Hybrid Simulation of a Seismically Isolated Nuclear Power Plant

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Outline

1. Motivation
2. Prototype Structure & Bearing Designs
3. Experimental Test Program
4. Hybrid Simulation Test Results
5. Characterization Test Results
6. Summary & Conclusions
Motivation
HS of large isolated structure

- On a shaking table the testing of large structures such as NPPs is impractical due to the size, weight and strength limitations imposed by the simulator platform.

- Using hybrid simulation:
  - The linear-elastic plant superstructure can be modelled analytically.
  - Only the nonlinear isolator behavior needs to be tested physically.
  - Large axial loads due to gravity and axial load fluctuations caused by overturning and vertical input can be imposed in force control.

- Need a testing facility that can be converted to perform real-time hybrid simulations on large full-scale isolators.
Hybrid Simulation Concept

\[ M \cdot \ddot{u} + C \cdot \dot{u} + P_r(u, \dot{u}, \ddot{u}) = P(t) \]
Prototype Structure & Bearing Designs
Prototype Structure

Korean Advanced Power Reactor (APR1400)
## Three Bearing Designs

<table>
<thead>
<tr>
<th>Isolation bearing</th>
<th>Design displacement, $D_d$ (mm)</th>
<th>Lateral force at $D_d$ (kN)</th>
<th>$Q_d$ (kN)</th>
<th>Plan dimension (mm)</th>
<th>Height (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unison eTech (LPRB)</td>
<td>210</td>
<td>1,900</td>
<td>1,010</td>
<td>1,520</td>
<td>533</td>
</tr>
<tr>
<td>ESCO RTS (EQSB)</td>
<td>152</td>
<td>2,920</td>
<td>1,090</td>
<td>2,900</td>
<td>607</td>
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<tr>
<td>Earthquake Protection Systems (TFPB)</td>
<td>584</td>
<td>1,510</td>
<td>730</td>
<td>1,980</td>
<td>711</td>
</tr>
</tbody>
</table>

![Graph showing isolator force vs. displacement](image)
Unison eTech

TOTAL WEIGHT: 5,206 Kg
### Unison eTech Bearing

#### Table 2.2-1  LPRB design properties.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical stiffness ($K_v$)</td>
<td>12,896 kN/mm</td>
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<tr>
<td>Initial stiffness ($K_1$)</td>
<td>545 kN/mm</td>
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<tr>
<td>Second slope stiffness ($K_2$)</td>
<td>4.2 kN/mm</td>
</tr>
<tr>
<td>Characteristic strength ($Q_d$)</td>
<td>1,002 kN</td>
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<tr>
<td>Equivalent stiffness ($K_{eq}$)</td>
<td>9.0 kN/mm</td>
</tr>
<tr>
<td>Equivalent damping ratio ($H_{eq}$)</td>
<td>0.335</td>
</tr>
</tbody>
</table>

\[ \varnothing_r = 1520 \text{ mm} \]
\[ P_{Gravity} = 9.7 \text{ MN} \]
\[ p = 5.5 \text{ MPa} \]
\[ \Sigma t_{Rubber} = 210 \text{ mm} \]
\[ \varnothing_l = 4 \times 200 \text{ mm} \]
ESCO RTS Bearing

EradiQuake Isolation Bearing - EQS-Qd 10000KN-Dis 150-350

Position: 오류: 착조 없음 - (수량: 오류: 착조 없음 set)

11
ESCO RTS Bearing

<table>
<thead>
<tr>
<th>Table 2.3-1</th>
<th>EQSB design properties.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of friction</td>
<td>0.11</td>
</tr>
<tr>
<td>Second slope stiffness ($K_2$)</td>
<td>11.6 kN/mm</td>
</tr>
<tr>
<td>Characteristic strength ($Q_a$)</td>
<td>1,092 kN</td>
</tr>
<tr>
<td>Equivalent stiffness ($K_{eq}$)</td>
<td>18.8 kN/mm</td>
</tr>
</tbody>
</table>

