Performance of Nonstructural Components in Critical Facilities

2012 PEER Annual Meeting

Gilberto Mosqueda

Associate Professor

University of California, San Diego

Department of Structural Engineering

Outline of this Presentation

- Performance of nonstructural systems in past earthquakes
  - Damage to nonstructural systems and failure modes
  - Contribution to disruption of critical services
- Recent research for component and system characterization of nonstructural systems
  - Component testing for development of fragility functions
  - System level experiments to capture interaction between nonstructural systems and with structures

Initial Remarks

- Damage to nonstructural components typically initiates at levels of shaking well below those required to initiate structural damage
- Buildings modify and often amplify ground motions therefore nonstructural elements in multistory buildings are often subjected to higher shaking intensity
- Seismic design of nonstructural systems is not as rigorous/ advanced as for structural systems

Importance of Nonstructural Systems

- Nonstructural Components and building contents (NSC's) typically account for over 80% of monetary investment in buildings (Miranda 2003)

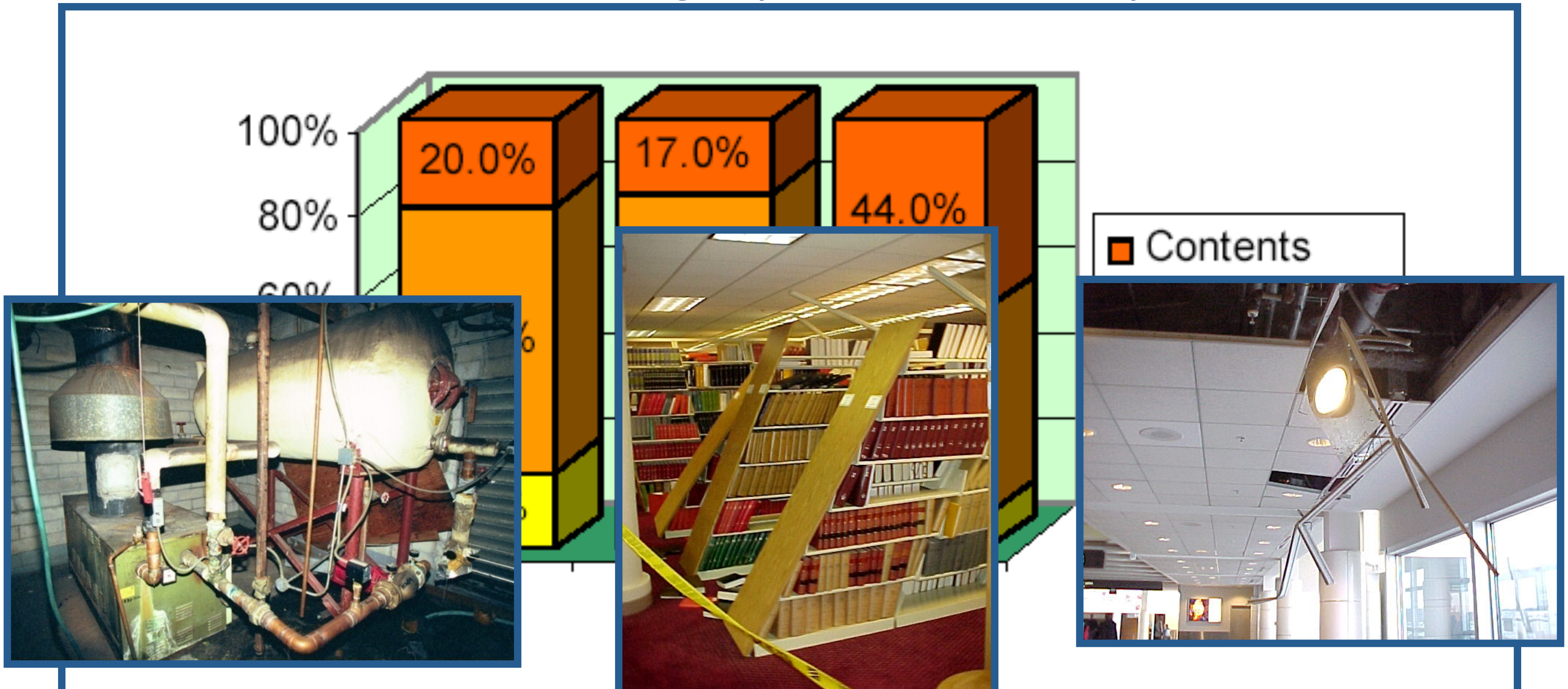


Figure 1. Typical investments in building construction (after E. Miranda)

2001 Nisqually Earthquake (Filiatrault)

February 27, 2010 Maule, Chile Earthquake

- Magnitude 8.8
- Local Time 3:35 am
- Felt by approximately 80% of the population
- 525 death
- Approx. 200,000 housing units affected
- Approx. 800,000 homeless
- Economic loss approx. $25B

Impact of nonstructural damage on hospitals

Felix Bulne Hospital in Santiago shut down primarily due to nonstructural damage

Photo by G.Mosqueda

Photo by G.Mosqueda

Impact of nonstructural damage on hospitals

Damage to wall-mounted monitors at Talcahuano and San Carlos Hospitals

Photo by G. Pekcan

Photos by G. Pekcan

Impact of nonstructural damage on hospitals

Photos E. Miranda

Impact of nonstructural damage on hospitals

Roof-mounted small AC units at the Clínica del Maule in Talca

Photo by G. Pekcan

Photo by G. Pekcan

Impact of nonstructural damage on hospitals

Damage to elevator equipment

Photos E. Miranda

Impact of nonstructural damage on hospitals

- 130 hospitals were affected in six regions (*represents 71% of all public hospitals in the country!*)
    - 4 were completely shut down
    - 12 loss more than 75 of their capacity
    - 8 partially loss their functionality
- 62% required repairs or replacement
- 18% of the hospital beds in public hospitals were lost for at least one month
- The ministry of health estimated it will require US$ 2,800 million to repair hospital damage

Impact of nonstructural damage on airports

Airport terminal at Santiago shut down mainly due to nonstructural damage

Photo by G. Mosqueda

Photo by G. Pekcan

Many suspended air handling units like this fell to the ground

Impact of nonstructural damage on airports

Photo E. Miranda

Impact of nonstructural damage on airports

Photo E. Miranda

Impact of nonstructural damage on airports

Photo E. Miranda

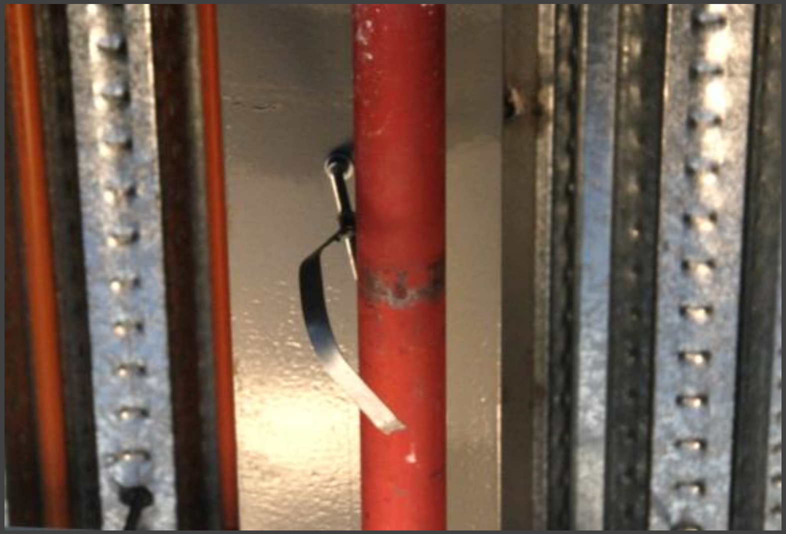
Impact of nonstructural damage on airports

