Cyber-Physical Systems

Andreas Schellenberg
Stephen Mahin

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UNIVERSITY OF CALIFORNIA

Outline of Presentation

1. Motivation
2. Cyber-Physical Systems
3. Hybrid Simulation Testing Method
4. OpenFresco Middleware
5. BLWT Applications
    1. Aerodynamic Loading
    2. Ramp/Hold Wind HS
    3. Real-Time Wind HS
6. Summary & Conclusions

Motivation

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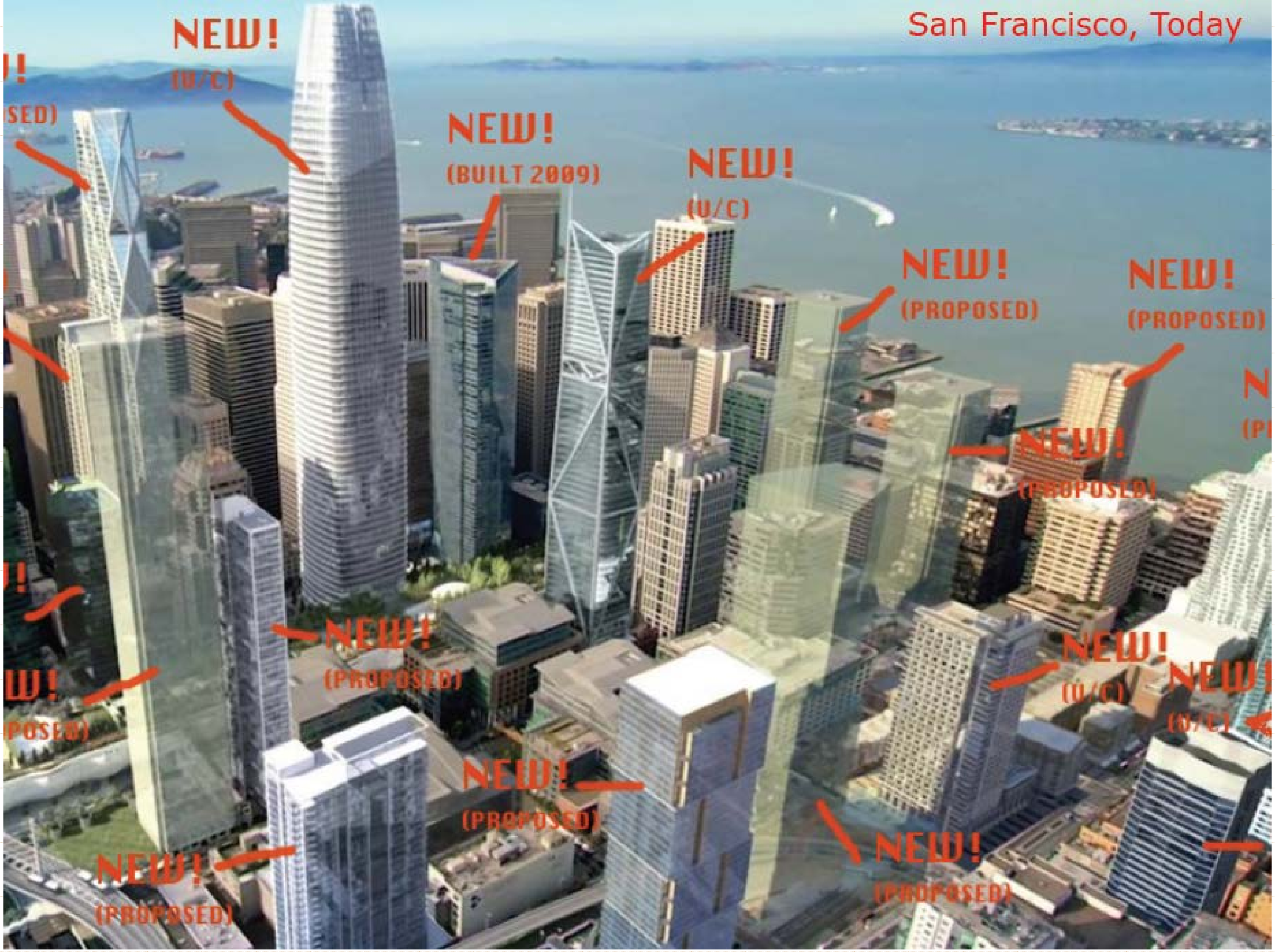
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Motivation

- Progress in natural hazard engineering is driven by:
  - Urbanization
  - Architecture
  - Natural Hazards
- Improve resilience to natural hazards by advancing knowledge and understanding of the complex response and behavior of new and existing civil structures during and after such events

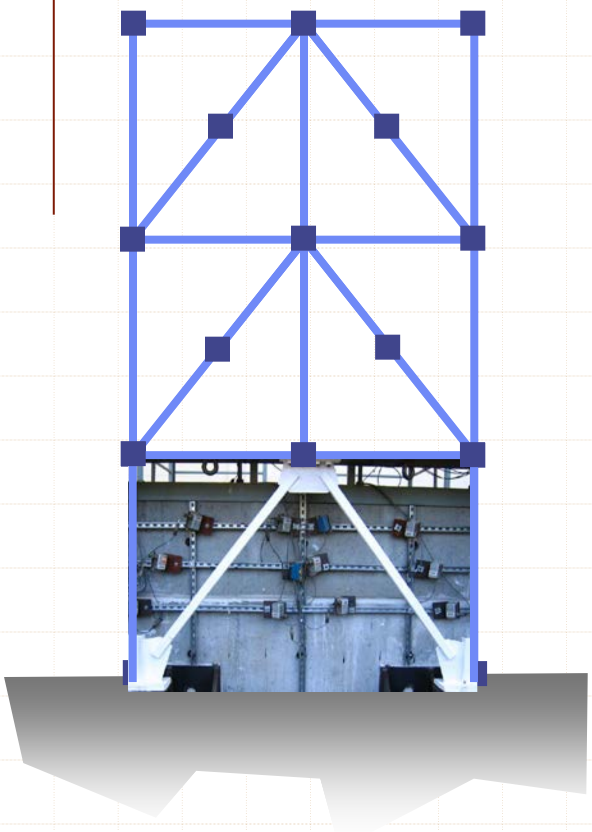
→ Cyber-physical systems that integrate experimental testing with numerical simulation are invaluable and foster collaboration

Cyber-Physical Systems (CPS)

