
Graduate Certificate in Design and Analysis of Tall Buildings

Seismic Design of Tall Structures

Seismic hazard refers to the probability and intensity of earthquakes that may affect a given site over a specified period. It is quantified using probabilistic seismic hazard analysis (PSHA), which integrates information on fault geometry, slip rates, and historical seismicity to produce a hazard curve expressing the likelihood of exceeding a certain ground-motion level. Understanding the seismic hazard is the first step in designing tall structures because it determines the level of seismic forces that must be resisted.

Earthquake source models describe the characteristics of the faults that can generate earthquakes near a site. Common source models include point sources, finite-fault sources, and area sources. The choice of source model influences the spectral content of ground motions, as larger faults tend to produce longer-period waves that are more critical for tall buildings. For example, a tall office tower located near a subduction zone may be subjected to low-frequency motions dominated by the rupture of a megathrust fault.

Ground motion is the actual movement of the earth's surface during an earthquake. It is recorded by accelerometers and expressed in terms of acceleration time histories, velocity histories, or displacement histories. The raw data are processed to obtain parameters such as peak ground acceleration (PGA) and spectral acceleration (S_a). In practice, engineers often use a suite of recorded or simulated ground motions that are compatible with the site's seismic hazard to assess the robustness of a design.

Peak ground acceleration (PGA) is the maximum absolute value of acceleration recorded at a site during an earthquake. While PGA is a convenient scalar measure, it does not capture the frequency content that governs the response of tall structures. Nevertheless, many design codes still require a minimum PGA value to be used in the equivalent static method, particularly for low-rise buildings where period effects are less pronounced.

Spectral acceleration (S_a) is the maximum response of a single-degree-of-freedom (SDOF) oscillator to a specific ground-motion record, plotted as a function of oscillator period. The resulting response spectrum provides the basis for estimating seismic forces on multi-story structures by relating each story's modal period to the appropriate S_a value. For tall buildings, the spectral values at periods between 0.5 s and 2.0 s are typically most critical because they correspond to the fundamental and higher modes of the structure.

Design spectrum is a code-specified representation of S_a that incorporates safety factors, site class adjustments, and importance factors. It is derived from the hazard-derived response spectrum but is simplified for use in design calculations. For example, the US ASCE 7 design spectrum includes separate curves for short periods (0–0.2 s), intermediate periods (0.2–1.0 s), and long periods (> 1.0 s), each multiplied by a factor that accounts for the seismic zone and site class.

Site class categorizes the ground conditions beneath a structure based on shear-wave velocity (V_{s30}) and other geotechnical parameters. Common classifications range from rock (Site A) to soft soil (Site E). Site class influences the amplification of seismic waves; soft soils can significantly increase S_a at long periods, thereby raising the seismic demand on tall buildings. A practical example is the design of a skyscraper in a city built on reclaimed land, where the site class may be classified as Site D, requiring a higher spectral amplification factor.

Soil-structure interaction (SSI) acknowledges that the foundation and the supporting soil do not act independently during an earthquake. The dynamic stiffness of the soil can modify the effective period and damping of the structure, often reducing the seismic demand for very stiff foundations but increasing it for flexible ones. In the case of a tall tower with a deep pile foundation, SSI analysis may reveal a shift of the fundamental period from 0.6 s to 0.8 s, which changes the applicable S_a from the intermediate to the long-period portion of the design spectrum.

Fundamental period (T_1) is the natural period associated with the first mode of vibration of a building. It can be estimated using empirical formulas, such as $T_1 \approx 0.1 N / \sqrt{m}$, where N is the number of stories and m is the total mass per unit height, or derived from a modal analysis. Accurate estimation of T_1 is essential because it determines which part of the design spectrum governs the seismic force. For a 60-story tower with a total height of 250 m, a typical T_1 might be around 1.2 s, placing it squarely in the long-period region.

Modal analysis is a technique that decomposes a structure's dynamic response into a set of independent SDOF systems, each characterized by a natural frequency, mode shape, and damping ratio. By solving the eigenvalue problem for the mass and stiffness matrices, engineers obtain the modal parameters needed for response spectrum analysis. In practice, only the first few modes (often three to five) are retained because they contribute the most to the overall response, especially in tall buildings where higher modes have decreasing participation factors.

