

Graduate Certificate in Design and Analysis of Tall Buildings

Performance-Based Design of Tall Buildings

Performance-Based Design (PBD) is a design methodology that defines the expected behavior of a tall building through a set of quantifiable performance objectives rather than prescriptive code limits. In PBD the designer selects target performance levels for different hazard scenarios, such as wind, seismic, and gravity loads, and then verifies that the structural system meets these targets using analytical, experimental, or hybrid approaches. The approach is inherently probabilistic, linking the probability of exceeding a performance level to the acceptable risk for the building's occupants, contents, and surrounding environment.

A fundamental concept in PBD is the limit state. A limit state refers to a condition beyond which the building no longer satisfies a particular performance requirement. Limit states are typically categorized as either ultimate or serviceability. The ultimate limit state (ULS) concerns the structural safety of the building, ensuring that collapse or catastrophic failure does not occur under extreme loading. The serviceability limit state (SLS) addresses functionality, comfort, and durability, such as limits on drift, vibration, and deflection that affect the building's usability.

The performance level is the quantitative expression of the building's response at a given limit state. Common performance levels include:

1. Operational – the building functions normally with minimal impact on occupants.
2. Damage-Limiting – minor, repairable damage occurs, but the building remains safe and usable after a severe event.
3. Life-Safety – the structure prevents loss of life, even though significant damage may be present.
4. Collapse-Prevention – the building avoids progressive collapse, preserving core integrity.

Each performance level is associated with a target probability of exceedance, often expressed as a "design probability of failure" (e.g., 10^{-4} per year for life-safety). The selection of these probabilities reflects the stakeholder's risk tolerance and the building's importance category (e.g., office tower versus hospital).

Load combinations in PBD are not fixed by code; instead, they are generated based on the probabilistic characteristics of each load type. For wind design, the load combination may consist of a wind pressure field combined with dead and live loads, while for seismic design the combination includes inertial forces derived from ground motion spectra. The designer must consider the appropriate combination factors (often denoted as γ) that scale the loads to reflect their variability and correlation.

The response spectrum is a key tool for seismic analysis. It represents the maximum response (e.g., acceleration, velocity, or displacement) of a single-degree-of-freedom oscillator subjected to a particular

ground motion as a function of its natural period. By matching the building's modal periods to the spectrum, the engineer can estimate seismic demands on each mode. In tall buildings, higher modes often contribute significantly to the response, requiring a modal analysis that accounts for modal coupling.

Modal analysis decomposes the structure's dynamic behavior into a set of independent vibration modes, each characterized by a natural frequency, mode shape, and damping ratio. The total response is obtained by superimposing the contributions of individual modes, weighted by participation factors that reflect the extent to which each mode is excited by the applied load. For wind loading, the quasi-static approach may be sufficient for low-rise structures, but for towers exceeding 200 m, the dynamic wind response must be captured through either time-domain simulations or spectral methods.

The dynamic amplification factor (DAF) quantifies the increase in structural response due to dynamic effects relative to a static analysis. It is defined as the ratio of peak dynamic response to the corresponding static response under the same load magnitude. In practice, DAF values for wind on tall buildings typically range from 1.1 to 1.5, depending on the building's natural period, damping, and aerodynamic characteristics.

A central element of wind engineering for tall buildings is the wind tunnel testing. Scale models of the building, often at 1:400 or 1:200, are placed in a wind tunnel that replicates the atmospheric boundary layer. Pressure taps distributed over the façade capture the spatial variation of wind pressure, while force balances record overall loads such as lift, drag, and overturning moment. The data from wind tunnel tests feed directly into the PBD process, providing realistic pressure coefficients (C_p) and aerodynamic damping estimates that are used to compute the wind-induced responses.

The overturning moment (M_o) is the moment generated by wind pressure about the building's base, tending to rotate the structure. It is a critical design parameter for the foundation system, especially for slender towers where M_o can be a substantial fraction of the total vertical load. Engineers typically design the foundation to resist the net overturning moment after accounting for the resisting moment provided by the weight of the structure (the restoring moment). The ratio $M_o/\text{Resisting Moment}$ is a key indicator of foundation stability.

