Opportunities for Seismic Shake Table Testing of Fenestration Products

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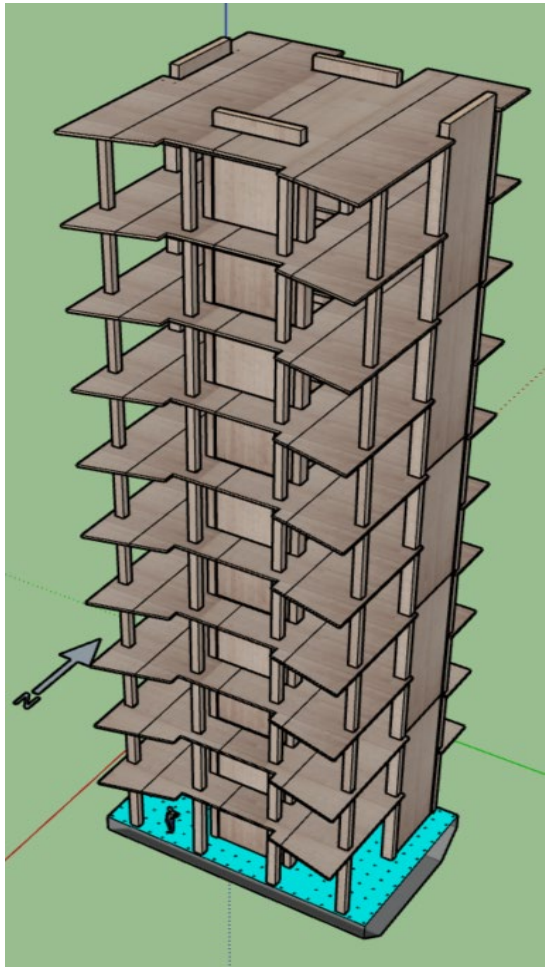
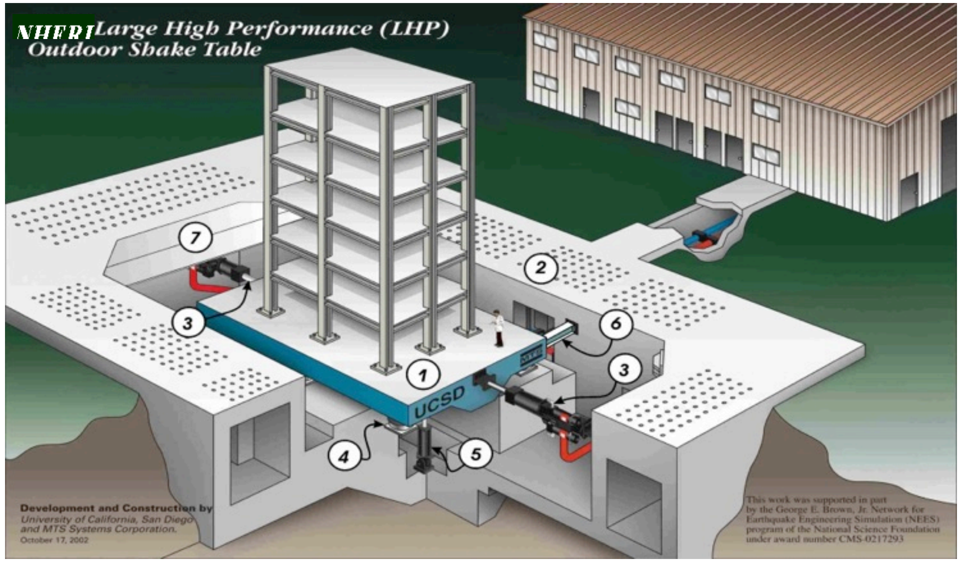
Outline of Presentation

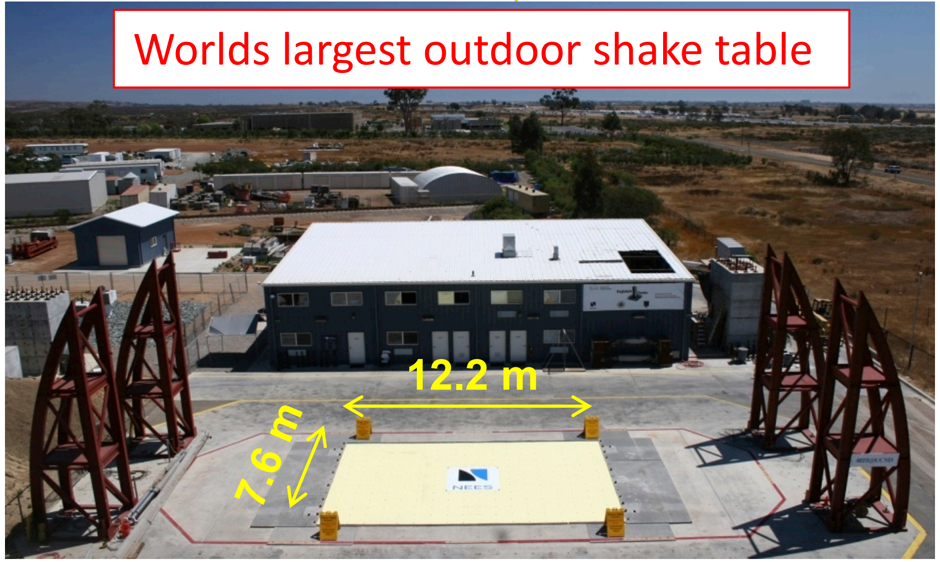
- Overview and Objectives of Test Program
- Architectural Vision for Tall Wood Buildings
- Field Observations and Prior Testing of Fenestration Products
- Benefits of Proposed Shake Table Testing for Fenestration Products
- How FGIA Members can Participate and Collaborate
- Details/Specifications of the Testbed Building
- Vision for the Shake Table Test Program
- Question and Answer

Overview and Objectives of Test Program

- In mid-2021, we will perform shake table testing of a 10-story mass timber building at UCSD's Large High-Performance Outdoor Shake Table (LHPOST).
- The primary objective of the test is to support the development of a seismic resilient lateral system for tall wood buildings.
  - Uses post-tensioned rocking walls built from cross-laminated timber panels.
  - Test will validate that the performance of the structure meets the design specifications.

