National Science Foundation

University of California at San Diego
NHERI
Natural Hazards Engineering Research Infrastructure

UC San Diego
JACOBS SCHOOL OF ENGINEERING
Structural Engineering

Recent experimental and analytical studies on the seismic performance of Ceiling, Piping, and Partition systems at UNR

Manos Maragakis

Dean, College of Engineering | Professor, Civil and Environmental Engineering

University of Nevada, Reno

Joint Researcher Workshop
UC San Diego, Lehigh & SimCenter

December 16-17, 2019
University of California, San Diego

LEHIGH NHERI
Real-Time Multi-Directional Testing Facility

University of California at San Diego
NHERI
Natural Hazards Engineering Research Infrastructure

SIMCENTER
COMPUTATIONAL MODELING AND SIMULATION CENTER

Research Contributors

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Presentation Outline

GC Nonstructural Project: An integrated Multi-Institutional Effort

- Introduction
- NEES Nonstructural Grand Challenge Project
- Experimental Studies (GC Projects)
- Experimentally Integrated Simulation Studies
- Future Directions

Definition of Nonstructural Components

- **Elements of a building that are NOT part of its gravity and/or seismic loading resisting system.**



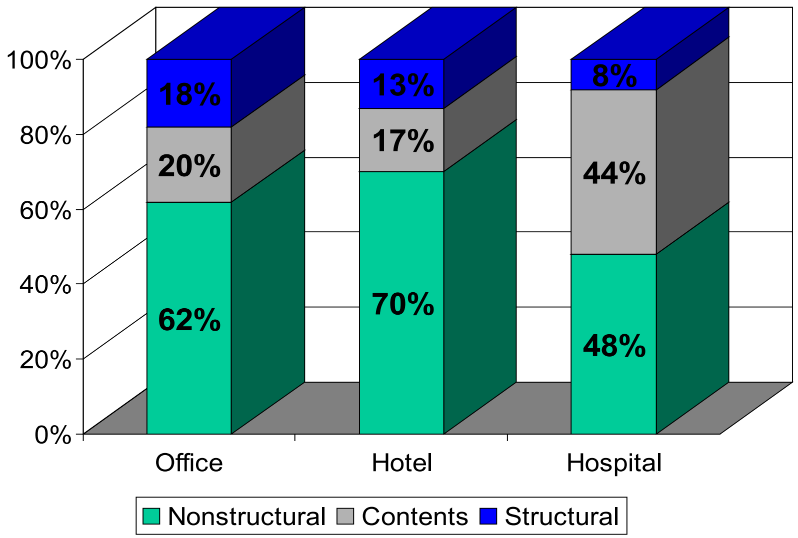



Why are Nonstructural Elements Important?

Nonstructural components account for 75-85% of total investment inside a structure

Nonstructural damage accounts for over 79% of the total earthquake damage

(Whittaker and Soong, 2003)



- **Subject to the dynamic environment of the building**
- **Damage can be triggered at response intensities smaller than those required to produce structural damage**

