Seismic Design of Cast-in-Place Concrete Diaphragms, Chords and Collectors
Presentation Outline

1. Introduction
2. Diaphragm Modeling
3. Analysis
4. Design & Detailing
Introduction
Introduction

- Estimating the inelastic properties for a real component is not a simple task.

- It may be tempting to argue that since the inelastic properties are so uncertain, there is little point in using inelastic analysis, and elastic analysis should be sufficient.

- If there is substantial inelastic behavior in an actual structure, the results of an elastic analysis may be of uncertain value for making design decisions, and may even be misleading.

- As a tool for obtaining information for design, even a crude inelastic model can be more useful than an elaborate elastic model.

- Please keep in mind that the goal is to get useful information for design, not to calculate "exact" response.

PERFORM-3D is an ideal tool for nonlinear performance-based analysis and design, created by Dr. Graham H. Powell, University of California at Berkeley Professor Emeritus of Civil Engineering.
The two mostly used guidelines for Performance-based seismic design are:

- PEER-TBI 2010
- LATBSDC 2014

They both refer to:

- ASCE 41
- ASCE 7 Standards
- ATC-72-1
<table>
<thead>
<tr>
<th>NEHRP</th>
<th>IBC 2012</th>
<th>ASCE 7-10</th>
<th>ACI 318-14</th>
</tr>
</thead>
<tbody>
<tr>
<td>(NIST GCR 10-917-4)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Building structures generally comprise structural elements to support \textit{gravity} and \textit{lateral loads}.

The seismic force-resisting system is composed of \textit{vertical elements}, \textit{horizontal elements}, and the \textit{foundation}.

The \textit{vertical elements} provide a \textit{continuous load path} to transmit gravity and seismic forces from the upper levels to the foundation.

The \textit{horizontal elements} typically consist of diaphragms, including collectors.
• Diaphragms transmit inertial forces from the floor system to the vertical elements of the seismic force-resisting system.

• They also tie the vertical elements together to stabilize and transmit forces among these elements.

• Thus, diaphragms are an essential part of the seismic force-resisting system and require design attention by the structural engineer to ensure the structural system performs adequately during earthquake shaking.
The Roles of Diaphragms

**Diaphragm in-plane forces:**
Diaphragms span between, and transfer forces to, vertical elements of the lateral-force resisting system.

**Diaphragm transfer forces:**
Force transfers between vertical elements which have different properties over their height, or their planes of resistance may change from one story to another.

A common location where planes of resistance change is at the grade level of a building with an enlarged subterranean plan (podium diaphragm).
• In general, low-rise buildings and buildings with very stiff vertical elements such as shear walls are more susceptible to floor diaphragm flexibility problems than taller structures.
Diaphragm Transfer Forces

Large diaphragm transfer forces should be anticipated at offsets or discontinuities of the vertical elements of the seismic-force-resisting system.

(a) **Setback** in the building profile

(b) Podium level at grade.
Diaphragm Components

- **Different parts** of a diaphragm include:
  - Diaphragm slab
  - Chords
  - Collectors (Drag struts or Distributors)
  - Connections to the vertical elements.

- These **different parts** can be identified by considering the load path in a simple diaphragm.

- We can idealize the diaphragm as a **simply supported beam spanning** between two supports, with reactions and shear and moment diagrams.
Diaphragm Components

1. Chord (Diaphragm)
2. Shear (Diaphragm)
3. Collector (Support)
4. Shear Friction (Support)
Diaphragm Modeling
**Nonlinear fiber elements automatically account for cracking of concrete because the concrete fibers have zero tension stiffness.**

In cases where the analysis results are sensitive to diaphragm stiffness assumptions, it may be prudent to “bound” the solution by analyzing the structure using both the lower and upper range of diaphragm stiffnesses, and selecting the design values as the largest forces from the two analyses.
This model treats the diaphragm as a horizontal beam spanning between idealized rigid supports. The rigid supports represent vertical elements such as shear walls.
• The equivalent-beam-on-springs model envisions the diaphragm as a beam supported by flexible supports. The stiffness of each spring is a representation of the stiffness of the supporting vertical element.
• **Strut-and-tie models** can be used to idealize the flow of force through a diaphragm. Such models have not been used extensively for the overall design of a diaphragm, although they can be useful for this purpose.
Finite element modeling of a diaphragm can be useful for assessing the force transfer among vertical elements, force transfer around large openings or other irregularities.
1. The first set of inertial design forces, $F_x$, is applied to the design of the vertical elements of the seismic-force-resisting system.

