Advanced numerical models for elastomeric and sliding isolators for nuclear structures

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Outline

• Framework for advanced models
  – All types of surface-mounted nuclear structures
  – United States Nuclear Regulatory Commission
    • NTTF and extended design basis
    • Seismic isolation NUREG
    • Analyzability
    • USNRC ESSI simulator
  – ASCE 4 (Department of Energy)
    • Beyond design basis
    • Section 7.7
    • Analyzability

• Qualification of new isolators and isolation systems
• Advanced models for elastomeric and sliding isolators
• On-going studies
Qualification of new isolators

• Building a body of knowledge and confidence in performance and manufacture
  – Compliance with NQA-1 or similar
  – Manufacturer-specific
• Testing of full-scale specimens
• V&V models of isolators
• Changes in material properties
• System-level testing
• V&V tools and codes to predict system response
• Deployment of isolation system
Verification and validation
Verification

- Process of determining that a computational model accurately represents the underlying mathematical model and its solution (ASME)
- Code verification
  - Numerical code verification
    - Code to code comparison
  - Software quality assurance
- Solution verification
Validation

• Process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model (ASME)

• Experimental validation
  – Results of verified computational model compared with experimental data
Plan for verification and validation

1. Reality
2. Update conceptual model
3. Mathematical model
4. Computational model
5. Computational solution
6. Experimental data
7. Theoretical solutions
8. Update parameter
9. Verification
10. Validated solution
11. Validation
Isolator displacements

- Isolated period ($K_d$) of 2 seconds, $Q_d = 0.06W$
- BDBE = 150% DBE in DOE space
- EDBE = max (167% DBE, UHS at MAFE = 10^{-5}) in NRC space
- North Anna, EUS, hard rock
  - 50%-ile DBE = 25 mm
  - 99%-ile DBE = 40 mm
  - 90%-ile BDBE = 50 mm
- Vogtle, CEUS, soil, $T_s = 1.6$ seconds
  - 50%-ile DBE = 250 mm
  - 99%-ile DBE = 415 mm
  - 90%-ile BDBE = 625 mm
- Diablo Canyon, WUS, rock
  - 50%-ile DBE = 475 mm
  - 99%-ile DBE = 765 mm
  - 90%-ile BDBE = 990 mm

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Numerical models of isolators

- Elastomeric isolators
  - Advanced models
  - OpenSees and ABAQUS
Advanced models
Advanced models

• User elements in OpenSees and ABAQUS
  – ElastomericX for LDR and LeadRubberX for LR bearing
• 2 Node, 12 DOF, 3D discrete element
Advanced models

• New model in axial direction
• Bouc-Wen and plasticity models in shear
## Advanced models

<table>
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<tr>
<th>Properties</th>
<th>3DBASIS</th>
<th>SAP2000</th>
<th>PERFORM3D</th>
<th>LSDYNA</th>
<th>ABAQUS</th>
<th>OpenSees</th>
<th>New</th>
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<tr>
<td>Coupled horizontal directions</td>
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</table>
ElastomericX V&V

Iwabe et al. (2000)

Warn and Whittaker (2006)
LeadRubberX V&V
LeadRubberX V&V

- Force (kN) vs. Displacement (mm)
- Simulation and experimental data comparison

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Summary: elastomeric

• New computational models to capture most behaviors of elastomeric bearings expected under beyond design basis earthquake shaking
  – Substantial extension of existing capabilities

• Code-to-code verification, OpenSees and ABAQUS, shows good agreement

• Calibration with experimental data needed for some unknowns

• Validation experiments to be performed
  – 16 bearings to be tested at UB
Numerical models of isolators

- Spherical sliding bearing
  - Friction Pendulum
    - Single concave
  - Advanced models
    - Pressure
    - Velocity
    - Temperature

![Diagram showing force vs. displacement relationship with a non-linear curve indicating a constant K value at point 1.](image)
Advanced models
Force-displacement relationship

- Characteristic strength (Q)
- Post yield stiffness (K)

Coefficient of friction (μ) → Axial load (P) → Velocity (v) → Temperature (T)

Radius of curvature (R)
Advanced models

• Reference coefficient of friction ($\mu_{\text{ref}}$) measured at
  – Reference temperature, $T_o = 20\,^\circ\text{C}$
  – Reference axial pressure, $p_o$
  – High velocity, 200+ mm/s

• Pressure ($p$), temperature ($T$), velocity ($v$)

\[
\begin{align*}
k_v &= 1 - 0.5e^{-100v} \\
k_T &= 0.79 \times \left( 0.70^{\frac{T}{50}} + 0.40 \right) \\
k_p &= 0.70^{\frac{(p-p_o)}{50}}
\end{align*}
\]

\[\mu(p, T, v) = \mu_{\text{ref}} \times k_p k_T k_v\]
Advanced models

- Friction and 1) temperature, and 2) pressure
  \[ \mu_{\text{ref}} = 0.06 \text{ at } p_o = 50 \text{ MPa, } T_o = 20^\circ \text{C, } v = 1000 \text{ mm/s} \]
Advanced models

• OpenSees ‘flatSliderBearing’ updated
  – Coefficient of friction
  – Lateral force
  – Lateral stiffness

• Single FP bearing
  – Sliding period = 3 s
  – Reference coefficient of friction of 0.06 measured at a static axial pressure of 50 MPa
  – Radius of contact area: 200 mm
Advanced models

• Ground motions for analysis
  – 30 sets of ground motions for Diablo Canyon
  – Scaled to match geomean spectra (H, V)
Advanced models

• Alternate friction models
  – Coulomb, $\mu = \text{Coulomb}$
  – Pressure dependent, $\mu = f(p)$
  – Temperature dependent, $\mu = f(T)$
  – Velocity dependent, $\mu = f(v)$
  – All dependencies, $\mu = f(p, T, v)$

• Impact on displacement responses
Advanced models

- Average friction over strong shaking duration

![Chart showing coefficient of friction over ground motion](chart.png)
Advanced models

- Force-displacement response for GM30
Advanced models

- History of coefficient of friction for GM30

![Graph showing coefficient of friction over time with marked strong shaking periods](image)
Advanced models

• Maximum displacement and temperature
Summary: sliding

• Sliding period = 3 sec, static pressure = 50 MPa
  – Median displacement
    • Temperature effects most significant
    • Pressure and velocity effects of secondary importance
  – 90+%-ile displacements
    • Impact of friction model not that important

• At lower static axial pressures, say 15-25 MPa
  – Temperature effect less important

• Scope of analysis being expanded

• Verification and validation of friction model

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On-going studies

• Sample model of NPP being developed
  – EPRI supplied; based on WEC AP1000
  – Modeled in LS-DYNA and OpenSees
  – To be modeled in ESSI

• Earthquake analysis for multiple sites
  – DBE and Extended DBE (hazard at $10^{-5}$ MAFE)
  – Identify what effects should be modeled
  – Soil-structure interaction analysis
    • Nonlinear time domain essential for soil sites

• Beyond design basis aircraft impact
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