Chapter 32: Response of Structures to Earthquake

Introduction

Understanding how structures respond to earthquake-induced ground motions is central to the field of Earthquake Engineering. Unlike static or wind loads, seismic loads are dynamic and involve significant horizontal forces, making the response of structures complex and highly dependent on mass, stiffness, damping, and the nature of the ground motion. The aim of this chapter is to explore the analytical modeling and behavior of structures under seismic excitation. We will cover both idealized single-degree-of-freedom (SDOF) systems and more realistic multi-degree-of-freedom (MDOF) systems, time-domain and frequency-domain responses, and the principles of seismic design and response control.

32.1 Seismic Excitation and Ground Motion Characteristics

- **32.1.1 Nature of Earthquake Ground Motion**
  - Ground motions caused by earthquakes consist of waves radiating from the focus.
  - Motions are recorded as accelerograms and are random in nature.
  - Components: horizontal (usually two orthogonal) and vertical.
- **32.1.2 Important Parameters of Ground Motion**
  - **Peak Ground Acceleration (PGA)**
  - **Peak Ground Velocity (PGV)**
  - **Peak Ground Displacement (PGD)**
  - **Duration and frequency content**
  - **Response Spectra**: crucial for understanding structural response.
- **32.1.3 Elastic and Inelastic Spectra**
  - Spectral Acceleration (Sa), Spectral Velocity (Sv), Spectral Displacement (Sd).

- Response spectrum curves derived from SDOF systems under specified damping ratios.

32.2 Dynamic Response of Structures

- **32.2.1 Equation of Motion**
  - For a Single Degree of Freedom (SDOF) system:

    $$m\ddot{x}(t)+c\dot{x}(t)+kx(t)=-m\ddot{u}_g(t)$$

    where $\ddot{u}_g(t)$ is ground acceleration.
- **32.2.2 Types of Structural Response**
  - **Elastic Response**
  - **Inelastic Response**
  - **Resonance Conditions**
- **32.2.3 Damping in Structures**
  - Types: Viscous damping, Hysteretic damping.
  - Effect of damping ratio on peak response.
- **32.2.4 Numerical Methods for Solving Equation of Motion**
  - **Time stepping methods**: Newmark-beta, Wilson-θ, Runge-Kutta.
  - Displacement, velocity, and acceleration computed at each time step.

32.3 Response of SDOF Systems to Earthquake Motion

- **32.3.1 Free Vibration Response**
  - Undamped and damped cases.
  - Natural frequency (ω_n) and damping ratio (ζ).
- **32.3.2 Forced Vibration Under Ground Motion**
  - Use of Duhamel's integral.
  - Importance of initial conditions.
- **32.3.3 Construction of Response Spectra**
  - Based on responses of SDOF systems for various natural periods.
  - Design spectrum in IS 1893.

- **32.3.4 Elastic vs Inelastic Response Spectrum**
  - Reduction factor (R) used in design spectrum.
  - Capacity spectrum method.

32.4 Response of Multi-Degree-of-Freedom (MDOF) Systems

- **32.4.1 Equation of Motion for MDOF**

$$[M]\{\ddot{x}(t)\}+[C]\{\dot{x}(t)\}+[K]\{x(t)\}=-[M]\{\ddot{u}_g(t)\}$$

- **32.4.2 Modal Analysis**
  - Transformation of coupled equations into uncoupled equations using mode shapes.
  - Mode superposition method.
- **32.4.3 Mode Participation Factor and Modal Mass**
  - Quantifying how much each mode contributes to total response.
- **32.4.4 Orthogonality of Modes**
  - Mathematical simplification due to orthogonality of mode shapes.
- **32.4.5 Response Spectrum Method for MDOF**
  - Modal responses computed separately.
  - Combination rules: SRSS (Square Root of the Sum of the Squares), CQC (Complete Quadratic Combination).

32.5 Base Shear and Design Forces

- **32.5.1 Concept of Base Shear**
  - Total horizontal force transmitted to the base due to earthquake motion.
- **32.5.2 Seismic Coefficient Method (IS 1893)**
  - Base shear:

$$V_b=A_h\cdot W$$

where $A_h = \frac{Z I S_a}{2 R g}$

- **32.5.3 Vertical Distribution of Seismic Forces**
  - Based on height and mass distribution.
  - Inverted triangular or parabolic shape.
- **32.5.4 Importance of Seismic Weight and Importance Factor**

32.6 Nonlinear Structural Response

- **32.6.1 Causes of Nonlinearity**
  - Material nonlinearity (e.g., yielding of steel).
  - Geometric nonlinearity (e.g., large displacements).
- **32.6.2 Idealized Hysteresis Models**
  - Bilinear, Takeda, Bouc-Wen models.
- **32.6.3 Time-History Analysis with Nonlinear Models**
  - Requires step-by-step integration using numerical methods.

32.7 Structural Control and Response Modification

- **32.7.1 Passive Control Systems**
  - Base Isolation (e.g., lead-rubber bearings)
  - Tuned Mass Dampers (TMD)
- **32.7.2 Active and Semi-Active Control Systems**
  - Sensors and actuators involved.
  - Real-time feedback control.
- **32.7.3 Ductility and Energy Dissipation**
  - Ductility demand and capacity.
  - Plastic hinges and energy absorption.
- **32.7.4 Response Modification Factors**
  - Importance in seismic design codes (R-factors).

