Graduate Certificate in Design and Analysis of Tall Buildings

Performance-Based Design of Tall Buildings

Acceleration – (a) the rate of change of velocity of a structural element during seismic excitation.
Related terms: response spectrum, peak ground acceleration, damping.
Explanation: In performance-based design (PBD) acceleration is used to quantify building demand and to compare with capacity curves derived from pushover analyses.
Example: A 70-story tower is assigned a design acceleration of 0.30 g for the Serviceability Limit State (SLS).
Challenges: Accurately capturing higher-mode effects and spatial variability of acceleration across the height of tall buildings.

Adaptive Damping System – (ADS) a semi-active or active device that adjusts its damping characteristics in response to measured motion.
Related terms: tuned mass damper (TMD), semi-active control, feedback control.
Explanation: ADS are integrated into the structural model to improve performance under wind and seismic loads by increasing energy dissipation when needed.
Example: An active hydraulic damper installed at the 30th floor of a 55-meter-wide tower reduces top-floor drift by 25 % during a design earthquake.
Challenges: Power supply reliability, control algorithm robustness, and additional maintenance requirements.

Analysis Model – (AM) the finite-element representation of a tall building used for linear or nonlinear assessments.
Related terms: global model, detailed model, substructure.
Explanation: The AM must capture the dominant stiffness, mass, and damping properties while remaining computationally tractable for iterative performance checks.
Example: A 120-story skyscraper is modeled with beam-column elements for the core and shear walls, supplemented by lumped masses at each floor.
Challenges: Balancing model fidelity with solution time, especially when conducting probabilistic performance assessments.

Aspect Ratio – (AR) the ratio of building height to its plan width.
Related terms: slenderness, height-to-width ratio, wind amplification.
Explanation: A high AR increases susceptibility to wind-induced vibrations and amplifies lateral drift, influencing the selection of performance criteria.
Example: A tower with an AR of 12:1 requires additional aerodynamic damping devices to meet the drift limit of 0.004 rad at the roof.
Challenges: Managing wind loads without excessive structural mass, and ensuring occupant comfort.

Baseline Performance Level – (BPL) the reference set of criteria (e.g., drift, acceleration) that defines acceptable performance for a given hazard level.

Related terms: target performance level, acceptability criteria, design spectrum.
Explanation: BPLs are established for Serviceability, Damage, and Collapse Limit States and serve as benchmarks for iterative design.
Example: For a Category II seismic event, the BPL may specify inter-story drift ≤ 0.005 rad for the Damage Limit State.
Challenges: Aligning BPLs with code provisions while accommodating site-specific risk tolerances.

Base Isolation – (BI) a seismic protection strategy that decouples the superstructure from ground motion using flexible bearings.
Related terms: isolation bearings, friction pendulum system, rocking.
Explanation: In PBD, base isolation modifies the input motion, reducing acceleration demand on the structural frame and improving performance at higher hazard levels.
Example: A 40-story office tower utilizes laminated rubber bearings with a period of 2.0 s, achieving a 40 % reduction in roof acceleration.
Challenges: Designing isolation devices for tall buildings where higher modes dominate, and handling vertical load transfer.

Building Information Modeling – (BIM) a digital representation of the physical and functional characteristics of a building.
Related terms: data integration, model coordination, clash detection.
Explanation: BIM facilitates the exchange of geometric, material, and performance data among architects, engineers, and contractors, supporting the performance-based workflow.
Example: Structural analysis results are linked to the BIM model, allowing automatic updating of member sizes when performance criteria change.
Challenges: Maintaining data consistency across disciplines and ensuring that performance-related parameters are accurately captured.

Capacity Curve – (CC) the relationship between base shear and roof displacement obtained from a pushover analysis.
Related terms: pushover analysis, yield point, target displacement.
Explanation: The CC represents the nonlinear static strength of the structure and is used together with the demand spectrum to assess performance.
Example: For a 70-meter-wide tower, the CC shows a bilinear shape with a yield displacement of 0.15 m and a post-yield stiffness reduction of 70 %.
Challenges: Capturing the influence of higher-mode effects and material nonlinearity in a single curve.

