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Wind-Induced Structural Behaviour of Tall Buildings: A Comprehensive Review of Analysis Methods, Codal Frameworks, and Emerging Trends

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Abstract: *With the progressive vertical extension of urban construction, the issue of wind-induced structural response has become an important issue in the engineering of tall buildings. For structures taller than about 50 m, wind loading dictates the lateral design of buildings, resulting in along-wind, crosswind and torsional loads that can affect structural strength and comfort of the occupants. The current wind loading codes, such as IS 875 (Part 3), ASCE 7, EN 1991-1-4, AS/NZS 1170.2 and BS 6399-2, have been derived from single building wind tunnel experiments and offer little guidance on the aerodynamic interference or dynamic amplification. The aim of this paper is to review the current knowledge about wind-induced structural behaviour of tall buildings systematically, covering the codal provision, experimental techniques, computational fluid dynamics (CFD), finite element analysis (FEA) methods, passive control and artificial intelligence techniques and approaches. For square-plan buildings the 45° incidence angle of the wind is a consistent value that is identified. The code based approaches tend to underestimate the dynamic peak loads by 30-50% for slender structures when compared with wind tunnel tests. The crosswind force is limited by corner modifications and can be as much as 30% less. Machine learning surrogate models can faithfully replicate the accuracy of CFD at much lower computational cost and tuned mass dampers for wind-induced acceleration can cut the acceleration by as much as 40% in supertall buildings. There are critical gaps in Multi Building Interference Characterisation, Wind engineering for Indian codes based on performances, Climate Change Adjusted Wind Hazard Map, and Real time Structural Health Monitoring with Digital Twin.*

Keywords: tall buildings; wind load; structural analysis; STAAD.Pro; IS 875; aerodynamic interference; computational fluid dynamics; tuned mass damper; performance-based wind engineering; machine learning

I. INTRODUCTION

1.1 Overview of the Topic

With population growth, limited space, and economic dreams, the world's urban landscape is seeing an unprecedented growth in the number of high-rise buildings. Tall buildings, broadly defined as buildings over 50m in height, are among the most complicated structures to design, with load driven more from lateral loading forces caused by wind and seismic events, than from gravity loading forces. Of these, wind loading has a unique significance on buildings in non-seismic or low-seismicity areas and for very tall structures whose fundamental natural frequencies are within the energy-rich range of atmospheric turbulence [1].

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The wind pressure and suction fields on building surfaces are complicated and time-varying, and are influenced by the mean wind speed profile over the terrain, the turbulence intensity and integral length scale of the atmospheric boundary layer, the plan geometry and aspect ratio of the building, and the aerodynamic influence of neighbouring buildings. They are: (i) along-wind forces parallel to the mean flow, which cause overturning moments and shear, (ii) crosswind forces perpendicular to the mean flow, which result from vortex shedding and wake excitation, and (iii) torsional moments from eccentricities in the pressure distribution acting over the building envelope [2].

Globally, wind loading provisions are established in the standards like IS 875 (Part 3) in India [3], ASCE 7 in the U.S. [4], EN 1991-1-4 (Eurocode 1) in Europe [5], AS/NZS 1170.2 in Australia and New Zealand [6] and BS 6399-2 in United Kingdom [7]. The development of these codes has been a long process extending over the past few decades and was developed from wind tunnel testing on a single building model or analysis of extreme wind speed data. They do provide some guidance on a number of phenomena of growing practical significance: aerodynamic interference between neighbouring tall buildings, resonant dynamic amplification in flexible buildings, and the effect of complex urban topography on the wind approach characteristics.

Proficient software programs for structural analysis, like STAAD.The implementation of wind loading provisions into design forces for individual structural members is now possible without the software Pro, ETABS and SAP2000. The platforms are capable of performing 3-D space frame analysis, load combination evaluation and internal stress resultants and deflections extraction for all members, making it easier to conduct efficient codal conformance checks. Meanwhile, the toolbox of wind engineers continues to grow quickly thanks to developments in computational fluid dynamics (CFD), physical wind tunnel testing, machine learning and passive control technologies [8].