Mode shape describes the deformation pattern associated with a particular mode of vibration. For a typical shear-type building, the first mode shape is dominated by a uniform lateral displacement, while higher modes exhibit curvature and may involve torsional components. Understanding mode shapes helps identify areas of concentration of seismic demand, such as the corners of a rectangular tower where torsional modes may produce significant eccentricities.

Damping ratio (ζ) quantifies the energy dissipation capacity of a structure during dynamic motion. It is expressed as a fraction of critical damping and typically ranges from 2 % to 5 % for ordinary concrete frames. Increased damping reduces the spectral acceleration values, as reflected in the design spectrum curves that are multiplied by a factor (η) depending on ζ . Adding supplemental damping devices, such as viscous dampers, can effectively raise the overall damping ratio to 8 % or higher, thereby lowering the seismic forces.

Equivalent lateral force method (ELFM) is a simplified approach that converts the distributed seismic load

into a single horizontal force applied at the building's centre of mass. The base shear V is calculated as $V = C \cdot W$, where C is the seismic coefficient derived from the design spectrum and site factors, and W is the total seismic weight. Although ELM does not capture higher-mode effects, it provides a quick and conservative estimate for preliminary design, particularly for regular, symmetric towers.

Base shear is the total horizontal seismic force that the foundation must resist. It is distributed among the stories according to a prescribed load distribution, often proportional to the product of story mass and height. For a 50-story building with a total seismic weight of 500,000 kN and a seismic coefficient of 0.12, the base shear would be 60,000 kN. This value is then apportioned to each floor to determine story forces and design member sizes.

Overtaking moment is the moment generated by the seismic forces about the base of the structure. It is calculated by summing the products of story forces and their respective lever arms (height). The overturning moment must be balanced by the resisting moment provided by the foundation and any anchorage systems. In a tall building, the overturning moment can be several hundred thousand kilonewton-meters, requiring careful design of the pile cap or mat foundation to prevent uplift.

Drift ratio is the relative lateral displacement between two consecutive floors divided by the story height. It is a key performance indicator because excessive drift can damage non-structural components, such as façade panels and interior partitions. Design codes often limit drift to 0.5 % of story height for serviceability, while allowing higher drift (up to 1.5 % or more) for ultimate limit state design. For a 3 m story, a 0.5 % drift limit corresponds to a maximum inter-story displacement of 15 mm.

Story drift is closely related to drift ratio but is expressed in absolute terms (millimetres). Engineers monitor story drift during nonlinear analysis to ensure that the structure remains within acceptable limits throughout the loading path. In performance-based design, different drift thresholds correspond to different damage states: minor (0.2 %–0.5 %), moderate (0.5 %–1.0 %), and severe (> 1.0 %). A practical example is a residential tower where a 0.8 % drift may be acceptable for an earthquake with a 10 % probability of exceedance in 50 years, but not for a design earthquake with a 2 % probability.

P-Δ effects (second-order effects) arise from the additional moments generated by the vertical loads acting on the displaced structure. In tall buildings, these effects can be significant because the vertical loads (gravity) are large relative to the horizontal seismic loads. Neglecting P-Δ can lead to underestimation of internal forces, especially in structures with soft-story configurations. Modern analysis tools automatically include P-Δ effects in nonlinear time-history simulations, but in simplified calculations, a factor may be applied to the base shear to account for them.

Performance-based design (PBD) shifts the focus from prescriptive force levels to desired performance outcomes, such as immediate occupancy, life safety, or collapse prevention. The design process involves defining performance objectives, selecting appropriate ground motions, and conducting incremental dynamic analysis (IDA) to map the probability of exceeding each damage state. For a landmark skyscraper, a

PBD approach might require that the building remain operational after a magnitude 7.0 event with a 10% exceedance probability, while allowing limited damage under a more severe event.

Capacity design is a design philosophy that ensures that plastic hinges form in predetermined, ductile regions of the structure, while other components remain elastic. By allocating sufficient rotational capacity to the “strong” elements (e.g., beam-column joints) and limiting the capacity of “weak” elements (e.g., columns at the base), the structure can dissipate energy through controlled inelastic deformation. In a moment-resisting frame, capacity design may involve designing the column sections to yield before the beam sections, thereby directing plasticity to the desired locations.