The interstory drift ratio (IDR) is defined as the relative lateral displacement between two successive floors divided by the story height. It serves as a primary indicator of both structural and non-structural performance. Serviceability limit states often impose an IDR limit of 0.5% to 1% for office towers, while damage-limiting performance may permit higher drifts (e.g., 1.5% to 2%). Excessive drift can cause cracking of façade panels, misalignment of mechanical systems, and, in extreme cases, failure of connections.

The choice of a structural system determines how the building resists lateral loads and controls drift. Common systems for tall buildings include:

- Core-and-outrigger systems, where a central reinforced-concrete or steel core is stiffened by outrigger trusses that connect to perimeter columns at selected levels. This configuration significantly reduces drift by increasing the effective width of the structure.

- Braced tube systems, which employ a dense network of diagonal steel braces forming a stiff tube around the perimeter. The braced tube provides high lateral stiffness and is often used in super-tall structures.
- Diagrid systems, where diagonal members form a grid on the façade, eliminating the need for a central core in some designs. The diagrid offers both architectural expression and structural efficiency.

Each system has distinct implications for construction, cost, and performance. For example, a core-and-outrigger system may require large openings in the core at outrigger levels, affecting elevator shafts and service cores. The selection must therefore balance structural efficiency with functional requirements.

The term soil-structure interaction (SSI) describes the mutual influence between the building's foundation and the underlying ground. In PBD, SSI is modeled using springs and dashpots that represent the stiffness and damping of the soil. Accurate SSI modeling is essential for predicting foundation settlement, rotation, and the modification of natural frequencies. In soft soil conditions, the added flexibility can increase seismic demands, necessitating mitigation measures such as base isolation or deep foundations.

Base isolation is a seismic mitigation technique that decouples the superstructure from ground motion using flexible bearings (e.g., lead-rubber or friction pendulum bearings). By lengthening the natural period of the isolated system, base isolation reduces the seismic forces transmitted to the structure, thereby lowering drift and demand on structural elements. In tall buildings, base isolation can be challenging due to the large axial loads on the isolators and the need to accommodate vertical movement without compromising serviceability.

Tuned mass damper (TMD) devices are passive control systems that consist of a mass, spring, and damper tuned to the building's dominant vibration mode. When the building sways, the TMD oscillates out of phase, dissipating energy and reducing peak displacement. The most famous example is the 660-ton TMD in Taipei 101, which reduces wind-induced acceleration by up to 40%. Designing a TMD requires careful tuning, placement (usually near the top), and consideration of the added mass and space constraints.

Active control systems, such as active mass dampers or active braces, use sensors and actuators to apply forces that counteract motion in real time. While offering greater performance than passive devices, active systems demand reliable power supplies, sophisticated control algorithms, and regular maintenance. Their application in tall buildings is still limited but growing as technology matures.

The aerodynamic damping generated by the building's shape can be harnessed to reduce wind response. Features such as setbacks, tapering, and rounded corners promote vortex shedding that is out of phase with the building motion, thereby increasing damping. Designers often perform wind tunnel tests on multiple façade configurations to identify shapes that provide beneficial aerodynamic damping without compromising architectural intent.

Performance criteria are specific quantitative targets that define acceptable behavior for each performance level. Typical criteria include:

- Maximum interstory drift ratio (e.g., 0.5 % for operational level).
- Peak floor acceleration (e.g., 0.2 g for occupant comfort).
- Maximum overturning moment ratio at the foundation (e.g., 0.7).
- Plastic hinge rotation capacity for seismic demand (e.g., 0.015 rad).

These criteria are used in the verification stage of PBD, where analytical results are compared against the targets. If the building fails to meet a criterion, the design must be iterated—by adjusting member sizes, adding dampers, or altering the structural system—to achieve compliance.

The target probability of failure (TPF) is a probabilistic measure that quantifies the likelihood that a specified performance level will be exceeded. In PBD, the TPF is derived from the reliability index (β) using the relationship $P_f = \Phi(-\beta)$, where Φ is the standard normal cumulative distribution function. For a typical life-safety performance level, β may be set to 3.5, corresponding to $P_f \approx 2 \times 10^{-4}$ per year. Designers must ensure that the computed reliability index for each load case meets or exceeds the target β .

