SEISMIC EVALUATION OF STRUCTURAL INSULATED PANELS

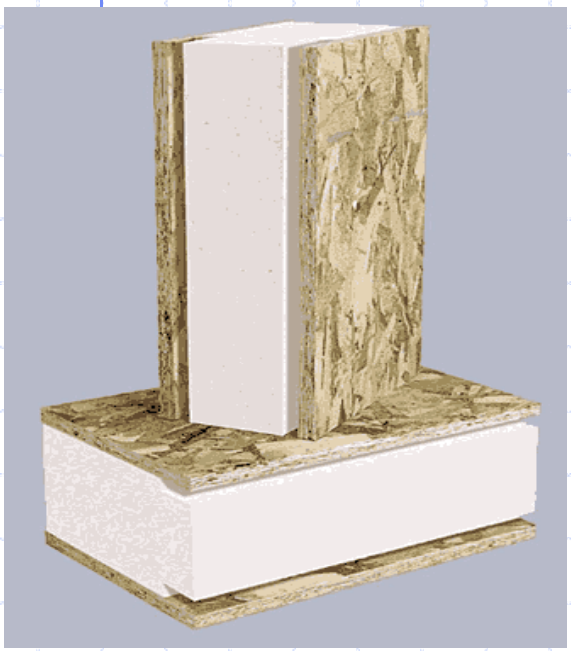
Khalid M. Mosalam, PhD, PE
Professor and Vice Chair for Research and Technical Services
Dept. of Civil and Environmental Engineering
University of California, Berkeley, CA 94720-1710
mosalam@ce.berkeley.edu

Acknowledgements
UC Lawrence Berkeley National Laboratory (LBNL)
US Department of Energy
Students & staff of μ-nees@berkeley laboratory

Outline

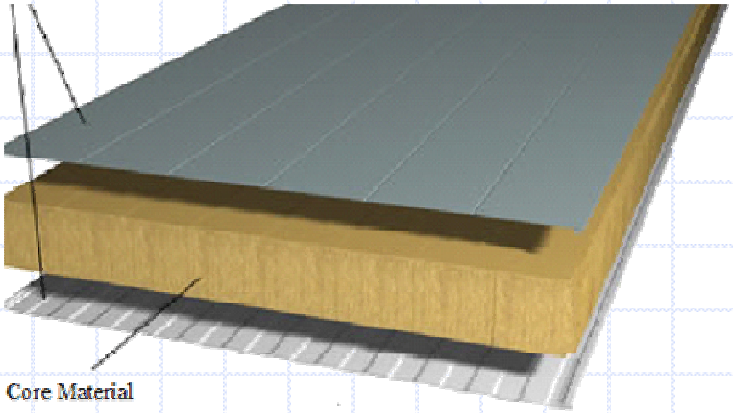
- Variations of SIPs and their advantages
- Few details and examples
- Construction example
- Material testing
- Earthquake-resistant testing
- Preliminary results for SIPs
- Concluding remarks and future research

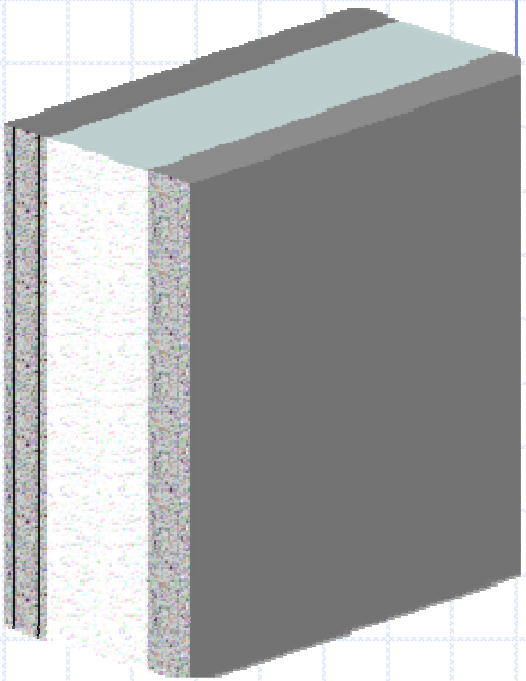
Variation of SIPs



WOOD

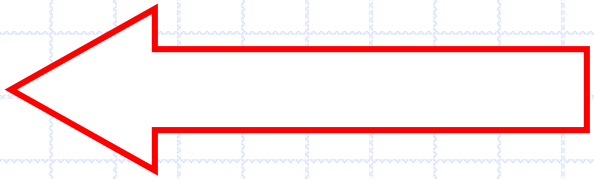
METAL





CEMENTITIOUS – Cement skins

MATURE Technology



In DEVELOPMENT

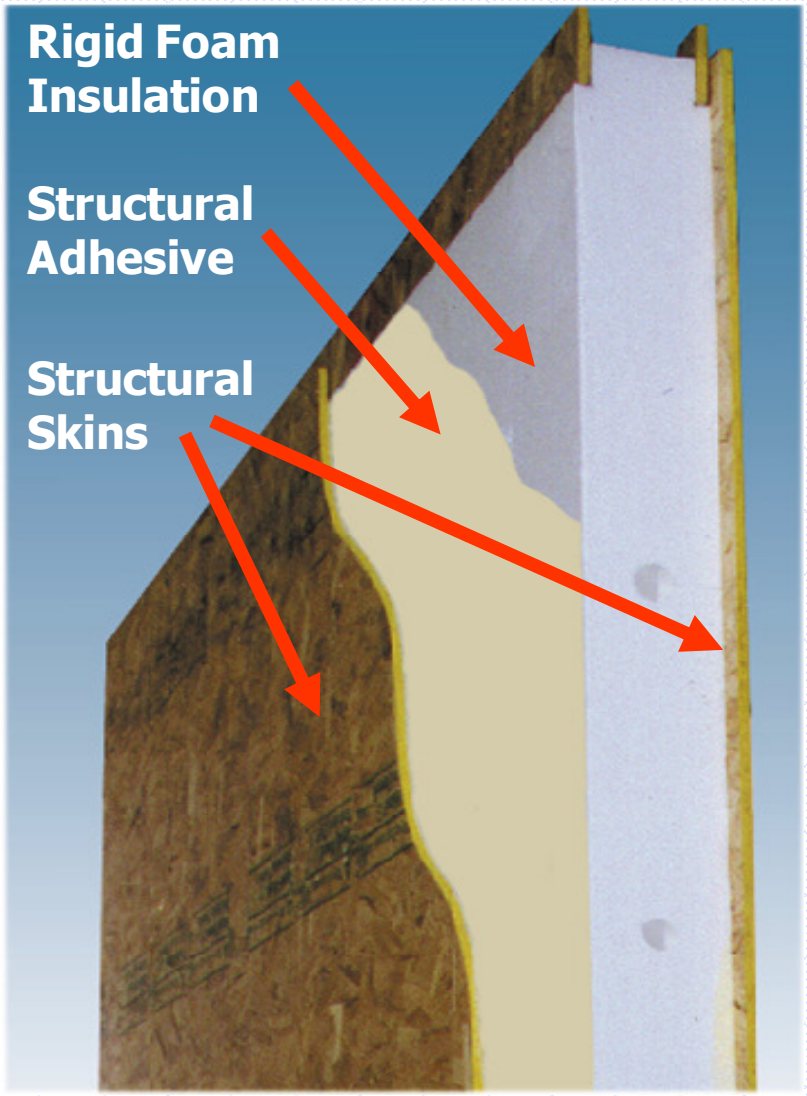
What are SIPs advantages ?

An Integrated Building System

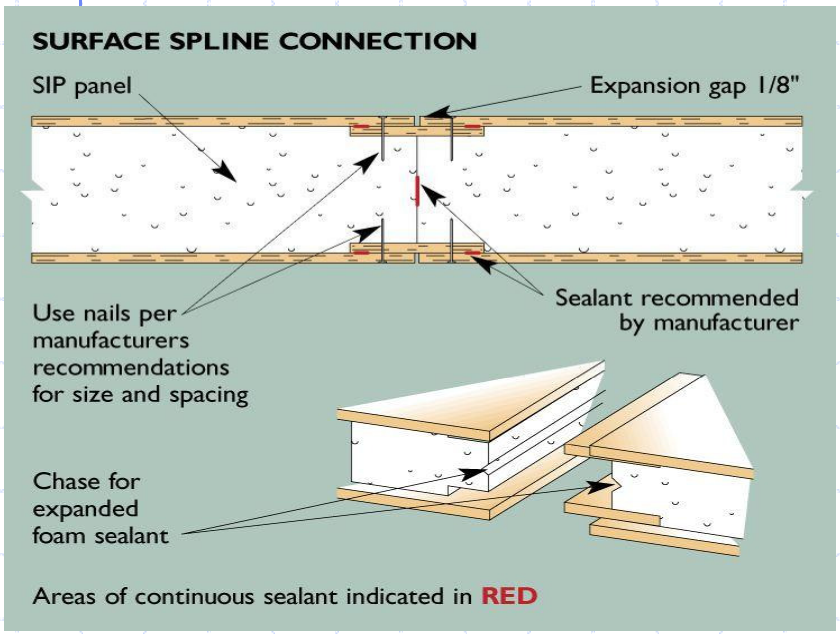
- Insulating foam core – providing whole house insulation
- Structural outer/inner skin providing enclosure, and
- Structural adhesive allowing the assembly to act as a homogeneous composite