Ductility is the ability of a structural component to undergo large inelastic deformations without loss of load-carrying capacity. Ductility is quantified by the ductility factor (μ), which is the ratio of the ultimate displacement to the yield displacement. A ductility factor of 4–6 is typical for steel moment frames, while reinforced-concrete frames may achieve $\mu \approx 3$ –4 when properly detailing confinement reinforcement. Ductility is crucial for tall buildings because it allows the structure to absorb seismic energy over an extended deformation path, reducing peak forces.

Energy dissipation mechanisms include material hysteresis, supplemental damping devices, and geometric nonlinearity. Hysteretic energy is released during loading-unloading cycles and is captured in nonlinear analysis through the stress-strain curves of steel and concrete. Supplemental devices, such as viscous dampers, can provide additional energy-absorbing capacity, thereby reducing the demand on the primary structural elements. For instance, installing a set of tuned mass dampers (TMDs) at the top of a 80-story tower can reduce peak inter-story drift by up to 30%.

Base isolation separates the superstructure from ground motion using flexible bearings, sliding devices, or elastomeric layers. The isolation system lengthens the fundamental period of the building, moving its response into a region of lower spectral acceleration. A common isolation device is the lead-rubber bearing, which combines a rubber matrix with a lead core to provide both stiffness and hysteretic damping. In practice, a base-isolated office tower may experience a 0.5 s period, compared with 1.2 s for a conventional fixed-base design, resulting in a substantial reduction in seismic forces.

Tuned mass damper (TMD) is a passive device consisting of a mass, spring, and damper tuned to the dominant vibration frequency of the structure. The TMD absorbs energy by moving out of phase with the building motion, thereby reducing resonant amplification. The most famous example is the 660-ton TMD installed in the Taipei 101 tower, which reduces the peak acceleration at the top by approximately 40%. For a new skyscraper, designers may consider multiple TMDs placed at different elevations to target several modes simultaneously.

Viscous damper operates on the principle of fluid resistance, generating a force proportional to velocity ($F = c \cdot v$). These devices can be installed between floors or within braces, providing adjustable damping that can be tuned to specific performance levels. In a braced frame, viscous dampers can reduce story shear

forces by 15–25 % and limit inter-story drift, allowing for smaller cross-sectional areas of the braces.

Friction damper uses sliding surfaces to generate resistance, typically with a force–displacement relationship that is nearly constant over a range of motion. Friction dampers are compact, require minimal maintenance, and can be integrated into existing structural elements, such as beam-column joints. In a concrete core system, friction dampers placed at strategic levels can help control torsional response during strong shaking.

Structural system classification includes moment frames, braced frames, shear walls, out-rigger systems, and tube systems. Each system offers distinct stiffness, strength, and ductility characteristics. Moment frames provide high ductility and are often used for residential towers, while braced frames deliver high strength and are common in office buildings. Shear walls, typically made of reinforced concrete, offer excellent stiffness and are frequently employed in mixed-use towers where large open floor plans are required.

Stiffness is the ratio of force to displacement and governs the natural period of a structure. In tall buildings, excessive stiffness can lead to high accelerations, while insufficient stiffness may cause large drifts. Designers must strike a balance; for example, a concrete core with a stiffness of 0.02 kN/mm may be combined with a peripheral moment frame to achieve a target period of 1.0 s, satisfying both strength and serviceability criteria.

Mass distribution influences the modal participation factors and the torsional response. An uneven mass layout, such as a heavy mechanical floor located on one side of the tower, can induce torsional irregularities that increase demand on certain columns. To mitigate this, designers may redistribute equipment, add counterweights, or adjust the layout of the structural core to achieve a more symmetric mass distribution.

Torsional irregularity occurs when the centre of mass (CM) does not coincide with the centre of rigidity (CR). The offset creates a torsional moment that must be resisted by the structural system. A common design remedy is to locate the main core near the CM, or to add diagonal bracing that stiffens the periphery. In a 70-story tower with an eccentricity of 2 m, the resulting torsional moment can increase base shear by up to 10 %, necessitating additional reinforcement in the core walls.

