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ASSESSMENT OF WIND LOAD EFFECTS AND LATERAL DISPLACEMENT CHARACTERISTICS IN HIGH-RISE BUILDING STRUCTURES

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ABSTRACT

Wind-induced response governs the serviceability of tall buildings, and increasingly their structural design, yet the relative weight of along-wind and across-wind effects shifts with height and slenderness in ways that single-direction code checks tend to hide. This paper presents a data-driven analysis of wind-induced displacement and acceleration for five square-plan reinforced concrete buildings, 100 m to 300 m tall, sharing a 40 m × 40 m plan (aspect ratios 2.5 to 7.5). Mean wind profiles, first-mode frequencies, and along-wind and across-wind responses were computed with a spectral random-vibration framework built on the gust-loading approach and empirical across-wind spectra, and then checked against drift and comfort criteria. Five analyses are reported: building and flow parameters, peak displacements, peak accelerations, cross-section modification, and damping sensitivity. Peak displacement scaled approximately with H^2.2 in the along-wind direction but with H^2.8 across-wind, so across-wind response overtook along-wind response between 200 m and 250 m, where the reduced velocity approached the vortex-shedding range (Vr ≈ 9). Across-wind acceleration rose from 2.2 to 24.7 milli-g and exceeded a 15 milli-g comfort threshold for the 250 m and 300 m buildings. For the 200 m building, corner chamfering, tapering and a 90° twist reduced across-wind acceleration by 38%, 44% and 56%, while raising damping from 2% to 5% reduced acceleration by about 37% in the 250 m case. The results indicate that aerodynamic shaping and added damping are complementary routes to serviceability, and that buildings beyond roughly 200 m should not be designed on along-wind checks alone.

Keywords: *Tall buildings[1]; Wind-induced response[2]; Across-wind vibration[3]; Occupant comfort[4]; Aerodynamic modification[5]; Structural damping[6]; Gust loading[7]*

1. INTRODUCTION

1.1 Background and Motivation

Skylines have grown faster than the stiffness of the structures beneath them. A 300 m concrete tower built today is usually lighter per unit floor area than a 100 m tower of the 1970s, thanks to higher-strength materials and more efficient cores, and that lightness comes at a price: lower natural frequencies and lower inherent damping. For low-rise buildings, wind is mainly a pressure to be resisted. For tall buildings it becomes a dynamic excitation to be managed [3], [4]. The fundamental frequency falls roughly in inverse proportion to height, so a 300 m tower sways with a period near seven seconds, a range in which both atmospheric turbulence and vortex shedding carry real energy. The consequences are not limited to safety. Occupants begin to notice horizontal motion at accelerations of only a few milli-g, and complaints of nausea, disturbed sleep and rattling fixtures have pushed owners of several well-known towers to retrofit dampers after construction [8], [15]. Serviceability therefore often governs before strength does. Because the designer cannot choose the wind, the available levers are geometry, stiffness and damping, and each has to be traded against cost and lettable floor area. Understanding how the response grows with height is the first step in deciding which lever is worth pulling.

1.2 Problem Statement and Research Gap

Most design offices still begin with a code-based along-wind estimate, the gust-loading approach of Davenport [2] in one of its codified forms [17], [18]. Across-wind response, which is driven by vortex shedding and the wake rather than by upstream turbulence, is treated in a less uniform way. Comparative studies have shown that international standards can differ by a factor of two in predicted across-wind loads for the same building [14]. The practical question is not whether across-wind motion matters, since it plainly does, but at what height and slenderness it takes over, and how much of it can be removed by modest changes in shape or damping. Published work answers parts of this question in isolation. Wind tunnel studies examine shape modifications on a single prototype [11], [13]. Full-scale monitoring reports damping and acceleration for particular towers [25], [26]. Parametric studies that vary height systematically, keep plan and exposure constant, and then test the same set of buildings against mitigation options are less common. This leaves a gap for a compact empirical comparison that places height, shape and damping effects on one consistent scale.

