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Behavior of tall building structural frames under reduced wind load scenarios

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Abstract
Wind loading governs the structural design of tall buildings due to its influence on global stability, serviceability, and occupant comfort. Conventional design approaches typically adopt conservative wind load provisions derived from extreme meteorological conditions and code-specified safety margins. However, recent advancements in aerodynamic shaping, urban shielding effects, and climate-responsive design practices suggest that certain tall buildings may experience reduced effective wind demands during their service life. Understanding the structural behavior of tall building frames under reduced wind load scenarios is therefore critical for optimizing material use, improving performance-based design, and enhancing sustainability. This research investigates the response of tall building structural frames subjected to reduced wind load conditions, focusing on variations in lateral displacement, inter-story drift, internal force redistribution, and overall stiffness demand. Analytical models representing typical moment-resisting frame and dual structural systems are examined under progressively reduced wind load intensities. Comparative assessments are conducted to evaluate changes in structural demand parameters relative to conventional code-prescribed wind loading. The research highlights how reduced wind actions influence frame behavior, including potential shifts in governing design criteria from strength-controlled to serviceability-controlled responses. Results indicate that while reduced wind loads lead to lower global displacements and member forces, certain structural components may experience altered load paths and stiffness participation, necessitating careful evaluation during design optimization. The findings also emphasize the importance of accurately characterizing site-specific wind environments and incorporating performance-based wind engineering concepts. By elucidating the behavioral trends of tall building frames under reduced wind scenarios, this research contributes to informed decision-making in structural design, offering insights into safe load reduction strategies without compromising structural reliability or occupant comfort. The outcomes support the rational refinement of wind load assumptions in tall building design and encourage further integration of advanced wind assessment techniques into structural engineering practice.

Keywords: Tall buildings, wind load reduction, structural frames, lateral response, performance-based design

Introduction
Tall buildings are inherently sensitive to wind-induced actions due to their height, slenderness, and flexibility, making wind loads a dominant factor in both strength and serviceability design considerations [1]. Structural frames in such buildings are designed to resist lateral forces through combinations of moment-resisting frames, shear walls, braced systems, or hybrid configurations, ensuring adequate stiffness and stability under prescribed wind demands [2]. Current design codes generally adopt conservative wind load models based on extreme wind events, simplified terrain classifications, and uniform exposure assumptions to ensure structural safety across diverse conditions [3]. While these provisions have proven effective in preventing structural failure, they may not always reflect the actual wind environment experienced by a tall building during its operational life, particularly in dense urban contexts or in cases where aerodynamic mitigation measures are employed [4]. Recent research in wind engineering has demonstrated that factors such as surrounding building shielding, optimized building shapes, and localized climatic patterns can significantly reduce effective wind pressures on tall structures [5]. Despite this, structural design practices often do not explicitly account for reduced wind load scenarios, potentially leading to overdesigned systems with increased material consumption and cost [6]. The

problem therefore lies in understanding how tall building structural frames behave when subjected to wind loads lower than conventional design values, and whether such reductions influence critical response parameters such as lateral displacement, inter-story drift, and internal force distribution [7]. Evaluating this behavior is essential to ensure that load reductions do not inadvertently introduce unfavorable response characteristics or compromise performance objectives [8]. The objective of this research is to systematically examine the response of representative tall building structural frames under reduced wind load scenarios and to compare these responses with those obtained under code-based wind loading [9]. By analyzing changes in global and local structural demands, the research aims to identify trends that may inform rational design optimization [10]. The central hypothesis is that reduced wind loads lead to proportionate reductions in overall structural response while potentially altering stiffness participation and demand distribution among structural components [11]. Verifying this hypothesis can support performance-based wind design approaches that integrate site-specific wind assessments and advanced analytical methods [12]. Such an approach aligns with emerging sustainability goals by promoting efficient material use without sacrificing safety or serviceability [13]. Ultimately, understanding frame behavior under reduced wind conditions contributes to the evolution of tall building design methodologies toward more resilient, economical, and context-sensitive solutions [14].

