Seminar on

Finite Element Analysis and Design of RC Buildings

25-26th May 2005
Multi Media Theater, UNIMAS Main Campus
Kota Samarahan, Sarawak, Malaysia

Organized By
Asian Center for Engineering Computations and Software
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The Institution of Engineers, Malaysia
Sarawak Branch
Finite Element Analysis and Design of RC Buildings

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Outline

- Overview of Computer Aided Analysis and Design of Buildings
- Structural Systems: Types, Selection and Behavior
- Modeling and Analysis of Buildings in 3D
- Design of Gravity Load Resisting Systems
- Design of Lateral Load Resisting Systems
- Special Modeling Techniques for Shear Walls, Transfer Girders, Deep Beams, Foundation Systems and Long Columns
- Analysis, Design and Detailing of Foundations
- Dynamic and Non-linear Analysis for Wind and Earthquake Loads
- Pushover Analysis for Performance Based Design
- Staged Construction Analysis
Building Systems

- Building is an assemblage of various Systems
  - Basic Functional System
  - Structural System
  - HVAC System
  - Plumbing and Drainage System
  - Electrical, Electronic and Communication System
  - Security System
  - Other specialized systems
The Building Structural System - Physical

- Frame and Shear Walls
- Lateral Load Resisting System
- Floor Diaphragm
- Floor Slab System
- Gravity Load Resisting System

The Building Structural System - Conceptual

- The Gravity Load Resisting System (GLRS)
  - The structural system (beams, slab, girders, columns, etc) that act primarily to support the gravity or vertical loads

- The Lateral Load Resisting System (LLRS)
  - The structural system (columns, shear walls, bracing, etc) that primarily acts to resist the lateral loads

- The Floor Diaphragm (FD)
  - The structural system that transfers lateral loads to the lateral load resisting system and provides in-plane floor stiffness
Structural System – Analysis Model

**STRUCTURE**

EXCITATION
- Loads
- Vibrations
- Settlements
- Thermal Changes

RESPONSES
- Displacements
- Strains
- Stress
- Stress Resultants

Structural Model
The Structural System

**STRUCTURE**

**EXCITATION**

**RESPONSES**

- Static
- Dynamic

- Elastic
- Inelastic

- Linear
- Nonlinear

Analysis of Structures

Real Structure is governed by "Partial Differential Equations" of various order.

Direct solution is only possible for:

- Simple geometry
- Simple Boundary
- Simple Loading.
The Need for Modeling

A - Real Structure cannot be Analyzed:
   It can only be “Load Tested” to determine response
B - We can only analyze a “Model” of the Structure
C - We therefore need tools to Model the Structure and to Analyze the Model

Finite Element Method: The Analysis Tool

- **Finite Element Analysis (FEA)**
  - “A discretized solution to a continuum problem using FEM”

- **Finite Element Method (FEM)**
  - “A numerical procedure for solving (partial) differential equations associated with field problems, with an accuracy acceptable to engineers”
Continuum to Discrete Model

3D-CONTINUUM MODEL
(Governed by partial differential equations)

CONTINUOUS MODEL OF STRUCTURE
(Governed by either partial or total differential equations)

DISCRETE MODEL OF STRUCTURE
(Governed by algebraic equations)

From Classical to FEM Solution

Classical

Actual Structure

\[ \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} + p = 0 \]

"Partial Differential Equations"

\[ \int \sigma \, dv = \int \sigma \, dv' + \int \rho \, dv \]

(Principle of Virtual Work)

FEM

Structural Model

\[ K_r = R \]

"Algebraic Equations"

\[ K = \text{Stiffness} \]

\[ r = \text{Response} \]

\[ R = \text{ Loads} \]
**Simplified Structural System**

Loads \( F \) → Deformations \( D \)

\[ F = K D \]

**The Structural System**

**EXCITATION** → **RESPONSES**

- Static
- Dynamic
- Elastic
- Inelastic
- Linear
- Nonlinear
The Equilibrium Equations

1. Linear-Static Elastic OR Inelastic
   \[ Ku = F \]

2. Linear-Dynamic Elastic
   \[ M\ddot{u}(t) + C\dot{u}(t) + Ku(t) = F(t) \]

3. Nonlinear - Static Elastic OR Inelastic
   \[ Ku + F_{NL} = F \]

4. Nonlinear-Dynamic Elastic OR Inelastic
   \[ M\ddot{u}(t) + C\dot{u}(t) + Ku(t) + F(t)_{NL} = F(t) \]

Analysis Type

The type of Analysis to be carried out depends on the Structural System

- The Type of Excitation (Loads)
- The Type Structure (Material and Geometry)
- The Type Response
Some More Solution Types

• Non-linear Analysis
  - P-Delta Analysis
  - Buckling Analysis
  - Static Pushover Analysis
  - Fast Non-Linear Analysis (FNA)
  - Large Displacement Analysis

• Dynamic Analysis
  - Free Vibration and Modal Analysis
  - Response Spectrum Analysis
  - Steady State Dynamic Analysis