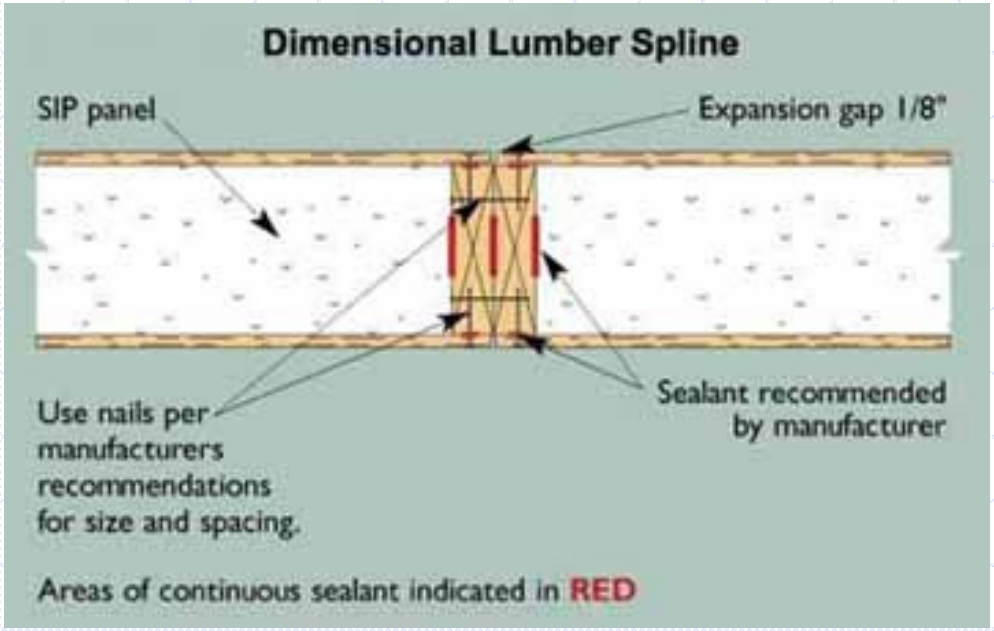
Offers Improved Construction Quality

- Straighter walls
- Tighter construction

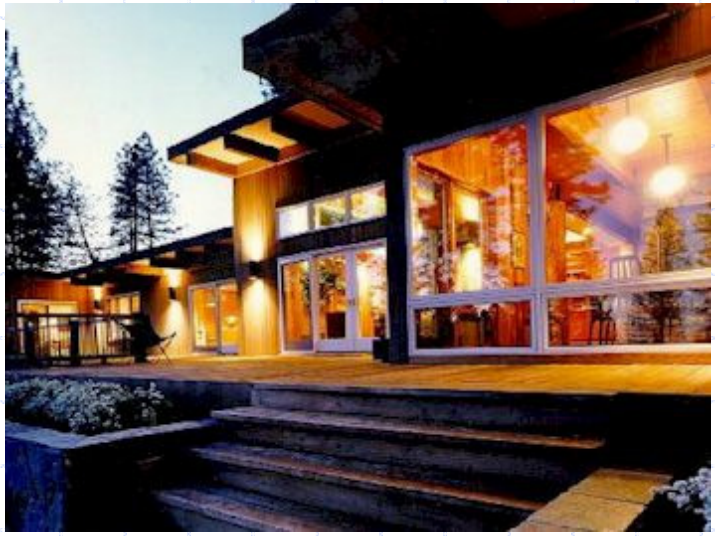


SIPs joints


SURFACE SPLINE CONNECTION
SIP panel
Expansion gap 1/8"
Use nails per manufacturers recommendations for size and spacing
Sealant recommended by manufacturer
Chase for expanded foam sealant
Areas of continuous sealant indicated in RED


Dimensional Lumber Spline
SIP panel
Expansion gap 1/8"
Use nails per manufacturers recommendations for size and spacing.
Sealant recommended by manufacturer
Areas of continuous sealant indicated in RED

Examples



Construction 1/4

Construction 2/4

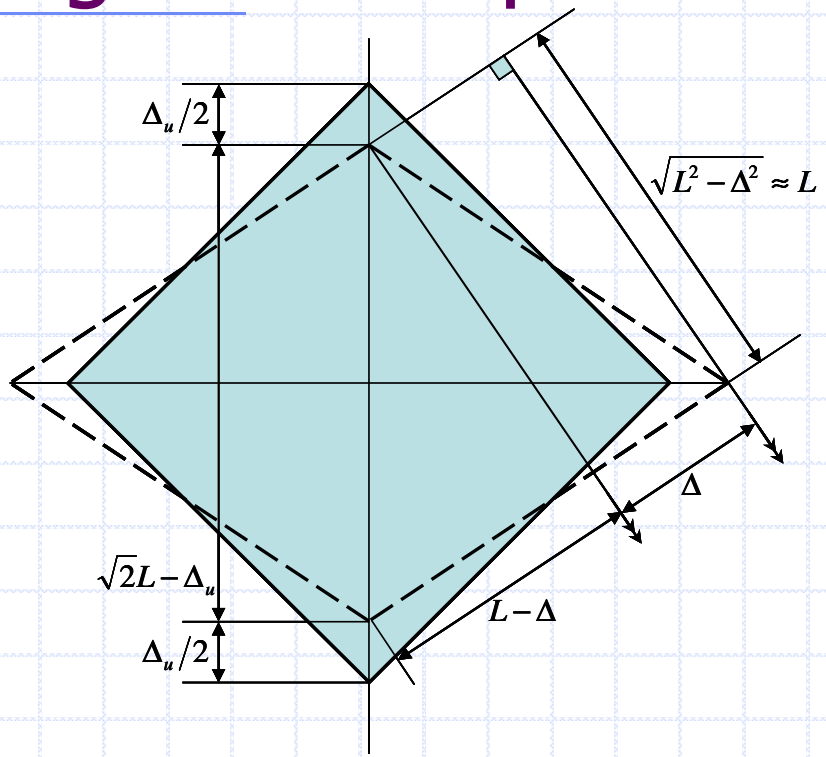
Construction 3/4

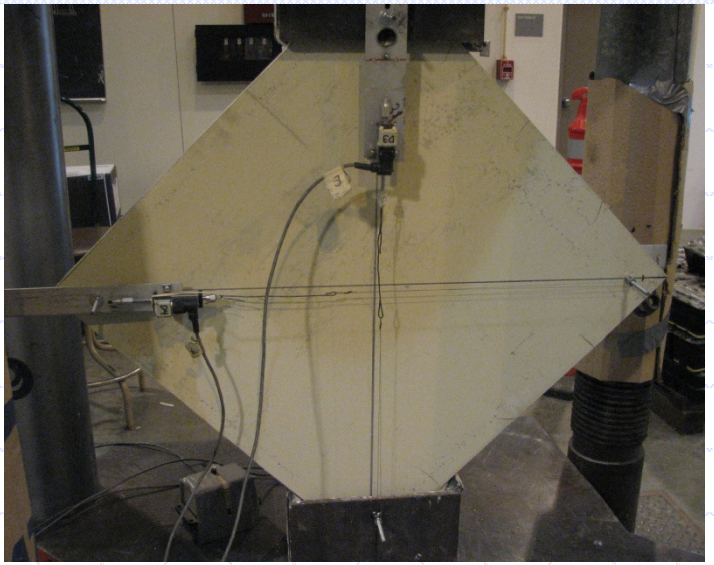
Construction 4/4

$30,000 US Affordable Housing

SIPs Material Tests

Diagonal compression test





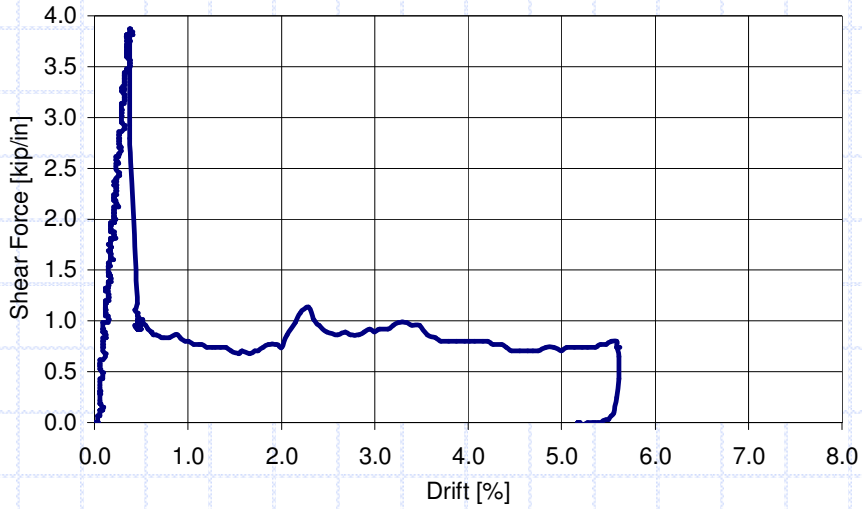
Exact: $L-\Delta=\sqrt{\left(\sqrt{2}L-\Delta_u\right)^2-\left(L^2-\Delta^2\right)}\Rightarrow(L-\Delta)^2=\left(\sqrt{2}L-\Delta_u\right)^2-(L-\Delta)(L+\Delta)\Rightarrow$

$$2L(L-\Delta)=\left(\sqrt{2}L-\Delta_u\right)^2\Rightarrow\Delta=L-\frac{\left(\sqrt{2}L-\Delta_u\right)^2}{2L}\Rightarrow\delta=1-\frac{\left(\sqrt{2}L-\Delta_u\right)^2}{2L^2}=1-\left(1-\frac{\Delta_u}{\sqrt{2}L}\right)^2 \quad (2)$$