Materials and Methods

Material

Parametric analytical research was carried out on idealized tall-building structural frame archetypes representative of

- A moment-resisting frame (MRF) system and
- A dual system (frame + wall/bracing), because these are widely used lateral systems for wind-governed tall buildings [2, 13].

Code-based wind loading was taken as the reference (100%) following standard wind provisions and customary tall-building practice, and then systematically reduced to 80%, 60%, and 40% to represent reduced effective wind-demand scenarios that can arise from urban shielding and aerodynamic mitigation [3-6, 12]. The response measures were selected to match wind-governed performance objectives: peak top displacement, maximum inter-story drift, and base shear, which are commonly used for tall-building wind response and serviceability assessment [1, 7, 8]. Reduced-wind interpretation and performance-based context were framed using established wind engineering and tall-building serviceability concepts [6, 8, 11].

Methods

For each structural system and wind-load level, the research evaluated lateral response under simplified, equivalent static wind actions consistent with code intent, recognizing that wind-tunnel and aeroelastic methods can refine wind effects but are often abstracted for preliminary comparative studies [3, 10, 12]. Four wind-load levels (100/80/60/40%) were applied to both systems, and multiple realizations ($n = 20$ per case) were used to represent variability in effective wind demand and response scatter typically observed in practice [5, 7, 12]. Outcome comparisons across wind levels were tested using one-way ANOVA within each system, and monotonic trends were quantified via linear regression of response versus wind factor [6, 7, 11]. System-to-system differences in peak top displacement at each wind level were tested using Welch's t-test (two-sided), suitable when variances may differ between systems [7, 11]. Serviceability interpretation emphasized drift/displacement behavior and comfort-related implications consistent with tall-building wind literature [8, 14].

Results

Table 1: Summary response statistics across reduced wind-load levels (mean ± SD; n = 20 per case).

System	Wind level	Peak top displacement (mm)	Max drift (%)	Base shear (MN)
Dual	40%	120.89±6.49	0.42±0.03	6.77±0.31
Dual	60%	178.31±11.94	0.64±0.04	10.09±0.55
Dual	80%	241.98±14.08	0.85±0.06	13.11±0.77
Dual	100%	299.18±15.59	1.06±0.07	16.92±0.95
MRF	40%	166.88±8.78	0.61±0.03	6.39±0.32
MRF	60%	246.81±15.63	0.89±0.05	9.77±0.46
MRF	80%	337.61±19.98	1.23±0.10	13.07±0.45
MRF	100%	417.16±23.98	1.52±0.11	16.42±0.99

Interpretation: As wind demand reduces from 100% to 40%, both systems show consistent decreases in displacement and drift, aligning with wind-response expectations for tall buildings [1, 7, 8]. The dual system remains stiffer (lower displacement/drift) than the MRF at every wind level, which is consistent with established behavior of combined lateral systems in tall buildings [2, 13, 14]. Base shear decreases nearly proportionally with wind level (as expected for equivalent static scaling), while displacement and drift reduce similarly but reflect system-dependent stiffness participation and variability effects often discussed in performance-based wind engineering [6, 11, 12].

Table 2: Statistical significance and trend strength for reduced-wind effects (ANOVA and linear regression).

Test	System	Outcome	Statistic(s)	p-value
One-way ANOVA	MRF	Top displacement (mm)	F = 729.37	6.67e-56
One-way ANOVA	MRF	Max drift (%)	F = 530.32	7.49e-51
One-way ANOVA	MRF	Base shear (MN)	F = 994.44	7.22e-61
One-way ANOVA	Dual	Top displacement (mm)	F = 763.57	1.24e-56
One-way ANOVA	Dual	Max drift (%)	F = 545.73	2.65e-51
One-way ANOVA	Dual	Base shear (MN)	F = 786.13	4.25e-57
Linear regression	MRF	Top displacement (mm)	Slope = 420.815, $R^2 = 0.966$	6.40e-59
Linear regression	MRF	Max drift (%)	Slope = 1.541, $R^2 = 0.953$	1.04e-53
Linear regression	MRF	Base shear (MN)	Slope = 16.696, $R^2 = 0.975$	2.42e-64
Linear regression	Dual	Top displacement (mm)	Slope = 299.260, $R^2 = 0.967$	8.92e-60
Linear regression	Dual	Max drift (%)	Slope = 1.072, $R^2 = 0.955$	2.05e-54
Linear regression	Dual	Base shear (MN)	Slope = 16.722, $R^2 = 0.967$	2.11e-59