- **Closure of the Santiago and Concepcion International Airports**
- **US$40 million for repairs of nonstructural damage at SCL**
- **US$10 million loss to Lan Chile**
- ***Two thirds of the Chilean air traffic interrupted !***

Damage to sprinkler bracings

Photos E. Miranda

Damage to piping hangers



Photos E. Miranda

Broken water pipes

Example of broken water pipes in San Carlos Hospital

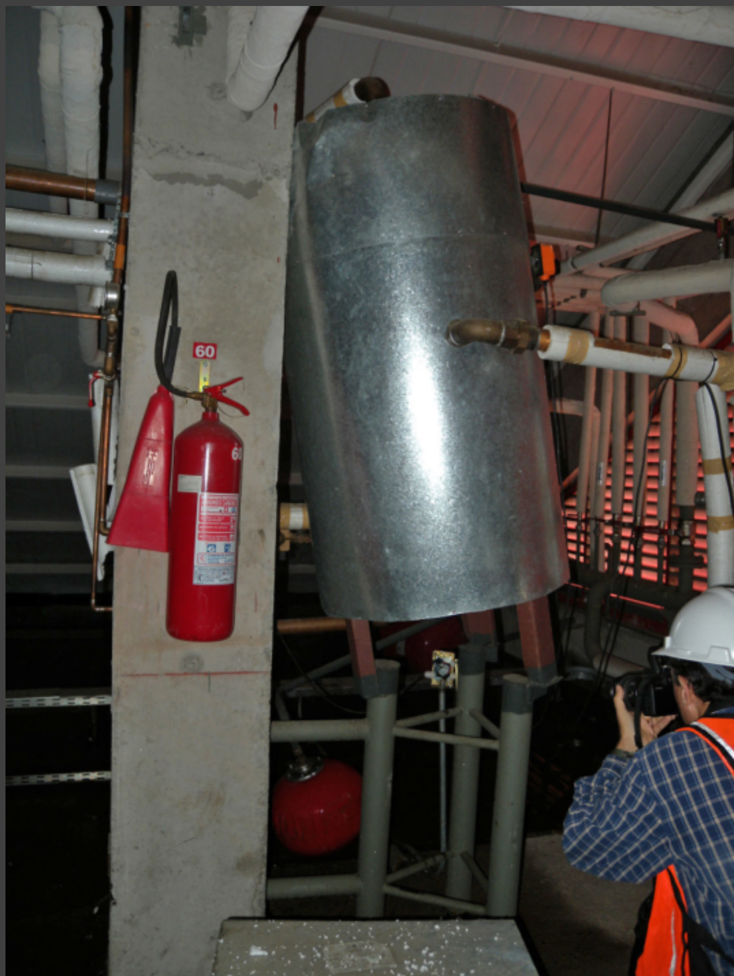


Photo by G.Mosqueda

Photos by G.Mosqueda

Broken copper water pipe of hot water caused by lack of lateral bracing of the boiler