2. The second set of inertial design forces, $F_{px}$, is applied to the design of the diaphragms.
Performance-Based Design

- There are alternative approaches to determine design forces in diaphragms. In performance-based seismic design (PBD), a nonlinear response history analysis typically is used.

- Ground motions sometimes are selected and scaled with a focus on the fundamental period of vibration.

- Diaphragm accelerations and the resulting forces can be determined directly from the analysis.

- If diaphragms are modeled as finite elements, section cuts can be used to track diaphragm forces at each time step.

- As with any computer model, the engineer should exercise good judgment when using the results of a nonlinear response history analysis.
Analysis Procedures

• **ASCE-41 permits four types of analyses:**
  1. Linear elastic static procedure (LSP)
  2. Linear dynamic procedure (LDP) or response spectrum analysis
  3. Non-linear static procedure (NSP) commonly referred to as the push-over analysis
  4. Dynamic nonlinear response analysis (NDP).

• **Tall Building Design Guidelines permit only two:**
  1. 3D LDP or NDP for serviceability check
  2. 3D NDP for all checks
## Analysis Types

<table>
<thead>
<tr>
<th>No.</th>
<th>Procedure</th>
<th>Analysis</th>
<th>Structure</th>
<th>External Force</th>
<th>Level of Modeling</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Linear Static Procedure (LSP)</td>
<td>Equivalent Static Analysis</td>
<td>Linear</td>
<td>Static</td>
<td>Easy</td>
<td>Least Accurate</td>
</tr>
<tr>
<td>2</td>
<td>Linear Dynamic Procedure (LDP)</td>
<td>Response Spectrum Analysis</td>
<td>Linear</td>
<td>Response Spectrum</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Time-History Analysis</td>
<td>Linear</td>
<td>Dynamic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Nonlinear Static Procedure (NSP)</td>
<td>Pushover Analysis</td>
<td>Nonlinear</td>
<td>Static</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Nonlinear Dynamic Procedure (NDP)</td>
<td>Time-History Analysis</td>
<td>Nonlinear</td>
<td>Dynamic</td>
<td>Complex</td>
<td>Most Accurate</td>
</tr>
</tbody>
</table>
Load Combinations

(a) **Response Spectrum Analysis**

\[ 1.0D + L_{exp} + 1.0E_x + 0.3E_y \]
\[ 1.0D + L_{exp} + 1.0E_y + 0.3E_x \]

(b) **Nonlinear Dynamic Response Analysis**

\[ 1.0D + L_{exp} + 1.0E \]

where \( D \) is the service dead load and \( L_{exp} \) is the expected service live load. \( L_{exp} \) may be taken as 25% of the unreduced live load unless otherwise substantiated and shall be included in all gravity calculations and P- analyses.

**C.3.4.3.** Building Code response modification factors do not apply (that is, \( R_0 = 1 \), and \( C_a \) are all taken as unity). \( L_{exp} \) need not be included in the mass calculations.
Dynamic Response of Buildings and Diaphragms

Story Acceleration

Level 9 acceleration, g
Level 7 acceleration, g
Level 5 acceleration, g
Level 3 acceleration, g
Level 1 acceleration, g
Base shear, kN

Time, s

\( \ddot{u}_g(t) \)
Before carrying out design checks at MCE, the linear analysis results of ETABS were scaled to match with the nonlinear time-history analysis results (NLTHA) from PERFORM-3D.
Diaphragm Forces
Diaphragm Forces

1. Create diaphragm model, then apply diaphragm forces
2. For a given load case, display any stress or shell force.
3. Where maximum chord forces are expected, draw or define a section cut.
Design & Detailing
# Typical Classification of Component Actions

Load combination for each ground motion pair: $1.0DL + 0.25LL + 1.0E_{MCE}$

<table>
<thead>
<tr>
<th>Actions</th>
<th>Type</th>
<th>Demand (D)</th>
<th>Capacity (C)</th>
<th>D/C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force-Controlled Actions</td>
<td>Critical Actions (Shear)</td>
<td>1) Seven or more pairs $F_u = 1.5\times\text{Mean}$</td>
<td>Expected strengths $F_n$</td>
<td>$\frac{D}{C} = \frac{F_u}{\phi F_n} \leq 1.0$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2) Less than seven pairs $F_u = \text{Max}$</td>
<td>$\phi = 1.0$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Non-Critical Actions (Flexure)</td>
<td>1) Seven or more pairs $F_u = \text{Mean}$</td>
<td>Expected strengths $F_n$</td>
<td>$\frac{D}{C} = \frac{F_u}{\phi F_n} \leq 1.0$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2) Less than seven pairs $F_u = \text{Max}$</td>
<td>$\phi = 1.0$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Deformation-Controlled Actions</td>
<td>1) Seven or more pairs $\text{Deformation} = \text{Mean}$</td>
<td>Deformation capacity obtained from ASCE 41-13 (acceptance criteria)</td>
<td>$\frac{D}{C} \leq 1.0$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2) Less than seven pairs $\text{Deformation} = \text{Max}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: 2014 LATBSDC
**Tension & Compression Chords**

The diagram illustrates the forces acting on a structural element, with a green arrow labeled "Inertia Force" pointing downward. Red arrows labeled "C" and "T" indicate the directions of compression and tension, respectively.

