Hybrid Simulation Evaluation of the Suspended Zipper Frame

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Introduction

Example of the hybrid simulation test.
- NEES suspended zipper brace frame test.

OpenSees Navigator
- Graphic user interface for OpenSees.

Example application
- Three span bridge, Two story Shear, …
Suspended Zipper Frame
Buffalo Shaking Table Test
GT Quasi-Static Test

Experimental Testing

Analytical Simulation
CUB Hybrid Simulation Test
Challenge of the zipper frame test

- Combine OpenSees with experimental elements
  - Nonlinear buckling behavior accounted in both analytical and experimental elements

- Analytical simulation of the brace
  - Modeling the analytical brace using OpenSees
  - Component testing of the brace sub-assembly

- Hybrid simulation of the frame
  - Experimental Testing Architecture
  - New Experimental Framework
  - Solution Algorithm
Analytical simulation of the brace

Modeling of the analytical brace
Analytical simulation of the brace

Brace behavior under cyclic displacement loading
Analytical brace

Hysteresis loop (Analytical)
Scope of the test

- Analytical simulation of the brace
  - Modeling the analytical brace using OpenSees

- Quasi-Static testing of the brace
  - Component testing of the brace sub-assembly

- Hybrid simulation of the frame
  - Analytical model + experimental sub-assembly
Test Setup
Instrumentation
Instrumentation
Instrumentation
Quasi-Static Test
Loading History
Damaged Specimen
Movie – Out Of Plane Buckling
Movie – Gusset Plate
Brace Axial Forces

0.75 % inter-story drift ratio
Unbalanced Forces
Beam Rotation
Close Up View of the Braces
More Photos
OpenSees Model
Brace Hysteresis

Brace 1 hysteresis

Brace 2 hysteresis

Normalized axial force [%]

Axial deformation/L_{brace} [%]
Scope of the Test

- Analytical simulation of the brace
  - Modeling the analytical brace using OpenSees

- Quasi-Static testing of the brace
  - Component testing of the brace sub-assembly

- Hybrid simulation of the frame
  - Analytical model + experimental sub-assembly
Equations of Motion

\[ M \ddot{u}_n + C \dot{u}_n + \text{Pr}(u_n, \dot{u}_n) = -M \ddot{u}_{g,n} \]
Solution Algorithm

Newmark integration method

\[ u_{n+1} = u_n + h \dot{u}_n + h^2 \left( \left( \frac{1}{2} - \beta \right) \ddot{u}_n + \beta \ddot{u}_{n+1} \right) \]

\[ \ddot{u}_{n+1} = \ddot{u}_n + h \left( (1 - \gamma) \ddot{u}_n + \gamma \ddot{u}_{n+1} \right) \]

\( \gamma \) and \( \beta \) are constant coefficients

When \( \gamma = 1/2 \) and \( \beta = 1/4 \) (average acceleration method)

When \( \gamma = 1/2 \) and \( \beta = 1/6 \) (linear acceleration method)
Solution Algorithm

**Newmark integration method**

\[
M \dddot{u}_{n+1} + C \ddot{u}_{n+1} + \Pr(u_{n+1}, \dot{u}_{n+1}) = -Mi \dddot{u}_{g,n+1}
\]

\[
F(u) = M \left( \frac{1}{\beta h^2} (u - u_n) - \frac{1}{\beta h} \ddot{u}_n - \left( \frac{1}{2 \beta} - 1 \right) \dddot{u}_n \right)
\]

\[
+ C \left( \frac{\gamma}{\beta h} (u - u_n) - \left( \frac{\gamma}{\beta} - 1 \right) \ddot{u}_n - h \left( \frac{\gamma}{2 \beta} - 1 \right) \dddot{u}_n \right)
\]

\[
+ \Pr(u, u_n, \dot{u}_n, \ddot{u}_n) - P_{n+1} = 0
\]
Experimental Testing Architecture

- xPC host
- Data acquisition host
- xPC target
- SCRAMnet
- Experiment setup
- Hybrid control host

Connections:
- Dsp from xPC host to xPC target
- Frc from xPC host to Data acquisition host
- Frc from Data acquisition host to SCRAMnet
- Frc from SCRAMnet to Experiment setup
- Frc from Experiment setup to Hybrid control host
- Dsp from Hybrid control host to Experiment setup
- Dsp from Hybrid control host to xPC target
- Dsp from xPC target to SCRAMnet
- Frc from SCRAMnet to Data acquisition host
Transform DOF (displacement)
Transform DOF (displacement)