Approximate: $L-\Delta=\sqrt{\left(\sqrt{2}L-\Delta_u\right)^2-L^2}\Rightarrow\Delta=L-\sqrt{\left(\sqrt{2}L-\Delta_u\right)^2-L^2}\Rightarrow$

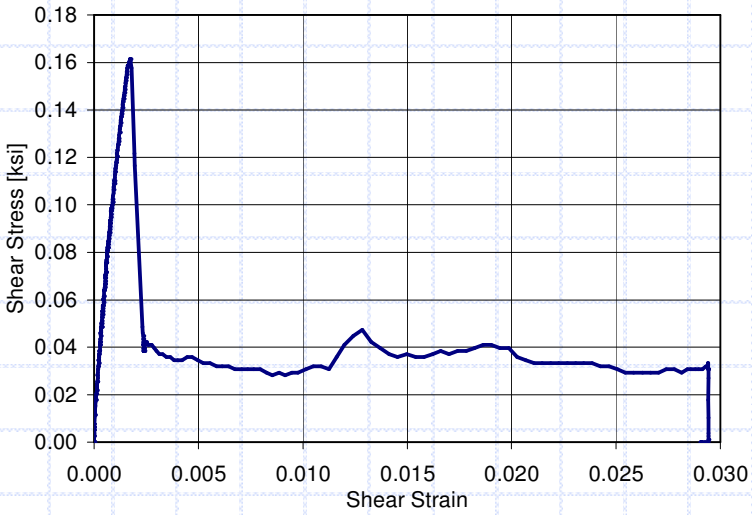
$$\delta=\frac{L-\sqrt{\left(\sqrt{2}L-\Delta_u\right)^2-L^2}}{L}=1-\sqrt{\left(\sqrt{2}-\frac{\Delta_u}{L}\right)^2-1} \quad (3)$$

Diagonal compression results (1/3)

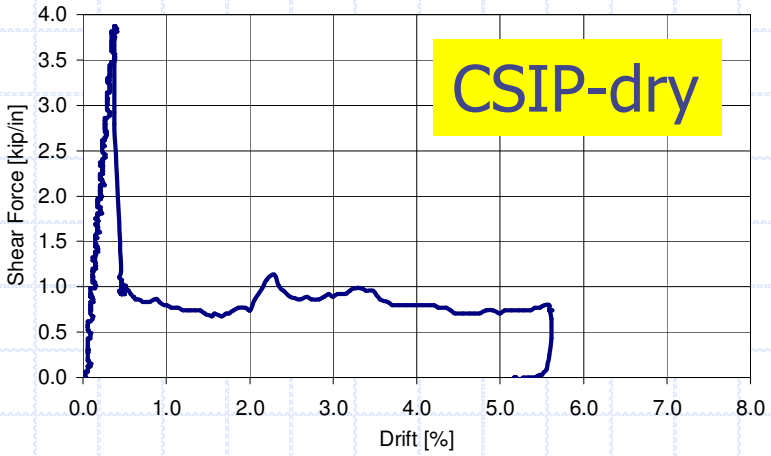


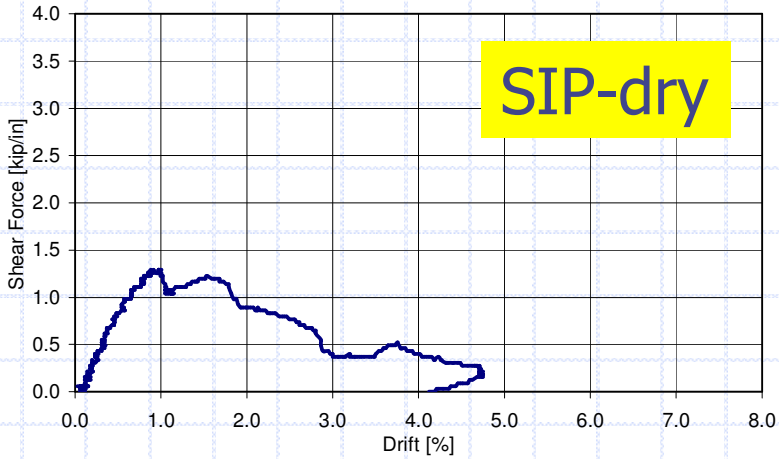
$$\gamma = \frac{\Delta V + \Delta H}{g_{avg}}$$

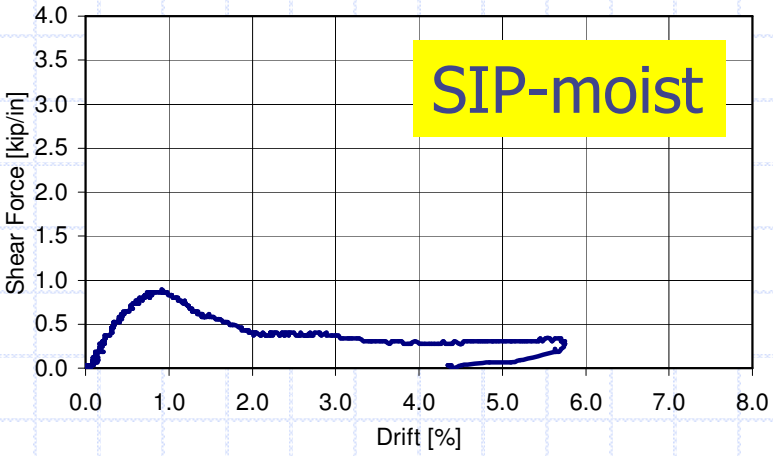
$$\tau = \frac{P}{\sqrt{2}} \frac{1}{wt}$$

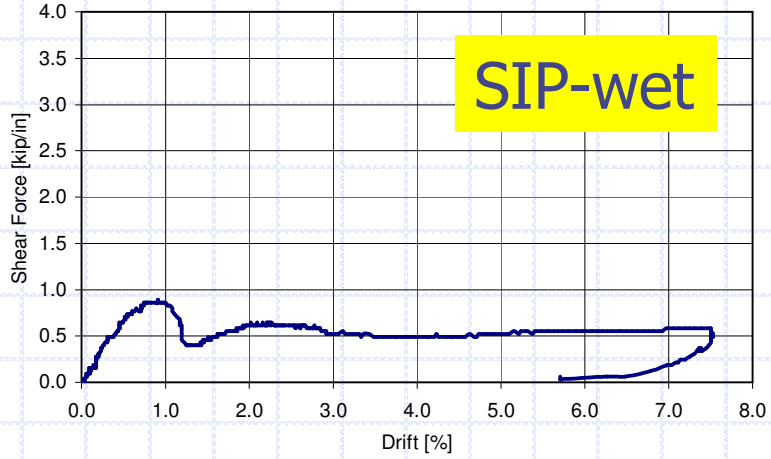


Diagonal compression results (2/3)









Diagonal compression results (3/3)

Drop ratio

Specimen	V/t (kip/in)	δ (%)	$(V/t)_r$ (kip/in)	δ_r (%)	$[1-(V/t)_r/(V/t)]\times 100$ (%)
CSIP1-Dry	3.87	0.37	1.01	0.49	73.9
CSIP2-Dry	3.07	0.37	1.57	0.49	48.9
OSB-Dry	1.29	0.88	0.40	3.00	69.0
OSB-Moist	0.86	0.74	0.37	3.00	57.0
OSB-Wet	0.86	0.74	0.52	3.00	39.5
CSIP-Dry	3.29	0.63	1.45	0.63	55.9
CSIP-Moist	4.06	0.40	1.08	0.63	73.4
CSIP-Wet	2.37	0.37	0.74	0.63	68.8

1. CSIPs experience sudden drop in the capacity, quantified by the drop ratio
2. The capacity of SIPs with OSB facing drops more gradually
3. Water exposure for SIPs lead to reduction of strength and drop ratio (i.e. more ductile behavior).
4. Water exposure for CSIPs has unclear trends where more brittleness is observed in terms of higher drop ratios but strength in the moist case increased while for the wet case decreased. Therefore, further studies are needed in this regard.

On-going effort ...

- Currently, there are no American National Standards covering Performance Rated SIPs, especially related to Seismic Performance.
- This standard, under development, will cover the manufacturing, qualification, quality assurance, design, and installation requirements for SIPs used in wall applications.
- Key stakeholders include SIPs manufacturers and component suppliers, distributors, designers, users, building code regulators, and government agencies.
- The APA PRS-610 Standards Committee is composed of members representing manufacturers, design professionals, code agencies, third-party inspection agencies, and testing laboratories in both the U.S. and Canada.
- On-going research focus on several structural issues.
- At UC-Berkeley, we are focusing on seismic issues and structural modeling.

