplification factor may be needed

Contradictions and interpretations

Issue	Observed difference	Interpretation
Code conservatism	Yao et al. (2022) and Song, Liang, Mei and Zou (2022) found measured coefficients lower than code values	Current standards may be conservative for some configurations
Response dominance	Some studies highlight displacement and vibration, while others emphasize tension or axial force	The governing response depends on tower type, conductor arrangement, and hazard type
Single-hazard vs multi-hazard	Wind-only studies and wind-rain/wind-sand studies give different load amplification patterns	Multi-hazard interaction cannot be captured reliably by wind-only design rules

Limitations across the studies

Limitation	Effect on results
Controlled laboratory conditions	May not fully represent real atmospheric variability
Case-specific tower geometry	Limits generalization to other tower types
Training data dependence in ML models	Reduces reliability outside the tested wind and hazard ranges
Simplified load assumptions	May underestimate true coupled response
Limited full-scale validation	Makes direct field application more uncertain

The ideal final result would be a method that predicts wind effects accurately in real time without requiring heavy computation or extensive manual modelling. The inventive direction is to combine physical experiments, numerical simulation, and machine learning so that each method covers the weaknesses of the others. Another useful principle is separation, that is instead of forcing one universal model for all cases, different approaches should be used for normal wind, directional wind, and multi-hazard conditions separately.

Structural Response of Transmission Towers Under Wind Loads

Recent research has significantly improved understanding of how transmission towers and related steel structures respond to wind loading, particularly in terms of nonlinear behaviour, collapse progression, fragility, and design optimization. Liu et al. (2024) developed a finite element model of a typical 220 kV transmission tower-line system and showed that wind-induced collapse usually begins with buckling in the compressed main members below the lower cross-arm. Their results also indicated that tower-line coupling reduces natural frequencies and increases the likelihood of resonance under strong winds near the design speed of about 37 m/s. The governing failure mode was identified as bidirectional compression-bending instability, highlighting the importance of dynamic lateral loads and interaction effects in structural design.

Li et al. (2023) focused on wind-induced vibration and fatigue damage in two-span tension cable-supported power transmission structures. Their nonlinear finite element model showed that wind direction has a strong influence on response, with 90° producing the most unfavourable condition. Fatigue damage was slightly greater near the cable ends than at the midpoints under 15 m/s wind speed. A notable strength of this study is its computational efficiency, since the proposed model required only about 4.19% of the cost of conventional ANSYS analysis while maintaining high accuracy. This makes it attractive for long-term fatigue assessment, although it is still limited to a specific structural configuration.

Campione (2024) shifted attention from the tower superstructure to the foundation, which is often overlooked in wind response studies. He proposed a closed-form analytical model for the moment-rotation behaviour of shallow reinforced concrete foundations supporting steel wind towers. The model explicitly includes foundation flexibility and correction factors for soil type, with values of 0.75 for cohesive soils and 1.3 for non-cohesive soils. The study also recommended practical design proportions such as a steel tube diameter of 1/15 of tower height, foundation diameter equal to 0.75 times the tower length, and foundation depth of 1/10 of its diameter. This work is useful because it simplifies foundation analysis, but it remains idealized and may not fully capture complex soil-structure interaction in highly variable field conditions.

Reliability considerations in structural wind engineering have increasingly shifted from checking individual members to evaluating the probability of global collapse. Arunachalam and Spence (2022) addressed this directly by building a collapse assessment framework for steel structures within a performance-based wind engineering context. The methodology paired a fiber-based nonlinear finite element environment - one capable of tracking progressive yielding, local buckling, and low-cycle fatigue damage simultaneously - with a stochastic wind load model calibrated against wind tunnel data. Stratified sampling replaced conventional Monte Carlo methods, cutting computational demands while still resolving the very small failure probabilities that govern rare collapse events. The braced-frame case study revealed a consistent and practically significant gap between member-level and system-level reliability estimates: the building as a whole proved more susceptible to collapse than any individual component assessment would suggest, with both along-wind and across-wind nonlinear responses contributing. For transmission towers - where geometric nonlinearity, slender member behaviour, and conductor coupling interact under high wind - this divergence between component checks and system performance is arguably even more pronounced and deserves direct attention in design.

Post-event damage surveys offer something that purely computational studies rarely can - ground truth at scale. Raj et al. (2022) exploited records from 2019 Cyclone Fani to build fragility curves for high-voltage towers in Odisha, a coastal Indian state battered repeatedly by severe cyclones and among the country's least-resourced in terms of infrastructure recovery capacity. Damage data from 87 collapsed and 128 partially damaged towers, obtained through formal government information requests, were used to fit lognormal fragility functions for two distinct damage states: outright structural collapse and the softer threshold of functionality disruption. Both aleatory uncertainty in the wind field and epistemic uncertainty tied to limited post-event wind speed records were explicitly carried through the analysis - a methodological rigour that many regional studies skip. The work did not stop at individual tower fragility. Simulating roughly 3,000 Fani-like tracks across a network of over 41,000 towers, the authors found that the cyclone's path relative to the coastline mattered as much as landfall intensity - a single degree of latitude shift could triple the number of damaged towers. Among 72 evaluated hardening strategies, those prioritizing towers by population weight of the served corridor consistently outperformed complex network-science metrics, pointing to a useful heuristic for resource-constrained grid operators. The limitation is one inherent to any region-specific fragility study: the curves reflect Odisha's particular tower stock, terrain, and wind climatology, and direct transfer to other coastal grids needs care.

Although much of the literature focuses on lattice towers, research on wind turbine towers offers useful insight for similar thin-walled steel shell structures. Gantes et al. (2024) showed through nonlinear finite element analysis that removing stiffening frames around door and ventilation openings, while moderately increasing shell thickness, can achieve similar stiffness and strength to conventional framed designs. In their example, a 65 mm thick shell without stiffeners performed comparably to framed designs in a 120 m tower section under realistic axial and flexural loading. This approach improves ductility and reduces fabrication complexity, although its direct transfer to transmission tower applications should be done carefully.

Ma et al. (2020) provided a more fundamental explanation of local buckling behavior in cylindrical steel shells under combined compression and bending. Using an energy-based analytical method supported by finite element validation, they showed that bending-induced ovalization can sharply reduce load-bearing capacity. Their result, expressed through the bifurcation moment relation $M_{Bi} = Er\pi t^3/[3(1-\nu^2)]$, gives a theoretical basis for understanding local instability in wind-exposed tubular members. While highly useful, this formulation is limited to idealized shell conditions and does not by itself capture the full complexity of tower assemblies.

These studies show a clear movement in the field from local member checks toward integrated analyses that include coupling, fatigue, foundation flexibility, probabilistic collapse, and regional fragility.