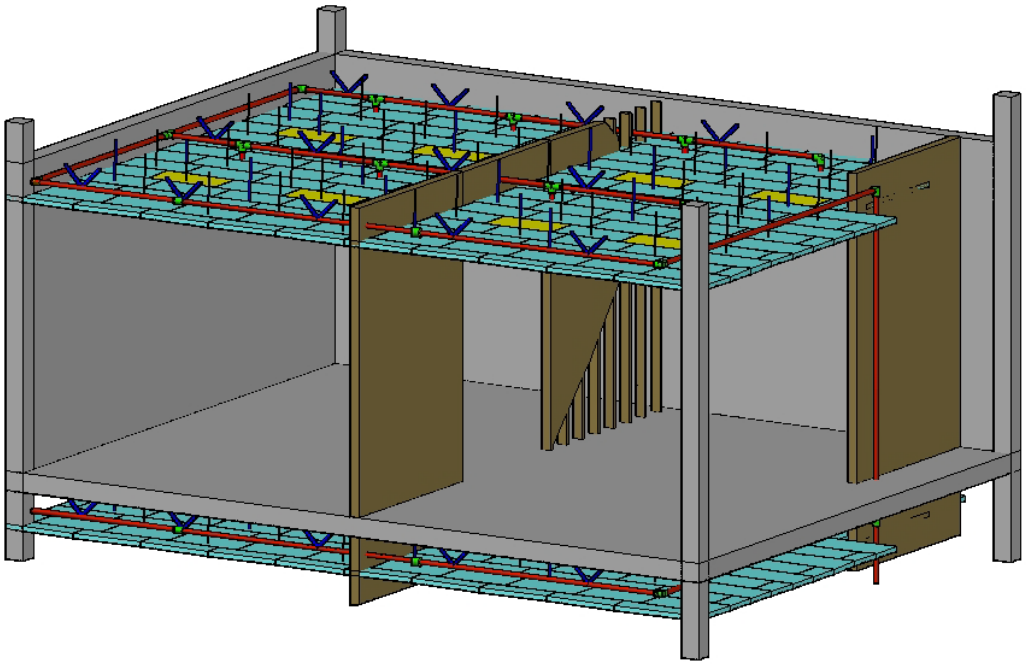
Ceiling-Piping-Partition Systems

The system is a set of three physically interacting subsystems

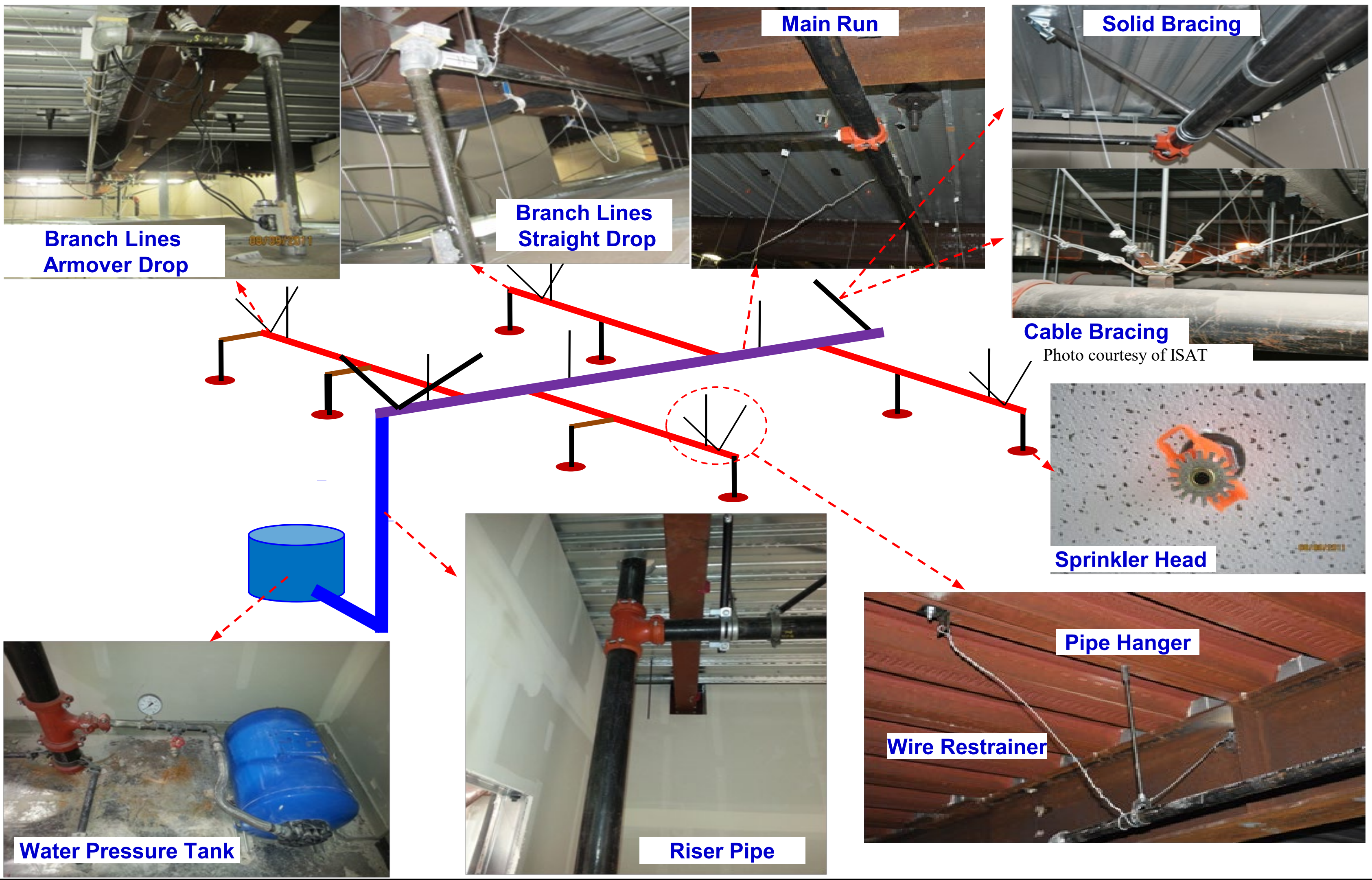
Ceiling Subsystem

Piping Subsystem

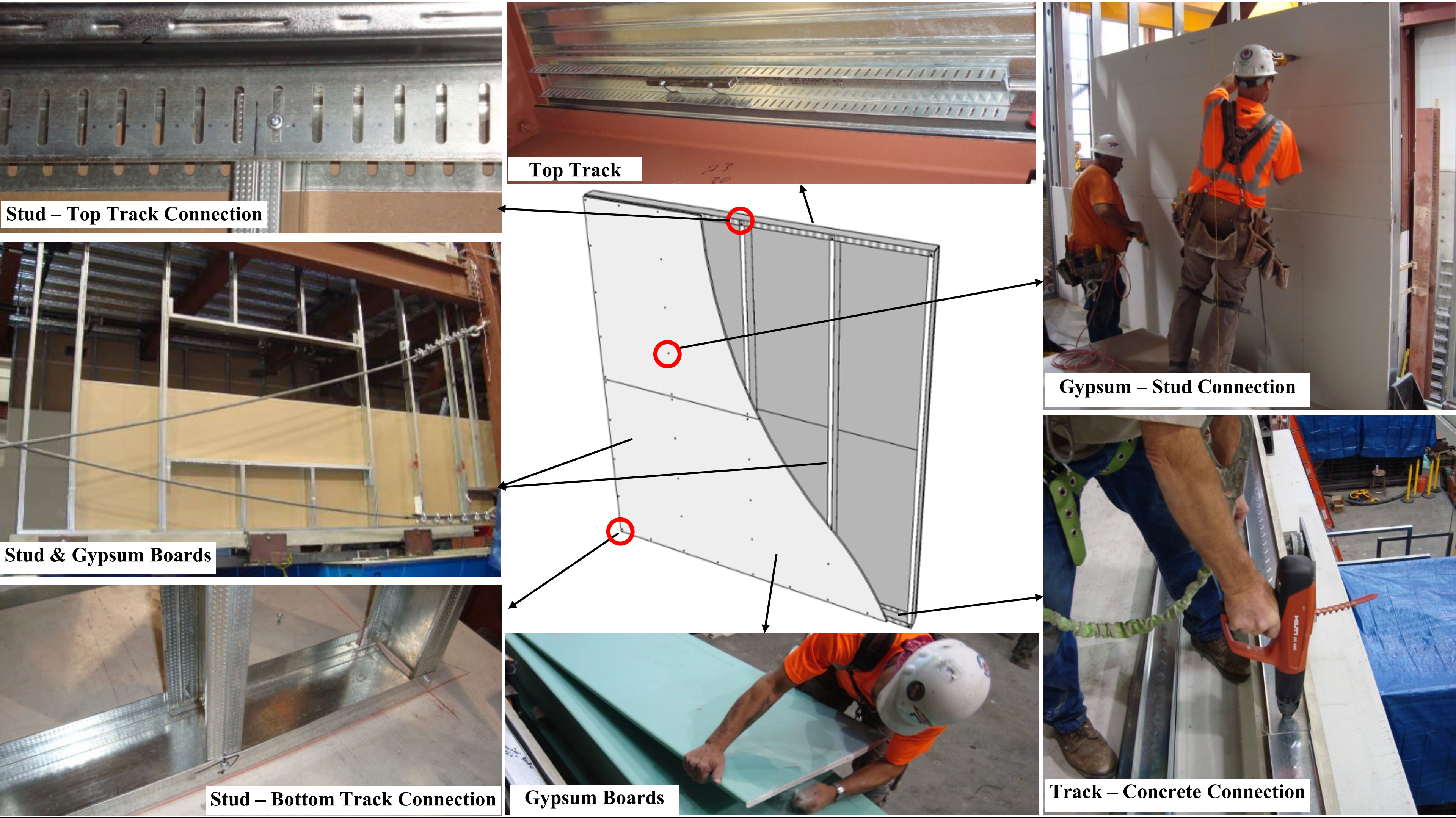
Partition Subsystem



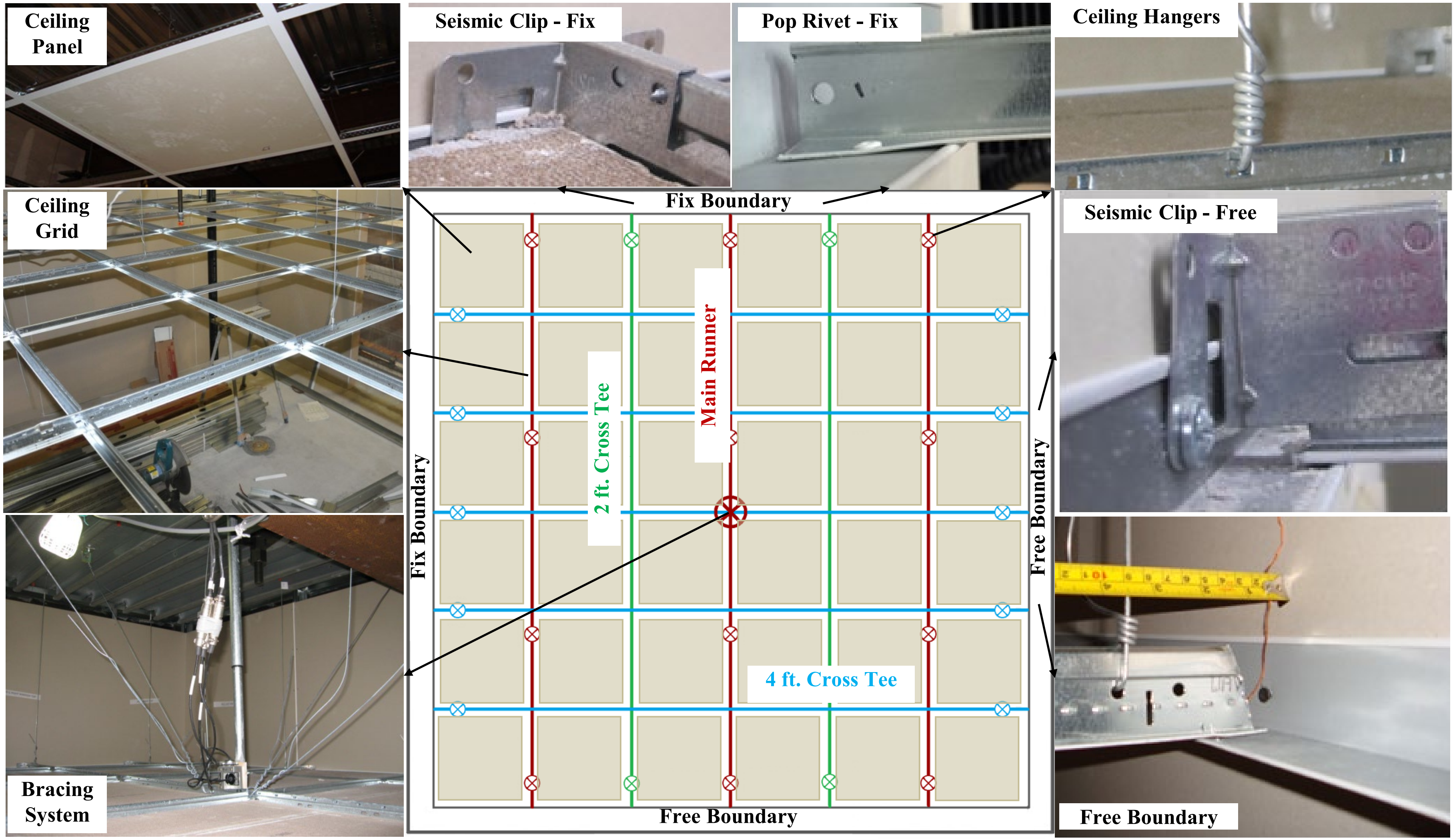
Fire Sprinkler Piping Systems



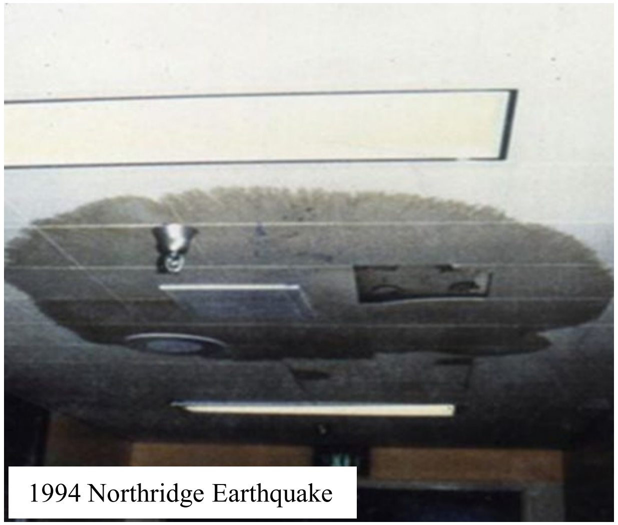
Cold-Formed Steel-Framed Gypsum Partition Walls

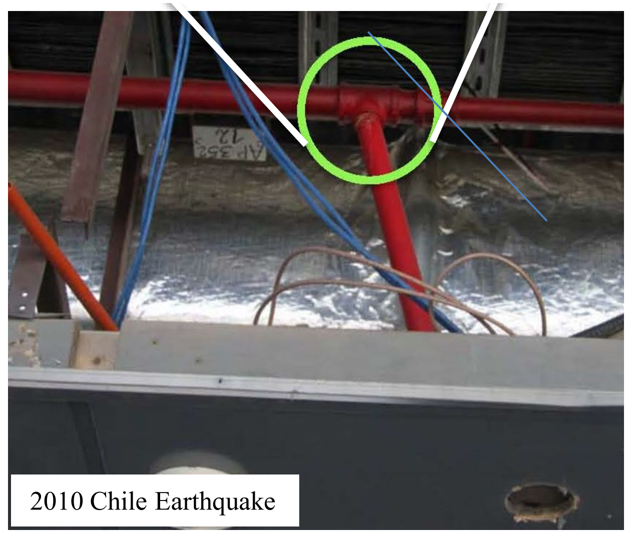


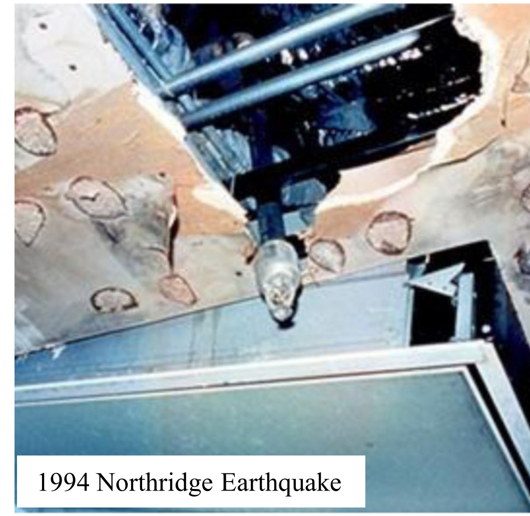
Acoustic Tile Suspended Ceiling System



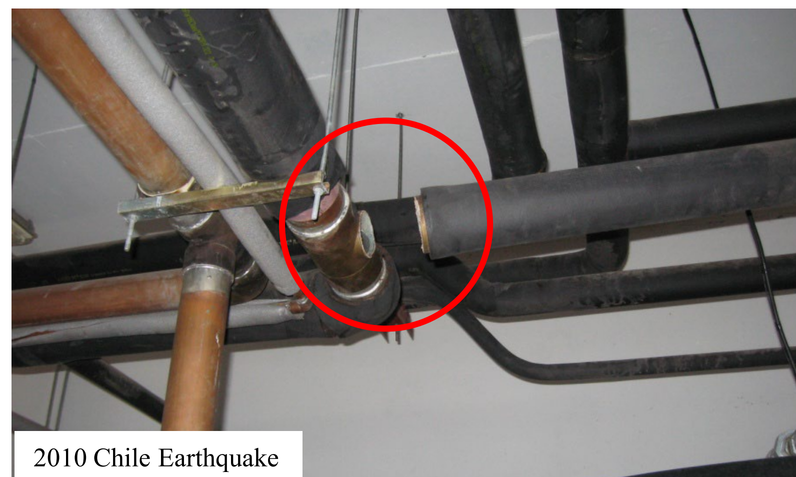
Damage During Past Earthquakes - Piping


1994 Northridge Earthquake


2010 Chile Earthquake


1994 Northridge Earthquake


2010 Chile Earthquake


2010 Chile Earthquake

Damage During Past Earthquakes - Partition

2010 Chile Earthquake

2010 Chile Earthquake

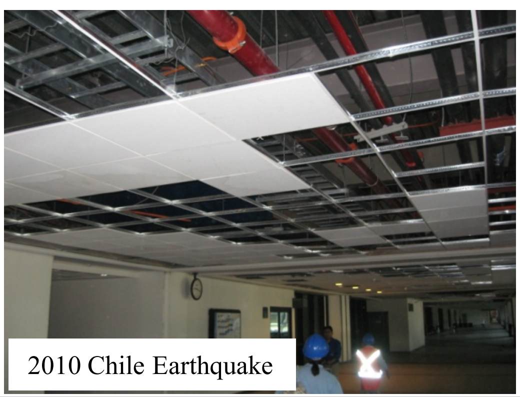
1994 Northridge Earthquake

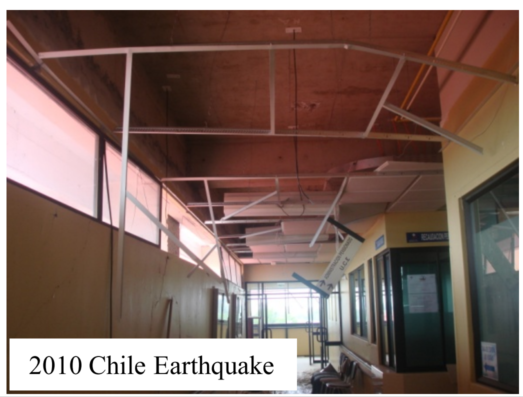
2010 Chile Earthquake

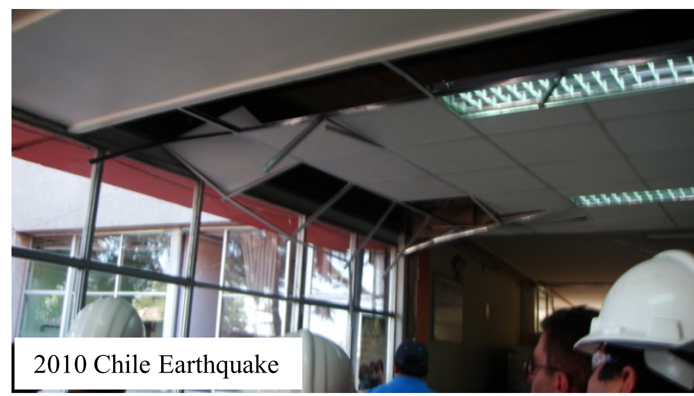
Damage During Past Earthquakes - Ceiling


2010 Haiti Earthquake


2005 Miyagi-oki


2010 Chile Earthquake


2010 Chile Earthquake


2010 Chile Earthquake

Outline

- Introduction
- **NEES Nonstructural Grand Challenge Project**
- Experimental Studies (GC Projects)
- Analytical Studies
- Future Directions

NEESR-GC: Project Team

Principal Investigator

E. "Manos" Maragakis
University of Nevada, Reno

Co- Principal Investigators

André Filiatrault (UB)
Steven French (Georgia Tech)
Tara Hutchinson (UCSD)
Bob Reitherman (CUREE)

Practice Committee

Bill Holmes (R&C)
Dennis Alvarez (CISCA)
Russell Fleming (NFSA)
John Gillengerten (OSHPD)
Ali Hosam (FM Global)
Robert Wessel (Gypsum. Assoc.)