Earthquake-Resistant Testing

Application to "House-Over-Garage"

- Low-rise residential wood houses represent ~90% of the US market
- Seismic vulnerability of such houses is demonstrated in recent earthquakes

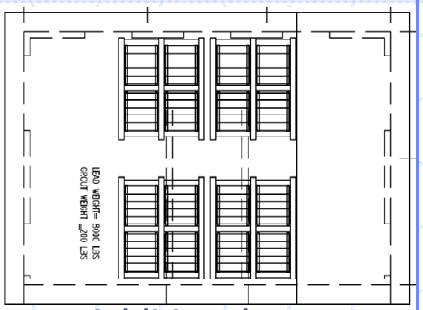
1994 Northridge Earthquake

1971 San Fernando Earthquake

Northridge Meadows Apartment Complex

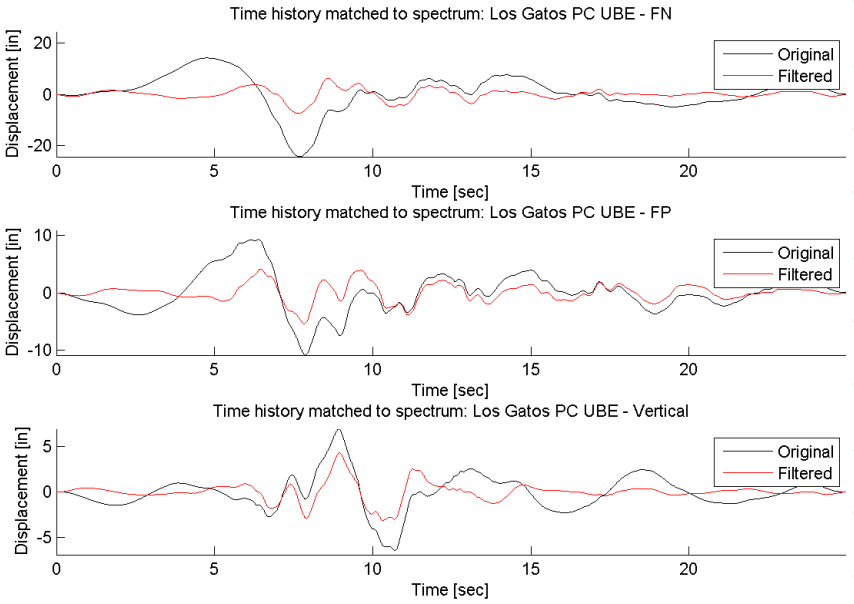
Prototype structure on the shaking table

Shaking table experiment



Additional mass

Why hybrid simulation?



Shaking table limitations

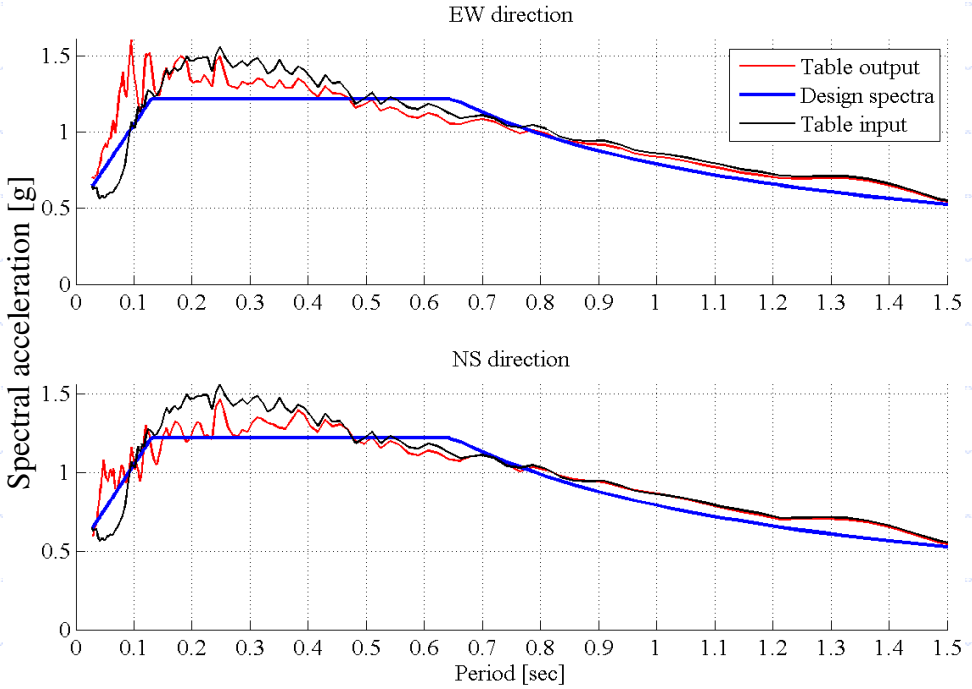


Table-structure interaction

Concept of hybrid simulation

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

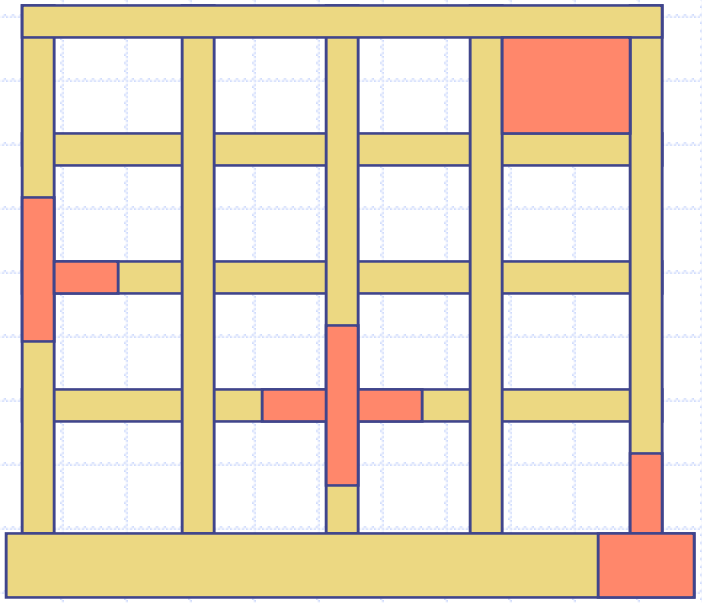
$$m\ddot{u} + C\dot{u} + f_r = -m\ddot{u}_g$$

$$m\ddot{u} + m\ddot{u}_g + C\dot{u} = -f_r$$

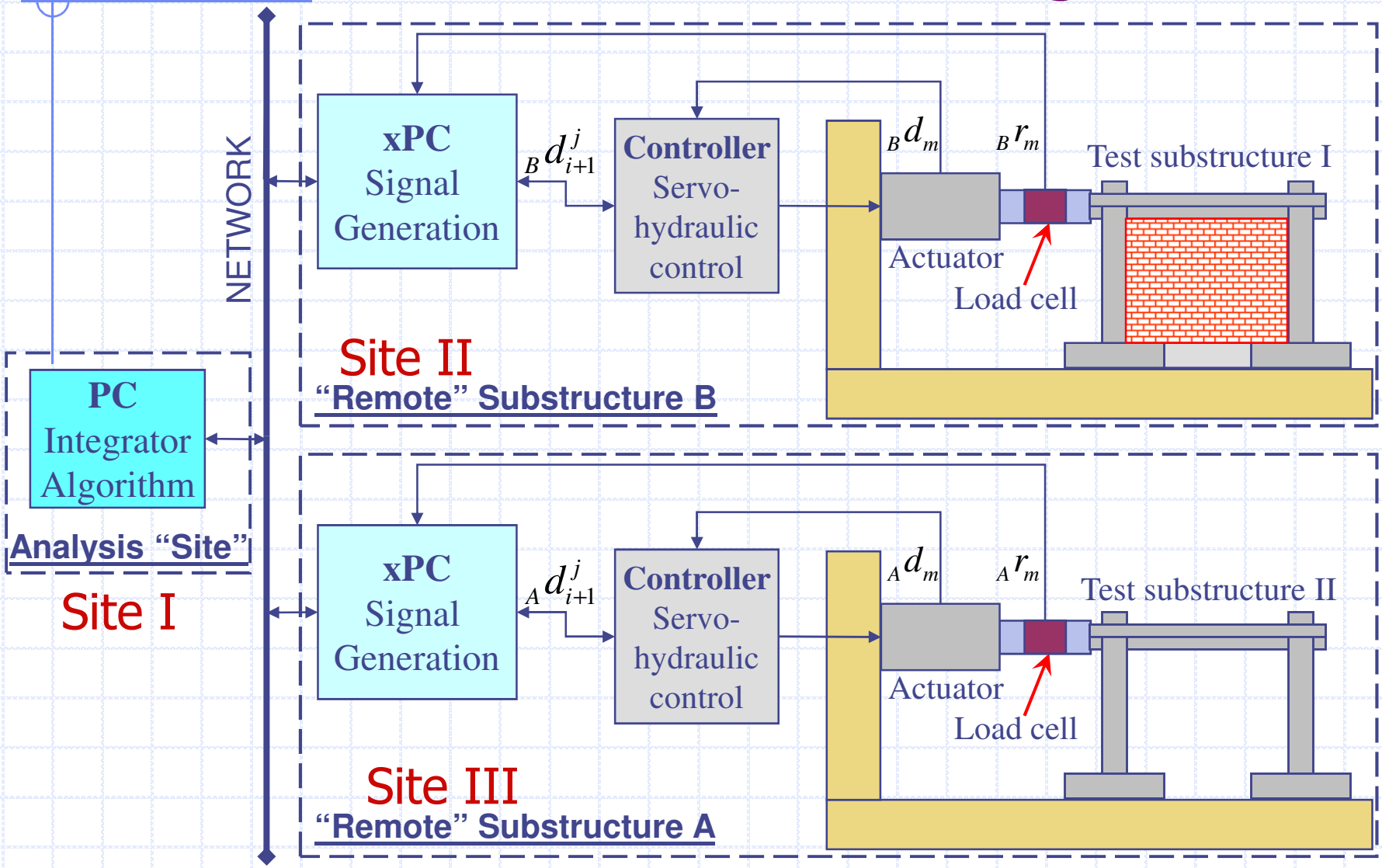
- Enables dynamic testing of full-scale models