Vertical irregularity includes variations in stiffness, mass, or geometry along the height of the building, such as setbacks, step-backs, or soft-story levels. These irregularities can concentrate seismic demand in specific zones. For instance, a soft-story level—where the floor stiffness is significantly lower than adjacent floors—can become a failure point during an earthquake. Mitigation strategies involve strengthening the soft story with additional shear walls, outrigger trusses, or moment frames.

Soft story is a floor with substantially reduced lateral stiffness, typically due to large openings for parking or commercial space. The soft story amplifies story shear and drift, making it a critical vulnerability. Retrofitting a soft story may involve installing steel moment frames, reinforced concrete shear walls, or adding deep foundation piles that increase the overall stiffness and ductility of the affected level.

Setback refers to a change in the building's plan geometry at a particular height, often introduced for architectural or zoning reasons. Setbacks can create abrupt changes in stiffness and mass, leading to concentration of seismic forces at the transition level. Designers account for setbacks by performing detailed finite-element models that capture the local stiffness reduction and by providing additional reinforcement or damping devices at the setback level.

Wind-seismic interaction acknowledges that both wind and earthquake loads may act simultaneously or sequentially, especially for ultra-tall structures. Wind loads dominate at higher elevations, while seismic loads dominate at lower to mid-height levels. The combined effect can be evaluated using multi-physics analysis, where the wind-induced response is superimposed on the seismic response, or through stochastic simulations that generate coupled load histories. For a 200-m tower, the wind-induced drift may be comparable to the seismic drift for a moderate earthquake, requiring a design that satisfies both criteria without excessive conservatism.

Design codes such as ASCE 7, International Building Code (IBC), Eurocode 8, and National Building Code of Canada (NBCC) provide the framework for seismic design. They define seismic zones, importance factors, site class adjustments, and load combinations. Understanding the specific provisions of each code is essential because the required force reduction factors and spectral shapes can differ significantly. For instance, Eurocode 8 employs a design spectrum based on the 95% confidence level, whereas ASCE 7 uses a 90% confidence level, leading to different seismic coefficients for the same site.

Seismic design categories (SDC) classify buildings into groups A, B, C, D, and E (or equivalent) based on the seismic risk and the importance of the occupancy. Tall office towers typically fall into SDC D, requiring higher seismic coefficients and more stringent detailing requirements than low-rise residential buildings (SDC B). The category influences the selection of the importance factor (I) and the required quality of construction, such as the use of high-strength concrete or advanced reinforcement detailing.

Importance factor (I) adjusts the seismic forces to account for the building's role in society. Critical facilities (e.g., hospitals, emergency response centers) have $I = 1.5$, whereas ordinary office buildings have $I = 1.0$. The factor multiplies the base shear, ensuring that essential structures are designed for higher performance levels. For a 40-story hospital, the base shear may be increased by 50% compared with a comparable office tower, reflecting the higher importance factor.

Risk category is a concept used in some codes to further refine the design requirements based on the probability of failure and associated consequences. It is often expressed as a numeric value (e.g., 1–4), with higher numbers indicating higher risk tolerance. The risk category influences the selection of load combinations, reliability targets, and acceptable damage states. In a performance-based framework, a risk-averse owner may select a lower risk category, resulting in stricter drift limits and higher redundancy.

Load combination is the process of superimposing various loads (gravity, wind, seismic) according to code-specified factors to obtain the worst-case design scenario. For seismic design, the common

combination is $1.2 \cdot \text{Dead} + 1.0 \cdot \text{Seismic}$, or $0.9 \cdot \text{Dead} + 1.0 \cdot \text{Seismic}$ for certain cases. The combination ensures that the structure can safely resist the simultaneous action of permanent and dynamic loads. In practice, engineers generate multiple combinations for each analysis case and verify that all governing limits are satisfied.

Nonlinear static analysis (pushover) applies a gradually increasing lateral load pattern to a nonlinear model of the structure until a target displacement is reached. The analysis produces a capacity curve (base shear versus displacement) that can be compared with the demand curve derived from the design spectrum. The intersection point defines the performance point, indicating the expected seismic demand. Pushover analysis is widely used for preliminary performance-based design because it is computationally efficient and provides insight into failure mechanisms.