Advisory Board

Robert Bachman(RE Bachman Structural Engineers)
William Petak(USC)
Stephen J. Eder P. E. (FRC)
Shannon Rose (ISAT)
Richard Kirchner (HPSA)
Chris Tokas (OSHPD)
Eduardo Miranda (Stanford)

International Collaborators

Jean-Angelo Beraldin (NRC, Canada)
Kazuhiko Kasai (Tokyo Institute of Techn)
Shojiro Motoyui (Tokyo Institute of Techn)

Industry Collaborators

Jim Hatch (Jarret Structures)
Paul Hough (Armstrong World Industries)
Doug Taylor (Taylor Devices)

Senior Personnel

Raymond Burby (UNC at Chapel Hill)
Jaque Ewing-Taylor (UNR)
Mircea Grigoriu (Cornell)
Abhinav Gupta (NC State)
Sameer Hamoush (NC A&T State Univ.)
Gee Hecksher (Architectural Resources)
Ahmad Itani (UNR)
Falko Kuester (UCSD)
Gokhan Pekcan (UNR)
Andrei Reinhorn (UB)
Gilberto Mosqueda(UCSD)
Arash E. Zaghi (UCONN)

Other Collaborators

Kurt McMullin (San Jose State Univ.)
Wayne Smith (Tech Museum)
Dave Schaefer (NCSU)

CUREE
Georgia Tech
RUTHERFORD & CHEKENE
UCSD
University at Buffalo
NC STATE UNIVERSITY
North Carolina A&T State University
AGEP!

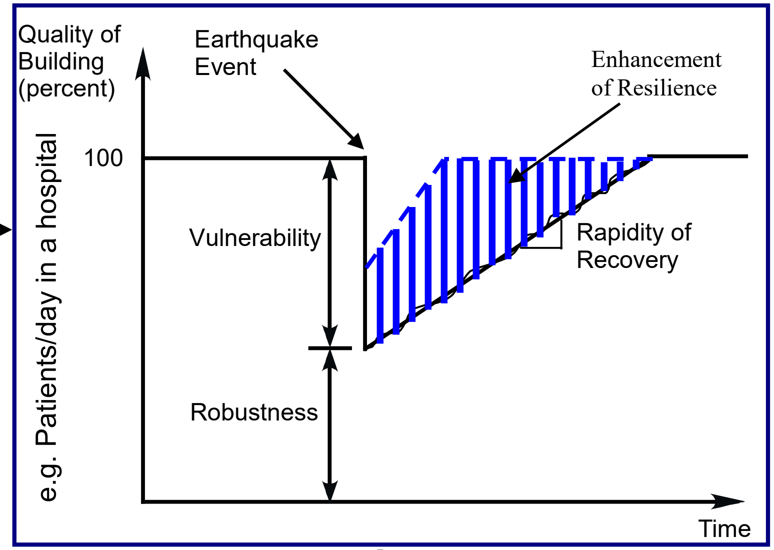
Vision Statement

To significantly enhance the seismic resilience of <u>buildings</u> and <u>communities</u> by providing practicing engineers and architects with verified tools and guidelines for the understanding, prediction and improvement of the seismic response of the ceiling-piping-partition nonstructural system.

Enhancement of Resilience

For individual buildings proposed research will:

- Decrease the risks to life and property
- Limit loss of functionality after an earthquake



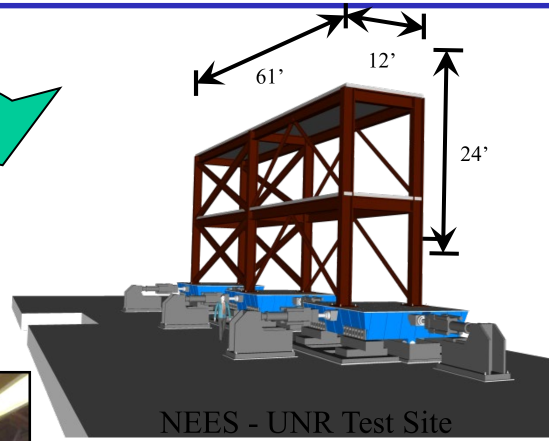
Quantify the impact of the research on the individual building and metropolitan scales - Implementation

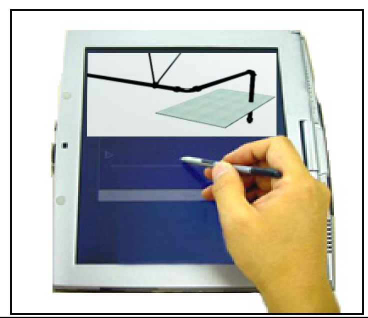
- Reduce failure at the metropolitan scale
- Improve the community ability to recover after an earthquake

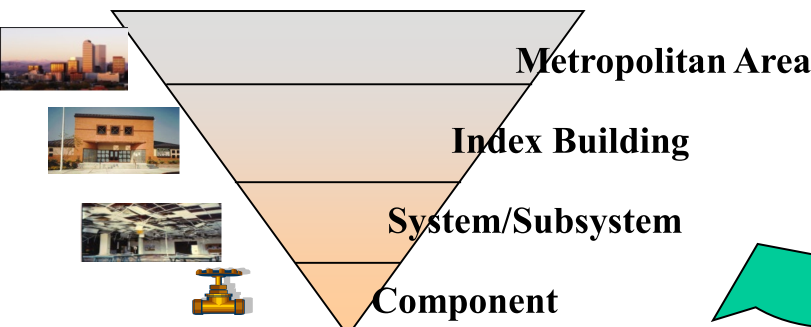
Enhancement of community resilience

NEESR-GC: Simulation of the Seismic Performance of Nonstructural Systems

NEES – UB Test Site







CUREE
Georgia Tech
North Carolina A&T State University
NC STATE UNIVERSITY
University at Buffalo
UCSD
AGEP!

NEES Nonstructural

Simulation of the Seismic Performance of Nonstructural Systems

Host Institution

Funded by

NSF

Outline

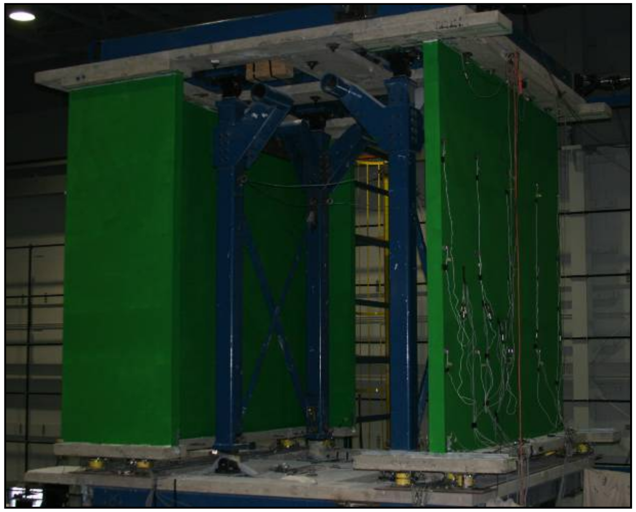
- Introduction
- NEES Nonstructural Grand Challenge Project
- Experimental Studies (GC Projects)
- Analytical Studies
  - Previous Studies
  - Experimentally Integrated Studies
- Future Directions

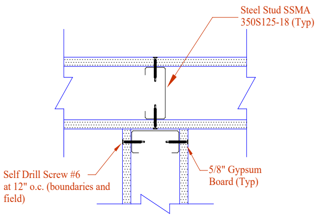
Component Level Experiments at UB NEES site

50 12-ft Wall Specimens

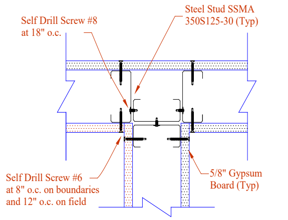
48 Pipe T-Joint Specimens
4 Piping Subsystems

10 Ceiling Specimens

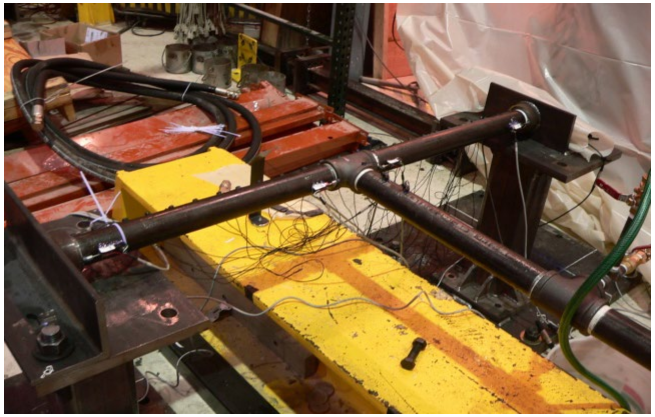


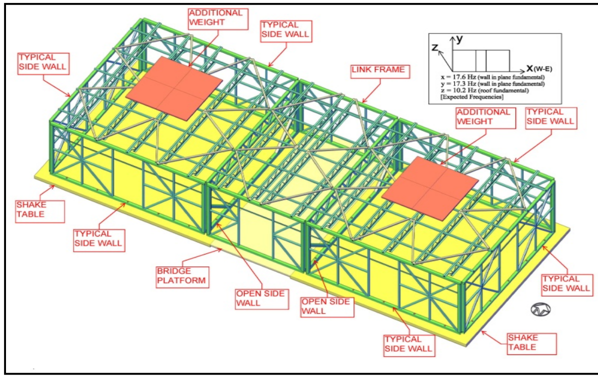


Commercial Construction (ASTM, 2007)



Institutional Construction (SSMA, 2001)





