Seismic Performance Evaluation of Large-scale Structural Systems using Hybrid Simulation

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Overview

- Hybrid Simulation
- Capabilities for hybrid simulation at UB-NEES
  - Available equipment
  - Versatile configurations
- Geographically distributed testing using NEESgrid
  - Fast-MOST
- Modeling of complex structural systems
  - Errors in hybrid simulation
  - Implementation of implicit integration algorithms
  - Monitoring errors in a simulation
- Experimental verification of new testing procedures
NEES

- Network for Earthquake Engineering Simulation (NEES)
  - 16 seismic testing facilities distributed throughout US
- “Transform” earthquake engineering research
  - Provide shared use and remote access to state-of-the-art experimental facilities
  - Distributed equipment sites linked through internet
  - Experimental data repository
Experimental Methods

Experimental Methods for Structural Evaluation:
- Quasi-Static Loading Testing
- Shaking Table Testing
- Effective Force Testing
- Hybrid Simulation
**Hybrid Simulation Testing 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
Multiple Substructures

- There are no limits:
  - Many physical substructures: **hard models**
  - Many analytical substructures: **soft models**
- Physical substructures are component that are difficult to model numerically
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
Test Procedure

Time-stepping integration algorithm

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

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

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

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

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

\[ v_{i+1} = v_i + \frac{\Delta t}{2} \left( a_i + a_{i+1} \right) \]
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 – substructures can be at different scales
Structural Model

- **Modeling Issues**
  - Assume force release at boundary to simplify experimental setup
  - Consider available equipment in laboratory

Assume pin connection
Structural Model

- Modeling Issues
  - Substructures at different length scales
Equipment for Hybrid Simulation at UB

- Provide a versatile national facility for earthquake engineering research
- Shake tables
- Static and dynamic actuators
  - Various displacement and force capacities
- MTS Hybrid Simulation Controller
- xPC programmable environment for real-time custom applications and compensation algorithms
- Instrumentation and data acquisition system
Relocatable Shake Tables

- Two 6-DOF Shake Tables (3.6x3.6m)
- 50 metric ton capacity (each) (100 ton combined)
- Relocatable in the 115 ft. trench
- Fully in phase or independent operation up to 100Hz
- Controllers
  - Conventional Control Techniques
  - MTS Adaptive Control Techniques
Large Dynamic and Static Actuators and Controllers

- 3 x 100 tons Dynamic Actuators
- 2 x 200 tons Static Actuators
- Flex-Test Controllers and Software
- STS Controller (MTS469) – Custom
2-D Large Scale Geotechnical Laminar Box

- Modular Multilayer-Laminate-Bearing Design; 5.0x2.75x6.2m (85 cubic meter maximum capacity)
- Simulate 2-D Ground Response for Soil-Foundation-Structure Interaction Studies at or Near Full Scale
- 1-g Geotechnical Studies (Compliment Centrifuge)
Nonstructural Component Simulator

- Two level platforms (3.8x3.8m)
- 3.1 metric ton capacity each level
- Dynamic loading-3g horizontal accelerations, 2.5 m/s velocities and ± 1m displacements
Control Hardware

Local or Remote Structural Simulator

Physical Substructure

Shake Table

Structural Actuator

Internet

Real Time Hybrid Simulation Controller

Structure Simulator Host

Compensating Controller

NTCP Server

General Purpose Device

SCRAMNet A/D & D/A Bridge

Compensation Controller Host

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New Hybrid Simulation Method

Real Time Dynamic Hybrid Simulation (RTDHS) -- Combined use of earthquake simulators, actuators and computational engines for simulation.

Real Time: Loading rate is real event rate

Dynamic: Inertia effect is physically realized

Hybrid: Combination of physical test and numerical simulation

Simulation: Replicate structure behavior under earthquake input

**Response Feedback**

- Acceleration input: Table introduce inertia force
- Actuator drive force control

**Ground/Shake Table**

**Physical Substructure**

**Computational Substructure**
**Applications**

- Allow testing of full scale substructures
- Allow testing of strain rate effects
- Includes inertial effects in distributed mass systems

**Test computational tools and physical specimens**
- Allow production of computational tools validated by experiments

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Example

Fast-MOST – Fast Multi-Site Online Simulation Test
6-span bridge model
- Deck and selected columns are numerical models
- Other columns are experimental models