$W \times L = 2400 \times 2400 \text{ mm}$

$H = 600 \text{ mm}$

$P_{Gravity} = 9.7 \text{ MN}$

$\mu = 11\%$

$k_2 = 11.6 \text{ kN/mm}$
EPS Bearing

TRIPLE PENDULUM BEARING
BEARING: FPT15678R/38-3OR/27-18

EARTQUAKE PROTECTION SYSTEMS
VALLEJO, CALIFORNIA (707) 844-5993

DATE 9/10/15
DRAWING: FPT15678R/38-3OR/27-18

CopyrightEarthquake Protection Systems 2013
EPS Bearing

COF = 2% - 9% - 9%

Stage 5-6 yielding
Experimental Test Program
Overview of SRMD @ UC San Diego

- Built by Caltrans, MTS and UCSD in 1999 to test Seismic Response Modification Devices at full scale
- Apply full-scale gravity loads, displacements and velocities to bearings and dampers
  - Designed for capacity rather than accuracy
- Required significant adaptations to enable hybrid simulation while minimizing experimental errors
  - Receive and apply command displacement/forces
  - Return measured force feedback
Overview of SRMD @ UC San Diego
Specifications of SRMD testing facility

### 6 DOF platen

<table>
<thead>
<tr>
<th>Component</th>
<th>Capacity</th>
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<tbody>
<tr>
<td>Vertical Force</td>
<td>53,400 kN</td>
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<tr>
<td>Longitudinal Force</td>
<td>8,900 kN</td>
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<tr>
<td>Lateral Force</td>
<td>4,450 kN</td>
</tr>
<tr>
<td>Vertical Displacement</td>
<td>± 0.127 m</td>
</tr>
<tr>
<td>Longitudinal Displacement</td>
<td>± 1.219 m</td>
</tr>
<tr>
<td>Lateral Displacement</td>
<td>± 0.610 m</td>
</tr>
<tr>
<td>Vertical Velocity</td>
<td>± 254 mm/s</td>
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<tr>
<td>Longitudinal Velocity</td>
<td>± 1,800 mm/s</td>
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<tr>
<td>Lateral Velocity</td>
<td>± 760 mm/s</td>
</tr>
<tr>
<td>Relative Platen Rotation (Roll, Pitch, &amp; Yaw)</td>
<td>± 2 degrees</td>
</tr>
<tr>
<td>Maximum Specimen Height</td>
<td>1.524 m</td>
</tr>
</tbody>
</table>
Implementation of Hybrid Simulation

- Requires **fast, accurate** and **reliable** communication between computer simulation and experimental setup to solve hybrid model

\[ M \cdot \ddot{u} + C \cdot \dot{u} + P_r(u, \dot{u}, \ddot{u}) = P(t) \]
Communication Details

OpenSees Finite Element Model

OpenFresco Middleware

SCRAMNet+

xPC Target real-time Predictor-Corrector

SCRAMNet+

MTS SRMD real-time Controller

Physical Specimen in Laboratory
OpenSees and OpenFresco Details

- Hybrid models with several thousand DOF can be tested in real-time
  - First-time use of OpenSeesSP for HS
  - All integrators specialized for HS are now available in OpenSeesSP
  - Execution on high performance overclocked 8-core analysis machine
  - If system is linear command “algorithm Linear –factorOnce” can be used

- Added new command “partition $eleTag”
- Added new element EEBearing
Time Delay Compensation Methods

- SRMD has delay of 60 msec
- Feedforward Gain
  - used last time, limited benefit for displ. control, did not work for vertical force control
- Polynomial Extrapolation
  - used last time, works for constant delays only, limited in how much delay it can compensate for
- Inverse Models
  - does not work well, relies on accurate system ID
- Adaptive Time Series (ATS) method
  - developed at Lehigh by Y. Chae, based on least squares method, self-adapting to changes
Horizontal Force Measurements

Load Cells on actuators include platen forces

Plan View of Test System

Key elements:
- Corner Fixture
- Platen
- Slide Bearing Actuator
- Steel Bearing Plate
- Horizontal Actuator
- Outrigger Arm

Dimensions:
- 10.4 m (34 ft)
- 18.3 m (60 ft)
Three-Loop Hardware Architecture

\[ dt_{\text{int}} = 0.01 \text{ sec} \]

\[ dt_{\text{con}} = 0.001 \text{ sec} \]