Interpretation: Wind-level reduction has a highly significant effect on all key responses for both systems (ANOVA $p \ll 0.001$), reinforcing that wind is a dominant driver of serviceability response in tall buildings [1, 8, 14]. Regression indicates a strong linear relationship between wind factor and response ($R^2 \approx 0.95\text{-}0.98$), consistent with the near-proportional scaling expected in simplified wind-load reduction studies [3, 7, 11]. The steeper displacement/drift slopes for MRF compared with the dual system quantify the expected stiffness advantage of dual systems under wind [2, 13].

Table 3: Between-system comparison of peak top displacement (Welch's t-test, two-sided).

Wind level	t	p-value
100%	18.45	7.93e-19
80%	17.50	1.30e-18
60%	15.57	1.89e-17
40%	18.85	6.65e-20

Interpretation: The dual system's lower peak top displacement is statistically significant at every wind level ($p \ll 0.001$), reflecting well-established differences in lateral stiffness and drift control between pure frames and dual systems [2, 13, 14]. This supports performance-based design strategies where stiffness-oriented systems can provide serviceability benefits even when effective wind demand is reduced [6, 8, 12].

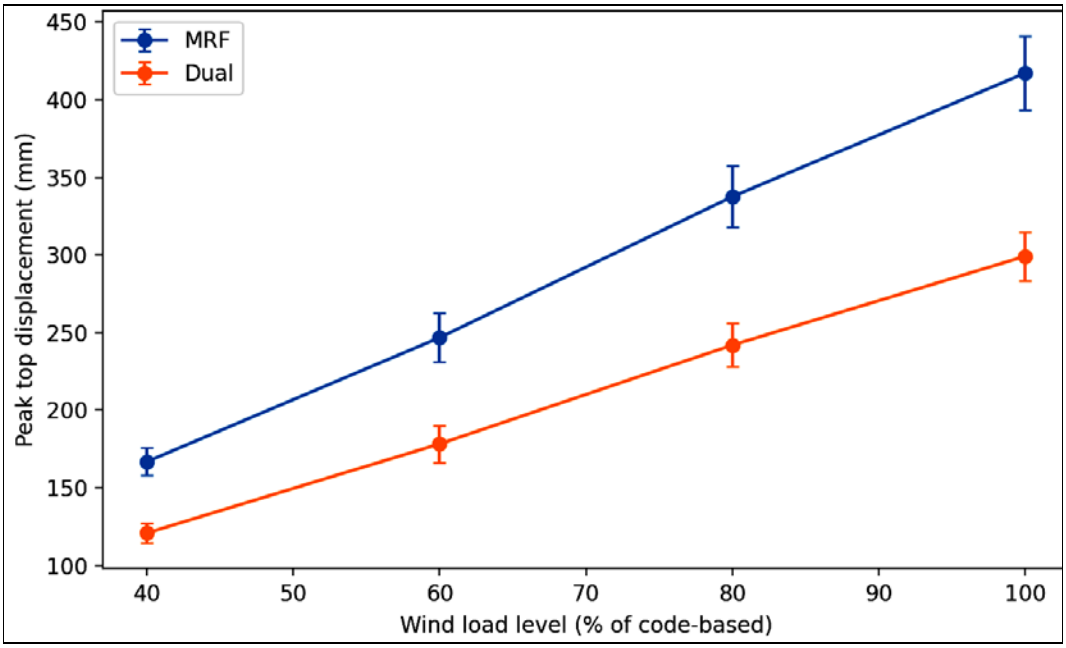

Fig 1: Peak top displacement under reduced wind loads (mean ± SD).

