Certificate in Civil Structural Engineering (Portugal)

Structural Dynamics

Structural dynamics is the branch of civil engineering that studies the behaviour of structures when they are subjected to loads that vary with time. Unlike static analysis, where loads are assumed to act slowly enough that inertial effects can be ignored, dynamic analysis must consider the mass of the structure, the stiffness that resists deformation, and the mechanisms that dissipate energy. The following glossary presents the essential terms and concepts that a student in the Certificate in Civil Structural Engineering (Portugal) must master in order to analyse, design, and assess structures under dynamic actions such as earthquakes, wind, traffic, and machinery vibrations.

Dynamic load – Any load whose intensity changes with time. Typical examples include seismic ground motion, gusting wind pressure, moving vehicular loads on bridges, and the periodic forces generated by rotating machinery. In contrast to a static load, a dynamic load can excite the natural vibration modes of a structure and produce responses that are significantly larger than those predicted by static methods.

Ground motion – The time-varying displacement, velocity, or acceleration of the earth's surface caused by an earthquake. It is usually recorded by a seismometer and expressed in terms of acceleration (g). Ground motion is the primary input for seismic analysis and is often represented by a set of acceleration time histories or by a response spectrum.

Response spectrum – A plot that gives the maximum response (typically acceleration, velocity, or displacement) of a series of single-degree-of-freedom (SDOF) systems subjected to a particular ground motion, as a function of their natural period (or frequency) and damping ratio. Engineers use the response spectrum to estimate the peak response of a multi-degree-of-freedom (MDOF) structure without performing a full time-history analysis.

Natural frequency – The frequency at which a structure tends to vibrate when it is disturbed and then allowed to vibrate freely, without external forcing or damping. It is related to the stiffness (k) and mass (m) of the system by the formula $\omega = \sqrt{(k/m)}$. In a building, each mode of vibration has its own natural frequency, and the lowest frequency (fundamental mode) usually governs the overall dynamic behaviour.

Period – The reciprocal of frequency, expressed in seconds. The period of the first mode of a typical low-rise building in Portugal may be in the range of 0.5 to 1.5 s, while a tall tower can have periods of several seconds. Period is a convenient measure because many design codes, including the Portuguese Seismic Code (NP-C-1), present spectra as a function of period.

Mode shape – The spatial distribution of deformation associated with a particular natural frequency. Mode shapes are often visualised as a series of arrows indicating the direction and relative amplitude of motion at each node of a finite element model. The first mode shape of most buildings resembles a sway of the entire structure, while higher modes may involve bending, torsion, or local deformations.

Modal analysis – The process of determining the natural frequencies, mode shapes, and associated modal masses of a structure. In linear dynamic analysis, the equations of motion can be decoupled using the orthogonality of the mode shapes, allowing each mode to be analysed independently. The total response is then obtained by superimposing the contributions of the individual modes.

Modal participation factor – A coefficient that quantifies the contribution of a particular mode to the overall response of the structure under a given load pattern. It is defined as the ratio of the modal effective mass to the total mass of the structure and is used to weight the response of each mode when applying the modal superposition method.

Effective mass – The portion of the total mass that participates in a specific mode of vibration. For the first mode of a regular building, the effective mass may be close to the total mass, while for higher modes it can be significantly lower.

Modal superposition – A technique whereby the dynamic response of a MDOF system is expressed as the sum of the responses of its individual modes. Because each mode behaves like an independent SDOF system, standard SDOF solutions (e.g., Newmark integration) can be applied and the results combined using the participation factors.

Time-history analysis – A numerical integration of the equations of motion over the duration of a specified load time series. This method provides the complete transient response (displacements, velocities, accelerations) at each degree of freedom and captures the effects of non-linear behaviour, varying damping, and multiple load components. It is the most accurate approach for seismic analysis, especially when the structure exhibits non-linear characteristics.

Direct integration – Any numerical method that solves the dynamic equilibrium equations step-by-step in time, without transforming the problem into the frequency domain. Common direct integration schemes include the explicit central-difference method, the implicit Newmark-β method, the Wilson-θ method, and the Hilber-Hughes-Taylor algorithm. Each scheme has its own stability and accuracy characteristics.