Multiple substructures

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

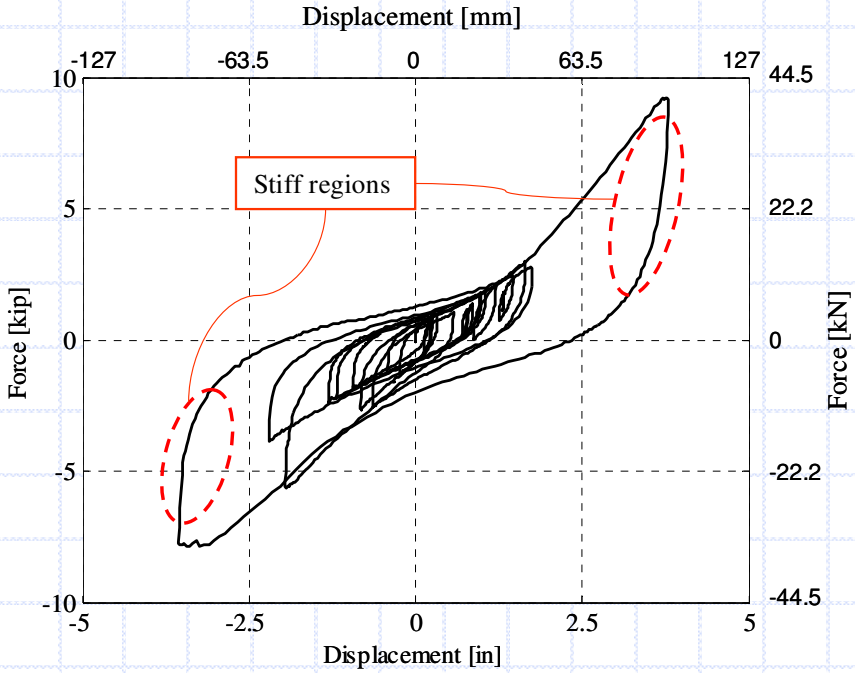


Distribution for network testing



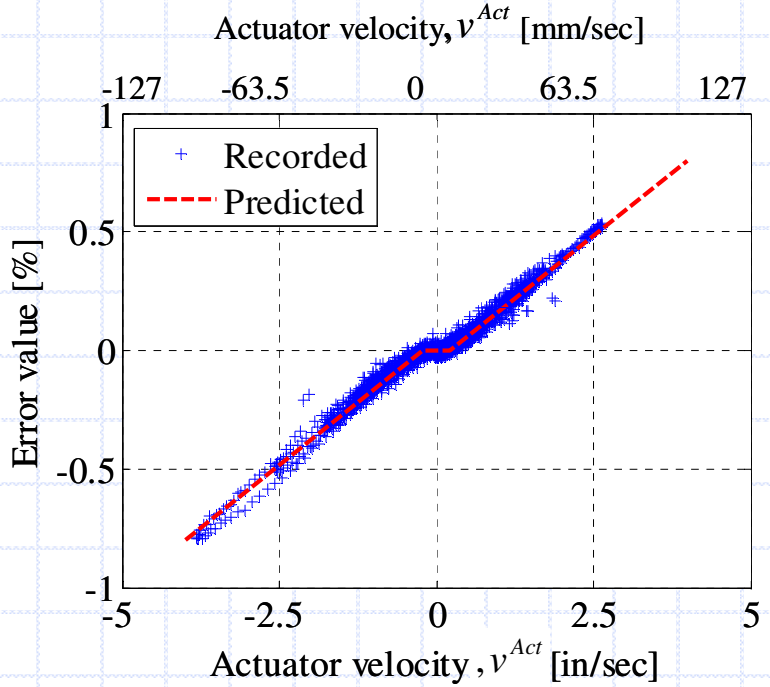
Two problems

Problem 1



Resolution of measured displacement is low in "stiff regions"

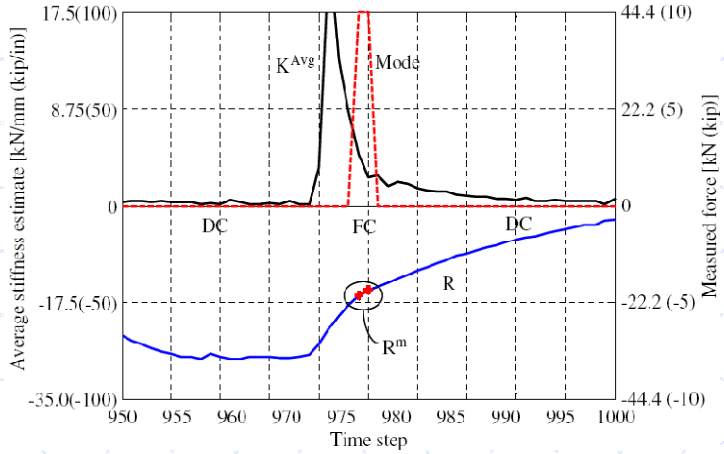
Problem 2

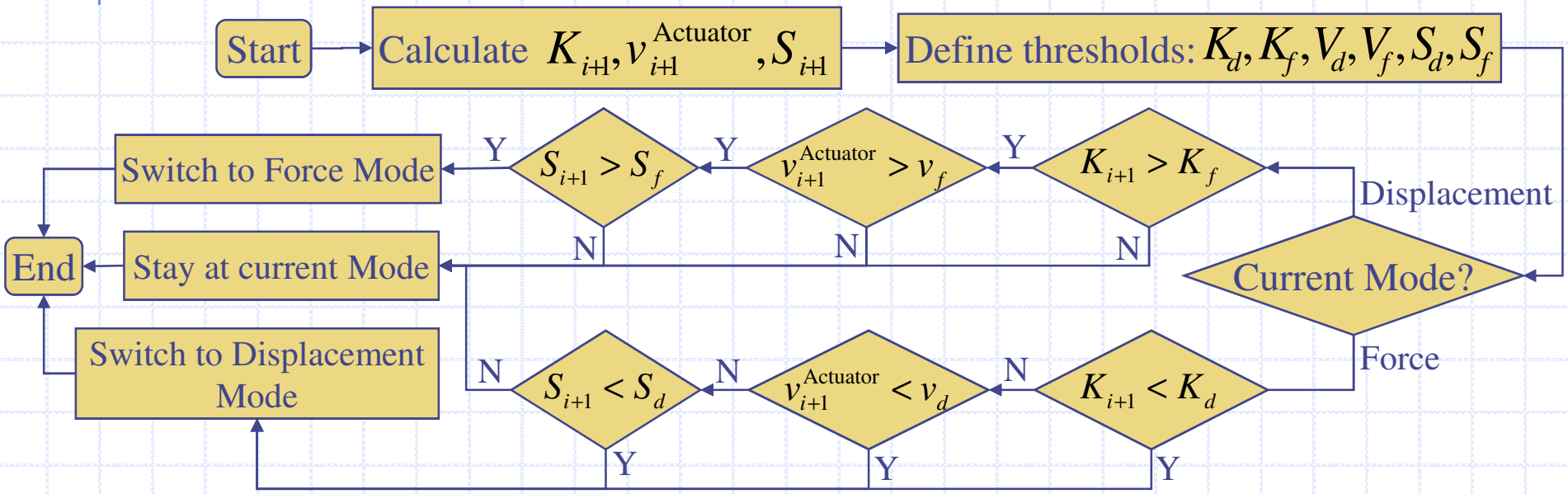


Error=calculated –measured correlated with actuator velocity making it harder for "real time"

