



LEVER

Shake Table Testing of Fenestration Products
FGIA Webinar, 01-21-2020



Natural Hazards
Engineering
Research
Infrastructure

Opportunities for Seismic Shake Table Testing of Fenestration Products



Keri Ryan
Associate Professor
Civil Engineering
University of Nevada Reno

Nonstructural Testing Lead



Shiling Pei
Associate Professor
Civil Engineering
Colorado School of Mines

Overall Test Program Lead



Tara Hutchinson
Professor
Structural Engineering
UCSD

*Nonstructural Testing
Collaborator and Test
Facility Expert*



Jonathan Heppner
Director of Projects
Lever Architecture

*Collaborator and
Architectural Vision for
Tall Timber Buildings*



LEVER

Shake Table Testing of Fenestration Products
FGIA Webinar, 01-21-2020



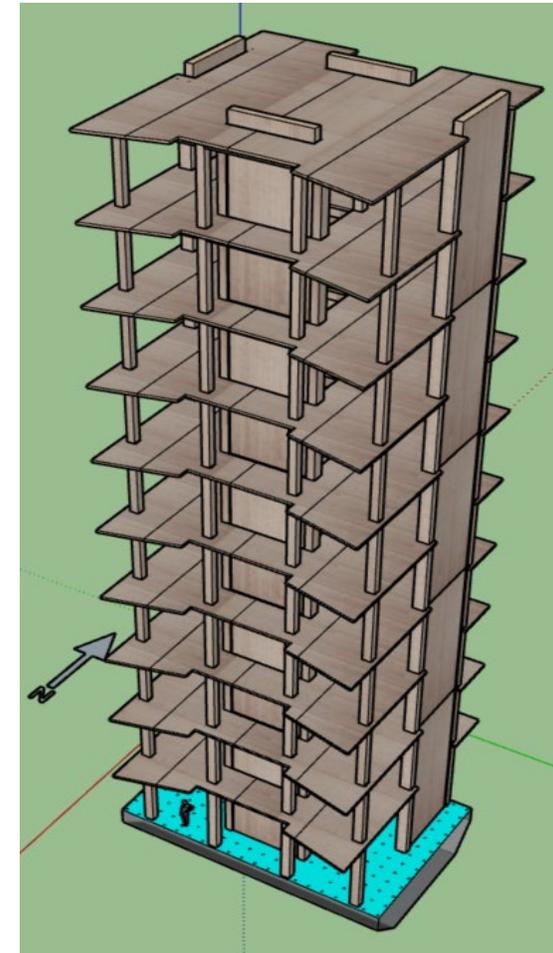
Natural Hazards
Engineering
Research
Infrastructure

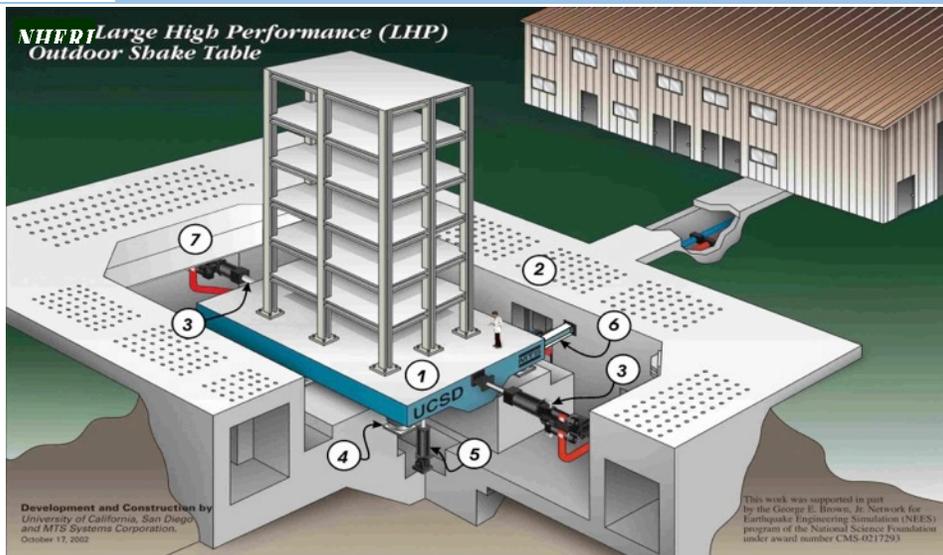
Outline of Presentation

- **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.