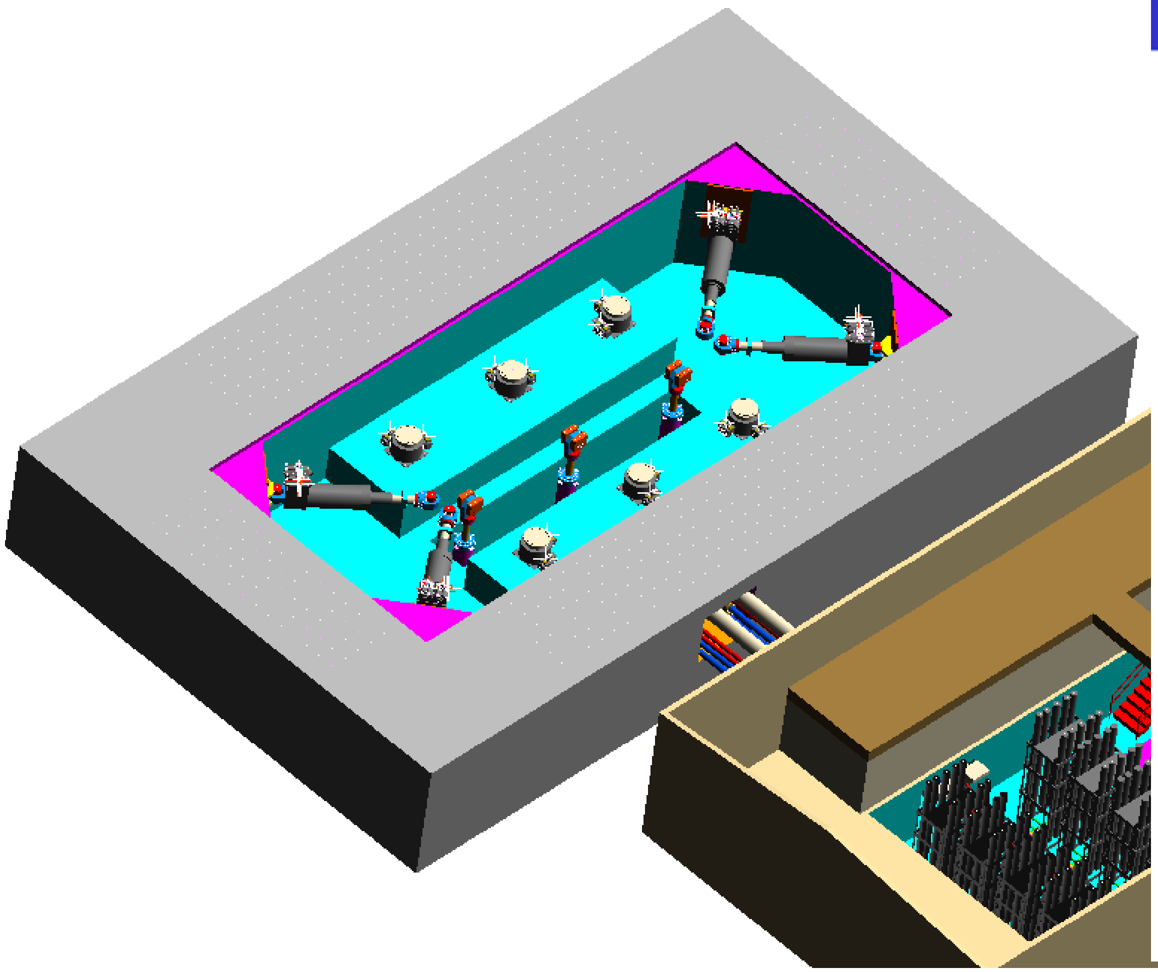






Performance Characteristics in Current 1-DOF Configuration	
Designed as a 6-DOF shake table, but built as a 1-DOF system to accommodate funding available	
Stroke	±0.75m
Platen Size	40 ft × 25 ft (12.2 m × 7.6 m)
Peak Velocity	**1.8 m/sec**
Peak Acceleration	4.7g (bare table condition); 1.2g (4.0MN/400 tons rigid payload)
Frequency Bandwidth	0-33 Hz
Horizontal Actuators Force Capacity	**6.8 MN (680 tonf)**
Vertical Payload Capacity	**20 MN (2,000 tonf)**
Overturning Moment Capacity	50 MN-m (5,000 tonf-m)

Table is being upgraded to 6DOF; operation ceased in Oct. 2019 and will commence again by March 2021.



Design Uni-axial Performance Characteristics of 6-DOF LHPOST

Platen size	12.2 m × 7.6 m (40 ft × 25 ft)		
Frequency Bandwidth	0 – 33 Hz		
Vertical Payload Capacity	20 MN (4,500 kip)		
	Horizontal X	Horizontal Y	Vertical Z
Peak Translational Displacement	±0.89 m (±35 in)	±0.43 m (±17 in)	±0.127 m (±5 in)
Peak Translational Velocity	2.5 m/sec (100 in/sec)	2.0 m/sec (80 in/sec)	0.6 m/sec (25 in/sec)
Peak Translational Force*	10.6 MN (2,380 kip)	8.38 MN (1,890 kip)	54.8 MN** (12,300 kip)
Peak Rotation*	2.5 deg	1.5 deg	9.9 deg
Peak Rotational Velocity*	21.0 deg/sec	12.4 deg/sec	40.5 deg/sec
Peak Moment*	37.2 MN-m (27,400 kip-ft)	49.0 MN-m (36,200 kip-ft)	47.0 MN-m (34,600 kip-ft)
Overturning Moment Capacity	45.1 MN-m (33,200 kip-ft)	50.0 MN-m (36,900 kip-ft)	

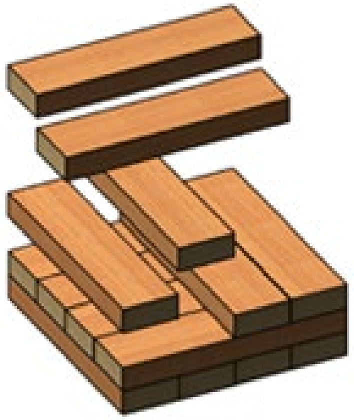
* peak demand obtained during sinusoidal motions
** peak compressive force in the compression-only vertical actuators

Table loaded with rigid payload of 1,100 kips (5 MN)

WHY TALL TIMBER?

- Sustainable regenerating material
- Supports healthy forest products industry
- Beautiful and lightweight buildings that require less raw materials

Concept



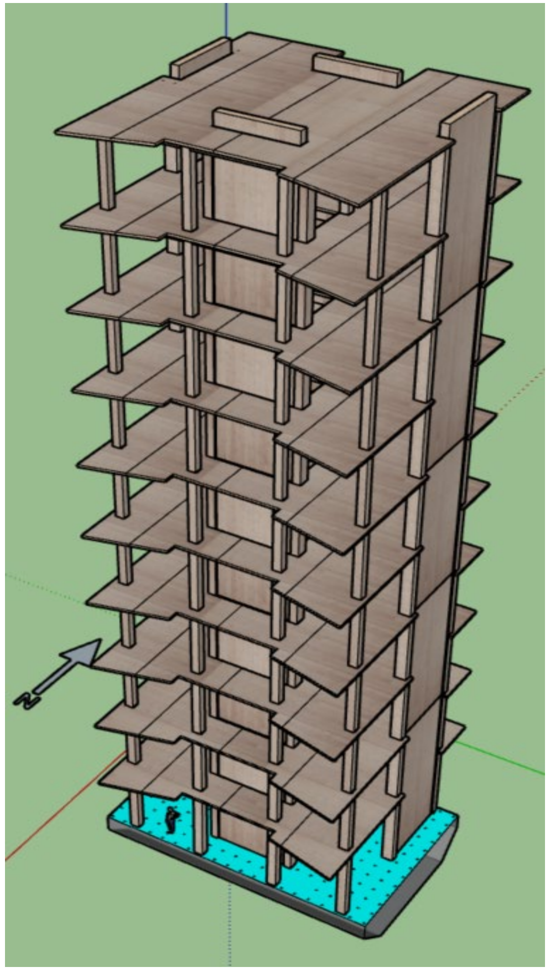
CLT Panel

Structural components are MASSIVE
Engineered wood products

Use CLT panels and the main structural components, walls and floors of the building.

Objectives

- Support the development of a ***seismic resilient*** tall wood buildings.
  - Obj. 1. Validate that the performance of the structure meets the design specifications.
  - ***An important notion of resilience is the ability of the building to quickly recover its function after an earthquake!***
  - ***Nonstructural components (NCS) have a very important role in resilience, as they contribute greatly to the function of the building.***
  - Obj. 2. Quantify the performance of select nonstructural components, in the context of functional recovery and resilience objectives.



We have identified building envelope as a priority nonstructural component.