Mode switching algorithm

Solution of problem 1



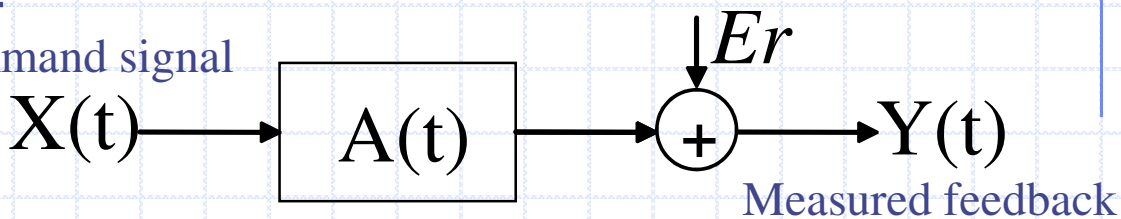


Error model and feed-forward compensation

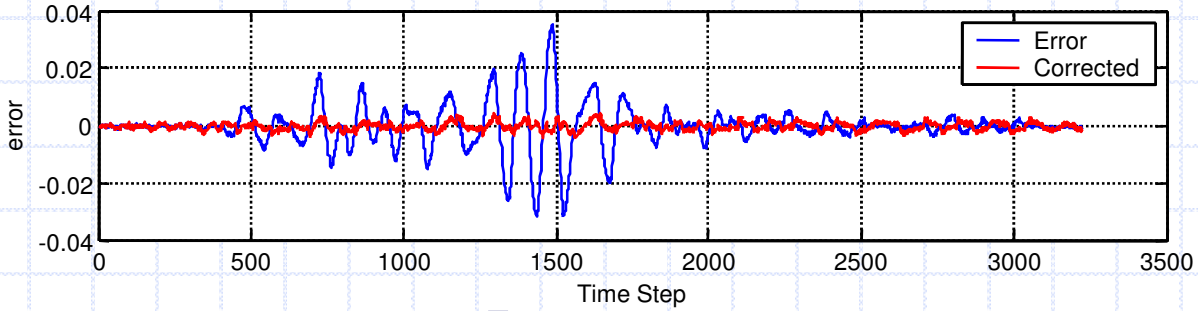
Solution of problem 2

Ideally $Y(t) = X(t)$, $A(t) = 1$

Command signal

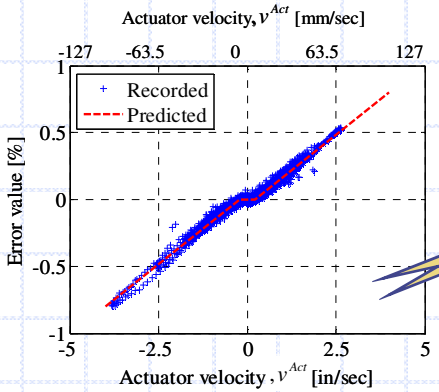


Measured feedback



To control

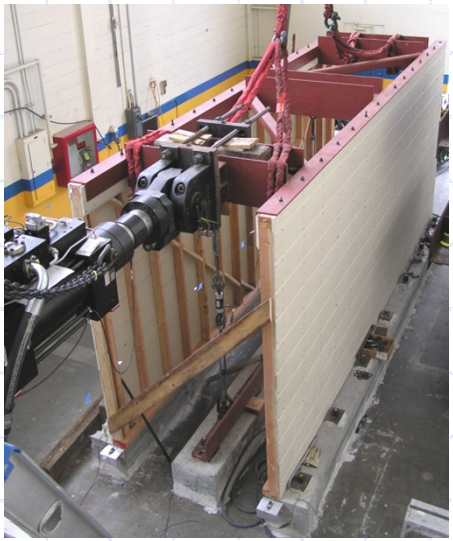
From calculation

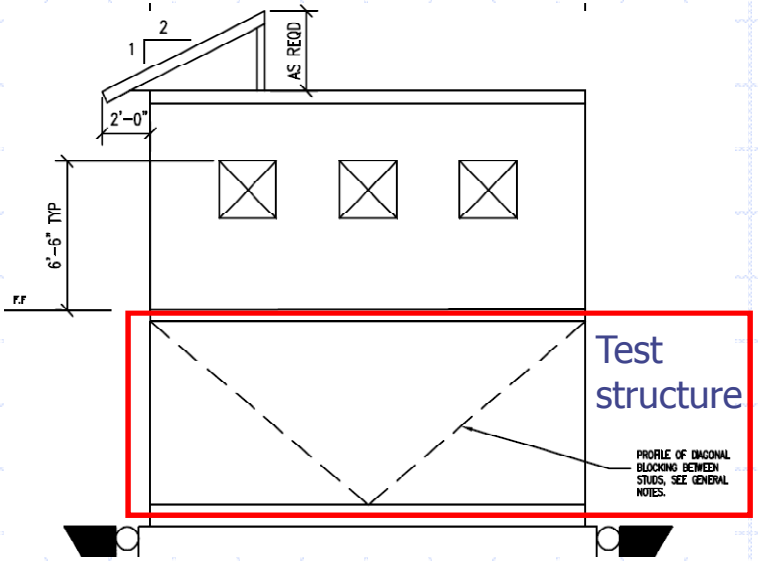


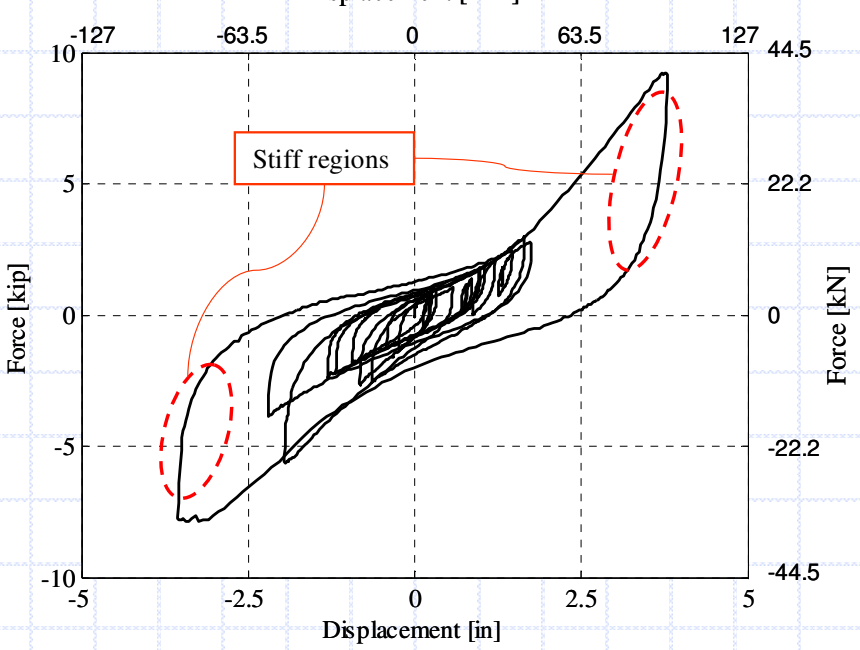
$$d_i^{command} = d_i^{target} - Er(v_i) \Rightarrow d_i^{feedback} = d_i^{command} + Er(v_i) = d_i^{target}$$