The formula for the moment analysis is given as:

\[ M_u = \text{Analysis (Section Cut)} \]

A table summarizes the actions, demands, and capacities for both compression and tension chords:

<table>
<thead>
<tr>
<th>Action</th>
<th>Demand (D)</th>
<th>Capacity (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression chord</td>
<td>[ T_u = C_u = \frac{M_u}{d} ]</td>
<td>[ C_u \leq 0.5f'_c ]</td>
</tr>
<tr>
<td>Tension chord</td>
<td>[ T_u = C_u = \frac{M_u}{d} ]</td>
<td>[ T_u = \phi A_s f_y ]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[ A_s = \frac{T_u}{\phi f_y} ]</td>
</tr>
</tbody>
</table>

In the table, \( T_u \) represents the tension force, \( C_u \) represents the compression force, \( M_u \) represents the moment, \( d \) is the depth, \( f'_c \) is the compression strength, \( \phi \) is the strength reduction factor, and \( f_y \) is the yield strength.
## Shear Diaphragm

### Inertia Force

![Diagram of Inertia Force](image)

### Table: Demand (D) vs. Capacity (C)

<table>
<thead>
<tr>
<th>Action</th>
<th>Demand (D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand (D)</td>
<td>( V_u = \text{Analysis (Section Cut)} )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Capacity (C)</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{V_u}{d} \leq \frac{\phi V_n}{d} )</td>
<td>( \frac{\phi V_n}{d} = \frac{\phi A_{cv} \left( 0.17 \sqrt{f_c} + \rho_t f_f \right)}{d} )</td>
</tr>
<tr>
<td></td>
<td>( \leq \phi 0.66 \frac{A_{cv}}{d} \sqrt{f_c'} )</td>
</tr>
</tbody>
</table>
### Collectors

#### Inertia Force

<table>
<thead>
<tr>
<th>Action</th>
<th>Demand (D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand (D)</td>
<td>$T_u = \text{Analysis (Section Cut)}$</td>
</tr>
<tr>
<td></td>
<td>$C_u = \text{Analysis (Section Cut)}$</td>
</tr>
<tr>
<td>Capacity (C)</td>
<td>$T_u = \phi A_s f_y \quad \rightarrow \quad A_s = \frac{T_u}{\phi f_y}$</td>
</tr>
<tr>
<td></td>
<td>$C_u \leq \min \left{ \phi 0.5 f'_c \right}$</td>
</tr>
<tr>
<td></td>
<td>$\left{ \phi 0.85 f_c A \right}$</td>
</tr>
</tbody>
</table>

Inertia Force

$T_u$ Analysis Section Cut

$C_u$ Analysis Section Cut
Shear Friction

\[ V_u = \text{Analysis (Section Cut)} \]

\[ V_u \leq \phi V_n \]

\[ \phi V_n = \phi A_{vf} \mu f_y \]

\[ \leq \min \left\{ \phi 0.2 f'_c A_c, \phi 5.5 A_c \right\} \]
Design Detailing - Chords

Lateral load

Diaphragm boundary

Vertical element

Zones for placement of reinforcement

Reinforcement for span $l_1$ placed within depth $h_1/4$.

Reinforcement can be developed outside shaded zones. Other reinforcement required for force transfer not shown.
Design Detailing - Collectors

(a) Partial plan

(b) Collector actions

(c) Force transfer to wall

\[ C_{u,max} = C_D + C_V \]

\[ T_{u,max} = T_D + T_V \]
Note: Collector reinforcement should extend as required to transfer forces into the vertical element and should be developed at critical sections.
Design Detailing – Large Openings

- For a larger opening, the diaphragm must be designed to transfer the forces around the opening.
Force Transfer to Vertical Elements

Dowels

Collector reinforcement distributed transversely into the diaphragm

Cold joint

Structural wall

$\text{Dowels}$

$\text{Collector reinforcement}$

$\text{distributed transversely into the diaphragm}$

$\text{Cold joint}$

$\text{Structural wall}$
Collector connection to shear wall boundary zone
Detailing

A long collector with confinement reinforcement

Form savers for dowel anchorage
Thank You