Measured forces

Force feedback to OpenSees

Equation 3
Damaged Specimen (100% LA22YY)
Movie – LA22YY(200%)
Movie – Out Of Plane Buckling
Hybrid Simulation Results

The graph shows the inter-story drift ratio (%) as a function of time (sec) for different floors. The x-axis represents time in seconds, ranging from 0 to 15, and the y-axis represents the inter-story drift ratio in percentage. The graph includes data for the 1st, 2nd, and 3rd floors, indicated by different line styles and colors.
Hybrid Simulation Results

3rd Story Left Brace

Axial Force [kips]

3rd Story Right Brace

Axial Force [kips]

2nd Story Left Brace

Axial Force [kips]

2nd Story Right Brace

Axial Force [kips]

1st Story Left Brace

Axial Force [kips]

1st Story Right Brace

Axial Force [kips]
Hybrid Simulation Results

3rd Story Zipper Column


2nd Story Zipper Column

Hybrid Simulation Results

3rd Story Left Column

3rd Story Right Column

2nd Story Left Column

2nd Story Right Column

1st Story Left Column

1st Story Right Column

Axial Force [kips]

Axial Deformation [in]

Axial Force [kips]

Axial Deformation [in]
Analytical Verification
OpenSees Verification

3rd Story Zipper Column

Axial Force [kips]

Time [sec]

Experiment
Analytical

2nd Story Zipper Column

Axial Force [kips]

Time [sec]

Experiment
Analytical
OpenSees Verification

3rd Story Left Column


3rd Story Right Column


2nd Story Left Column


2nd Story Right Column


1st Story Left Column


1st Story Right Column

OpenSees Verification

3rd Story Left Brace

Axial Force [kips]

3rd Story Right Brace

Axial Force [kips]

2nd Story Left Brace

Axial Force [kips]

2nd Story Right Brace

Axial Force [kips]

1st Story Left Brace

Axial Force [kips]

1st Story Right Brace

Axial Force [kips]
Distributed Hybrid Simulation
Summary

- System evaluation of the suspended zipper frame

- Analytical simulation of the brace
  - Modeling the analytical brace using OpenSees

- Quasi-Static testing of the brace
  - Component testing of the brace sub-assembly

- Hybrid simulation test
  - Analytical model + experimental sub-assembly
Conclusion

- Results of the hybrid simulation
  - Excellent match between the hybrid simulation results and analytical simulation.
  - Good analytical brace model and experimental testing.
  - Solution algorithm and experimental testing architecture works.
Application of hybrid simulation test
- Can be used to test multiple sub-assemblies.
- Larger and more complex structural system.
- More extreme loading.
Conclusion cont.

- Behavior of the suspended zipper frame
  - Behave as intended.
  - Many redundancies.
  - Brace buckled of out plane.
  - Zipper column effective transferring unbalanced load.
  - Inter-story drift ratio & permanent story drifts.
  - Rotates the beam. Need to be braced.
  - Axial forces in columns to the support.
OpenSees Navigator

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Stick Model
Beam Model
Inverted-V Braced Frame
Moment Frame
EBF Model
Zipper Frame
Shell & Plate
zipper frame geometry has been generated successfully.
Zipper frame geometry has been generated successfully.
Zipper frame geometry has been generated successfully.
OpenSees Navigator

Define Material:

- Uniaxial Materials:
  - Steel01/Steel02
  - EPP/Elastic/Hysteric
  - Hardening Material
  - Concrete01/Concrete02/Concrete03
  - ...

- nD Materials:
  - Elastic Isotropic
  - Plane Stress
  - ...

OpenSees Navigator

Define Uniaxial Material:

- **Steel01**
  - \( F_y = 50 \text{ ksi} \)
  - \( E = 29000 \text{ ksi} \)
  - \( b = 0.05 \)

Name: A50
### Define Steel01 Material

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Name</td>
<td>A50</td>
</tr>
<tr>
<td>Yield Stress (Fy)</td>
<td>50</td>
</tr>
<tr>
<td>Modulus of Elasticity (E)</td>
<td>29000</td>
</tr>
<tr>
<td>Hardening Ratio (b)</td>
<td>0.05</td>
</tr>
</tbody>
</table>

**Optional Parameters:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iso Hardening Parameter (a1)</td>
<td>0.0</td>
</tr>
<tr>
<td>Iso Hardening Parameter (a2)</td>
<td>1.0</td>
</tr>
<tr>
<td>Iso Hardening Parameter (a3)</td>
<td>0.0</td>
</tr>
<tr>
<td>Iso Hardening Parameter (a4)</td>
<td>1.0</td>
</tr>
</tbody>
</table>
### Define Uniaxial Material