From control

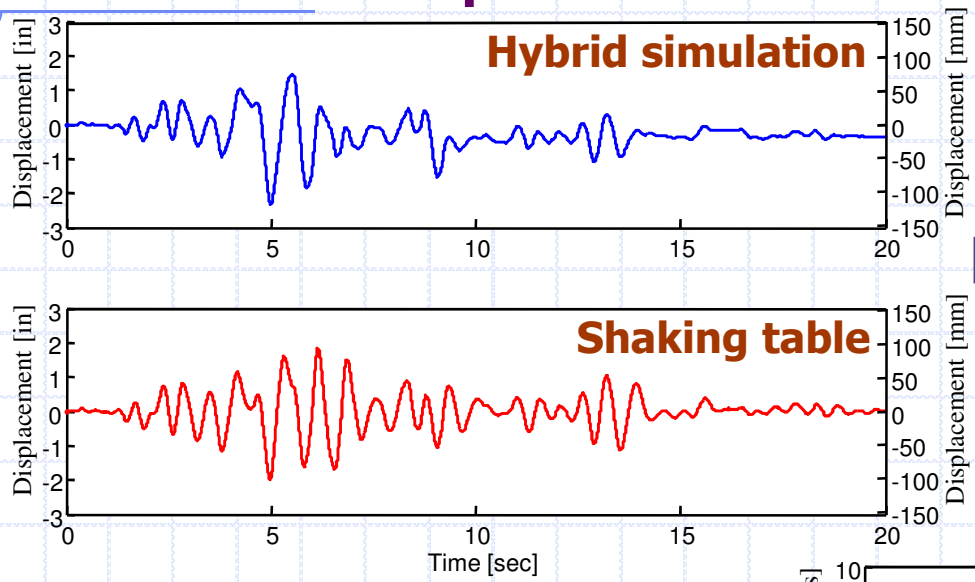
Pseudo-dynamic experiments



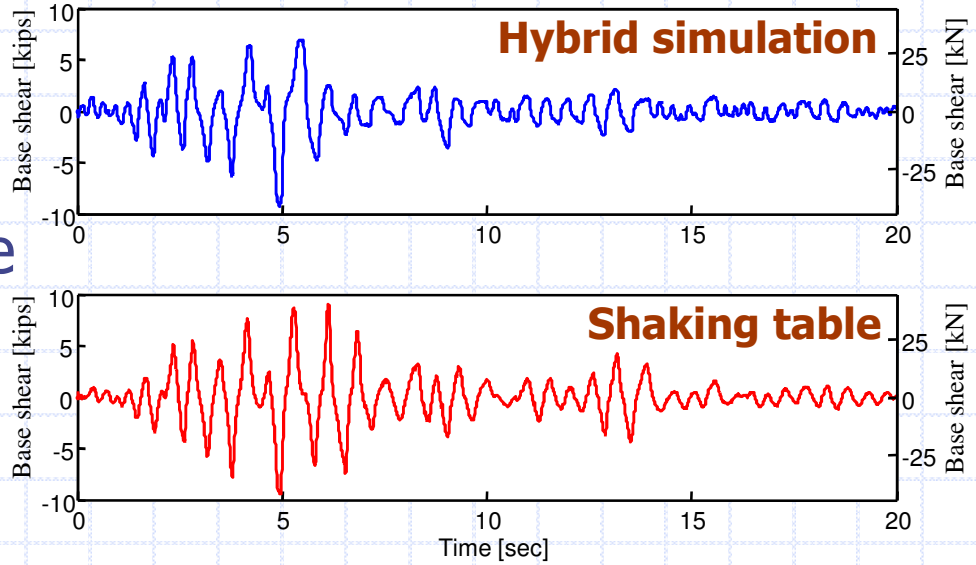




Global comparison



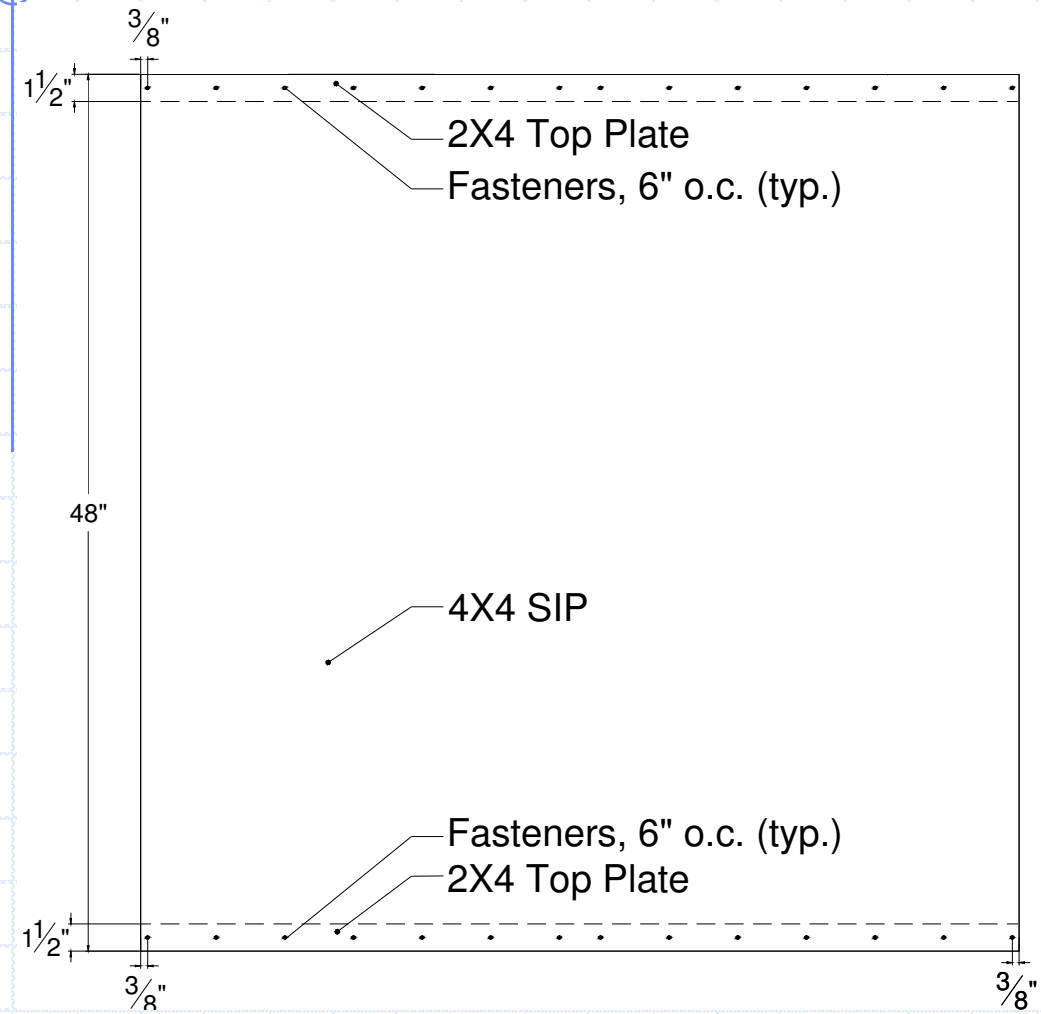
Deformations versus time

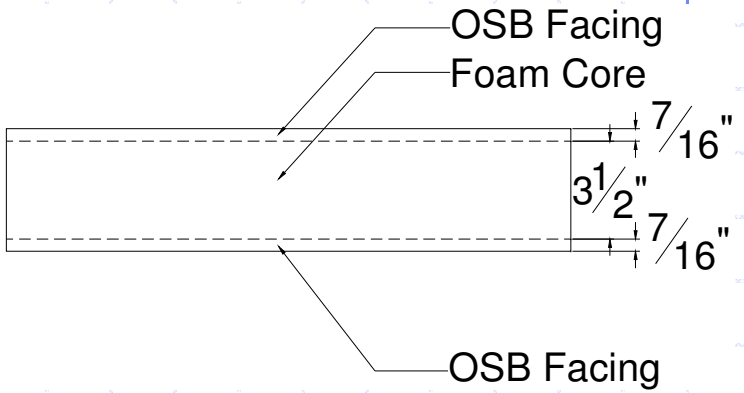


Forces versus time

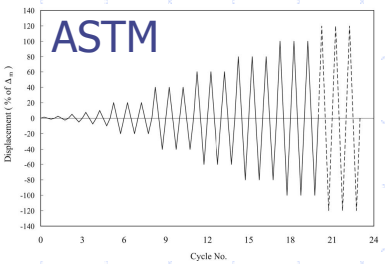
SIPs Preliminary Results

Test specimen and setup

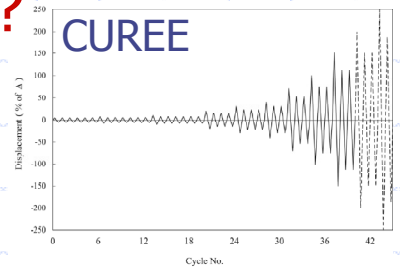


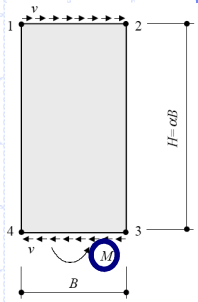


Conventional panels versus SIPs

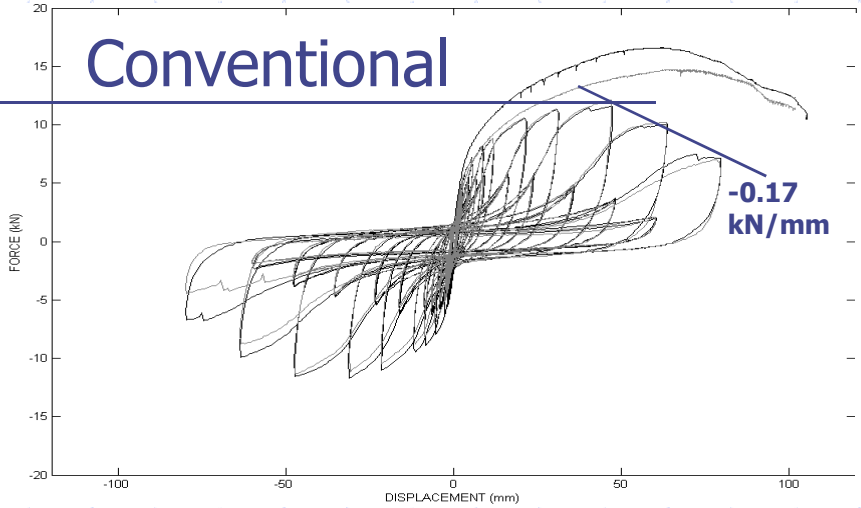


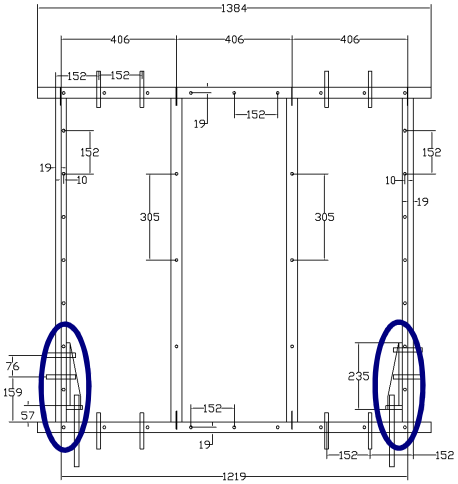
?