Comparative results of different researchers

Researcher	Main focus	Key result	Practical significance
Liu et al. (2024)	Tower-line collapse behavior	Collapse starts in compressed main members below lower cross-arm; coupling lowers frequency	Shows importance of dynamic interaction and resonance
Li et al. (2023)	Fatigue in cable-supported structures	90° wind angle is most unfavorable; model uses only 4.19% of ANSYS cost	Efficient fatigue assessment tool
Campione (2024)	Foundation flexibility	Soil type strongly affects moment-rotation response	Supports inclusion of foundation behavior in design
Arunachalam and Spence (2022)	Collapse reliability of wind-excited steel structures	Fiber-based nonlinear model with stratified sampling captures yielding, buckling, and fatigue; system-level collapse probability is consistently	Elastic member checks alone are insufficient; system reliability must be assessed independently

Researcher	Main focus	Key result	Practical significance
		higher than member-level estimates predict	
Raj et al. (2022)	Regional fragility and network resilience	Cyclone Fani damage data yields tower fragility curves for collapse and functionality disruption; population-weight-based hardening of coastal towers is most effective in reducing network functionality loss	Directly applicable to cyclone-prone coastal grids in developing regions
Schumann and Chini (2023)	Network-scale vulnerability	Older wooden poles and larger hurricanes cause greater efficiency loss	Links local damage to system performance
Gantes et al. (2024)	Thin-shell structural optimization	Removing stiffeners and thickening shell can maintain strength	Reduces complexity and fabrication effort
Ma et al. (2020)	Shell buckling theory	Bending-induced ovalization reduces capacity strongly	Explains local instability mechanism

Observations and interpretations

Issue	Different observations	Interpretation
Component vs system safety	Arunachalam and Spence (2022) found the gap between member-level and system-level failure probability to be practically significant, while earlier transmission tower studies largely stopped at component strength checks	Relying solely on member acceptance criteria risks overestimating the safety margin of the full structure under extreme wind
Strong wind effect location	Liu et al. (2024) identify lower cross-arm members as most critical, while Campione (2024) emphasizes foundation flexibility	Different parts of the structural system govern failure under different conditions
Code conservatism	Some studies suggest simplified designs may be conservative, while others show hidden vulnerabilities under nonlinear loading	Current codes may be adequate in some cases but unconservative in extreme or coupled conditions
Shell strengthening strategy	Gantes et al. (2024) show that removing stiffeners may still preserve strength, whereas Ma et al. (2020) show that shell ovalization can severely reduce capacity	Geometry optimization can improve performance, but local instability must still be controlled

Limitations across the studies

Limitation	Effect on findings
Idealized finite element models	May not fully reproduce actual boundary conditions and material imperfections
Limited field validation	Reduces confidence in transferring results to real towers
Region-specific fragility data	Limits generalization across climate zones and terrain types
Simplified soil and foundation models	May overlook nonlinear soil-structure interaction
Limited multi-hazard coupling	Wind-only or single-mode studies may underestimate real-world risk

At the outset the transmission towers must be economical and lightweight, yet they also need to withstand extreme wind loads with high reliability. The main intention is to create a design that provides full safety without adding unnecessary cost, weight, or complexity. One solution is to combine local buckling theory, foundation flexibility, probabilistic collapse assessment, and system-level modelling so that each part of the problem is addressed more effectively. The separation principle suggests that member failure, global collapse, and regional hazard characterization should not be treated as one single problem, but as linked design issues that require different modelling strategies.

Experimental and Numerical Investigations

Recent experimental and numerical studies have increasingly adopted hybrid methods that combine physical insight with high-fidelity simulation, especially for terrain effects and non-synoptic wind conditions that are difficult to reproduce accurately in conventional wind tunnel testing. Zhang et al. (2022a) used CFD to model airflow over a 100 m high butte with a 400 m diameter and its interaction with a transmission tower-line system. Their results showed a clear wind speed-up effect near the crest, where the speed ratio approached 1.0 at higher elevations, and the strongest vibration response occurred when the tower-line system was placed at the hilltop. On the windward side, the predicted dynamic response was reasonably close to Australian Standard and Eurocode estimates, whereas the leeward-side response was noticeably lower than code predictions. Since the study was carried out entirely in ANSYS using an average wind speed of 18 m/s at 10 m height, it demonstrates how CFD can capture terrain-induced flow distortion that is difficult to simulate in a standard boundary-layer wind tunnel.

The growing use of numerical methods for terrain-sensitive and non-synoptic wind analysis has also highlighted the increasing role of open-source CFD tools. Ricci (2024) reviewed nearly 300 studies in computational wind engineering and reported that OpenFOAM has emerged as the most widely used open-source platform, accounting for about 58% of built-environment studies and 12% of complex-terrain applications. The review also noted strong use of OpenFOAM in wind-structure interaction problems, especially because it supports advanced turbulence modelling, LES, and coupling with finite element solvers. This makes it highly relevant for transmission towers and conductors exposed to downbursts, tornadoes, and other localized winds. In that sense, the CFD framework used by Zhang et al (2022a) reflects a broader shift toward open-source, high-resolution simulation as a practical complement to aeroelastic testing.

A related development is the comparison of turbulence modelling strategies for unsteady aerodynamic prediction. Sheidani et al. (2023) compared URANS with the k-ω SST model and LES with the WALE subgrid-scale model for the wake of a 3-bladed NACA0021 vertical-axis wind turbine. They found that LES reproduced vortex shedding and wake structure much more accurately, while RANS produced larger modal energy but lost detail after the third POD mode. With more than 82% energy resolution and y+ values well below 1, LES was clearly superior for unsteady wake prediction. Although the geometry is different from a transmission tower, the underlying lesson is relevant: highly unsteady flow fields around slender structures are better represented by LES than by simpler averaged models.

For stationary tall structures, Moradi et al. (2024) compared RNG k-epsilon URANS with time-resolved DDES for a tall telecommunication tower. Both methods predicted mean pressure coefficients fairly well, but DDES performed better in capturing peak suction and short-duration pressure fluctuations near the tower head. Their results agreed well with experimental observations, showing that while standard URANS remains useful for average loading, hybrid RANS-LES approaches are preferable when unsteady peak loads are important. This creates an important distinction in practice: simplified turbulence models may be acceptable for mean response, but not for accurate estimation of extreme local loads.

Michioka (2024) studied a 21.6 m high cylindrical observation tower using large-eddy simulation to examine how local flow separation influences wind velocity and drag coefficient measurement. The study showed that wind accelerates above the tower due to separation effects and that Reynolds shear stress can distort drag coefficient estimation. Reliable measurement required sonic anemometers to be placed at least 10 m above the tower top, and using two anemometers improved accuracy further. This finding is especially useful for transmission towers in complex terrain because it shows that sensor placement strongly affects measured aerodynamic quantities. However, the study was limited to a cylindrical tower, so direct transfer to lattice towers should be done cautiously.