Reliability analysis techniques, such as first-order reliability method (FORM) or Monte-Carlo simulation, are employed to evaluate the probability of failure. These methods require probability distribution functions for loads (e.g., wind speed following a Weibull distribution) and resistances (e.g., material strength following a lognormal distribution). By propagating uncertainties through the structural model, the analyst obtains a probability distribution of the response, from which the reliability index is extracted.

A practical challenge in PBD is the accurate representation of load uncertainties. Wind loads are variable in both space and time, and their statistical characterization depends on the site's terrain category and exposure. Seismic ground motions exhibit variability in amplitude, frequency content, and duration, requiring the selection of appropriate ground-motion suites that reflect the seismic hazard at the site. Inadequate modeling of these uncertainties can lead to non-conservative designs or overly conservative designs that increase cost.

The capacity-demand ratio (CDR) is a dimensionless metric used to assess whether a structural component satisfies the required performance level. It is defined as $CDR = \text{Capacity} / \text{Demand}$, where capacity is the strength or deformation capacity of an element, and demand is the computed demand from analysis. A CDR greater than 1.0 indicates that the component is sufficient, while a CDR less than 1.0 signals the need for redesign. In PBD, the CDR is evaluated for each performance level, allowing designers to allocate material efficiently where it is most needed.

Plastic hinge concepts are central to seismic performance assessment. A plastic hinge is a localized region where inelastic rotation occurs during large seismic events. The plastic hinge rotation capacity (θ_p) is a function of section geometry, reinforcement detailing, and strain hardening behavior. In performance-based design, the cumulative plastic hinge rotation across the height of the building is limited to ensure that drift limits are not exceeded and that the structure retains sufficient strength after the event.

The capacity spectrum method (CSM) is a widely used approach for evaluating seismic performance of tall

buildings. The method plots the demand spectrum (derived from the ground-motion response spectrum) and the capacity curve (relating base shear to roof displacement) on the same axes. The intersection point provides the performance point, from which drift, base shear, and other quantities are extracted. The CSM is particularly useful for structures where higher modes are significant, as it can incorporate modal participation in the capacity curve.

Time-history analysis offers a more detailed assessment of dynamic response by applying a sequence of ground-motion accelerograms directly to the structural model. This approach captures nonlinear behavior, such as yielding and stiffness degradation, and can account for the interaction of multiple load types (e.g., simultaneous wind and seismic). However, it is computationally intensive, especially for tall buildings with many degrees of freedom, and requires careful selection of representative ground motions to avoid bias.

In the context of wind-induced vibrations, the gust factor (G_f) is used to scale the mean wind speed to a higher instantaneous speed that accounts for short-duration gusts. The gust factor is defined as $G_f = V_{gust} / V_{mean}$, where V_{gust} is the peak gust velocity over a specified time interval (usually 10 minutes). Design codes often prescribe a default gust factor of 1.3 for open terrain, but PBD allows the gust factor to be refined based on wind tunnel measurements or computational fluid dynamics (CFD) simulations.

Computational fluid dynamics (CFD) has become an important tool for predicting wind pressures on complex geometries. By solving the Navier-Stokes equations for turbulent flow, CFD provides detailed pressure fields that can be used to supplement or replace wind tunnel data, particularly for early-stage design when physical models are not yet available. Nevertheless, CFD results must be validated against experimental data, as turbulence modeling introduces uncertainties that can affect the reliability of the pressure coefficients.

The structural damping ratio (ζ) represents the inherent ability of the structure to dissipate vibrational energy. In practice, ζ is often assumed to be 5% for steel structures and 2% for concrete structures, but actual damping can be higher due to non-structural components, façade systems, and aerodynamic effects. In PBD, an accurate estimate of ζ is crucial for predicting wind-induced accelerations, which directly influence occupant comfort criteria.

Occupant comfort criteria are especially relevant for residential and office towers where wind-induced accelerations can cause discomfort or motion sickness. The commonly used metric is the root-mean-square (RMS) acceleration level, expressed in units of gravity (g). Standards such as ISO 10137 provide threshold values: for example, a 0.15 g RMS acceleration may be acceptable for short-duration exposure, while continuous exposure should stay below 0.05 g. Designers may employ aerodynamic modifications, tuned mass dampers, or increased structural stiffness to meet these comfort limits.

