Council on Tall Buildings and Urban Habitat Korea

International Journal of
High-Rise Buildings
www.ctbuh-korea.org/ijhrb/index.php

International Journal of High-Rise Buildings
December 2025, Vol 14, No 4, 251-255
https://doi.org/10.21022/IJHRB.2025.14.4.251

A Case Study on the Application of Performance-Based Wind Design to a Tall Building

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Abstract This study investigates the application of Performance-Based Wind Design (PBWD) to a representative building using linear and nonlinear time-history analyses with floor-by-floor time-series wind forces. The 1-year, 50-year, and 500-year return-period winds were used to evaluate occupant comfort, displacement serviceability, and structural safety, respectively. The linear analyses demonstrated that both acceleration and displacement responses satisfied the prescribed acceptance criteria. Under the 500-year wind, the nonlinear analysis revealed localized yielding and limited inelastic behavior, while residual displacement, interstory drift, deformation damage index, and fatigue demand remained within allowable limits. A pushover analysis further confirmed that a conventional wind-governed design may lead to brittle shear failure in critical members, whereas the PBWD-based design exhibited stable ductile behavior with improved structural reliability. The results highlight that PBWD provides a rational and resilient design framework, ensuring consistent structural performance for buildings governed by wind effects.

Keywords: Pure-Timber High-rise, Fire-Resistant, Seismic Isolation

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1. Introduction

Performance-Based Wind Design (PBWD) has gained increasing attention as wind engineering practices evolve toward performance-driven methodologies. PBWD establishes explicit performance objectives for buildings subjected to wind hazards, addressing serviceability, structural safety, and continued functionality. The ASCE (2019) Prestandard for Performance-Based Wind Design offers analytical procedures and performance criteria that permit limited nonlinear behavior under extreme wind events. Similarly, the Korean structural design standard KDS 41 12 00 (2022) provides provisions defining the scope, analysis methods, and target performance levels for PBWD, enabling its application to tall buildings.

Despite these advancements, practical guidance and readily applicable examples remain limited, indicating the need to develop clearer workflows and accumulate real-world applications to support broader implementation of PBWD in practice. In this study, PBWD procedures based on the ASCE Prestandard are applied to representative high-rise buildings, and the associated analysis steps and performance evaluations are examined. The results aim to provide technically reproducible insights that facilitate the practical use of PBWD.

2. Overview of PBWD

Performance-Based Wind Design (PBWD) provides a structured framework for evaluating building performance under wind hazards by defining three performance levels: Occupant Comfort, Operational, and Continuous Occupancy. Each level corresponds to a specific wind return period and requires different analytical approaches. Occupant Comfort is evaluated under a 1-year return period wind, focusing on human perception and horizontal vibration. The Operational level uses a 50-year return period wind to verify that the building maintains functional usability through displacement limits. The Continuous Occupancy level is assessed under 500-year or 900-year return period winds and requires evaluation of structural safety, including maximum displacement, member forces, Deformation Damage Index (DDI), residual displacement, residual drift ratio, and fatigue-related demands.

The ASCE (2019) Prestandard outlines procedures and acceptance criteria for PBWD and allows designers to incorporate nonlinear behavior by applying a response modification factor, R, to the resonant component of the wind load. This can reduce design wind forces, although Korean KDS provisions limit R to a maximum of 2 and prohibit its use for comfort and operational evaluations. After preliminary design using codified load combinations, PBWD requires linear or nonlinear time-history analysis depending on the targeted performance objective.

A key requirement for PBWD is the use of time-series floor-level wind loads, which cannot be derived solely from code formulas. Instead, they must be obtained through simultaneous pressure measurement wind tunnel tests,