To reduce the cost of nonlinear wind performance analysis under uncertainty, Cai and Wan (2021) proposed a limit-capacity model for wind-resistant transmission towers using adaptive kriging response surfaces. Their model expressed tower capacity as a function of wind speed, attack angle, and line span, and it was applied to a 45.5 m high double-circuit steel lattice tower. The surrogate captured nonlinear behavior effectively and enabled fast fragility estimation under typhoon winds. Compared with direct Monte Carlo simulation, this approach greatly reduces computational effort while still supporting probabilistic evaluation. Its main limitation is that surrogate accuracy depends on the quality and range of the training data, so extreme conditions outside the sampled domain may not be predicted reliably.

These studies show a clear evolution from terrain-focused CFD modelling to surrogate-based fragility analysis. The common direction across the literature is toward methods that can represent complex flow, uncertain loading, and nonlinear structural response more efficiently than classical deterministic approaches. The main contradiction is that transmission towers need both high-fidelity response prediction and low computational cost. The creative solution is to separate the problem into layers: use CFD or LES for detailed aerodynamic understanding, use hybrid turbulence models for practical unsteady prediction, and use kriging or other surrogates for rapid probabilistic assessment.

Compare results of different researchers

Study	Main focus	Key result	Practical meaning
Zhang et al (2022a)	CFD over complex terrain	Crest location produced the strongest vibration response	Terrain effects can dominate tower-line response
Ricci (2024)	Open-source CFD review	OpenFOAM dominates many CWE applications	Open-source tools are now central to wind simulation
Sheidani et al. (2023)	URANS vs LES	LES captured vortex shedding and wake details better	Detailed unsteady flows need higher-fidelity models
Moradi et al. (2024)	RNG k-epsilon vs DDES	DDES predicted peak suction more accurately	Hybrid models are better for extreme local loads
Michioka (2024)	Flow around observation tower	Sensor height strongly affects drag estimation	Instrument placement affects wind-load measurement
Cai and Wan (2021)	Kriging surrogate fragility model	Fast fragility estimation with reduced cost	Surrogate models are suitable for probabilistic analysis

Main findings and Interpretations

Issue	Different findings	Interpretation
Terrain response vs code estimates	Zhang et al. (2022a) found windward response close to code but leeward response lower than code values	Code predictions may be conservative in some terrain positions but not uniformly accurate
Model fidelity vs efficiency	URANS gave reasonable mean pressure, but LES/DDES captured peaks better	Simplified models are efficient, but they may miss critical short-duration loads
Measurement vs true flow	Michioka (2024) showed drag estimates vary with anemometer placement	Experimental measurements can be sensitive to setup, not only to wind physics
Surrogate vs full simulation	Cai and Wan (2021) reduced cost substantially, but only within the trained domain	Fast models may lose reliability outside the calibration range

Code Provisions and Design Limitations

Although numerical and data-driven approaches have advanced rapidly, many studies have shown that existing national and international wind design standards still have important shortcomings when applied to transmission towers under extreme, skewed, or non-synoptic wind conditions. Lee et al. (2021) evaluated the Busan Tower using four international standards, namely KBC2009, ASCE7-10, EUROCODE, and AIJ2004, and compared the predicted loads with wind tunnel results. They reported design wind speeds at 120 m height ranging from 52.0 to 64.1 m/s, while the corresponding base shear values followed the trend KBC > EUROCODE > AIJ > ASCE. The design-to-experimental shear ratios varied from 1.07 to 1.53, which suggests that the codes generally provide acceptable safety margins, but they do not estimate loads with equal conservatism. This means that while the standards are broadly safe, the degree of conservatism differs significantly between codes.

Kempner (2009) extended this comparison to transmission line towers and conductors by examining ASCE 74, IEC 60826, and NESC. A major difference was found in the way wind speed is defined: ASCE uses 3-second gust wind speeds, whereas IEC is based on 10-minute mean winds. Because of this difference, ASCE and NESC produced wind pressure estimates that were about 20% lower than IEC. This highlights a basic inconsistency in how design wind is interpreted across standards. The study therefore argued for better harmonization of code assumptions, especially regarding gust duration and terrain effects, because differing definitions can lead to different design outcomes even for the same site.

Tanuku and Rao (2020) examined lattice towers under Indian and international standards by comparing IS 875 (Part 3)–2015 with ANSI/TIA-222G. Their results showed that IS 875 often gives higher wind load estimates, overpredicting by as much as 52% for square towers and 29% for triangular towers. In contrast, ANSI/TIA-222G produced lower and more realistic values for the same configurations. This suggests that some regional standards may be overly conservative for Indian lattice tower applications, potentially leading to uneconomical design. At the same time, the study also indicates that tower geometry strongly influences the degree of conservatism, so one standard may not be uniformly appropriate for all tower shapes.

The limitations of code assumptions become even clearer under skewed wind conditions. Tang et al. (2022) performed wind tunnel tests on square angle-steel transmission tower sections and found that the global drag coefficient decreases as solidity ratio increases. They also observed that the maximum skewed wind load factor occurred at a wind direction of 30°, rather than the commonly assumed 45°. Current Chinese code provisions underestimated these effects, and the researchers developed calibrated expressions that improved prediction accuracy for solidity ratios between about 0.05 and 0.3. The important implication here is that directionality and structural solidity are not captured well enough by generalized code formulas.

Zhou et al. (2021) reached a similar conclusion for lattice transmission towers under skewed winds. Their wind tunnel tests covered yaw angles up to 90° and attack angles between -30° and 30°. They found that current standards underestimated wind loads by up to 10%, while a proposed combined wind load factor reduced prediction error to below 7% for critical design angles. Compared with Tang et al. (2022), this study supports the same general concern: standard code equations are too simplified for real skew wind loading, especially when directional effects become important. However, the exact magnitude of underestimation differs from one geometry and test setup to another.

Practical utility experiences also show how standards are adapted when real conditions exceed code assumptions. Lu and Chakrabarti (2023) described BC Hydro’s reliability-based design approach for overhead transmission lines, including return periods from 50 to 400 years and combined ice and wind loading. Their work incorporated broken wire and galloping effects and used unequal ice accumulation on dead-end structures to reduce cascading failure risk. This demonstrates that utility practice often goes beyond what is explicitly stated in standards such as IEC 60826. The limitation here is that the design framework is utility-specific, so while it is highly practical, it is not a universal code solution.

A more fundamental limitation of code compliance was demonstrated by Vettoretto et al. (2023), who used nonlinear finite element analysis with geometric imperfections and joint stiffness effects to study collapse under exceptional wind loads. Their results showed that a tower may still fail under wind even when it satisfies standard requirements. Buckling occurred elastically, without yielding in braces, and the ultimate capacity varied strongly depending on the imperfection mode. This is important because it reveals that code compliance alone does not guarantee safety under extreme wind, especially when geometric imperfections and nonlinear instability govern the response. The study also shows that current design checks are often insufficiently sensitive to local instability phenomena.

