Hybrid Simulation: Sub-structures

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Hybrid Model

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

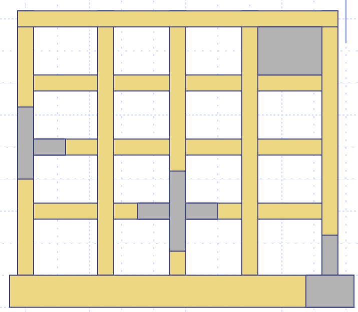
$$ma + cv + r = -m\ddot{u}_g$$

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

- By definition, a hybrid model is sub-structured

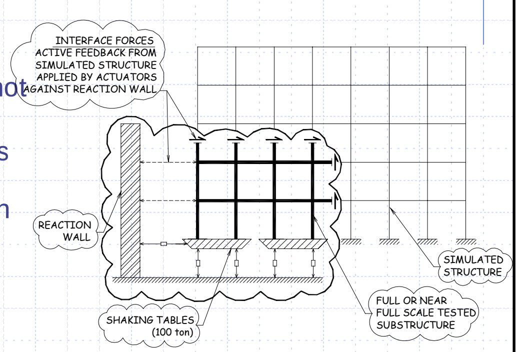
Multiple Substructures

- 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

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

- Geometry corrections
  - Actuator movements

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: $\overline{r} = r - K_g d$

Thank you!

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http://nees.berkeley.edu

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