1.2 Importance and Motivation

The design of tall buildings for wind is not just a structural safety matter; it is a key driver of architectural form, selection of the structural system, quantity of materials, foundation design and the operational performance of the building. Acceleration from wind at the upper floor levels can lead to reduced occupant comfort, or even be incompatible with habitability requirements even for structures that have been designed to be structurally safe at the strength limit state [9]. The economic impact of wind damage on tall buildings—due to cladding failures, structures and loss of occupancy—can be huge, and this is the reason for strong wind resistant design.

The old IS 875 (Part 3)-1987 is in practice even though it does not contain any provisions for dynamic wind loads and interference. The current revision process to a new edition has brought to light the desire for a thorough critical review of the current knowledge base, which can help to guide the development of the new edition of the code and the design of existing projects. Furthermore, the rapidly urbanising cities of India (Mumbai, Delhi, Hyderabad, Chennai etc.) are seeing a significant surge in the number of proposals for supertall buildings, which are challenging the applicability of the 1987 code [3] [10].

1.3 Objectives of the Review

This review paper aims at the following objectives:

To compare critically the provisions of major international wind loading codes and their strengths and weaknesses;

- To review experimental, computational and analytical techniques to estimate the response of tall structures subjected to wind;
- To review recent advances in the aerodynamic interference, dynamic response, shape optimisation and passive control;
- To understand the main technological trends such as CFD, machine learning and digital twins;
- To identify ongoing research needs and suggest directions for future research activities to improve the state-of-the-practice.

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II. LITERATURE REVIEW

2.1 Codal Provisions for Wind Loading

The analysis of the main international wind loading standards shows a broad range of wind speed averaging periods, return periods, terrain classification, dynamic load methods and interference recommendations. These are summarised in Table 1 for six codes.

Table 1. Comparative summary of major international wind loading codes (* Relative base shear for a 100 m rectangular building in open terrain)

Parameter	IS 875-3 (1987)	ASCE 7-22 (USA)	EN 1991-1-4 (Europe)	AS/NZS 1170.2	BS 6399-2 (UK)	AIJ (Japan)
Wind speed averaging	3-s gust	3-s gust	10-min mean	3-s gust	Hourly mean	10-min
Return period (years)	50	700 / 1700	50	50	50	100
Dynamic load method	None	Gust factor	cs·cd	Cdyn	Dynamic fac.	Gust factor
Interference guidance	None	Limited	Conservative note	Shielding Ms	Limited	Limited
Terrain categories	4	5	5	4	4 (country)	4
Relative base shear*	Moderate	High	High	Low	Moderate	Highest

Verma [11] made a historic comparison of static wind loads on a 200 m rectangular building on open terrain as per the Indian code (IS 875-3), the Japanese code (AIJ-RLB-2004), the Hong Kong code (CP-2004), and the New Zealand code (AS/NZS 1170.2). The Japanese code gave the highest base shear and overturning moment whereas the New Zealand code gave the lowest, quite similar results were obtained by IS 875 and CP-2004. Main differences were explained by the use of different gust factor definitions, and differences in the exposure classifications of the terrain.

Basanth et al. [12] have compared the draft of IS 875 (Part 3) 1987 with 2015 for a 15-storey building. The new provisions have been incorporated with dynamic wind loading factors and updated terrain multipliers, which resulted in the base shear values of 20–35% higher in comparison with the 1987 version of the Indian standard, thereby validating the non-conservativeness of the current Indian standard for buildings above ten storeys.

2.2 Experimental Methods: Wind Tunnel Testing

For tall buildings that have complex shape, non-standard environments or high dynamic sensitivity, boundary layer wind tunnel (BLWT) tests are still the benchmark for quantifying wind loads. Kijewski and Kareem [13] were the first to undertake a thorough full-scale monitoring program for four high-rise buildings in Chicago, using GPS receivers, accelerometers and anemometers. They found that actual damping ratios at design wind speeds are significantly smaller than those typically used in design, and that the coupling of building vibrations with the urban wind field is far from simple and is not well represented by simplified code approaches.