- Importance of building envelope to building safety and function.
  - Prevent falling hazards due to envelope detachment in an earthquake.
  - Maintain protective air, water, and insulating barrier.
- Building envelope are among the most vulnerable NCS.
  - Distributed vertically floor-to-floor.
  - Must accommodate both the interstory drifts and the accelerations; i.e. “along for the ride”.
- Lack of understanding about seismic performance.
  - Racking tests show that inter-story drifts can be accommodated.
  - But in prior earthquakes, glass cracking and fallout is frequent.
  - Limited shake table test data compared to other NCS.

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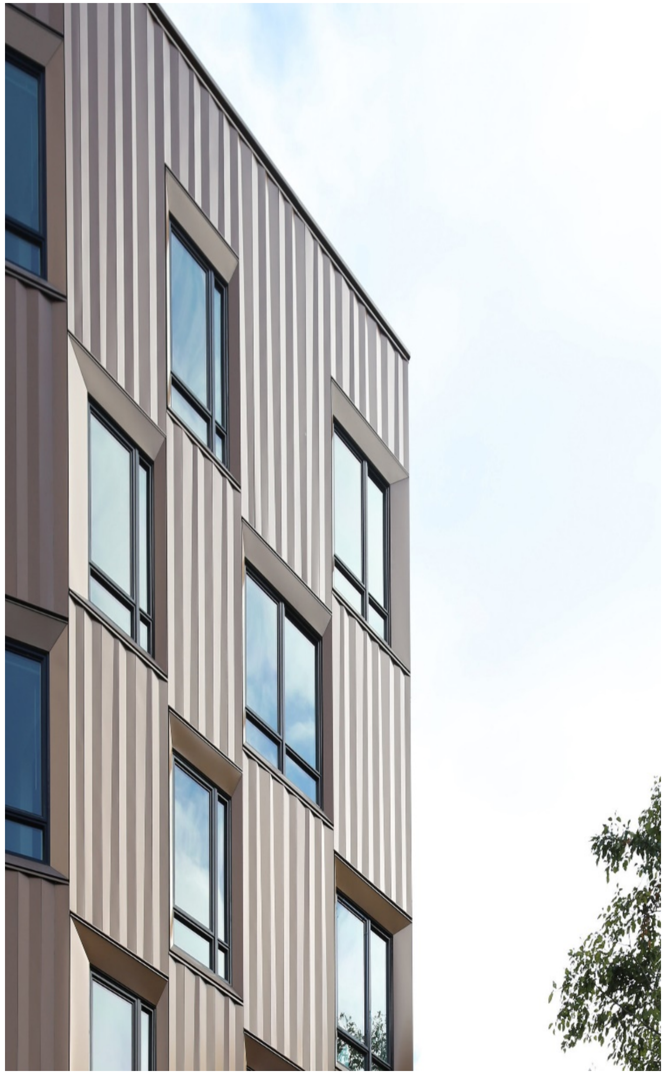
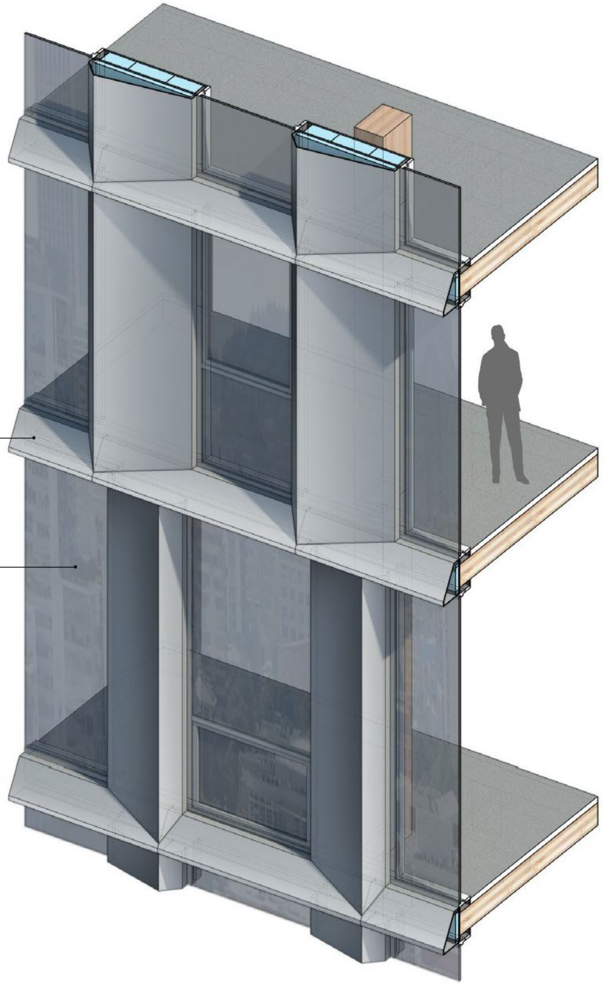
Architectural Vision for Tall Wood Buildings

12-story Framework Building designed for Portland, OR exemplifies the tall timber archetype

- Design was conceived as a mixed-use building combines retail, office space and affordable housing.
- Architectural vision is to display the rocking walls and much of the structural wood. The building should be perceived as high rise timber from the street level.
- The primary skin is an aluminum composite metal (ACM) with fiberglass windows.
- Storefront in the lower lobby space.
- Curtain wall up the height in the middle displays the rocking wall from the street.
- Shift in panel geometry at mid-height differentiates lower office floors from upper residential floors.

Innovation to Elevate Human Experience





Sheet Metal Panels (Economical)

Skin Systems We are Interested in Testing

Basic Skin System	Class of Variation	Variations Considered
Storefront	Glazing method	Mechanically captured vs structurally glazed
Curtain wall w/ glazing	Glass aspect ratio	Varied from 1:2 to 2:1
Stick built curtain wall	Glass treatment	Heat strengthened vs. fully annealed
Unitized curtain wall	Glass type	Laminated and insulating glass units (IGU)
Light-framed with windows	Framing style	Balloon vs platform framed
Light gage steel stud framing	Finish material	Metal panel, wood shingle, and stucco
Wood stud framing	Window type	Fixed or operable, variable size
	Window framing	Metal or wood framed
	Glass variations	Same variables as for curtain walls may be applied