1.3 Objectives and Contribution

This paper has four objectives. First, to quantify how peak displacement and acceleration scale with height for a fixed plan and exposure, separating along-wind from across-wind contributions. Second, to identify the height at which across-wind response becomes dominant and to relate it to the reduced velocity. Third, to test the occupant-comfort implications against an accepted acceleration threshold [21]. Fourth, to measure the benefit of cross-section modification and of increased damping on the same set of buildings. The contribution is a single, consistent data set of five analyses, each supported by a table and an explanation, tied directly to the claims made in the

abstract and conclusion. The study does not replace wind tunnel testing, and its limits are discussed in Section 6, but it offers a transparent basis for deciding when such testing becomes unavoidable.

2. LITERATURE SURVEY

The statistical treatment of wind loading begins with Davenport [1], who showed that the response of a flexible structure to turbulent wind could be estimated from the spectrum of turbulence, the mechanical admittance of the structure and a peak factor. His gust-loading factor [2] turned this into a design tool and remains the backbone of the along-wind provisions in several codes. Vickery [28] questioned the reliability of the gust factor for tall, flexible structures, and Solari [22] later provided closed-form solutions that made the along-wind estimate easier to apply and to check. Holmes [4], Simiu and Scanlan [3] and Dyrbye and Hansen [30] consolidated the theory in textbooks that are still the usual starting point. Across-wind response needed a different approach, because turbulence in the approaching flow is not its main driver. Kareem [5] proposed a spectral model for across-wind forces based on aeroelastic and pressure measurements, and Kwok and Melbourne [9] examined the lock-in excitation that appears when the shedding frequency approaches the natural frequency. Gu and Quan [29] later assembled across-wind force data for typical rectangular buildings, giving designers a more practical database. Full-scale evidence agrees broadly with these models: Li et al. [25] measured wind effects on tall buildings in Hong Kong during typhoons, and Kijewski-Correa et al. [26] compared monitored and predicted responses of Chicago towers, finding that frequencies were predicted well but damping remained the largest uncertainty.

Aerodynamic shape has received sustained attention. Kwok [10] found that corner treatment and cross-section shape significantly changed response, and Miyashita et al. [11] showed that corner cuts and openings reduced both across-wind and torsional effects in square buildings. Kim and Kanda [12] studied height variations, and Tanaka et al. [13] tested a wide range of unconventional configurations, including tapered, twisted and set-back forms, reporting reductions in across-wind force of up to about half for twisted and tapered shapes. Irwin [15], [16] linked these findings to supertall practice, noting that shaping is typically the first choice because it reduces loads without adding mass or mechanical devices. On the damping side, Kareem and Gurley [27] documented how uncertain and amplitude-dependent damping is, and Kareem et al. [6] reviewed motion mitigation with tuned mass and liquid dampers in real buildings. Comfort criteria were examined by Kwok et al. [8], who compared perception thresholds and showed that human tolerance varies with frequency, duration and context, consistent with the framework in ISO 10137 [21]. Equivalent static wind load models by Chen and Kareem [24] and the probabilistic turbulence modelling of Solari and Piccardo [23] extended the toolkit to three-dimensional responses. Code comparisons by Kwon and Kareem [14] revealed notable disagreement among AIJ [19], ASCE 7 [17], Eurocode [20] and other standards, especially for across-wind effects. Taken together, the literature supports three conclusions: along-wind theory is mature, across-wind prediction depends heavily on empirical databases, and damping is the weakest input. What it offers less often is a compact side-by-side data set in which height, shape and damping are varied against one consistent exposure and plan. That arrangement is adopted here.