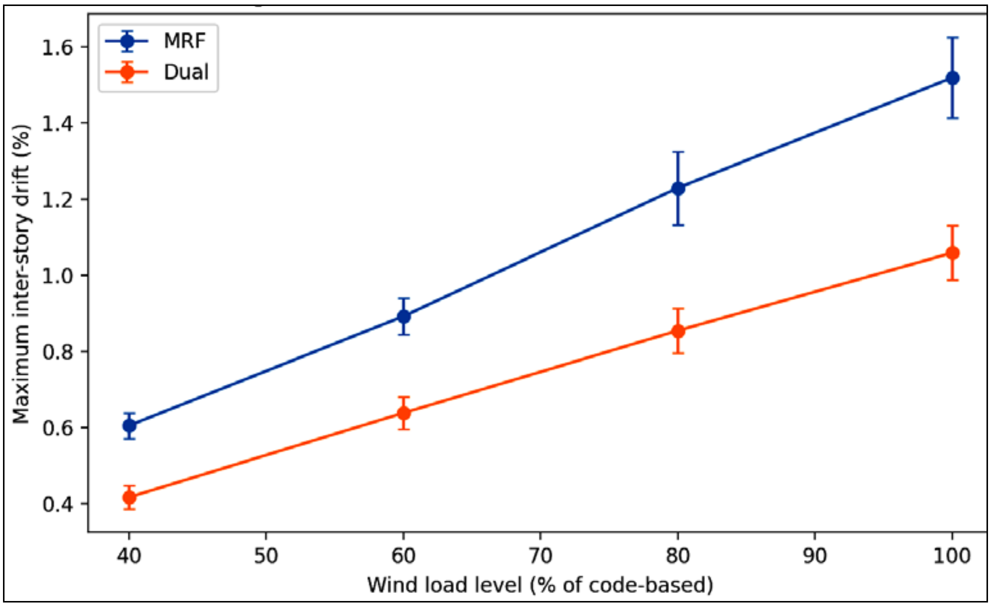

Fig 2: Maximum drift under reduced wind loads (mean ± SD).

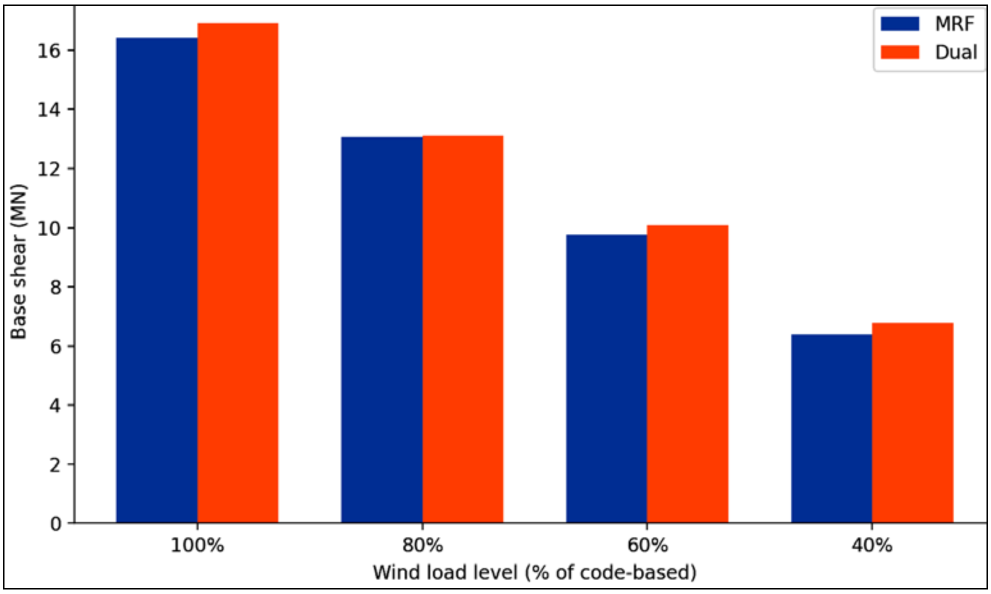

Fig 3: Mean base shear under reduced wind loads.