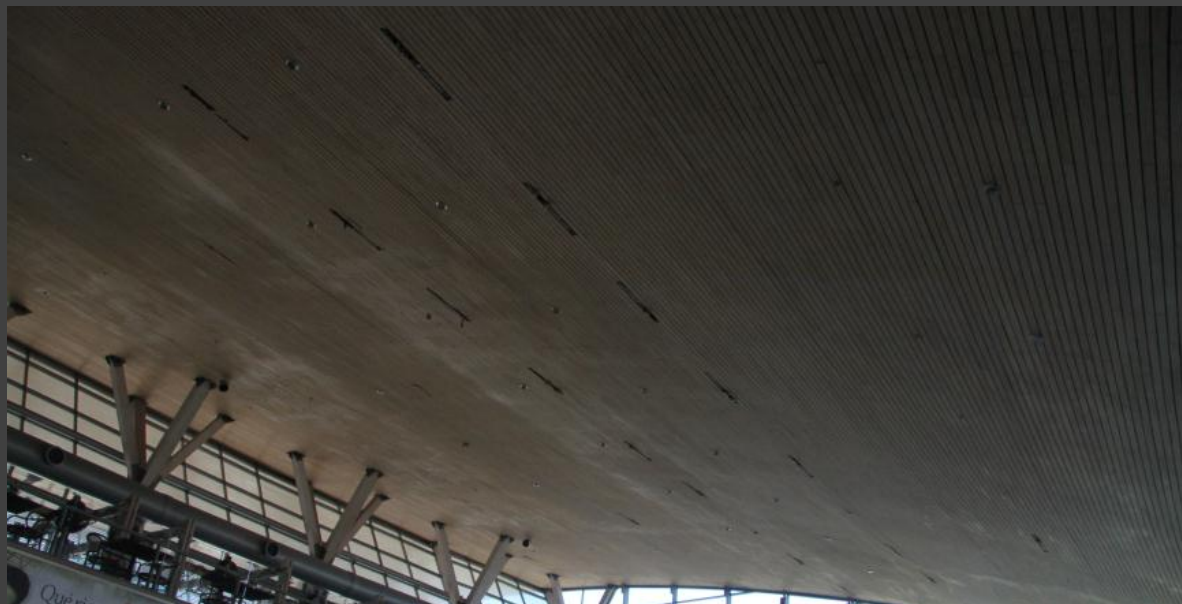
Broken water pipes

Photo E. Miranda

Ceiling-sprinkler head dynamic interaction

Photos by E. Miranda

Ceiling-sprinkler head dynamic interaction



Overall view of wood ceiling

Photos by E. Miranda

Closeup view of some sprinkler heads sheared off

Ceiling-sprinkler head dynamic interaction

Broken sprinkler piping at the Santiago Airport

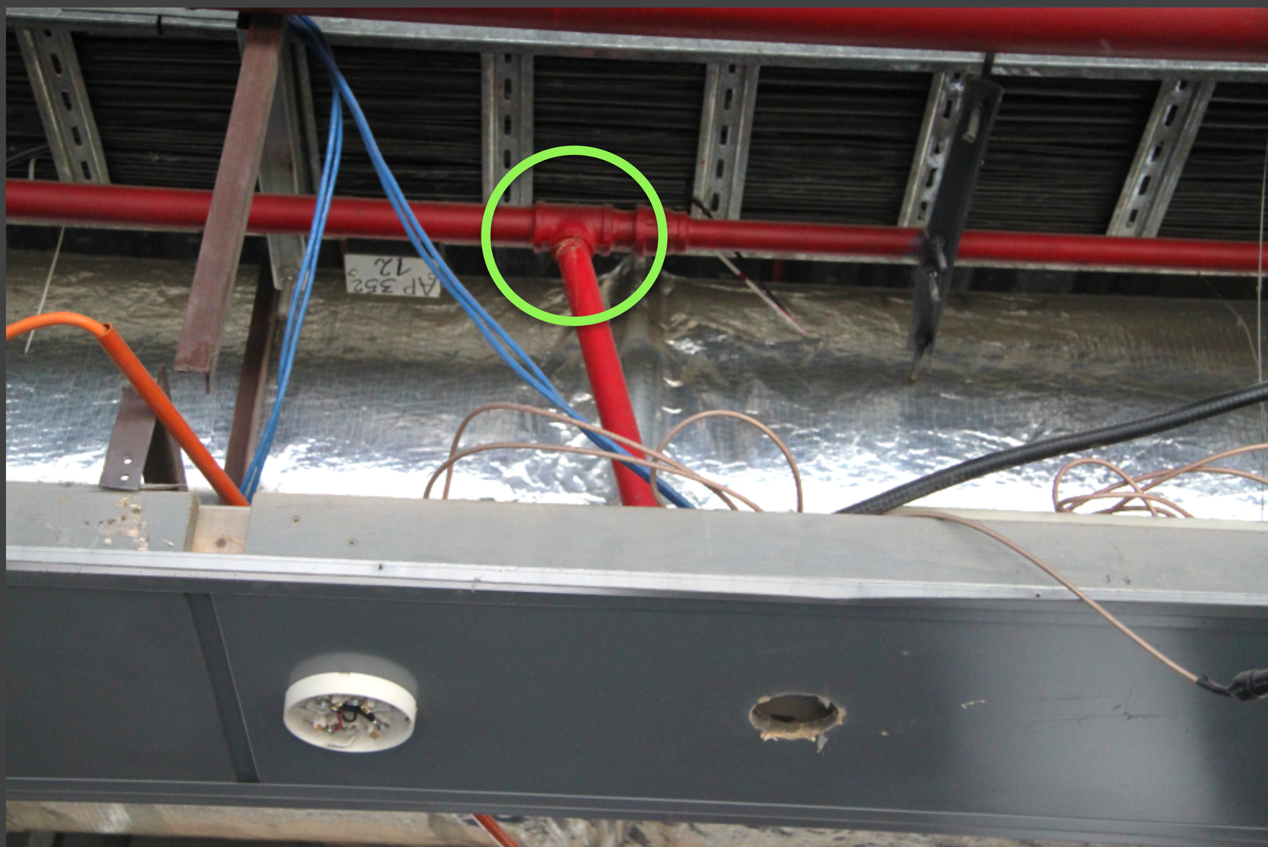
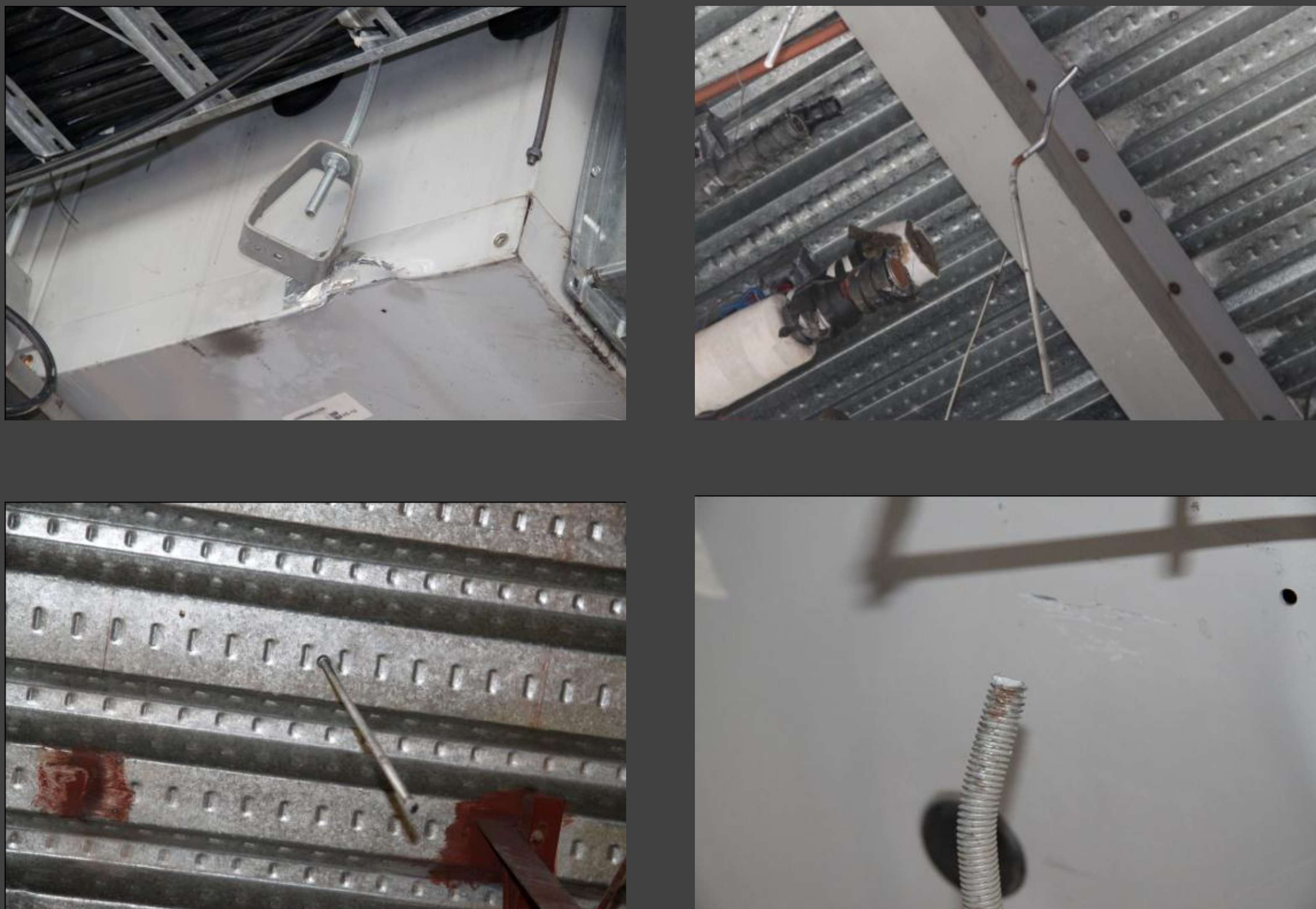