The concept of redundancy is essential for ensuring robustness against unexpected damage. Redundancy is achieved when multiple load paths exist, allowing the structure to redistribute forces if a primary component fails. In tall buildings, redundancy can be introduced by incorporating secondary bracing

systems, outrigger trusses at multiple levels, or a combination of core and perimeter frames. Quantifying redundancy often involves performing a “progressive collapse” analysis, where elements are sequentially removed to assess the residual capacity of the building.

Progressive collapse analysis follows a prescribed removal sequence (e.g., removal of a critical column) and evaluates the subsequent redistribution of forces. The analysis can be performed using linear static methods (e.g., the Alternate Path Method) or more sophisticated nonlinear dynamic simulations. The goal is to verify that the building retains an acceptable level of performance after localized damage, consistent with the damage-limiting performance level.

The term architectural envelope refers to the exterior façade that encloses the building. In performance-based design, the envelope’s interaction with wind is a major factor. Features such as double-skin façades, ventilated cavities, and louvers can alter pressure distribution and improve aerodynamic damping. However, these features must be coordinated with structural engineers to avoid unintended wind loads or increased drift.

Facade attachment systems are critical components that transfer wind loads from the cladding to the structural frame. The design of these connections must consider both static pressure and dynamic cyclic loading, especially for high-rise applications where façade panels may be subjected to large fluctuations. Failure of attachment systems can lead to panel loss, which is a major safety concern. The performance criteria for these systems often include a maximum allowable panel displacement of 5 mm under design wind loads.

The building code provides baseline requirements, but PBD allows designers to exceed or relax these requirements based on performance objectives. For instance, a code may limit interstory drift to 0.005 for a 20-story office building, while a PBD approach could permit a drift of 0.015 if the building is designed to a higher performance level that includes a controlled damage scenario. The key is to document the rationale, demonstrate compliance with the target reliability, and obtain stakeholder approval.

Stakeholder engagement is a vital part of the PBD process. Owners, occupants, insurers, and regulators all have different risk tolerances and performance expectations. Early communication ensures that the selected performance levels, acceptable probabilities of failure, and cost implications align with the project’s goals. For example, an insurance company may require a life-safety performance level with a target probability of failure of 1×10^{-4} , which could influence the decision to incorporate a tuned mass damper.

Another important term is value engineering. In the context of PBD, value engineering involves optimizing the design to achieve the required performance at the lowest life-cycle cost. This may include selecting alternative structural systems, adjusting material grades, or incorporating passive control devices that provide the necessary damping without excessive cost. The trade-off analysis must consider both initial construction costs and long-term operation and maintenance expenses.

Life-cycle cost analysis (LCCA) quantifies the total cost of a building over its service life, including

construction, maintenance, repair, and eventual demolition. When performance-based design leads to higher upfront expenditures—for example, by installing a large tuned mass damper—the LCCA can reveal whether the reduction in expected damage and downtime offsets the initial investment. LCCA is especially relevant for buildings located in high-risk regions where the probability of severe wind or seismic events is non-negligible.

The structural health monitoring (SHM) system is an emerging technology that provides real-time data on the building's performance during service. Sensors such as accelerometers, strain gauges, and displacement transducers are installed at strategic locations (e.g., at the top of the core, on outrigger trusses, and at critical façade connections). SHM data can be used to validate the PBD models, detect abnormal behavior after an event, and inform post-event inspection strategies.

Post-event inspection protocols are defined based on the performance level achieved during the event. If the building experiences only operational or damage-limiting performance, a visual inspection may suffice. However, if a life-safety performance level is exceeded, more detailed investigations, including non-destructive testing of critical connections, may be required. The inspection criteria are usually expressed in terms of observed drift, crack width, and residual deformations.

The term seismic hazard analysis (SHA) describes the process of evaluating the probability of various ground-motion intensities at a site. SHA involves selecting an appropriate seismic source model, defining the attenuation relationships (ground-motion prediction equations), and integrating over the spatial distribution of potential earthquakes. The resulting hazard curves provide the spectral accelerations for different return periods, which serve as input for the PBD seismic analysis.

Ground-motion prediction equations (GMPEs) are empirical relationships that estimate the expected ground-motion parameters (e.g., peak ground acceleration, spectral acceleration) based on earthquake magnitude, distance, site conditions, and fault mechanism. Selecting a GMPE that reflects the regional tectonic setting is crucial for accurate seismic demand estimation. In PBD, the GMPE uncertainties are explicitly accounted for in the reliability analysis.

