Integration algorithms for hybrid simulation of structural response through collapse

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### Performance Characteristics in Current 1-DOF Configuration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Designed as a 6-DOF shake table, but built as a 1-DOF system to accommodate funding available</td>
<td></td>
</tr>
<tr>
<td>Stroke</td>
<td>±0.75m</td>
</tr>
<tr>
<td>Platen Size</td>
<td>40 ft × 25 ft (12.2 m × 7.6 m)</td>
</tr>
<tr>
<td>Peak Velocity</td>
<td>1.8 m/sec</td>
</tr>
<tr>
<td>Peak Acceleration</td>
<td>4.7g (bare table condition); 1.2g (4.0MN/400 tons rigid payload)</td>
</tr>
<tr>
<td>Frequency Bandwidth</td>
<td>0-33 Hz</td>
</tr>
<tr>
<td>Horizontal Actuators Force Capacity</td>
<td>6.8 MN (680 tons)</td>
</tr>
<tr>
<td>Vertical Payload Capacity</td>
<td>20 MN (2,000 tons)</td>
</tr>
<tr>
<td>Overturning Moment Capacity</td>
<td>50 MN-m (5,000 ton-m)</td>
</tr>
</tbody>
</table>
REAL-TIME HYBRID SHAKE TABLE TESTING

Basic hardware and software in place for real-time hybrid shake-table testing:

- Multi-channel MTS FlexTest controller
- SCRAMNet ring for real-time communication and synchronization of data flow between shake-table controller, FlexTest controller, and real-time target PC running the Matlab/SIMULINK Real-time Workshop and xPC Target software
- Easy integration of OpenSees/OpenFresco open-source software framework
- 50-ton dynamic actuator
- Portable hydraulic power system
Overview of Hybrid Testing to Collapse

- Experimental simulation of framed structures to collapse
  - Previous shake table tests
  - Description of structural models
    - Numerical modeling
    - Substructuring techniques
- Challenges in hybrid simulation to collapse
  - Use of complex numerical models
  - Stability issues
- Comparison of hybrid and shake table tests
  - Validation
- Large scale application of hybrid simulation for structural performance assessment
Shake table test to collapse of moment frame

Full scale four story steel moment resisting frame tested to collapse at E-Defense Shake Table, Sept. 2007
Shake table test to collapse of moment frame

- 1:8 scale moment frame structure was subjected to 5 ground motion intensities of the Northridge 1994 Canoga Park station
  - Captures response range from linear elastic to collapse
- Frame has replaceable fuse type elements for repeated testing
- Provides baseline data for validation of hybrid simulation to reproduce collapse – improve acceptance of test method

NEES Project on collapse assessment using shake table testing (Lignos, Krawinkler and Whittaker 2011)
Shake table test to collapse of moment frame

- Loading sequence for shake table tests – Canoga Park Record
  - Same loading sequence used in hybrid simulations

<table>
<thead>
<tr>
<th>Intensity</th>
<th>Name</th>
<th>Seismic Hazard Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>40%</td>
<td>SLE</td>
<td>Service Level EQ. Level</td>
</tr>
<tr>
<td>100%</td>
<td>DBE</td>
<td>Design Basis EQ. Level</td>
</tr>
<tr>
<td>150%</td>
<td>MCE</td>
<td>Maximum Considered EQ. Level</td>
</tr>
<tr>
<td>190%</td>
<td>CLE</td>
<td>Collapse Level EQ.</td>
</tr>
<tr>
<td>220%</td>
<td>CLEF</td>
<td>Final Collapse Level EQ.</td>
</tr>
</tbody>
</table>
OpenSees
Calibrated Numerical Model

Numerical model of moment frame

Modified Ibarra Krawinkler Deterioration Model

Chord Rotation $\theta$

Mass/Gravity

Plastic Hinges

Rigid Link

Leaning Columns

Gravity Loads

- Concentrated Mass
- Rotational Friction Springs

Pin
Improved Substructuring Techniques

- Substructuring Technique with Overlapping Domain using force feedback at top of first story columns
- Define New Experimental Setup Class in OpenFresco
Numerical Verification