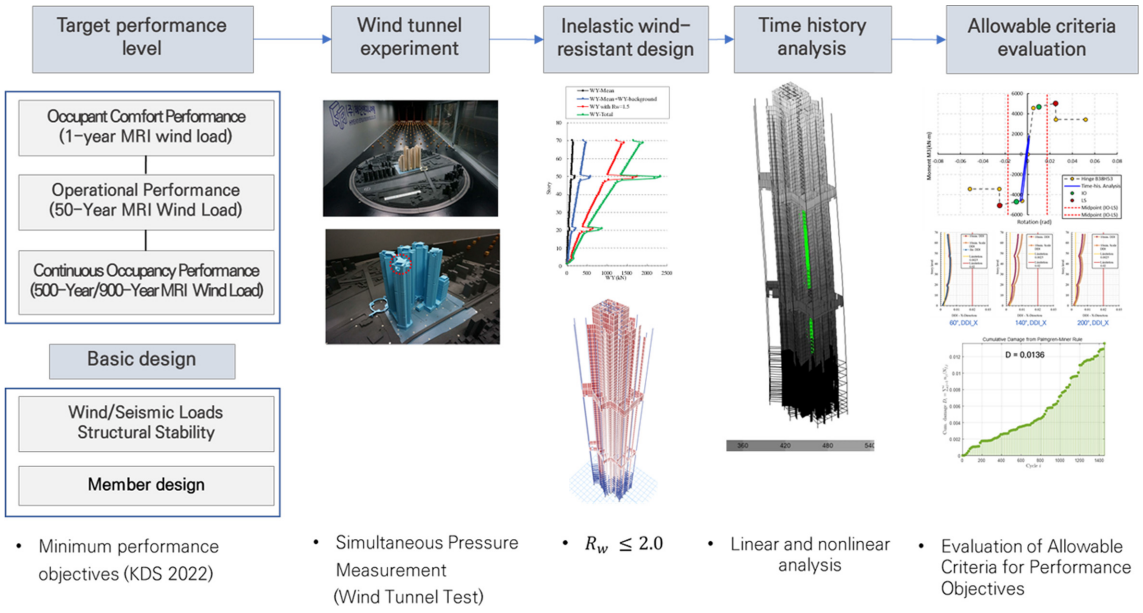


Figure 1. Overall procedure of PBWD.

where pressure time histories on the building envelope are integrated to generate dynamic wind loads for structural analysis. These detailed load histories enable accurate assessment of elastic and inelastic structural responses, supporting design verification and potential optimization. PBWD thus provides a more comprehensive and performance-driven approach to wind design, especially for tall and complex buildings.

3. Application

3.1. Overview

In this study, the procedures of Performance-Based Wind Design (PBWD) were applied to a sample building. The example structure is an office building with a height of 120 m, a plan width of approximately 30 m, and a slenderness ratio of 4. The lateral-force-resisting system consists of a reinforced concrete shear wall core combined with perimeter moment-resisting frames. The preliminary structural design followed KDS 2022, incorporating the 500-year return period wind load for the Busan region together with seismic and other prescribed load combinations. Based on this design framework, Case 1 represents conventional elastic wind design, while Case 2 corresponds to PBWD, where a response modification factor of R = 1.5 was applied to the resonant component of the wind load.

Following the preliminary design phase, Case 2 underwent the PBWD evaluation process. Linear time-history analysis was performed to verify performance at the occupant comfort, operational, and continuous occupancy levels. Effective stiffness properties were used for the elastic performance assessments, and nonlinear behavior was captured through a structural model utilizing concentrated hinges and fiber hinges.

Time-series floor-level wind loads were required for the dynamic analyses. These loads were derived from synchronized pressure measurement wind tunnel tests, in which measured pressure time histories were integrated over tributary surface areas. The wind tunnel experiments were conducted at a wind tunnel laboratory, providing high-resolution wind pressure data suitable for PBWD application.

The structural design of the sample building was performed in accordance with the KDS structural design provisions, applying the required design loads and load combinations to evaluate the main lateral-force-resisting system. Wind loads for both the X- and Y-axis wind directions were calculated based on the KDS wind load criteria, including along-wind and across-wind components, and the combined loads were applied to the structural analysis. The building's first-mode natural frequencies were 0.31 Hz and 0.313 Hz in the X and Y directions, respectively. Using a damping ratio of 1.2%, the 500-year return period wind load was derived, and the corresponding displacement for the 50-year wind was approximately 76% of the 500-year displacement.