The site class is a classification of the ground conditions (e.g., rock, stiff soil, soft soil) that influences the seismic response spectra. Site class affects both the amplitude and the shape of the response spectrum, particularly at periods longer than 0.5 s, which are most relevant for tall buildings. For example, a site classified as "D" (soft soil) may double the spectral acceleration at a 1-s period compared to a rock site, leading to higher seismic forces.

A key performance measure for tall buildings under seismic loading is the story shear. Story shear is the horizontal force transmitted through a floor level, which must be resisted by the structural elements (core walls, perimeter columns, braces). The distribution of story shear influences the design of connections and the sizing of members. In PBD, the story shear is compared against the capacity of each element to ensure that the plastic hinge rotations remain within acceptable limits.

Column buckling is a potential failure mode for slender vertical elements under combined axial load and lateral displacement. The critical buckling load for a column is given by Euler's formula, modified for effective length and end conditions. In tall buildings, the lower columns often carry large axial loads from the weight of the structure above, making buckling a critical design consideration. Designers may increase column dimensions, add intermediate bracing, or use high-strength steel to mitigate buckling risk.

The term torsional response refers to the twisting motion that occurs when the lateral loads are not symmetrically distributed about the building's centroid. Torsional effects are pronounced in irregular plans, such as L-shaped or T-shaped floor plans, where the center of mass does not coincide with the center of stiffness. Torsional response can increase drift at certain locations and complicate the design of outriggers and braced tubes. Mitigation strategies include adding mass or stiffness to balance the torsional irregularities, or employing additional outriggers to increase torsional rigidity.

Dynamic interaction between wind and structural motion is often captured using the spectral density function (SDF). The SDF describes how wind energy is distributed across frequencies and is used in the calculation of wind-induced responses via the random vibration theory. By integrating the product of the SDF and the structure's frequency response function, engineers obtain the variance of displacement, velocity, or acceleration. This approach is especially valuable for very tall and flexible structures where wind turbulence interacts with the building's natural frequencies.

The wind-induced acceleration is a critical metric for serviceability. It is commonly expressed as a ratio of the peak floor acceleration to gravity (g). Values above 0.2g can be perceptible to occupants, while values exceeding 0.5g may cause motion sickness. In performance-based design, the acceleration limit is incorporated as a performance criterion, and design modifications (e.g., adding aerodynamic features or damping devices) are pursued until the target is met.

A term frequently encountered in the assessment of wind loads is the effective wind speed. This speed is obtained by multiplying the basic wind speed by a series of factors that account for terrain roughness, topographic effects, and gustiness. The effective wind speed is then used to compute the design pressure using the formula $p = \frac{1}{2} \rho V^2 C_p$, where ρ is the air density, V is the effective wind speed, and C_p is the pressure coefficient.

Pressure coefficient (C_p) values are derived from wind tunnel tests or CFD simulations and represent the ratio of local wind pressure to the dynamic pressure of the reference wind speed. C_p can be positive (pressure) or negative (suction) and varies across the façade. In tall building design, the most critical C_p values are often found at corners and edges, where vortex shedding creates high suction pressures.

The dynamic wind load factor (D_w) is used to scale static wind pressures to account for dynamic amplification. It is defined as $D_w = V_{\text{dynamic}} / V_{\text{static}}$, where V_{dynamic} is the peak dynamic pressure derived from the spectral analysis, and V_{static} is the static pressure obtained from the mean wind speed. Designers may apply a D_w of 1.2 to 1.5 depending on the building's natural period and damping.

Structural performance grading is a systematic way to categorize the building's response into grades such as A, B, C, or D, based on compliance with performance criteria. Grade A may correspond to the operational level, while Grade D may indicate unacceptable performance. The grading system provides a clear communication tool for stakeholders, allowing them to understand the implications of design decisions in terms of risk and cost.

The concept of design optimisation in PBD involves iteratively adjusting design variables (e.g., member sizes, damper parameters, material properties) to achieve the desired performance at minimal cost. Gradient-based optimisation algorithms, genetic algorithms, or surrogate-model approaches can be employed. The optimisation problem is typically constrained by performance criteria (e.g., drift, acceleration) and reliability requirements (target β).

