University of Naples Federico II
Department of Structures for Engineering and Architecture
2-years Master in Structural and Geotechnical Engineering

FEM in Nonlinear Structural Analysis Course
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Nonlinear Dynamic Analysis of Structures

Topics for Master Thesis

Nonlinear analysis is becoming increasingly important in earthquake-resistant design, particularly with the development of the performance-based earthquake engineering, which requires more detailed information about the displacements, drifts and inelastic deformation of a structure than traditional design procedures. In particular, the role of nonlinear dynamic analysis for design is being expanded in order to quantify building performance more completely.

In professional services firms, such as SOM or ARUP, structural engineers are more likely to employ nonlinear dynamic analyses for seismic performance assessment of new and existing buildings.

In contrast to linear elastic analysis and design methods that are well established, nonlinear structural analysis techniques and their application to design are still evolving and may require engineers to develop new skills.

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Structural Analysis Procedures

A structural analysis procedure requires:

- a model of the structure;
- a representation of the earthquake ground motion or the effects of the ground motion;
- a method of analysis for assembling and solving the governing equations.

Structural Analysis Procedures for Earthquake-Resistant Design are:

- Plastic Analysis Procedure
- Linear Static Procedure
- Linear Dynamic Procedure
- **Nonlinear Static Procedure**
- **Nonlinear Dynamic Procedure**

Nonlinear Static Procedure

In the nonlinear static procedure, the structural model is subjected to an incremental lateral load whose distribution represents the inertia forces expected during ground shaking. The lateral load is applied until the imposed displacements reach the so-called *target displacement*, which represents the displacement demand that the earthquake ground motions would impose on the structure. Once loaded to the target displacement, the demand parameters for the structural components are compared with the respective acceptance criteria for the desired performance state. System level demand parameters, such as story drifts and base shears, may also be checked. The nonlinear static procedure is applicable to low-rise regular buildings, where the response is dominated by the fundamental sway mode of vibration. It is less suitable for taller, slender, or irregular buildings, where multiple vibration modes affect the behavior.

Nonlinear Dynamic Procedure

In contrast to the nonlinear static procedure, the nonlinear dynamic procedure, when properly implemented, provides a more accurate calculation of the structural response to strong ground shaking. Since the nonlinear dynamic analysis model incorporates inelastic member behavior under cyclic earthquake ground motions, the nonlinear dynamic procedure explicitly simulates hysteretic energy dissipation in the nonlinear range. Only the damping in the linear range and other non-modeled energy dissipation need to be added as viscous damping. The dynamic response is calculated for input earthquake ground motions, resulting in response history data on the pertinent demand parameters. Due to the inherent variability in earthquake ground motions, dynamic analyses for multiple ground motions are necessary to calculate statistically robust values of the demand parameters for a given ground motion intensity or earthquake scenario. As nonlinear dynamic analysis involves fewer assumptions than the nonlinear static procedure, it is subject to fewer limitations than nonlinear static procedure. However, the accuracy of the results depends on the details of the analysis model and how faithfully it captures the significant behavioral effects. Acceptance criteria typically limit the maximum structural component deformations to values where degradation is controlled and the nonlinear dynamic analysis models are reliable.

Structural Analysis Procedures

Nonlinear Static Versus Nonlinear Dynamic Analysis

Nonlinear dynamic analysis methods generally provide more realistic models of structural response to strong ground shaking and, thereby, provide more reliable assessment of earthquake performance than nonlinear static analysis. Nonlinear static analysis is limited in its ability to capture transient dynamic behavior with cyclic loading and degradation. Nevertheless, the nonlinear static procedure provides a convenient and fairly reliable method for structures whose dynamic response is governed by first-mode sway motions. One way to check this is by comparing the deformed geometry from a pushover analysis to the elastic first-mode vibration shape. In general, the nonlinear static procedure works well for low-rise buildings (less than about five stories) with symmetrical regular configurations. However, even when the nonlinear static procedure is not appropriate for a complete performance evaluation, nonlinear static analysis can be an effective design tool to investigate aspects of the analysis model and the nonlinear response that are difficult to do by nonlinear dynamic analysis. For example, nonlinear static analysis can be useful to:

- check and debug the nonlinear analysis model;
- augment understanding of the yielding mechanisms and deformation demands;
- investigate alternative design parameters and how variations in the component properties may affect response.

Termination of the Response Spectrum Method | Ed Wilson – July 13, 2015

The Response Spectrum Method must be terminated before engineers will use Performance Based Design.
After they perform time history analysis, engineers will realize nonlinear analysis is easy using the Fast Nonlinear Analysis method. This will allow many structures to be reparable after a large earthquake.

References

Deierlein GG, Reinhorn AM and Willford MR 2010, Nonlinear structural analysis for seismic design, NEHRP Seismic Design Technical Brief No. 4, produced by the NEHRP Consultants Joint Venture, a partnership of the Applied Technology Council and the Consortium of Universities for Research in Earthquake Engineering, for the National Institute of Standards and Technology, Gaithersburg, MD, NIST GCR 10-917-5.