Incremental dynamic analysis (IDA) extends the pushover concept by subjecting the structure to a series of nonlinear time-history analyses with ground motions scaled to different intensity levels. The resulting capacity-demand curves are probabilistic, allowing the estimation of collapse probabilities and fragility functions. IDA is especially valuable for tall buildings where higher modes and inelastic behavior play a significant role. For a 60-story tower, an IDA study might involve 30 ground motions, each scaled to 10 intensity levels, producing a comprehensive set of response data.

Time-history analysis directly integrates the equations of motion for the structure using actual or simulated ground-motion records. It captures the full nonlinear response, including P- Δ effects, material hysteresis, and damping devices. While computationally intensive, time-history analysis is the most accurate method for assessing seismic performance, particularly for irregular or highly ductile structures. In practice, engineers select a representative subset of records that satisfy target spectra and run detailed nonlinear simulations to verify the design.

Ground-motion records are the raw acceleration time histories obtained from instrumented earthquakes or generated synthetically. Selecting appropriate records involves matching the target spectral shape, scaling to the required intensity, and ensuring a diversity of fault mechanisms and site conditions. The use of a suite of at least seven records is a common requirement in many codes for reliability. For a design earthquake with a 10% probability of exceedance in 50 years, the selected records must collectively represent the variability of possible shaking.

Scaling of ground-motion records adjusts the amplitude to achieve the desired spectral acceleration level while preserving the frequency content. Linear scaling preserves the shape of the spectrum but may produce unrealistic accelerations if the original record is far from the target. Alternative scaling methods, such as spectrum matching or time-domain scaling, modify the record to better fit the target spectrum while maintaining realistic energy content. Proper scaling is essential to avoid over- or under-estimating seismic demand.

Site response analysis evaluates how local soil layers modify the incoming seismic waves. Using a

one-dimensional wave propagation model, engineers compute the amplification factor for each frequency, producing a site-specific response spectrum. The analysis accounts for nonlinear soil behavior, which can reduce amplification at high strain levels. For a tower built on a soft clay deposit, site response analysis may reveal a spectral amplification factor of 2.5 at a 1.5-s period, significantly increasing the seismic demand on the structure.

Equivalent static method (ESM) is a code-based approach that approximates the seismic forces by applying a static horizontal load derived from the design spectrum. The method assumes a uniform distribution of forces based on the product of mass and height, and is suitable for regular, low-rise buildings. For tall structures with significant higher-mode effects, ESM may be overly conservative or non-conservative, prompting the use of more advanced methods such as response spectrum analysis or time-history analysis.

Response spectrum analysis (RSA) combines the benefits of modal analysis and the design spectrum. Each mode's response is computed using the modal participation factor and the spectral acceleration at the mode's period. The modal responses are then combined using the square-root-of-sum-of-squares (SRSS) or complete-quadratic-combination (CQC) method to obtain the total displacement, shear, and moment demands. RSA is widely adopted for tall buildings because it captures the contribution of multiple modes without the computational cost of full time-history analysis.

Seismic performance objectives define the acceptable level of damage for different earthquake intensities. Typical objectives include immediate occupancy (IO), life safety (LS), and collapse prevention (CP). Each objective is associated with specific drift limits, plastic hinge rotations, and energy dissipation capacities. For a high-rise office tower, the IO objective may require a maximum drift of 0.5 % for a design earthquake, while the LS objective may allow up to 1.5 % drift for a rare, severe event.

Damage states are qualitative descriptions of the condition of a building after an earthquake. They range from slight (minor cosmetic damage) to extensive (severe structural damage) to complete collapse. Quantitative thresholds, such as drift ratios or plastic hinge rotations, are used to define each state. Fragility curves are then constructed to relate the probability of reaching or exceeding each damage state to a seismic intensity measure (e.g., S_a at a specific period).

Fragility curves plot the probability of exceeding a particular damage state as a function of seismic intensity. They are derived from statistical analyses of multiple nonlinear simulations, often using the lognormal distribution. Fragility curves enable risk-based decision making, such as estimating expected repair costs or planning post-earthquake emergency response. For a 45-story tower, a fragility curve for the LS objective may show a 20% probability of exceedance at $S_a = 0.4 g$ for the 1-s period.

