ROSE School

The ROSE School Master's in Earthquake Engineering

Nonlinear Response Analysis

Lecturers: **Rui Pinho, Giammaria Gabbianelli**
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Semester: Second
Credits: 6 ECTS (CFU)

Course Description

This course provides an in-depth exploration of advanced nonlinear analysis and computational modelling techniques for structures subjected to strong earthquake ground motion or other extreme loading scenarios. Students will learn to develop and analyse complex finite element and discrete element models, addressing geometric nonlinearity, material inelasticity, and failure mechanisms. The course emphasizes both theoretical understanding and practical implementation using state-of-the-art software tools.
The course is divided into three main parts, covering nonlinear finite element (FE) modelling of RC and steel structures, and discrete/applied element (DE/AEM) modelling for structural collapse analysis.

Part A – Finite Element Nonlinear Modelling of RC Frame Structures

This section focuses on the nonlinear finite element modelling of reinforced concrete (RC) structures subjected to cyclic and seismic loading. Topics include:

- Geometric nonlinearity and material inelasticity in RC frames.
- Concentrated plasticity vs. distributed inelasticity modelling.
- Displacement-based vs. force-based beam–column formulations.
- Fibre sectional analysis and constitutive modelling of concrete and reinforcement.
- Nonlinear solution procedures and convergence criteria.
- Nonlinear Dynamic Analysis (NDA): numerical integration algorithms, equivalent viscous damping, and numerical damping.
- Selection and scaling of ground motion records for nonlinear dynamic analysis.
- Modelling of seismic isolation and energy-dissipation devices.
- Incremental Dynamic Analysis (IDA) and Nonlinear Static Analysis (Pushover).
- Incremental loading strategies and adaptive pushover procedures.
- Nonlinear Static Procedures (NSP): N2 Method, Capacity Spectrum Method, and Adaptive Capacity Spectrum Method.
- Nonlinear modelling of structural and non-structural components, including:
    - Walls and wall cores, stairs, infill panels, beam–column joints.
    - Rebar slippage, shear deformation, rigid and flexible diaphragms.
    - Constraints and boundary conditions using geometrical transformations, Lagrange multipliers, and penalty functions.

Part B – Finite Element Nonlinear Modelling of Steel Frame Structures

This section examines the nonlinear response of steel structures under cyclic and seismic demands, emphasizing connection behaviour, instability phenomena, and member interaction effects.
Topics include:

- Hysteretic behaviour of steel members and connections.
- Modelling of welded and bolted joints under cyclic and monotonic loading.
- Modelling of concentric and eccentric braces, including shear-dissipative links.
- Nonlinear modelling of braces and connections using advanced FE formulations.
- Local instability and buckling behaviour of thin-walled sections.
- Warping effects in slender cold-formed steel open sections.
- Formulation and application of the 7-DOF beam element for steel rack analysis.
- Nonlinear response and failure mechanisms of steel racks.
- Global and local buckling analysis of frame and rack systems.

Part C – Discrete Element Nonlinear Modelling of Structures under Extreme Loading

This section introduces discrete element and applied element modelling (AEM) approaches for simulation of structural collapse and progressive failure under extreme conditions.

Topics include:

- Fundamentals of discrete element modelling and its distinction from continuum-based FE methods.
- The Applied Element Modelling (AEM) method:
  - Historical development and theoretical formulation.
  - Element interaction, contact algorithms, and crack propagation mechanics.
- Application of AEM for collapse simulation and progressive failure analysis.
- Explicit modelling of wall cores, masonry structures, bridges, and building collapses under extreme loading.
- Comparison of AEM and traditional FE results for failure prediction and damage assessment.

Learning Outcomes

Upon successful completion of this course, students will be able to:

- Understand and implement advanced nonlinear analysis techniques for RC and Steel structures.
- Model complex material and geometric nonlinearities using FE and DE/AEM formulations.
- Evaluate structural performance under cyclic, seismic, and extreme loading conditions.
- Apply numerical integration, damping, and convergence control strategies effectively.
- Conduct comparative analyses between nonlinear static, dynamic, and collapse simulation approaches.

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