Photo by E. Miranda

Photo by E. Miranda

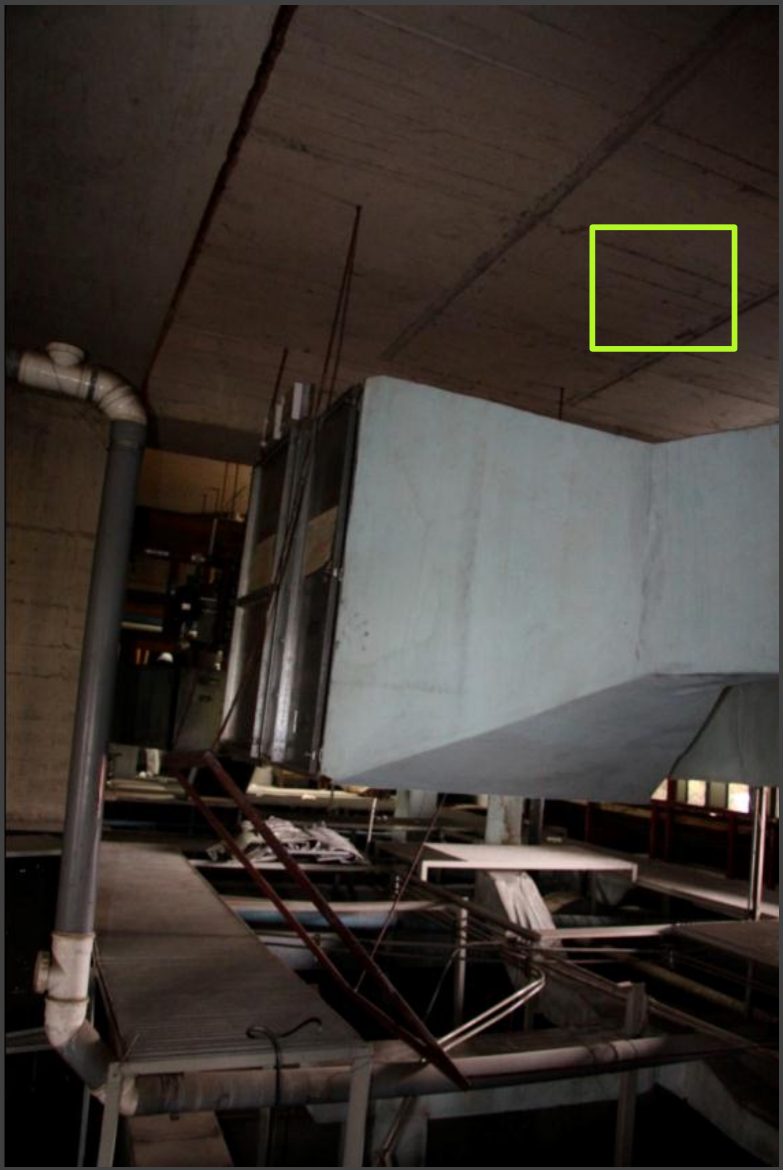
Closeup view

Damage to threaded rods



Photos by E. Miranda

Damage to anchors



Photos by E. Miranda

Damage to Elevators

Damage in Elevators at the Clínica del Maule in Talca

Photo by R. Retamales

Derailed and disassembled counterweight

Photo by G. Pekcan

Elevator cabin hit by derailed counterweight

Damage to Elevators

Photos E. Miranda

Some examples of good performance

Examples of well anchored hospital equipment that performed well at Santiago General Hospital

Photo by G. Pekcan

Photo by G. Pekcan

Some lessons from the 2010 Chile Earthquake

- In general very good structural performance of building relative to the magnitude of the event (8.8)
- Massive amount of nonstructural damage that lead to large impact and significant disruption to Chilean society.
- Very large economical losses (approx. US$25 billion) which represents 12% of their GDP!
- There were many examples in which details, similar to those used in the U.S., were not enough to prevent significant damage and impact.

2010 and 2011 Christchurch, New Zealand Earthquakes

September 4th, 2010	February 22nd, 2011
Magnitude 7.1	Magnitude 6.3
Local Time 4:35 am	Local Time 12:51 pm
No fatalities	181 fatalities

Three main types of damage observed in these earthquakes:

- Damage/collapse to URM structures
- Massive liquefaction and associated damage
- Large amount of non-structural damage

Christchurch Women’s Hospital

- **Only base isolated building in region of strong shaking**
  - Damage mainly to sacrificial nonstructural components at the seismic gap
  - Other damage reported included overturned small contents and water sloshing from birthing tub

(Gavin et al. 2012)

Damage to Stairs

Damage in the main stairs inside the Christchurch City Council building in the Sept. 2010 earthquake

Photo Tao Lai

Damage to Stairs

People being lowered through the windows in the 17-storey Forsyth Barr building due to failure of the stairs in the February 2011 earthquake

Hotel Grand Chancellor's stairwells also disintegrated into rubble

Lessons from 2010 and 2011 New Zealand Earthquakes

- Relatively small number of collapses/fatalities
- Good structural behavior of new engineered construction
- Extremely large economical losses (approx. US$17 billion) considering the magnitude of the events (7.1 and 6.3) and especially relative to the population of Christchurch (385,000)
- Nonstructural damage is costly and affects business recovery.
- Long-lasting effect for the economy of Christchurch specially for the downtown commercial district.

March 11, 2011 Eastern Japan Earthquake Mw 9.0

Lessons related to nonstructural damage

- **Not considering tsunami inundation zone and nuclear incident, there was very little structural damage considering intensity of shaking**
- **Majority of damage in large cities including Tokyo and Sendai was mainly nonstructural**
- **Frequently observed non-structural damage**
  - **Ceiling damage / collapse**
  - **Damage / collapse older ACC façade panels**
  - **Overturning of contents**

August 23, 2011 Virginia Mw5.8 Earthquake

- **Damage to suspended ceilings, masonry chimneys, masonry veneer, masonry infills was widespread**
- **Damage to contents in residential and commercial buildings**
- **Reports of pipe burst in Pentagon causing minor flooding**
- **Damage resulted in closure and reduced functionality of some buildings including schools**

Source: CNBC News

Source: Richmond Times Dispatch

Lessons from Recent Earthquakes

- Recent earthquakes have occurred in countries with modern earthquake engineering design standards.
- Structural damage in these earthquakes was relatively small in structures designed according to recent codes.
- Large amounts of nonstructural damage occurred that lead to significant impacts on facilities and society in general.
- Nonstructural damage often occurs as a result of problems in the bracing and anchorage.
- In many cases the failure is due to the deformation, vibration, and pounding of neighboring components. In current practice the deformation of the components is typically not addressed.

Experimental Research on Nonstructural Systems

- There are a large variety of nonstructural systems and installation conditions that need to be examined
  - Testing protocols have limitations in reproducing full-scale building motions
  - Focus on either acceleration sensitive or displacement sensitive components
  - Dynamic testing limited by capacity of shaking tables
- Current experimental research seeks to apply more realistic demands on nonstructural systems
  - Develop equipment and loading protocols that can apply full-scale floor motions
  - Install nonstructural systems in full-scale structural building simulations on shaking table

NEESR GC: Simulation of the Seismic Performance of Nonstructural Systems

PI: Manos Maragakis, University of Nevada, Reno

Co-PI's: Tara Hutchinson, UCSD, Andre Filiatrault, U Buffalo,

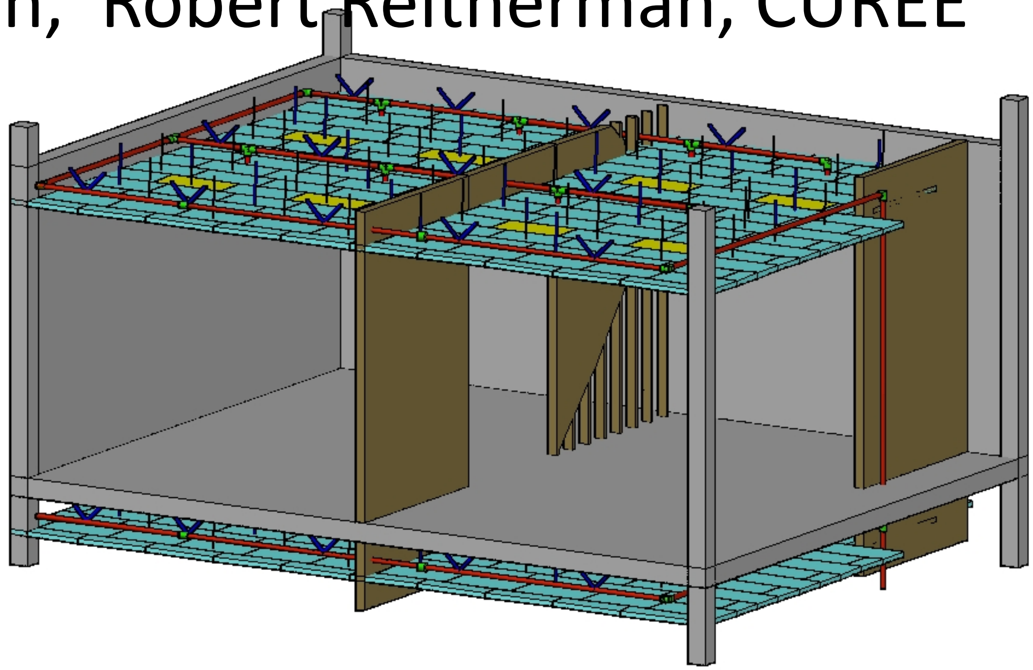
Steve French, Georgia Tech, Robert Reitherman, CUREE

