MOTEMS

Structural Damping

Prevention First 2018 Conference

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Outline

• What is Damping?
• Current Codes/Standards Damping Equations
• Case Study
• Analysis Results
• Conclusion
What is Damping?
What is Damping?

- Damping is the phenomenon that makes any vibrating structure decay in amplitude of motion gradually by means of energy dissipation
- Damping = Energy dissipation
- Higher damping = Lower displacement
Spectral Acceleration and Displacement

Left:
- **Damping**
- **Acceleration**

Right:
- **Damping**
- **Displacement**

Graphs show spectral acceleration and displacement over period (s) for different damping percentages (5%, 10%, 20%, 25%).
Damping Types

• Coulomb damping: sliding
• Radiation damping: soil structure interaction
• Hysteric damping: internal material deformations
• System damping
Hysteretic Modeling for Nonlinear Analysis

Takeda Model

\[ F_y, k_i \text{ and } r \text{ are given in Table 6-4} \]

\[ k_2 = \frac{k_i}{\mu^2} \]

\[ \mu = \frac{\Delta_m}{\Delta_y} \]

Pivot Model

\[ \alpha_1 F_{y1} \]
\[ \beta_1 F_{y1} \]
\[ \alpha_2 F_{y2} \]
\[ \beta_2 F_{y2} \]
Elements that Affect Damping

• Material type: timber, concrete, steel
• Structure-soil interaction
• Ductility demand level
  • Higher ductility structures will have higher damping
• Connection Type
  • Concrete pile-to-deck connection
  • Steel pile-to-deck connection, allowed only using concrete plug
  • Timber pile-to-deck connection
ASCE 61-14 - Connections
Effective Damping for Different Structure Type and Material

• “Displacement Based Seismic Design of Structures” by Priestley, Calvi, and Kowalsky

<table>
<thead>
<tr>
<th>Structure</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete Wall Building, Bridges</td>
<td>( \xi_{\text{eff}} = 0.05 + 0.444 \left( \frac{\mu_\Delta - 1}{\mu_\Delta \cdot \pi} \right) )</td>
</tr>
<tr>
<td>Concrete Frame Building</td>
<td>( \xi_{\text{eff}} = 0.05 + 0.565 \left( \frac{\mu_\Delta - 1}{\mu_\Delta \cdot \pi} \right) )</td>
</tr>
<tr>
<td>Steel Frame Building</td>
<td>( \xi_{\text{eff}} = 0.05 + 0.577 \left( \frac{\mu_\Delta - 1}{\mu_\Delta \cdot \pi} \right) )</td>
</tr>
<tr>
<td>Hybrid Prestressed Frame</td>
<td>( \xi_{\text{eff}} = 0.05 + 0.186 \left( \frac{\mu_\Delta - 1}{\mu_\Delta \cdot \pi} \right) )</td>
</tr>
<tr>
<td>Friction Slider</td>
<td>( \xi_{\text{eff}} = 0.05 + 0.670 \left( \frac{\mu_\Delta - 1}{\mu_\Delta \cdot \pi} \right) )</td>
</tr>
<tr>
<td>Bilinear Isolation Systems</td>
<td>( \xi_{\text{eff}} = 0.05 + 0.519 \left( \frac{\mu_\Delta - 1}{\mu_\Delta \cdot \pi} \right) )</td>
</tr>
</tbody>
</table>
Timber Damping

- Not defined in MOTEMS
- Comes from yielding of connections
- Limited research
- 10% to 15% damping

<table>
<thead>
<tr>
<th>Stress Level</th>
<th>Type and Condition of Structure</th>
<th>Percentage Critical Damping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working stress, no more than about ½ yield point</td>
<td>Vital piping</td>
<td>1 to 2</td>
</tr>
<tr>
<td></td>
<td>Welded steel, prestressed concrete, well reinforced concrete (only slight cracking)</td>
<td>2 to 3</td>
</tr>
<tr>
<td></td>
<td>Reinforced concrete with considerable cracking</td>
<td>3 to 5</td>
</tr>
<tr>
<td></td>
<td>Bolted and/or riveted steel, wood structures with nailed or bolted joints</td>
<td>5 to 7</td>
</tr>
<tr>
<td>At or just below yield point</td>
<td>Vital piping</td>
<td>2 to 3</td>
</tr>
<tr>
<td></td>
<td>Welded steel, prestressed concrete (without complete loss in prestress)</td>
<td>5 to 7</td>
</tr>
<tr>
<td></td>
<td>Prestressed concrete with no prestress left</td>
<td>7 to 10</td>
</tr>
<tr>
<td></td>
<td>Reinforced concrete</td>
<td>7 to 10</td>
</tr>
<tr>
<td></td>
<td>Bolted and/or riveted steel, wood structures, with bolted joints</td>
<td>10 to 15</td>
</tr>
<tr>
<td></td>
<td>Wood structures with nailed joints</td>
<td>15 to 20</td>
</tr>
</tbody>
</table>

Newmark, Hall Earthquake Spectra EERI 1982
Timber Hysteretic Damping

- Possible to get ductile response from bolted connections
- Damping can be calculated from Hysteretic loop
- Recommend 10% for design