<table>
<thead>
<tr>
<th>Define Uniaxial Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Add Material</td>
</tr>
<tr>
<td>Modify Material</td>
</tr>
<tr>
<td>Delete Material</td>
</tr>
</tbody>
</table>
### Define AISC Patch

<table>
<thead>
<tr>
<th>Patch Name</th>
<th>AISC_Patch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Type</td>
<td>A50</td>
</tr>
<tr>
<td>AISC Section Name</td>
<td>W24X68</td>
</tr>
<tr>
<td>Number of Fibers along dw (nfdw)</td>
<td>10</td>
</tr>
<tr>
<td>Number of Fibers along tw (nftw)</td>
<td>1</td>
</tr>
<tr>
<td>Number of Fibers along bf (nfbf)</td>
<td>10</td>
</tr>
<tr>
<td>Number of Fibers along tf (nfft)</td>
<td>1</td>
</tr>
<tr>
<td>Optional Arguments</td>
<td></td>
</tr>
<tr>
<td>Counter-Clockwise Rot (Theta)</td>
<td>0.</td>
</tr>
</tbody>
</table>
## Define Fiber Section

<table>
<thead>
<tr>
<th>Section Name</th>
<th>1st FI Beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Add Fiber</td>
<td>Fiber</td>
</tr>
<tr>
<td>Modify Fiber</td>
<td></td>
</tr>
<tr>
<td>Delete Fiber</td>
<td></td>
</tr>
<tr>
<td>Add Patch</td>
<td>Quadrilateral</td>
</tr>
<tr>
<td>Modify Patch</td>
<td>AISC_Patch</td>
</tr>
<tr>
<td>Delete Patch</td>
<td>AISC_Patch</td>
</tr>
<tr>
<td>Add Layer</td>
<td>Straight</td>
</tr>
<tr>
<td>Modify Layer</td>
<td></td>
</tr>
<tr>
<td>Delete Layer</td>
<td></td>
</tr>
</tbody>
</table>
Define Section

Add Section: Elastic
Modify Section: 1st Fl Beam
Delete Section: 1st Fl Beam
OpenSees Navigator

Define Element:

◆ Line Element:
  - Truss
  - Elastic Beam Column
  - Nonlinear Beam Column
  - Zero Length Element
  - ...

◆ Solid Element:
  - Quad
  - Shell
  - ...

Define Force Beam Column Element

<table>
<thead>
<tr>
<th>Element Name</th>
<th>Column</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number Integration Points (NIP)</td>
<td>5</td>
</tr>
<tr>
<td>Section Type</td>
<td>Column</td>
</tr>
</tbody>
</table>

Optional Arguments:
- Mass Density (massDens): 0.
- Maximum Iterations (maxIter): 10
- Tolerance (tol): 1E-8
Define Elastic Beam Column Element

Element Name: EColumn
Modulus of Elasticity (E): 29000
Cross-Sectional Area (A): 13.3
Moment of Inertia (Iz): 248

Select Section from Database
Database: AISC
Section Name: W10X45
Direction: strong
OpenSees Navigator

**Define:**
- Geometry
- Material
- Section
- Element
- Loading
- Recorder
- Analysis Option

**Assign:**
- Element
- Loading
To Run OpenSees

Steps:
1. Write OpenSees Input Files (writes TCL files)
2. Save OpenSees.exe Path (needs to be done only once)
3. Run OpenSees
Mode Shape: 1st Mode
Mode Shape: 3rd Mode
Response

![Graph showing response analysis with parameters and nodes/elements indicated.](image-url)
Hysteresis Loops

Nonlinear Dynamic Analysis
Hybrid Simulation Example

Experimental Chevron Brace Element
Define Experimental Control

Templates:
- dSpace 1104
- xPC Target
- SCRAMNET 150
- BeamColumnSim
- ChevronBraceSim
Define ExpControl: xPC Target
Define Experimental Setup

Templates:
- OneActuator
- TwoActuators
- ThreeActuators
- ChevronBrace
- ChevronBraceJntOff
Define ExpSetup: ChevronBrace