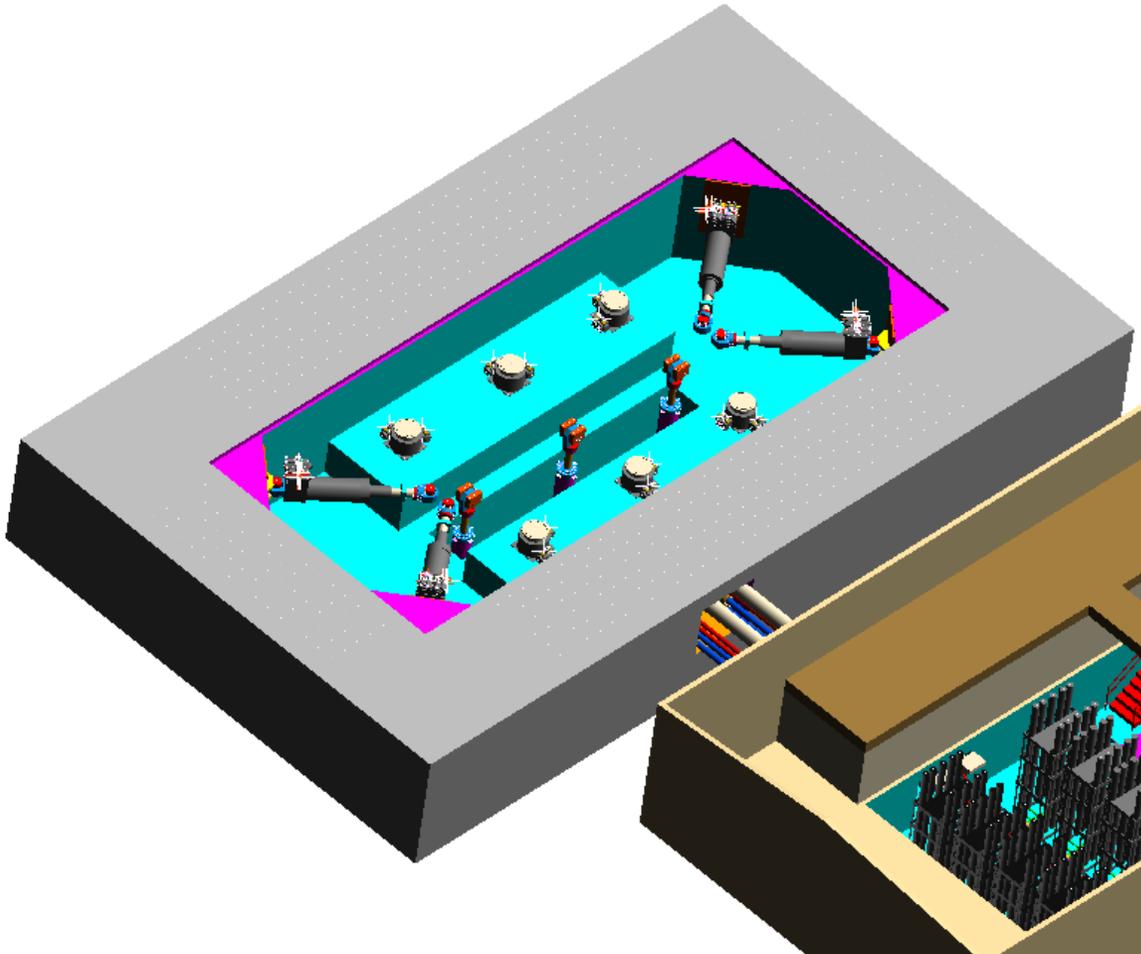




Worlds largest outdoor shake table

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)
Overtopping 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 x 7.6 m (40 ft x 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)

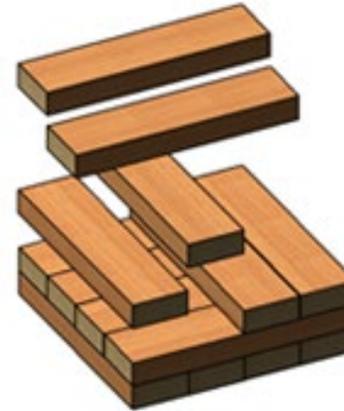
WHY TALL TIMBER?

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



Structural components are MASSIVE Engineered wood products

Concept



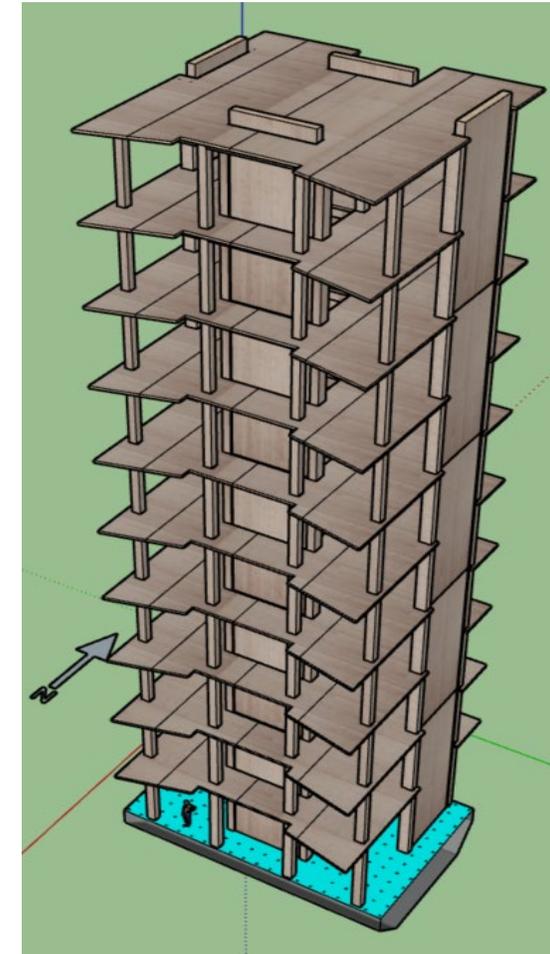
CLT Panel



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.