Experimental Program- System Level

Combination of Ceiling-Piping-Partition

E-Defense Experiment

Two Floors of Nonstructural Systems

43 Earthquake Simulations

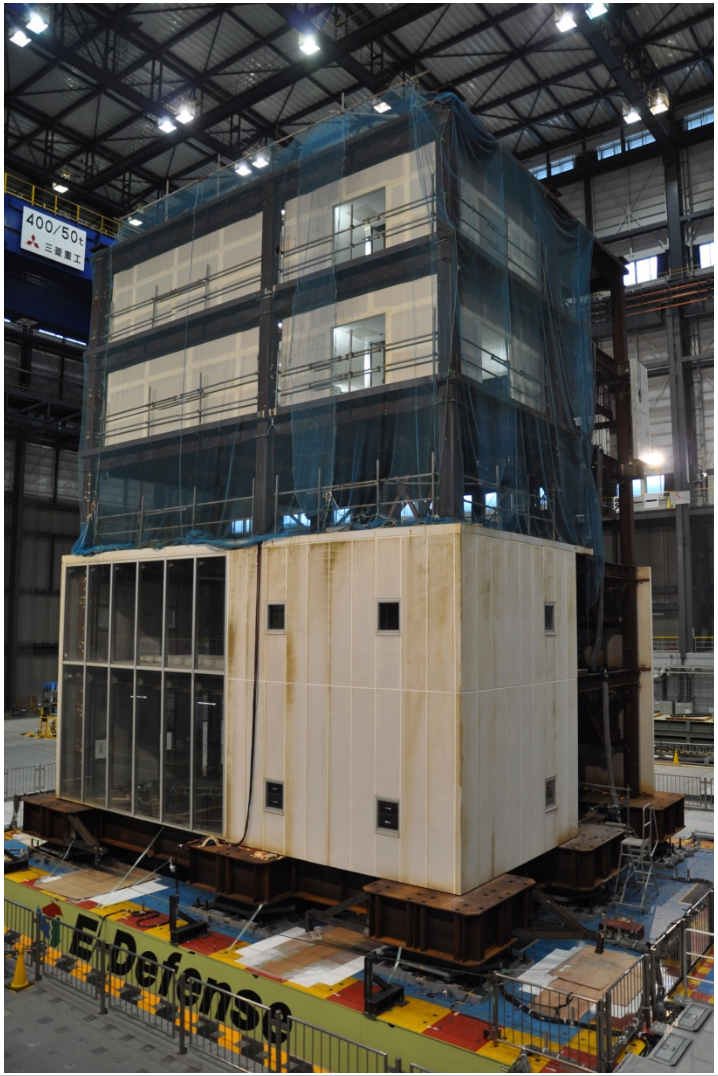
UNR Experiment

Two Floors of Nonstructural Systems

8 Sets of Experiments

E-Defense Experiment

- **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



E-Defense Experiment – Ceiling Performance

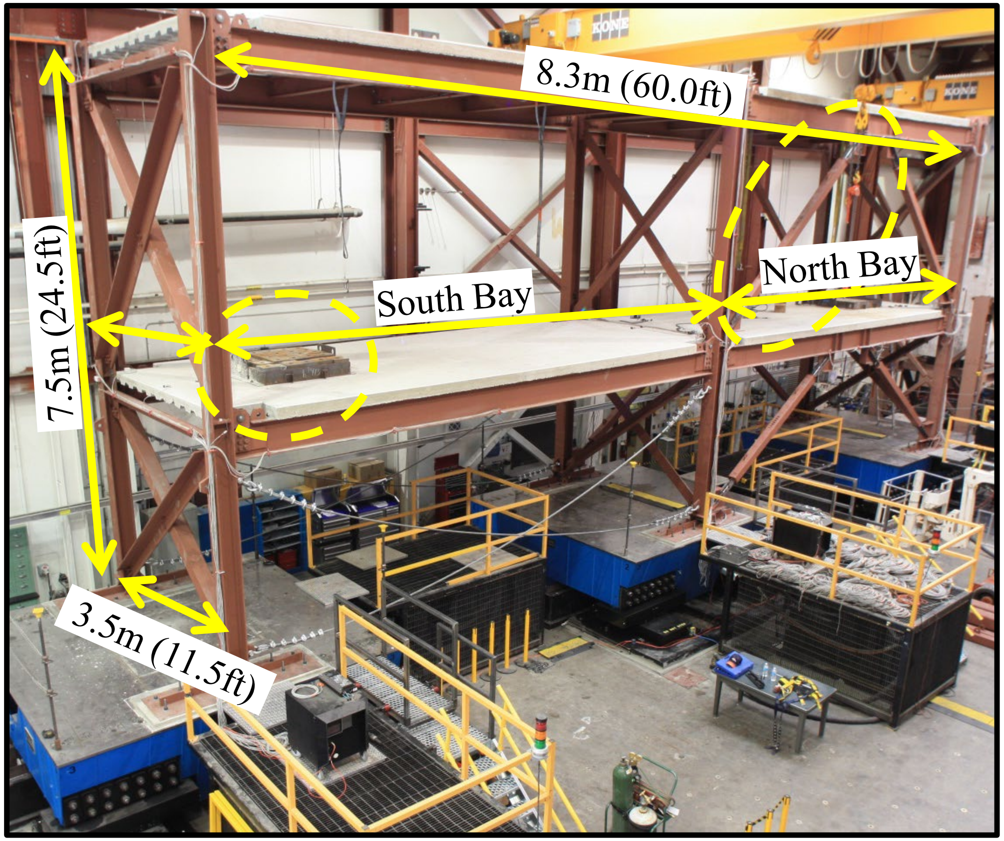
Mid Span

Near Riser

5th Floor - Braced

4th Floor - Unbraced

Test-bed Structure: Overview



Steel Braced-Frame Structure
- Full-Scale
- Two-by-one bay

Approx. Dimensions
- 7.5m x 3.5m x 18.3m
- (24.5ft x 11.5ft x 60.0ft)

Configuration Variables
- Brace properties
- Addition attached floor mass

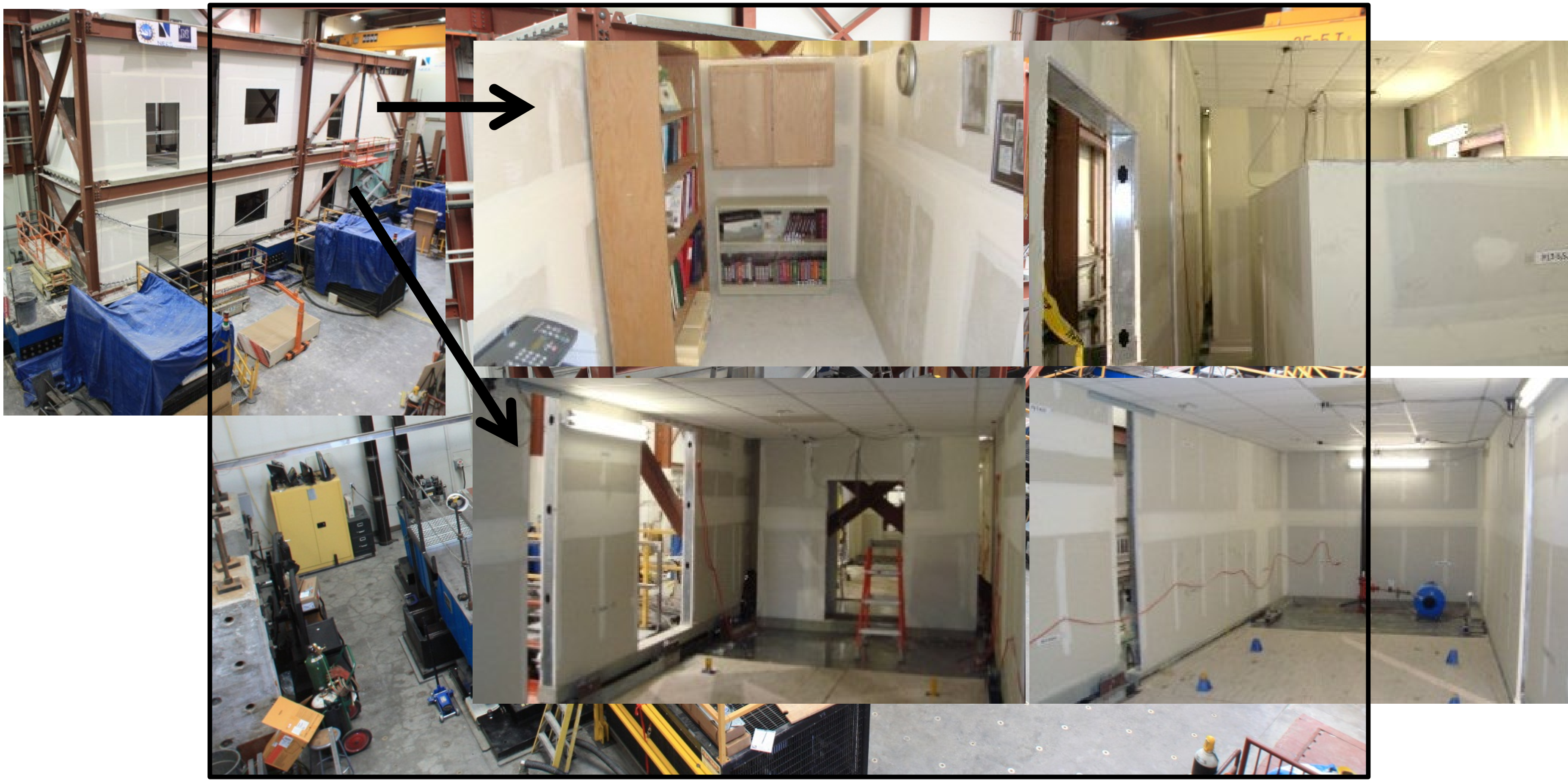
Test-bed Structure: Configurations

Two Configurations

- Linear: Large Accelerations
- Nonlinear: Large Inter-story Drift

Floor	Linear Configuration		Nonlinear Configuration	
	BRB Yield Capacity	Attached Mass	BRB Yield Capacity	Attached Mass
First	283 kN (64Kips)	30.7 kN (6.9Kips)	89 kN (20.0Kips)	62.5 kN (14.0Kips)
Second		17.6 kN (4.0Kips)		279.1 kN (62.8Kips)
T_n	0.2 sec		0.34 sec	

Test-bed Structure: Floor Layout



UNR Experiments

➢ Linear Tests:

- ✓ Braces Remained Linearly Elastic
- ✓ Objective: Achieve High Floor Acceleration
- ✓ 5 linear tests → 42 Motions → PGA= 0.12-1.17g

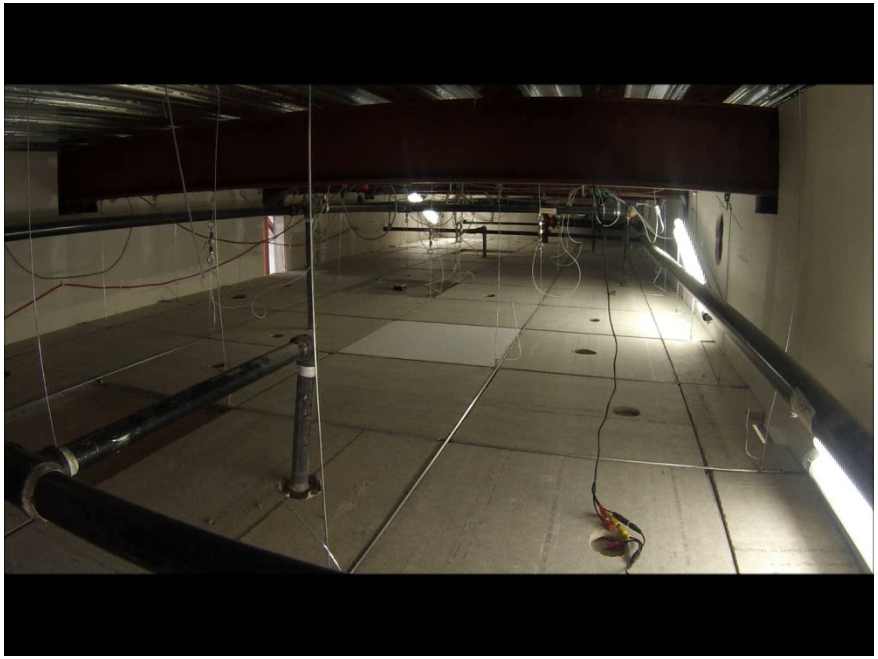
➢ Nonlinear Tests

- ✓ Braces with Lower Yield Force
- ✓ Braces Yielded
- ✓ Objective: Achieve Large Story Drift
- ✓ 3 Nonlinear tests → 17 Motions → PGA= 0.24-2.04g