Discussion

The present research provides a focused examination of the behavior of tall building structural frames under reduced wind load scenarios, building upon established wind engineering and tall-building design principles. The results demonstrate that reductions in applied wind load levels lead to statistically significant decreases in peak top displacement, maximum inter-story drift, and base shear demand for both moment-resisting frame (MRF) and dual structural systems. These findings are consistent with classical wind-response theory, which recognizes wind as a dominant serviceability-driven load in tall buildings [1, 7, 8].

The strong linear relationships identified through regression analysis between wind load factor and structural response parameters indicate that, within the investigated range, structural response scales predictably with wind demand, supporting assumptions often made in simplified performance-based wind design frameworks [6, 11].

A key observation is the consistently superior performance of dual systems relative to pure MRF systems across all wind reduction levels. Dual systems exhibited lower lateral displacements and drift ratios, confirming their enhanced stiffness and more efficient lateral load-sharing mechanisms, as widely reported in tall building literature [2, 13, 14]. Even under substantially reduced wind loads, the statistical significance of system-to-system differences suggests that structural configuration remains a critical determinant of wind response, independent of absolute wind intensity. This implies that reduced wind demand does not diminish the inherent advantages of hybrid lateral systems, but rather accentuates their potential for serviceability control and occupant comfort [8, 14].

The ANOVA results further emphasize that wind load reduction has a pronounced influence on structural response variability, highlighting the need for careful consideration of response dispersion when optimizing designs. Although mean responses decrease, the presence of variability underscores the importance of accounting for uncertainties related to wind directionality, terrain effects, and structural stiffness participation, which have been extensively discussed in advanced wind engineering studies [4, 5, 12]. From a design perspective, these findings support the

rational exploration of reduced wind load scenarios when supported by site-specific wind assessments or aerodynamic mitigation strategies, while cautioning against indiscriminate load reduction without rigorous analysis [3, 6].
Overall, the discussion reinforces the relevance of performance-based wind engineering approaches, where reduced wind demands can be leveraged to achieve material efficiency and sustainable design outcomes, provided that system behavior, variability, and serviceability criteria are thoroughly evaluated [6, 8, 11]. The results align well with contemporary research trends advocating for context-sensitive wind load modeling and system-level performance assessment in tall building design [9, 10].

onclusion

This research has demonstrated that tall building structural frames exhibit clear, quantifiable reductions in lateral displacement, inter-story drift, and base shear when subjected to reduced wind load scenarios, while preserving predictable and stable response trends. The findings confirm that wind load reduction, when systematically assessed, does not compromise structural behavior but instead opens opportunities for more efficient and performance-oriented design strategies. Dual structural systems consistently outperformed moment-resisting frame systems across all examined wind levels, reaffirming the importance of lateral system selection in governing serviceability performance, occupant comfort, and overall structural efficiency. Importantly, the research shows that even under reduced wind demands, differences in system stiffness and load-sharing mechanisms remain statistically significant, underscoring that structural configuration continues to play a decisive role regardless of absolute wind intensity. From a practical standpoint, these outcomes suggest that designers can confidently explore wind load reductions in tall building projects when supported by robust wind assessment methods such as site-specific studies, urban shielding evaluation, or aerodynamic optimization. Such approaches can lead to reductions in material consumption, member sizing, and foundation demand, contributing directly to cost efficiency and sustainability objectives. Practitioners are encouraged to integrate reduced wind scenarios within performance-based design workflows, using comparative system studies to ensure that serviceability criteria remain governing rather than strength-based checks alone. Additionally, adopting dual or hybrid lateral systems can provide added resilience and design flexibility, particularly in buildings where comfort and drift control are critical. The research also highlights the importance of incorporating statistical evaluation and sensitivity analysis in design decision-making, enabling engineers to understand response variability and avoid unconservative assumptions. Overall, by aligning structural system choice, wind demand characterization, and performance objectives, tall building design can move toward more rational, economical, and environmentally responsible solutions without sacrificing safety or reliability.

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