Computational Sites:
Buffalo (deck)
UIUC
Lehigh

Experimental Sites:
Berkeley
Boulder
Buffalo
Numerical Simulation

- Bridge model was subjected to 15 seconds of ground shaking
- Operator-splitting integration algorithm
  - Integration time step of 0.01 seconds
  - 1500 simulation steps
- Numerical simulation integrated with the Simulation Coordinator
Improvements for Fast Continuous Testing

- Parallel communication with remote sites
  - Implement multi-threaded Simulation Coordinator
- Streamlined communications protocol (NTCP)
  - Minimize network communication
  - Reduce overhead caused by security protocols
- Event-driven controller
  - Fault-tolerant mechanics to deal with uncertainties
  - Reduce load time for experimental substructures
  - Implement algorithms for continuous loading
Structural Model

6-span bridge model
- Modeled as planar frame – pin connection at deck interface
- Experimental substructure have similar displacement demands
Remote Substructures

**Berkeley**
- Stiffness 0.49kN/mm
- Yield disp. 16mm
- Max. disp. 100mm

**Buffalo**
- Stiffness 0.32kN/mm
- Yield disp. 8mm
- Max. disp. 25mm

The displacement and forces were scaled to match the initial stiffness of the numerical full-scale column. Different length scales used for each site
Simulation Protocol

Preparation steps to verify network communication with all experimental and numerical substructures

- Local numerical simulation at each sites
- Local simulation including experimental setup
- Distributed test with remote numerical simulations
- Distributed test with single experiment included, other sites simulated numerically
- Complete distributed test

Simulink models of UB-NEES equipment available for pre-test simulations
Simulation Results

- Response is due to the actual measured behavior of the physical specimens (Buffalo & Berkeley)
- Remaining (3) column substructures were simulated numerically
Timing Results

- Simulation took 1074 sec.
- Average step time 0.66 sec.
- Four substantial delays
  - Three ~ 23 sec.
  - One ~ 3 sec.
- Multiple recovery from network timeouts in the TCP and Application layers
Effects of Pausing Experiment

- Force relaxation during network delays introduces errors into numerical simulation – avoided in other steps through continuous loading methods

![Restoring force vs. Displacement graph]

- Restoring force (kN) vs. Displacement (mm)
Lessons Learned

• Scheduling multi-site tests is difficult
  – Organizing 5 different sites and having equipment and personnel free at the same time is not easy

• Usage of some communication channel is essential – several options available at NEES sites
  – Audio/Video conference
  – Chat room
Simplification of Structural Models

Discretization

Condensation

Model Condensation Example
Testing of Complex Structures

- 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 in the presence of higher modes or stiff systems
- Current research efforts
  - Measures to monitor quality of simulation results in real-time
  - Mitigation measures for experimental errors
  - Implicit integration algorithms
Errors in Hybrid Simulation

- Structural model idealization
- Numerical integration of equation of motion
- Experimental errors - random and systematic
  - Actuator displacement control errors
  - Actuator response lag
  - Measurement errors
  - Strain-rate effects and force relaxation
Errors in Hybrid Simulations

- integrator
- signal generation
- on-line computer
- D/A
- PID
- Controller
- servo-valve actuator
- hydraulic supply
- servo-hydraulic system
- specimen transducers
- experimental substructure

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

Loading and unloading of linear-elastic element

Overshooting

Undershooting (lag)

energy absorbed

energy added

resisting force

displacement

resisting force

displacement

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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

\[ E^E = \int r_m d(d_c) \]
Results of hybrid simulation with and without actuator delay compensation

(a) Second story drift (mm)

(b) First story drift (mm)
Energy Errors

\[ E^{\text{error}} = \int r_m d(d_m) - \int r_m d(d_c) \]
Hybrid Simulation Error Monitor

\[
\left( \frac{E_{\text{error}}}{E_{\text{strain}}} \right)
\]

\[
\left( \frac{E_{\text{error}}}{E_{\text{input}} + E_{\text{strain}}} \right)
\]

(a)