LEVER

Shake Table Testing of Fenestration Products
FGIA Webinar, 01-21-2020



Natural Hazards
Engineering
Research
Infrastructure

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

Architectural Vision for Tall Wood Buildings



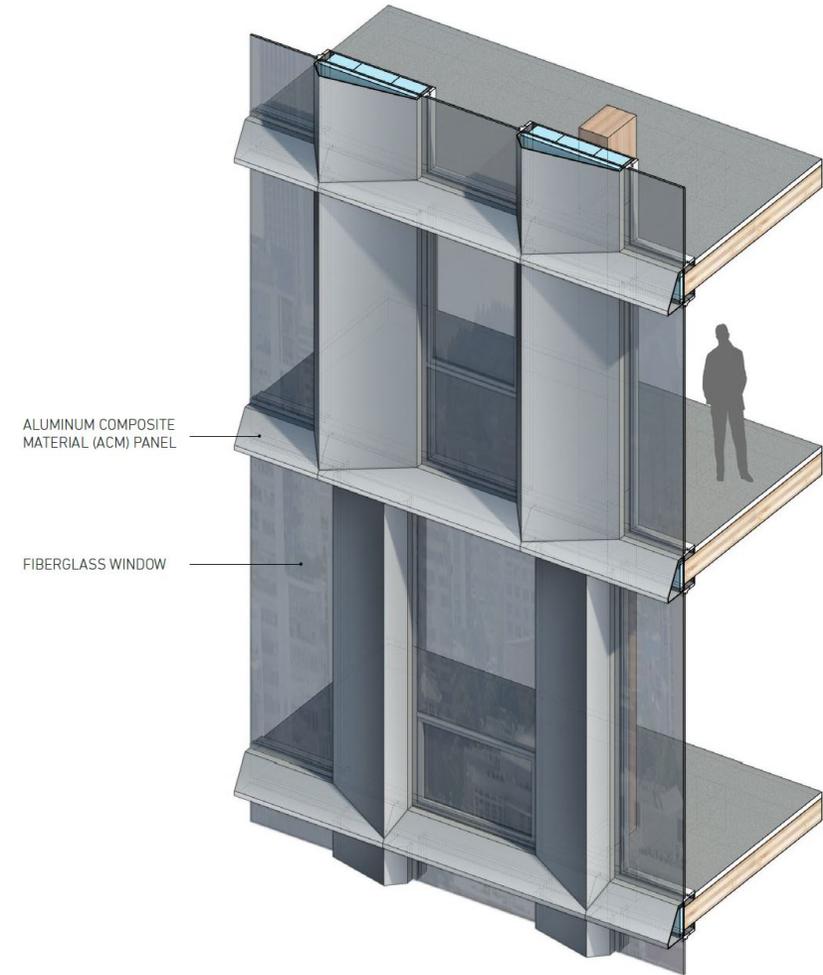


12-story Framework Building designed for Portland, OR exemplifies the tall timber archetype

- 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)



LEVER

Shake Table Testing of Fenestration Products
FGIA Webinar, 01-21-2020



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



LEVER

Shake Table Testing of Fenestration Products
FGIA Webinar, 01-21-2020



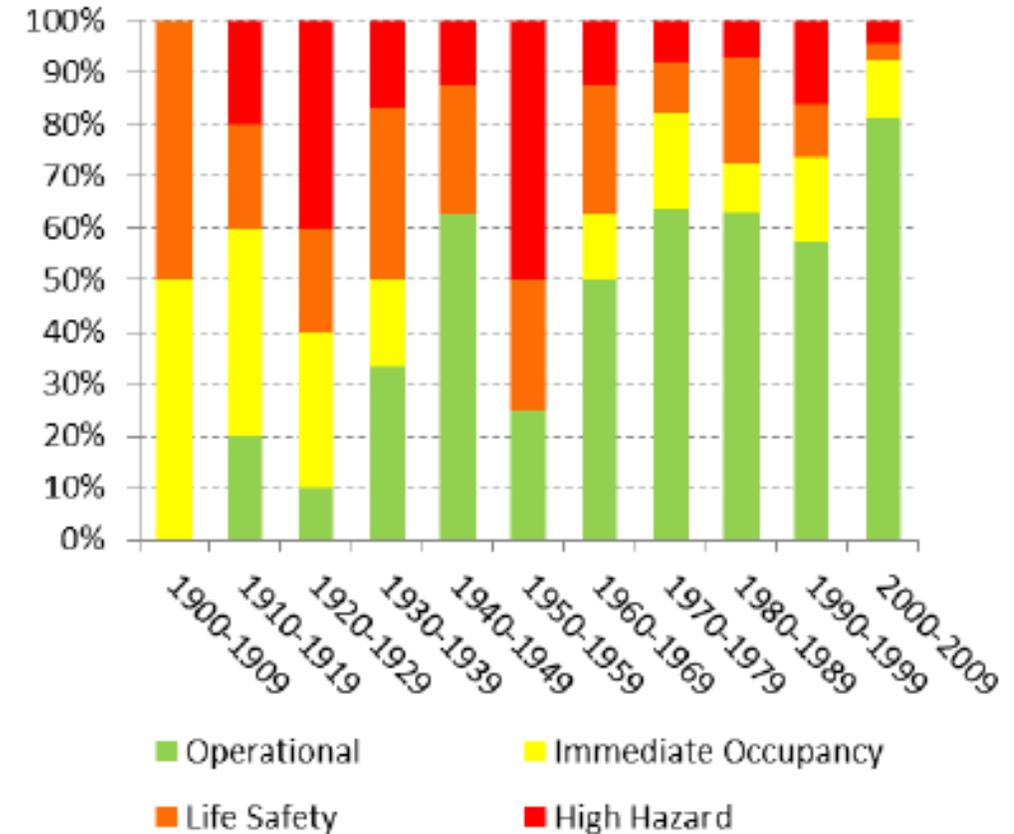
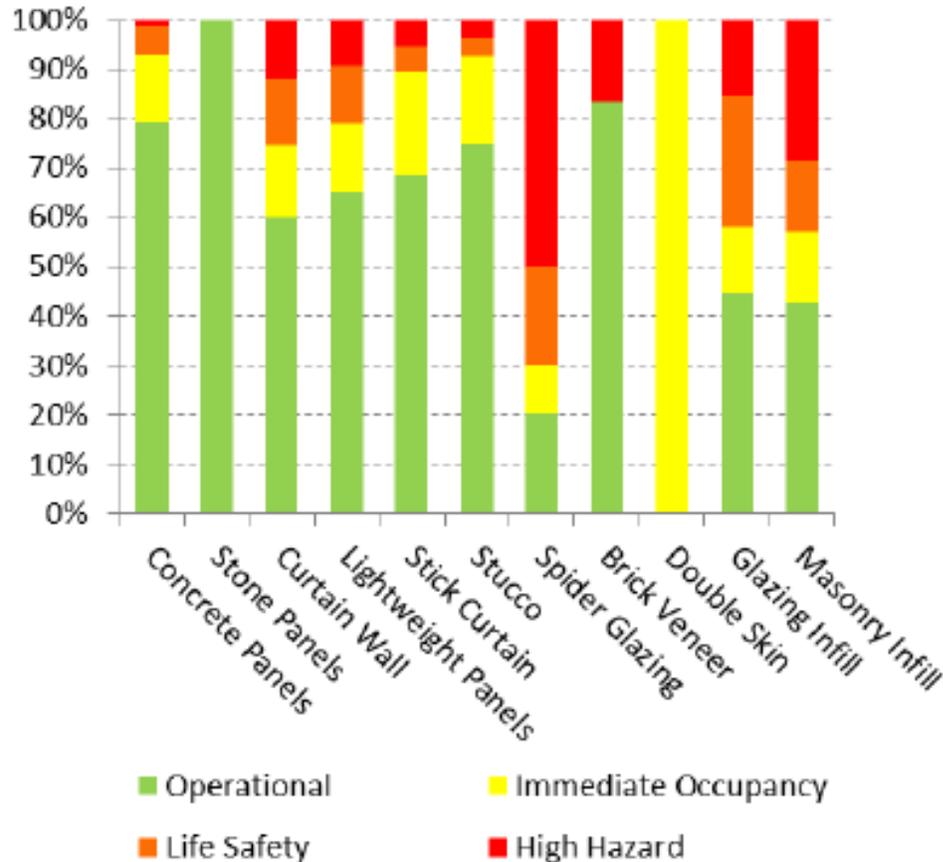
Natural Hazards
Engineering
Research
Infrastructure