Surrogate modelling is a technique that creates a simplified representation (e.g., response surface, kriging model) of a complex structural analysis, enabling rapid evaluation of design alternatives. In the context of PBD, surrogate models can approximate the relationship between design variables and performance metrics such as interstory drift, allowing the optimisation loop to converge efficiently.

The term incremental dynamic analysis (IDA) is used to assess the progressive nonlinear response of a structure under a series of scaled seismic records. By incrementally increasing the intensity of each record, the analyst identifies the point at which the structure reaches a target performance level (e.g., 0.5 % drift). IDA results are plotted as capacity-versus-demand curves, from which the probability of exceeding a performance level can be estimated.

Nonlinear time-history analysis extends IDA by incorporating material and geometric nonlinearity, such as concrete cracking, steel yielding, and large-displacement effects. This analysis provides a realistic picture of how the building will behave under extreme seismic loading, capturing phenomena like soft-story collapse or pounding between adjacent structures. The computational cost is high, but the insights gained are valuable for high-risk projects.

Performance-based fire design is an emerging sub-discipline that aligns fire safety objectives with the PBD framework. It defines performance levels for fire resistance, such as maintaining structural integrity for a specified duration (e.g., 2 hours) while allowing limited deformation. Fire-induced thermal loads are applied as temperature profiles, and the resulting thermal expansion and loss of strength are evaluated against the performance criteria.

The thermal expansion coefficient (α) of structural materials becomes significant in fire scenarios. For steel, $\alpha \approx 12 \times 10^{-6} / ^\circ\text{C}$, leading to considerable elongation when temperatures rise to 600°C . In PBD, the thermal strain is incorporated into the analysis to assess whether connections can accommodate the expansion without losing load-carrying capacity.

Facade fire protection is a critical component of overall building safety. In PBD, the fire performance of façade systems is evaluated against criteria such as flame spread, smoke development, and structural

contribution. The performance level may require that the façade maintain its integrity for a certain period to prevent vertical fire spread, which influences material selection and attachment detailing.

The term serviceability drift limit is a specific SLS criterion that controls the maximum allowable lateral displacement of the building's occupied floors. For office towers, a common limit is 1/500 of the building height, while for residential towers it may be 1/400. Exceeding this limit can cause discomfort, damage to non-structural components, and misalignment of architectural elements.

Acoustic performance is sometimes included in the performance-based framework, especially for buildings with mixed uses (e.g., residential and office). Acoustic criteria such as sound transmission class (STC) or impact insulation class (IIC) can be linked to the structural system, as excessive vibration may transmit noise through floor slabs. Designers may increase floor slab thickness or add resilient layers to meet acoustic performance targets.

The wind-induced vortex shedding frequency (f_v) is a key parameter governing dynamic wind response. It is estimated using the Strouhal number (St) relationship $f_v = St \cdot V / D$, where V is the wind speed and D is a characteristic dimension (e.g., building width). When f_v approaches a natural frequency of the building, resonance can occur, leading to amplified vibrations. Modifying the building shape or adding aerodynamic features can shift f_v away from critical frequencies.

Strouhal number (St) is a dimensionless parameter that characterizes vortex shedding. Typical values for rectangular prisms range from 0.2 to 0.3. By changing the façade geometry (e.g., adding setbacks or rounded edges), designers can influence St and thereby control the vortex shedding frequency, reducing the likelihood of resonance.

The term structural redundancy index (RI) quantifies the degree to which alternative load paths exist in a structure. One common definition is $RI = \sum (C_i / D_i)$, where C_i is the capacity of member i and D_i is the demand on that member. A higher RI indicates greater robustness. In performance-based design, the RI can be used as a design objective, encouraging the inclusion of multiple bracing systems or supplemental cores.

Progressive collapse resistance is often mandated for high-rise buildings in densely populated urban areas. The design approach involves ensuring that the removal of a critical column does not lead to a disproportionate loss of capacity. Numerical simulations of column removal, combined with the application of the alternate path method, help verify that the building meets the damage-limiting performance level.

Design wind speed (V_d) is the reference wind speed used for structural design, derived from the basic wind speed (V_b) after applying topographic and exposure factors. V_d is the basis for calculating design pressures, and in PBD it may be refined using site-specific wind tunnel data to capture local turbulence characteristics.