To introduce limited inelastic behavior in the building, an equivalent static inelastic design wind load was developed using the response modification factor R=1.5. The resonant component of the equivalent design wind load was divided by the R factor. The inelastic design wind load was then combined with other required KDS load combinations to perform structural reanalysis. During redesign, the structural system and member dimensions were maintained, while reinforcement quantities were adjusted. The redesign resulted in an overall reduction in reinforcement, indicating that limited inelastic behavior is

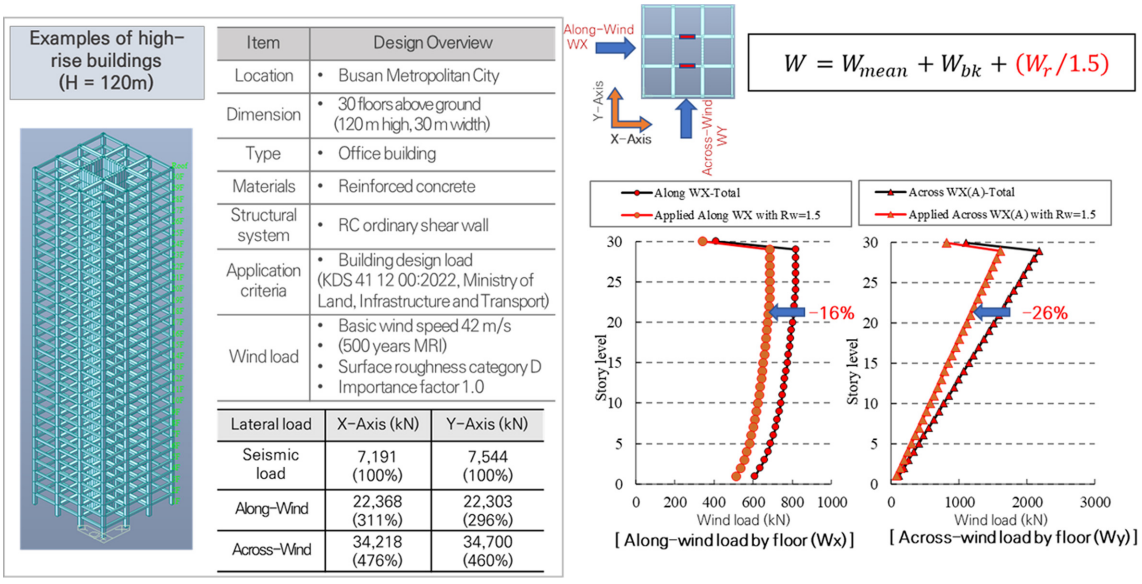


Figure 2. Example building for PBWD application and design wind loads.

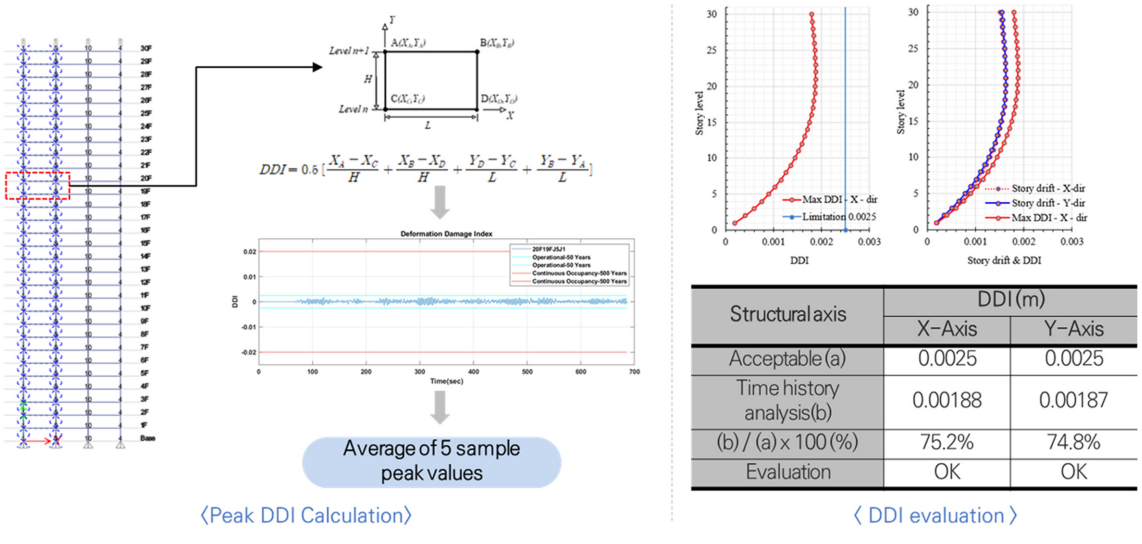
expected under the 500-year return period wind event.