32.8 Code Provisions and Design Guidelines (IS 1893 and IS 13920)

- **32.8.1 Seismic Zoning and Zone Factors (Z)**
  - Seismic zones in India: II, III, IV, V.
- **32.8.2 Importance Factor (I) and Response Reduction Factor (R)**
  - Depend on usage and structural system.
- **32.8.3 Design Spectrum Provided in IS 1893**
  - Spectral acceleration vs time period for 5% damping.
- **32.8.4 Capacity Design Principles in IS 13920**
  - Strong column–weak beam philosophy.
  - Detailing for ductility and confinement.

32.9 Practical Considerations in Seismic Design

- **32.9.1 Influence of Soil-Structure Interaction (SSI)**
  - Alteration of natural frequency due to flexibility of soil.
- **32.9.2 Torsional Effects in Irregular Structures**
  - Asymmetric stiffness and mass distribution.
- **32.9.3 Pounding Between Adjacent Structures**
  - Separation joints and expansion gaps required.
- **32.9.4 Progressive Collapse and Redundancy**
  - Need for alternate load paths in structural design.
- **32.9.5 Performance-Based Design Approach**
  - Targeting various performance levels: Operational, Immediate Occupancy, Life Safety, Collapse Prevention.

32.10 Time-History Analysis and its Applications

- **32.10.1 Definition and Purpose**
  - Time-history analysis evaluates the dynamic response of a structure by applying actual or synthetic ground motion records.

- **32.10.2 Types of Time-History Records**
    - Recorded earthquakes (e.g., El Centro, Kobe, Bhuj).
    - Artificial or spectrum-matched records.
- **32.10.3 Linear Time-History Analysis**
    - Assumes elastic behavior.
    - Useful for serviceability checks.
- **32.10.4 Nonlinear Time-History Analysis**
    - Captures yielding, plastic hinge formation, and energy dissipation.
    - Requires complex iterative numerical algorithms.
- **32.10.5 Comparison with Response Spectrum Method**
    - Time-history provides complete response history.
    - Response spectrum gives peak values only.

32.11 Pushover Analysis and Capacity Spectrum Method

- **32.11.1 Concept of Pushover Analysis**
    - Static nonlinear analysis technique.
    - Applies lateral loads incrementally until target displacement or collapse.
- **32.11.2 Capacity Curve**
    - Base shear vs top displacement.
    - Reflects structural stiffness degradation.
- **32.11.3 Performance Point and Capacity Spectrum**
    - Intersection of demand and capacity curves.
    - Used in performance-based design.
- **32.11.4 Limitations and Assumptions**
    - Valid mainly for low- to mid-rise buildings.
    - Assumes invariant mode shapes.

32.12 Earthquake Response of Special Structures

- **32.12.1 Bridges**

- Expansion joints, bearings, and abutments.
- Seismic isolation often employed.

- **32.12.2 Elevated Water Tanks**
  - Staging flexibility, sloshing effects.
  - Modal mass participation often concentrated in first mode.
- **32.12.3 Towers and Chimneys**
  - Higher mode effects significant.
  - Large overturning moments.
- **32.12.4 Dams and Embankments**
  - Hydrodynamic effects of water.
  - Pseudo-static analysis methods used.

32.13 Soil-Structure Interaction (SSI)

- **32.13.1 Fundamentals of SSI**
  - Mutual interaction between soil and structure alters dynamic behavior.
- **32.13.2 Fixed Base vs Flexible Base Analysis**
  - Fixed base ignores foundation flexibility.
  - Flexible base includes foundation stiffness and damping.
- **32.13.3 Foundation Types and their Seismic Behavior**
  - Isolated footings, mat foundations, pile foundations.
- **32.13.4 Modelling Soil Flexibility**
  - Winkler model (springs), finite element method.
- **32.13.5 Effects on Response Parameters**
  - Natural period elongation, increase in damping.

32.14 Retrofitting and Strengthening of Structures

- **32.14.1 Need for Retrofitting**
  - For pre-code buildings or after moderate seismic damage.
- **32.14.2 Retrofitting Strategies**

- **Local methods**: Jacketing, steel bracing, shear wall insertion.
- **Global methods**: Base isolation, energy dissipation devices.

- **32.14.3 Evaluation of Existing Structures**
  - Visual inspection, non-destructive testing (NDT), and performance evaluation.
- **32.14.4 IS 13935 Guidelines for Seismic Strengthening**
  - Provides techniques and prioritization.

32.15 Recent Developments and Advanced Topics

- **32.15.1 Performance-Based Seismic Design (PBSD)**
  - Design based on multiple performance objectives.
  - Use of nonlinear static and dynamic analyses.
- **32.15.2 Seismic Resilience and Lifecycle Cost**
  - Emphasizes rapid recovery and cost-effectiveness.
- **32.15.3 Smart Structures and Structural Health Monitoring (SHM)**
  - Use of sensors, data acquisition, and AI for real-time monitoring.
- **32.15.4 Seismic Isolation and Energy Dissipation Systems**
  - Devices: Lead rubber bearings, friction pendulum systems, viscous dampers.
- **32.15.5 Tall Building Seismic Design**
  - Performance under high-frequency ground motions.
  - Consideration of higher modes and lateral-torsional coupling.