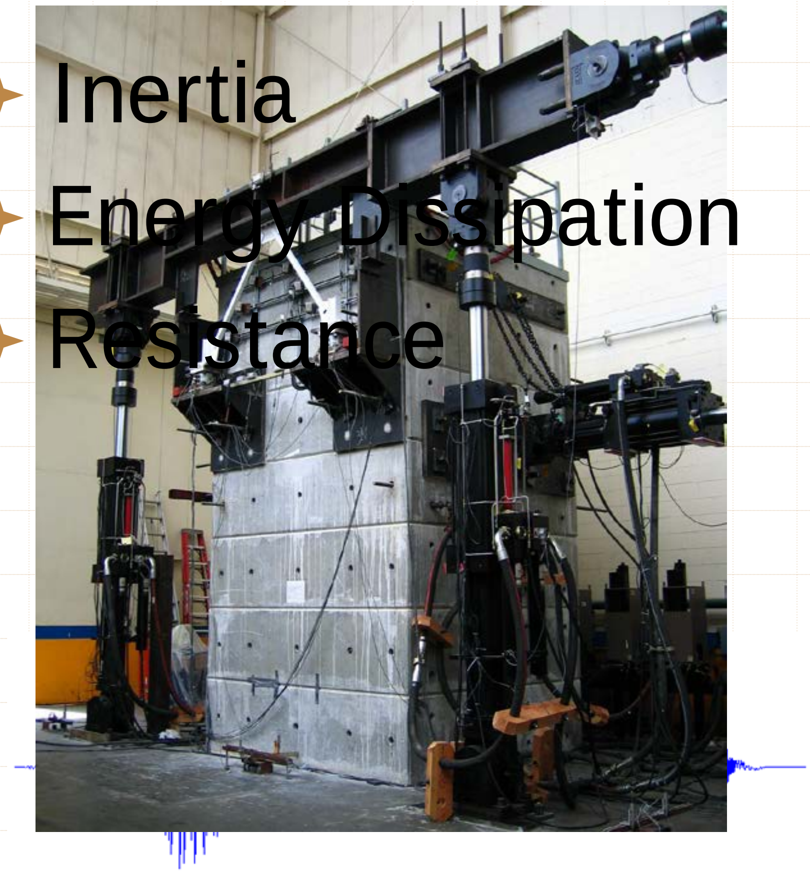
- A system where *physical and software components are deeply intertwined, each operating on different spatial and temporal scales, exhibiting multiple and distinct behavioral modalities, and interacting with each other in a myriad of ways that change with context* (from US NSF)
- Hybrid Simulation (HS), a flexible and economical experimental testing method, can be considered a cyber-physical system
- Control system aspects play a central role in CPS as well as HS

Structural Hybrid Simulation

$$\mathbf{M}\cdot\ddot{\mathbf{u}}+\mathbf{C}\cdot\dot{\mathbf{u}}+\mathbf{P_r}(\mathbf{u})=\mathbf{P}(t)$$



- Inertia
- Energy Dissipation
- Resistance

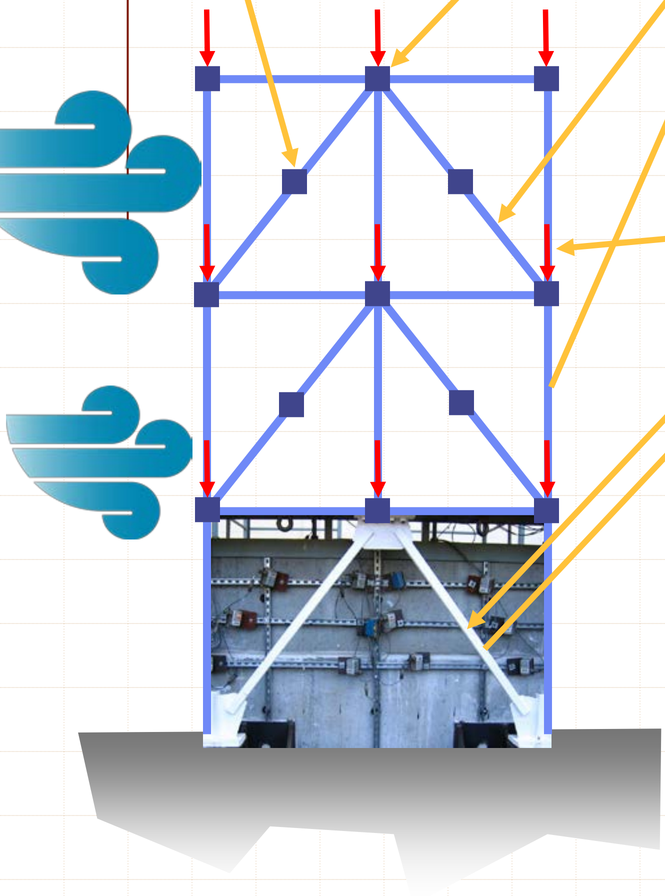


Struct. Hybrid Simulation

$$\mathbf{M}\cdot\ddot{\mathbf{u}}+\mathbf{C}\cdot\dot{\mathbf{u}}+\mathbf{P_r}(\mathbf{u})=\mathbf{P}(t)$$

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

Static Loading:
- Gravity
- Prestress



analytically add nonlinear geometric effects to measured resisting forces

analytical model of structural energy dissipation and inertia

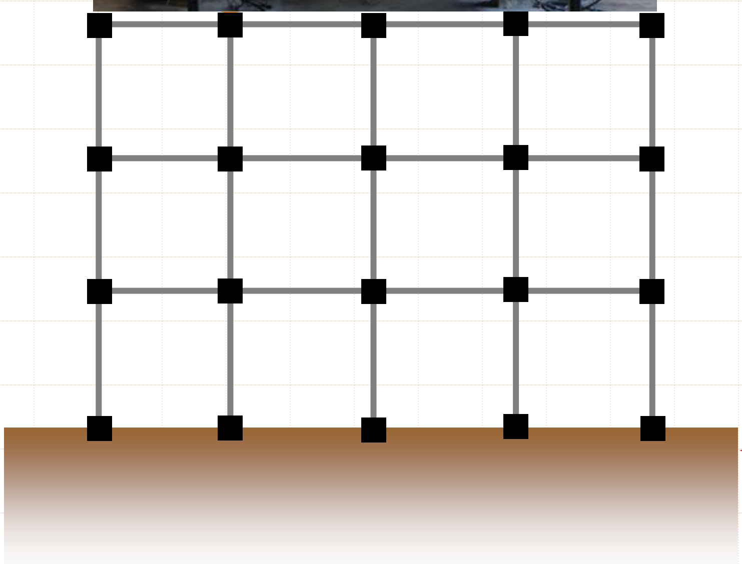
physical model of structural resistance

Hybrid Shake Table

$$\mathbf{M}\cdot\ddot{\mathbf{u}}+\mathbf{C}\cdot\dot{\mathbf{u}}+\mathbf{P}_{\mathbf{r}}\left(\mathbf{u},\dot{\mathbf{u}},\ddot{\mathbf{u}}\right)=\mathbf{P}\left(t\right)$$

Dynamic Loading:

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



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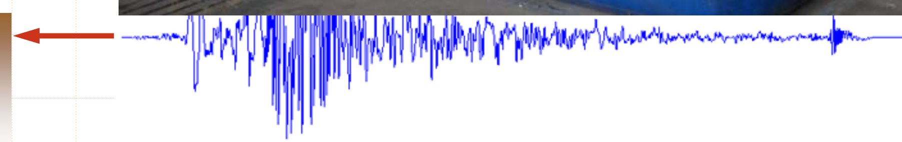


Hybrid Simulation

- Model the well understood parts of a structure in a finite element program on one or more computers (HPC possible)
- Leave the construction and testing of the highly nonlinear and/or numerically hard to model parts of the structure or loading conditions in one or more laboratories
- Can be considered as a conventional finite element analysis where physical models of some portions of the structure are embedded in the numerical model

Testing Methods

- Conventional hybrid simulation test where specimen is loaded using a ramp-and-hold loading procedure
- Continuous test where specimen is loaded at a continuous slow to moderately slow rate to avoid load relaxations
- Real-time test where specimen is loaded at correct velocities to account for rate-dependent material behaviors
- Geographically distributed network test

Equations of Motion

1. Slow test

$$\mathbf{M}\ddot{\mathbf{U}}_{i+1} + \mathbf{C}\dot{\mathbf{U}}_{i+1} + \mathbf{P}_{\mathbf{r}}^{A}\left(\mathbf{U}_{i+1},\dot{\mathbf{U}}_{i+1}\right) + \mathbf{P}_{\mathbf{r}}^{E}\left(\mathbf{U}_{i+1}\right) = \mathbf{P}_{i+1} - \mathbf{P}_{\mathbf{0},i+1}$$

2. Rapid test

$$\mathbf{P}_{\mathbf{r}}^{E}\left(\mathbf{U}_{i+1}\right) = \mathbf{P}_{\mathbf{r},i+1}^{E} - \mathbf{M}^{E}\ddot{\mathbf{U}}_{i+1}^{E} - \mathbf{C}^{E}\dot{\mathbf{U}}_{i+1}^{E}$$

3. Real-time test

$$\mathbf{M}^{A}\ddot{\mathbf{U}}_{i+1} + \mathbf{C}^{A}\dot{\mathbf{U}}_{i+1} + \mathbf{P}_{\mathbf{r}}^{A}\left(\mathbf{U}_{i+1},\dot{\mathbf{U}}_{i+1}\right) + \mathbf{P}_{\mathbf{r}}^{E}\left(\mathbf{U}_{i+1},\dot{\mathbf{U}}_{i+1},\ddot{\mathbf{U}}_{i+1}\right) = \mathbf{P}_{i+1} - \mathbf{P}_{\mathbf{0},i+1}$$

$$\mathbf{P}_{\mathbf{r}}^{E}\left(\mathbf{U}_{i+1},\dot{\mathbf{U}}_{i+1},\ddot{\mathbf{U}}_{i+1}\right) = \mathbf{P}_{\mathbf{r},i+1}^{E} + \mathbf{M}^{E}\ddot{\mathbf{U}}_{i+1}$$

4. Hybrid shake table test

$$\mathbf{P}_{\mathbf{r}}^{E}\left(\mathbf{U}_{\mathbf{t},i+1},\dot{\mathbf{U}}_{\mathbf{t},i+1},\ddot{\mathbf{U}}_{\mathbf{t},i+1}\right) = \mathbf{P}_{\mathbf{r},i+1}^{E} + \mathbf{M}^{E}\ddot{\mathbf{U}}_{\mathbf{t},\,i+1}$$

What is OpenFresco?

- Open source Framework for Experimental Setup and Control
- Secure, object oriented, network enabled "middleware" -- Pairs computer analysis software with laboratory control/daq systems and other software to connect components in cyber-physical systems:
  - Computational Drivers
    - OpenSees
    - OpenFresco*Express*
    - Abaqus
    - LS-DYNA
    - Matlab
    - Simulink
    - Ansys
    - UI-SimCor
    - OpenFOAM
  - Control and DAQ Systems
    - dSpace
    - MTS
      - STS family
      - Flextest/CSI
      - Flextest/Scramnet
      - 469D
    - National Instruments
    - Pacific Instruments
    - ADwin

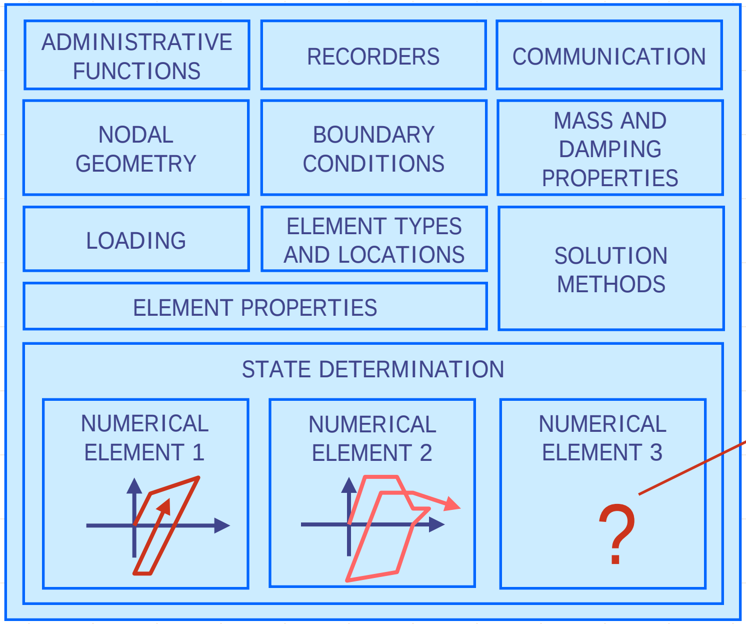
Why a Software Framework?