- Focus on seismic response of ceiling-piping-partition subsytems and their interactions

Ceiling Subsystem

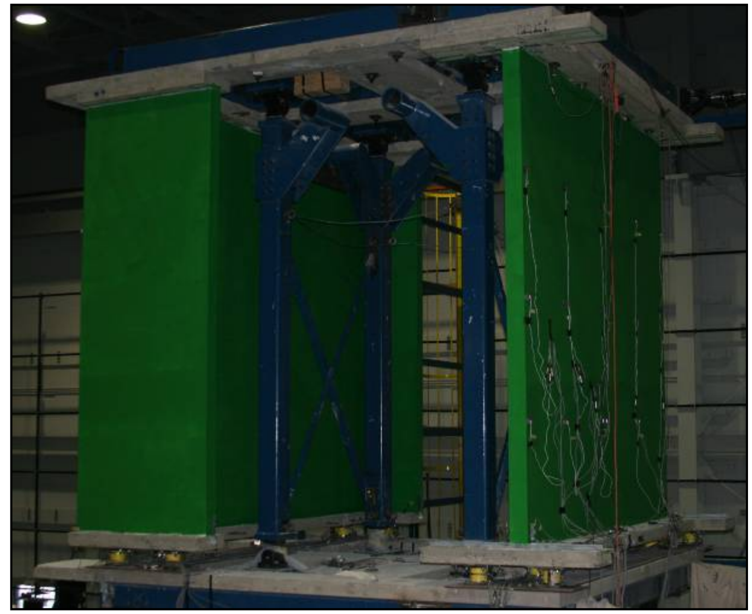
Piping Subsystem

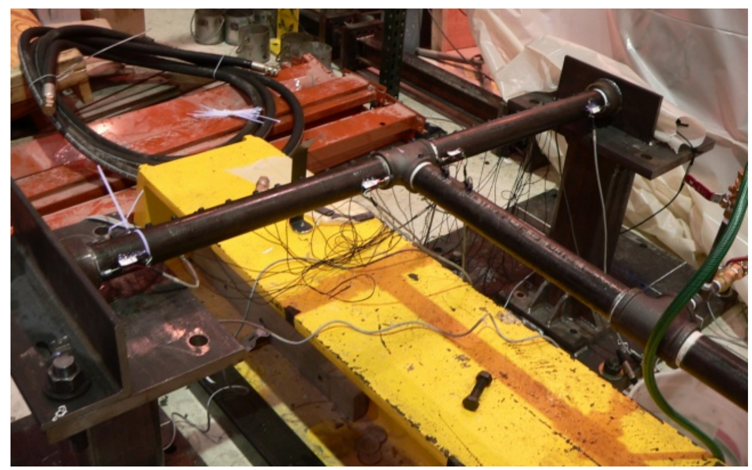
Partition Subsystem



NEESR Nonstructural GC Subsystem Experiments at UB

- Carry out an extensive experimental program to evaluate the seismic response, failure mechanisms, and fragilities of
  - **cold formed steel frame gypsum partition walls**
  - **sprinkler piping**
  - **ceiling systems**
- Develop protective technologies and design details to enhance seismic performance of nonstructural systems



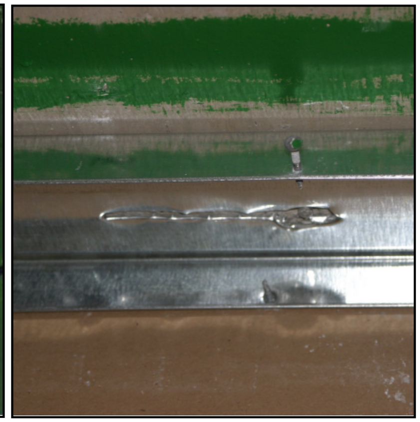


Partition Wall Subsystems

Summary of Observed Damage for 50 Walls

Damage in transverse wall top track

Damage along cornerbeads and boundary studs



Tearing along top track fastener

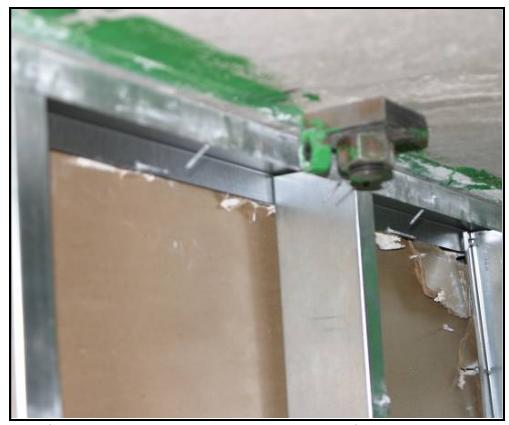
Hinges forming in studs (commercial construction)

Buckling of diagonal braces

Damage in transverse walls

Damage of joints between gypsum panels

Hinges forming in studs (institutional construction)

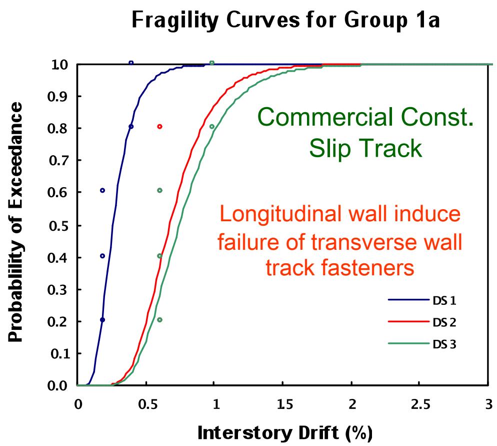


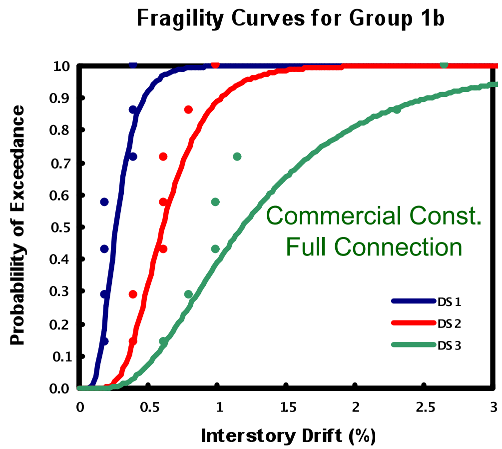
Crushing and shearing of gypsum around screws in connection to top track

