Hybrid Simulation of Complex Structural Systems

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Outline

• Failure of Bridges during Past Earthquakes
• Need for Advanced Experimental Simulation Capabilities
• Hybrid Simulation
  – Capabilities and Challenges
  – Numerical Integration Procedures
  – Monitoring of Experimental Errors
  – Distributed Testing Capabilities
Bridge Failures in Past Earthquakes
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Need for Experimental Research in Earthquake Engineering

• Provide an improved understanding of structural behavior
• Verify numerical modeling
• Proof-of-concept testing of new materials and protective systems
• Provide laboratory test data for developing structural fragilities from initial loading to collapse
Experimental Facilities in the U.S.

- **Network for Earthquake Engineering Simulation (NEES)** is a shared national network of 14 experimental facilities, collaborative tools, a centralized data repository, and earthquake simulation software.
Experimental Methods

Seismic Performance Assessment of Structural Systems
- Quasi-Static Testing
- Shaking Table Testing
- Effective Force Testing
- Hybrid Simulation
Seismic Performance of Precast Segmental Bridges - University at Buffalo Shake Tables

- 1/2.4 scale single span bridge specimen
- ABC (Accelerated Bridge Construction) techniques
- Unbonded internal tendons
- Simple friction-type connections

http://seesl.buffalo.edu/projects/accelbridge/default.asp
Seismic effects on Multi-span bridges with high degrees of horizontal curvature - University of Nevada, Reno Shake Tables

- 2/5 scale model of a three-span bridge.
- 145 ft long with an 80 ft radius at the centerline.
- Test on four shake tables in the laboratory.
- The superstructure consists of three steel girders and a 12 ft wide concrete deck.

http://nees.unr.edu/projects/curved_bridge.html
Hybrid Simulation Test Method

- Equation of motion for prototype structure

\[ ma + cv + r = f \]

- Hybrid simulation combines:
  - Physical models of structural resistance
  - Computer models of structural damping and inertia

- Enables seismic testing of large- or full-scale structural models

- Solve equation of motion using numerical integration algorithms
Test Procedure

Newmark time-stepping integration algorithm

\[ ma_{i+1} + cv_{i+1} + r_{i+1} = f_{i+1} \]

\[ d_{i+1} = d_i + \Delta t v_i + \frac{1}{2} \Delta t^2 a_i \]

\[ v_{i+1} = v_i + \frac{1}{2} \Delta t (a_i + a_{i+1}) \]
Methods of Hybrid Simulation

• Conventional pseudodynamic test
  – Ramp and hold loading procedure

• Continuous pseudodynamic test
  – Specimen is loaded continuously at slow rates to avoid the hold phase and relaxation in specimen

• Real-time pseudodynamic test
  – Specimen is loaded at correct velocities to account for rate-dependent behavior
  – Dynamic inertial forces are modeled numerically

• Real-time dynamic hybrid testing
  – Dynamic inertial loads included in experiment
  – Shake table substructures

• Geographically distributed tests
  – One or more remote substructures
Implementation Issues

- **Integration Algorithms**
  - Implicit or explicit
  - Integration time step
- **Rate of testing**
  - Time scaling
  - Pseudo-dynamic vs. dynamic
  - Continuous vs. ramp-hold load history
  - Material strain rate effects
  - Observation of damage
- **Experimental Errors**
  - Actuator tracking errors
  - Propagation of errors

**Central Difference**

**Newmark’s Method**

\[
ma_{i+1} + cv_{i+1} + r_{i+1} = f_{i+1}
\]

\[
d_{i+1} = d_i + \Delta t v_i + \frac{1}{2} \Delta t^2 a_i
\]

\[
v_{i+1} = v_i + \Delta t (a_i + a_{i+1})
\]
Structural Model

• Modeling Issues
  – Selection of experimental substructures – components of structure that are difficult to model
  – Interface boundary conditions between physical and numerical model
  – Scale of experimental substructure limited by equipment capabilities
Modeling Issues

- Assume force release at boundary to simplify experimental setup
- Consider available equipment in laboratory
Holistic Simulation

- Substructures at different length scales
Hybrid Testing of a Bridge – NEES/E-Defense Collaborative Research

- Simulates seismic response of a continuous bridge by a distributed hybrid simulation with OpenFresco and OpenSees.
- The bridge consists of a RC C-bent column, a RC single column, a steel single column, steel girder and elastomeric bearings.

http://nees.berkeley.edu/Projects/reports/nees-edefensePresentation.pdf
Hybrid Testing of a Bridge – NEES/E-Defense Collaborative Research