Taken together, these studies show a common pattern that current standards generally provide baseline safety, but they are not equally accurate across tower types, wind definitions, directions, or hazard combinations. Some codes are conservative and may overestimate loads, while others miss important skewed or non-synoptic effects and may underestimate demand. The main challenge is that the design codes must be simple enough to apply in practice, yet detailed enough to capture complex wind behaviour. The inventive solution is to separate the problem into layers: use code-based methods for preliminary design, then apply tower-specific calibration, reliability analysis, and nonlinear verification for critical cases.

Compare results of different researchers

Study	**Main focus**	**Key result**	**Practical implication**
Lee et al. (2021)	Busan Tower under four international codes	All codes gave reasonable safety margins, but conservatism varied	Codes are safe, but not equally predictive
Kempner (2009)	Transmission line code comparison	ASCE/NESC gave about 20% lower pressures than IEC	Wind definition differences affect load estimates
Tanuku and Rao (2020)	Indian lattice towers	IS 875 overestimated loads by up to 52%	Some standards may be overly conservative
Tang et al. (2022)	Skewed wind on tower sections	Maximum load factor occurred at 30°, not 45°	Directional assumptions in codes need refinement
Zhou et al. (2021)	Skewed wind on lattice towers	Standards underestimated loads by up to 10%	Combined Wind Load Factor improves prediction accuracy
Lu and Chakrabarti (2023)	Reliability-based utility design	Combined ice-wind design improved cascading failure resistance	Utilities often need design rules beyond code minimums

Study	Main focus	Key result	Practical implication
Vettoretto et al. (2023)	Collapse under exceptional wind	Code-compliant towers can still fail due to imperfections	Code compliance does not always ensure safety

Observations and Interpretations

Issue	Different observations	Interpretation
Conservatism of codes	Lee et al. (2021) and Tanuku and Rao (2020) found codes to be conservative, while Zhou et al. (2021) and Tang et al. (2022) found underestimation	Code accuracy depends on tower type, geometry, and wind angle
Wind speed definition	Kempner (2009) showed ASCE/NESC and IEC differ because of gust duration	Different averaging periods create inconsistent pressures
Safety from code compliance	Vettoretto et al. (2023) found compliant towers can still collapse	Meeting code requirements does not eliminate instability risk
Directional effect	Tang et al. (2022) found maximum load at 30°, not 45°	Real directional behavior is more complex than code assumptions

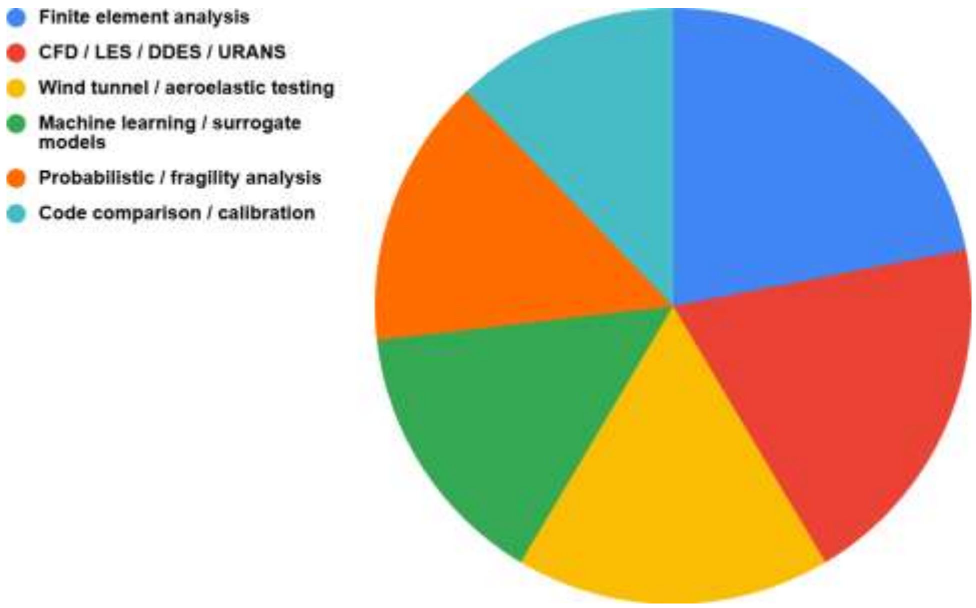


Figure 1 Relative use of experimental, numerical, and machine-learning methods.

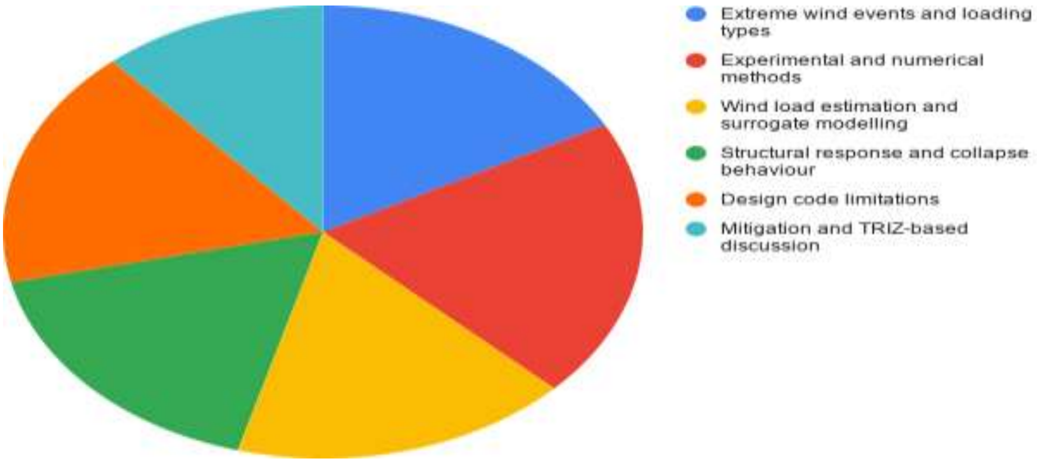


Figure 2 Distribution of major research themes in recent transmission tower wind literature

Distribution of major research themes in recent transmission tower wind literature

Future research should focus on better full-scale measurements, coupled system modeling, multi-hazard loading, and hybrid methods that combine experiments, computation, and data-driven prediction. The overall direction should be toward resilience-based design rather than only conservative code compliance.