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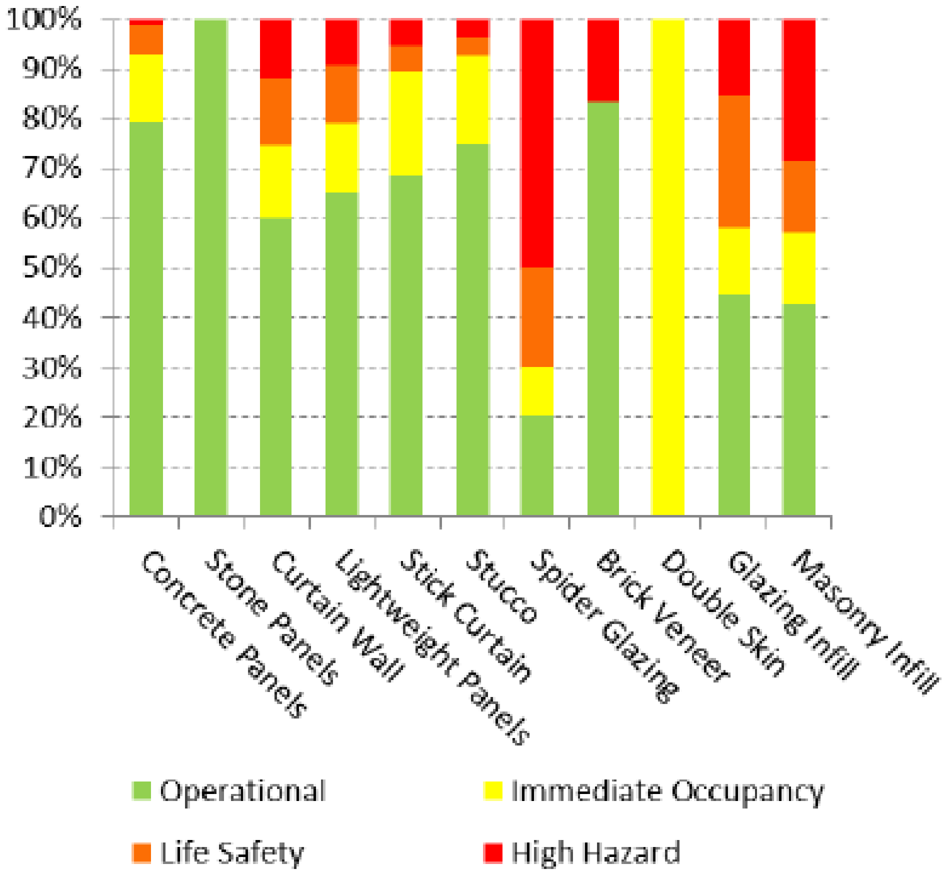
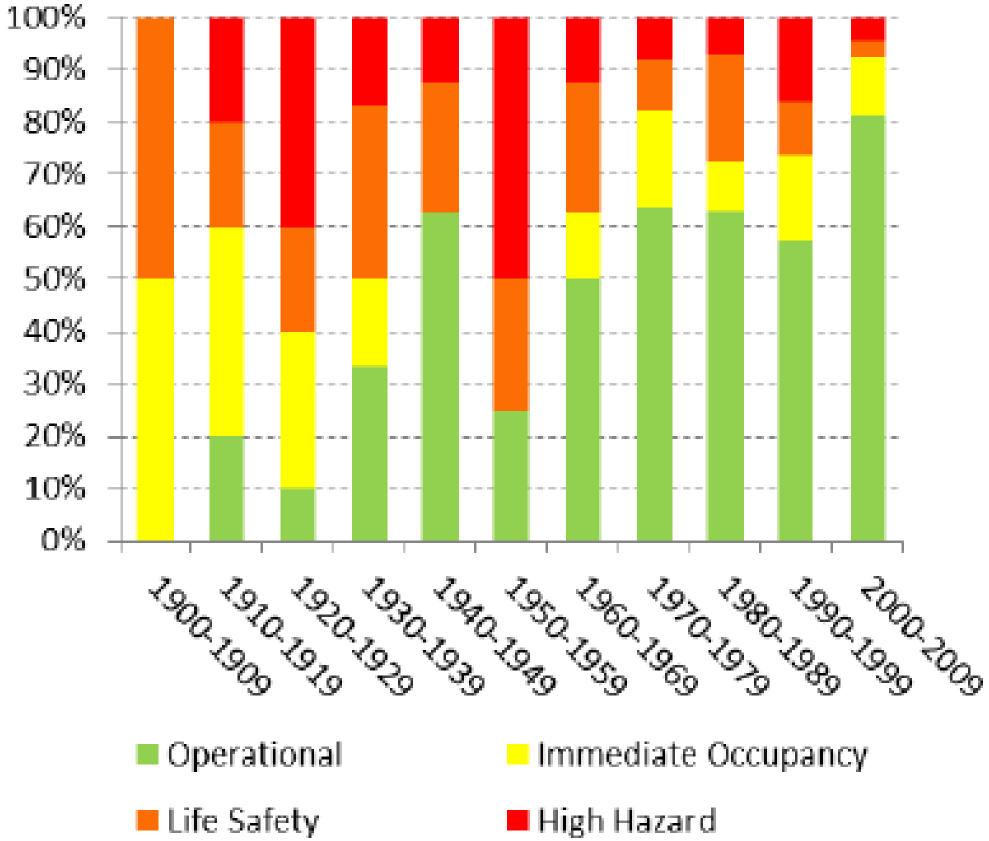
Seismic Performance of Facades

- Statistics from examination of 217 buildings after 2011 Christchurch Earthquake (Baird et al. 2012)





Examples of Damage Observed in Prior Earthquakes

1994 Northridge

- Glazing system damage was extensive and extended to areas where most other NCS damage was rare (Reitherman and Sabol 1995).
- More damage to storefront than curtain wall.
- Glazing with SSG performed better than glazing with vinyl gaskets (Harter 1994).
- Damage due to gasket dislocation was often not apparent until after rainfall. Required costly resetting of the glazing (Reitherman and Sabol 1995).

2001 Nisqually Earthquake (Filiatrault et al. 2001).

- Frequent observations of glass damage; broken windows.

2011 Christchurch EQ (Baird et al 2012)

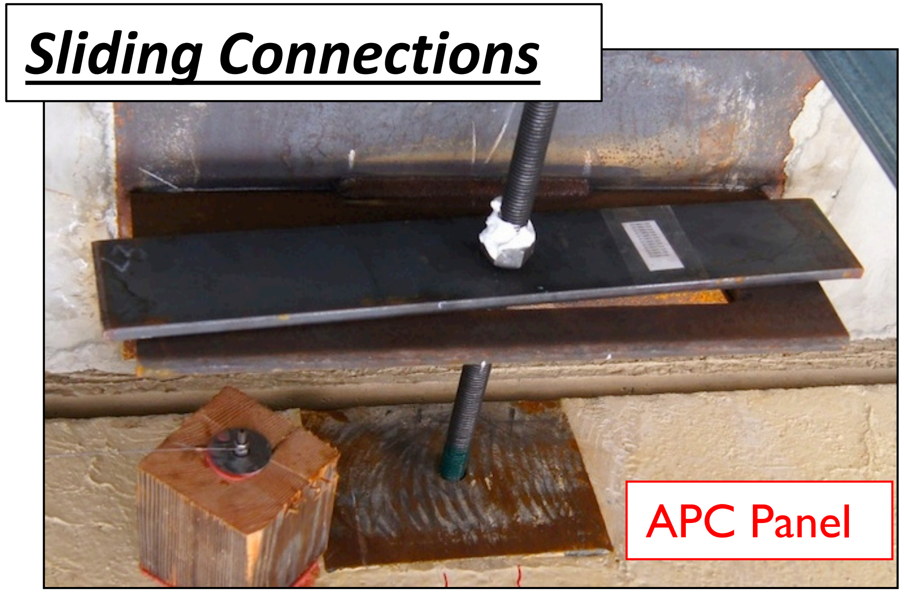
- Cracked or broken glass, more prominent in older buildings designed for less glazing movement
- Full panel fallout in systems with tougher glass (e.g. laminated or tempered)
- Frames were bent or warped
- Complete detachment of curtain wall as a result of bolt shearing.

Section of curtain wall completely detached from building

Typical glass fallout

A Prior Test Focused on Nonstructural Components

- Several years ago the BNCS project constructed a full-scale building with a variety of NCS.
- In this test, the building was fully cladded, and two different systems were featured:
  - Light gage steel "balloon framed" system
  - Precast concrete cladding panels
- Led to important advancements (Hutchinson et al. 2015)
  - Sliding tieback connection did not work as intended. Changes were implemented to ASCE 7-16 as a result.
- No windows were included in the test.