Newmark-β method – A widely used implicit integration algorithm that introduces two parameters, β and γ, to control numerical damping and stability. The classic choice $\beta = 1/4$ and $\gamma = 1/2$ yields the average-acceleration method, which is unconditionally stable for linear systems and provides second-order accuracy. By adjusting β and γ, engineers can introduce numerical damping to suppress high-frequency spurious oscillations.

Central-difference method – An explicit integration scheme that approximates the acceleration at the current time step by the finite difference of velocities at the neighbouring steps. It is conditionally stable, requiring the time step Δt to satisfy the Courant condition $\Delta t \le 2/\omega\_max$, where ω_max is the highest natural frequency of the model. The method is computationally cheap but may suffer from numerical instability if the time step is too large.

Wilson-θ method – An implicit integration technique that introduces an artificial parameter θ (typically 1.0–1.4) to extend the time interval over which the equilibrium equations are satisfied. Larger values of θ increase numerical damping, which can be beneficial for controlling high-frequency noise in non-linear analyses. The method remains unconditionally stable for linear systems.

Finite element method (FEM) – A discretisation technique that divides a continuous structure into a set of simpler sub-structures (elements) connected at nodes. Each element contributes to the global mass matrix, stiffness matrix, and damping matrix. FEM is the backbone of modern structural dynamics software, allowing the modelling of complex geometries, material non-linearities, and boundary conditions.

Mass matrix – A matrix that stores the inertial properties of the discretised structure. In most applications a consistent mass matrix is assembled from element shape functions, although a lumped (diagonal) mass matrix is sometimes used for computational efficiency. The mass matrix relates the nodal accelerations to the inertial forces.

Stiffness matrix – A matrix that captures the elastic resistance of the structure to deformation. It is derived from the element stiffness contributions, which depend on material properties (Young’s modulus, shear modulus) and cross-sectional geometry. The stiffness matrix links nodal displacements to internal forces.

Damping matrix – A matrix that represents the energy-dissipating mechanisms within the structure. Damping is often modelled as a linear combination of the mass and stiffness matrices (Rayleigh damping), expressed as $C = \alpha M + \beta K$, where α and β are coefficients that control mass-proportional and stiffness-proportional damping, respectively. More sophisticated models, such as hysteretic or frequency-dependent damping, may be required for highly non-linear structures.

Rayleigh damping – A convenient proportional damping model in which the damping matrix is a linear combination of the mass and stiffness matrices. By selecting α and β to match target damping ratios at two chosen frequencies (usually the first and a higher mode), the damping ratio for all intermediate modes is interpolated. This approach is widely used because it requires only two parameters and integrates easily with FEM formulations.

Damping ratio – The ratio of actual damping to critical damping for a given mode. Critical damping is the minimum amount of damping that prevents oscillation. A typical damping ratio for reinforced-concrete structures is 5 % of critical damping, while steel structures may be assigned 2 %–3 %. The damping ratio influences the shape of the response spectrum and the rate at which vibrations decay.

Critical damping – The specific amount of damping that results in a system returning to equilibrium without oscillating. It is defined as $c_{critical} = 2\sqrt{km}$ for an SDOF system. In practice, most structures are under-damped (c Viscous damping – A model in which the damping force is proportional to velocity (F_d =

c v). This linear relationship is simple to implement but does not capture the energy dissipation mechanisms of concrete cracking or steel yielding, which are inherently non-linear.

Hysteretic damping – A non-linear damping model that accounts for energy loss due to material inelasticity, such as concrete cracking, steel yielding, and friction at connections. Hysteretic damping is represented by a force-displacement loop, where the area enclosed by the loop equals the energy dissipated per cycle. It is essential for accurate seismic modelling of structures that undergo large inelastic deformations.

Dynamic amplification factor (DAF) – Also called the dynamic magnification factor, it is the ratio of the maximum dynamic response to the corresponding static response under the same load magnitude. For a perfectly elastic SDOF system subjected to a harmonic load, $DAF = 1 / \sqrt{[(1-(\omega/\omega_n)^2)^2 + (2\zeta\omega/\omega_n)^2]}$, where ω is the load frequency, ω_n the natural frequency, and ζ the damping ratio. In seismic design, the DAF is approximated by the spectral amplification factor.

Dynamic magnification factor – Synonym of DAF; used interchangeably in many textbooks. It highlights the fact that dynamic effects can “magnify” the response compared to a static analysis, especially when the load frequency is close to the natural frequency (resonance).