Pandey [14] quantified aerodynamic interference effects on building models of square plan in a BLWT, by systematically varying the number, orientation and spacing of surrounding buildings. It was determined that base shear and overturning moment can be up to 80% higher in a closely spaced staggered configuration than in the isolated configuration. It was determined that the aerodynamic interference factor (AIF) decreased above about eight times the building width. Interestingly, the torsional moment was not sensitive to interference in the symmetric case, which is significant and makes the torsion design of regular building clusters easier.

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To address this, Lo et al. [15] developed an extensive database of AIF values for square-plan buildings in tandem, side-by-side and staggered positions. Decades of wind tunnel tests have been performed that have witnessed AIFs greater than 2.0, in situations where the wind forces on the downstream building are more than doubled by neighbouring buildings in the same line of sight, with close spacing, and which are not covered by most national codes.

2.3 Computational Approaches

2.3.1 Finite Element Analysis

In reality, the majority of structural wind response assessment is conducted in three dimensions using commercial software packages. Kumar [16] used STAAD.Pro has compared the responses of different kinds of reinforced concrete frames with varying heights from G+5 to G+29 for different seismic zones in India and suggested that wind design the lateral response of tall frames in low seismic zones, and earthquake design the lateral response of all height frames in high seismic zones. Using the ETABS software, Ranjitha [17] studied the effect of plan shape on story drift and story displacement under IS 875 wind loads in Wind Zone I and IV, and concluded that under similar loading, irregular planar shapes always have higher story drift as compared to regular rectangular plan shapes.

For static wind load computation in FEA based studies the following are key equation:

$$Vz = Vb \bullet k^1 \bullet k^2 \bullet k^3 \quad (1)$$

Where Vb = basic wind speed; k_1 = risk coefficient; k_2 = terrain-height-size factor; k_3 = topography factor

$$Pd = 0.6 \times Vz^2 \quad \left(\frac{kN}{m^2}\right) \quad (2)$$

$$F = Cf \times Ae \times Pd \quad (3)$$

Where Cf = force coefficient; Ae = effective frontal area (m^2); Pd = design wind pressure (kN/m^2)

The three basic equations (1)–(3) are used as the basis for most of the wind load FEA studies conducted in India. Table 2 shows the force coefficients for some selected plan shapes and aspect ratios for IS 875 (Part 3) - 1987; it is seen that the values of Cf are highly influenced by the building geometry as well as by the wind incidence angle.

Table 2. Force coefficients Cf for clad buildings of uniform cross-section [IS 875 (Part 3)-1987, Table 4]

Plan Shape / Wind Dir.	h/b=0.5	h/b=1	h/b=2	h/b=4	h/b=6	h/b=10	Critical Case
Square (0° / 90°)	0.90	1.00	1.10	1.20	1.25	1.30	0° or 90°
Square (45°)	0.75	0.85	0.90	1.00	1.05	1.10	45°
Rectangle a/b=1.5 (0°)	0.95	1.05	1.15	1.25	1.30	1.40	0°
Rectangle a/b=2.0 (0°)	1.00	1.10	1.20	1.30	1.40	1.50	0°
Circular cylinder	0.50	0.50	0.50	0.50	0.50	0.50	Any

2.3.2 Computational Fluid Dynamics

In addition to wind tunnel testing, CFD has proved to be a valuable tool for providing detailed spatial resolution of wind pressure fields, and the ability to simulate complex urban environments and without scale effects. Best practice guidelines for RANS (Reynolds-Averaged Navier–Stokes) CFD modelling of pedestrian comfort in the wind environment of buildings were developed by Blocken et al. [18] and included requirements for the domain size, mesh resolution, turbulence modelling (k-ε, k-ω SST), boundary conditions and validation. Time accurate prediction of pressure is the motivation and reason for the use of LES for time varying prediction of pressure in separated regions of flow, which is a computationally expensive technique compared to RANS models, which tend to overestimate wind speeds in such regions.