Damage States and Fragilities from Racking Tests

Fragilities were developed for 44 different CW and SF configurations examined based on laboratory tests using a racking facility (FEMA P-58: BD 3.9.1, Memari et al. 2011)

- Stick built and unitized systems, dry and wet-glazed.
- The fragilities depend on details, such as: framing system, flexibility of the connection to the structural frame, glass-to-frame clearance, panel aspect ratio, and overall dimensions.

Other Observations from Memari et al. (2011)

- Natural corner rounding action displayed by glass specimens with substandard clearances gives additional seismic failure capacity to those systems beyond what would be expected.
- STOREFRONTS – Gasket seal failures and frame damage dominated.
- UNITIZED SYSTEMS – Unitized systems can sustain drifts of 2.5%; no glass damage. They perform well due to the flexibility of the sealant.
- STICK SYSTEMS – Greater than half can sustain drift of 2% with no damage; gasket failure occurs at lower drifts.
- General – fragility functions are expected to be conservative, because they were developed with racking tests which implicitly assumes rigid frame to component connection.

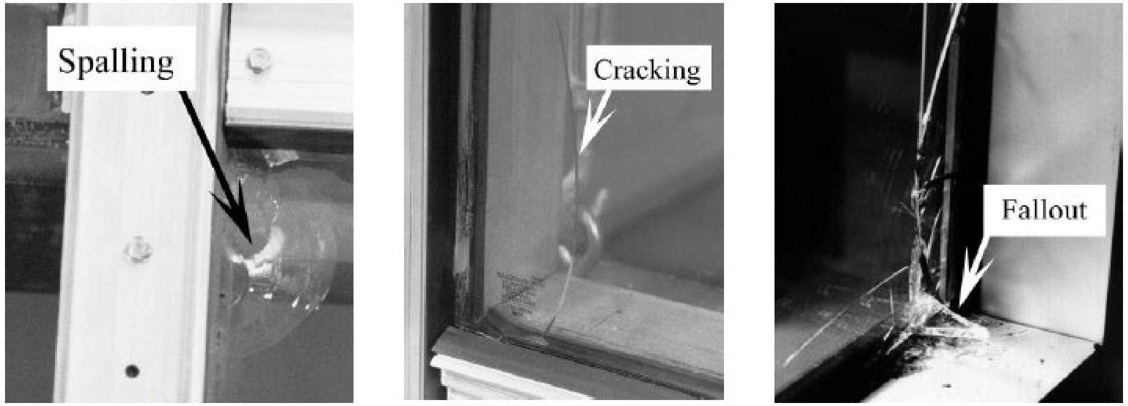


Figure 4: Typical glass damage progression at the corners of insulating glass units constructed with annealed monolithic glass panes with picture (a) showing spalling; (b) cracking; and (c) fallout.

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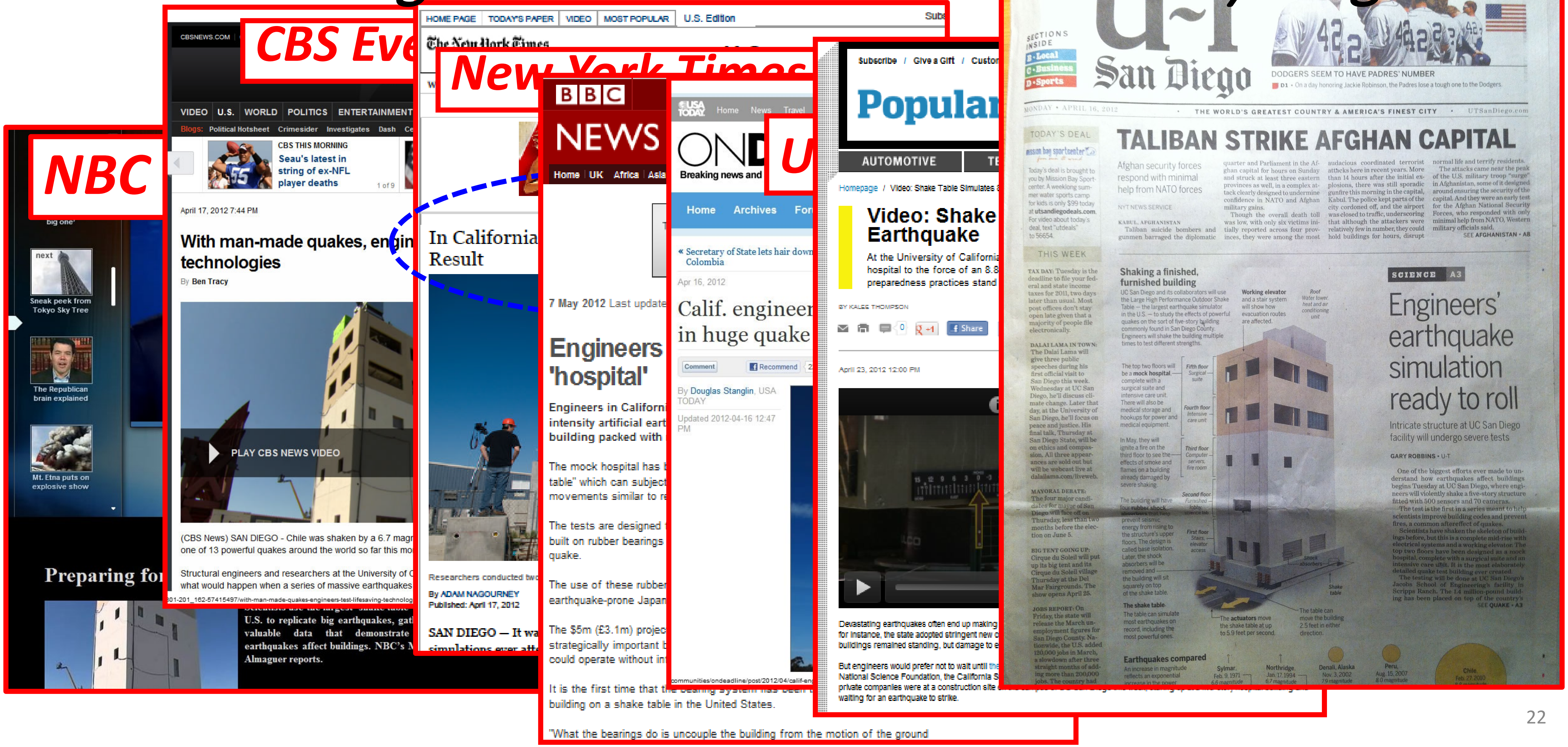
Benefits of Proposed Shake Table Testing for Fenestration Products

- Evaluate the complexities of dynamic shaking and how they impact racking performance of building skins
  - Interaction between the primary system (structure) and the building skin
    - Flexing of the structural framing (e.g. bending/flexure of beams, vertical vibration of floor diaphragms)
    - Out-of-plane movement or combination of in-plane and out-of-plane movement
  - Dynamic loading effects, using realistic (prior recorded) earthquake motions with different characteristics (e.g., broadband frequency, multi-directional pulses)
- Evaluate deformation compatibility of corner joints.
- Use the data to develop standardized drift limit states for various systems.
- Identify better performing details or detailing improvements.
- Opportunities to work collectively and advance design codes.

Media Coverage and Outreach is a Part of Any Large Test



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How FGIA Members can Participate and Collaborate

We are seeking product donations, in-kind and financial support to support the installation and testing of a variety of skins on the building.

- Material/product donations with delivery to the test site.
- In-kind engineering/drafting support to design the test specimens.
- Contractor services to install specimens on the testbed building.*
- Contractor services to remove specimens from testbed building and arrange for disposal.
- Cash donations to support other costs of testing.