- Lack of a common framework for development and deployment of HS
- Problem specific implementations which are site and control system dependant
- Such highly customized software implementations are difficult to adapt to different cyber-physical problems

→ Need a robust, transparent, adaptable, and easily extensible software framework for research and deployment

Rethinking implementation strategies

- Embed test specimen(s) in an existing computational framework of user's choice

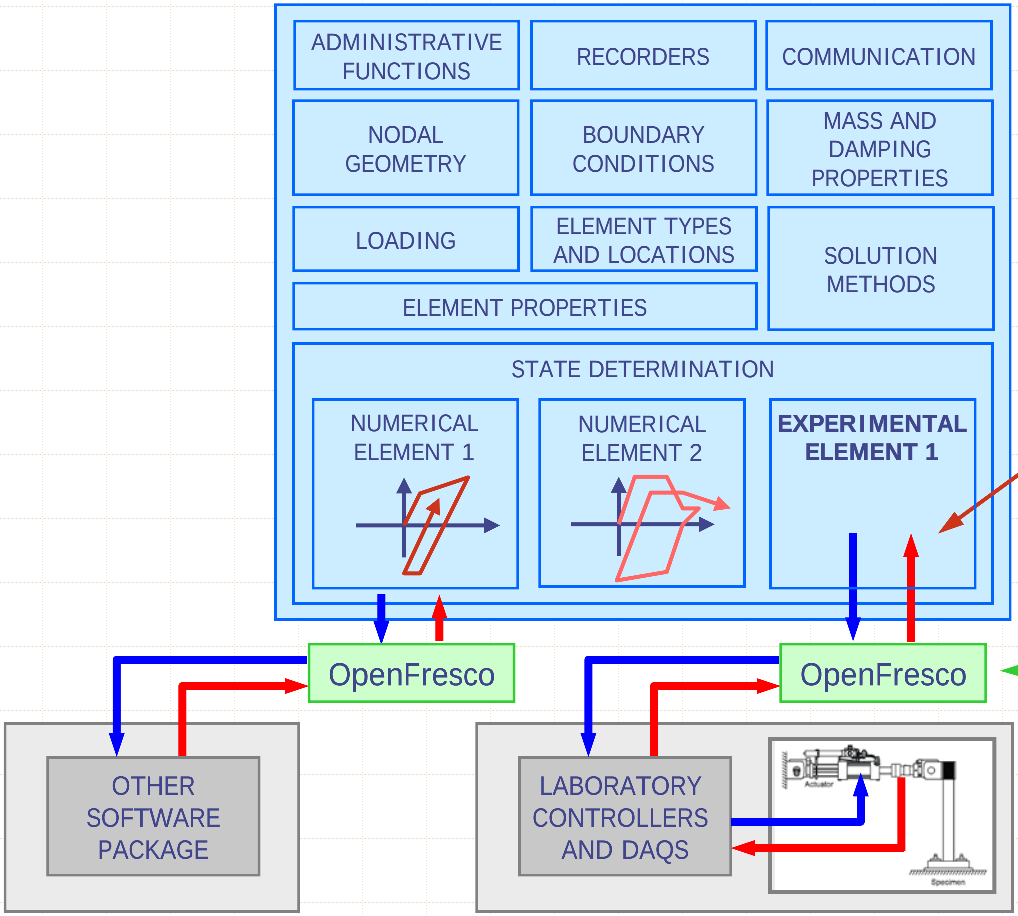


Typical features of an analysis framework

Proper numerical model uncertain

Rethinking implementation strategies

- Embed test specimen(s) in an existing computational framework of user's choice



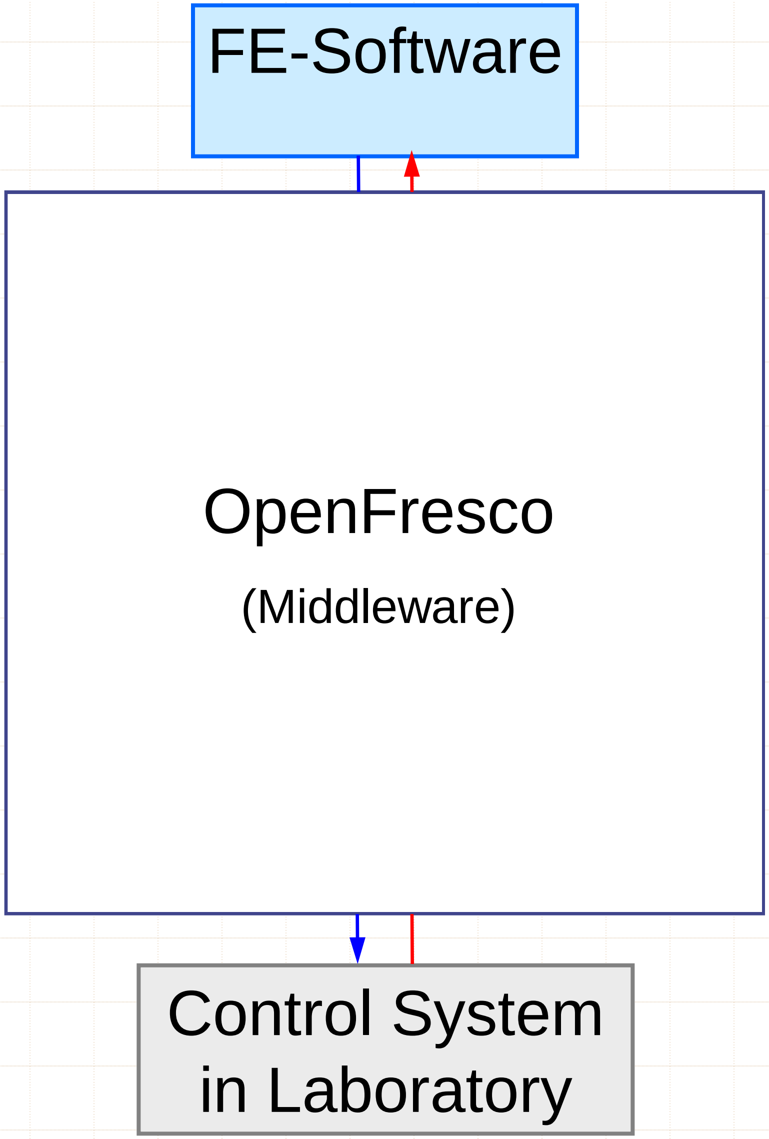
Typical features of an analysis framework

Define element as an "Experimental Element"