Wind turbulence intensity (I) is a statistical measure of wind speed fluctuations, defined as the standard deviation of wind speed divided by the mean wind speed. Higher turbulence intensity leads to larger gust

factors and greater dynamic amplification. In performance-based design, I is incorporated into the spectral density function to predict wind-induced responses more accurately.

Seismic design category (SDC) classifies structures based on the seismic hazard at the site and the importance of the building. While traditional codes assign a single SDC, PBD allows the designer to tailor the seismic performance level for each building function, potentially assigning a higher SDC to critical areas (e.g., a hospital wing) while using a lower SDC for ancillary spaces.

Reliability target (β_{target}) is the reliability index that corresponds to the desired probability of failure. For example, $\beta_{\text{target}} = 3.5$ yields a failure probability of roughly 2×10^{-4} per year, which may be required for life-safety performance. The reliability target guides the selection of load factors and safety factors in the design equations.

Load factor (γ) is a multiplicative factor applied to nominal loads to account for uncertainty and variability. In PBD, load factors are derived from reliability analysis rather than prescribed by code, allowing for load-specific factors (e.g., $\gamma_{\text{wind}} = 1.3$, $\gamma_{\text{seismic}} = 1.5$) that reflect the statistical properties of each load type.

Resistance factor (ϕ) reduces the nominal strength of structural components to account for uncertainties in material properties, modeling, and construction. Typical values are $\phi = 0.9$ for steel, $\phi = 0.85$ for concrete, but in PBD these factors can be calibrated based on reliability analysis to achieve the target β .

Partial safety factor is another term for load factor, emphasizing that each load type (dead, live, wind, seismic) may have its own γ . The combination of partial safety factors with resistance factors yields the design equation: $\phi R \geq \sum \gamma_i L_i$, where R is the nominal resistance and L_i are the individual loads.

Design spectrum is a set of spectral acceleration values plotted against period, representing the maximum expected seismic response for a given site. In PBD, the design spectrum may be adjusted to reflect the target reliability index, resulting in a higher or lower spectral shape compared to the code-specified spectrum.

Site response analysis examines how local soil and geological conditions modify the incoming seismic waves. Techniques such as equivalent linear analysis or nonlinear time-domain analysis generate site-specific response spectra that are then used in the structural analysis. Accurate site response is crucial for tall buildings, whose periods often fall in the range where soil amplification is most pronounced.

Structural damping augmentation involves adding devices or mechanisms that increase the effective damping of the building. Examples include viscous dampers, tuned liquid column dampers, and friction dampers. Increased damping reduces vibration amplitudes and can significantly lower wind-induced accelerations, helping meet occupant comfort criteria without excessive stiffening.

Viscous damper devices consist of a piston moving through a fluid, providing resistance proportional to

velocity. They are effective over a wide frequency range and can be placed at strategic locations (e.g., between the core and perimeter frames) to target specific modes. The damper's force–velocity relationship is described by $F = c \cdot v$, where c is the damping coefficient and v is the relative velocity.

Friction damper operates on the principle of Coulomb friction, offering a constant resisting force independent of velocity. Friction dampers are simple, robust, and require minimal maintenance, but their performance is limited to a narrow range of motion. They are often used in conjunction with other damping devices to provide a baseline level of energy dissipation.

Hybrid control systems combine passive and active devices, such as a tuned mass damper paired with an active actuator that fine-tunes the system in response to changing wind conditions. Hybrid systems aim to achieve the reliability of passive devices while exploiting the adaptability of active control to enhance performance under a broader range of scenarios.

Wind-induced fatigue is a concern for structural members that experience cyclic stresses due to wind loading over the building's service life. Fatigue analysis uses S-N curves (stress–life) to estimate the number of cycles to failure. In performance-based design, fatigue criteria may be included as part of the serviceability performance level, ensuring that the cumulative damage remains below a specified threshold (e.g., $D = 0.5$).

Damage index (DI) is a scalar measure that quantifies the extent of damage in a structural component, ranging from 0 (no damage) to 1 (complete failure). The index can be based on plastic hinge rotation, strain, or energy dissipation. In PBD, the DI is used to assess whether a component meets the damage-limiting performance level, often requiring $DI < 0.2$ for critical