Filippou FC and Fenves GL 2004, Methods of Analysis for Earthquake-Resistant Structures, in: Earthquake Engineering: From Engineering Seismology to Performance-Based Engineering (eds. Bozorgnia Y and Bertero VV), CRC Press, New York, Chapter 6.

The Role and Use of Nonlinear Analysis in Seismic Design

The vast majority of buildings, generally designed for seismic resistance using elastic analysis, experience significant inelastic deformations under large earthquakes. Modern **performance-based design methods** require ways to determine the realistic behavior of structures under such conditions. Enabled by advancements in computing technologies and available test data, nonlinear analyses provide the means for calculating structural response beyond the elastic range, including strength and stiffness deterioration associated with inelastic material behavior and large displacements. Thus, **nonlinear analysis can play an important role in the design of new and existing buildings**.

Typical instances where nonlinear analysis is applied in **structural earthquake engineering practice** are to:

- assess and design seismic retrofit solutions for existing buildings;
- design new buildings that employ structural materials, systems, or other features that do not conform to current building code requirements;
- assess the performance of buildings for specific owner/stakeholder requirements as in the case of the New headquarters of San Francisco Public Utility Commission Building, shown in Figure 1, designed using nonlinear time history analysis to meet stringent immediate occupancy performance criteria.

Figure 1. New headquarters of San Francisco Public Utility Commission Building

In contrast to linear elastic analysis and design methods that are well established, nonlinear inelastic analysis techniques and their application to design are still evolving and may **require engineers to develop new skills**.

The Role and Use of Nonlinear Analysis in Seismic Design | Skidmore, Owings & Merrill LLP (SOM)

SOM is one of the world's leading architecture, urban design, engineering, and interior architecture firms.

Engineers at SOM use CSI software, such as SAP2000, ETABS, SAFE, PERFORM 3D, and have close interactive relationships with CSI developers.

Figure 2a shows the new 111 Main office tower in Salt Lake City designed by SOM. The SOM structural design team developed a **two-stage performance-based seismic design method** which included a Stage 1 **Linear Dynamic Modal Response Spectrum Analysis** (MRSA) and a Stage 2 tri-directional **Nonlinear Response History Analysis** (NLRHA) to demonstrate that the structure design, determined in Stage 1, satisfied the performance-based inelastic design criteria of the PEER TBI guidelines. A 3d ETABS model was developed for the MRSA whereas a 3d PERFORM 3D model, shown in Figure 2b, was developed for the NLRHA.

a)

b)

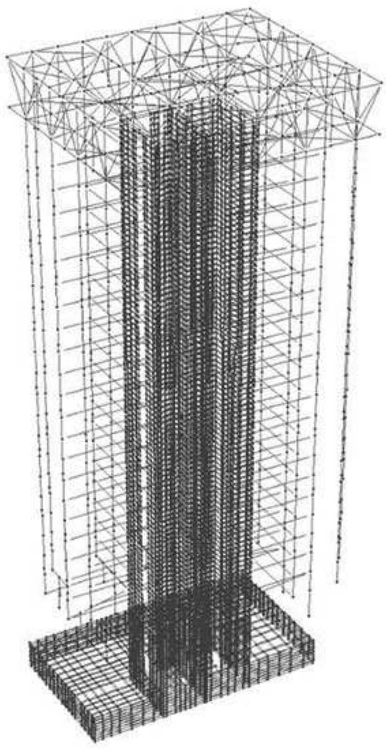


Figure 2. (a) 111 Main Office Tower in Salt Lake City and (b) its Structural Model.

SOM

The Role and Use of Nonlinear Analysis in Seismic Design | ARUP

ARUP is a professional services firm which provides engineering, design, planning, project management and consulting services for all aspects of the built environment.

In addition to conventional structural analysis software such as ETABS, SAP2000 and PERFORM 3D, ARUP utilizes the nonlinear dynamic analysis code **LS-DYNA** extensively for **performance-based seismic analysis**. ARUP has worked in conjunction with the authors of LS-DYNA to develop a large number of new features specifically for seismic analysis over the past 20 years.

LS-DYNA has advantage of an extremely fast explicit solver running in parallel processing, which makes practical the analysis of much larger and more detailed analysis models than any other program available.
LS-DYNA is used for all major performance-based analysis tasks including **nonlinear analysis of structures** (Figure 3), foundations, soils, fluids, **dampers** and **isolators** and the dynamic interactions between all these components.

