Seismic Evaluation of Structural Insulated Panels

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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

MATURE Technology

METAL

CEMENTITIOUS – Cement skins

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"
- Sealant recommended by manufacturer
- Use nails per manufacturers recommendations for size and spacing
- Chase for expanded foam sealant
- Areas of continuous sealant indicated in RED

**Dimensional Lumber Spline**

- SIP panel
- Expansion gap 1/8"
- Sealant recommended by manufacturer
- Use nails per manufacturers recommendations for size and spacing
- Areas of continuous sealant indicated in RED
Examples
Construction 2/4
Construction 3/4
Construction 4/4

$30,000 US Affordable Housing
SIPs Material Tests
Diagonal compression test

\[ L - \Delta = \sqrt{(2L - \Delta_u)^2 - L^2} \Rightarrow (L - \Delta)^2 = (\sqrt{2L - \Delta_u})^2 - (L - \Delta)(L + \Delta) \Rightarrow \]

\[ 2L(L - \Delta) = (\sqrt{2L - \Delta_u})^2 \Rightarrow \Delta = L - \frac{(\sqrt{2L - \Delta_u})^2}{2L} \Rightarrow \delta = 1 - \frac{(\sqrt{2L - \Delta_u})^2}{2L^2} = 1 - \left(1 - \frac{\Delta_u}{\sqrt{2L}}\right)^2 \tag{2} \]

Approximate:

\[ \delta = \frac{L - \sqrt{(2L - \Delta_u)^2 - L^2}}{L} = 1 - \sqrt{\left(\frac{\Delta_u}{L}\right)^2 - 1} \tag{3} \]
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)

- CSIP-dry
- SIP-dry
- SIP-moist
- SIP-wet
Diagonal compression results (3/3)

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

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
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

\[ m\ddot{u} + Cu + f_r = -m\ddot{u}_g \]

\[ m\ddot{u} + m\ddot{u}_g + Cu = -f_r \]

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

**Site I**
- xPC Signal Generation
- Controller
  - Servo-hydraulic control

**Site II**
- xPC Signal Generation
- Controller
  - Servo-hydraulic control

**Site III**
- xPC Signal Generation
- Controller
  - Servo-hydraulic control

**Remote” Substructure B**
- Test substructure I
  - Actuator
  - Load cell

**Remote” Substructure A**
- Test substructure II
  - Actuator
  - Load cell

**Analysis “Site”**
- PC
  - Integrator
    - Algorithm
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

Start

Calculate $K_{i+1}, v_{\text{Actuator}}^{i+1}, S_{i+1}$

Define thresholds: $K_d, K_f, V_d, V_f, S_d, S_f$

Current Mode?

Displacement

Force

Switch to Force Mode

Switch to Displacement Mode

End

Stay at current Mode

$S_{i+1} > S_f$ Y

$V_{\text{Actuator}}^{i+1} > V_f$ Y

$K_{i+1} > K_f$ Y

$S_{i+1} < S_d$ N

$V_{\text{Actuator}}^{i+1} < V_d$ N

$K_{i+1} < K_d$ N
Error model and feed-forward compensation

Solution of problem 2

Ideally
\[ Y(t) = X(t) \]
\[ A(t) = 1 \]

\[ X(t) \rightarrow A(t) \rightarrow Y(t) \]

\[ X(t) = Y(t) + A(t) \]
Pseudo-dynamic experiments

Test structure

Displacement [mm]

Stiff regions

Displacement [in]

Force [kip]

Force [kN]

22.2

0

-22.2

-44.5

-127

-63.5

0

63.5

127

44.5

-10

-2.5

0

2.5

5

-44.5

-22.2

-10
Global comparison

Deformations versus time

Hybrid simulation

Shaking table

Forces versus time

Hybrid simulation

Shaking table
SIPs Preliminary Results
Test specimen and setup

- 2X4 Top Plate
- Fasteners, 6" o.c. (typ.)
- 4X4 SIP
- Fasteners, 6" o.c. (typ.)
- 2X4 Top Plate

- OSB Facing
- Foam Core

- OSB Facing
Conventional panels versus SIPs

Conventional

- Force: 11.5 kN
- Displacement: -0.17 kN/mm

SIP

- Force: 17.5 kN
- Displacement: -0.33 kN/mm

ASTM

CUREE

+52%

-93%

Displacement [mm]
Quasi-static results and failure mode

Specimen 3, Run 04

- Displacement, inches
- Force, kips

EPS core crushing

Fasters failure-bottom

Fasters failure-bottom

Fasters failure-top
Hybrid simulation results

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

1.82” Ultimate

µ_u = 1.82/0.44 > 4.0

Low Level: 25% UBE

Yield” onset

100% DBE

100% UBE

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!