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

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

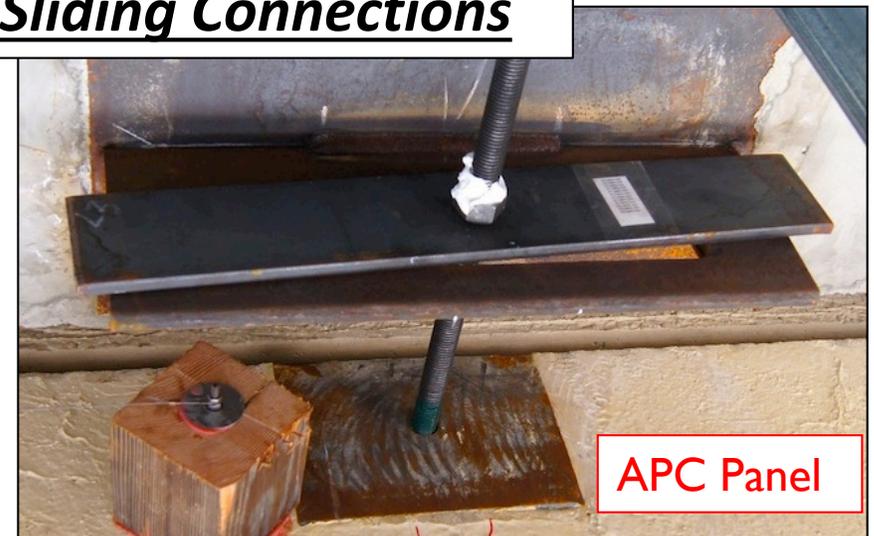


A Prior Test Focused on Nonstructural Components

- 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.



Sliding Connections



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.

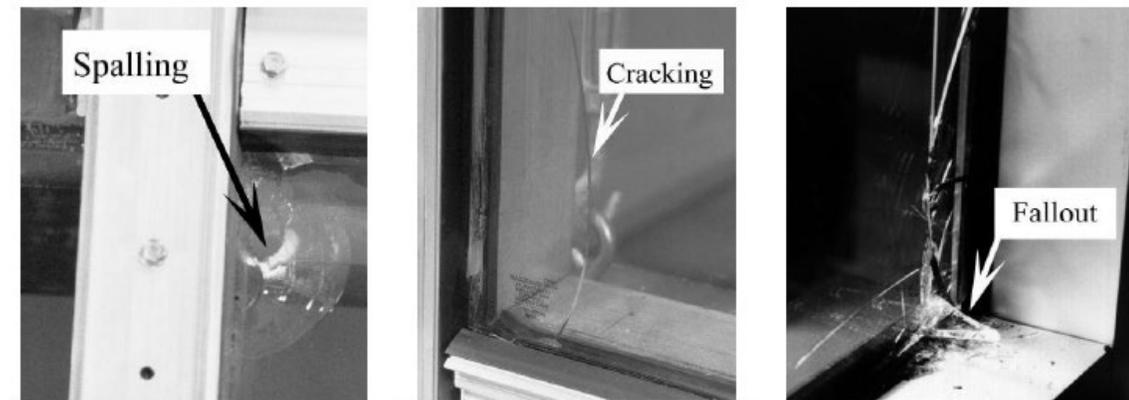


Figure 4: Typical glass damage progression at the corners of insulating glass units constructed with annealed monolithic glass panes with picture (a) showing spalling; (b) cracking; and (c) fallout.



LEVER

Shake Table Testing of Fenestration Products
FGIA Webinar, 01-21-2020



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

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.



LEVER

Shake Table Testing of Fenestration Products
FGIA Webinar, 01-21-2020



Natural Hazards
Engineering
Research
Infrastructure

Media Coverage and Outreach is a Part of Any Large Test

CBS Evening News
CBS THIS MORNING
Seau's latest in string of ex-NFL player deaths
April 17, 2012 7:44 PM
With man-made quakes, engineers test living technologies
By Ben Tracy
PLAY CBS NEWS VIDEO
(CBS News) SAN DIEGO - Chile was shaken by a 6.7 magnitude earthquake, one of 13 powerful quakes around the world so far this month.
Structural engineers and researchers at the University of California San Diego are using the world's largest shake table to replicate big earthquakes, gathering valuable data that demonstrate earthquakes affect buildings. NBC's Almaguer reports.

New York Times
In California Result
Researchers conducted tests on a mock hospital building packed with medical equipment.
By ADAM NAGOURNEY
Published: April 17, 2012
SAN DIEGO — It was the first time that a building system has been tested on a shake table in the United States.

BBC NEWS
Engineers 'hospital'
Engineers in California intensify artificial earthquake tests on mock hospital building.
The mock hospital has been built on rubber bearings which can subject movements similar to real earthquakes.
The tests are designed to be built on rubber bearings which can subject movements similar to real earthquakes.
The use of these rubber bearings is a strategically important building which can subject movements similar to real earthquakes.