Site-Specific Hazard Assessment: A Tiered Framework

No single design standard can adequately cover the wind hazard diversity that transmission corridors encounter across different geographies, terrains, and climates -and the evidence reviewed here points toward a structured three-tier site-specific approach to fill that gap. At the first tier, regional climatological records should determine the governing hazard type for each corridor - synoptic cyclone, convective downburst, combined wind-sand, or tornado - rather than relying on a uniform national wind speed map; Raj et al. (2022) showed that even a one-degree latitude shift in cyclone track can triple tower damage counts within a single state, making corridor-level hazard classification essential before any design wind speed is chosen. At the second tier, terrain-specific CFD or LES analysis – now practically accessible through open-source tools like OpenFOAM, which Ricci (2024) found accounts for the majority of modern computational wind engineering studies - should replace generic code terrain categories at critical locations, particularly ridge crests where Zhang et al. (2022a) demonstrated that tower-line dynamic response can substantially exceed code predictions. At the third tier, probabilistic fragility curves calibrated to actual tower stock, foundation type, and soil conditions should replace single safety factors, drawing on adaptive kriging or equivalent surrogate methods shown by Cai & Wan (2021) to deliver accurate collapse probability estimates at a fraction of full Monte Carlo cost — especially relevant for ageing towers where Vettoretto et al. (2023) confirmed that geometric imperfections erode capacity below code-assumed levels. Across all three tiers, climate-adjusted wind speed distributions should be embedded from the outset rather than treated as a post-design sensitivity check, given that rising sea surface temperatures and increasing convective energy are progressively undermining the reliability of historically anchored return period assumptions over a typical 50-year tower service life.

Patent Landscape on Extreme-Wind Effects for Transmission-Line Towers (1995 – 2025)

In this section, a systematic review of key patents from 1990-2025 has been carried out. It is very clear there has been a sharp rise in intellectual-property activity aimed at safeguarding overhead power-transmission infrastructure against typhoons, downbursts, hurricanes, tornadoes and galloping conductors. The figure below shows a pictorial representation of the patents filed in the last 3 decades.

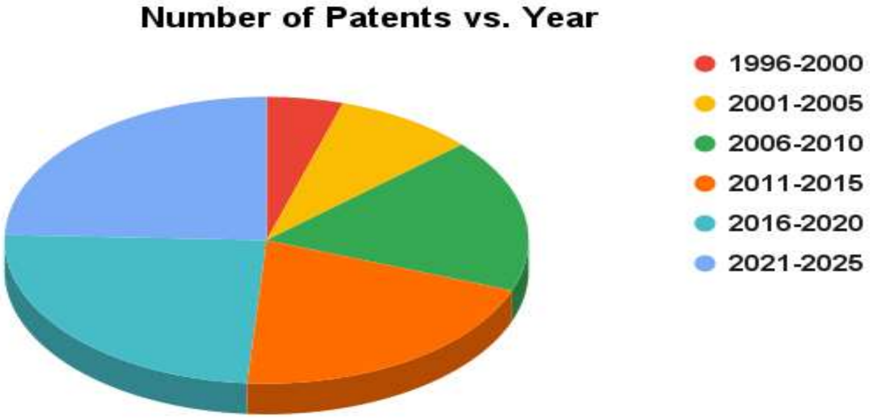


Figure 3 -Graphical representation of filed patents from last 3 decades

During 1990s the filed number of patents are relatively low, meanwhile the accelerated innovation post-2010 as utilities and research organizations respond to more frequent extreme weather events. The patent counts reflect a relatively low but growing activity in the late 1990s and early 2000s, followed by notable peaks correspond to years after severe storm/failure events, with a consistently higher output seen after 2010.The increase in number of filings after 2010 underscores the sector's response to high-impact storms such as Hurricanes Katrina (2005) and Fani (2019), and to widespread ice-galloping failures in China and North America.

Methodology

In the present study, the patents were retrieved from Google Patents, EPO, USPTO, CNIPA, and WIPO databases using the search keywords "transmission tower", "wind load", "galloping", "typhoon", "downburst", "damping" and "monitoring". After screening, only patents explicitly addressing wind- or icing-related aerodynamic, structural, or sensing solutions for lattice, tubular-steel, or monopole towers were retained. Each qualifying patent was then coded into one of five thematic clusters and benchmarked for geographic origin, filing trajectory, and claimed novelty.

Thematic Clusters

Area of study	Approximate Contribution	Main Findings

Structural Reinforcement & Novel Tower Forms	26%	The ultimate wind capacity is increased by 30-60% in Shape-optimized cross-arms, FRP composite members, narrow-base cyclone-resistant towers CN215107815U (2021), US8122647B2 (2012)
Wind-Load Identification & Design Methods	22%	Angle-dependent load-coefficient extraction, identical-guarantee-rate wind-load algorithms, finite-element–based load maps. CN109029896B (2018), WO2014081171A1 (2013)
Galloping & Vibration Control Devices	23%	Disruptors, spiral rods, tuned pendulums, and spacer-dampers cut galloping amplitude by >50%. US11217983B2 (2022), CA1302532C (2009
Monitoring & Smart Sensors	18%	Triaxial accelerometer nodes, fibre-optic tilt arrays and AI-aided vision classify hazardous oscillations in real time. US11237078B2 (2022), CN114353880A (2022)
Hybrid Energy & Dual-Use Towers	5%	Co-locating wind rotors with grid towers; limited adoption due to aero-elastic complexity. US20050230980A1 (2004)

Geographical Trends

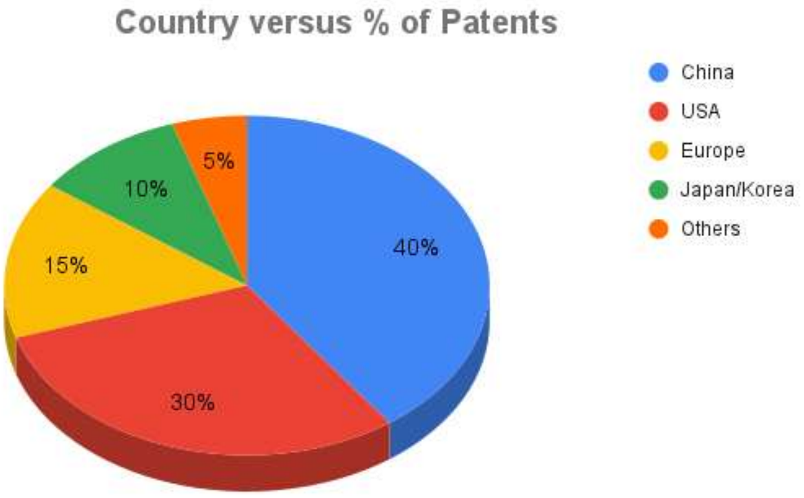


Figure 4- Geographic trend of filed patents

Key Technological Insights

Structural Solutions

- **Composite Cross-Arms** (US9698585B2 / WO2014063645A1): replace steel with pultruded GFRP, lowering wind-induced moment by 35%

Advanced Load Modelling

- **Angle-specific Coefficients** (CN109029896B): wind-tunnel plus FE inversion delivers ±5% accuracy versus full CFD, enabling leaner designs.
- **Shared-Tower FEA Load Method** (CN119720701B 2025) node-level anomaly factors capture stiffness degradation, crucial for 5G co-located masts.