Resonance – The condition in which the frequency of the applied load coincides with a natural frequency of the structure, causing the DAF to reach a peak. In practice, perfect resonance is rare because damping prevents infinite amplification, but near-resonant conditions can still produce large responses. Designers mitigate resonance by altering stiffness, adding damping, or shifting natural periods away from dominant excitation frequencies.

Quality factor (Q) – A dimensionless parameter defined as $Q = 1/(2\zeta)$. It measures the sharpness of resonance; a high Q indicates low damping and a narrow resonance peak, while a low Q corresponds to high damping and a broader peak. In seismic engineering, Q values typically range from 10 to 30 for concrete structures.

Frequency domain – An analysis perspective where the response is expressed as a function of frequency rather than time. Techniques such as Fourier transform, spectral analysis, and transfer-function methods operate in the frequency domain. For linear systems, the frequency-domain solution is equivalent to the time-domain solution, but the former can be more convenient when dealing with random or stationary loads.

Fourier transform – A mathematical operation that decomposes a time-varying signal into its constituent sinusoidal components, each characterised by an amplitude and phase at a specific frequency. The transform enables the conversion of a ground-motion time history into a frequency-domain representation (amplitude spectrum) that can be used for spectral analysis.

Power spectral density (PSD) – The distribution of power (variance) of a random signal as a function of frequency. For wind loads, the PSD describes how turbulent energy is distributed across frequencies.

Engineers use PSD functions to generate synthetic wind time histories that possess the same statistical characteristics as measured data.

Random vibration – Vibration induced by loads that are stochastic in nature, such as wind gusts, traffic, or seismic ground motion considered as a random process. Random vibration analysis involves statistical measures (mean, variance, standard deviation) of response quantities, often using PSD methods or Monte-Carlo simulation.

Stochastic processes – Mathematical models that describe random phenomena evolving over time. In structural dynamics, ground motion and wind pressure are treated as stochastic processes with known statistical properties (e.g., mean zero, specified autocorrelation). Stochastic analysis provides probabilistic estimates of structural response, which are valuable for reliability-based design.

Seismic zone – A geographic region defined by the level of seismic hazard, based on historical earthquake records and tectonic considerations. Portugal is divided into several seismic zones (e.g., Zones 1, 2, 3), each associated with a different design ground-motion intensity. The seismic zone determines the spectral shape factors, importance factors, and site coefficients used in the design spectrum.

Site class – A classification of the local soil conditions that influences the amplification of seismic waves. The Portuguese code defines site classes A (hard rock), B (rock), C (stiff soil), D (soft soil), and E (very soft soil). Site class is used to compute the site amplification factor (S) that modifies the elastic response spectrum.

Importance factor – A factor, denoted I, that accounts for the consequences of failure of a particular structure. Critical facilities (hospitals, emergency shelters) receive higher importance factors (e.g., I = 1.5) than ordinary residential buildings (I = 1.0). The importance factor multiplies the design spectrum, increasing the required strength and ductility.

Design spectrum – The elastic response spectrum prescribed by the code for a given seismic zone, site class, and importance factor. The design spectrum provides the target spectral accelerations (S_a) as a function of period and damping. Engineers use the design spectrum to select target periods for the structure, to compute seismic forces, and to verify that the dynamic analysis results satisfy code requirements.

Base shear – The total horizontal seismic force that must be transferred to the foundation of a building. In the equivalent static method, base shear V is computed as V = C_s W, where C_s is the seismic coefficient derived from the design spectrum and W is the total weight of the structure. In dynamic analysis, base shear is obtained by integrating the internal forces resulting from the imposed ground motion.

Equivalent static method – A simplified seismic design approach that replaces the dynamic effects of an earthquake by a set of static forces applied at discrete levels (typically at floor elevations). The method uses the base shear and a vertical distribution factor (often proportional to floor mass and height) to generate a set of lateral forces. While conservative for low-rise buildings, the method may be inadequate for tall or irregular structures, where dynamic analysis is recommended.

Dynamic stiffness – The frequency-dependent stiffness of a structure, defined as $K(\omega) = K - \omega^2 M + i \omega C$, where i is the imaginary unit. Dynamic stiffness combines the elastic stiffness, inertial effects, and damping, and is used in frequency-domain analyses to compute the transfer function between input motion and structural response.