- **Integrator Loop**
  - OpenSees & OpenFresco
  - xPC- Host

- **Predictor-Corrector Loop**
  - External ref. (Fiber Optic)
  - measSignal

- **Actuator-Control Loop**
  - External ref. (Fiber Optic)
  - Feedback

- **ATS delay compensator**
- **Inertia & friction compensation, filtering & noise reduction**
- **PID+F+\( \Delta p \)+Notch ctrl.**
Ground Motions
## NRC Set: Motion Parameters

<table>
<thead>
<tr>
<th>Record #</th>
<th>NGA #</th>
<th>Earthquake</th>
<th>Station</th>
<th>Mag</th>
<th>Dist (km)</th>
<th>Vs30 (m/s)</th>
<th>Scale Factor</th>
<th>NPTS</th>
<th>dt (s)</th>
<th>Duration (s)</th>
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<td>Niland Fire Station</td>
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<td>Amboy</td>
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<td>428</td>
<td>5.0</td>
<td>13204</td>
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<td>66.02</td>
</tr>
</tbody>
</table>
NRC Set: Response Spectra

NRC: Horizontal Mean Response Spectra

NRC: Vertical Mean Response Spectra

ATLSS & NHERI Lehigh Seminar, December 6, 2016
NRC RG1.60: Spectral Matching
Hybrid Simulation Test Results
Result output locations

- RCB 101.7m (333.5')
- ACB 63.4m (208.0')
- INS 58.2m (191.0')
- RCB, INS, ACB 23.8m (78.0')
- RCB, INS, ACB 47.5m (156.0')
2D Hybrid Simulation (LPRB)
1D vs. 2D real time (LPRB)

\[ \gamma_{\text{max}} = 82\%, 113\% \]
1D vs. 2D 2x-slower (LPRB)

\[ \gamma_{\text{max}} = 73\%, 125\% \]
1D vs. 2D (LPRB)

Reactor containment building
Damping ratio = 5%

Internal structure
Damping ratio = 5%

Auxiliary building
Damping ratio = 5%

real time

2x-slower
2D 2x-slower vs. 3D 10x-slower (LPRB)

\[ \gamma_{\text{max}} = 125\%, 125\% \]
2D vs. 3D (LPRB)

Reactor containment building

Internal structure

Auxiliary building

Damping ratio = 5%

2x/10x-slower
Conclusions wrt LPRB isolator

- Need analytical model that can capture v-h force interaction correctly
- Need analytical model that can capture v-h displacement coupling
- Need analytical isolator model that can account for the reduction in the lead yield strength with increasing bearing temperature
1D vs. 2D real time (EQSB)

\[ \delta_{\text{max}} = 137\text{mm}, 157\text{mm} \]
1D vs. 2D 2x-slower (EQSB)

\[ \delta_{\text{max}} = 200\text{mm}, 205\text{mm} \]
1D vs. 2D (EQSB)

Reactor containment building
Damping ratio = 5%

Internal structure
Damping ratio = 5%

Auxiliary building
Damping ratio = 5%

real time

2x-slower
2D 2x-slower vs. 3D 10x-slower (EQSB)

\[ \delta_{\text{max}} = 205\text{mm}, 211\text{mm} \]
2D vs. 3D (EQSB)

**Reactor containment building**
- Damping ratio = 5%
- Graph showing pseudo acceleration vs. frequency for different elevations.

**Internal structure**
- Damping ratio = 5%
- Graph showing pseudo acceleration vs. frequency for different elevations.

**Auxiliary building**
- Damping ratio = 5%
- Graph showing pseudo acceleration vs. frequency for different elevations.

2x/10x-slower
Conclusions wrt EQSB isolator

- Need analytical model that can capture v-h force interaction correctly
- Need analytical isolator model that can capture adhesion (break-away) effects on COF
- Need analytical isolator model that can capture temperature effects on COF
1D vs. 2D 2x-slower (TFPB)

\[ \delta_{\text{max}} = 393\text{mm}, 450\text{mm} \]
1D vs. 2D 10x-slower (TFPB)

\[ \delta_{\text{max}} = 380\text{mm}, 364\text{mm} \]
1D vs. 2D (TFPB)