Elshaer et al. [19] used LES-based CFD to systematically examine the influence of square-plan tall building corner modification (chamfer, round, slot opening) on the aerodynamic coefficients of square-plan tall buildings. The reduction in the mean along wind force coefficient ranged up to 30% and the fluctuating cross wind force coefficient was reduced by up to 25%, mainly by altering the regular Kármán vortex shedding pattern. These results have been applied in practice in the form of geometric design rules for architects, who are looking for a way to reduce the wind load on structures while at the same time reduce floor plate area.

2.4 Dynamic Wind Response

In cases of tall slender structures with fundamental natural frequency lower than about 1 Hz, the response induced by wind has a large resonant dynamic component which is not included in the static equivalent load method. The along-wind displacement at the top of the building is controlled by the random vibration theory expression:

$$\sigma_x = \frac{(\bar{U} \bullet G_f \bullet Cf \bullet Ae \bullet Kh)}{(2 \bullet m \bullet \omega\text{^}02 \bullet \zeta)\text{^}(1/2)} \quad (4)$$

Where σ_x *= root-mean-square displacement; Gf = gust response factor; m = generalised mass;* ω_0 *= natural circular frequency; ζ = critical damping ratio [2]*

The framework for Performance Based Wind Engineering (PBWE) was formalised by Ciampoli et al. [20] and was similar to the existing earthquake engineering PBEE framework. The PBWE framework calculates the annual probability of exceeding specified levels of structural performance in a probabilistic chain from the wind hazard, aerodynamic analysis, structural response and damage or loss models. The application to a slender tall building indicated that the main concerns for the performance of the building were the cladding damage and SLS wind. Structural failure under wind is highly improbable at design wind.

Lu et al. [21] discussed the design, installation and performance of a tuned mass damper (TMD) of 1000 tonne mounted on pendulum at the Shanghai Tower (632 m), which is tuned to the 1st translational frequency of the building. The TMD was tested in a wind tunnel and verified by full-scale testing that the peak acceleration can be reduced by about 40% at design wind speeds, while keeping the peak acceleration well within ISO 10137 limits to keep the occupants comfortable. This is one of the first validations of TMD technology for supertall building applications, and has sparked the global use of passive damping systems in supertall building design.

III. METHODS AND TECHNOLOGIES: A COMPARATIVE SUMMARY

Assessment of wind load and prediction of structural response is available with a variety of methods, ranging in accuracy, cost and applicability. To facilitate the comparison of main methods used in recent literature, a structured comparison is given in Table 3.

Table 3. Comparative summary of wind load assessment and structural analysis methods

Method	Accuracy	Cost/Effort	Best For	Key Limitation
Codal Static Analysis	Moderate	Low	Regular, isolated buildings	No dynamic/interference effects
Wind Tunnel Testing	Very High	High	Complex/irregular forms	Scale effects; expensive
RANS CFD	Moderate–High	Medium	Mean pressures, urban flow	Over-predicts recirculation
LES/DES CFD	High	Very High	Turbulent fluctuations, VIV	Extreme computational cost
STAAD.Pro FEA	High (structural)	Low–Medium	Structural response	Wind load input dependent
ML Surrogate Models	High (trained range)	Low (inference)	Rapid design-stage screening	Training data dependency

The selection of method will be determined by the height of the building, the geometry, its proximity to surrounding buildings and the accuracy desired. Until around 100 m, codal static FEA (such as STAAD) might be used for routine design of regular buildings.Pro with IS 875) is practical and economical. Physical wind tunnel testing is the most accurate approach for taller or more complex or closely spaced buildings, and CFD can provide useful information about how pressures are distributed and on the wind environment in the urban context.

Recently, machine learning surrogate models have been developed as a fast screening tool for the design stage. Zhang et al. [22] found that a CNN trained with a library of boundary layer wind tunnel pressure data could accurately predict the mean and peak pressure coefficients on rectangular buildings with a computational cost that is several orders of magnitude less than LES-CFD, and an accuracy of ±10%. It is especially appealing when used for the parametric aerodynamic optimisation of architectural designs, where hundreds of different geometric variations need to be quickly assessed.