OpenFresco

Laboratory

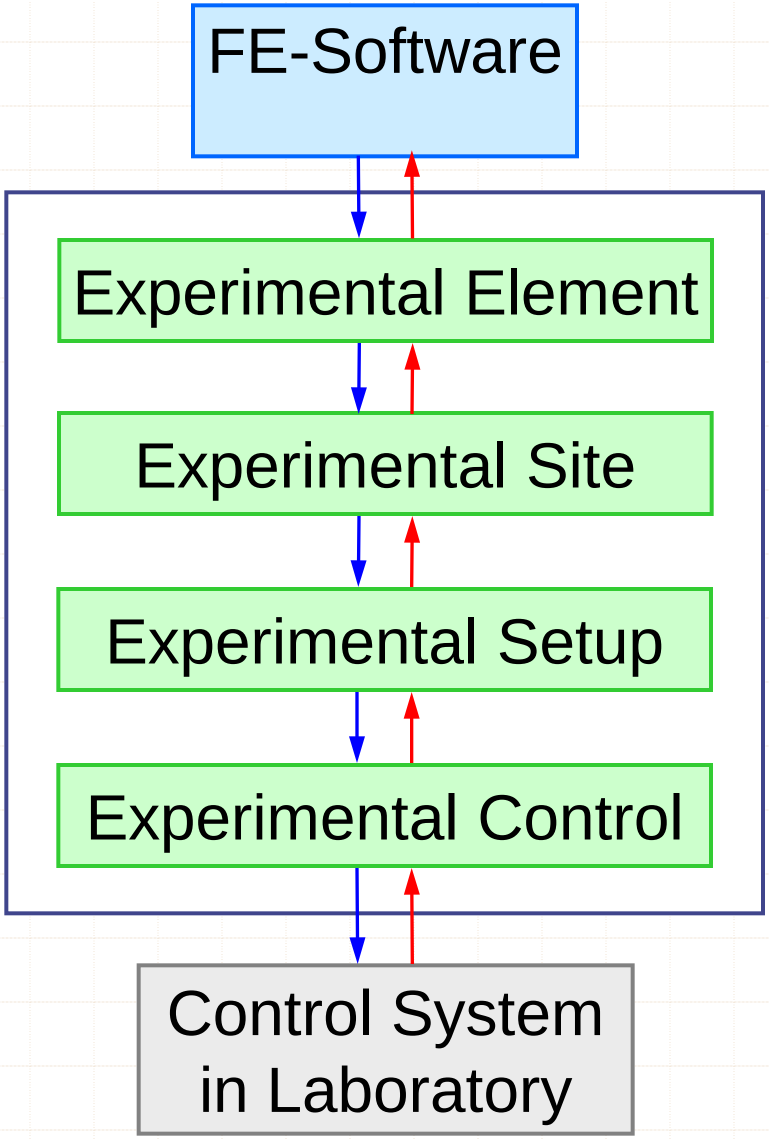
OpenFresco Components



provides all features of unmodified computational framework, including parallel and network computing

provides control of physical actuators as well as data acquisition using physical instrumentation devices

OpenFresco Components



provides all features of unmodified computational framework, including parallel and network computing

represents the part of the structure that is physically tested and provides the interface between the FE-software and the experimental software framework

stores data and provides communication methods for distributed testing

transforms between the experimental element degrees of freedom and the actuator degrees of freedom (linear or non-linear transformations)

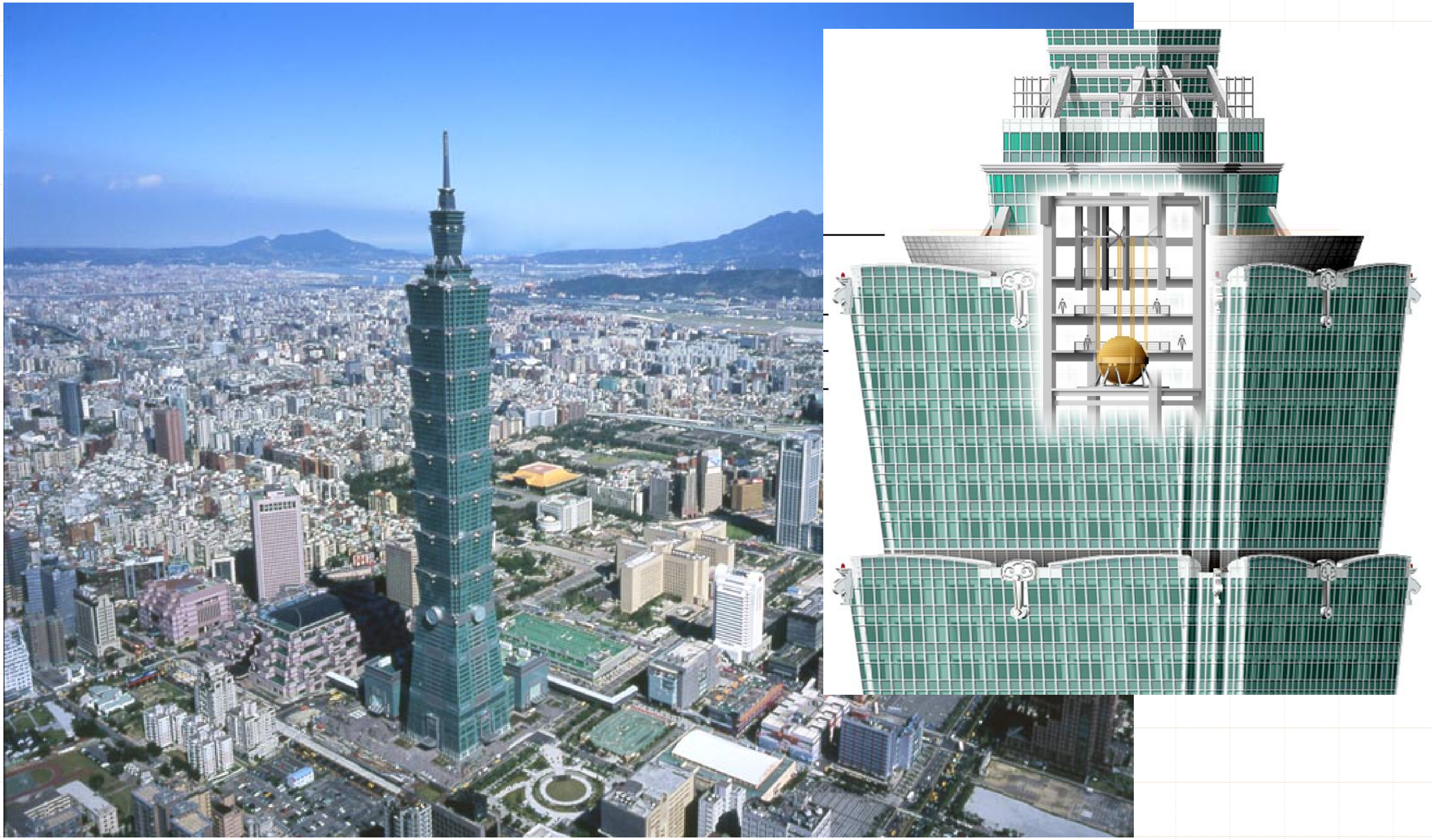
interfaces to the different control and data acquisition systems in the laboratories

provides control of physical actuators as well as data acquisition using physical instrumentation devices