Code-Based Design – (CBD) a deterministic approach that prescribes minimum strength and stiffness requirements based on prescriptive rules.
Related terms: performance-based design, prescriptive design, safety factors.
Explanation: While CBD ensures basic safety, PBD offers a more nuanced assessment of how a building behaves under different hazard levels.
Example: A CBD approach may dictate a minimum column size, whereas PBD would adjust column dimensions to meet specific drift and acceleration targets.

Challenges: Integrating code compliance with performance objectives without excessive conservatism.

Combined Load Cases – (CLC) the simultaneous application of wind, seismic, gravity, and live loads in a structural analysis.
Related terms: load combinations, load factor, ultimate limit state.
Explanation: In PBD, combined load cases are evaluated to verify that the building satisfies all performance criteria under realistic multi-hazard scenarios.
Example: A design scenario includes a 0.8 g seismic load combined with a 0.5 kN/m² wind pressure and dead load.
Challenges: Determining appropriate load factors and interaction effects for tall structures with complex geometries.

Control Devices – (CD) mechanical or hydraulic systems that modify structural response, such as dampers, braces, or mass tuners.
Related terms: energy dissipation, tuned mass damper, active control.
Explanation: CD are incorporated into the performance model to achieve target drift, acceleration, or comfort levels.
Example: A viscous damper brace system installed in the perimeter columns reduces peak drift by 18 % during a wind event.
Challenges: Balancing cost, reliability, and effectiveness across the building's service life.

Design Spectrum – (DS) a plot of pseudo-spectral acceleration versus period that defines the seismic demand for a site.
Related terms: response spectrum, site class, spectral shape.
Explanation: The DS is used to generate target displacement values for each performance level in the PBD process.
Example: For a site classified as Soil C, the DS peaks at 0.45 g for a period of 0.7 s.
Challenges: Adjusting the spectrum for tall buildings where higher modes dominate the response.

Dynamic Amplification Factor – (DAF) the ratio of peak dynamic response to the corresponding static response.
Related terms: modal analysis, resonance, wind loading.
Explanation: DAF quantifies how natural frequencies and damping affect the response to wind or seismic excitation.
Example: A 55-story tower exhibits a DAF of 2.3 for the first mode under a 20-year wind event.
Challenges: Accurately predicting DAF for structures with variable stiffness due to time-dependent effects.

Elastic-Perfectly Plastic Model – (EPP) a simplified material representation that assumes linear elastic behavior up to yield, followed by a constant plastic plateau.
Related terms: material nonlinearity, yield stress, hardening.
Explanation: The EPP model is often employed in pushover analyses to generate capacity curves efficiently.
Example: Steel columns are modeled with an EPP behavior, yielding at 250 MPa and maintaining that stress level thereafter.
Challenges: Over-simplification of strain-hardening and strain-rate effects in tall building components.

Elastic Response Spectrum – (ERS) a curve that provides maximum elastic response (displacement, velocity, acceleration) for a range of periods under a given ground motion.
Related terms: design spectrum, linear analysis, modal superposition.
Explanation: The ERS is the basis for constructing target displacement values in the performance-based workflow.
Example: The ERS for a design earthquake shows a peak displacement of 0.025 m at a period of 1.2 s.
Challenges: Translating elastic results to inelastic performance expectations for very tall structures.

Envelope of Demand – (EDD) the upper bound of structural demand (e.g., drift, acceleration) across a suite of ground motions or wind simulations.
Related terms: probabilistic analysis, exceedance probability, safety margin.
Explanation: The EDD is compared against the capacity to determine the probability of meeting each performance level.
Example: The 5 % exceedance envelope for roof drift is 0.006 rad for the Damage Limit State.
Challenges: Generating sufficient simulation data to reliably estimate the envelope for extreme events.

Exceedance Probability – (EP) the likelihood that a given demand will surpass a specified performance threshold.
Related terms: reliability, probabilistic performance, risk assessment.
Explanation: EP informs the selection of performance targets for different hazard levels (e.g., 10 % EP for Serviceability).
Example: An EP of 2 % is adopted for the Collapse Limit State, meaning the design must limit collapse probability to 2 % in a 500-year event.
Challenges: Accurately quantifying EP for rare, high-intensity hazards in tall buildings.

