

Hybrid Simulation: Sub-structures

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The George E. Brown, Jr. Network for Earthquake Engineering Simulation



Hybrid Model

- ◆ Physical model of structural resistance
- ◆ Computer models of structural damping and inertia

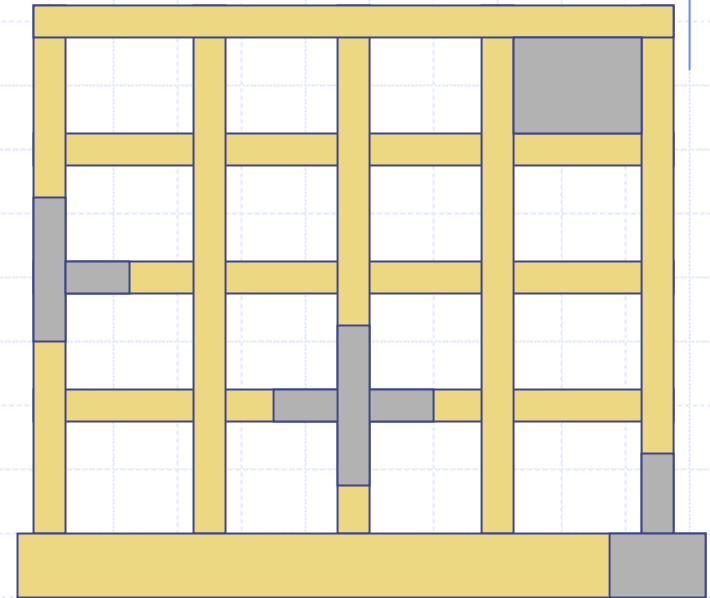
$$ma + cv + r = -m\ddot{u}_g$$

$$ma + m\ddot{u}_g + cv = -r$$

- ◆ By definition, a hybrid model is sub-structured

Multiple Substructures

- ◆ There are no limits:
 - Many physical substructures: **hard models**
 - Many analytical substructures: **soft models**
- ◆ Testing infrastructure must enable:
 - Simulation of individual substructures
 - Integration of the equations of motion



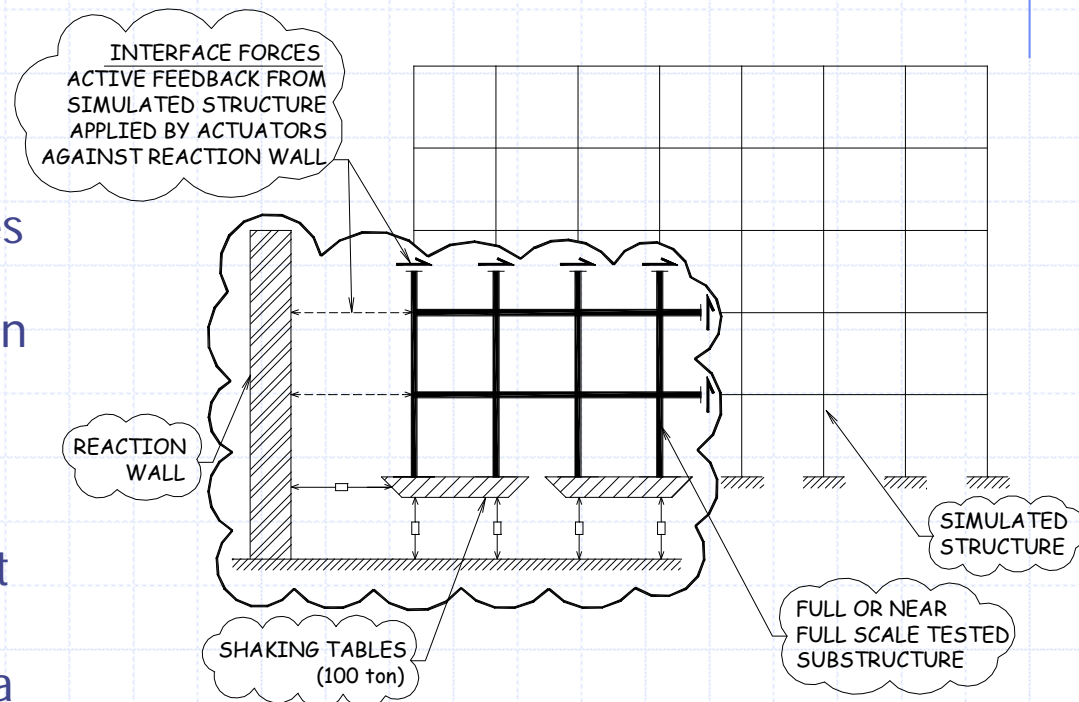
Advantages and Disadvantages

◆ Advantages:

- Physically model resistance of sub-structures whose computer models are not good enough
- Model the inertia forces (and damping, and second order effects) in the computer

◆ Disadvantages:

- Sub-structures are connected and interact at their boundaries
- Specimens have inertia and damping, too



Equation of Motion

$$\begin{bmatrix} m_{pp} & m_{pc} \\ m_{cp} & m_{cc} \end{bmatrix} \begin{Bmatrix} \ddot{u}_p \\ \ddot{u}_c \end{Bmatrix} + \begin{bmatrix} c_{pp} & c_{pc} \\ c_{cp} & c_{cc} \end{bmatrix} \begin{Bmatrix} \dot{u}_p \\ \dot{u}_c \end{Bmatrix} + \begin{Bmatrix} R_p \\ R_c \end{Bmatrix} = - \begin{bmatrix} m_{pp} & m_{pc} \\ m_{cp} & m_{cc} \end{bmatrix} \begin{Bmatrix} \ddot{u}_{pg} \\ \ddot{u}_{cg} \end{Bmatrix}$$

◆ Restoring forces can be assembled

◆ However, so can:

- Damping forces from physical dampers
- Inertia forces from the mass of the physical specimens

Interfaces btw. sub-structures

- ◆ Equilibrium and compatibility must be satisfied
- ◆ Deformations and forces
 - Displacement (relatively easy)
 - Rotation (very difficult)
- ◆ Opportunity to do:
 - DOF condensation
- ◆ Coordinate transformations
 - Physical to numerical DOF's
- ◆ Geometry corrections
 - Actuator movements

$$d = T\bar{d}$$

More sub-structuring

◆ Damping and inertia:

- Explicit consideration of physical dampers and physical masses, based on measured velocities and accelerations
- DOF condensation must be done carefully
- Coordinate transformations must be propagated to velocities and accelerations

◆ Second order effects:

- Geometric stiffness may be assembled into the resistance: $\bar{r} = r - K_g d$

Thank you!

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<http://nees.berkeley.edu>

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