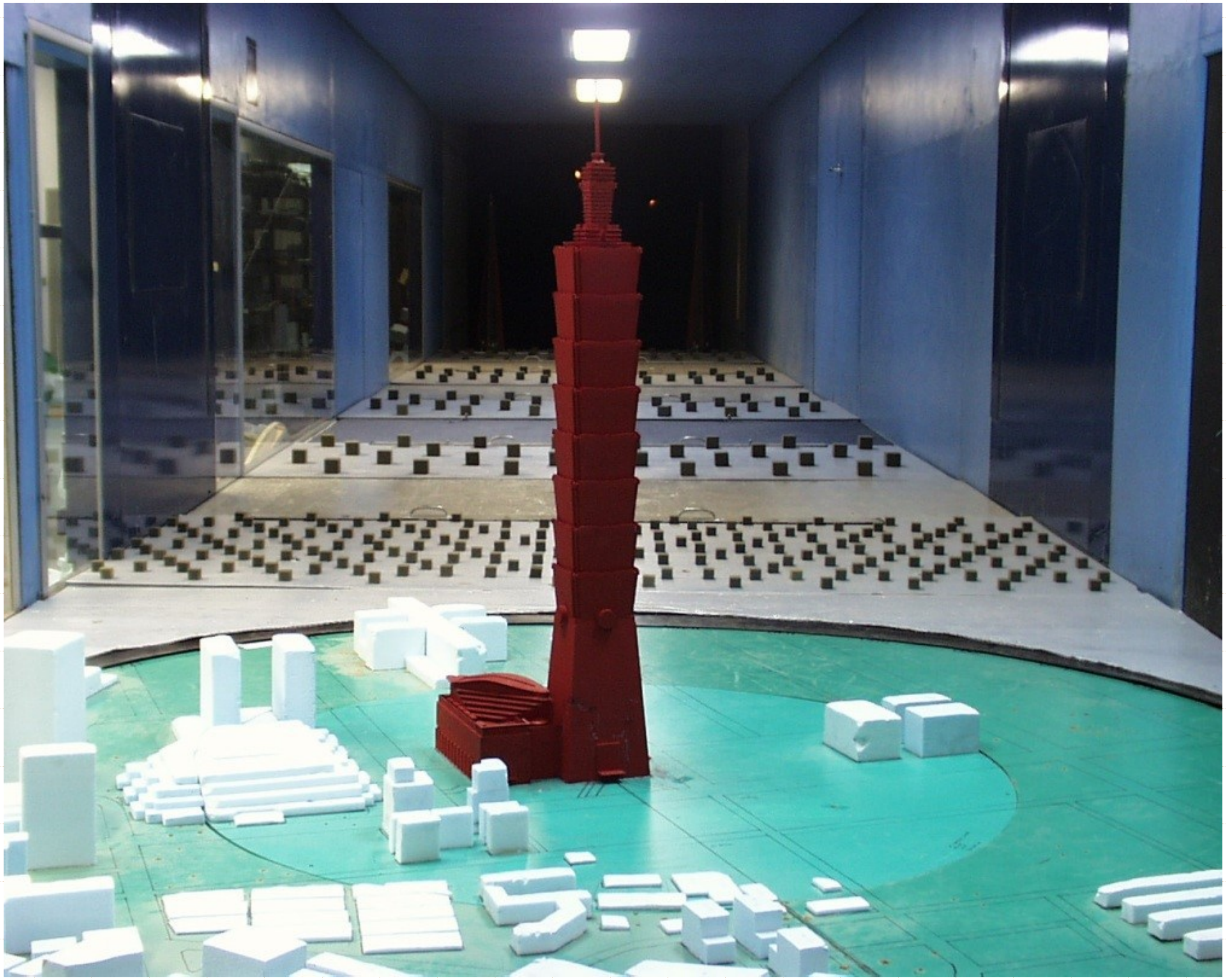
Testing Methods using BLWT

Aerodynamic Loads	Ramp/Hold Wind HS	Real-Time Wind HS
BLWT is used preceding HS to determine envelope Cp distribution histories on rigid model.	BLWT is used iteratively to determine statistical (min, max, x%tile, ...) envelope Cp distribution on rigid model.	BLWT is used to determine instantaneous loads on rigid envelope model.
Quasi-static or real-time structural hybrid simulation is then performed given these wind loads.	Static numerical analysis is performed to determine geometric change in envelope of structure.	Dynamic numerical analysis based on instantaneous wind loads is performed on structural model to adjust envelope of structure in real time.
Assumption that movement/deformation of structure has minimal effect on wind loads.	Use if geometric change is slow or for optimization problems (see B. Phillips).	Capture aero-elastic effects with more accurate structural model (see T. Wu).