Hybrid Modeling for Bridge System

Numerical Component (fiber model) at Kyoto University
Experimental Component of C-bent RC column at Kyoto University
Experimental Component of Steel single column at nees@berkeley

Coupling of torsion and flexure can be considered automatically.

http://nees.berkeley.edu/Projects/reports/nees-edefensePresentation.pdf
Multi-Site Soil-Structure-Foundation Interaction Test (MISST)

University of Illinois at Urbana-Champaign (UIUC), Rensselaer Polytechnic Institute (RPI), and Lehigh University (Lehigh)

Multi-Site Soil-Structure-Foundation Interaction Test (MISST)

Division of model structure

Multi-Site Soil-Structure-Foundation Interaction Test

Multi-Site Soil-Structure-Foundation Interaction Test (MISST)

May 16-17, 2006

Testing of Complex Structures

- Most previous applications of hybrid simulation have been on simple structural models with few degrees of freedom
  - Lack of robust implicit integration algorithms
  - Sensitivity of the results to experimental errors for stiff systems of higher modes

(Shao 2007)
Integration Algorithms

• Fully implicit methods typically used in numerical simulations are difficult to implement with experimental substructures
  - Iterations can cause erroneous damage or energy dissipation in experimental substructures
  - Tangent stiffness matrix is difficult to estimate

• Hybrid Simulation integration procedures are predominantly explicit, or use initial stiffness matrix approximations, e.g., Operator-Splitting Method (Nakashima et al. 1990)

• Implicit integration with specialized implementation schemes mainly focused on real-time testing
New Integration Procedures for Hybrid Simulation

- Develop integration procedures with improved stability and accuracy suitable for hybrid simulation
  - Combined Implicit and Explicit Integration Procedure
    - Implicit procedure that limits communication between integrator and experiments
    - Fail-safe procedures provides backup explicit solution in case numerical integrator does not converge
  - Modified Operator-Splitting Integration with Tangent Stiffness Estimation
    - Capture the instantaneous behavior of experimental substructure and improves corrector step
  - Implementation procedure for fully implicit integration methods designed for pure numerical simulations
    - Strategy for safe iterations and procedure to estimate tangent stiffness implemented at element level
Implicit Integration Procedure

- An implicit $\alpha$-operator-splitting method formulation is used
- Determine the predictor displacement:
  \[
  \tilde{d}_n = d_{n-1} + \Delta t \ v_{n-1} + \frac{\Delta t^2}{2} a_{n-1}
  \]
- Apply displacement and measure restoring force
- Update the experimental tangent stiffness matrix,
- Use the updated tangent stiffness to calculate new states:
  \[
  a_n = B_n^{-1} \left\{ \begin{array}{l}
  M^i \bar{u}_g \left( t_n + \alpha \Delta t \right) - C \left[ v_{n-1} + \left( 1 + \alpha \right) \left( 1 - \gamma \right) \Delta t \ a_{n-1} \right] \\
  + \alpha \left( K d_{n-1} + r_{n-1} - M^e a_{n-1} \right) \\
  - \left( 1 + \alpha \right) \left[ \bar{r}_n + \left( K + K^e \right) \left( \tilde{d}_n - \beta \Delta t^2 a_{n-1} \right) - T^T K^e l \tilde{l}_{i,m} \right]
  \end{array} \right. 
  \]
  \[
  d_n = \tilde{d}_n + \beta \left( \Delta t \right)^2 \left( a_n - a_{n-1} \right) 
  \]
  \[
  v_n = v_{n-1} + \left( 1 - \gamma \right) \Delta t a_{n-1} + \gamma \Delta t a_n 
  \]
  \[
  r^l_n = \bar{r}^l_n + K^e l \left( d^l_n - \tilde{d}_{i,m}^l \right)
  \]
- Iterate until convergence criteria is satisfied
Iteration Strategy for Experimental Substructures

- *In iterations*, estimate experimental restoring force for iterative displacements using fitted polynomials
- Note that for distributed test, iterative displacements do not need to be sent to remote sites
Convergence Issues

- Convergence is not guaranteed, but simulation must go on....
  - If the iterations do not converge:
    - Leave the displacement unchanged and use explicit expressions to update acceleration and velocity:
      \[
      a_n = A^{-1} \left\{ M \dddot{u}_g (t_n) - \left[ C^a \left( v_{n-1} + \frac{\Delta t}{2} a_{n-1} \right) + K^a d_n + r^e \right] \right\}
      \]
      \[
      v_n = v_{n-1} + \frac{\Delta t}{2} (a_{n-1} + a_n)
      \]
      \[
      A = M^a + \frac{\Delta t}{2} C^a
      \]
    - Or make a one-step correction using initial stiffness or tangent stiffness (Operator-Splitting approach):
Use of sporadic explicit steps