* We are working to arrange collaborations with other organizations, such as International Union of Painters and Allied Trades (IUPAT).

Costs Covered Through our Grants and Resources

- Fabrication and de-erection of the main structure.
- Operation of the shake table/staff support during testing.
- Purchasing and installing instrumentation.
- Collecting and processing data.
- Preparing test reports.

Other Costs not Covered by Project

- UCSD staff support during the NCS construction/fabrication phase.
- Large equipment rental (crane, forklift) as needed for installation.
- Any other costs related to erection/de-erection/disposal contracted out to third party organizations.
- Previous sponsors have contributed on the order of $10K - $50K depending on complexity of the product contribution.

Partners and collaborators should know:

- Collaborators are welcome to be on-sight during all testing, to participate in inspection and to collect your own data.
- We will provide all collaborators with useful data for your purposes:
  - Key responses of the primary structure.
  - All data (measurements, photos, videos) for your system.
- Collaborators may selectively use data from the test for your own interests: marketing, further R&D, etc.
- All data collected by the project team will be uploaded and curated on the NHERI database *DesignSafe,* from which it can be publicly accessed by any interested parties.
- Project team will acknowledge collaborators in all research and outreach products:
  - Media coverage
  - Conference presentations
  - Journal papers and trade articles
  - Lessons for college and K-12 students
  - Presentations for industry organizations
- Project team welcomes collaboration on preparation of research products

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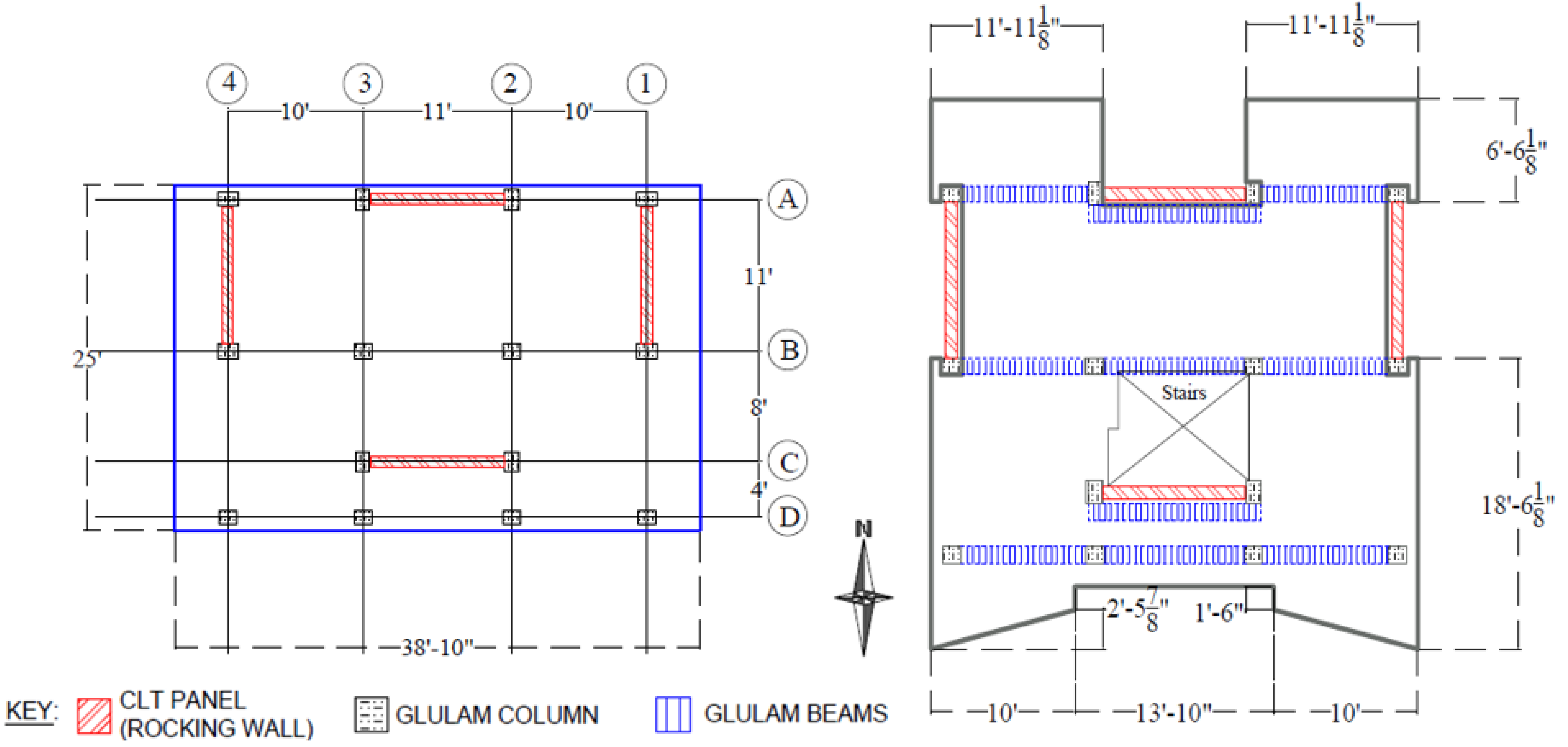
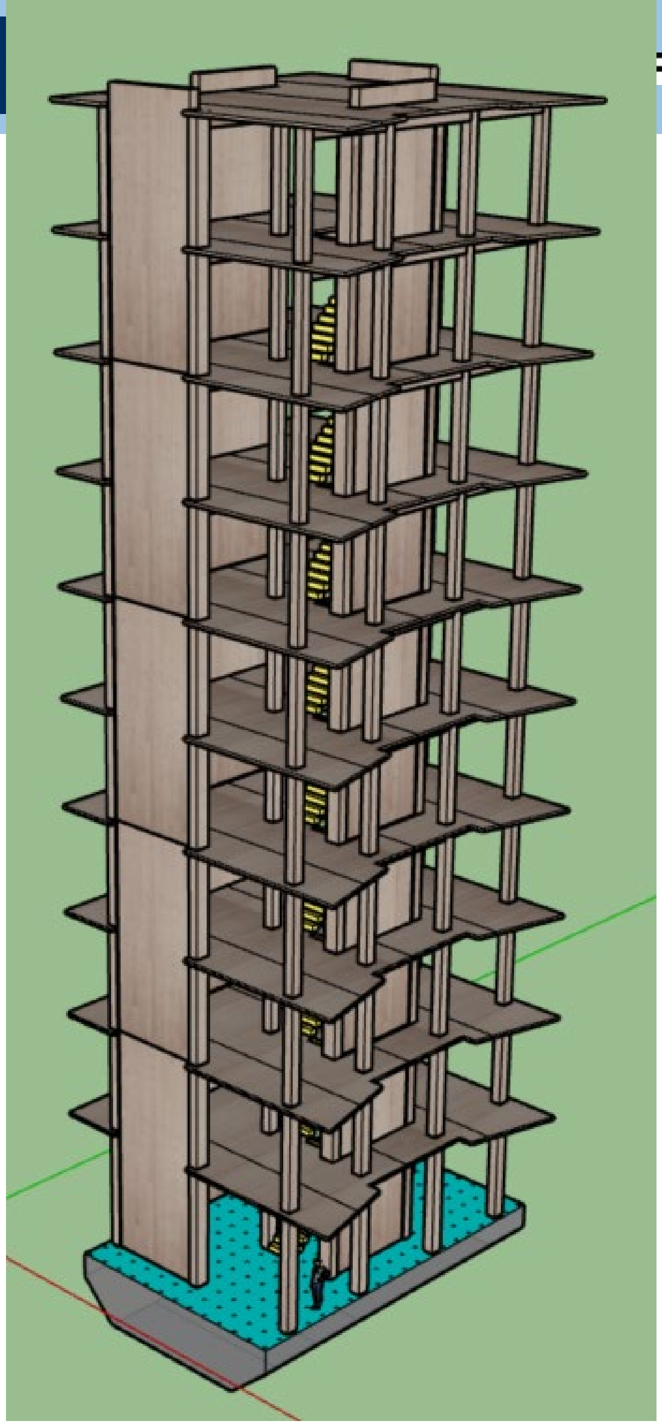
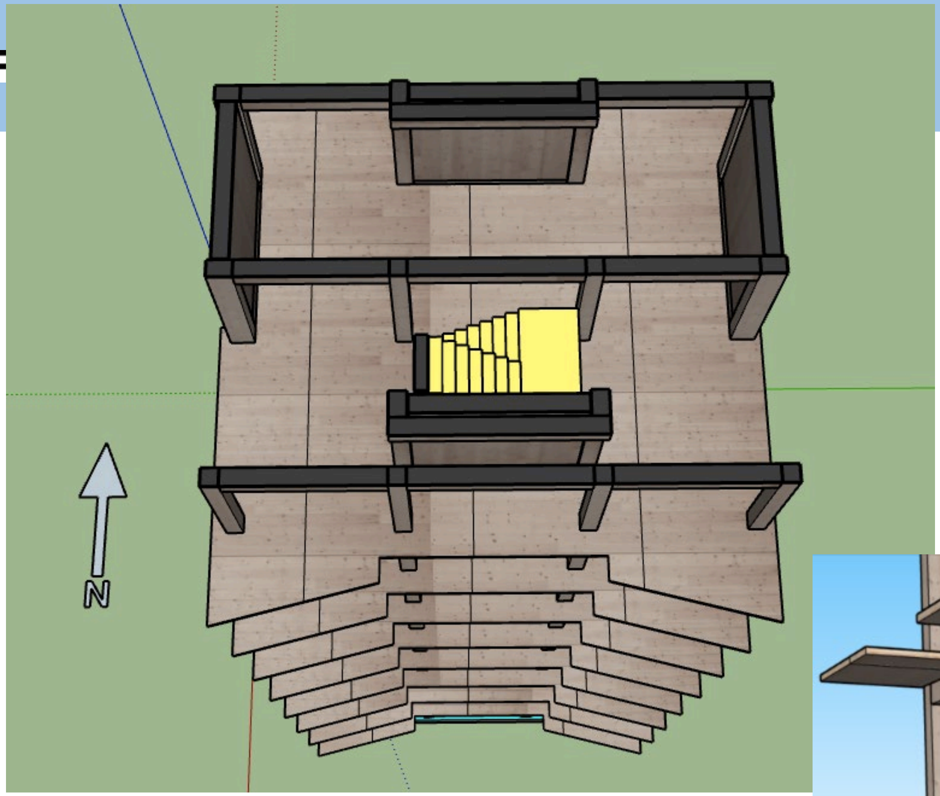
Details/Specifications of the Test Building