UNR Experiment-Test Video

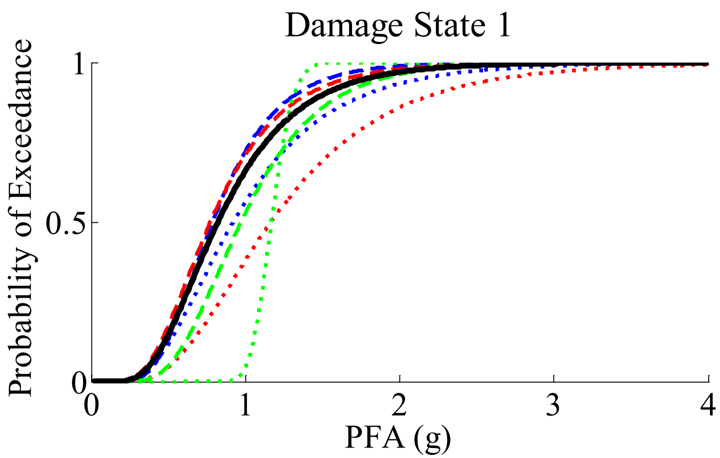
- Nonlinear Test

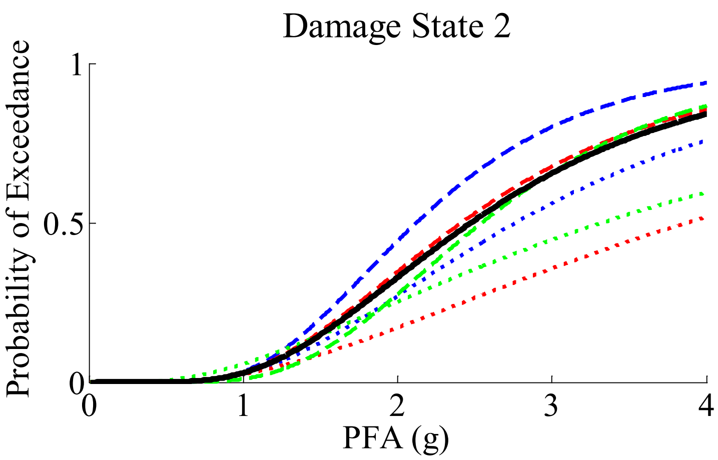
UNR Experiment – Ceiling Performance

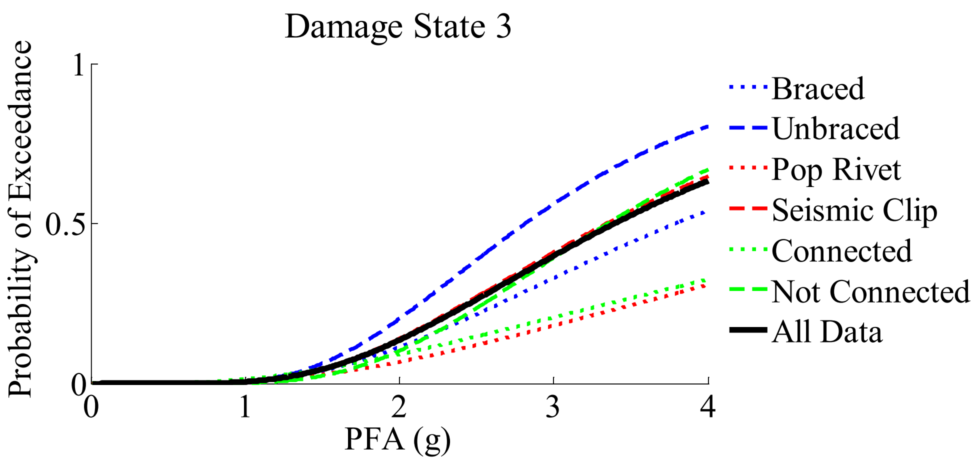


Experimental Fragility Analysis: Ceiling Performance

Damage State	Description	Repair	Percentage of Fallen Ceiling Area
DS1	Ceiling tiles dislodge and fall	Reinstall tiles	5%
DS2	Ceiling grid and tile damage	Replacement for grid and tile	30%
DS3	Major ceiling damage and some grid collapse	Total replacement of grid and tile	50%



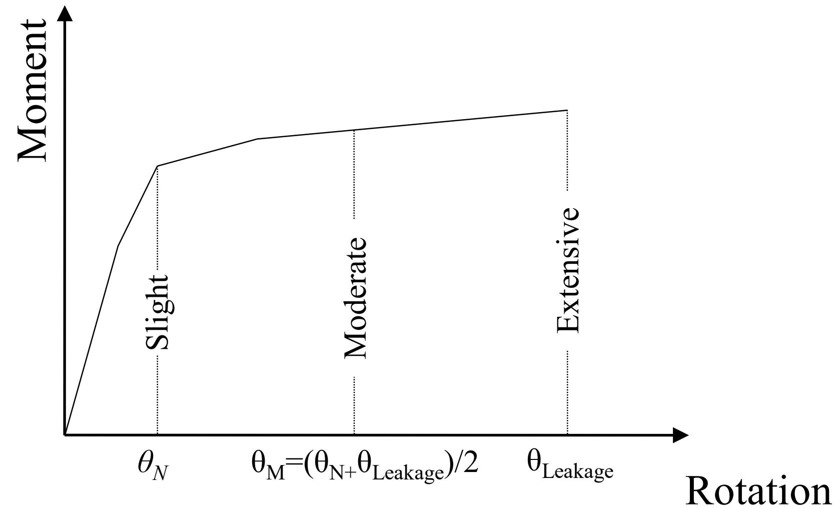


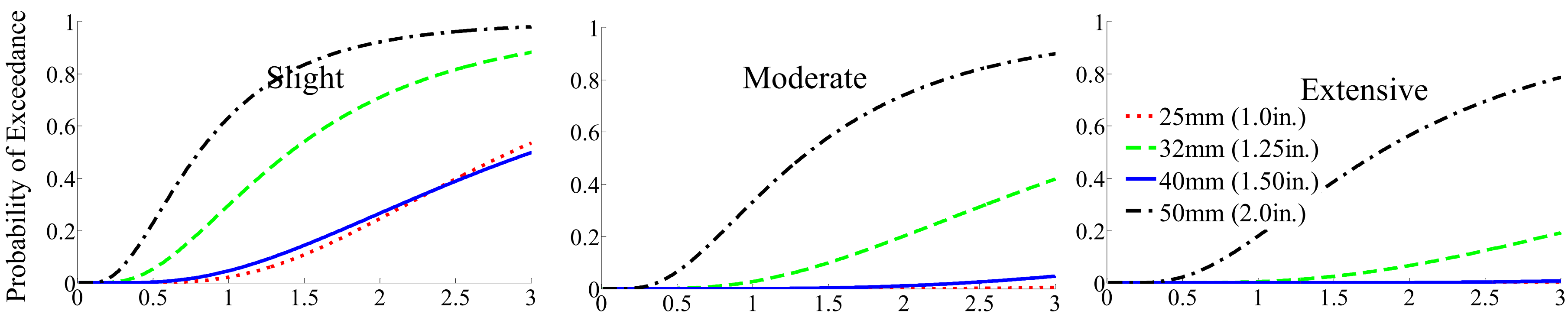


Experimental Fragility Analysis: Pipe Joint Rotation

Damage State Descriptions

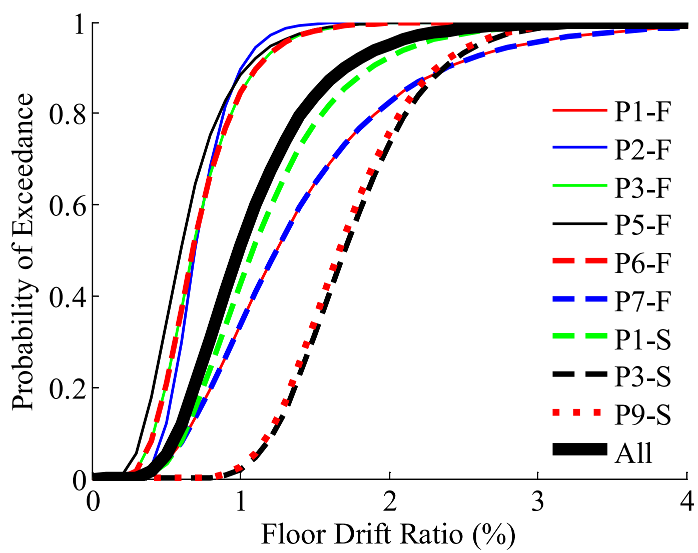
- Slight: Start of nonlinear behavior
- Moderate: Dripping/Spraying
- Extensive: First significant leakage

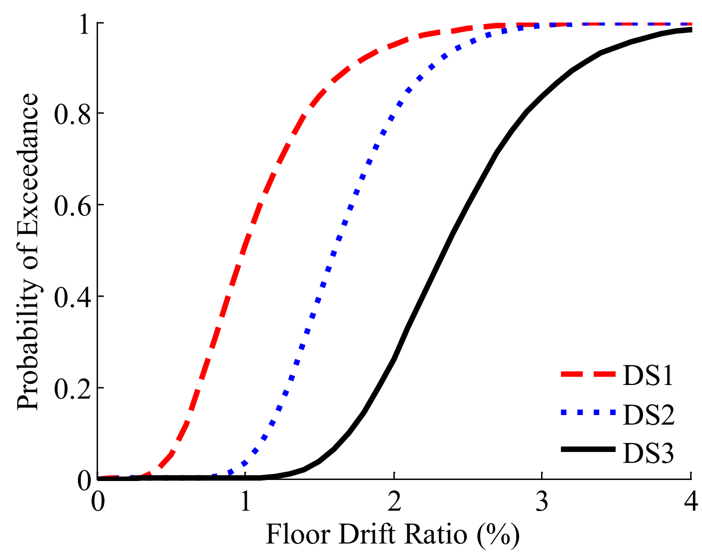




Experimental Fragility Analysis: Partition Walls

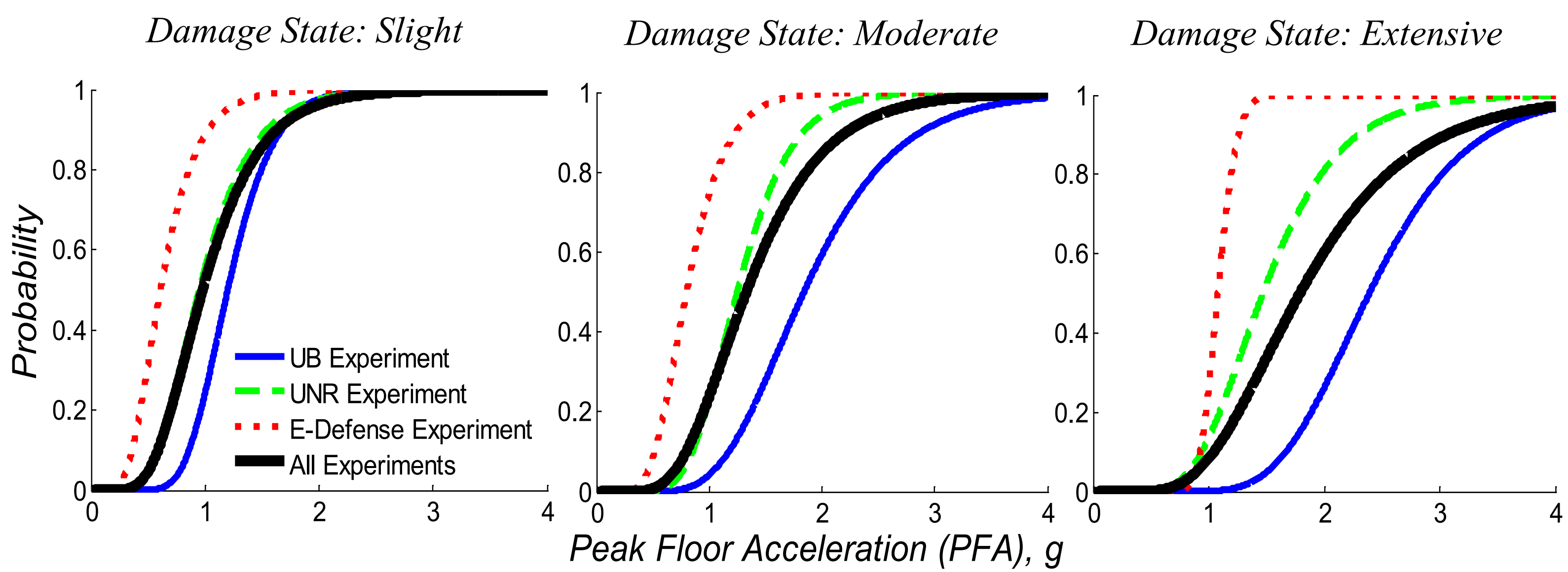
Damage State	Definition	Required Repair
DS1	Minor Damage: Popping out or rocking of gypsum board screws (field and boundary); Cracks forming at corners of openings; Minor gypsum cracking or crushing; Joint paper damage; Sliding of studs in top track.	Tape replacement at corners; gypsum board screw replacement at pop out locations; minor repairs to cracking.
DS2	Local Damage: Boundary stud deformation (bending, twisting, pulling out from top track); Crushing of gypsum boards; Damage to partial height brace connection.	Boundary stud replacement; replacing partial sections of gypsum board; replacing partial height brace system.
DS3	Severe Damage: Plastic hinging forming in field studs; tearing in steel track through slab fasteners.	Removal of full gypsum board sections and replacement of field studs; replacement of new full height gypsum wall boards; replacement of top tracks.