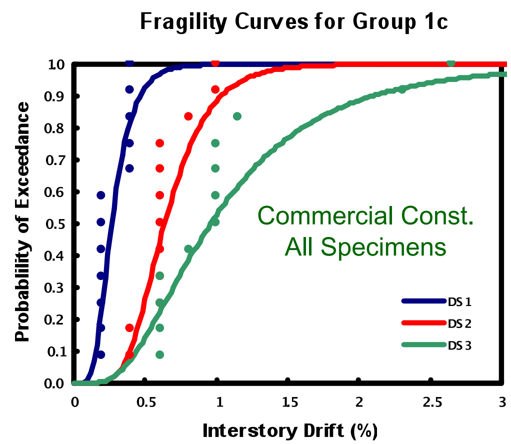
Collapse of partition wall

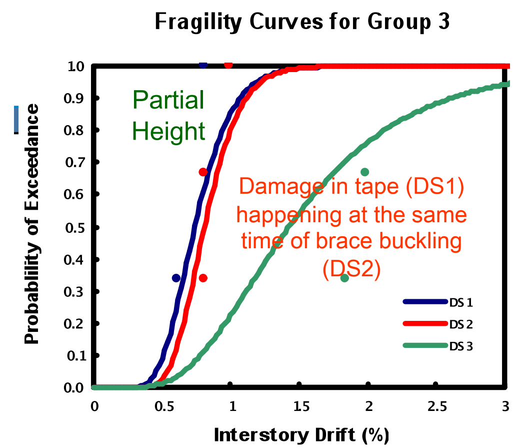
Damage States

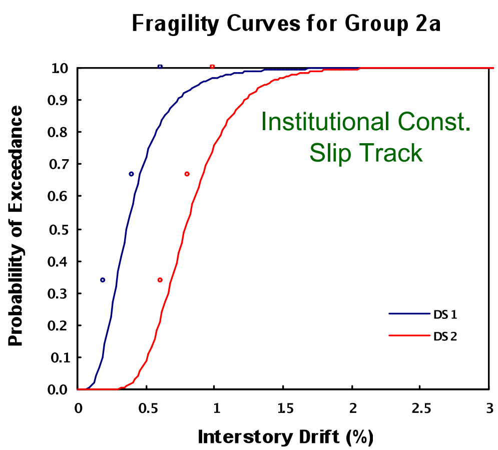
Damage State		Description of Damage Associated	Repair Actions
DS1	**Superficial damage to the walls**	Cracks along cornerbeads, cracks along joint paper tape, screws pulled out from connections of gypsum boards to steel framing, buckling of partial height wall brace	Cosmetic repairs, including: replacement of cornerbeads, replacement of screws pulled out, replacement of joint paper tape, application of joint compound, sanding, and painting, replace braces
DS2	**Local damage of gypsum wallboards and/or steel frame components**	Crushing of wall corners, out-of-plane bending and cracking of gypsum wallboards at wall intersections, damage of screws connecting wallboards to boundary studs, bending of boundary studs, buckling of diagonal braces (partial height partition walls)	Local repairs, including: repair or replacement of gypsum wallboards, replacement of boundary studs, replacement of seismic braces
DS3	**Severe damage to walls**	Tears in steel tracks around connectors of track to concrete slab, track fasteners passing thru track webs, track flanges bent at wall intersections, hinges forming in studs	Replacement of partition wall (Steel framing and wallboards)

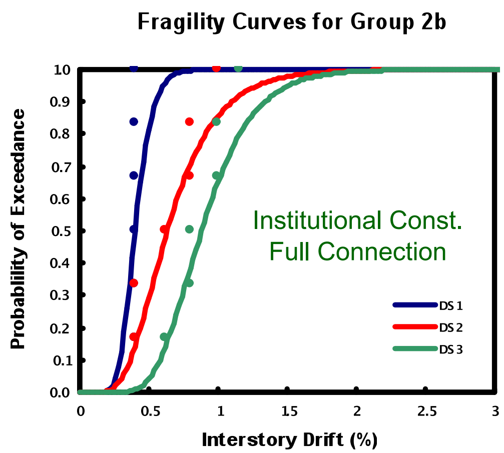


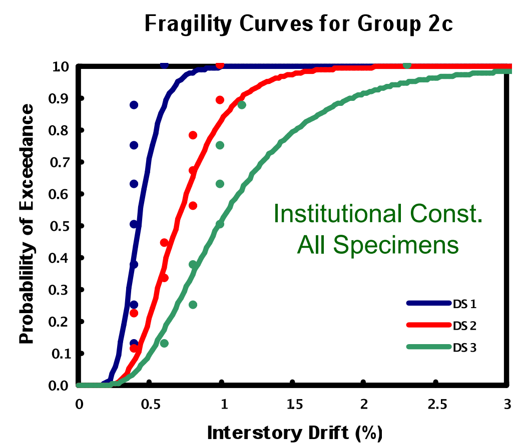


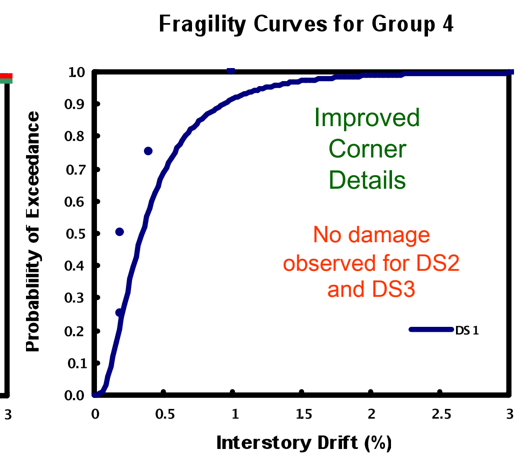












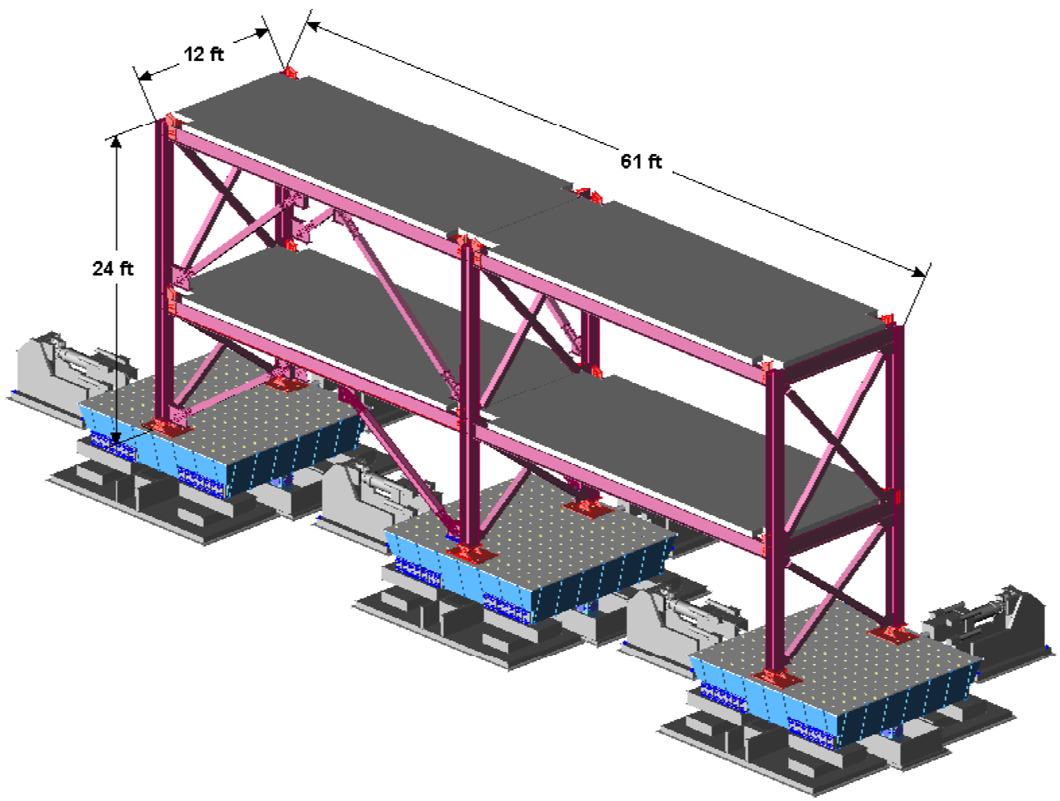
Group	Sub Group	Description	DS_1		DS_2		DS_3	
			x_m	β	x_m	β	x_m	β
0	0	All specimen data	0.35	0.56	0.69	0.39	1.04	0.55
1	1a	Full-height specimens. Commercial construction practice and slip tracks	0.26	0.45	0.68	0.35	0.75	0.36
	1b	Full-height specimens. Commercial construction practice and partial/full connections	0.27	0.44	0.61	0.41	1.18	0.59
	1c	Full-height specimens. Commercial construction practice (slip tracks and full connection)	0.27	0.43	0.64	0.38	0.96	0.61
2	2a	Full-height specimens. Institutional construction practice and slip tracks	0.36	0.55	0.79	0.34	-	-
	2b	Full-height specimens. Institutional construction practice and partial/full connections	0.40	0.25	0.63	0.43	0.88	0.33
	2c	Full-height specimens. Institutional construction practice (slip tracks and full connection)	0.42	0.31	0.69	0.40	0.98	0.52
3	3	Partial-height specimens	0.74	0.29	0.81	0.25	1.43	0.47
4	4	Specimens including improved corner details	0.34	0.77	-	-	-	-