• Characteristics:
  – Prevents the accumulation of errors as it may occur using a fully explicit algorithm:

  ![Graph showing displacement over time with different integration methods]
Tangent Stiffness Matrix

- Many popular integrators such as Operator-Splitting method use initial stiffness matrix for corrector step
  - Tangent stiffness better captures the actual behavior of the experimental substructure and improves rate of convergence:
Estimation of Tangent Stiffness Matrix

- Updating the Stiffness Matrix
  - In each step, only one pair of force-displacement measurement is available per actuator \(\implies\) need to decouple the stiffness matrix to reduce the number of unknowns and directly use experimental measurements
    - Define an intrinsic coordinate system or modal coordinate system in which stiffness matrix is diagonal:
      \[
      K_{n}^{e,l} = T_{p}^{T} P_{n} T_{p}
      \]
      with transformation from actuator (local) to global coordinate system being:
      \[
      K_{n}^{e} = T^{T} K_{n}^{e,l} T
      \]
Tangent Stiffness Estimation

- Experimental verifications with 2DOF building model:
Experimental Studies

- Sample Experimental Results from hybrid simulation
Experimental Studies

- Sample Experimental Results

Estimated Experimental Stiffness Matrix in Actuator Coordinate System
Experimental Studies

- Sample Experimental Results

**Estimated Experimental Stiffness Matrix in Diagonal Form – local element DOFs**
Experimental Studies

• Sample Experimental Results

Captured Experimental Hysteretic Behavior
Numerical Studies

- Numerical Simulation Results

Energy Balance Error versus Ductility and Time Step – Use of Tangent Stiffness improves simulation accuracy
Numerical Studies

- Numerical Simulation with Highly Nonlinear Experimental Substructure

Actual Hysteresis

Observed Hysteresis

Converged Hysteresis

Measured Moment, kN-m

Feedback Moment, kN-m

Final Moment, kN-m

Measured Rotation, Deg

Desired Rotation, Deg

Final Rotation, Deg

Conventional Operator-Splitting Method
Numerical Studies

- Numerical Simulation with Highly Nonlinear Experimental Substructure

*Improved Operator-Splitting Method with Experimental Tangent Stiffness*
Errors in Hybrid Simulations

- $d_a$ = actual imposed displacement
- $d_c$ = command displacement
- $d_m$ = measured displacement
- $r_m$ = measured restoring force
Effects of actuator delay on measured specimen response

Loading and unloading of linear-elastic element

- Resisting force
- Displacement
- Energy added
- Energy absorbed

Undershooting (lag)  Overshooting
Effects of actuator delay on measured specimen response

Loading and unloading of linear-elastic element

Best Estimate of energy in experimental element

\[ E^{BE} = \int r_m d(d_m) \]

Energy introduced into numerical simulation

\[ E^E = \int r_m d(d_c) \]
Numerical Errors

• Objective is to solve equation of motion using time stepping integration procedure
  – e.g., Newmark’s Method in explicit form

\[
ma_{i+1} + c v_{i+1} + r_{i+1} = f_{i+1}
\]

\[
d_{i+1} = d_i + \Delta t v_i + \frac{1}{2} \Delta t^2 a_i
\]

\[
v_{i+1} = v_i + \frac{1}{2} \Delta t \left( a_i + a_{i+1} \right)
\]

• Satisfy dynamic equilibrium
• Satisfy kinematics relations – derivatives of displacement and computed velocity and acceleration
Numerical Errors

- Comparison of integration methods ($\Delta t=0.05$) for 2DOF shear building ($T=0.6,0.13$ sec),
Numerical Errors

- How can results be verified when the “exact” answer is not known?
- Unbalance error between input energy from earthquake excitation and internal energy stored and dissipated by structural model (Filiatrault et al. 1994)
Monitoring Errors in Hybrid Simulation

Although equilibrium is satisfied in each step, need to examine relationships between displacement, velocity and acceleration.

\[ \mathbf{v} = \dot{\mathbf{u}}, \quad \mathbf{a} = \ddot{\mathbf{u}} \]

- Use time derivative of displacement in place of velocity for displacement in place of velocity.

This is the energy observed by the numerical simulation based on command displacement;

But actual experimental displacements may be modified by delay compensation, and forces may be corrected for actuator tracking errors.

- Use actual energy dissipated by or stored in the experimental substructure.