Factor of Safety – (FoS) a numerical multiplier applied to structural capacities to account for uncertainties.
Related terms: reliability index, conservatism, safety factor.
Explanation: In PBD, FoS is replaced by explicit reliability targets, but some codes still require a minimum FoS for certain components.
Example: A FoS of 1.5 is applied to concrete column capacities when checking against the Damage Limit State.
Challenges: Balancing traditional FoS with performance-based probabilistic criteria.

Fire Performance Level – (FPL) the set of criteria that define acceptable structural behavior under fire exposure.
Related terms: thermal analysis, structural fire resistance, fire design.
Explanation: PBD extends to fire by specifying allowable drift, strength loss, and post-fire residual capacity.
Example: An FPL may require that inter-story drift not exceed 0.015 rad after a 2-hour standard fire exposure.
Challenges: Coupling thermal and structural analyses for tall buildings with complex fire compartments.

Flexibility Index – (FI) a dimensionless measure of a building's lateral flexibility, often expressed as the ratio of fundamental period to height.
Related terms: stiffness, period-height relationship, wind response.

Explanation: FI helps classify tall buildings as stiff, regular, or flexible, influencing wind-load modeling strategies.
Example: A 60-story tower with a fundamental period of 2.8 s yields an FI of 0.047, indicating a flexible structure.
Challenges: Adjusting design measures (e.g., damping, bracing) based on FI while maintaining architectural intent.

Force-Based Design – (FBD) an approach that directly controls internal forces (shear, moment) rather than displacements.
Related terms: performance-based design, capacity design, ductility.
Explanation: In PBD, force-based checks are complemented by displacement checks to ensure both strength and serviceability are satisfied.
Example: The shear force in the core wall is limited to 1.2 × design load, while drift limits are also verified.
Challenges: Reconciling force checks with performance criteria that are inherently displacement-driven.

Generalized Displacement – (GD) a vector of modal coordinates representing the building's deformation shape.
Related terms: mode shapes, modal participation factor, dynamic analysis.
Explanation: GDs are used in modal superposition to compute responses for wind and seismic loading.
Example: The first three GDs capture 85 % of the total kinetic energy in a 100-story tower's seismic response.
Challenges: Selecting an adequate number of modes to achieve accurate results without excessive computational cost.

Global Stability – (GS) the overall ability of a tall building to maintain equilibrium under combined loads without experiencing overall collapse.
Related terms: buckling, overall stability, lateral–torsional interaction.
Explanation: PBD requires verification that the global stability margin satisfies the desired performance level for each hazard scenario.
Example: A global stability analysis shows a safety factor of 1.8 against overturning for a Category III wind event.
Challenges: Accounting for eccentricities, irregularities, and dynamic amplification in the stability assessment.

Ground Motion Selection – (GMS) the process of choosing appropriate earthquake records that reflect site characteristics and hazard levels.
Related terms: hazard spectrum, scaling, conditional spectrum.
Explanation: In PBD, the selected motions are scaled to match the design spectrum and are used to develop the demand envelope.
Example: Ten compatible ground motions are selected for a site with a 0.3 g PGA, then scaled to the target spectrum.
Challenges: Maintaining realism while meeting spectral requirements, especially for very tall structures with long periods.

High-Rise Wind Tunnel Testing – (HRWT) experimental testing of scaled building models to capture aerodynamic forces and motions.
Related terms: wind load coefficients, aerodynamic damping, pressure tap data.
Explanation: HRWT provides site-specific wind coefficients, which feed into the performance-based analysis to predict drift and acceleration.
Example: A 1:400 scale model of a 80-story tower is tested at wind speeds up to 30 m/s, yielding a mean roof drift of 0.004 rad.
Challenges: Scaling effects, Reynolds number matching, and translating test results to full-scale performance predictions.

Hybrid Simulation – (HS) a combined numerical-experimental technique where part of the structure is physically tested while the remainder is modeled computationally.
Related terms: real-time testing, substructure testing, system identification.
Explanation: HS enables validation of complex PBD models, especially for novel damping devices or irregular configurations.
Example: The core of a 45-story building is physically tested on a shaking table, while the peripheral frame is simulated.
Challenges: Synchronization of data, ensuring boundary condition fidelity, and cost of experimental setup.