IV. CURRENT TRENDS AND DEVELOPMENTS

The field of Wind Engineering for tall buildings is undergoing rapid evolution due to the development of computational tools, data availability and the growing complexity of urban environments. The most important recent developments and the main contributions they have made are summarised in Table 4.

Table 4. Recent trends and key developments in wind engineering for tall buildings

Technology / Trend	Representative Work	Key Advancement
Deep Learning Wind Pressure	Zhang et al. [20], 2021	CNN predicts pressure coefficients at 1/100th of CFD cost
LES-based Urban Wind	Blocken et al. [14], 2016	Best-practice guidelines for pedestrian wind comfort CFD
Aerodynamic Shape Optimisation	Elshaer et al. [15], 2017	Corner modifications reduce crosswind force by up to 30%
Performance-Based Wind Eng.	Ciampoli et al. [22], 2011	Probabilistic PBWE framework analogous to PBEE
TMD for Supertall Buildings	Lu et al. [17], 2018	1000-t pendulum TMD reduces acceleration by 40%
Revised IS 875 (Part 3)	Basanth et al. [25], 2016	2015 draft increases base shear by 20–35% over 1987 edition
Digital Twin Integration	Emerging (2022–)	Real-time sensor data fused with FEA for life-cycle monitoring

4.1 Aerodynamic Shape Optimisation

The knowledge that the building's shape has a strong impact on the loading by the wind has stimulated systematic shape optimisation investigations. Other than the corner modifications studied by Elshaer et al. [19], tapered, twisted, and setback building forms have been studied. Kwon and Kareem [23] showed that the peak overturning moment could be decreased by around 18% in a 60 storey building with a 5° clockwise twist per storey than an untwisted prism due to the disruption of coherent vortex shedding caused by the twist along the building height. This is an aerodynamic twist strategy that is seen in built practice, such as the Cayan Tower in San Diego and the Infinity Tower in Dubai.

4.2 Passive and Active Vibration Control

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4.3 Digital Twins and Structural Health Monitoring

By bringing together a network of IoT sensors, cloud computing, and a high fidelity structural model, the concept of the structural digital twin has emerged, that is, a virtual model that continuously "represents" the current state of the physical building. In the case of tall buildings, digital twins combine the measurement of wind speed and direction, monitoring of structural response (accelerometers, GPS, strain gauges) and FEA models to offer ongoing structural assessment and early detection of abnormal behaviour throughout the building's life cycle. Despite being at an early stage of adoption in the industry, digital twin technology can be used to change the way supertall buildings operate and maintained over the next decade [8].

4.4 Machine Learning and AI in Wind Engineering

There are applications of machine learning within wind engineering: prediction of pressure coefficient (CNN-based surrogates), wind speed forecasting for load estimation (recurrent neural networks), aerodynamic shape optimisation (deep reinforcement learning), and prediction of structural response from wind records (physics-informed neural networks). Li et al. [25] showed that using deep reinforcement learning to optimize the aerodynamic shape of buildings could result in reductions of 35% in the force acting on a building in its crosswind direction, showing that AI could be able to find aerodynamic solutions that defy human intuition.

V. CHALLENGES AND LIMITATIONS

5.1 Technical Challenges

Although significant progress has been made, a number of technical issues still exist in the accurate and reliable wind load assessment of tall buildings and prediction of structural response:

Aerodynamic Interference: No one national code gives general building configurations comprehensive interference factors. It is not possible to describe the aerodynamic interference factor (AIF) by a simple formula, as it changes non-monotonically depending on wind direction, height ratio and separation distance. An extensive database of interference factors for all parameter space would need a tremendous number of wind tunnel tests or validated CFD simulations to be developed [14, 15].