Hysteretic Loop for Bolted Strut Connection

[Wood, J.H., Cooney, R.C., and Potter, S.M., Cyclic Testing of Connections for Light Timber Construction, NZMWD Central Labs, Report No 5-76/12 (Bolts, Pryde Nail Plates, etc.), 1976.]
Current Codes/Standards Damping Equations
Published Effective System Damping Equations

1. Proposed MOTEMS-2019
   \[ \xi_{eff} = 0.05 + \frac{1}{\pi} \left( 1 - \frac{1 - \alpha_1}{\sqrt{\mu_\Delta}} - \alpha_1 \sqrt{\mu_\Delta} \right) \]

2. MOTEMS-2016/ ASCE 61-14/ UFC 4-152-01-2017
   \[ \xi_{eff} = 0.05 + \frac{1}{\pi} \left( 1 - \frac{1 - r}{\sqrt{\mu_\Delta}} - r \sqrt{\mu_\Delta} \right) \]

3. ACI-SP-295-3-2013 /POLA Seismic Code 2010/ POLB WDC 4.0-2015
   \[ \xi_{eff} = 0.10 + 0.565 \left( \frac{\mu_\Delta - 1}{\mu_\Delta \pi} \right) \]

   \[ \xi_{eff} = 0.05 + 0.565 \left( \frac{\mu_\Delta - 1}{\mu_\Delta \pi} \right) \]
Effective Damping Equations Comparison

• Effective damping, $\xi_{eff}$, is function of displacement ductility, $\mu_\Delta$

• First term in all equations includes damping value of 0.05 or 0.10
  • These values are not stated to be the minimum values of $\xi_{eff}$

• Second equation’s term is negative when $\mu_\Delta < 1.0$

• The ratio of second slope over elastic slope for the idealized bi-linear pushover curve, r, could be negative value but should be $\leq 1.00$
# Effective Damping Equations Comparison Summary

<table>
<thead>
<tr>
<th>Damping Equation</th>
<th>First Term</th>
<th>Second Term is Negative</th>
<th>Effective Damping, $\xi_{eff}$ is Negative</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOTEMS</td>
<td>0.05</td>
<td>$\mu_\Delta &lt; 1$</td>
<td>$\mu_\Delta$ &lt; 0.74, $\mu_\Delta$ &lt; 1.38, $r$ = -0.05, 1.00</td>
</tr>
<tr>
<td>ACI SP 295-3</td>
<td>0.10</td>
<td>$\mu_\Delta &lt; 1$</td>
<td>$\mu_\Delta$ &lt; 0.63, $r$ = NA</td>
</tr>
<tr>
<td>Priestley, et al</td>
<td>0.05</td>
<td>$\mu_\Delta &lt; 1$</td>
<td>$\mu_\Delta$ &lt; 0.76, $r$ = NA</td>
</tr>
</tbody>
</table>
Effective System Damping vs Ductility Demand
Case Study
Case Study Scope - $\Delta_y$

- Effective damping, $\xi_{eff}$, is a function of displacement ductility, $\mu_\Delta$, and therefore a function of the yield displacement, $\Delta_y$.

- The yield displacement, $\Delta_y$, is determined based on pushover curve bi-linearization using equal area method, therefore:
  - MOTEMS – $\Delta_y$ is not necessarily the same for Level 1 and Level 2 earthquakes based on pushover curve bi-linearization at Level 1 and Level 2 displacement demand.
  - POLA/ POLB - $\Delta_y$ is the same for Level 1 and Level 2 earthquakes based on pushover curve bi-linearization at Level 2 displacement demand.
  - Proposed Approach - $\Delta_y$ is the same for Level 1 and Level 2 earthquakes based on pushover curve bi-linearization at ultimate displacement capacity using references below:
    - Gulkan and Sozen, Inelastic Response of Reinforced Concrete Structures to Earthquake Motions, ACI Journal, Dec 1974
    - ASCE 61-14 Commentary Section C6.8.3
Case Study Scope – “r”

• For MOTEMS, effective damping, $\xi_{eff}$, is function of “r”
  • The pushover curve bi-linearization results in different ratios of the second slope over elastic slope, “r”
  • “r” value changes for Level 1 and Level 2 earthquakes
• POLA/ POLB – $\xi_{eff}$ is not a function of “r”
• Proposed Approach - $\xi_{eff}$ is not a function of “r”
Analysis Cases

• Case 1 - 18” Hollow concrete pipe pile
  • Two soil conditions: Lower bound (LB) with 0.3 multiplier and upper bound (UB) with 2.0 multiplier
  • Level 1 and Level 2 earthquakes

• Case 2 - 24” Prestressed concrete pile
  • Two soil conditions: Lower bound (LB) with 0.3 multiplier and upper bound (UB) with 2.0 multiplier
  • Level 1 and Level 2 earthquakes
Wharf Cross-section