- Substructuring Technique with Overlapping Domain
- Finite Element Coupling Simulation
Numerical Verification

1994 Canoga Park Record

Global Response:

Local Response:

Full Numerical Model
Model 11
Model 21
Model 00

Displacement at Collapse (in)
Height (in)

Moment (kips.in)
Rotation (rad)

ISBRA Oct 5-6, 2015
Issues with Numerical Instability

- Model with 2.5 story experimental substructure
- Pretest numerical simulations provided good results with integration parameters selected
  - Newmak Method with fixed number of iterations
  - $\Delta t=0.0039$ with 4 iterations for MCE
Issues with Numerical Instability

- Response traced well until MCE record (24.9 sec)
Experimental Verification

• Model with 1.5 story experimental substructure
Experimental Verification

Full Ground Motion Test Series:

- Results:

- Northridge 1994 Canoga Park Station Record
• Integration parameters were revised especially for MCE and above, and stiff elements were relaxed
  – Newmark Method with fixed number of iterations
  – $\Delta t = 0.00156$ with 8 iterations for MCE
Large-scale Application

- Two $\frac{1}{2}$-scale subassemblies of a moment and gravity frames were tested via hybrid simulation.
- 4-Story Moment Frame Prototype Structure

After Lignos and Krawinkler, 2012
Experimental Program

- Hybrid Model #1 (Moment Frame)

- Subjected to 25%, 100%, 160% & 200% Loma Prieta (LGPC)
Physical Sub-Structures

- Physical Sub-Structure #1 (1/2-Scale Subassembly)

Composite Floor Slab

- W12×3
- W8
- Contin
- Note: not shown

(a) Front View
(b) Top View
Test Setup

(a) Front Elevation

(b) Cross Section

(c) Deformed Configuration
Test Setup

(a) Panoramic south view of test setup and specimen #2
Substructuring Technique

- Substructuring Technique with Overlapping Domain and Simplified Boundary DOFs
Integration Method

- Similar to previous test, used Newmark Method with Fixed number of iterations
- Conducted numerical studies to examine modeling approaches, time step and iterations

<table>
<thead>
<tr>
<th>Numerical Model</th>
<th>Geometric Transf.</th>
<th>Stiffness Factor “n”</th>
<th>Integration Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>Corotational</td>
<td>10</td>
<td>INM-HS</td>
</tr>
<tr>
<td>M4</td>
<td>Corotational</td>
<td>1</td>
<td>HHT-HS</td>
</tr>
<tr>
<td>M5</td>
<td>P-Delta</td>
<td>1</td>
<td>HHT-HS</td>
</tr>
<tr>
<td>M6</td>
<td>P-Delta</td>
<td>1</td>
<td>INM-HS</td>
</tr>
</tbody>
</table>

INM: Implicit Newmark Method
HHT: Hilber, Hughes and Taylor
"n" is used to distribute the rotational elastic stiffness between the elastic beam and rotational springs (plastic-hinge elements) in a concentrated plasticity model (Ibarra and Krawinkler 2005)
Substructuring

- Hybrid Sim. #1

Substructuring Algorithm
Test Results: Hybrid Simulation #1

- Roof Drift Ratio
Test Results: Hybrid Simulation #1

- Base Shear: Hybrid Model #1
Test Results: Hybrid Simulation #1

- East Column Plastic-Hinge Region
Concluding Remarks

• Application of hybrid simulation to realistic and complex structural models to collapse was validated
  – Application to small scale moment frame compared well to previous results from shake table test
  – Use of complex models presents challenges in numerical integration – monitoring of unbalance force errors seems to be indicator of stability
  – Use of substructuring techniques simplified experimental setup

• Application of hybrid simulation to large-scale structures provides insight into system level structural response
  – Test provided insight into response of columns, beams with composite slab, panel zones, and interaction between these components
  – Damage to each component is clearly documented after each level of loading
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