3. METHODOLOGY

The study adopts an analytical–numerical case-study design. Five square-plan reinforced concrete buildings were defined with heights of 100, 150, 200, 250 and 300 m, a constant plan of 40 m × 40 m and a core-and-frame lateral system, giving aspect ratios between 2.5 and 7.5. Exposure was held constant at open suburban terrain (a power-

law exponent of 0.22), with a reference mean wind speed of 33 m/s at 10 m. First-mode frequencies were obtained from a three-dimensional finite element idealisation with cracked section properties and compared with the empirical estimate f1 ≈ 46/H, and structural damping was set at 2% of critical for the base cases, a value typical for concrete buildings at serviceability level [27]. Along-wind response was calculated in the frequency domain using the gust-loading framework of Davenport [2] with the closed-form refinements of Solari [22], combining a background and a resonant component and applying a peak factor. Across-wind response was computed from the empirical across-wind force spectrum of Kareem [5] with the force coefficients of Gu and Quan [29], and it was evaluated as a function of the reduced velocity Vr = V_H/(f1·B). Peak top displacement and peak top acceleration were reported at a 10-year return period for comfort and at the design level for drift. Comfort was judged against a 15 milli-g threshold, which lies within the range recommended by ISO 10137 [21] and discussed by Kwok et al. [8].

Shape and damping scenarios were then applied to the same framework. For the 200 m building, five cross-sections were compared: square, 15% chamfered corners, 15% recessed corners, a 10% linear taper and a 90° twist over the height, using force-reduction ratios drawn from the experimental trends in [10], [11] and [13]. For the 250 m building, damping was varied from 1% to 5%, using the inverse-square-root dependence of resonant response on the damping ratio [4].

4. DATA COLLECTION AND ANALYSIS

The data set consists of five tables, each addressing one part of the central question: how height, flow, shape and damping together shape the wind response of tall buildings. The same buildings appear throughout, so every table can be read against the others.

Table 1.: Geometric, dynamic and flow parameters of the study buildings

Building	H (m)	H/B	V^H (m/s)	f1, FE (Hz)	f1, 46/H (Hz)	Vr = V^H/(f1·B)
B1	100	2.50	54.7	0.440	0.460	3.11
B2	150	3.75	59.9	0.300	0.307	4.99
B3	200	5.00	63.8	0.220	0.230	7.25
B4	250	6.25	67.0	0.175	0.184	9.57
B5	300	7.50	69.7	0.145	0.153	12.02

Table 1 shows that the mean wind speed at roof level rises by about 27% from B1 to B5, while the first-mode frequency falls by about 67%. The finite element frequencies sit 2–5% below the empirical 46/H estimate, which is reasonable given the cracked-section assumption. The reduced velocity more than triples across the set, from 3.11 to 12.02. B4 has Vr = 9.57, which falls close to the vortex-shedding resonance region (Vr near 1/St, about 9 for a square section), while B5 lies beyond it. This explains why the later tables show a sharp change in the 250 m and 300 m cases, and it ties the flow parameters directly to the claim in the abstract.

Table 2: Peak top displacement in the along-wind and across-wind directions

Building	H (m)	Along-wind (mm)	Along drift ratio	Across-wind (mm)	Across drift ratio
B1	100	62	1/1613	41	1/2439
B2	150	148	1/1014	121	1/1240
B3	200	281	1/712	276	1/725

B4	250	462	1/541	515	1/485
B5	300	718	1/418	884	1/339

Table 2 shows the crossover. At 100 m the along-wind displacement is 51% larger than the across-wind one; at 200 m the two are almost equal (281 mm against 276 mm); at 250 m and 300 m the across-wind displacement is larger by 11% and 23%. A power-law fit through the five points gives exponents of about 2.2 for along-wind and 2.8 for across-wind displacement, so the across-wind component grows markedly faster with height. The drift ratio of B5 (1/418) would fail a commonly applied limit of 1/500, and it does so because of the across-wind component, not the along-wind one. A design that checks along-wind drift only would underestimate the demand in B4 and B5.

Table 3: Peak top acceleration (10-year return period) and comfort check

Building	H (m)	Along-wind (milli-g)	Across-wind (milli-g)	Governing direction	Within 15 milli-g?
B1	100	3.1	2.2	Along	Yes
B2	150	4.8	5.1	Across	Yes
B3	200	6.9	9.8	Across	Yes
B4	250	9.4	16.3	Across	No
B5	300	12.6	24.7	Across	No

Acceleration is more sensitive to height than displacement. Between B1 and B5 the along-wind acceleration rises about four times, while the across-wind acceleration rises about eleven times, from 2.2 to 24.7 milli-g. Across-wind motion governs from 150 m upward, which is earlier than the displacement crossover in Table 2, because acceleration depends on frequency squared and the lower frequencies of taller buildings amplify the resonant component. B4 exceeds the 15 milli-g threshold by 9%, and B5 exceeds it by 65%. This is the central finding of the study: comfort fails before strength or drift would fail, and across-wind response is the cause.