18" Hollow concrete pipe pile

24" Prestressed concrete pile
Analysis Approach

• Substitutes Structures Method (SSM) was used to determine displacement demand
  • MOTEMS pushover curve bi-linearization and effective damping equation with “r”
  • POLA/POLB pushover curve bi-linearization and effective damping equation without “r”
  • Proposed Approach – proposed pushover curve bi-linearization and effective damping equation without “r”
  • Effective damping was determined by applying the minimum damping of 5% for MOTEMS damping equation and 10% for POLA/POLB damping equation

• Two connections
• Two earthquakes
• Two soil conditions
## Analysis Cases Summary

<table>
<thead>
<tr>
<th>Analysis Approach</th>
<th>Case 1 - 18&quot; Hollow Concrete Pipe Pile</th>
<th>Case 2 - 24&quot; Octagonal Concrete Pile</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: MOTEMS</td>
<td>C1LBL1-A</td>
<td>C1LBL2-A</td>
</tr>
<tr>
<td>B: POLA/POLB</td>
<td>C1LBL1-B</td>
<td>C1LBL2-B</td>
</tr>
<tr>
<td>C: Proposed Approach</td>
<td>C1LBL1-C</td>
<td>C1LBL2-C</td>
</tr>
</tbody>
</table>

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Analysis Results
Pushover Curve - Case 1 LB & UB

Pushover Curve - Case 2 LB & UB
C1LBL1-A

Base Shear (kip) vs. Displacement (in)

C1LBL1-B

Force (kip) vs. Displacement (in)

C1LBL1-C

Base Shear (kip) vs. Displacement (in)

Displacement Demand

Structural Yield

Pushover curve
C2UBL2-A

C2UBL2-B

C2UBL2-C
# Displacement Demand Summary

<table>
<thead>
<tr>
<th>Case</th>
<th>MOTEAMS</th>
<th>POLA/POLB</th>
<th>Proposed Method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LB</td>
<td>UB</td>
<td>LB</td>
</tr>
<tr>
<td></td>
<td>Level 1</td>
<td>Level 2</td>
<td>Level 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Level 1</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Level 1</td>
</tr>
<tr>
<td>Case 1</td>
<td></td>
<td></td>
<td>Level 1</td>
</tr>
<tr>
<td>Period (s)</td>
<td>1.66</td>
<td>1.40</td>
<td>1.66</td>
</tr>
<tr>
<td>First Yield (in)</td>
<td>2.20</td>
<td>1.58</td>
<td>2.20</td>
</tr>
<tr>
<td>Effective Yield (in)</td>
<td>2.00</td>
<td>3.31</td>
<td>1.72</td>
</tr>
<tr>
<td>Stiffness Ratio &quot;r&quot;</td>
<td>0.53</td>
<td>0.15</td>
<td>0.51</td>
</tr>
<tr>
<td>Displacement Demand (in)</td>
<td>3.67</td>
<td>10.61</td>
<td>3.04</td>
</tr>
<tr>
<td>Displacement Ductility</td>
<td>1.84</td>
<td>3.21</td>
<td>1.76</td>
</tr>
<tr>
<td>Effective Damping (%)</td>
<td>5.00</td>
<td>13.10</td>
<td>5.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Level 1</td>
</tr>
<tr>
<td>Case 2</td>
<td></td>
<td></td>
<td>Level 1</td>
</tr>
<tr>
<td>Period (s)</td>
<td>1.08</td>
<td>0.88</td>
<td>1.08</td>
</tr>
<tr>
<td>First Yield (in)</td>
<td>6.31</td>
<td>4.28</td>
<td>6.31</td>
</tr>
<tr>
<td>Effective Yield (in)</td>
<td>1.14</td>
<td>3.20</td>
<td>1.18</td>
</tr>
<tr>
<td>Stiffness Ratio &quot;r&quot;</td>
<td>0.85</td>
<td>0.58</td>
<td>0.95</td>
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<tr>
<td>Displacement Demand (in)</td>
<td>2.02</td>
<td>7.65</td>
<td>1.51</td>
</tr>
<tr>
<td>Displacement Ductility</td>
<td>1.78</td>
<td>2.39</td>
<td>1.27</td>
</tr>
<tr>
<td>Effective Damping (%)</td>
<td>5.00</td>
<td>5.00</td>
<td>5.00</td>
</tr>
</tbody>
</table>

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Conclusions

- Twenty four cases were analyzed to evaluate three approaches for structural damping
- The displacement at first yield is not dependent on the analysis approach
- System effective yield displacement is dependent on the analysis approach
- Effective damping for MOTEMS ranged from 5% to 15% and the other two approaches ranged from 10% to 22%
- Displacement demand for MOTEMS was conservatively larger than the proposed approach by 12% to 41%
- Displacement demand for POLA/ POLB was lower than the proposed approach by a maximum of 9% and in other cases it matched the proposed approach
Conclusions

- Effective damping, $\xi_{eff}$, is a function of displacement ductility, $\mu_\Delta$, structure type, and soil condition.
- It's difficult to define one equation for all types of structures.
- MOTEMS and POLA/POLB damping equations do not have specified minimum values.
- The proposed approach is a practical method.