USA TODAY
Calif. engineers in huge quake
By Douglas Stanglin, USA TODAY
Updated 2012-04-16 12:47 PM
The top two floors will be a mock hospital complete with a surgical suite and intensive care unit.
In May, they will ignite a fire on the third floor to see the effects of smoke and flames on a building already damaged by severe shaking.
The building will have four rubber shock absorbers that prevent seismic energy from rising to the structure's upper floors. The design is called base isolation. Later, the shock absorbers will be removed and the building will sit squarely on top of the shake table.
The shake table. The table can simulate most earthquakes on record, including the most powerful ones.
Earthquakes compared
The table can simulate most earthquakes on record, including the most powerful ones.
Sybilmar, Feb. 9, 1971, 6.5 magnitude
Northridge, Jan. 17, 1994, 6.7 magnitude
Denali, Alaska, Nov. 3, 2002, 7.9 magnitude
Peru, Aug. 15, 2007, 8.0 magnitude
Chile, Feb. 27, 2010, 8.8 magnitude

Popular Mechanics
Video: Shake Earthquake
At the University of California hospital to the force of an 8.8 preparedness practices stand
BY KALEE THOMPSON
April 23, 2012 12:00 PM
Devastating earthquakes often end up making for instance, the state adopted stringent new building codes, but damage to existing buildings is still a problem. But engineers would prefer not to wait until the National Science Foundation, the California State private companies were at a construction site waiting for an earthquake to strike.

San Diego U-T
TALIBAN STRIKE AFGHAN CAPITAL
Afghan security forces respond with minimal help from NATO forces
KABUL, AFGHANISTAN
Taliban suicide bombers and gunmen barraged the diplomatic quarter and Parliament in the Afghan capital for hours on Sunday and struck at least three eastern provinces as well, in a complex attack clearly designed to undermine confidence in NATO and Afghan military gains.
Though the overall death toll was low, with only six victims initially reported across four provinces, they were among the most audacious coordinated terrorist attacks here in recent years. More than 14 hours after the initial explosions, there was still sporadic gunfire this morning in the capital, Kabul. The police kept parts of the city cordoned off, and the airport was closed to traffic, underscoring that although the attackers were relatively few in number, they could hold buildings for hours, disrupt normal life and terrify residents.
The attacks came near the peak of the U.S. military troop "surge" in Afghanistan, some of it designed around ensuring the security of the capital. And they were an early test for the Afghan National Security Forces, who responded with only minimal help from NATO. Western military officials said.
SEE AFGHANISTAN • A8

Engineers' earthquake simulation ready to roll
Intricate structure at UC San Diego facility will undergo severe tests
GARY ROBBINS - U-T
One of the biggest events ever made to understand how earthquakes affect buildings begins Tuesday at UC San Diego, where engineers will violently shake a five-story structure fitted with 500 sensors and 70 cameras.
The test is the first in a series meant to help scientists improve building codes and prevent fires, a common aftereffect of quakes.
Scientists have shaken the skeleton of buildings before, but this is a complete mid-rise with electrical systems and a working elevator. The top two floors have been designed as a mock hospital, complete with a surgical suite and an intensive care unit. It is the most elaborately detailed quake test building ever created.
The testing will be done at UC San Diego's Jacobs School of Engineering's facility in Scripps Ranch. The 14 million-pound building has been placed on top of the country's largest shake table.
SEE QUAKE • A3



LEVER

Shake Table Testing of Fenestration Products
FGIA Webinar, 01-21-2020



Natural Hazards
Engineering
Research
Infrastructure

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



LEVER

Shake Table Testing of Fenestration Products
FGIA Webinar, 01-21-2020



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).



LEVER

Shake Table Testing of Fenestration Products
FGIA Webinar, 01-21-2020



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.



LEVER

Shake Table Testing of Fenestration Products
FGIA Webinar, 01-21-2020



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



LEVER

Shake Table Testing of Fenestration Products
FGIA Webinar, 01-21-2020

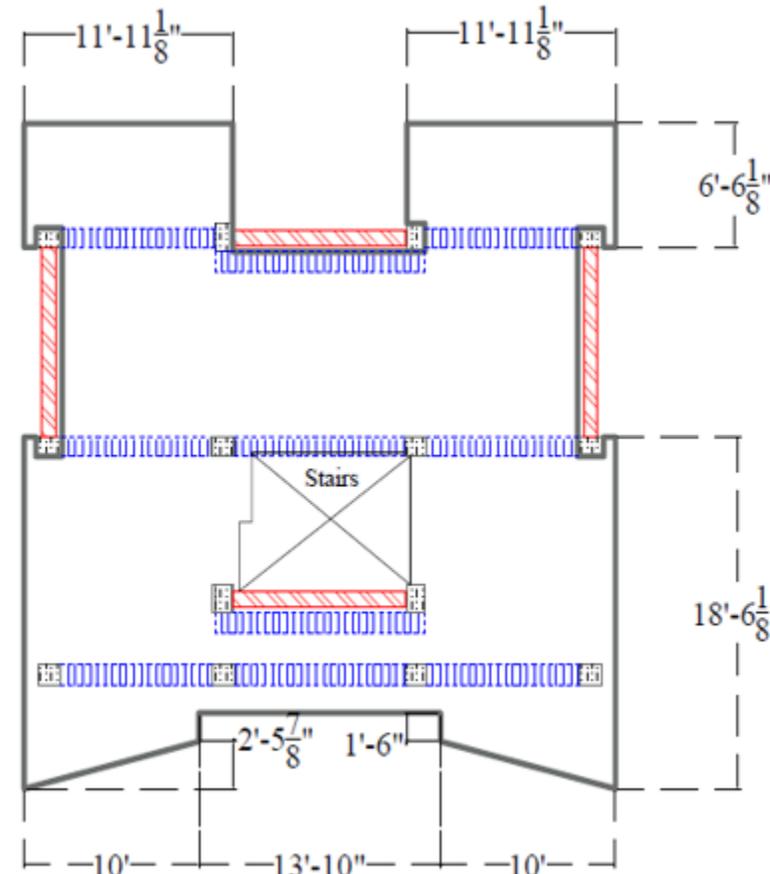
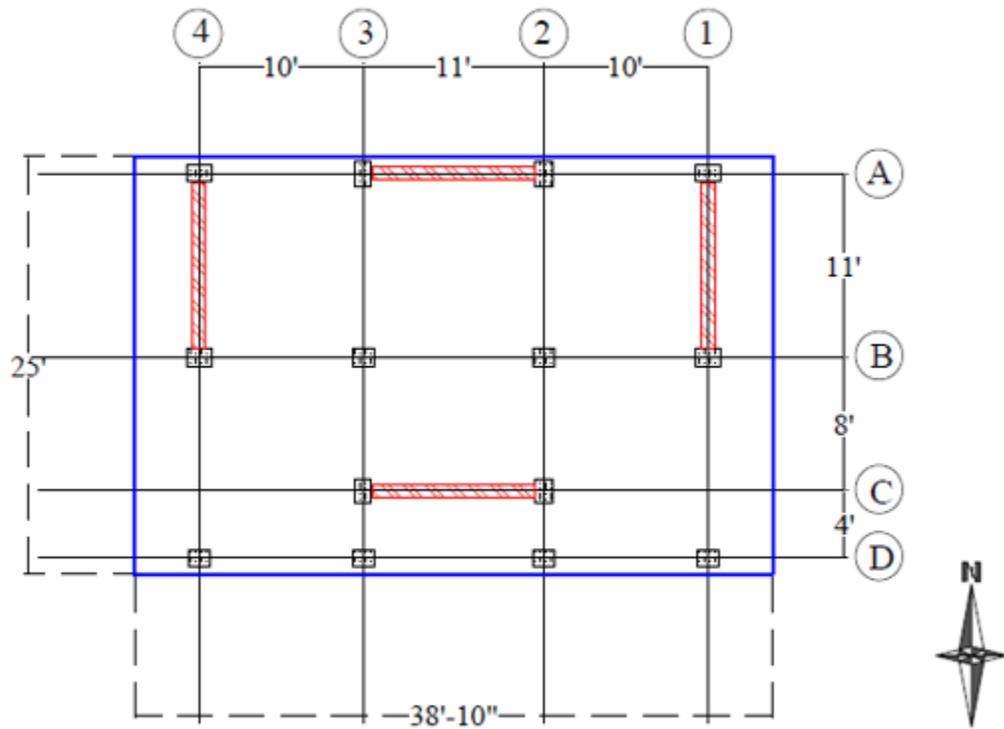