Fragility Curve Development Using UB, UNR, and E-Defense

Example: Ceiling System



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  - **Previous Studies**
  - Experimentally Integrated Studies
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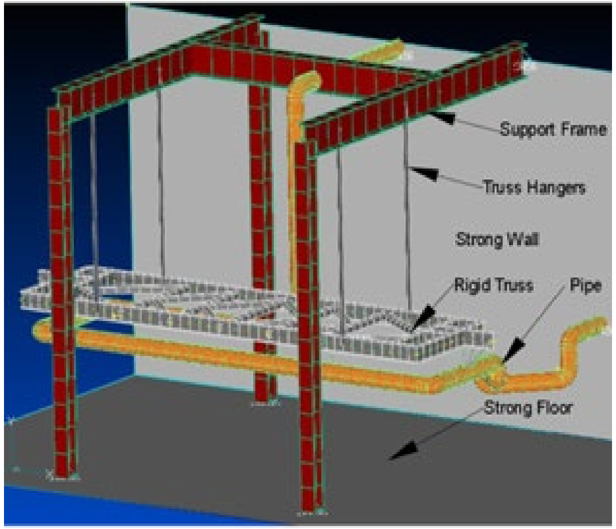
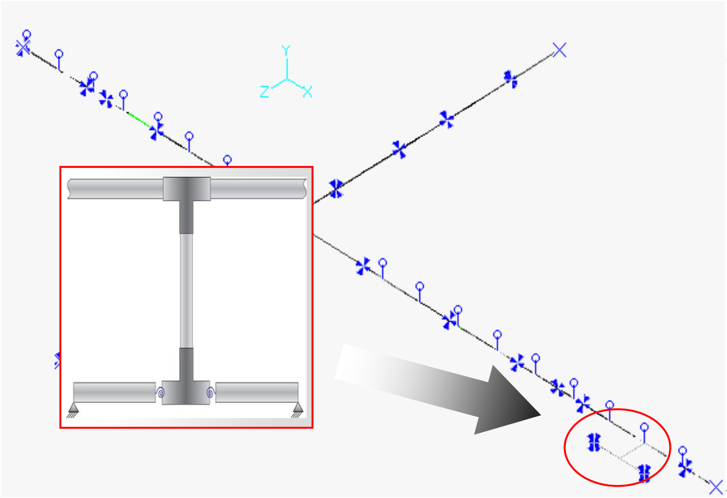
Previous Analytical Studies - Piping

NOT Considered in Previous Studies

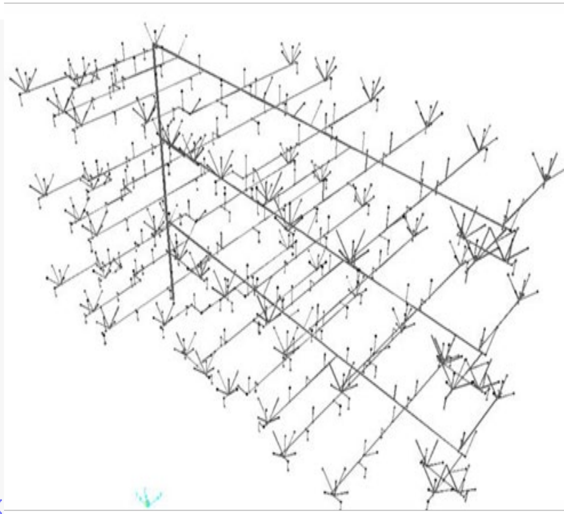
- Nonlinearity of pipe joints and supporting elements.
- Propagation of damage due to the failure of supporting elements.
- Interaction with suspended ceiling system.



Martinez and Hodgson (2007)



Ju and Gupta (2012)

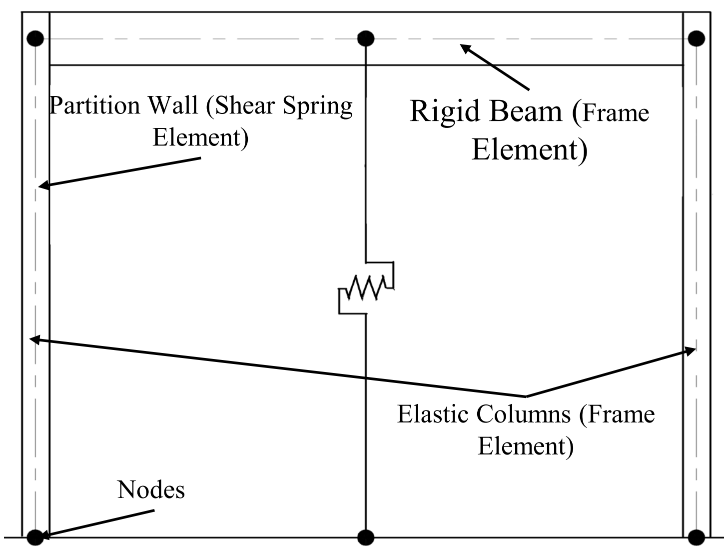


Soroushian et al. (2011)

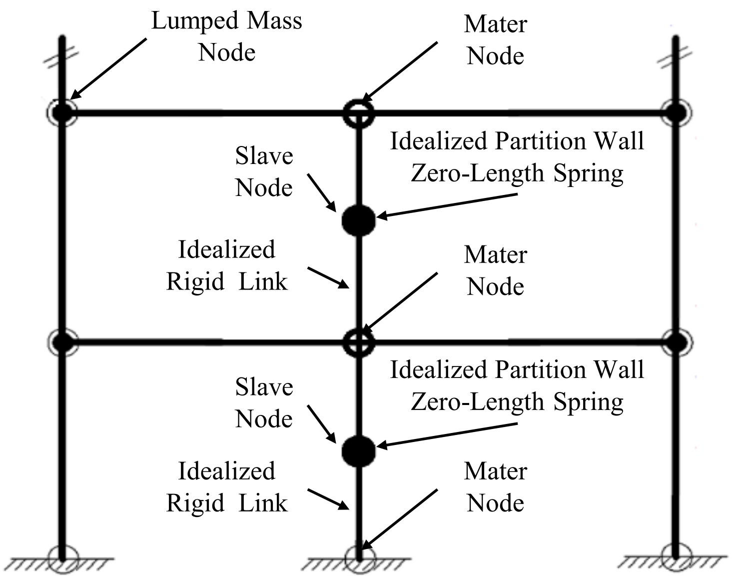
Previous Analytical Studies - Partitions

Limitations of Previous Studies

- Only lumped spring analytical models (limited to their experimental setups).
- Not able to identify local damage modes.
- Not useful for different design variables (e.g. spacing between studs).



Davies et al. (2011)

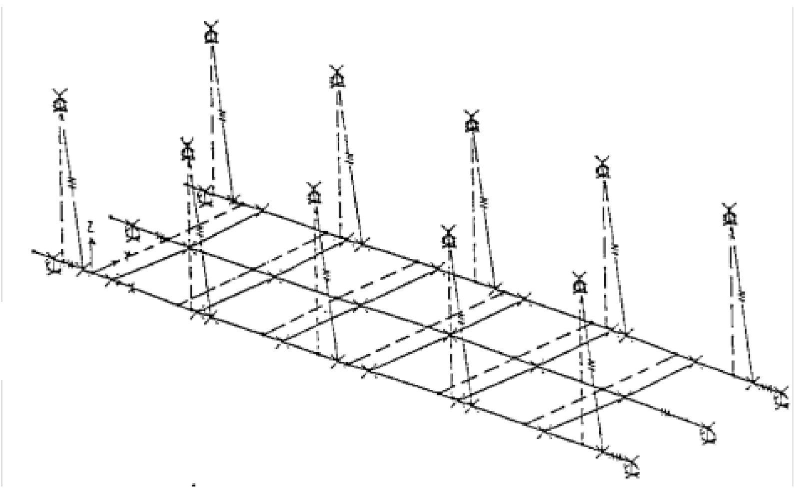


Wood et al. (2014)

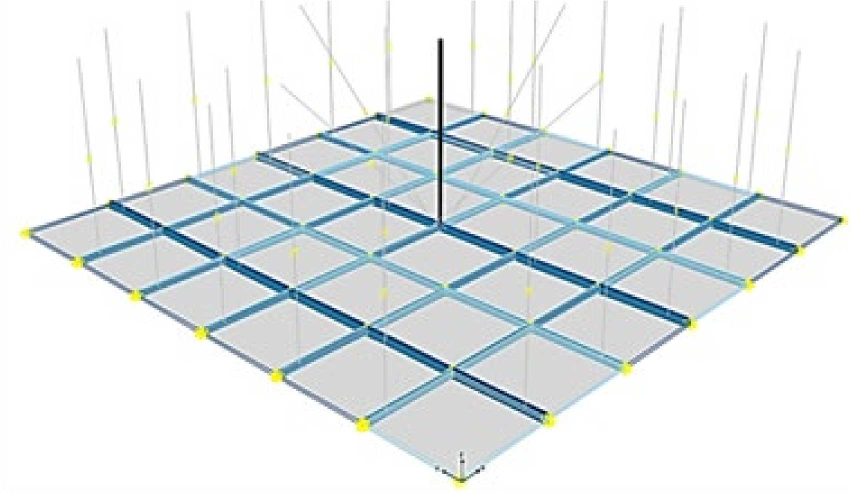
Previous Analytical Studies - Ceiling

NOT Considered in Previous Studies

- Nonlinearity of ceiling joints and supporting elements.
- Propagation of damage due to the failure of ceiling panels and supporting elements.
- Interaction with fire sprinkler piping system.