(b)
Integration Algorithms

- Fully implicit methods typically used in FEM are not straightforward to implement in a hybrid simulation
  - Iterations difficult to implement with experimental substructures
  - Tangent stiffness matrix of experimental substructure is difficult to estimate due to noise in measurements.
- As a result, most integration procedures are either explicit, or use initial stiffness matrix approximations
- Most popular integration algorithm is Operator-Splitting Method (Nakashima et al. 1990)
  - Use explicit method for experimental substructure, implicit method for numerical substructure
**Integration Algorithms**

- Proposed procedures for improved stability and accuracy in hybrid simulation:
  - Combined Implicit and Explicit Integration Procedure
  - Modified Operator-Splitting Integration with Tangent Stiffness Estimation

Designed for high-frequency, stiff, or highly nonlinear systems, where current methods are not satisfactory.
Combined Implicit and Explicit Approach

- Based on a modified implicit procedure that updates the states (displacement, velocity and acceleration) in the same way as an explicit method.

- Uses the measurements along the loading path to estimate forces corresponding to iterative displacements.

- Defaults to the explicit solution in case of convergence failure.
Combined Implicit and Explicit Approach

Algorithm:

- Determine displacement using an explicit expression:

\[ d_n^d = d_{n-1} + v_{n-1} \Delta t + a_{n-1} \frac{\Delta t^2}{2} \]

- Measure experimental restoring force
- Fit polynomials to measured force and displacements versus time
- Solve iteratively:

\[ a_n^{i+1} = \frac{1}{m} \left(-m \ddot{u}_{g,n} - r^i_n - c v_n^i\right) \]

\[ v_n^{i+1} = v_{n-1} + \Delta t \left[(1 - \gamma) a_{n-1} + \gamma a_n^{i+1}\right] \]

\[ d_n^{i+1} = d_{n-1} + \Delta t v_{n-1} + \Delta t^2 \left[\left(\frac{1}{2} - \beta\right) a_{n-1} + \beta a_n^{i+1}\right] \]
Combined Implicit and Explicit Approach

Algorithm:

- In iterations, estimate experimental restoring force for iterative displacements using fitted polynomials:
Combined Implicit and Explicit Approach

- Algorithm:
  - If convergence of implicit integration method fails, use explicit method solution in current step:

\[
a_n = \frac{1}{m + c \Delta t/2} \left( -m \ddot{u}_{g,n} - r^e_n - c v_{n-1} - c a_{n-1} \frac{\Delta t}{2} \right)
\]

\[
v_n = v_{n-1} + \frac{\Delta t}{2} \left( a_{n-1} + a_n \right)
\]

- Next step ...
Combined Implicit and Explicit Approach

• Benefits:

  – Improve the accuracy and stability of simulation by minimizing accumulation of errors in implicit steps

  – Can be combined with operator-splitting method to use the initial stiffness in steps with failed convergence.

  – Enables the user to use longer time steps, or test stiffer systems.
Combined Implicit and Explicit Approach

- Experimental verifications of 2DOF building model:
Combined Implicit and Explicit Approach

- Sample Experimental Results:

**Explicit Integration (First Period = 0.5 s, 2.5% Tabas Earthquake)**
Combined Implicit and Explicit Approach

- Sample Experimental Results:

![Combined Implicit and Explicit Integration](image)

- Displacement, in
- Time, s

DOF 1
DOF 2
Estimation of Tangent Stiffness Matrix

- Difficult to extract specimen tangent stiffness matrix from measured data
  - Several procedures have been proposed for purposes other than integration algorithms
- Convergence of implicit integration methods can be improved by using updated tangent stiffness matrix
- Operator-splitting integration method can be improved by using updated tangent stiffness matrix
- A reduced stiffness matrix is proposed to estimate tangent stiffness
- Stiffness matrix remains unchanged in steps with small displacement increments.
Estimation of Tangent Stiffness Matrix

**Algorithm:**

- Determine predictor displacement:
  \[
  \ddot{d}_{n+1} = d_n + \Delta t v_n + \left(\frac{1}{2} - \beta\right) \Delta t^2 a_n
  \]

- Apply displacement and measure restoring force.