UNR Test Bed Structure

Test Bed Structure to simulate dynamic environments for nonstructural systems in multistory buildings

Study configurations of Ceiling-Piping-Partition systems

- Interactions within the nonstructural components.
- Interactions between the structural and nonstructural systems.
- Effects of structural yielding on response of the nonstructural components.



E-Defense Experiments

Shake table tests of a full-scale 5-story steel moment frame building

- **Isolated with triple friction pendulum isolators**
- **Isolated with lead rubber bearing/ cross linear slider**
- **Fixed base**

- Simulations designed to impose large displacement demands in isolation systems (comparable motions could not be applied to fixed-base buildings for safety reasons)
- Simulations both with and without vertical component of ground motion
- 4th and 5th floor included nonstructural systems

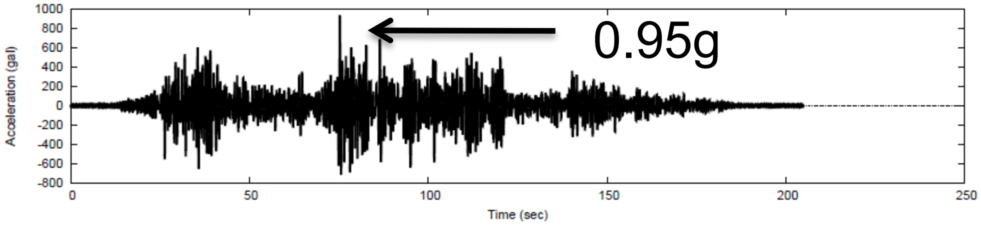
Horizontal Shaking Only

5th floor partial height wall failure

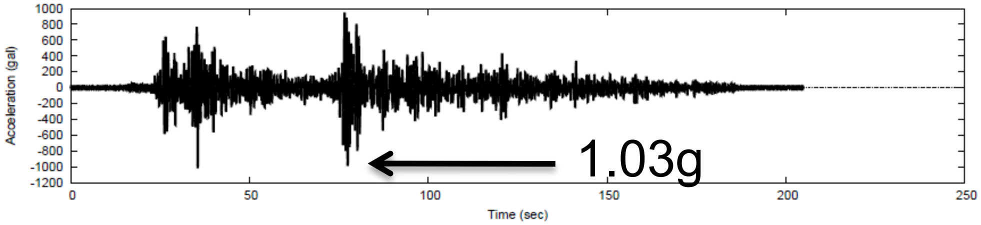
5th floor ceiling failure

- Nonstructural damage was not observed in any test of the base-isolated structure subjected to horizontal only motion
- Damage was observed in the fixed-base structure subjected to 70% Tohoku-Iwanuma x-y

Acceleration at roof – x-direction



Acceleration at roof– y-direction



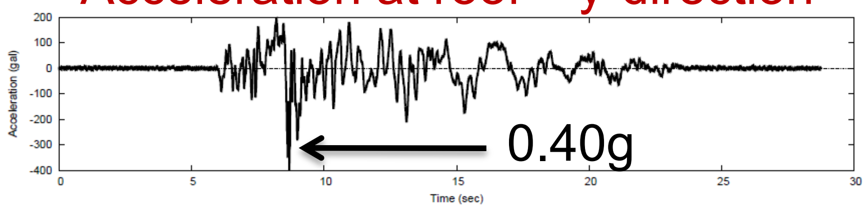
(b) Y

2D vs. 3D Loading – Rinaldi Rec. Sta.

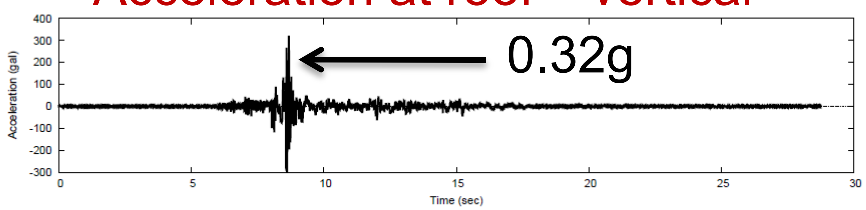
- The observed vertical excitation in the structure was amplified from the intended motion by the shake table and additionally by the dynamics of the structural system.
- A horizontal vertical coupling appears to amplify the horizontal floor accelerations significantly compared to “horizontal only” loading.