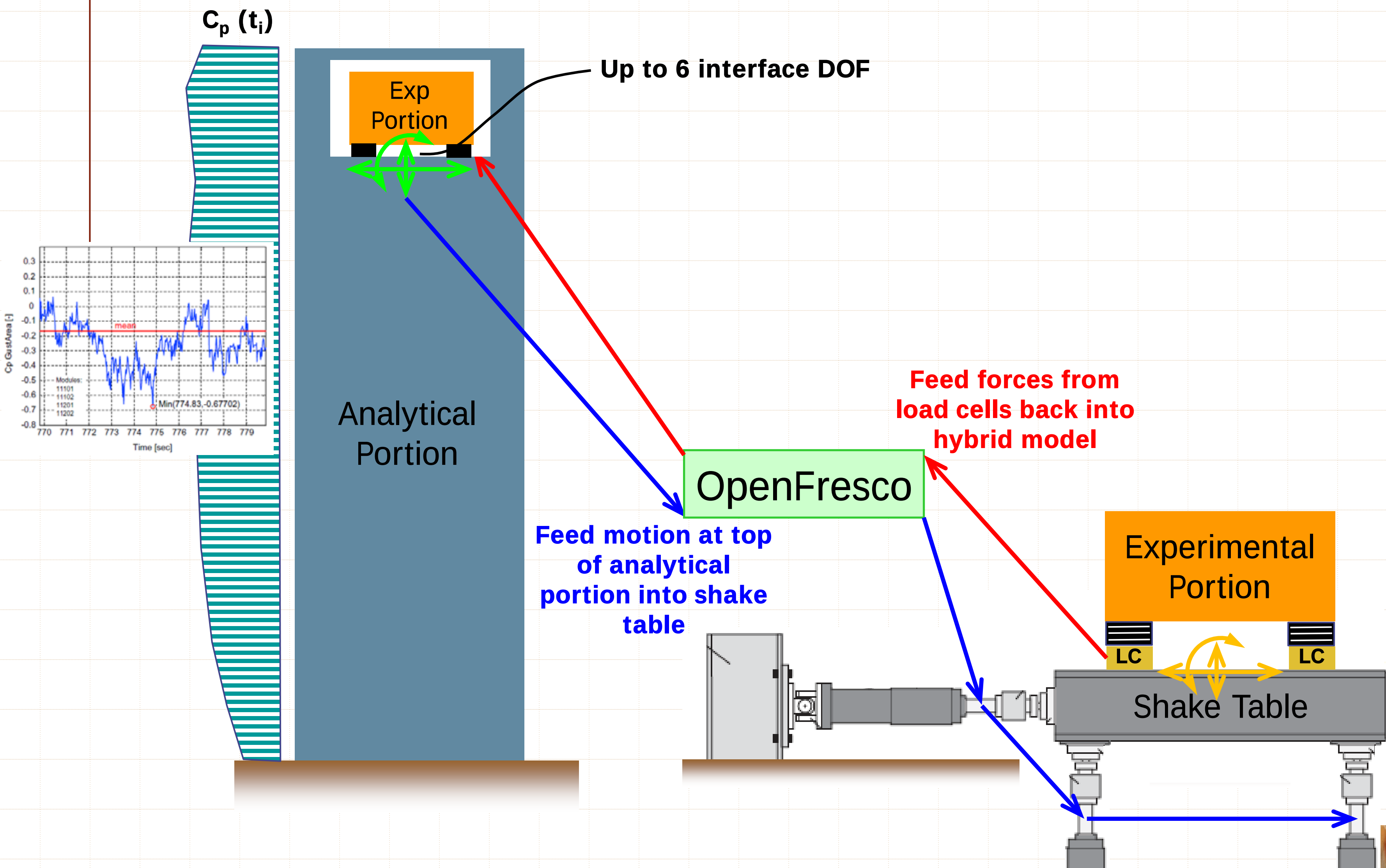
Aerodynamic Loads + Struct. HS



Aerodynamic Loads + Struct. HS



Aerodynamic Loads + Struct. HS



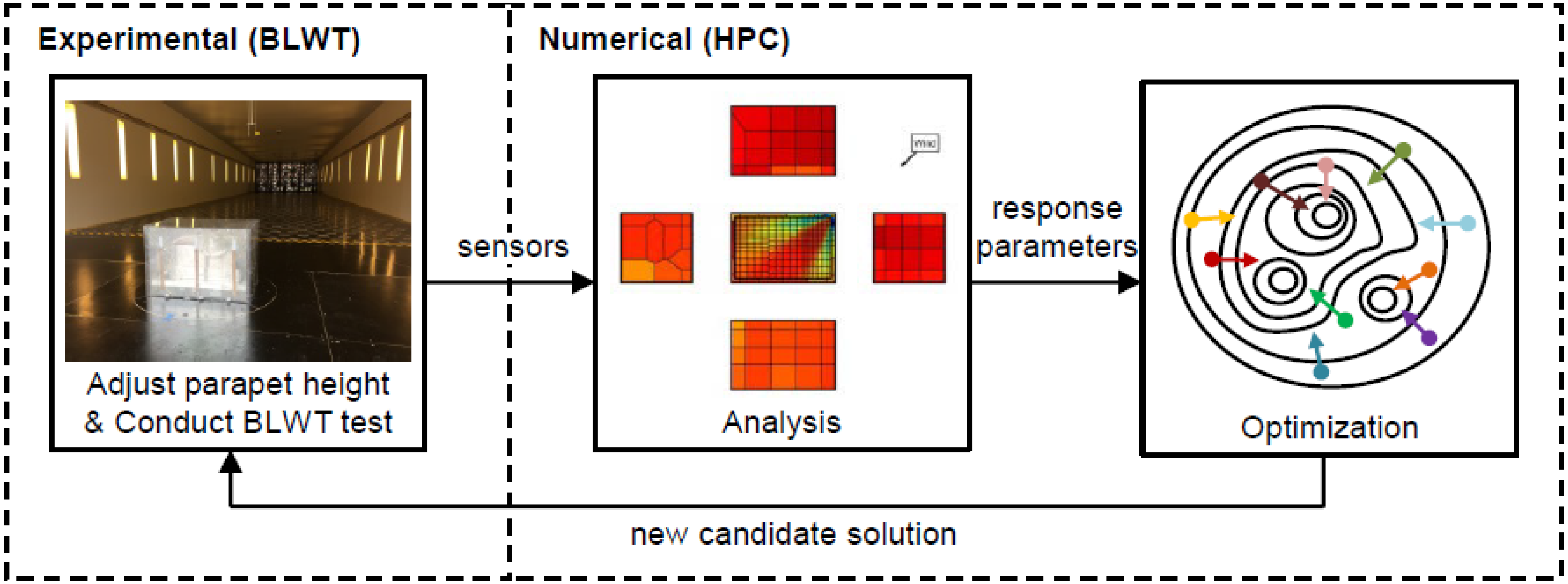
Similitude Laws for BLWT scaling

Similitude laws for fluid–elastic models with Froude number neglected.

Physical quantity	Dimension	Scaling factor with S_l, S_v, S_ρ	Scaling factor with S_l, S_v, $S_\rho=1$	Scaling factor with $S_l=1/30$, $S_v=0.364$, $S_\rho=1$
Length, l	L	S_l	S_l	0.033
Displacement, d	L	S_l	S_l	0.033
Velocity, v	LT^{-1}	S_v	S_v	0.364
Acceleration, a	LT^{-2}	$S_l^{-1}S_v^{2}$	$S_l^{-1}S_v^{2}$	3.978
Force, F	F	$S_l^2S_v^2S_\rho$	$S_l^2S_v^2$	0.000147
Time, t	T	$S_lS_v^{-1}$	$S_lS_v^{-1}$	0.092
Modulus, E	FL^{-2}	$S_v^2S_\rho$	S_v^2	0.133
Pressure, p	FL^{-2}	$S_v^2S_\rho$	S_v^2	0.133
Pressure Coeff, C_p	1	1	1	1
Stress, σ	FL^{-2}	$S_v^2S_\rho$	S_v^2	0.133
Strain, ε	1	1	1	1
Strain-Rate, $\dot{\varepsilon}$	T^{-1}	$S_l^{-1}S_v$	$S_l^{-1}S_v$	10.924
Density, ρ	$FL^{-4}T^2$	S_ρ	1	1
Mass, m	$FL^{-1}T^2$	$S_l^3S_\rho$	S_l^3	0.000037
Damping, c	$FL^{-1}T$	$S_l^2S_vS_\rho$	$S_l^2S_v$	0.000405
Stiffness, k	FL^{-1}	$S_lS_v^2S_\rho$	$S_lS_v^2$	0.004420
Period, T	T	$S_lS_v^{-1}$	$S_lS_v^{-1}$	0.092
Frequency, f	T^{-1}	$S_l^{-1}S_v$	$S_l^{-1}S_v$	10.924

Ramp/Hold Wind HS

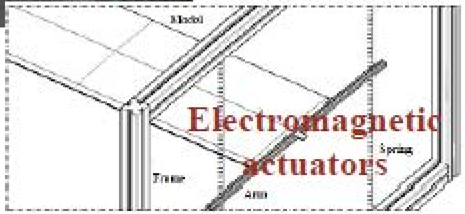
- Applicable if change in building envelope geometry is much slower than aerodynamic excitation
- Ideal for optimizing static building envelopes (see next presentation by Brian Phillips)