Yao (2000)



Echevarria et al. (2012)

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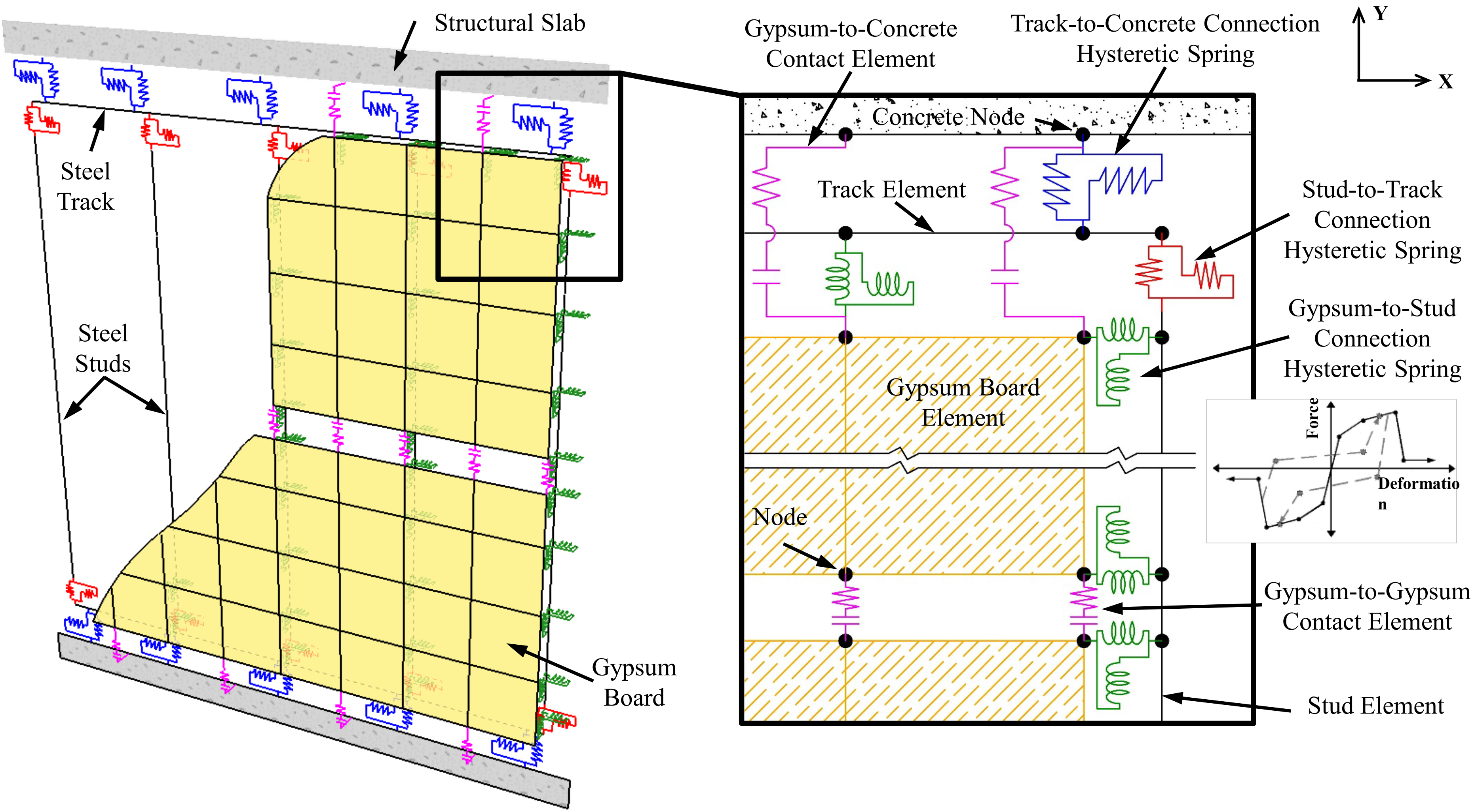
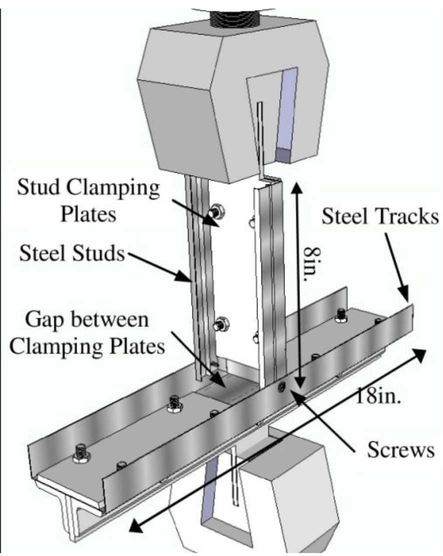
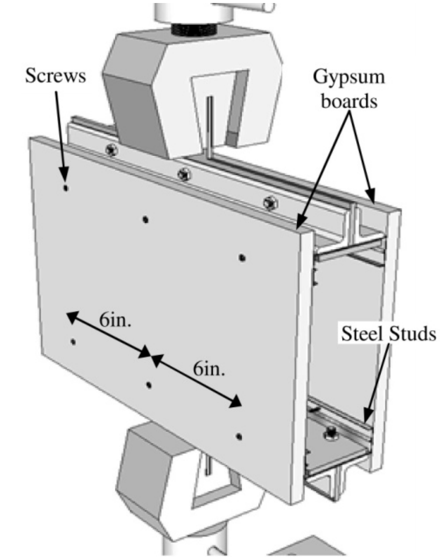
Analytical Model of Partition Walls

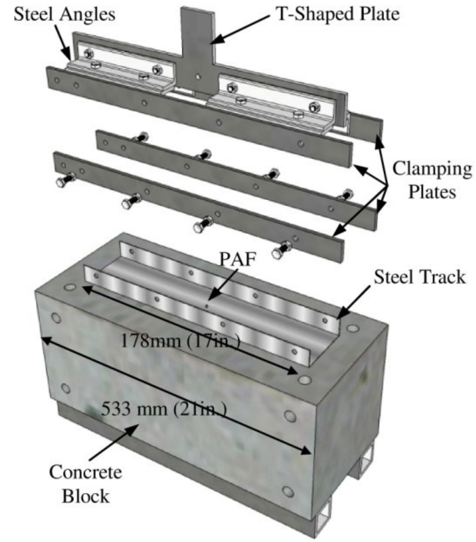


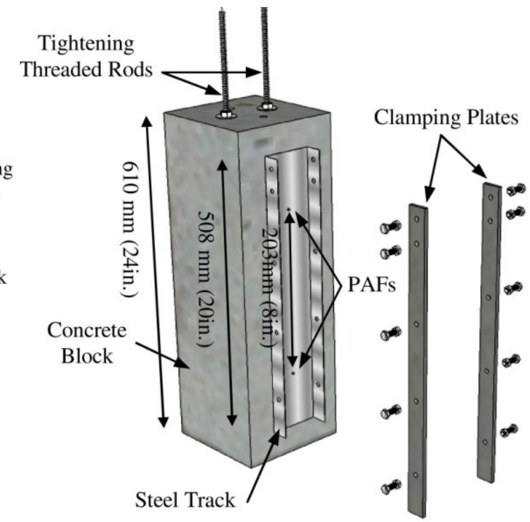
Partition Joint Tests at the University of Nevada, Reno

More than 100 Partition Joint Specimens Tested Under Monotonic and Cyclic Loading

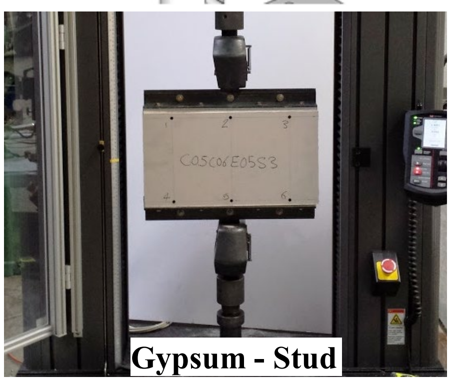









Stud - Track


Gypsum - Stud


Track – Concrete - Tension

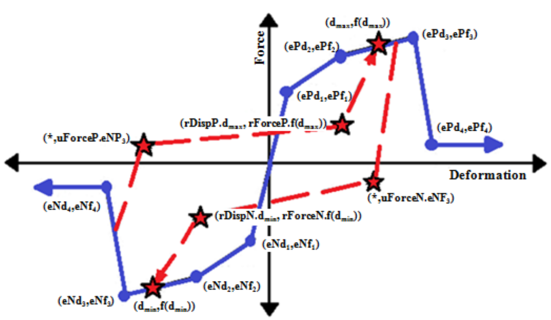

Track – Concrete - Shear

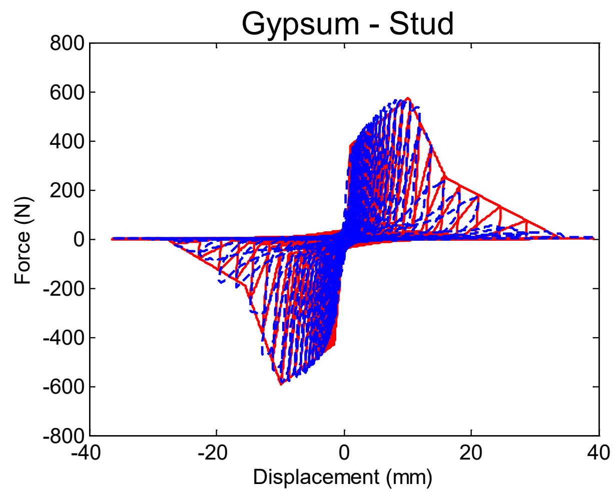
NEES Nonstructural
Simulation of the Seismic Performance of Nonstructural Systems

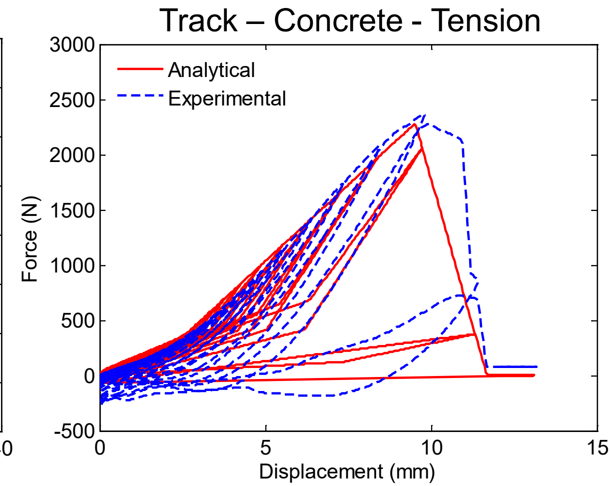
Host Institution Funded by

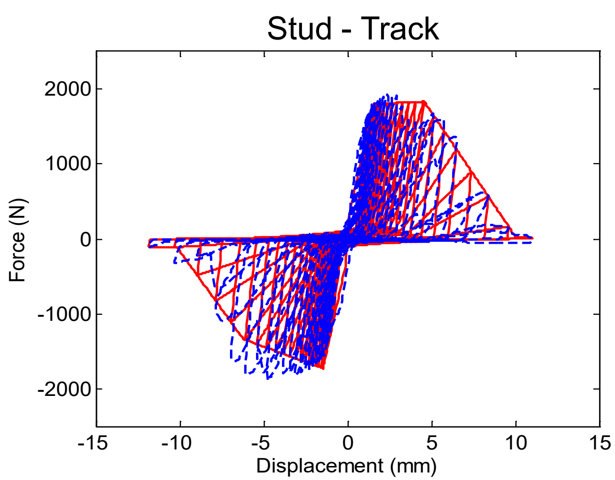
Development of an Analytical Model for Partition Joints

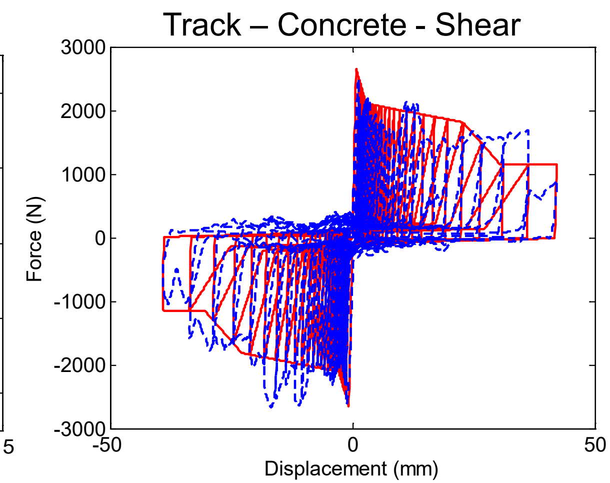
- The "Pinching4" uniaxial material along with a "TwoNodeLink" element was used to simulate the force-displacement response of the joints (OpenSees)