Inelastic Time History Analysis – (ITHA) a dynamic simulation that captures material yielding and hysteresis under realistic load histories.
Related terms: pushover analysis, nonlinear dynamic analysis, damping models.
Explanation: ITHA provides detailed demand histories for each performance level, allowing direct comparison with capacity.
Example: An ITHA of a 90-meter-wide tower under a 0.4 g earthquake shows peak inter-story drift of 0.006 rad.
Challenges: Selecting appropriate time steps, modeling accurate hysteretic behavior, and managing computational expense.

Inter-Story Drift – (ISD) the relative lateral displacement between two consecutive floors, expressed as a ratio or angle.
Related terms: drift limit, performance metric, serviceability.
Explanation: ISD is a primary performance indicator in PBD, governing both structural safety and occupant comfort.
Example: The design target for the Damage Limit State is an ISD of 0.005 rad for the uppermost 20 floors.
Challenges: Controlling ISD in highly flexible towers while keeping floor area efficiency.

Joint Modeling – (JM) the representation of connections between structural members, capturing stiffness, strength, and rotational capacity.
Related terms: beam-column joint, semi-rigid connection, moment transfer.
Explanation: Accurate JM is essential for predicting the distribution of forces and drift in tall building frames.
Example: A semi-rigid moment connection is modeled with a rotational spring of stiffness 5×10^6 Nm/rad.
Challenges: Balancing model complexity with analysis time, especially when many joints are present.

Load Path Redundancy – (LPR) the presence of multiple independent routes for load transfer, enhancing robustness.
Related terms: robustness, alternative load path, structural redundancy.
Explanation: PBD assesses redundancy to ensure that failure of a primary element does not precipitate disproportionate collapse.
Example: A dual-core system provides an alternative load path if one core is compromised.
Challenges: Quantifying redundancy and incorporating it into performance criteria without over-design.

Mass Dampers – (MD) devices that add a tuned mass to the structure to counteract vibrations, typically for wind-induced motion.
Related terms: tuned mass damper, passive control, frequency tuning.
Explanation: MDs are sized and tuned based on the building's dominant mode to reduce acceleration and improve comfort.
Example: A 150-ton tuned mass damper placed at the 85th floor of a 100-story tower reduces peak acceleration by 30 %.
Challenges: Space allocation, tuning for variable wind directions, and long-term maintenance.

Maximum Allowable Drift – (MAD) the upper limit of inter-story drift prescribed for a given performance level.
Related terms: drift limit, serviceability limit state, code requirement.
Explanation: MAD is derived from occupant comfort studies, equipment tolerances, and structural safety considerations.
Example: For a residential tower, the MAD for the Serviceability Level is set at 0.003 rad.
Challenges: Reconciling differing drift limits for mixed-use buildings and for extreme wind events.

Modal Participation Factor – (MPF) a scalar that quantifies the contribution of each mode to the overall response.
Related terms: mode shape, effective modal mass, dynamic analysis.
Explanation: MPFs are used to weight modal responses when superimposing wind or seismic effects.
Example: The first mode has an MPF of 0.85, while the second mode contributes 0.12 to roof displacement.
Challenges: Accurate computation for irregular or tapered towers where mode shapes are non-classical.

Nonlinear Static Pushover Analysis – (NSPA) a simplified method that incrementally applies lateral loads to a structural model until a target displacement is reached.
Related terms: capacity curve, target displacement, limit state.
Explanation: NSPA provides a quick estimate of the structure's capacity and is often used for preliminary performance checks.
Example: A pushover analysis of a 55-story tower yields a peak base shear of 1.8 × gravity at a roof displacement of 0.25 m.
Challenges: Capturing higher-mode effects and accurately representing material nonlinearity in a static framework.

O-Profile System – (OPS) a structural configuration where the building core and perimeter frames form an "O" shape, providing stiffness in both directions.

Related terms: tube system, outrigger, lateral load resistance.
Explanation: OPS enhances torsional rigidity and reduces drift, beneficial for tall, slender structures.
Example: An O-profile system with outrigger trusses at the 30th and 60th floors limits roof drift to 0.004 rad under wind loads.
Challenges: Designing effective connections between the core and perimeter frames and managing construction sequencing.