Table 4: Effect of cross-section modification on the 200 m building (B3)

Cross-section	Across-wind base moment (GN·m)	Reduction (%)	Across-wind acceleration (milli-g)	Reduction (%)
Square (reference)	3.4	–	9.8	–
15% chamfered	2.2	35.3	6.1	37.8
15% recessed	2.4	29.4	6.6	32.7
10% tapered	2.0	41.2	5.5	43.9
90° twisted	1.6	52.9	4.3	56.1

Table 4 shows that every modification reduces across-wind effects, and that the reduction in acceleration slightly exceeds the reduction in base moment, since a weaker vortex-shedding force also reduces the resonant amplification. Chamfering and recessing deliver reductions of about one third at small cost in floor area, tapering adds roughly another ten points, and twisting delivers the largest reduction at over half. The ordering is consistent with the trends reported in wind tunnel work [11], [13]. The practical value is that B4 (16.3 milli-g) could be brought below the comfort limit by chamfering alone (assuming a similar 38% reduction, about 10 milli-g), without any mechanical device.

Table 5: Sensitivity of peak acceleration to structural damping for the 250 m building (B4)

Damping ratio (%)	Along-wind (milli-g)	Across-wind (milli-g)	Across-wind reduction vs 2% (%)	Within 15 milli-g?
1	13.3	23.1	−41.7	No
2	9.4	16.3	–	No
3	7.7	13.3	18.4	Yes
5	5.9	10.3	36.8	Yes

Table 5 illustrates the sensitivity of response to damping, which is the most uncertain input in the analysis [27]. Halving the damping ratio from 2% to 1% raises across-wind acceleration by about 42%, while increasing it to 3% brings B4 below the 15 milli-g limit and 5% gives a 37% reduction. Because real damping in concrete buildings at serviceability levels can plausibly fall anywhere between 1% and 3%, the comfort status of B4 depends on a parameter that cannot be known before construction. This justifies designing a margin into either the shape or a provision for supplemental damping.

5. DISCUSSION

5.1 Critical Analysis of the Data

The five tables tell one consistent story. Height raises both mean wind speed and flexibility, and the combined effect is non-linear: Table 1 shows the reduced velocity entering the vortex-shedding range just where Tables 2 and 3 show across-wind response taking over. The crossover therefore is not a coincidence of the numbers, since it has a physical mechanism, namely a shedding frequency approaching the natural frequency. Beyond the crossover the response rises steeply, as the exponent of 2.8 in displacement and the elevenfold growth in acceleration both indicate. The data also show why a drift-based and a comfort-based check can lead to different conclusions. B3 passes both checks with room to spare, B4 passes drift (1/485 is slightly worse than 1/500, so it is marginal in fact) and fails comfort, and B5 fails both. The comfort check therefore flags the problem earlier. A designer who relied on strength and along-wind drift would have approved a 250 m building that occupants would find uncomfortable.

Several limitations deserve attention. The data come from a spectral model and not from wind tunnel or full-scale records, so absolute values carry uncertainty of perhaps ±20–30% in across-wind effects, reflecting the scatter in the underlying force databases [29]. Only one plan shape, one terrain category and one wind direction (normal to a face) were considered, so torsional response, oblique winds and interference from neighbouring buildings are outside the study, even though they can govern in practice [15]. The reduction ratios in Table 4 are transferred from experimental trends and applied uniformly, though real reductions depend on the wind direction and on the exact corner geometry [11]. Finally, damping is treated as constant, whereas it is known to depend on amplitude [27], so Table 5 is a sensitivity trend and not a prediction. The main conclusion survives these limitations because it rests on ratios and trends, not on single absolute values, though the exact height of the crossover would shift under other conditions.

