Hybrid simulation evaluation of the suspended zipper braced frame

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Inverted-V braced frame
Suspended zipper braced frame

Shaking table test
Quasi-static test

Analytical simulation

Experimental testing

Hybrid simulation test

Advantages:

- Numerical hard to model.
- New systems.
  \[ \Rightarrow \] Economical.
- Test structure to extreme states.
  \[ \Rightarrow \] Collapse.
- Geographically distributed tests.
  \[ \Rightarrow \] Share resources.
  \[ \Rightarrow \] Larger and complex structures.
Scope of the test

- Develop an analytical brace model
  - Simulate the brace buckling response.

- Quasi-static test of the brace sub-assembly
  - Verify the analytical brace force-deformation hysteretic response.

- Hybrid simulation test of the suspended zipper braced frame
  - Model the system response using both analytical elements and physical elements in the laboratory.

Modeling of analytical brace

- Material: $\sigma - \varepsilon$
- Section: $M - \kappa$
- Component: $F - \Delta$
Modeling of analytical brace

Displacement-based nonlinear beam column element

Force-based nonlinear beam column element

Brace behavior under cyclic displacement loading

Rotational spring  Mid node  Rotational spring

Force-based NL BC element  Force-based NL BC element

Uriz and Yang
Hysteretic response of analytical brace

Axial deformation [in.]  
Axial force [kips]

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Test setup

1/3 - scale

Instrumentation
Instrumentation
Quasi-static test

Displacement

Applied displacement history

Inter-story drift ratio [%] vs Time [sec]

SF = 2, Time = 0 sec

Brace 1

Brace 2

Normalized axial force [%] vs Normalized axial deformation [%]
Photograph of damaged specimen

Out-of-plane buckling of the braces
Out-of-plane buckling of the gusset plate

Brace deformation
Axial forces of the braces

- Brace 1
- Brace 2

0.75 % inter-story drift ratio

Unbalanced forces

- Unbalanced vertical force [kips]
- Unbalanced out-of-plane force [kips]
Rotation of the supporting beam

![Graph showing rotation of the supporting beam over time.]

Finite element model

![Diagram of a finite element model with rotational springs and force-based BC elements.]
Hysteretic response of the braces

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Equations of motion

\[ M \ddot{u}_n + C \dot{u}_n + P_r (u_n, \dot{u}_n) = P_n \]

- Dynamic Loading
  - Seismic
  - Wind
  - Blast/Impact
  - Wave
  - Traffic

analytical model of structural energy dissipation and inertia

physical model of structural resistance

Integration algorithm

- Newmark average acceleration integration method
  \[ u_{n+1} = u_n + h \dot{u}_n + h^2 (\ddot{u}_n + \ddot{u}_{n+1}) / 4 \]
  \[ \dot{u}_{n+1} = \dot{u}_n + h (\ddot{u}_n + \ddot{u}_{n+1}) / 2 \]
  No added numerical damping and unconditionally stable.

- Form equilibrium equations at next time step

\[ M \ddot{u}_{n+1} + C \dot{u}_{n+1} + P_r (u_{n+1}, \dot{u}_{n+1}) = P_{n+1} \]

\[ F(u) = M \left( \frac{4}{h^2} (u - u_n) - \frac{4}{h} \dot{u}_n - \ddot{u}_n \right) + C \left( \frac{2}{h} (u - u_n) - \ddot{u}_n \right) \]

\[ + P_r (u, u_n, \dot{u}_n, \ddot{u}_n) - P_{n+1} = 0 \]
Experimental testing architecture

- Simulation PC
- Finite element model
- Physical specimen(s)
- Random time interval
  - Model complexity
  - Processor speed
  - Communication delay
  - Force

Fixed time interval (@ 1024 Hz)

- Test PC
- Servo-control Program

Transformation of displacement dof

- Ignore rotational dof
- Equation 1
- Equation 2
Equation 3

Transformation of force dof

Measured forces

Feedback forces to finite element model

Movie – 100% Kobe Earthquake

NEES Lab Thu Jun 16 12:31:35 2005
Movie – 200% Kobe Earthquake

Out-of-plane buckling of the braces
Hysteric responses of the braces

Brace axial deformations [in.]

Brace axial forces [kips]

1st story left brace
1st story right brace
2nd story left brace
2nd story right brace
3rd story left brace
3rd story right brace

Hysteric responses of the zipper columns

Axial force [kips]

Axial deformations [in.]

3rd story zipper column
2nd story zipper column
Hysteric responses of the columns

Analytical verification - roof drift ratio
Analytical verification – brace axial forces

Experiment  Analytical

Analytical verification – ZC axial forces

Experiment  Analytical
Geographically distributed test

University of California, Berkeley

University of Colorado, Boulder

Test setup at Colorado University Boulder
Transformation of displacement dof

Transformation of force dof
Input ground motions – Kobe (80% - 100%)

Ground accelerations [g]

Time [sec]

Hysteric responses of the braces

Brace axial forces [kips]

Brace axial deformation [in.]
Hysteric responses of the zipper columns

3rd story zipper column

Axial Force [kips]

-50 -50 -0.08 -0.06 -0.04 -0.02 0 0.02 0.04 0.06 0.08 0.1
Axial deformation [in.]

2nd story zipper column

Axial Force [kips]

-50 -50 -0.08 -0.06 -0.04 -0.02 0 0.02 0.04 0.06 0.08 0.1
Axial deformation [in.]

Hysteric responses of the columns

3rd story left column

Axial forces [kips]

-50 -50 -0.05 0 0.05
2nd story left column

Axial forces [kips]

-50 -50 -0.05 0 0.05
1st story left column

Axial forces [kips]

-50 -50 -0.05 0 0.05
3rd story right column

Axial forces [kips]

-50 -50 -0.05 0 0.05
2nd story right column

Axial forces [kips]

-50 -50 -0.05 0 0.05
1st story right column

Axial forces [kips]

-50 -50 -0.05 0 0.05
Summary

- Conduct a system evaluation of the suspended zipper braced frame.
- Develop an analytical brace model
  - Simulate the brace buckling response.
- Quasi-static test of the brace sub-assembly
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Conclusions

- Behavior of the suspended zipper braced frame
  - Behave as intended.
  - Many redundancies.
  - Braces buckled out of plane.
  - Zipper columns are effective in transferring unbalanced vertical forces.
  - Beams are rotated out of plane, needed to be braced.
  - Plastic hinges developed at the column base. Base plate of the column bases need to be designed for the ultimate strength of the column.
Conclusions (cont.)

- Results of the hybrid simulation test
  - First hybrid simulation test to combine complex analytical and experimental elements.
  - Excellent match between the hybrid and analytical simulation results.
  - This shows the analytical brace model, 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.
  - Can test the structure to extreme states.

Question!

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Resource:
http://peer.berkeley.edu/~yang/NEESZipper/