Performance Target – (PT) a quantitative goal (e.g., drift, acceleration) that the building must achieve for a specific hazard level.
Related terms: performance level, design objective, acceptability criteria.
Explanation: PTs are derived from the baseline performance level and adjusted for site-specific risk and user requirements.
Example: The PT for the Damage Limit State under a 475-year earthquake is a roof drift of 0.008 rad.
Challenges: Aligning multiple PTs (e.g., drift, acceleration, residual strength) in a single design iteration.

Probabilistic Seismic Hazard Analysis – (PSHA) a statistical method that quantifies the likelihood of different ground-motion intensities at a site.
Related terms: hazard curve, exceedance probability, seismic risk.
Explanation: PSHA provides the design spectra for various return periods used in performance-based seismic design.
Example: PSHA results indicate a 0.2 g spectral acceleration for a 10 % probability of exceedance in 50 years.
Challenges: Incorporating epistemic uncertainty and ensuring that the resulting spectra are appropriate for very tall buildings with long periods.

Quasi-Static Wind Load – (QSWL) a simplified representation of wind effects assuming constant pressure over a short time interval.
Related terms: wind pressure coefficient, static wind analysis, equivalent static load.
Explanation: QSWL is often used for preliminary design, but PBD requires dynamic wind analysis for accurate performance prediction.
Example: An equivalent static wind pressure of 0.9 kN/m² is applied to the façade to estimate base shear.
Challenges: Capturing gust effects and vortex shedding phenomena that influence occupant comfort.

Reliability Index – (β) a measure of safety expressed as the number of standard deviations between the mean demand and mean capacity.
Related terms: probability of failure, first-order reliability method, risk.
Explanation: In PBD, β is used to set target reliability levels for each performance state.
Example: A β of 3.0 corresponds to a failure probability of roughly 0.13 % for the Collapse Limit State.
Challenges: Computing β for complex, high-dimensional models typical of tall buildings.

Response Modification Factor – (R-factor) a code-provided reduction factor that accounts for a structure’s ductility and overstrength.
Related terms: ductility factor, capacity design, seismic code.
Explanation: In a performance-based framework, the R-factor is replaced by explicit capacity curves, but it remains useful for preliminary sizing.

Example: An R-factor of 6 is applied to the shear wall system for the Damage Limit State.
Challenges: Translating code-based R-factors to probabilistic performance targets without double counting safety.

Safety Margin – (SM) the difference between calculated demand and available capacity, expressed in terms of drift, acceleration, or force.
Related terms: reliability, design margin, performance verification.
Explanation: SM is evaluated for each performance level to ensure that the building meets or exceeds the required criteria.
Example: A safety margin of 0.002 rad is achieved for the Serviceability Level under wind loading.
Challenges: Maintaining adequate SM across all floors while optimizing material usage.

Shear Wall – (SW) a vertical structural element that resists lateral loads through in-plane shear and flexure.
Related terms: core, out-of-plane stiffness, shear capacity.
Explanation: SWs form the primary lateral load-resisting system in many tall buildings, and their performance is critical in PBD.
Example: A 2.5 m × 2.5 m reinforced concrete shear wall provides a lateral stiffness of 1.2×10^6 kNm/rad.
Challenges: Designing connections to the floor diaphragms and accommodating architectural openings.

Site-Specific Wind Model – (SSWM) a computational fluid dynamics (CFD) or wind tunnel model that reflects the actual terrain, surrounding structures, and topography of a project site.
Related terms: wind tunnel testing, terrain classification, aerodynamic coefficients.
Explanation: SSWM supplies accurate wind pressure coefficients for each façade segment, essential for performance-based wind design.
Example: CFD simulation of a downtown site predicts a peak pressure coefficient of 1.2 on the windward façade.
Challenges: High computational cost and the need for validation against physical testing.

Stiffness Degradation – (SD) the reduction of structural stiffness due to material yielding, cracking, or damage under cyclic loading.
Related terms: hysteresis, post-yield behavior, energy dissipation.
Explanation: SD is incorporated into nonlinear analyses to predict how capacity evolves during severe events.
Example: After a design earthquake, the effective stiffness of a steel moment frame reduces by 30 %.
Challenges: Modeling degradation accurately for diverse material systems and for long-duration wind events.