Outline of Presentation

- 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

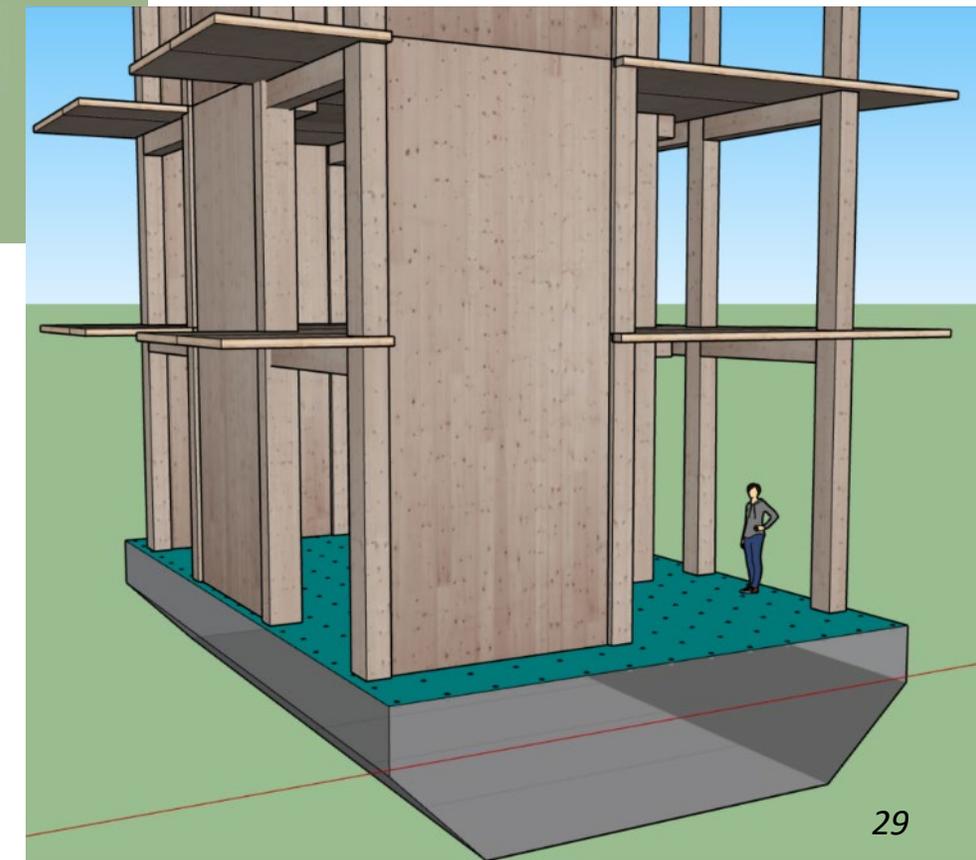
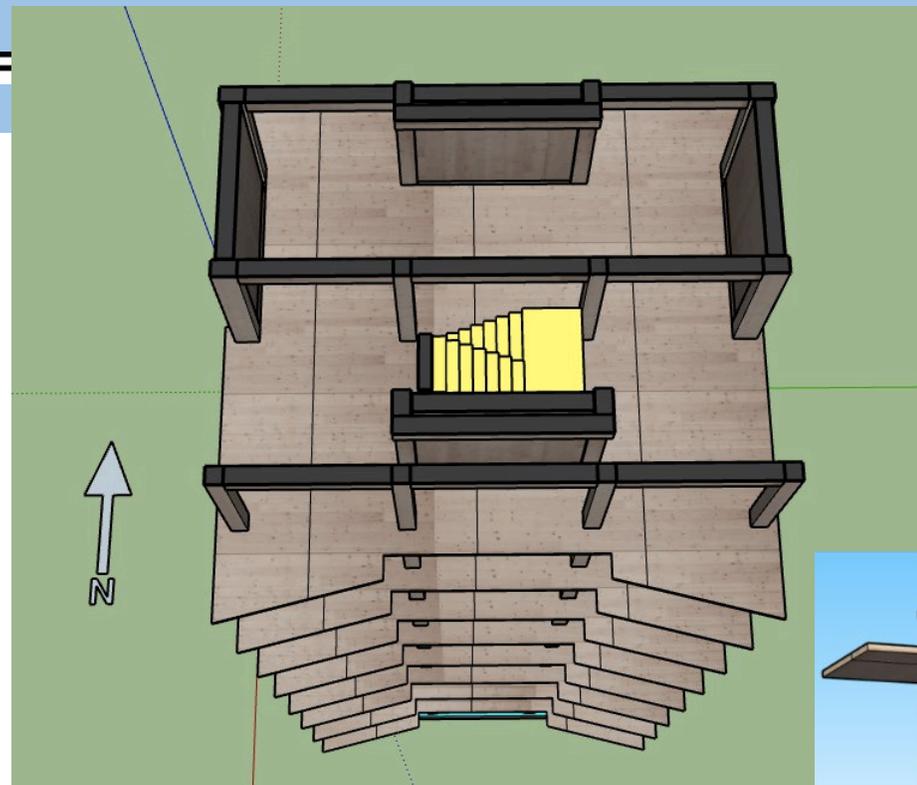
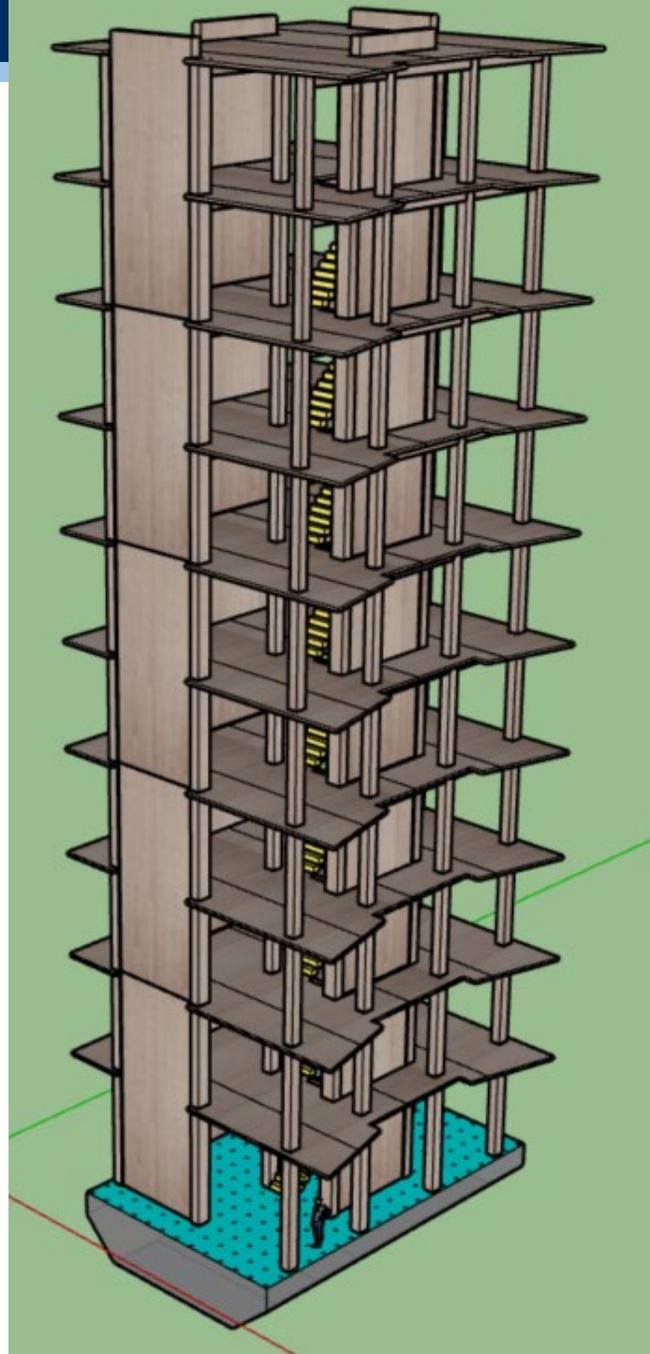
Details/Specifications of the Test Building