<table>
<thead>
<tr>
<th>Setup Name</th>
<th>BraceExpSetupIntOff</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental Control Type</td>
<td>braceExpCtrlIntOff</td>
</tr>
<tr>
<td>Geometry Type (nGeomFlag)</td>
<td>nonlinear, horizontal right</td>
</tr>
<tr>
<td>Actuator Length 1 (La1)</td>
<td>121.5</td>
</tr>
<tr>
<td>Actuator Length 2 (La2)</td>
<td>175.625</td>
</tr>
<tr>
<td>Actuator Length 3 (La3)</td>
<td>175.625</td>
</tr>
<tr>
<td>Rigid Link Length 1 (L1)</td>
<td>53</td>
</tr>
<tr>
<td>Rigid Link Length 2 (L2)</td>
<td>108</td>
</tr>
<tr>
<td>Rigid Link Length 3 (L3)</td>
<td>108</td>
</tr>
<tr>
<td>Rigid Link Length 4 (L4)</td>
<td>53</td>
</tr>
<tr>
<td>Rigid Link Length 5 (L5)</td>
<td>24.625</td>
</tr>
<tr>
<td>Rigid Link Length 6 (L6)</td>
<td>24.625</td>
</tr>
</tbody>
</table>

**Optional Parameters**

- Dsp Control Factor (dspCtrlFact): [1 1 1]
- Vel Control Factor (velCtrlFact): [1 1 1]
- Acc Control Factor (accCtrlFact): [1 1 1]
- Dsp Daq Factor (dspDaqFact): [1 1 1 1 1]
- Force Daq Factor (frcDaqFact): [1 1 1 -1 -1]

![Image of Chevron Brace setup](image)
Define Experimental Site

Templates:
- LocalSite
- RemoteSite
- NEESExprSite
Define ExpSite: RFS
Define ExpElement: ChevronBrace

<table>
<thead>
<tr>
<th>Element Name</th>
<th>ExpBrace1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental Site Type</td>
<td>RFS</td>
</tr>
<tr>
<td>Initial Stiffness (initStif)</td>
<td>250 0 0 0 0 0 434.4 0 0</td>
</tr>
<tr>
<td>I-Modification (iMod)</td>
<td>no</td>
</tr>
<tr>
<td>Optional Arguments</td>
<td></td>
</tr>
<tr>
<td>Mass Density 1 (massDens1)</td>
<td>0</td>
</tr>
<tr>
<td>Mass Density 2 (massDens2)</td>
<td>0</td>
</tr>
</tbody>
</table>
Modify Analysis Options

Integrator Type:
Use AlphaOS Method for Hybrid Simulation

Solution Algorithm:
The AlphaOS Method requires a Linear solution algorithm
Mode Shape: 1\textsuperscript{st} Mode
Response

![Plot Response](image)

- **AnalysisCase**: LA22YY
- **Recorder**: Dep[10,1], Dep[10,2]
- **Parameter**: DefoShape, Time, Node, Sec, DOF
- **Node/Elem**: 10, 2
- **DOF**: 0

Time = 0.000
Application Examples

1) Three-Span-Bridge

Properties of Model:

- num. DOF = 12 (4 with mass)
- Period: $T_1 = 0.918$ sec
- Damping: $\zeta_1 = 0.02$
- ExpElement: EEBeamColumn2d
- ExpSetup: ESOOneActuator
- ExpControl: ECxPCtarget
Application Examples

2) Two-Story-Shear

Properties of Model:

- num. DOF = 14 (6 with mass)
- Period: \( T_1 = 0.618 \text{sec} \)
  \( T_2 = 0.236 \text{sec} \)
- Damping: \( \zeta_1 = 0.02 \)
- ExpElements: EEBeamColumn2d
- ExpSetups: ESOneActuator
- ExpControl: ECxPPtraget
Application Examples

3) Two-Story-Frame

Properties of Model:
- num. DOF = 28 (4 with mass)
- Period: $T_1 = 0.473$ sec, $T_2 = 0.071$ sec
- Damping: $\zeta_1 = 0.02$
- ExpElements: EEBeamColumn2d
- ExpSetups: ESOOneActuator
- ExpControl: ECxPControl
Conclusion

A hybrid simulation test has been conducted.
- Close match between the analytical and experimental results verifies the applicability of the experiment method.

Graphical user interface creates the OpenSees hybrid model and graphically displays results before, during and after a test.

Three additional examples of hybrid simulation test presented.
Thank you!

Development and operation of the nees@berkeley Equipment Site is sponsored by NSF George E. Brown Jr. NEES grants.

http://nees.berkeley.edu
http://peer.berkeley.edu/~yang/NEESZipper/
http://peer.berkeley.edu/OpenSeesNavigator/