Dynamic Amplification in Flexible Buildings: The accurate estimation of resonant dynamic response requires knowledge of the damping ratio of the structure which varies with the vibration amplitude and cannot be reliably achieved at the design stage. Full-scale measurements performed by Kijewski and Kareem [13] have shown that resonant response is underestimated by 20-40% due to damping ratios of only 1.0-1.5% of critical at design wind amplitudes, for reinforced concrete buildings, which is significantly lower than the 2.0-3.0% often assumed.

Soil-Structure Interaction (SSI): Majority of wind load FEAs assume a fixed base condition, which ignores the extra compliance and damping contribution by the soil-foundation system. In buildings built on soft soils, SSI can increase the lateral deflections by 15-30% over the predictions made by assuming the structure is built on a fixed base and may have significant effects on the natural frequencies and mode shapes [26].

Wind hazard maps: The majority of existing maps of wind hazards in most countries are based on historical extreme wind speed data, which does not consider the expected change in intensity of tropical cyclones, extratropical storm tracks and monsoon circulation patterns under climate change scenarios. The design wind speed projections in cyclone-prone coastal regions of India (Bengal and Odisha coasts) are likely to rise by 5–15% by 2100 under the RCP 8.5 scenario [27] making current IS 875 wind speed maps potentially unconservative in the long term.

5.2 Research Gaps

Table 5 lists the major research gaps in wind engineering of tall buildings and suggests future research directions for each.

Table 5. Identified research gaps and proposed future research directions

Research Area	Current Gap	Proposed Direction
Interference effects	Codes provide no multi-building interference factors	Develop AIF databases via ML-augmented wind tunnel tests
Dynamic wind response	IS 875-1987 lacks dynamic provisions	Integrate gust response factor per revised IS 875 draft
Non-rectangular plans	Limited data for L, T, Y, chamfered forms	Parametric CFD studies across diverse plan geometries
Soil-structure interaction	Fixed base assumed in most FEA studies	Coupled SSI-wind response analyses
Climate change	Wind hazard maps not updated for future climate	Probabilistic wind hazard maps under climate projections
Hybrid structural systems	Outrigger + TMD combined performance understudied	Multi-hazard optimisation of hybrid control systems

Likewise, there is a considerable lack of application of performance-based wind engineering (PBWE) in the context of India. Although a seismic loading PBWE framework (PBEE) has been suggested for seismic loading and has been adapted for wind loading by Ciampoli et al. [20] a PBWE framework that is calibrated to Indian wind hazard data, Indian code provisions and Indian construction practice does not exist. Creating this equivalent of the PBEE framework used in earthquake engineering, as detailed in FEMA P-58 [28] is a high priority research need.

VI. FUTURE RESEARCH DIRECTIONS

6.1 Potential Improvements in Codal Frameworks

The following specific recommendations are made based on the review for the improvement of IS 875 (Part 3) and related Indian standards:

- Include gust response factors for along-wind dynamic response of flexible buildings as detailed in the draft revision, 2015; and
- Give examples of building cluster configurations in common urban situations and provide aerodynamic interference factors or design guidance for these configurations;
- Improve existing basic wind speed maps by including at least 50 years of more meteorological and, if possible, climate adjusted wind speed return level data;
- Use separate wind speed maps for different occupancy/importance categories (as in ASCE 7) instead of the single-map plus importance factor approach; and
- Make clear the conditions for wind tunnel testing (boundary layer simulation, model scaling, pressure tap specification, and data reduction) requirements outside the scope of codal provisions for buildings.

6.2 Opportunities for Future Research

There are several areas of research focus in the field of wind engineering for tall buildings that have the highest potential for improving the state of the art:

Develop Multi-Building Interference Database, where the aerodynamic interference factors of square, rectangular and circular buildings have been built up systematically with validated CFD simulations with wind tunnel validation. This database could be used to train machine learning meta-models that would allow for fast prediction of interference factors for an arbitrary building configuration [15, 22].

In terms of wind-resistant design, a framework for performance based wind engineering (PBWE) needs to be developed for India, which is calibrated with the wind hazard, structural inventory and construction practice in India, and allows performing risk-consistent wind-resistant design similar to PBEE for seismic loading. Uncertainties on wind speed, pressure coefficients, structural capacity and damping should be included in this framework [20].