Transfer function – The ratio of output to input in the frequency domain, often expressed as $H(\omega) = X(\omega)/U(\omega)$, where X is the response (e.g., displacement) and U is the input (e.g., ground acceleration). The magnitude of the transfer function indicates the amplification at each frequency, while its phase describes the time lag between input and output.

Impedance – Another term for dynamic stiffness, especially in the context of soil-structure interaction. Impedance characterises how a foundation resists motion under dynamic loading and is a key parameter when modelling the interaction between a building and the underlying soil.

Soil-structure interaction (SSI) – The mutual influence between the dynamic behaviour of a structure and the surrounding ground. SSI can reduce the effective natural frequencies (soil softening) and increase damping (energy radiation into the soil). Accurate SSI modelling may involve springs and dashpots representing the foundation’s translational and rotational stiffness and damping, or more sophisticated sub-structure finite element models.

Foundation stiffness – The elastic resistance of the foundation to translation and rotation. For a shallow foundation, the stiffness can be approximated using empirical formulas based on soil shear modulus and foundation dimensions. For deep foundations (piles), the stiffness is obtained from pile-shaft and tip stiffness calculations.

Foundation damping – The energy dissipation associated with wave radiation and material damping in the soil. In SSI models, foundation damping is often represented by dashpots whose coefficients are derived from the soil’s shear wave velocity and density.

Hinge formation – The development of a plastic rotation zone (hinge) in a structural member when the moment reaches the yield capacity. In seismic design, the formation of plastic hinges allows the structure to dissipate energy through inelastic deformation while preserving overall stability. The location and number of hinges are crucial for ensuring adequate ductility.

Plastic deformation – Permanent strain that remains after the removal of loads. In the context of seismic analysis, plastic deformation is intentionally allowed in certain zones (e.g., plastic hinges) to absorb seismic energy. The extent of plastic deformation is controlled by the design’s ductility requirements.

Ductility factor – The ratio of ultimate displacement capacity to elastic displacement capacity for a given mode. A ductility factor of 3, for example, means the structure can undergo three times the elastic displacement before reaching failure. Design codes prescribe minimum ductility factors based on the importance class and seismic zone.

Limit state – A condition beyond which the structure no longer satisfies the required performance criteria. In seismic design, limit states may include yielding, excessive drift, or collapse. The analysis seeks to keep the structure within the elastic or near-elastic limit state for serviceability, and within the ultimate limit state for safety.

Story drift – The relative horizontal displacement between two consecutive floors, usually expressed as a ratio of the story height (Δ/h). Codes often limit story drift to a certain percentage (e.g., 0.003 for serviceability, 0.01 for seismic) to prevent damage to non-structural components and to maintain occupant comfort.

Torsional response – The rotational motion of a building about its vertical axis, induced by eccentric seismic forces or irregular mass distribution. Torsional effects are significant for buildings with asymmetric plans, irregular elevation, or uneven stiffness distribution. Torsional analysis requires the inclusion of rotational degrees of freedom in the dynamic model.

Rotational degree of freedom – A degree of freedom that represents rotation about an axis, typically the vertical axis (torsion) or horizontal axes (out-of-plane bending). In a 3-D finite element model, each node usually possesses three translational and three rotational degrees of freedom, allowing the capture of complex deformation patterns.

Coupling – The interaction between different modes or between translational and rotational motions. In irregular structures, translational and torsional modes may be coupled, leading to combined deformation patterns. Coupled analysis requires the full MDOF system without simplifying assumptions that decouple the motions.

Non-linear dynamics – The study of structural response when the relationship between forces and displacements is not linear. Non-linearity arises from material yielding, geometric large-displacement effects, contact, and boundary condition changes. Non-linear analysis typically involves incremental-iterative solution procedures (Newton-Raphson) and may use time-history integration.

Geometric non-linearity – Non-linear behaviour caused by large deformations that alter the structure’s geometry, thereby affecting stiffness. For slender frames, P-Δ effects (secondary moments due to axial loads acting on displaced geometry) are a common source of geometric non-linearity. Including geometric non-linearity improves the accuracy of seismic predictions for tall, flexible structures.