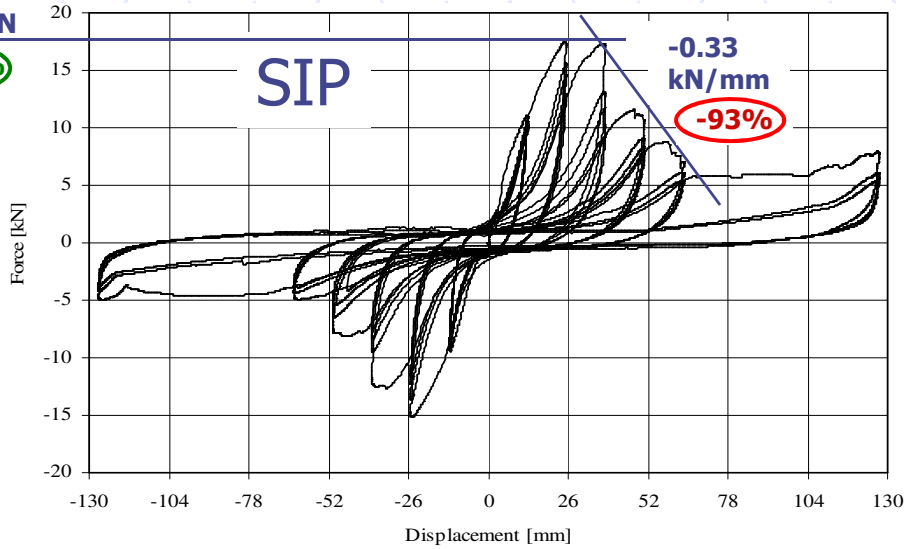
11.5 kN

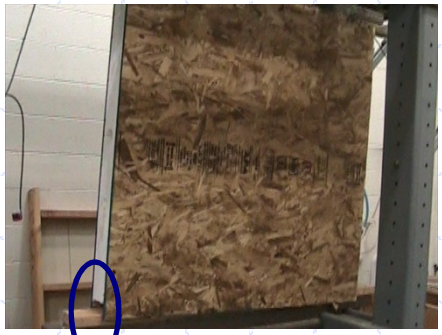


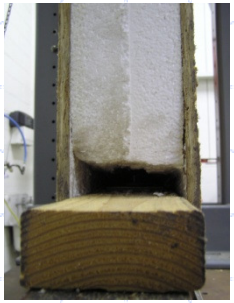


17.5 kN

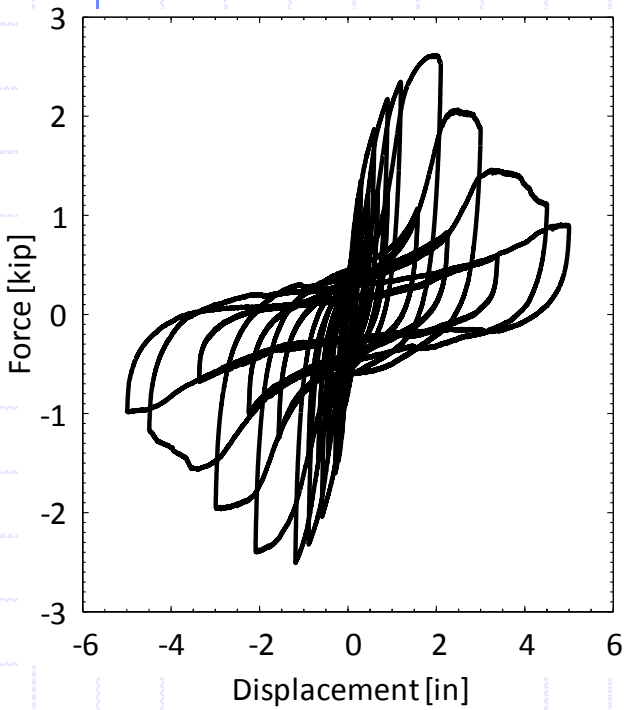
+52%



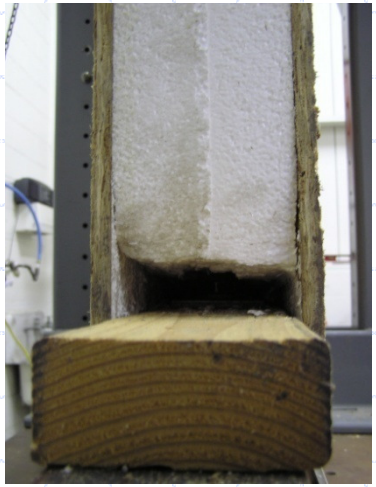




Quasi-static results and failure mode



Fasters failure-bottom



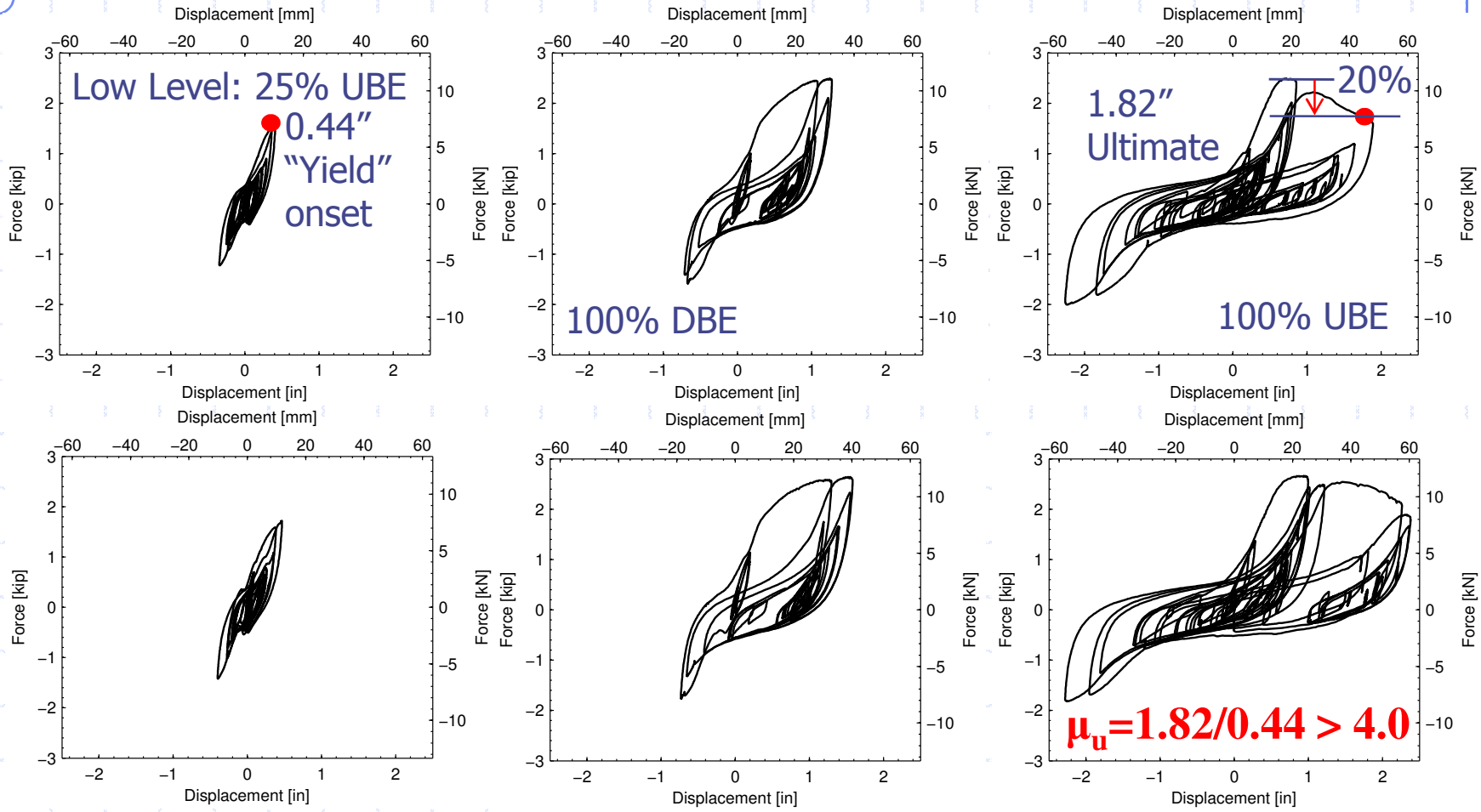
EPS core crushing

Fasters failure-bottom

Fasters failure-top

Hybrid simulation results

Record: Loma Prieta, CA, 1989 earthquake, Los Gatos station (stiff site)



DBE: Design basis earthquake (10% probability of exceedance in 50 years)
UBE: Upper-bound earthquake (10% probability of exceedance in 100 years)

Concluding remarks

- SIPs is an energy-efficient alternative to stick-frame construction.
- Durability issues for SIPs and CSIPs need to be looked at more comprehensively.
- Hybrid simulation is a viable approach for seismic evaluation of SIPs.
- Reasonable energy dissipation and ultimate displacement ductility slightly above 4.0 are obtained for SIPs without panel-to-panel connections.
- SIP strength is maintained up to and including 100% of the design basis earthquake (DBE) – 10% probability of exceedance in 50 years.
- Significant reduction of strength with large energy dissipation is observed for a longer duration upper-bound earthquake (UBE) – 10% probability of exceedance in 100 years.

Future research

- A thorough investigation of the development of common connection types would be beneficial, as this is the most likely point of failure in SIPs and CSIPs.
- Both panel-to-panel and panel-to-diaphragm connections should be considered. Of special importance is the function of the adhesive within the connections, and whether its use represents any improvements of the performance.
- Developing coupled computational tools for SIPs and CSIPs to account for thermal and structural behavior can advance this research beyond the realm of structural engineering to treat SIPs and CSIPs designs in the context of optimization problems.
- From sustainability point of view and due to increased environmental awareness, life-cycle analysis and assessment of SIPs and CSIPs is an important task.

Thank You!