### Kinetic Energy
\[ E_K = \frac{1}{2} \mathbf{u}^T \mathbf{M} \mathbf{u} \]

### Damping Energy
\[ E_D = \int \mathbf{u}^T \mathbf{C} \mathbf{u} \, \mathrm{d}t \]

### Strain Energy
\[ E_S = \int \mathbf{u}^T \mathbf{K} \mathbf{u} \, \mathrm{d}t \]

### Experimental Energy
\[ E_E^C = \int \mathbf{r}^T \, \mathrm{d}u \]

### Actual Experimental Energy
\[ E_E = \int (\mathbf{r}^m)^T \, \mathrm{d}u^m \]
Relation between displacement and velocity

- Computing velocity as derivative of displacement in numerical simulation

\[ \dot{u}_n = \frac{1}{2} (u_n - u_{n-1}) \]

(a) Explicit Newmark

(b) Operator-splitting
Overall Energy Error in Hybrid Simulation

- Effect of integration time step on displacement history and error indicator for numerical simulation
  - Explicit Newmark method
Overall Energy Error in Hybrid Simulation

- Effect of integration time step on displacement history and error indicator for numerical simulation
  - Operator Splitting Method
Overall Energy Error in Hybrid Simulation

- Unbalance energy measure also captures difference between observed and measured behavior of experimental substructure (experimental errors)
Experimental Simulation

- Monitoring of energy unbalance during actual hybrid simulation can indicate large errors in a simulation and possible instability
- Provide early warning of instability
Towards Collapse Simulation of Structures

• Develop advanced hybrid testing methods that can simulate seismic response to collapse
  – Implicit numerical integration algorithms
  – Substructuring techniques, how to partition structure and apply boundary conditions
  – Compensation of experimental errors
• Apply hybrid simulation to complex structural models
  – Evaluate seismic response of realistic buildings models
• Verify capability to trace failure to collapse
  – Compare response of hybrid simulation to shake table test of full-scale steel moment frame building
Four story steel moment resisting frame tested to collapse at E-Defense Japan, Sept. 2007
Internationally Distributed Test, July 2009

Reproduce E-Defense shake table collapse using hybrid simulation

Half-scale experimental substructures of lower 1 ½ stories – collapse mechanism

Buffalo, USA

Kyoto, Japan

Coordinator
Hardware architecture

Kyoto Facilities Through GPBIB

Kyoto

StationUS with Matlab (Local Socket)

Kyoto Buffalo through Scramnet

TCP/IP

xPC

Buffalo Facilities

Coordinator and Numerical Model

Proxy Socket

Proxy PC

Proxy Socket

Proxy Socket

Kyoto Buffalo
Selection of substructures

Test first story experimentally, also include half of second story to simplify boundary with assumed hinges at center of beams and columns.
Distributed Hybrid Simulation of a Steel Moment Frame to Collapse

University at Buffalo, USA

Kyoto University, Japan
Comparison of shake table and hybrid test

Top of first story center column
Comparison of shake table and hybrid test

First Story Hysteretic Behavior

E-Defense
Distributed Test

Drift Angle (rad)

Story Shear (kN)

-1500 -1000 0 500 1000 1500

-0.05 -0.04 -0.03 -0.02 -0.01 0 0.01 0.02 0.03 0.04 0.05

First story force-displacement response for 60% Takatori
Comparison of shake table and hybrid test

First Story Hysteretic Behavior

- Story Shear (kN)
- Drift Angle (rad)

- E-Defense
- Distributed Test
Summary

• Integration procedure provides improved stability and accuracy as a step towards testing large and complex structural systems
  – Use of general implicit integration algorithms designed for pure numerical simulations
  – Procedure to estimate tangent stiffness matrix for experimental substructures
  – Safe iteration strategy for experimental substructures
• These procedures are being implemented in OpenSEES/Openfresco framework as experimental substructure element
• Framework can be applied to real-time simulations and provide significant advantages for fast distributed testing
Summary

- Verified effectiveness of hybrid testing for realistic collapse simulation by comparison with shake table test results of full scale frame
- Demonstrate that hybrid testing is a safe and economical alternative for collapse simulation
- Use of international geographically distributed testing for large scales testing of structural systems
- Use of advanced numerical modeling (FEM, implicit integration) to capture degradation of numerical model
- Examined substructuring techniques and effects of boundary condition assumptions
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THANK YOU!

Questions?
Questions

• What are the advantages of hybrid simulation?
• What additional difficulties are encountered in implementing implicit methods in a hybrid simulation compared to a numerical simulation?
• Why is there a need to compute the tangent stiffness matrix for experimental substructures?
• In addition to those errors found in numerical simulations, what additional sources of errors are present in a hybrid simulation?
• What are the effects of errors in a hybrid simulation and how can errors be measured in a hybrid test?