- Make corrections using updated acceleration:
  \[
  d_{n+1} = \tilde{d}_{n+1} + \beta \Delta t^2 a_{n+1}
  \]
  \[
  v_{n+1} = v_n + \frac{\Delta t}{2} (a_n + a_{n+1})
  \]
  \[
  r^e_{n+1} = \tilde{r}^e_{n+1} + K^{el} (d_{n+1} - \tilde{d}_{n+1}) = \tilde{r}^e_{n+1} + \beta \Delta t^2 K^{el} a_{n+1}
  \]

where the updated acceleration is found using initial stiffness approximation:

\[
a_{n+1} = \left( M^a - \alpha M^e + (1 + \alpha) \gamma \Delta t C^a + \beta \Delta t^2 (1 + \alpha) (K^a + K^{el}) \right)^{-1} \times
\]

\[
\begin{bmatrix}
C^a (v_n + (1 - \gamma) \Delta t a_n) + K^a \tilde{d}_{n+1} + (1 + \alpha) \tilde{r}^e_{n+1} - \alpha r_n + \\
\alpha (M^e a_n + (1 - \gamma) \Delta t C^a a_n + K^a (\Delta t v_n + \left(\frac{1}{2} - \beta\right) \Delta t^2 a_n))
\end{bmatrix}
\]
Estimation of Tangent Stiffness Matrix

- Algorithm Modification by Updating Stiffness Matrix:
  - Define an intrinsic coordinates system in which stiffness matrix is diagonal:
    \[ K^E_i = T_p^T P T_p \]
    with transformation from actuator (local) to global coordinates system being:
    \[ K^E = T^T K^E_i T \]

\[
K^E_i = \begin{bmatrix}
    k_{11} & k_{12} \\
    k_{21} & k_{22}
\end{bmatrix}
\]

\[
P = \begin{bmatrix}
    s_1 & 0 \\
    0 & s_2
\end{bmatrix}
\]
Estimation of Tangent Stiffness Matrix

- Algorithm Modification by Updating Stiffness Matrix:
  - Each “significant” force-displacement pair is transformed to intrinsic coordinates system using

  \[ \Delta x^p_i = T_p \Delta x^l_i = T_p T \Delta x_i \]

  \[ \Delta r^p_i = T_p^{(-T)} \Delta r^l_i \]

  \[ \Delta r^p_i = P T_p \left( K^E_{i,i} \right)^{-1} \Delta r^l_i = T_{p,i}^{(-T)} \Delta r_i^l \]

  For statically determinate substructures:

  For indeterminate substructures:

- The new stiffness matrix in the intrinsic coordinates system is then:

  \[ P = \text{diag} \left( \Delta x^p_i \right)^{-1} \text{diag} \left( \Delta r^p_i \right) \]

  which can be transformed to actuator coordinates system using:

  \[ K^E_i = T_p^{T} P T_p \]
Estimation of Tangent Stiffness Matrix

- Sample Experimental Results:

*First Period=0.6 s, 40% Tabas Earthquake*
Estimation of Tangent Stiffness Matrix

- Sample Experimental Results:

  → Shows acceptable performance of stiffness estimation.
Estimation of Tangent Stiffness Matrix

- Estimated Stiffness Matrix in Actuator Coordinates System:

![Graph showing stiffness over time](image)
Estimation of Tangent Stiffness Matrix

- Numerical Simulation with Highly Nonlinear Experimental Substructure:

**Operator-Splitting Method**

- Actual Hysteresis
- Observed Hysteresis
- Converged Hysteresis
Estimation of Tangent Stiffness Matrix

- Numerical Simulation with Highly Nonlinear Experimental Substructure:

**Operator-Splitting Method Combined with Implicit Steps**

- Actual Hysteresis
- Observed Hysteresis
- Converged Hysteresis

![Graphs showing hysteresis comparisons](image)
Estimation of Tangent Stiffness Matrix

- Numerical Simulation with Highly Nonlinear Experimental Substructure:

**Operator-Splitting Method with Tangent Stiffness**
Summary

• Improve capabilities for experimental testing using hybrid simulation and NEES
• Procedures for fast distributed testing have been developed and implemented
• Examined sources of error and proposed mitigation strategies to enable testing of complex structural systems
  - Real-time hybrid simulation error monitor to detect unacceptable level of errors
  - Compensation procedures to improve force and displacement measurements
  - Procedure to estimate tangent stiffness matrix for experimental substructures
  - Use of implicit integration algorithms for hybrid testing
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Questions?