3.2. Analyses and Evaluations

A linear time-history response analysis was first performed by applying the 1-year return-period floor-by-floor wind force time series to the structural analysis model, and the wind-induced acceleration response at the uppermost occupied floor was obtained. Gravity loads, including dead load and expected live load, were applied separately and combined with the time-history wind response. A 10-minute sample record of wind-induced acceleration was generated, peak accelerations were extracted, and the expected peak acceleration was evaluated using the sample mean. The analysis results showed that the peak accelerations in both the X and Y directions were approximately 95% of the ISO serviceability limit, indicating that the occupant comfort performance objective was satisfied.

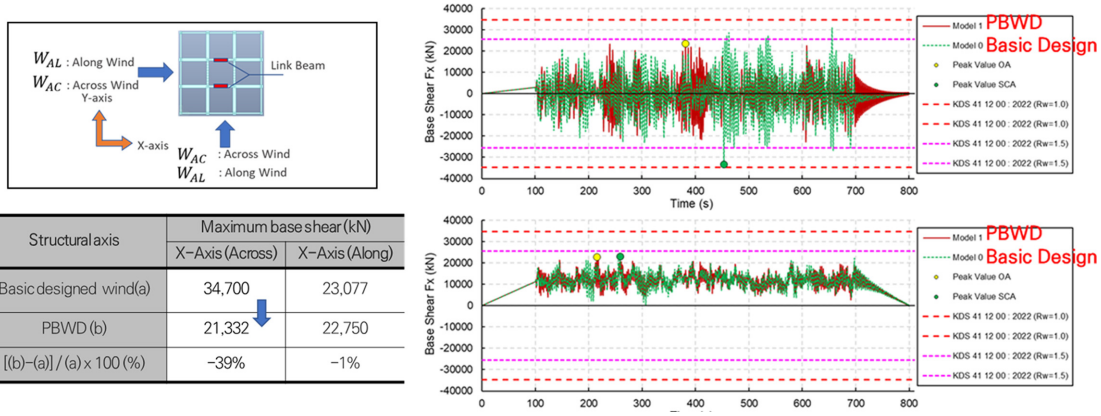
Next, the 50-year return-period wind force time series was applied to conduct a linear time-history response analysis for displacement serviceability. All structural members remained within the elastic range, and no residual displacement occurred. Peak values of roof displacement and the Deformation Damage Index (DDI) were obtained from the time-domain responses, and their expected values were computed using sample means. The roof drift ratios in both principal directions were approximately 77% of the allowable limit of H/500, and the DDI values were approximately 75% of the acceptance criterion of 0.0025. Therefore, the functional preservation (displacement serviceability) performance objective was satisfied.

A nonlinear time-history response analysis was then performed using the 500-year return-period floor-by-floor



Structural axis	DDI (m)	
	X-Axis	Y-Axis
Acceptable (a)	0.0025	0.0025
Time history analysis(b)	0.00188	0.00187
(b) / (a) x 100 (%)	75.2%	74.8%
Evaluation	OK	OK

Figure 3. Evaluation of displacement serviceability performance.



Structural axis	Maximum base shear (kN)	
	X-Axis (Across)	X-Axis (Along)
Basic designed wind(a)	34,700	23,077
PBWD (b)	21,332	22,750
[(b)-(a)] / (a) x 100 (%)	-39%	-1%

Figure 4. Energy dissipations due to limited inelastic behaviors along x-direction.