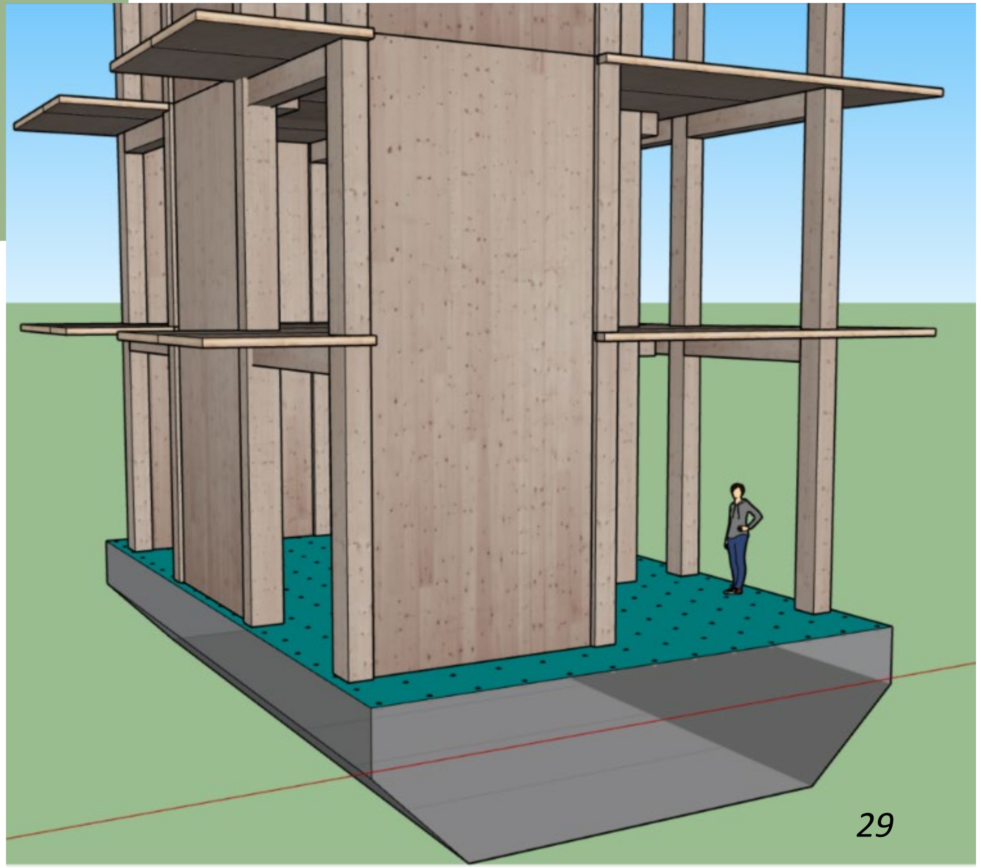
- Story heights are 13’ for first story and 11’ for all subsequent stories.
- Building footprint on shake table (left) and typical floor plan (right)



- Floor slabs are cantilevered from beams/columns to increase floor area.
- Skins must be hung from floor slabs, which are 5-ply (6.875” thick) CLT panels.
- Top of slab lag bolt anchor envisioned for systems that are hung.