Material non-linearity – Non-linear behaviour arising from the stress-strain characteristics of the material. Concrete exhibits cracking and crushing, while steel shows yielding and strain hardening. Material models such as the Concrete Damage Plasticity model or the Bilinear steel model are implemented in FEM software to capture these effects.

Incremental–iterative method – A solution strategy for non-linear dynamic analysis in which the time step is divided into increments, and for each increment a set of equilibrium equations is solved iteratively until convergence criteria (force and displacement residuals) are satisfied. The method ensures that the stiffness matrix is updated to reflect the current state of the structure.

Convergence – The condition that the iterative solution approaches a stable solution within a prescribed tolerance. Poor convergence may indicate excessive time step size, inadequate damping, or modelling errors. Strategies to improve convergence include reducing the time step, adjusting damping parameters, or employing line search techniques.

Numerical stability – The property of a time integration scheme that prevents the growth of spurious oscillations or divergence of the solution. Stability is governed by the algorithm's characteristics (explicit vs implicit) and the chosen time step. Implicit schemes (e.g., Newmark average-acceleration) are generally unconditionally stable for linear problems, whereas explicit schemes require careful selection of Δt.

Courant condition – A stability criterion for explicit integration methods that relates the time step to the smallest element size and the wave speed. It can be expressed as $\Delta t \le L_{min} / c$, where L_{min} is the smallest element dimension and c is the wave velocity in the material. Violating the Courant condition leads to numerical instability.

Eigenvalue problem – The mathematical formulation used to determine natural frequencies and mode shapes. In matrix form, the problem is expressed as $(K - \omega^2 M)\varphi = 0$, where K is the stiffness matrix, M the mass matrix, ω^2 the eigenvalue (square of natural frequency), and φ the eigenvector (mode shape). Solving the eigenvalue problem yields the set of frequencies and corresponding mode shapes.

Eigenvector – The vector that defines the displacement pattern of a mode. In structural dynamics, eigenvectors are normalised to unit mass, unit displacement, or maximum component equal to 1, depending on the convention. The eigenvector components indicate the relative motion of each degree of freedom in that mode.

Orthogonality – A property of mode shapes that states the mass-weighted and stiffness-weighted inner products of different modes are zero: $\varphi_i^T M \varphi_j = 0$ and $\varphi_i^T K \varphi_j = 0$ for $i \neq j$. Orthogonality enables the decoupling of the equations of motion into independent SDOF equations during modal analysis.

Modal assurance criterion (MAC) – A quantitative measure of the similarity between two mode shapes, defined as $MAC = |\varphi_i^T \varphi_j|^2 / ((\varphi_i^T \varphi_i)(\varphi_j^T \varphi_j))$. MAC values range from 0 (completely different) to 1 (identical). The criterion is used to validate experimental modal data against analytical predictions.

Participation mass – The portion of the total mass that contributes to a particular mode, obtained by projecting the total mass onto the mode shape. Participation mass is essential for determining the effective modal mass and for calculating the contribution of each mode to the overall response.

Dynamic magnification factor – See dynamic amplification factor. The term underscores the idea that the dynamic response can be “magnified” relative to the static response due to inertia and resonance effects.

Input motion – The prescribed ground acceleration, velocity, or displacement time history used as the excitation in a dynamic analysis. Input motions may be recorded earthquake data, synthetic motions generated from a target spectrum, or filtered white-noise signals for wind analysis.

Response acceleration – The acceleration of a point in the structure (e.g., floor, roof) resulting from the input motion. Response acceleration is a key quantity for assessing occupant comfort, equipment performance, and for checking against code-specified limits.

Response velocity – The velocity of a structural point derived from the integration of response acceleration. Velocity is often used in fatigue assessment of mechanical components attached to the structure.

Response displacement – The relative displacement of a point with respect to a reference (usually the ground). Displacement is directly related to story drift and is a primary indicator of structural damage during earthquakes.

Amplification factor – A term used interchangeably with dynamic amplification factor. It may also refer to the ratio of spectral acceleration to the peak ground acceleration (PGA) for a given period.

Design base shear – The seismic force computed according to the design spectrum and applied to the structure as a static equivalent. It serves as the starting point for the distribution of lateral forces across the height of the building.

Force distribution – The method by which the base shear is allocated to the various floors. Common distribution rules include the "mass-height" proportional method ($V_i = V \cdot (m_i \cdot h_i) / \Sigma(m \cdot h)$), where V_i is the shear at level i, m_i the floor mass, and h_i the height above the base.