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

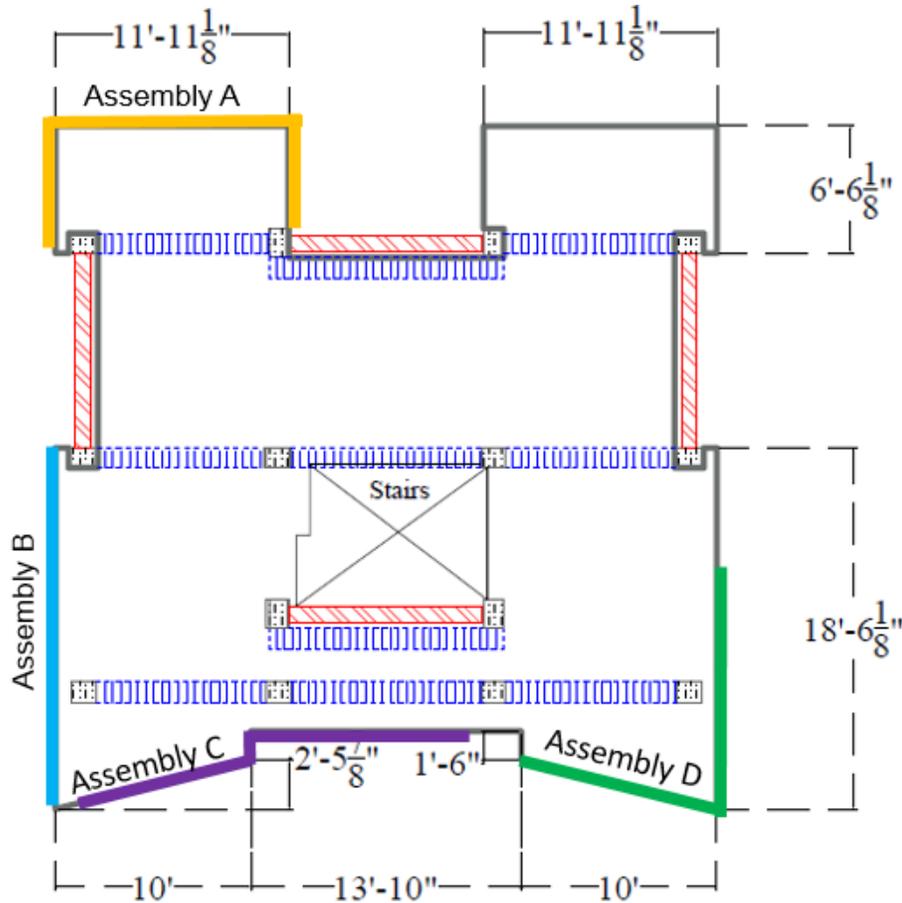


KEY: CLT PANEL (ROCKING WALL) GLULAM COLUMN GLULAM BEAMS

- 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.