Reliability in seismic design quantifies the confidence that a structure will meet its performance objectives under uncertainty. It incorporates variability in material properties, construction quality, ground-motion characteristics, and modeling assumptions. Reliability-based design methods use target reliability indices (β) to determine the required safety factors. For example, a target $\beta = 3.0$ corresponds to a probability of failure

of 0.13 % over the design life, guiding the selection of load factors and detailing requirements.

Resilience is the ability of a building to absorb, adapt to, and recover from seismic events with minimal loss of functionality. Resilience metrics consider not only structural performance but also non-structural components, occupancy, and economic impact. Strategies to enhance resilience include incorporating base isolation, adding supplemental damping, designing redundant load paths, and ensuring rapid post-earthquake inspection procedures. A resilient design may accept higher initial costs in exchange for reduced downtime after a major quake.

Retrofit involves upgrading existing structures to improve their seismic performance. Common retrofitting techniques for tall buildings include adding exterior braced frames, installing supplemental damping devices, strengthening columns with fiber-reinforced polymer (FRP) wraps, and enhancing foundation stiffness with micropiles. The choice of retrofit strategy depends on the building's existing deficiencies, the available budget, and the desired performance level. For an older concrete tower, a typical retrofit might consist of adding steel braces at the lower levels and installing viscous dampers to control higher-mode responses.

Seismic isolation devices, such as lead-rubber bearings, friction pendulum systems, and elastomeric isolators, are designed to decouple the superstructure from ground motion. The devices are characterized by their stiffness, damping, and load-bearing capacity. In tall buildings, isolation can be implemented at the base or at intermediate levels (e.g., "soft-story" isolation) to target specific modes. The design of isolation systems must address issues like bearing wear, temperature effects, and the need for post-earthquake inspection.

Energy-absorbing devices include hysteretic dampers, buckling-restricted braces (BRBs), and shape-memory alloy (SMA) dampers. These devices dissipate seismic energy through controlled inelastic deformation, reducing the forces transmitted to primary structural elements. For example, a set of BRBs installed in a peripheral frame may provide a yielding strength of 1,200 kN, allowing the system to absorb a substantial portion of the earthquake energy while limiting the demand on the core walls.

Capacity-drift curves plot the relationship between base shear and roof displacement, illustrating the structure's ability to resist increasing seismic demands. The curve typically exhibits an initial linear elastic branch, followed by a yielding plateau where plastic hinges develop, and finally a descending branch as damage accumulates. By overlaying the demand curve derived from the design spectrum, engineers can identify the performance point and assess whether the building meets the intended objectives.

Modal participation factor (Γ) quantifies the contribution of each mode to the overall response. It is calculated as $\Gamma = (\Phi^T M r) / (\Phi^T M \Phi)$, where Φ is the mode shape vector, M is the mass matrix, and r is the load vector (typically uniform lateral load). Modes with higher participation factors dominate the response and must be included in the analysis. In a tall, slender tower, the first three modes may have participation factors of 0.85, 0.12, and 0.03, indicating that the first mode carries the majority of the seismic demand.

Higher-mode effects become increasingly important as building height grows. While the first mode often governs the overall displacement, higher modes can significantly influence internal forces, especially shear and moment distributions. Ignoring higher-mode contributions can lead to underestimation of peak story forces by up to 20 % in a 70-story tower. Accurate assessment requires either a response spectrum analysis that includes multiple modes or a full time-history analysis.

Mass participation assesses the proportion of total mass that is captured by each mode. The cumulative mass participation is used to determine how many modes are needed to achieve a target percentage (commonly 90 % or 95 %). For a typical high-rise building, the first three modes may capture 95 % of the total mass, justifying the inclusion of those modes in the design analysis.

Rayleigh damping is a common method for modeling structural damping in dynamic analysis. It combines mass-proportional and stiffness-proportional damping coefficients (α and β) to achieve a desired damping ratio for selected modes. The coefficients are solved from the system of equations $\alpha + \beta \cdot \omega_1^2 = 2 \zeta \cdot \omega_1$ and $\alpha + \beta \cdot \omega_2^2 = 2 \zeta \cdot \omega_2$, where ω_1 and ω_2 are the natural frequencies of two chosen modes. Proper selection of α and β ensures that the target damping ratio applies to the most critical modes.