Seismic demand – The amount of response (e.g., base shear, story drift, inter-story forces) that a structure is expected to experience under the prescribed seismic input. Demand is compared with the capacity of structural components to assess safety.

Seismic capacity – The ability of a structural element or system to resist seismic demand without exceeding allowable limits. Capacity is expressed in terms of strength (e.g., moment capacity), ductility, and energy dissipation.

Performance-based design (PBD) – An approach that defines explicit performance objectives (e.g., immediate occupancy, life safety, collapse prevention) and designs the structure to achieve those objectives under different levels of seismic intensity. PBD relies on detailed nonlinear dynamic analyses and probabilistic assessments.

Limit-state design – The traditional approach that ensures the structure does not exceed predefined limit states (serviceability, ultimate). The seismic limit state is often the "collapse" limit state, which is evaluated using a combination of linear and nonlinear analyses.

Reliability analysis – A probabilistic method that quantifies the likelihood of failure based on uncertainties in loads, material properties, and modelling assumptions. In structural dynamics, reliability analysis can be combined with random vibration theory to assess the probability that seismic demand exceeds capacity.

Monte-Carlo simulation – A statistical technique that generates a large number of random samples of input variables (e.g., ground-motion parameters) and evaluates the structural response for each sample. The results provide probability distributions of response quantities, enabling the estimation of failure probabilities.

Statistical scaling – The process of adjusting recorded ground-motion amplitudes to match a target design spectrum. Scaling may be performed uniformly (same factor for all components) or by applying site-specific amplification factors. Care must be taken to preserve the frequency content and duration of the original record.

Duration – The length of time over which significant energy is present in a ground-motion record. Longer duration generally leads to higher cumulative damage, especially for structures with low damping. Duration is quantified by parameters such as the 5-%–95 % significant duration (D5-95).

Peak ground acceleration (PGA) – The maximum absolute acceleration value recorded during an earthquake. PGA is a key parameter in the definition of seismic zones and influences the shape of the design spectrum.

Spectral acceleration (Sa) – The maximum absolute acceleration response of an SDOF system with a given period and damping, obtained from the response spectrum. Sa is used to compute equivalent static forces for each mode in modal analysis.

Spectral displacement (Sd) – The maximum absolute displacement response of an SDOF system, also derived from the response spectrum. Sd is useful for checking displacement-based design criteria, such as story drift limits.

Spectral velocity (Sv) – The maximum absolute velocity response of an SDOF system. Sv is less commonly used in building codes but can be important for equipment vibration and fatigue assessment.

Elastic response spectrum – The spectrum that assumes the structure remains elastic throughout the excitation. It provides the upper bound of response for a given period and damping. In practice, the elastic spectrum is modified by a reduction factor (R) to account for inelastic behaviour.

Reduction factor (R) – Also called the response modification factor, it quantifies the expected reduction in elastic demand due to inelastic energy dissipation. For reinforced-concrete moment-resisting frames, typical R values range from 3 to 5, while for steel frames they may be 5 to 8. The factor is applied to the elastic spectral acceleration to obtain the design demand.

Overstrength factor (Ω) – The ratio of the actual strength of a structural component to the design strength prescribed by the code. Overstrength arises from material variability, detailing, and construction quality. It is used together with the reduction factor to compute the total design capacity: $C = \Omega \cdot R \cdot S_a$.

Design lateral force – The seismic force applied to a particular floor after multiplying the elastic spectral acceleration by the reduction factor, overstrength factor, and participation factor. The force is then distributed according to the chosen force distribution rule.

Seismic load path – The sequence of structural elements that transmit seismic forces from the roof to the foundation. A continuous, well-defined load path is essential for ensuring that forces are efficiently transferred and that the structure behaves as a cohesive system during an earthquake.

Redundancy – The presence of alternative load-transfer mechanisms that allow the structure to maintain its integrity even if some elements yield or fail. Redundant structures exhibit improved seismic performance because the failure of a single component does not lead to a global collapse.

Soft-story – A story in a building that has significantly less lateral stiffness than the stories above it, often due to large openings (e.g., parking levels). Soft-stories are prone to large drifts and hinge formation during earthquakes, and codes impose special restrictions or require additional reinforcement.