Galloping Mitigation

- **V-rod Disruptors** (US11217983B2) multi-section hooks break span-wise coherence; utility data show 80% icing-gallop suppression on 345 kV lines.
- **Pendulum Tower Tuners** (US5070663A, DE102018100868B3) adjustable liquid or mass dampers tuned to first sway mode reduce tip displacement by 40%.

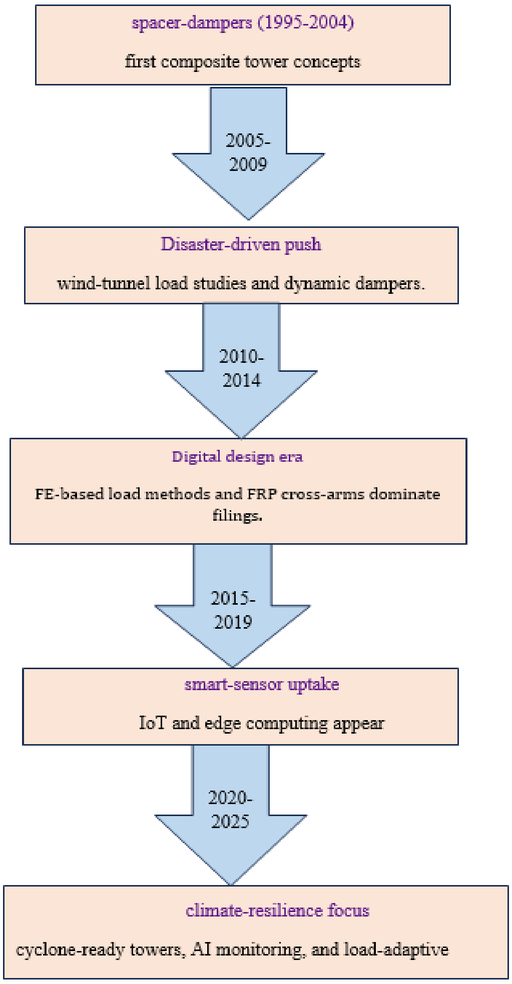
Monitoring & Digital Twins

- **Multi-node Accelerometry** (US11237078B2) reconstructs continuous mode shapes; alarms at 90% of critical amplitude.
- **Vision-AI Insulator-String System** (CN114353880A) extracts frequency and phase from video; lab accuracy ±0.2 Hz.

Dual-Use Wind-Energy Towers

- Field trials (US20050230980A1) show 15-20% capacity factor gains but highlight maintenance conflicts; no large-scale deployment yet.

Temporal Evolution



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Research Gaps & Future Directions

Identified Gaps	**Reason**	**Probable solution**
The method for design of strong wind gusts not well defined	About 7% of patents focus on short, extreme wind loads	For quick, intense winds design codes need to be updated incorporating time-based gust factors
For old (40 + years) lattice towers no easy retrofitting kits are available	No patents found for modular reinforcement kits that on bolt.	Develop bolt-on fiber-reinforced sleeves that can be installed on old towers without needing to shut off the power lines
No proper recycling process defined for composite tower parts after its life	No patents exist for recycling or reusing these materials	The Design of tower parts from special plastics that can be melted and reused on-site when the tower is no more in use, or can look into bio composite structures
In the case of digital tower model systems the data can not be easily shared	Most systems use unique, non-standard data formats	Standardized data file formats so that sensor and model data work together across all the companies

Recommended Updates to Design Standards

The evidence assembled across this review points to five specific changes that current international standards — particularly ASCE 74, IEC 60826, and IS 875 — need to incorporate. These are not speculative suggestions; each is grounded in quantified findings from peer-reviewed studies reviewed here and remains unaddressed in any current edition of those standards.

Sl.No.	**Proposed Change**	**Evidence Base**	**Standard(s) to Update**

1	Introduce non-synoptic wind load provisions - Prescribe spatially varying downburst velocity profiles and dynamic amplification factors of 1.1–3.5 as a supplementary load case for towers in convective storm-prone regions, applied alongside — not instead of — existing ABL wind checks	Aboshosha et al. (2016); Zhu et al. (2023) confirmed that quasi-static ABL-based load models underestimate peak downburst demand by factors that vary with tower height and characteristic radius	ASCE 74; IEC 60826
2	Correct the critical skewed wind angle from 45° to 30° - Replace the 45° directional assumption in skewed wind load clauses with 30°, the experimentally verified angle of peak load factor for typical lattice tower solidity ratios	Tang et al. (2022) and Zhou et al. (2021) independently found maximum skewed loads at 30° incidence; current provisions underestimate demand at this angle by up to 10%	Chinese GB 50545; IS 875 Part 3; potentially ASCE 74
3	Add region-specific multi-hazard amplification factors - Introduce optional annexes prescribing a 1.25 wind load amplification factor for arid sandstorm-prone corridors and a combined wind-rain load model covering up to 35 m/s and 120 mm/h rainfall for tropical regions	Zhang et al. (2022b) quantified up to 25.6% increase in displacement and axial force under wind-sand loading; Yang et al. (2025) validated a combined wind-rain surrogate across nine realistic scenarios	IS 875 Part 3; IEC 60826; regional annexes of ASCE 74
4	Include foundation flexibility correction factors - Add soil-type correction factors to tower foundation design guidance: 0.75 for cohesive soils and 1.3 for non-cohesive soils, with recommended proportions of tube diameter equal to tower height divided by 15, and foundation depth equal to one-tenth of foundation diameter	Campione (2024) showed that ignoring foundation flexibility significantly distorts moment-rotation behaviour and that simple closed-form corrections are adequate for preliminary design	IEC 60826 Annex; ASCE 74 foundation guidance
5	Harmonise wind speed averaging period across standards - Adopt a unified gust-averaging convention that reconciles the 3-second gust basis of ASCE and NESC with the 10-minute mean basis of IEC 60826, with explicit conversion factors tied to terrain category and height	Kempner (2009) showed that the current inconsistency produces wind pressure differences of approximately 20% for the same site, creating unpredictable design outcomes when engineers reference multiple standards	ASCE 74; IEC 60826; joint ISO/IEC harmonisation

Each of these changes is technically feasible with existing research evidence. None requires new experimental campaigns before adoption - the data are already in the literature. What is missing is the institutional step of converting peer-reviewed findings into normative text, a task that code committees for each standard are positioned to take up with the material reviewed here as a starting point.