Nonlinear material models describe the stress-strain behavior of steel and concrete beyond the elastic range. For steel, the model may include an elastic-perfectly plastic region followed by strain hardening. For concrete, the model incorporates cracking in tension, compression softening, and confinement effects. Accurate material models are essential in pushover and time-history analyses to capture the development of plastic hinges and the energy dissipation capacity of the structure.

Plastic hinge is the localized region where inelastic rotation occurs during seismic loading. The hinge length is typically taken as a fraction of the member depth (e.g., $0.1 \cdot h$ for beams) and is critical for calculating ductility and rotation capacity. Detailing requirements, such as confinement reinforcement, ensure that the hinge can undergo large rotations without loss of load-carrying capacity. For a moment-resisting frame, a typical plastic hinge rotation capacity might be 0.03 rad, corresponding to a ductility factor of 5 for the given yield rotation.

Confinement reinforcement (e.g., spiral ties, hoops) enhances the ductility of concrete columns by providing lateral support to the core concrete. The confinement pressure increases the peak compressive strength and strain capacity, allowing the column to sustain larger axial loads after yielding. Design guidelines specify the spacing and diameter of confinement reinforcement based on the desired confinement pressure and the column dimensions.

Shear wall is a vertical element that provides lateral stiffness and strength, often made of reinforced concrete. In tall buildings, a central core of shear walls serves as the primary lateral-resisting system, offering high torsional rigidity. The walls are typically spaced at regular intervals and designed to act in unison, reducing the overall drift. For a 55-story tower, the core may consist of four shear walls each 4 m wide, delivering a combined stiffness of $8 \times 10^8 \text{ kN}\cdot\text{m/rad}$.

Outrigger system connects the central core to peripheral columns using stiff horizontal trusses or braces at one or more levels, effectively widening the building's lateral-resisting width. This system significantly reduces drift and increases the fundamental period, allowing for a more slender core. An outriggers placed at the 30th and 45th floors of a 70-story tower can reduce roof drift by up to 40 % compared with a core-only system.

Tube system utilizes the building's exterior perimeter as a stiff, hollow tube, with closely spaced columns and deep spandrel beams forming a rigid frame. The tube action provides high lateral stiffness and reduces the need for interior shear walls. The Burj Khalifa employs a variation of the tube-in-tube concept, where an inner core tube works together with an outer tube to achieve exceptional stability. Designing a tube system requires careful attention to the distribution of shear forces along the perimeter.

Redundancy refers to the presence of multiple load-path alternatives that can carry forces if one element fails. In seismic design, redundancy improves robustness and reduces the likelihood of progressive collapse. Redundant systems may include a combination of moment frames, braced frames, and shear walls, each capable of sustaining loads independently. For a high-rise building, designing at least two independent lateral-resisting systems is a common practice to achieve high redundancy.

Robustness is the ability of a structure to maintain its integrity under extreme loading, including accidental impacts, blast, or severe earthquakes. Robustness is achieved through continuity of elements, avoidance of concentration of forces, and provision of alternate load paths. Design guidelines, such as the American Institute of Steel Construction (AISC) Robustness provisions, prescribe criteria for connection detailing, column spacing, and shear wall continuity.

Seismic detailing encompasses the specific reinforcement layouts, connection configurations, and material specifications required to ensure ductile behavior. Key detailing aspects include proper anchorage of bars, confinement reinforcement in columns, adequate lap splices, and provision of shear reinforcement in walls. For example, a typical seismic detailing requirement for a concrete column may call for a minimum of 8 % longitudinal reinforcement and 0.5 % ties spaced at 75 mm.

Seismic zoning maps the geographic distribution of seismic hazard levels, assigning each region to a seismic zone (e.g., Zone 1, Zone 2, Zone 3). The zones are used to select site coefficients and design spectra in building codes. In the United States, the West Coast is largely classified as Zone 4, indicating higher seismic forces than the Central and Eastern regions, which are typically Zone 2 or Zone 3. Understanding the local seismic zone