Static Vs Dynamic

• Static Excitation
  - When the Excitation (Load) does not vary rapidly with Time
  - When the Load can be assumed to be applied "Slowly"

• Dynamic Excitation
  - When the Excitation varies rapidly with Time
  - When the "Inertial Force" becomes significant

• Most Real Excitation are Dynamic but are considered "Quasi Static"
• Most Dynamic Excitation can be converted to "Equivalent Static Loads"
Elastic Vs Inelastic

- **Elastic Material**
  - Follows the same path during loading and unloading and returns to initial state of deformation, stress, strain etc. after removal of load/excitation

- **Inelastic Material**
  - Does not follow the same path during loading and unloading and may not return to initial state of deformation, stress, strain etc. after removal of load/excitation

- Most materials exhibit both, elastic and inelastic behavior depending upon level of loading.

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Linear Vs Nonlinear

- **Linearity**
  - The response is directly proportional to excitation
  - (Deflection doubles if load is doubled)

- **Non-Linearity**
  - The response is not directly proportional to excitation
  - (Deflection may become 4 times if load is doubled)

- Non-linear response may be produced by:
  - Geometric Effects (Geometric non-linearity)
  - Material Effects (Material non-linearity)
  - Both
Basic Analysis Types

<table>
<thead>
<tr>
<th>Excitation</th>
<th>Structure</th>
<th>Response</th>
<th>Basic Analysis Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static</td>
<td>Elastic</td>
<td>Linear</td>
<td>Linear-Elastic-Static Analysis</td>
</tr>
<tr>
<td>Static</td>
<td>Elastic</td>
<td>Nonlinear</td>
<td>Nonlinear-Elastic-Static Analysis</td>
</tr>
<tr>
<td>Static</td>
<td>Inelastic</td>
<td>Linear</td>
<td>Linear-Inelastic-Static Analysis</td>
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</tr>
</tbody>
</table>

Some More Solution Types

- Non-linear Analysis
  - P-Delta Analysis
  - Buckling Analysis
  - Static Pushover Analysis
  - Fast Non-Linear Analysis (FNA)
  - Large Displacement Analysis

- Dynamic Analysis
  - Free Vibration and Modal Analysis
  - Response Spectrum Analysis
  - Steady State Dynamic Analysis
Elastic vs Inelastic

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Linear vs Nonlinear

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  - Both
Elasticity and Linearity

- Linear, but inelastic
- Elastic, but nonlinear

Loads to Actions

- Loads
  - Load Cases
    - Load Combinations
      - Design Envelopes
        - Design Actions
Load Cases

- Load cases are defined by the user and used for analysis purpose only

- Static Load Cases
  - Dead Load
  - Live Load
  - Wind Load

- Earthquake Load Cases
  - Response Spectrum Load Cases
  - Time History Load Cases

- Static Non-Linear Load Cases

Load Combinations

- The Load Combinations may be created by the program, user defined or a combination of both.

- Some Examples: [Created by the program]
  - 1.4\(\Sigma DL\)
  - 1.4\(\Sigma DL + 1.7(\Sigma LL + \Sigma RLL)\)
  - 0.75(1.4\(\Sigma DL + 1.7(\Sigma LL + \Sigma RLL)\) + 1.7WL)
  - 0.75(1.4\(\Sigma DL + 1.7(\Sigma LL + \Sigma RLL)\) - 1.7WL)
  - 0.9\(\Sigma DL + 1.3WL\)
  - 0.9\(\Sigma DL - 1.3WL\)
  - 1.1 [1.2\(\Sigma DL + 0.5(\Sigma LL + \Sigma RLL)\) + 1.0E]
  - 1.1 [1.2\(\Sigma DL + 0.5(\Sigma LL + \Sigma RLL)\) - 1.0E]
Obtaining Envelop Results

<table>
<thead>
<tr>
<th>Load Case</th>
<th>Comb1</th>
<th>Comb2</th>
<th>Comb3</th>
<th>Comb N</th>
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</thead>
<tbody>
<tr>
<td>Case -1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case -2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case -3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case -M</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>P1</td>
<td>P2</td>
<td>P3</td>
<td>P N</td>
</tr>
</tbody>
</table>

Envelop Results: \[ \text{Max}, P \] \& \[ \text{Min}, P \]

Can Envelop Results be Used for Design?

- Actions interact with each other, effecting the stresses
- For Column Design: \( P, M_x, M_y \)
- For Beam Design: \( M_x, V_y, T_z \)
- For Slabs: \( M_x, M_y, M_{xy} \)
- At least 3 Actions from each combination must be considered together as set
- Therefore, Envelop Results **Can Not** be Used
- Every Load Combinations must be used for design with complete “Action Set”
Design Actions For Static Loads

- For static loads, Design Actions are obtained as the cumulative result from each load combination, as set for all interacting actions.
- The final or critical results from design of all load combinations are adopted.