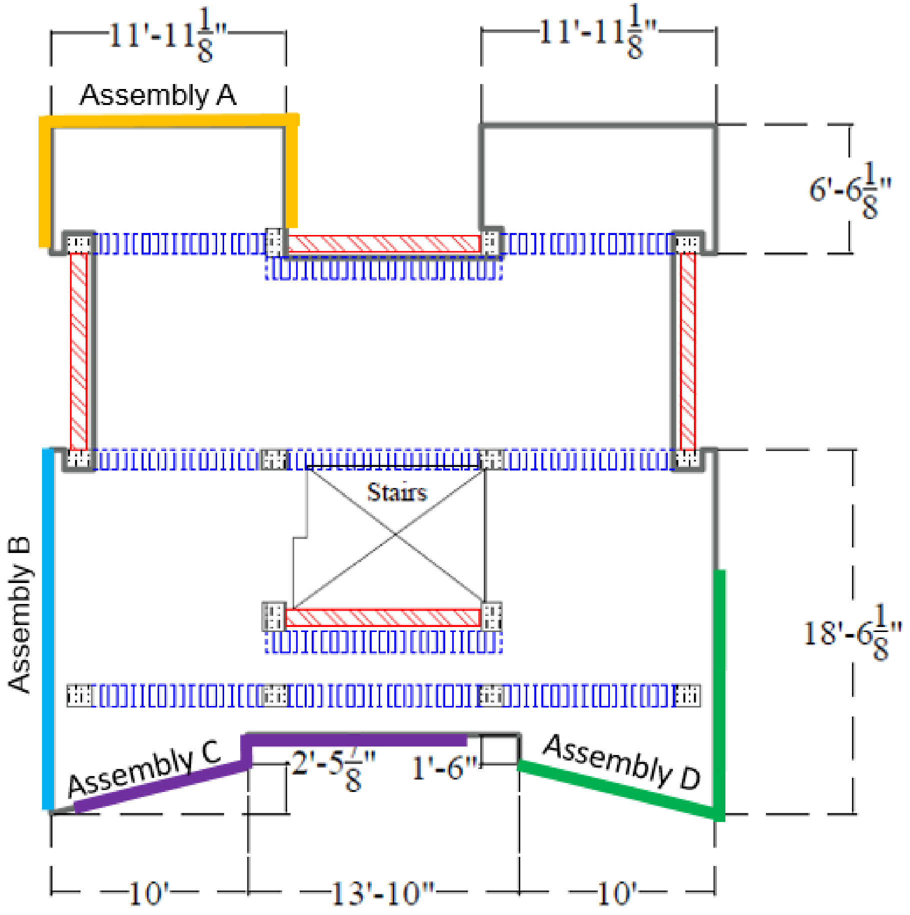






Natural Hazards Engineering Research Infrastructure

Potential skin subassembly layouts shown in color



- Building has about 10,000 sf of usable exterior area
- Individual skin subassemblies on the order of 500-2000 sf are considered desirable.
- Figure illustrates possible skin subassemblies that vary from about 200-250 sf per floor.
- We do not intend to consider interactions between skin systems for this test, and boundary joints between skin systems are not needed.

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Vision for the Shake Table Test Program

- Shakes of the structure without building skins may occur first (to be decided)
- Install building skins
- Place instrumentation for building skins
  - Displacement transducers to measure relative deformations across components (e.g. slip joint).
  - Accelerometers to measure accelerations in any direction.
  - Load cells to measure forces across connections.
  - Strain gages to measure localized strain at a point.
  - Video cameras to "watch" the close-up movement at a location.
  - Interstory drifts and floor accelerations of the primary structure will be measured.
- Shake table program
  - Pre-select a sequence of shakes
  - Between each shake, we will access the building for inspection.
    - Document cracks and damage according to the shake intensity at which they occurred.
    - Take photos.
    - Possible air and water testing after selected shakes.

Concept of the Loading Protocol

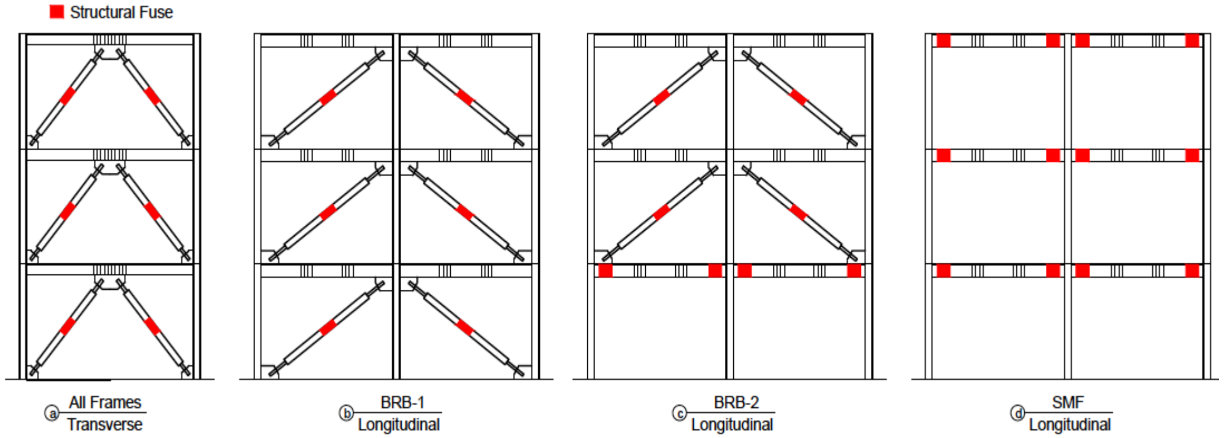
- Select one or two recorded motions to be run at different shaking intensities
- Increase intensity of the shakes from low to high intensity
  - e.g. 25%, 50%, 75%, 100%, 150%, 200%, 250%, 300%
  - Repeat each motion single direction and bidirectional
  - Identify serviceability, design, and maximum considered earthquake (MCE) levels.
  - White noise between tests for system identification.
- At the end, repeat select shakes with vertical.

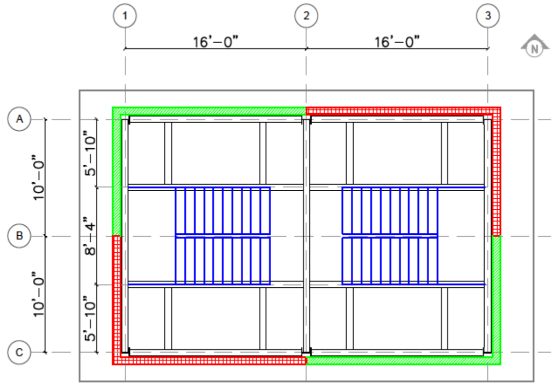
Tentative Time Frame for the Test Program

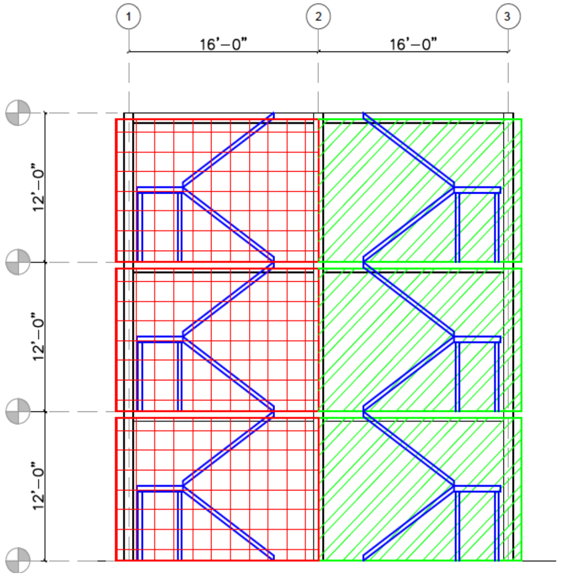
- End of 2020: All nonstructural suppliers committed, design and construction drawings complete
- Feb 2021: Materials delivered to UCSD site
- March 2021: Fabrication of structure and instrumentation
- May 2021: Shaking of the structure without building skins
- June 2021: Installation of building skins and instrumentation
- July 2021: Shaking of the structure with building skins
- Sept. 2021: Test with PT rocking wall system complete

Future Opportunities for Collaboration

- A follow-up project may occur pending review and selection for funding by NSF.
  - This project will use a 3-story steel frame testbed structure to achieve targeted drift demands in each story.
  - The testbed structure will be constructed in 2020 and characterization testing in 2021.
  - Main skin systems: curtain wall and glass fiber reinforced panels
  - Interface joint compatibility will be examined.







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Question and Answer

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