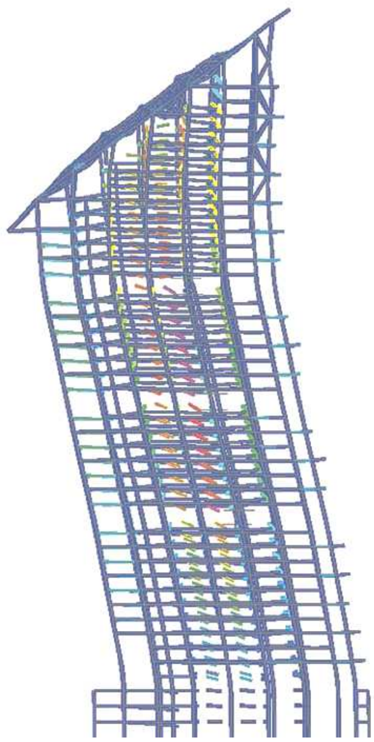


Figure 3. Nonlinear Response History Analysis of a 45 Story Building Using LS-DYNA

PERFORMANCE BASED SEISMIC ENGINEERING

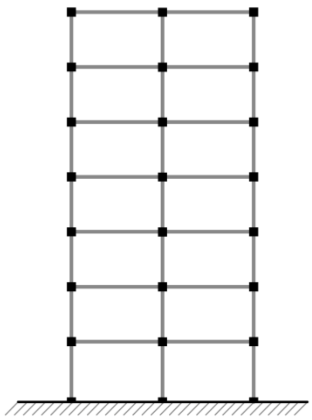
ARUP

Topics for Master Thesis

Nonlinear Time History Analysis (NLTHA) of Structures

The following topics are divided into two groups, namely, **Numerical Methods** and **Material Models**.
Topics belonging to the first group have the main aim of studying the accuracy and the computational efficiency of numerical methods used to solve the nonlinear dynamic equilibrium equations of structures subjected to earthquake excitation.
Topics belonging to the second group have the main aim of developing a path-dependent model able to simulate the material nonlinear behavior.

Required Computer Programs: Matlab, OpenSees, Sap2000NL, LS-DYNA.



Numerical Methods

- **Study of accuracy and computational efficiency of iterative procedures adopted in the NLTHA of structures**
  - comparisons between numerical results obtained using the Newton-Raphson and Pseudo-Force Method
  - use of Bathe implicit time integration method
- **NLTHAs of structures adopting recently developed time integration methods**
  - study of accuracy, stability and computational efficiency of Bathe explicit time integration method
  - study of accuracy and computational efficiency of Bathe implicit time integration method

Material Models

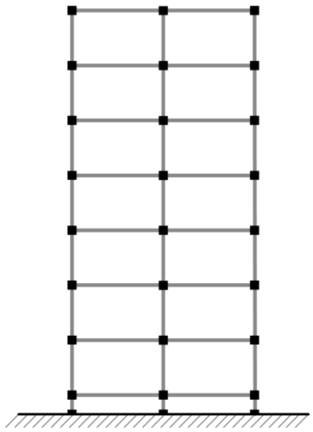
- **Development of nonlinear hysteretic material models for structures subjected to earthquake excitation**
  - Nonlinear Exponential Model (NEM)
  - Parallel Model (PM)
  - comparisons with Bilinear Model and Bouc-Wen Model (study of the accuracy and computational efficiency)
- **Development of advanced hysteretic models able to take into account the stiffness and strength degradation**
  - Advanced Nonlinear Exponential Model (ANEM)
  - Advanced Parallel Model (APM)
  - comparisons with the Bouc-Wen Model (study of the accuracy and computational efficiency)
- **Development of a procedure to systematically identify the NEM parameters from experimental tests results**

Topics for Master Thesis

Nonlinear Time History Analysis (NLTHA) of Base-Isolated Structures (BISs)

The following topics are divided into two groups, namely, **Numerical Methods** and **Mathematical Models**.
Topics belonging to the first group have the main aim of studying the accuracy and the computational efficiency of numerical methods used to solve the nonlinear dynamic equilibrium equations of seismically base-isolated structures.
Topics belonging to the second group have the main aim of developing models able to simulate the nonlinear behavior of seismic isolators.

Required Computer Programs: Matlab, Sap2000NL, 3D-BASIS, LS-DYNA.



Numerical Methods

- **Mixed Explicit-Implicit time integration Methods (MEIMs) for NLTHA of BISs**
  - use of Bathe explicit and implicit time integration methods
  - comparisons with numerical results obtained adopting the Pseudo-Force Method
  - study of accuracy, stability and computational efficiency
- **Comparison between the proposed MEIMs and the Fast Nonlinear Analysis (FNA) Method (Wilson)**
  - study of accuracy, stability and computational efficiency

Mathematical Models

- **Influence of isolator models on the computational effort of NLTHAs**
  - comparison among numerical NLTHAs results obtained adopting the bilinear model, the BWM, and the NEM
  - comparison among numerical NLTHAs results obtained adopting the bilinear model, the BWM, and the PM
- **Development of a 2d model for seismic isolators having softening behavior**
  - 2d Parallel Model
  - comparisons with the 2d Bouc-Wen Model (study of the accuracy and computational efficiency)
- **Development of a procedure to systematically identify the NEM (PM) parameters from experimental tests results**