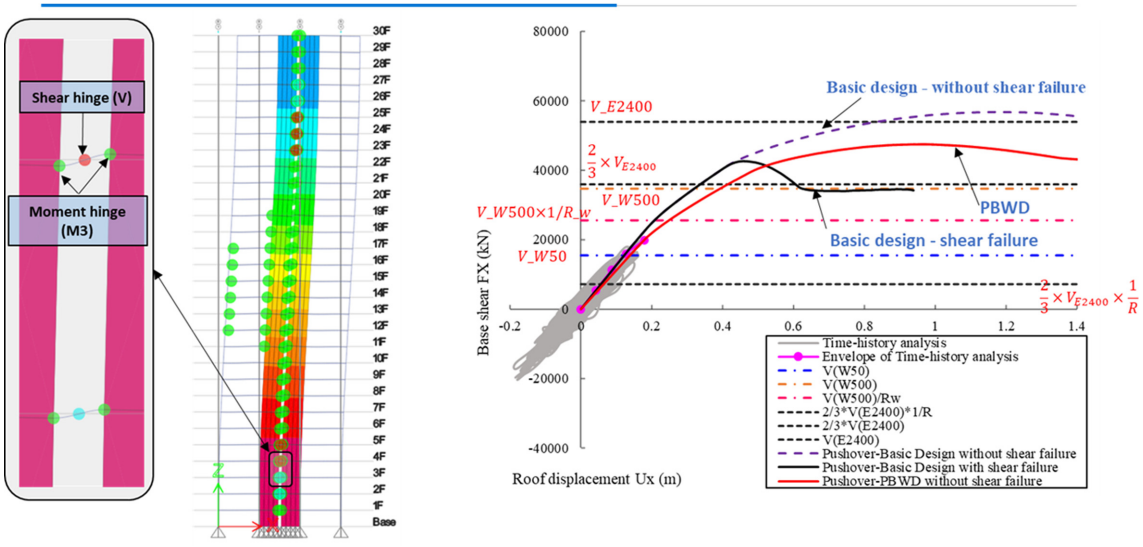


Figure 5. Ductile Behavior Induced by PBWD for x-direction.

wind force time series to evaluate structural safety (continuous occupancy). The analysis indicated that yielding and hysteretic behavior occurred in lintel beams in the X-direction, although the shear demand-to-capacity ratios remained below 1.0, satisfying the acceptance criteria. Residual displacement, residual interstory drift, and fatigue performance were also examined. In accordance with the guideline, convergence of inelastic wind response was verified for time-histories shorter than one hour, and the results were extrapolated to the required one-hour duration for performance evaluation. Both residual displacement (H/1000 limit) and residual interstory drift (0.001 limit) satisfied the criteria, and DDI also met the acceptance limit of 0.02. Fatigue performance was within allowable limits, and inelastic deformation demands, including beam rotation and reinforcing bar strain, were within the expected range of limited inelastic behavior.

To investigate the structural implications of PBWD, a nonlinear static pushover analysis was conducted. Since yielding was observed in the link beams during the time-history analysis, both moment and shear hinges were assigned to these members. The pushover curves showed that the seismic force reduced by the response modification factor (R) was lower than the 500-year design wind force, suggesting that brittle failure may occur under wind-governed design conditions. When shear failure was explicitly considered, the link beams experienced sudden shear failure and rapid strength degradation. However, in the PBWD case, the structure exhibited stable ductile behavior, indicating that brittle failure would not be expected even under the 2,400-year seismic load. Therefore, when wind governs the design, applying PBWD is necessary to ensure structural robustness against combined wind and seismic demands. demands.

4. Concluding Remarks

This study applied Performance-Based Wind Design (PBWD) procedures to the building under study and evaluated its wind performance through linear and nonlinear

time-history analyses. Using floor-by-floor time-series wind forces corresponding to 1-year, 50-year, and 500-year return periods, the wind-induced responses were assessed for occupant comfort, displacement serviceability, and structural safety. The linear analyses confirmed that both acceleration and displacement responses satisfied the relevant acceptance criteria, indicating adequate performance at the comfort and operational levels.

Under the 500-year wind loads, the nonlinear analysis revealed localized yielding and limited inelastic behavior while maintaining acceptable demand-to-capacity ratios for force-controlled elements. Residual displacement, residual interstory drift, deformation damage index, and fatigue demands all remained within prescribed limits, demonstrating that the building can sustain extreme wind events without compromising continuous occupancy performance.

The pushover analysis further showed that PBWD provides improved structural reliability compared to conventional wind-based design, which may otherwise lead to brittle shear failure in critical members. In contrast, the PBWD-based design exhibited stable ductile behavior and maintained its load-carrying capacity even under severe loading scenarios. Overall, the results highlight the value of PBWD in achieving a more resilient and performance-consistent design, especially for buildings governed by wind effects.

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