Research–Patent Gap Analysis Across Six Thematic Clusters (1995–2025)

Theme / Cluster	Prior Art Reference	Research Approach & Methodology	Core Findings	Patent Reference (No.)	Patented Innovation	Research-Patent Gap / Convergence
1 | Extreme Wind Characterisation - Downburst & Non-Synoptic Events						
Downburst fragility & amplification	Aboshosha et al. (2016); Fang et al. (2022); Zhu et al. (2023)	FE modelling, fragility curves, nonlinear dynamic analysis under idealised	DAF = 1.0-3.5; first tower segment most vulnerable; peak demand at ~1.6x downburst diameter; downburst risk > ABL risk	CN215107815U (2021); WO2014081171A1 (2013)	Narrow-base cyclone-resistant tower; wind-load guarantee-rate algorithms with dynamic provisions	GAP: Patents use static peak pressures. Downburst DAF values and spatially varying profiles not yet codified in any patent methodology

Theme / Cluster	Prior Art Reference	Research Approach & Methodology	Core Findings	Patent Reference (No.)	Patented Innovation	Research-Patent Gap / Convergence
		downburst fields				
Tornado response & fatigue	Hamada et al. (2010); Zhang et al. (2024)	CFD F2/F4 tornado fields in nonlinear FE; Wen's 3-D tornadic velocity model on a 131 m tower	F4 loads exceed F2 and ABL by up to 15% with full 3-D field; lateral loading governs; joint optimisation cuts fatigue ~30%	No matched patent	No commercial patent addresses tornado-resistant tower geometry or fatigue design	GAP: Tornado tower design remains entirely academic; significant IP opportunity for tornado-resilient structural forms
2 | Structural Reinforcement & Novel Tower Forms						
Collapse mechanism & failure initiation	Liu et al. (2024); Rao et al. (2012); Vettoretto et al. (2023)	Full-scale destructive tests; nonlinear FE with geometric imperfections at ~37 m/s design wind	Collapse starts in compressed members below lower cross-arm; compression-bending instability governs; code-compliant towers can still fail	CN215107815U (2021); US8122647B2 (2012)	Cyclone-resistant narrow-base lattice; octagonal FRP-arm tower; 30-60% higher wind capacity claimed	CONVERGENCE: Patented designs reduce moment in the critical cross-arm zone identified by research. Imperfection sensitivity data could further strengthen patent claims
Composite & FRP members	Gantes et al. (2024); Ma et al. (2020)	Nonlinear FE of tubular steel shells; energy-based buckling theory for cylindrical shell ovalization	65 mm shell without stiffeners matches framed designs; bending-induced ovalization sharply reduces local buckling capacity	US9698585B2 (2017); WO2014063645A1 (2014)	Pultruded GFRP cross-arm; 35% lower wind-induced moment; composite tower for HV lines	CONVERGENCE: Ovalization theory validates composite cross-arm rationale. End-of-life GFRP recycling unaddressed in both literature and patents
Foundation flexibility & soil-structure	Campione (2024)	Closed-form model for shallow RC foundations; soil correction factors (cohesive 0.75; non-cohesive 1.3)	Foundation flexibility alters moment-rotation significantly; D = H/15; base dia = 0.75x tower length; depth = dia/10	No patent identified	Foundation design outside all existing patent clusters	GAP: No patent on foundation flexibility under extreme wind; modular wind-resilient foundation systems represent open IP space
3 | Wind-Load Estimation, Code Provisions & Advanced Modelling						
Aeroelastic testing & gust response	Yao et al. (2022); Song et al. (2022)	Wind-tunnel aeroelastic tests on 380 m tower & bundled conductors; vision-based displacement measurement	GRF ~1.38, below code predictions; along-wind = cross-wind response; force coefficients lower than	CN109029896B (2018)	Angle-dependent load-coefficient extraction via wind-tunnel + FE inversion; +/-5% accuracy vs. full CFD	CONVERGENCE: Both show directional coefficients diverge from code. Patent operationalises the approach; research provides

Theme / Cluster	Prior Art Reference	Research Approach & Methodology	Core Findings	Patent Reference (No.)	Patented Innovation	Research-Patent Gap / Convergence
			Chinese code for angles >40 degrees			experimental validation
Skewed wind & code accuracy	Tang et al. (2022); Zhou et al. (2021)	Wind-tunnel tests at yaw angles up to 90 degrees; comparison with Chinese code provisions	Peak load factor at 30 degrees incidence (not code-assumed 45 degrees); codes underestimate by up to 10%; CWLF reduces error to <7%	WO2014081171A1 (2013)	Guarantee-rate wind-load algorithm for directional variation and exceedance probability	GAP: Patent predates the 30 degree finding; no patent yet includes the experimentally verified CWLF or corrected critical angle
Code cross-comparison	Lee et al. (2021); Kempner (2009); Tanuku and Rao (2020)	Systematic comparison: KBC, ASCE 7, Eurocode, AIJ, IS 875, ANSI/TIA-222G, IEC 60826	Design wind speeds 52-64.1 m/s at 120 m across codes; IS 875 overpredicts by up to 52%; ASCE ~20% below IEC due to gust-duration differences	CN119720701B (2025)	FEA-based shared-tower load map with node-level stiffness-degradation factors	GAP: Research shows clear international inconsistency; no patent proposes a harmonised multi-code compliance framework
4 | Galloping, Vibration Control & Damping Devices						
Tower-line coupling dynamics	Zhang et al. (2024); Bi et al. (2023)	Long-term field monitoring; nonlinear dynamic coupled tower-line simulation; orientation analysis	Ignoring coupling underestimates transverse forces; resonance risk increases near 37 m/s; worst orientation ~90 degrees	CA1302532C (2009); US5362920A (1996)	Anti-galloping twist-weight device; spacer-damper for bundled conductors; >50% galloping reduction	CONVERGENCE: Patented spacer-dampers reduce conductor input to tower. Adaptive damping responsive to real-time coupling forces remains unaddressed
Fatigue under wind vibration	Li et al. (2023)	Nonlinear FE with cable-end fatigue monitoring; model uses only 4.19% of ANSYS cost	90 degree wind most unfavourable for fatigue; damage higher near cable ends; efficient surrogate suitable for long-term assessment	US5070663A (1991); DE102018100868B3 (2020)	Liquid-column tower damper; steel-cable pendulum damper; ~40% tip displacement reduction	GAP: Patented dampers optimised for peak displacement, not fatigue. Li et al. (2023) framework could re-tune dampers for cumulative fatigue - not yet in any patent claim
Ice-shedding & galloping suppression	Wen et al. (2022)	Full-scale field data and nonlinear FE simulation; ice-shedding response from span, ice thickness, and temperature inputs	Jump height, swing angle, and unbalanced tension reliably estimated; response varies nonlinearly	US11217983B2 (2022)	V-rod galloping disruptors; multi-section hooks break span-wise coherence; 80% icing-gallop suppression on 345 kV lines	CONVERGENCE: FE-based icing response quantification supports V-rod disruptor design criteria. No patent links site-specific ice-load parameters to