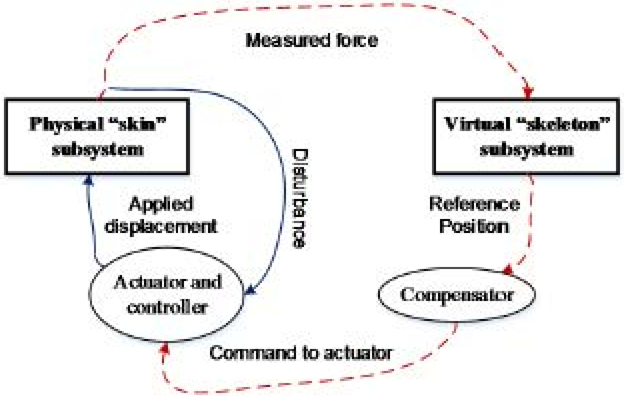


Real-Time Wind HS

Concept:
Real-Time Aerodynamics Hybrid Simulation

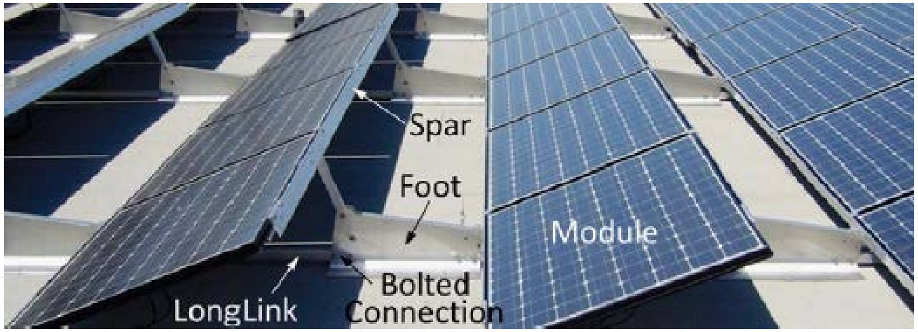
Rigid sectional model (2DOF) has been implemented for illustration purpose

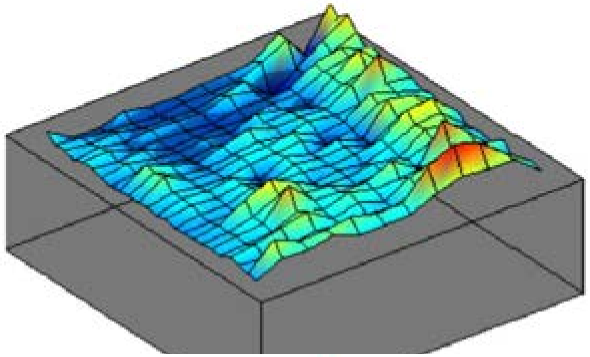


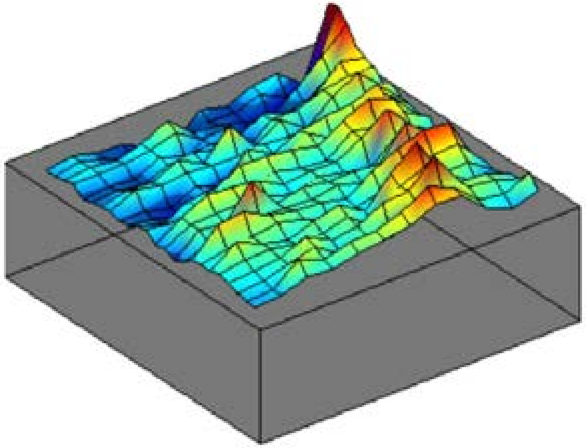


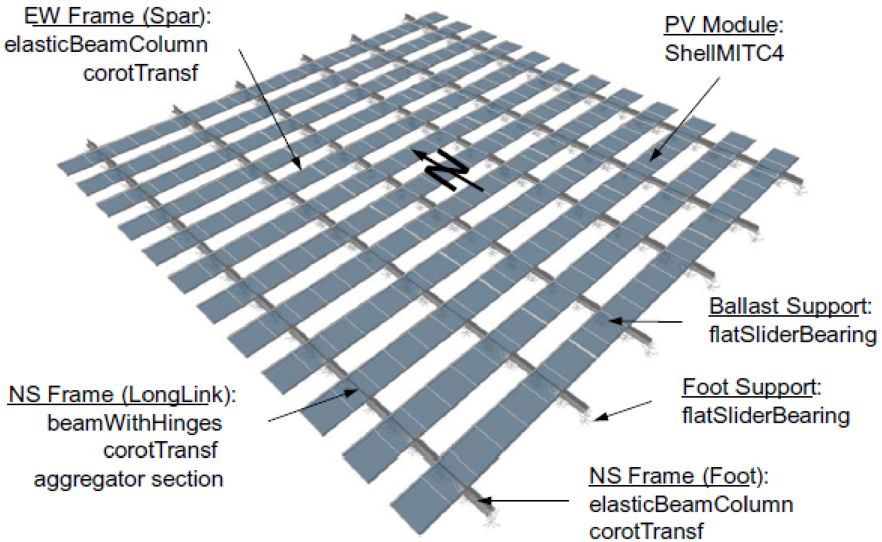
by Teng Wu, Mettupalayam Sivaselvan

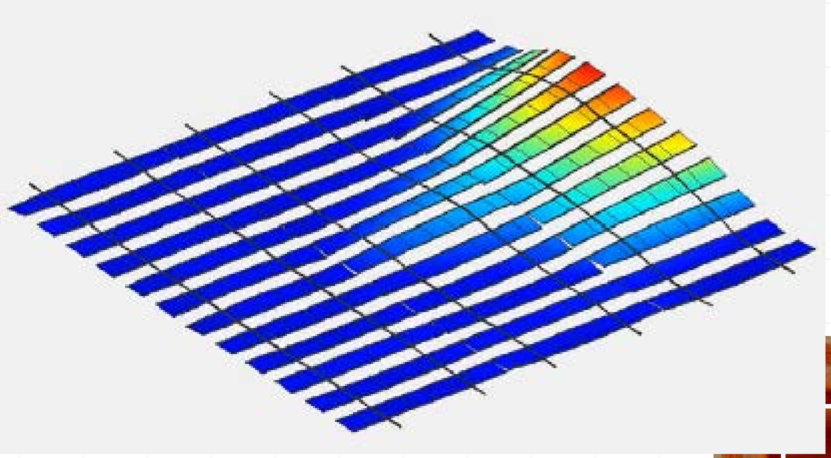
Real-Time Wind HS











Summary & Conclusions

- Cyber-physical systems such as hybrid simulation testing methods are essential in moving towards improved resilience to natural hazards
- The application of hybrid simulation to wind engineering, especially BLWT testing, provides many exciting research opportunities that also foster collaboration
- The OpenFreco middleware can readily be deployed and easily adapted for these new cyber-physical testing applications

Questions?
Discussion

http://openfresco.berkeley.edu