Triple Pendulum Isolators
88% Rinaldi – Horizontal Only

Acceleration at roof – y-direction

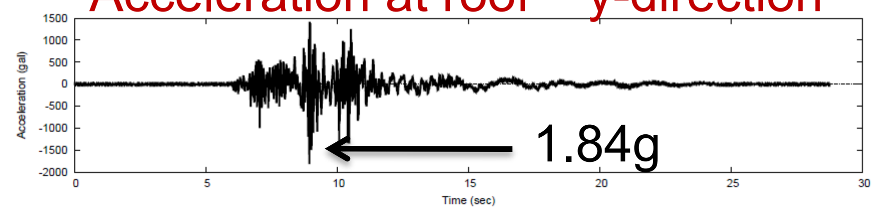


Acceleration at roof – vertical

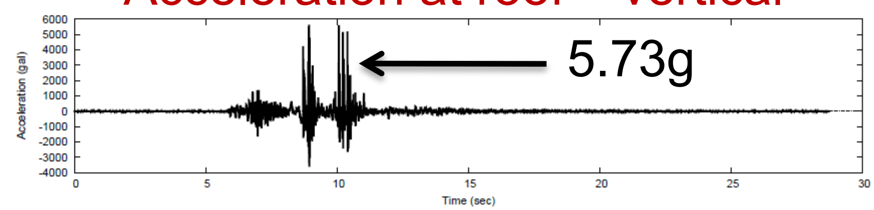


Triple Pendulum Isolators
88% Rinaldi – 3D Excitation

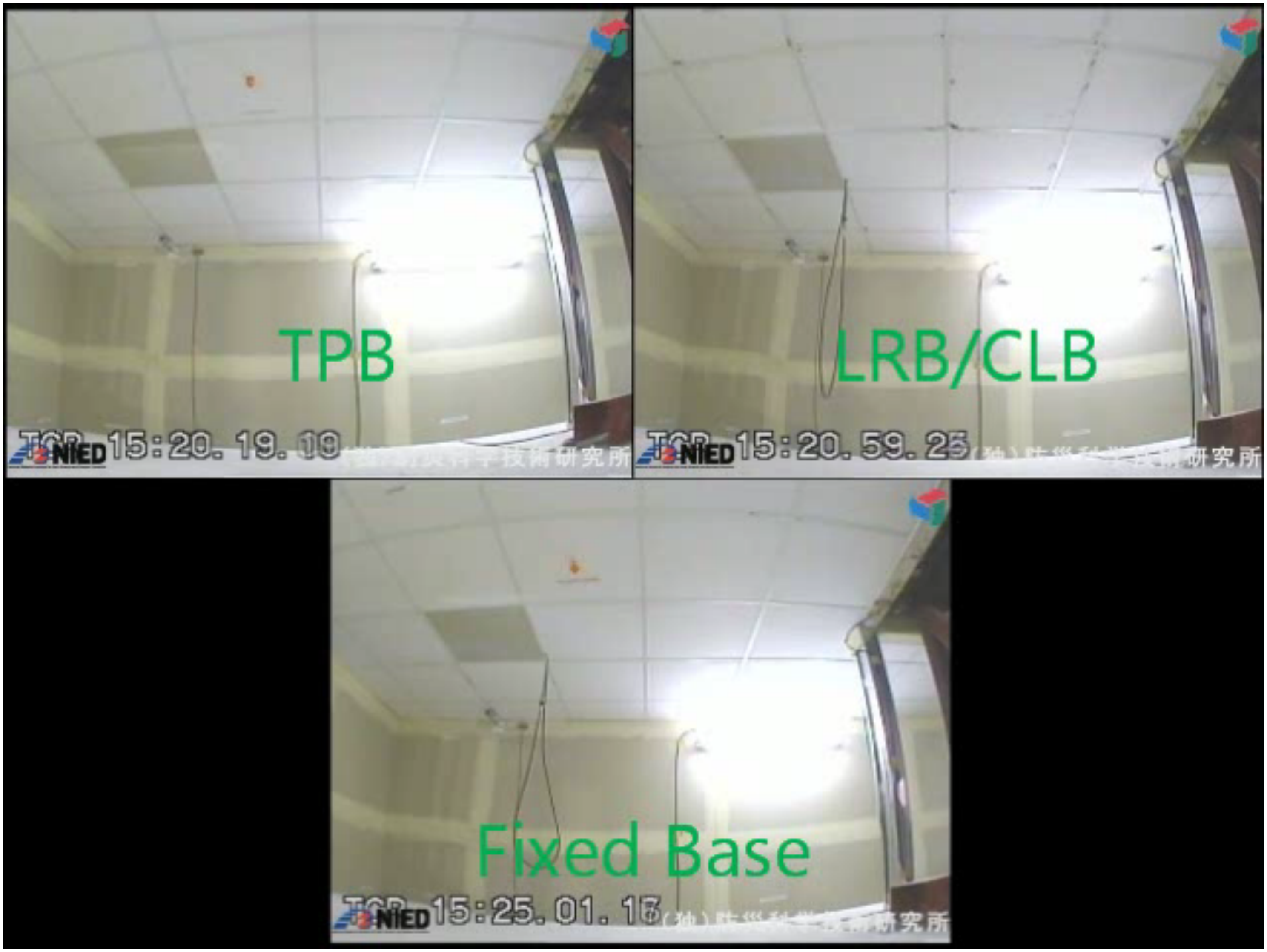
Acceleration at roof – y-direction



Acceleration at roof – vertical



3D Loading – Rinaldi Rec. Sta.



Similar damage was observed in all three systems, induced by vertical excitations.

Earthquake and Post-Earthquake Fire Testing of a Full-scale 5-story Building outfitted with Nonstructural Components on the World's Largest Outdoor Shake Table

PI: Tara C. Hutchinson, Professor

Co-PI: Jose Restrepo, Professor

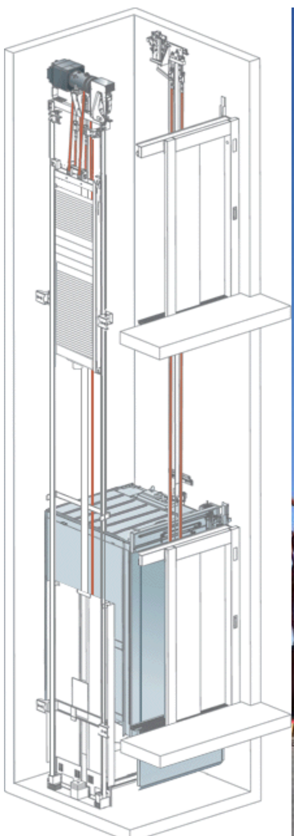
Co-PI: Joel Conte, Professor

University of California, San Diego

UCSD WPI HOWARD UNIVERSITY SAN DIEGO STATE UNIVERSITY

Overall Scope: UCSD-BNCS Project (bncs.ucsd.edu)

- <u>Centerpiece of Project:</u> Three-phased full-scale test program conducted on a 5-story building-NCS system
  - @Largest outdoor shake table in the world (nees.ucsd.edu)

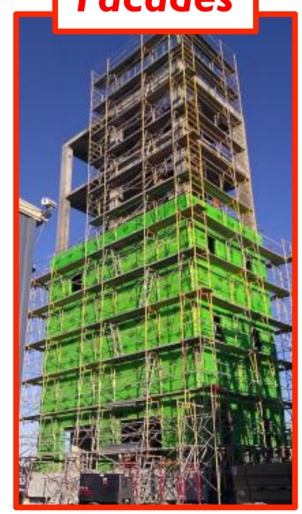


<u>Summary of Major NCSs:</u>

- <u>Egress systems:</u>
  - Operable Elevator
  - Stairs
- <u>Facades:</u>
  - Concrete cladding
  - Balloon framing
- Hospital equipment
- Roof mounted equipment
- Sprinkler and riser systems
- Ceilings
- Interior partition walls

HVAC

Facades



Hospital Floor

Expected Major Outcomes

Base isolation performance

- Seismic response and damage data for a broad range of nonstructural systems placed in a full-scale, building environment (<u>system-level behavior</u>):
  - Landmark data set for the engineering community
  - Numerical model validation & improvement
  - Design code evaluation & improvement
  - Improvement of construction practices and methods

Stair detachment

Elevator door distortion

Balloon framing clip detachment

Structural rebar fracture

Concluding Remarks

- In order for a critical building or facility to remain operational after an earthquake, both structural and nonstructural systems must remain intact. Compatible seismic performance of nonstructural components is essential to achieve global performance objectives.

- Recent earthquakes highlight the need of performance based design for controlling economic losses and downtime in addition to life safety through enhanced seismic design of nonstructural systems.

- Current experimental research is focused on better understanding seismic behavior of nonstructural systems through realistic experimental simulations and developing fragility functions for improved performance assessment.

Acknowledgements

Eduardo Miranda – Collaborator on presentation describing damage from past earthqakes to nonstructural systems

Manos Maragakis, Tara Hutchinson and Andre Filiatrault for sharing slides on different projects

Research Needs

- Better understanding of how nonstructural systems actually fail in earthquakes
- Fragilities of nonstructural systems supported by experimental research. The challenge is that there is a large variety of components and installation details.
- Integration of nonstructural systems in performance based assessments.