Irregularity – Any deviation from a regular, symmetrical plan or elevation that can adversely affect seismic performance. Irregularities include plan asymmetry, vertical stiffness variation, torsional irregularity, and concentration of mass at specific levels. Irregular buildings require more sophisticated dynamic analysis to capture their behaviour.

Vertical mode – A vibration mode in which the primary deformation is in the vertical direction. Although vertical accelerations are usually smaller than horizontal ones in earthquakes, vertical modes can become important for tall, slender structures or for structures subjected to strong vertical ground motions.

Coupled translational-torsional mode – A mode that combines horizontal sway and torsional rotation. The coupling arises when the centre of mass does not coincide with the centre of stiffness. Accurate modelling of coupled modes demands the inclusion of both translational and rotational degrees of freedom.

Mass proportional damping – Damping that is proportional to the mass matrix (αM term in Rayleigh damping). It provides uniform damping across all modes, but may over-damp higher modes and under-damp lower modes.

Stiffness proportional damping – Damping that is proportional to the stiffness matrix (βK term). It tends to increase damping for higher-frequency modes, which can be advantageous when those modes are less critical.

Frequency-dependent damping – A more realistic representation where damping varies with frequency, often expressed through a damping curve derived from experimental data. Frequency-dependent damping can be implemented using modal damping ratios that are interpolated from a prescribed damping curve.

Viscous damper – A mechanical device that dissipates energy by fluid shear, providing a force proportional to velocity. Viscous dampers are commonly added to structures to increase damping and reduce seismic response. In analysis, they are modelled as dashpots attached to the structural model.

Hysteretic damper – A device that dissipates energy through material yielding (e.g., steel yielding plates, yielding metal braces). The force-displacement relationship follows a hysteresis loop, and the damper provides a constant resisting force over a range of deformation. Hysteretic dampers are effective for high-energy dissipation.

Base isolation – A seismic protection strategy that inserts flexible, low-stiffness bearings (e.g., elastomeric, sliding) between the superstructure and foundation. Isolation reduces the transmitted acceleration to the building, lengthens the natural period, and increases the damping. The design of isolated systems requires special dynamic analysis to capture the altered frequency content.

Isolator stiffness – The horizontal stiffness of a base-isolator, which determines the isolated system's natural period ($T_{iso} = 2\pi\sqrt{(M_{total} / K_{iso})}$). Reducing K_{iso} shifts the period away from the dominant frequencies of the input motion, thereby reducing seismic demand.

Isolator damping – The inherent damping of the isolator, often provided by the material's viscoelastic properties or by supplemental dampers. Isolator damping contributes to the overall energy dissipation of the isolated system.

Effective period – The period of the isolated system after accounting for the contribution of the superstructure's stiffness. The effective period is used in the design spectrum to determine the spectral acceleration that the isolated building will experience.

Energy dissipation – The process by which mechanical energy is transformed into heat or other non-recoverable forms. In seismic engineering, energy dissipation occurs through material hysteresis, damper action, and radiation of waves into the surrounding soil.

Capacity spectrum method (CSM) – A performance-based seismic analysis technique that plots the demand spectrum (elastic response spectrum reduced by the reduction factor) together with the capacity curve (relationship between base shear and roof displacement) of the structure. The intersection point provides the target displacement, and the corresponding demand is checked against capacity.

Capacity curve – A plot of the structure's base shear versus roof displacement, obtained from a series of static pushover analyses or from a non-linear dynamic analysis. The curve captures the progressive reduction of stiffness as the structure yields.

Pushover analysis – A static, non-linear analysis in which a gradually increasing lateral load pattern is applied to the structure until a target displacement is reached. The pushover provides insight into the sequence of plastic hinge formation, the overall stiffness degradation, and the capacity curve.

Target displacement – The displacement at which the structure is expected to reach a certain performance level (e.g., life-safety). In the capacity spectrum method, the target displacement is obtained from the intersection of the demand and capacity curves.

Seismic performance level – A classification of expected behaviour under a given seismic intensity, ranging from “operational” (no damage) to “collapse”. The performance level determines the required ductility, overstrength, and detailing requirements.

Design acceleration – The design ground-motion parameter (often denoted a_ds) derived from the design spectrum for a specific period. It is used to compute design forces and to check that the structure satisfies