Static, Dynamic and Nonlinear Results

For a Single Action:
- Static Load Case
- Response Spectrum Load Case
- Time History Load Case
- Static Non-linear Load Case

Load Combination Table

1 for each Time Step OR 1 for envelop

1 for each Load Step OR 1 for Envelop
Special Load Cases

- Response Spectrum Cases
  - All response spectrum cases are assumed to be earthquake load cases
  - The output from a response spectrum is all positive.
  - Design load combination that includes a response spectrum load case is checked for all possible combinations of signs (+, -) on the response spectrum values
  - A 3D element will have eight possible combinations of P, M2 and M3 and eight combinations for M3, V, T

Response Spectrum Results for Action Set

Design Actions needed for Columns:

- Maximum Results obtained by: SRSS, CQC, etc.
- P, Mx, My

- P, +Mx, +My
- P, +Mx, -My
- P, -Mx, +My
- P, -Mx, -My
- -P, +Mx, +My
- -P, +Mx, -My
- -P, -Mx, +My
- -P, -Mx, -My

Load Combination Table
Time History Analysis Results

Option – 2: Design For All Values
(At each time step)

Max Val

Option – 1: Envelope Design

Min Val

Response Curve for One Action

- The default design load combinations do not include any time history results
- Define the load combination, to include time history forces in a design load combination
- Can perform design for each step of Time History or design for envelopes for those results
- For envelope design, the design is for the maximum of each response quantity (axial load, moment, etc.) as if they occurred simultaneously.
- Designing for each step of a time history gives correct correspondence between different response quantities
Time History Results

- The program gets a maximum and a minimum value for each response quantity from the envelope results for a time history.

- For a design load combination any load combination that includes a time history load case in it is checked for all possible combinations of maximum and minimum time history design values.

- If a single design load combination has more than one time history case in it, that design load combination is designed for the envelopes of the time histories, regardless of what is specified for the Time History Design item in the preferences.

Static Non Linear Results

- The default design load combinations do not include any Static Nonlinear results.

- Define the load combination, to include Static Nonlinear Results in a design load combination.

- For a single static nonlinear load case the design is performed for each step of the static nonlinear analysis.
Dr. Naveed Anwar
Asian Institute of Technology, AIT

Wind Load Cases

- At least 3 basic Wind Load Cases should be considered
  - Along X-Direction
  - Along Y Direction
  - Along Diagonal
- Each Basic Wind Load Case should be entered separately into load combinations twice, once with (+ve) and once with (-ve) sign
- Total of 6 Wind Load Cases should considered in Combinations, but only 3 Load Cases need to be defined and analyzed

Wind Load Combinations

<table>
<thead>
<tr>
<th>WX</th>
<th>Comb1</th>
<th>Comb2</th>
<th>Comb3</th>
<th>Comb4</th>
<th>Comb5</th>
<th>Comb6</th>
</tr>
</thead>
<tbody>
<tr>
<td>+f</td>
<td>-f</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Wy</td>
<td>0</td>
<td>0</td>
<td>+f</td>
<td>-f</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Wxy</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+f</td>
<td>-f</td>
</tr>
</tbody>
</table>

(f) Is the load factor specified for Wind in the design codes

Example:
Comb = 0.75(1.4D + 1.7W) will need Six Actual Combinations

Comb1 = 0.75(1.4D + 1.7Wx)
Comb2 = 0.75(1.4D - 1.7Wx)
Comb3 = 0.75(1.4D + 1.7Wy)
Comb4 = 0.75(1.4D - 1.7Wy)
Comb5 = 0.75(1.4D + 1.7Wxy)
Comb6 = 0.75(1.4D - 1.7Wxy)

Six Additional Load Combinations are required where ever "Wind" is mentioned in the basic Load Combinations.
The Building Structural System

- **The Gravity Load Resisting System (GLRS)**
  - The structural system (beams, slab, girders, columns, etc) that act primarily to support the gravity or vertical loads

- **The Lateral Load Resisting System (LLRS)**
  - The structural system (columns, shear walls, bracing, etc) that primarily acts to resist the lateral loads

- **The Floor Diaphragm (FD)**
  - The structural system that transfers lateral loads to the lateral load resisting system and provides in-plane floor stiffness
Main Slab Types: Usage

- Buildings
  - Flat Slabs, One way Slabs, Two way Slabs
  - Isolated Footings, Combined Footings, Rafts
  - Pre-cast slab panels, hollow core slabs

- Bridges and Highways
  - Deck Slab on Girders
  - Box Girder Slabs
  - Slab on Grade: Pavements, Approach Slabs,

- Water Retaining Structures
  - Retaining Wall Systems
  - Tank Roof and Floor slabs

Basic Definition

- Plate
  - Any member, or part of member whose thickness is much less than its other dimensions

- Slab
  - A plate resting on supports, generally horizontal and transferring vertical loads directly.

- Slab System
  - A combination of various components, such as slabs, beams, drop panels, stiffeners, joists, girders, ribs, all acting together to transfer the loads to supports