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.



LEVER

Shake Table Testing of Fenestration Products
FGIA Webinar, 01-21-2020



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

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.





LEVER

Shake Table Testing of Fenestration Products
FGIA Webinar, 01-21-2020



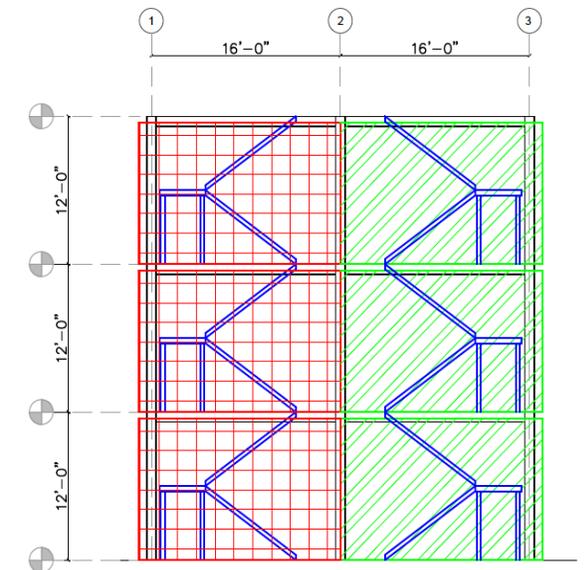
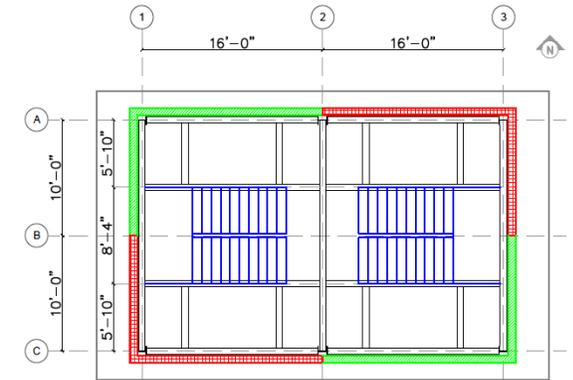
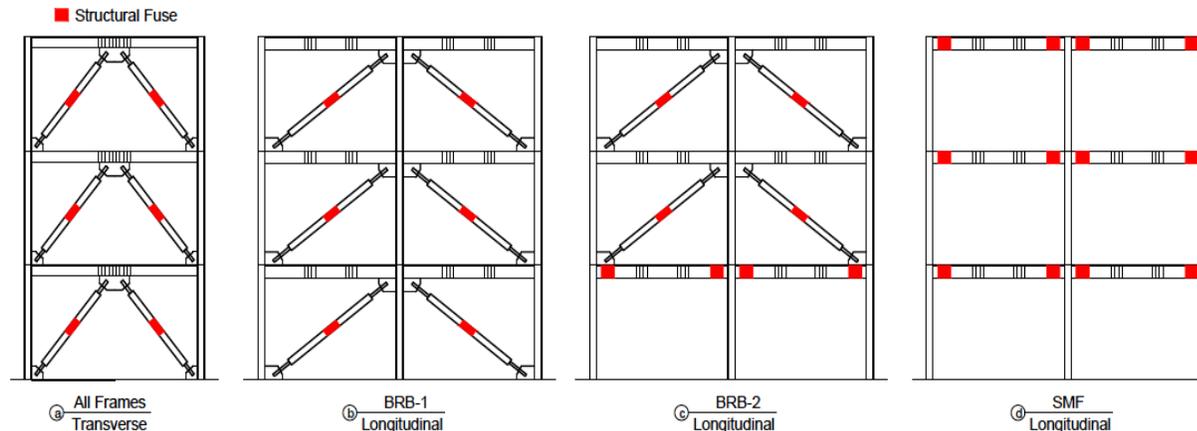
Natural Hazards
Engineering
Research
Infrastructure

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.





LEVER

Shake Table Testing of Fenestration Products
FGIA Webinar, 01-21-2020



References

1. Baird, A., Palermo, A., Pampanin, S. (2012). “Façade damage assessment of multi-story buildings in the 2011 Christchurch Earthquake”, *Bulletin of the New Zealand Society for Earthquake Engineering*, 44(4):368-376.
2. Filiatrault, A., Uang, C-M., Folz, B., Christopoulos, C., and Gatto, K. (2001). Reconnaissance Report of the February 28, 2001 Nisqually (Seattle-Olympia) Earthquake, Structural Systems Research Project Report No. SSRP-2000/15, University of California, San Diego, La Jolla, CA.
3. Harter, D. (1994). “Earthquake in Los Angeles. Glazing,” California Glass Association.
4. Hutchinson, T.C., Pantoli, E., McMullin, K., Hildebrand, M., and Underwood, G. (2015). Seismic drift compatibility of architectural precast concrete panels and connections: a design guide for engineers. *Structural Systems Research Project Report Series, SSRP 14/16*. University of California San Diego, La Jolla, CA.
5. Memari, A. M., O’Brien, W.C., Hartman, K. J., Kremer, P.A., Behr, R.A. (2011). “Architectural Glass Seismic Behavior Fragility Curve Development”, *FEMA P-58/BD-3.9.1*, Prepared for the Federal Emergency Management Agency.
6. Reitherman, R., and Sabol, T. (1995). “Nonstructural Damage,” in John Hall, (ed.), *Northridge Earthquake of January 17, 1994 Reconnaissance Report, Earthquake Spectra*, Vol. 11, Supplement C, Earthquake Engineering Research Institute, Oakland, CA.

Question and Answer

If you are interested in collaborating with us, please contact:

Keri Ryan, Associate Professor

University of Nevada, Reno

klryan@unr.edu

775-784-6928