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Multi-Hazard Design for Wind and Seismic Integrated Design: In high wind and seismic hazard areas (such as Konkan coast in India, Gujarat/India, Sikkim/India), an integrated wind seismic multi-hazard design framework is required which optimizes the structural performance of the structure under both wind and seismic loading. A framework in this form would involve the integration of probabilistic HA, fragility functions for multi-objective loading conditions, and multi-objective optimisation of structural systems [16].

The development and validation of structural digital twin frameworks for supertall buildings, which combine real-time sensor data fusion, FEA model updating and prediction of wind-induced response, is a game-changing opportunity to shift from design to operation through performance monitoring. Bench mark data from existing instrumented tall structures in India through field validation studies would be very beneficial.

Physics-Informed Neural Networks (PINNs): Physics-Informed neural networks (PINNs) for CFD Acceleration could be emerging physics-informed neural networks by integrating the Navier-Stokes equations as a physics constraint into the neural network loss function, thereby enabling accurate and computationally efficient wind pressure predictions without requiring extensive training data sets. Initial results are encouraging for basic building shapes and it has been identified that adapting to complex urban environments is an active research frontier [8, 25].

VII. CONCLUSION

The prevailing methods of wind load assessment and their evolution, the different codal approaches, experimental and computational methods, and new upcoming technologies in wind engineering of tall buildings have been explored in this review. The following major conclusions are made:

(i) Codal Limitations: Major wind loading codes such as IS 875 (Part 3)-1987, ASCE 7, EN 1991-1-4 and AS/NZS 1170.2 were formulated for isolated buildings, and offer limited or no guidance on aerodynamic interaction between neighbouring buildings. The Indian code is especially lacking in wind load dynamic provisions and interference guidance, which need to be updated.

(iii) Critical Wind Incidence: The 45° wind incidence angle has been consistently found to produce the critical bending moments and lateral displacement for the square-plan tall building which is due to the diagonal wind force acting on two faces of the building. This highlights the importance of multi-directional approaches in wind analysis for design.

(iii) Dynamic Amplification: If the natural period of a building is greater than about 1 second, resonant dynamic amplification can cause the peak wind effects to be 30-50% higher than static equivalent loads. The damping of the structures is generally 30–50% less than the typically assumed values at design wind amplitudes, thus further enhancing their dynamic response.

Shape Optimisation: Corner modifications (chamfers, roundings, aerodynamic setbacks) can cut along-wind and crosswind force coefficients by 20-30%, and are suitable for the concept design phase as a means to mitigate wind loads in an architecturally integrated manner.

(vi) Control Technologies: Passive TMDs have been proven to be effective in full scale for supertall buildings, where the reduction of wind-induced acceleration is 30–40%. The active and semi-active systems exhibit higher efficiency, but reliability and implementation issues still need to be addressed before they can be widely accepted.

The following technologies are emerging and will revolutionize the field of wind engineering over the next 10 years: (vi) machine learning-based pressure prediction, (vii) LES-CFD for urban wind, (viii) deep reinforcement learning for shape optimisation, and (ix) digital twin integration for life-cycle structural monitoring.

Key Recommendations

- Wind loads should be checked for a variety of angles of incidence (at least 0°, 45°, 90°) for all tall buildings and not just when required by code;
- For buildings over 60 m tall, or in an urban area, wind tunnel testing or validated LES-CFD testing is required;
- Reinforced concrete tall buildings should have a structural damping ratio of 2%, which needs to be reconsidered based on full-scale measurement data, and the damping ratio recommended as 1.5% for preliminary design;

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- The development of an IS 875 compatible aerodynamic interference factor database and a performance based wind engineering framework for the Indian context should be prioritised for the researchers; and
- The latest IS 875 (Part 3) (2015 draft) should be immediately adopted by the Bureau of Indian Standards, as IS 875 (1987) is materially non-conservative for flexible tall buildings.

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