Theme / Cluster	**Prior Art Reference**	**Research Approach & Methodology**	**Core Findings**	**Patent Reference (No.)**	**Patented Innovation**	**Research-Patent Gap / Convergence**
			with ice accumulation pattern			disruptor selection or deployment thresholds
5 | Smart Monitoring, Digital Twins & Data-Driven Methods						
Surrogate modelling for wind response	Yang et al. (2025); Zhao et al. (2025); Cai and Wan (2021)	Kriging surrogate on FE data; wind-rain FE simulation (35 m/s + 120 mm/h); nonlinear dynamic analysis of tower-line systems	Adaptive kriging cuts Monte Carlo cost by ~95%; failure probability ~7x10^-7; multi-hazard FE shows coupled wind-rain response not captured by wind-only models	US11237078B2 (2022); CN114353880A (2022)	Multi-node accelerometer reconstructing mode shapes; fibre-optic tilt array for real-time structural monitoring	CONVERGENCE: Kriging surrogate and multi-hazard FE provide reliable probabilistic response estimates at low cost. No patent covers combined wind-rain or wind-sand fragility methods - direct IP opportunity
CFD terrain & turbulence modelling	Zhang et al. (2022a); Ricci (2024); Sheidani et al. (2023); Moradi et al. (2024)	CFD over 100 m butte; URANS vs. LES comparison; OpenFOAM review (>300 studies)	Crest placement most severe for tower-line response; LES outperforms URANS; DDES best for peak suction; OpenFOAM ~58% of CWE studies	CN109029896B (2018); CN119720701B (2025)	Wind-tunnel + FE load-coefficient extraction; FEA-based load maps with anomaly factors	GAP: Academic LES/DDES substantially outperform patent wind-field models. No patent claims an automated LES-informed load-coefficient pipeline
Probabilistic fragility analysis	Cai and Wan (2021); Arunachalam and Spence (2022); Raj et al. (2022)	Adaptive kriging surrogate; stratified stochastic simulation; post-Cyclone Fani fragility curves	Adaptive kriging cuts Monte Carlo cost by ~95%; system reliability lower than member reliability; population-weight hardening most effective for coastal grids	No matched patent	Probabilistic fragility and reliability-based design absent from patent literature	GAP: Most active research area (2021-2024) with zero patent coverage; fragility-based design tools represent wide-open IP space
6 | Multi-Hazard Loading & Climate-Driven Considerations						
Wind-rain & wind-sand loading	Yang et al. (2025); Zhang et al. (2022b)	TimesNet for wind-rain; SAP2000 wind-sand simulation with momentum-conservation sand loads	Wind-rain up to 35 m/s + 120 mm/h; sandstorms increase response by up to 25.6% at 25 m/s; amplification factor ~1.25 for arid regions	CN215107815U (2021)	Cyclone-resistant lattice tower; no combined sand/rain load provisions included	GAP: No patent covers region-specific multi-hazard amplification factors; 1.25 sand multiplier has direct potential for a novel design-code patent

Theme / Cluster	**Prior Art Reference**	**Research Approach & Methodology**	**Core Findings**	**Patent Reference (No.)**	**Patented Innovation**	**Research-Patent Gap / Convergence**
Hurricane risk & network resilience	Reinoso et al. (2020); Schumann and Chini (2023)	Hurricane fragility with tower-cable interaction; Hazus simulation of 18,363 towers; annual loss estimation	EAL up to USD 181,000/line segment; tower location errors shift risk by 22%; older poles most vulnerable	US20050230980A1 (2004); No network-risk patent	Dual-use wind-turbine tower concept; no patent covers network-level resilience optimisation	GAP: System-level risk frameworks have no patent counterpart; grid-topology-aware reinforcement scheduling is unpatented
7 | Cross-Cutting Research-Patent Gaps (Summary)						
Non-synoptic gust design method	Aboshosha et al. (2016); Fang et al. (2022)	DAF-based analysis; downburst fragility curves	DAF 1.0-3.5; quasi-static codes significantly underestimate peak demand	Only ~7% of patents address extreme short-duration gusts	No time-resolved gust-factor method patented	CRITICAL GAP: Updated gust-factor provisions must be translated into a patentable design method
Retrofit kits for ageing towers	Vettoretto et al. (2023); Rao et al. (2012)	Collapse load analysis; full-scale failure testing	Towers with imperfections fail below design wind speed; lower cross-arm zone consistently critical	No modular bolt-on reinforcement patent found	No patent covers live-line retrofitting of existing towers	CRITICAL GAP: Bolt-on FRP/steel sleeves for the lower cross-arm zone are high-value, unpatented territory
Recycling of composite members	Gantes et al. (2024)	Nonlinear FE shell optimisation; stiffener-removal study	Composite members improve efficiency but generate non-recyclable waste at end of life	No recycling or bio-composite patent found	No patent addresses composite material recovery at decommissioning	EMERGING GAP: Thermoplastic or bio-composite tower parts reprocessable on-site are unaddressed in both research and IP
Interoperable digital-twin data standards	Yang et al. (2025); Zhao et al. (2025)	Multi-node accelerometer and fibre-optic sensor frameworks for structural health monitoring of tower-line systems	Sensor outputs from different systems use incompatible formats; no standardised data exchange protocol exists	US11237078B2; CN114353880A - proprietary protocols	No open IoT data format patented for tower digital twins	EMERGING GAP: Standardised open-format schema for cross-platform tower monitoring has both research impact and commercial IP value

Conclusion

Across six thematic areas - extreme wind characterisation, structural failure mechanics, wind load estimation, vibration control, smart monitoring, and multi-hazard loading -this review exposes a consistent and widening gap between what research knows and what design standards require. Collapse under extreme wind is not random: it initiates predictably at compressed members below the lower cross-arm through bidirectional instability, is amplified by dynamic factors reaching 3.5 under downburst loading, and is made worse by geometric imperfections that code-compliant towers carry routinely. The critical skewed wind angle sits at 30°, not the 45° that several standards assume, and sandstorm or combined wind-rain conditions add structural demand that no current provision accounts for. These are not marginal discrepancies - they are systematic, quantified, and unaddressed.

None of the tools needed to close these gaps are missing — high-fidelity CFD, adaptive kriging surrogates, LSTM and TimesNet prediction frameworks, probabilistic fragility methods. What has not happened is the institutional translation: peer-reviewed findings sitting in journals for years without ever reaching normative code text, patent claims, or utility maintenance schedules. Five code modifications were proposed here, each grounded in quantified evidence and none requiring new experimental campaigns before adoption. A tiered site-specific hazard framework — built on regional climatology, terrain-sensitive CFD, and fragility-calibrated safety factors — offers a practical route beyond uniform national wind speed maps. The hard work ahead is not discovery. It is the less glamorous task of converting what is already known into the standards, retrofit kits, and resilience strategies that the towers being built today will actually need over their fifty-year service lives.

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