5.2 Comparison with Past Work

The scaling of across-wind response with height found here agrees with the theory in [4] and [5], in which across-wind response grows faster than along-wind response with slenderness because it is governed by the shedding

force and by the lower damping ratio relative to mass. The identification of Vr near 9 as the onset of intense response matches the lock-in behaviour described by Kwok and Melbourne [9], who observed large amplitudes when the shedding frequency approached the natural frequency of tall structures. The crossover height of 200–250 m is also consistent with the practical experience described by Irwin [15], [16], where across-wind effects begin to dominate in buildings with aspect ratios above about 5 to 6. The shape results compare well with experiments. Miyashita et al. [11] reported significant reductions in across-wind response for square buildings with corner cuts and recesses, and the 30–38% reductions in Table 4 fall within the range of those experimental findings. Tanaka et al. [13] reported across-wind force reductions for tapered and twisted buildings of up to roughly half, which is consistent with the 44% and 56% acceleration reductions found here, although the values for twisting are at the high end and depend on the rate of twist. Kwok [10] noted that corner modification was among the most efficient changes, which fits the finding that chamfering gives about one third of the benefit at a small cost in usable area.

The damping results are consistent with the established inverse-square-root dependence [4], and with the review by Kareem et al. [6], who show that supplemental dampers can lower acceleration by amounts similar to the 37% found for a rise from 2% to 5% damping. The sensitivity to damping also echoes Kijewski-Correa et al. [26], who found that frequency prediction in monitored buildings was accurate but damping remained uncertain, and Kareem and Gurley [27], who emphasised the same point. In that sense the data confirm a long-standing message: the model is dependable, but its inputs are not. Some differences with past work should be stated plainly. Kwon and Kareem [14] found that code-based across-wind predictions vary widely between standards, so the absolute accelerations of Table 3 would shift if a different code database were used, and the 15 milli-g threshold is itself a simplification of the frequency-dependent criteria in [8] and [21]. Full-scale evidence from [25] and [26] generally shows somewhat lower damping at small amplitudes than the 2% used here, which suggests that the real comfort performance of B3 and B4 might be worse than shown. Unlike many studies in the literature that focus on one building and one mitigation measure, this study varies height, shape and damping together, which allows the relative size of the benefits to be compared directly: shaping reduces response by 30–56%, damping from 2% to 5% by 37%, and both are far larger than the 5–10% changes that come from modest stiffness adjustments. The finding is consistent with the practice described in [15] of choosing shape first and damping second.

6. CONCLUSION

This paper analysed the wind-induced displacement and acceleration of five tall buildings between 100 m and 300 m, and the results support the central claim made in the abstract. Across-wind response grows faster with height than along-wind response, with fitted displacement exponents of about 2.8 against 2.2, and it overtakes the along-wind component between 200 m and 250 m, at the point where the reduced velocity approaches the vortex-shedding range of about 9. Peak across-wind acceleration rose from 2.2 to 24.7 milli-g, so the 250 m and 300 m buildings exceeded the 15 milli-g comfort threshold, and comfort failed before strength or drift limits would have flagged a problem. The mitigation results show that response can be reduced without extra mass. Chamfering, tapering and twisting lowered across-wind acceleration of the 200 m building by about 38%, 44% and 56%, and raising damping from 2% to 5% reduced acceleration in the 250 m building by about 37%. Because damping is also the least certain input, a design that depends on a fixed 2% value carries real risk. The practical

recommendation is that buildings beyond roughly 200 m or an aspect ratio near 5 should be evaluated for across-wind comfort at an early stage, with aerodynamic shaping considered first and supplemental damping reserved as a provision. The study is limited by its analytical data, single plan form, single terrain and single wind direction. Future work should validate these trends with wind tunnel and full-scale records, extend the set to torsion, oblique winds and neighbouring-building interference, and treat damping as an amplitude-dependent, uncertain quantity.

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