**Reactor containment building**
- Damping ratio = 5%

1D vs. 2D (TFPB)

- 2x-slower
- 10x-slower

**Internal structure**
- Damping ratio = 5%

**Auxiliary building**
- Damping ratio = 5%
2D vs. 3D 10x-slower (TFPB)
2D vs. 3D (TFPB)

Reactor containment building

Damping ratio = 5%

10x-slower

Internal structure

Damping ratio = 5%

Auxiliary building

Damping ratio = 5%
Conclusions wrt TFPB isolator

- Need analytical model that can capture \( v-h \) force interaction correctly
- Need analytical model that can capture \( v-h \) displacement coupling
- Need analytical isolator model that can capture adhesion (break-away) effects on COF
- Need analytical isolator model that can capture temperature effects on COF
Average Delay Assessment (Long)

real time -> 6 msec

2x slower -> 0 msec

Error between Measured and Command Displacements from xPC-Target: DOF 01

Error between Measured and Target Displacements from xPC-Target: DOF 01
Normalized RMS Error (Long)

real time

2x slower
Average Delay Assessment (Lat)

real time -> 4 msec

2x slower -> 1 msec
Normalized RMS Error (Lat)

real time

2x slower
Characterization Tests
Axial Response under Compression
Failure Tests (LPRB and EQSB)

LPRB by Unison eTech

EQSB by ESCO RTS

Rupture due to delamination

Bolt slip at peak load
Failure Test (LPRB)
Failure Tests (LPRB and EQSB)

LPRB by Unison eTech

Rupture due to delamination

EQSB by ESCO RTS

Bolt slip at peak load
Failure Tests (TFPB)

TPFB by EPS

Stage 5-6 yielding of slider lip
Failure Tests (TFPB)
Failure Tests (TFPB)

TFPB by EPS

Stage 5-6 yielding of slider lip
Summary & Conclusions
Conclusions RTHS

- Real-time hybrid simulation is possible in 2D and is a viable testing method to experimentally assess the behavior of large isolators at full-scale.
- The SRMD bearing test machine was successfully converted to perform rapid and real-time hybrid simulation tests for large hybrid models.
- Despite the lack of a load cell to directly measure the experimental bearing forces, reliable results were obtained using a real-time correction model.
- To achieve acceptable performance and accuracy in the force controlled vertical DOF a hybrid simulation should be performed at a minimum 10x-slower than real time.
- It was demonstrated that it is possible to use a high-performance computing platform with parallel processing capabilities (OpenSeesSP) to perform real-time hybrid simulations of large structures with many DOFs, such as nuclear power plants.
Conclusions Bearing Behavior

- Overall, the seismically isolated plant facilities behaved as expected. Base shears and floor accelerations were generally reduced substantially compared to what might be expected for a fixed-base structure. However, the tests were able to identify specific differences associated with different bearings, loading conditions, and earthquake excitations.

- Heat generation in the LPRB was larger during 2D testing than during 1D testing, causing the yield strength of the lead cores to decrease faster, and leading to larger displacement demands in the hybrid tests.

- The real-time execution of the hybrid simulations had a moderate effect on the hysteresis loops of the LPRB.

- The LPRB showed substantial vertical–horizontal coupling behavior.

- In terms of overturning effects, net tension was not recorded in any of the bearings.
Conclusions Bearing Behavior

- For the hybrid simulations on the EQSB, breakaway, static and dynamic friction values influence the response of the system.
- The EQSB isolator showed substantial vertical–horizontal coupling behavior.
- For the TFPB shear forces are significantly lower than the ones that were seen in the LPRB and EQSB. Lower isolator shear forces mean that less force is transmitted into the power plant superstructure; hence, the superstructure is better protected during seismic shaking.
- The TFPB isolator showed substantial vertical–horizontal coupling behavior.
- For the hybrid simulations on the TFPB, adhesion and static friction influence the response of the system. For modeling purposes a simple velocity dependent friction model is not sufficient. A friction model that can include adhesion, static, and dynamic friction needs to be developed and implemented.
Questions?
Discussion