Structural Health Monitoring – (SHM) the continuous acquisition and analysis of data (e.g., accelerations, strains) to assess the condition of a building.
Related terms: sensors, real-time monitoring, damage detection.
Explanation: SHM provides feedback on actual performance relative to the design targets, enabling post-event assessments.
Example: Fiber-optic strain sensors embedded in the core detect a 0.001 rad drift increase after a moderate earthquake.

Challenges: Data management, interpreting signals in the presence of environmental noise, and integrating SHM with maintenance planning.

Systematic Uncertainty – (SU) the component of uncertainty arising from modeling assumptions, material property variability, and measurement errors.
Related terms: epistemic uncertainty, modeling error, probabilistic analysis.
Explanation: SU is quantified and incorporated into reliability calculations to ensure realistic performance predictions.
Example: A 10 % coefficient of variation is assigned to concrete compressive strength in the reliability model.
Challenges: Distinguishing systematic from random uncertainties and reducing SU through calibration and validation.

Target Displacement – (TD) the displacement value at a specific performance level derived from the design spectrum or demand envelope.
Related terms: capacity curve, drift target, performance level.
Explanation: TD serves as the benchmark against which the pushover or dynamic analysis results are compared.
Example: The TD for the Serviceability Level at the roof is 0.12 m, corresponding to a drift of 0.004 rad.
Challenges: Selecting appropriate scaling factors for tall buildings where higher modes affect the displacement distribution.

Tuned Mass Damper – (TMD) a passive vibration control device consisting of a mass, spring, and damper tuned to a target frequency.
Related terms: mass damper, frequency tuning, passive control.
Explanation: TMDs are widely used in tall buildings to mitigate wind-induced accelerations and improve occupant comfort.
Example: A 200-ton TMD installed near the top of a 70-story tower reduces the 0.2 Hz wind-induced acceleration by 35 %.
Challenges: Ensuring the TMD remains effective over the building's lifespan despite changes in mass distribution and stiffness.

Ultimate Limit State – (ULS) the performance condition where structural collapse is imminent, representing the maximum considered load effect.
Related terms: collapse limit state, failure condition, safety factor.
Explanation: In PBD, the ULS is defined probabilistically, often with a very low exceedance probability (e.g., 0.1 %).
Example: The ULS for a 500-year earthquake requires that the residual inter-story drift not exceed 0.02 rad.
Challenges: Accurately modeling post-yield behavior and residual capacities for very tall structures.

Vertical Load Distribution – (VLD) the manner in which gravity, live, and equipment loads are allocated among structural members.
Related terms: floor load, load path, axial force.
Explanation: VLD affects axial stresses in core walls and columns, influencing overall stability and

performance.
Example: A uniform VLD of 9 kN/m² is assumed for each floor, with additional point loads for mechanical equipment.
Challenges: Accounting for irregularities such as sky-lobbies, atriums, and variable occupancy.

Wind Load Coefficient – (WLC) a factor that quantifies the effect of wind pressure on a building surface, derived from aerodynamic analysis.
Related terms: pressure coefficient, aerodynamic factor, wind tunnel data.
Explanation: WLCs are applied to the façade to compute lateral forces and moments for performance-based wind design.
Example: The windward façade of a slender tower receives a WLC of 1.3, while the leeward side gets –0.6.
Challenges: Capturing three-dimensional flow effects around complex geometries and ensuring consistency with code wind maps.

Yield Drift Ratio – (YDR) the inter-story drift at which a structural component reaches its yield point.
Related terms: ductility, post-yield drift, material nonlinearity.
Explanation: YDR is a key parameter in defining the shape of the capacity curve and the ductility factor for performance assessment.
Example: The shear wall system exhibits a YDR of 0.006 rad before yielding.
Challenges: Determining YDR for composite sections and for elements that exhibit strain-hardening.

Zero-Period Approximation – (ZPA) a simplification in wind analysis that assumes instantaneous response, neglecting dynamic effects.
Related terms: static wind load, quasi-static approximation, dynamic amplification.
Explanation: ZPA is generally unsuitable for tall buildings, where dynamic amplification is significant.
Example: Using ZPA would underestimate roof acceleration by more than 50 % for a 100-meter-tall tower.
Challenges: Avoiding reliance on ZPA in performance-based design and ensuring that dynamic analysis captures the full frequency spectrum.