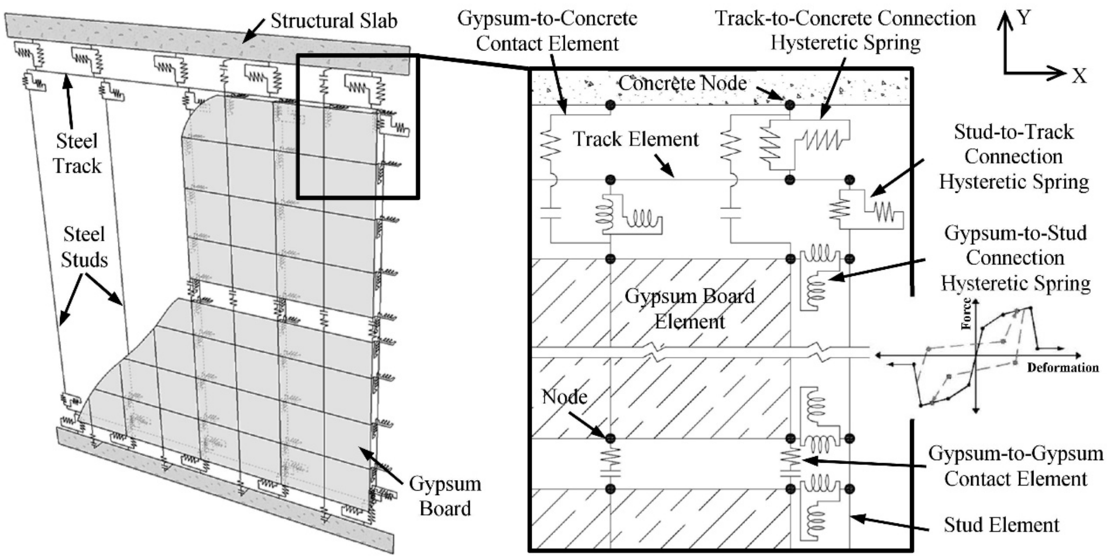


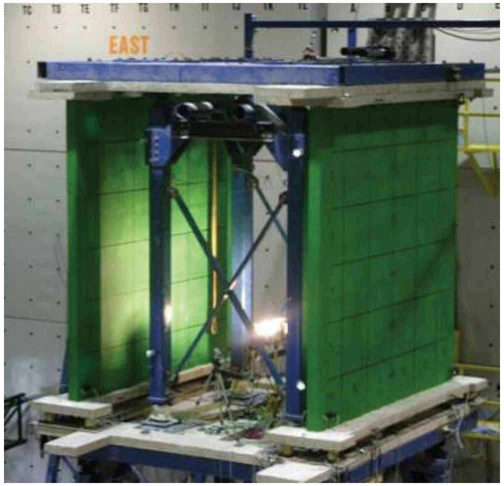


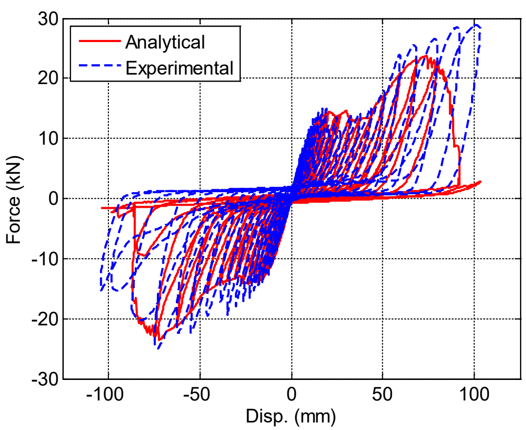


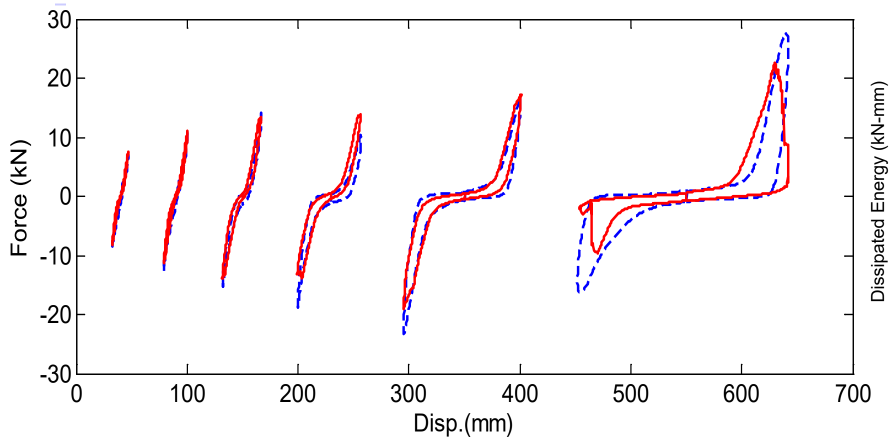


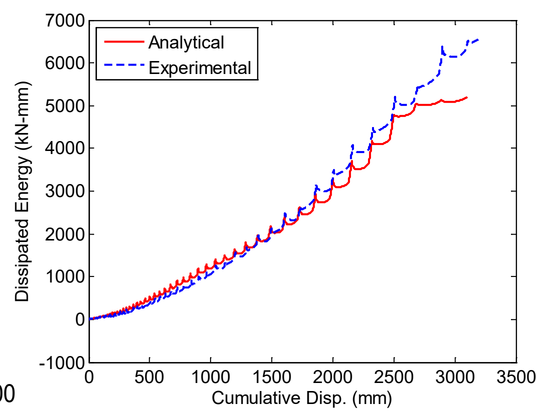
Validation of the Analytical Model for Partition Walls



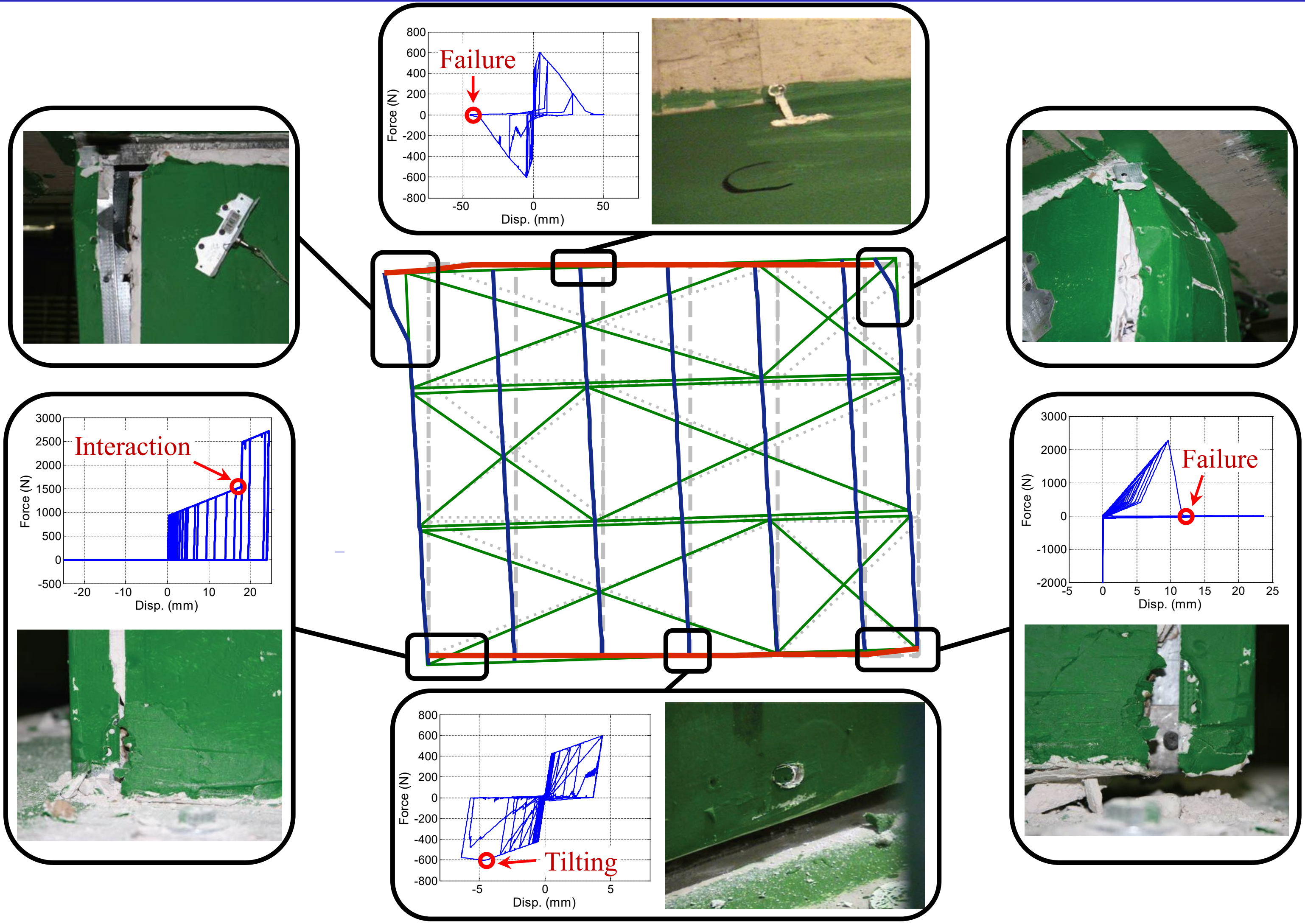






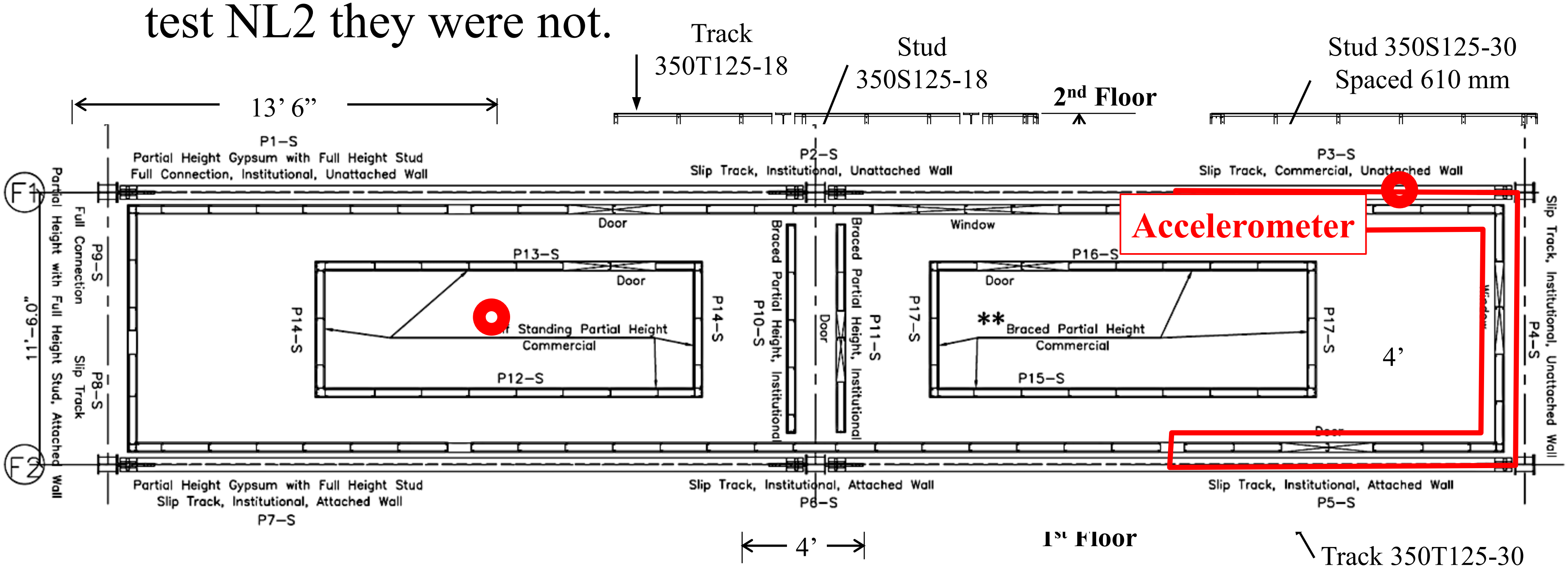


Damage Mechanisms Detected by Analytical Model

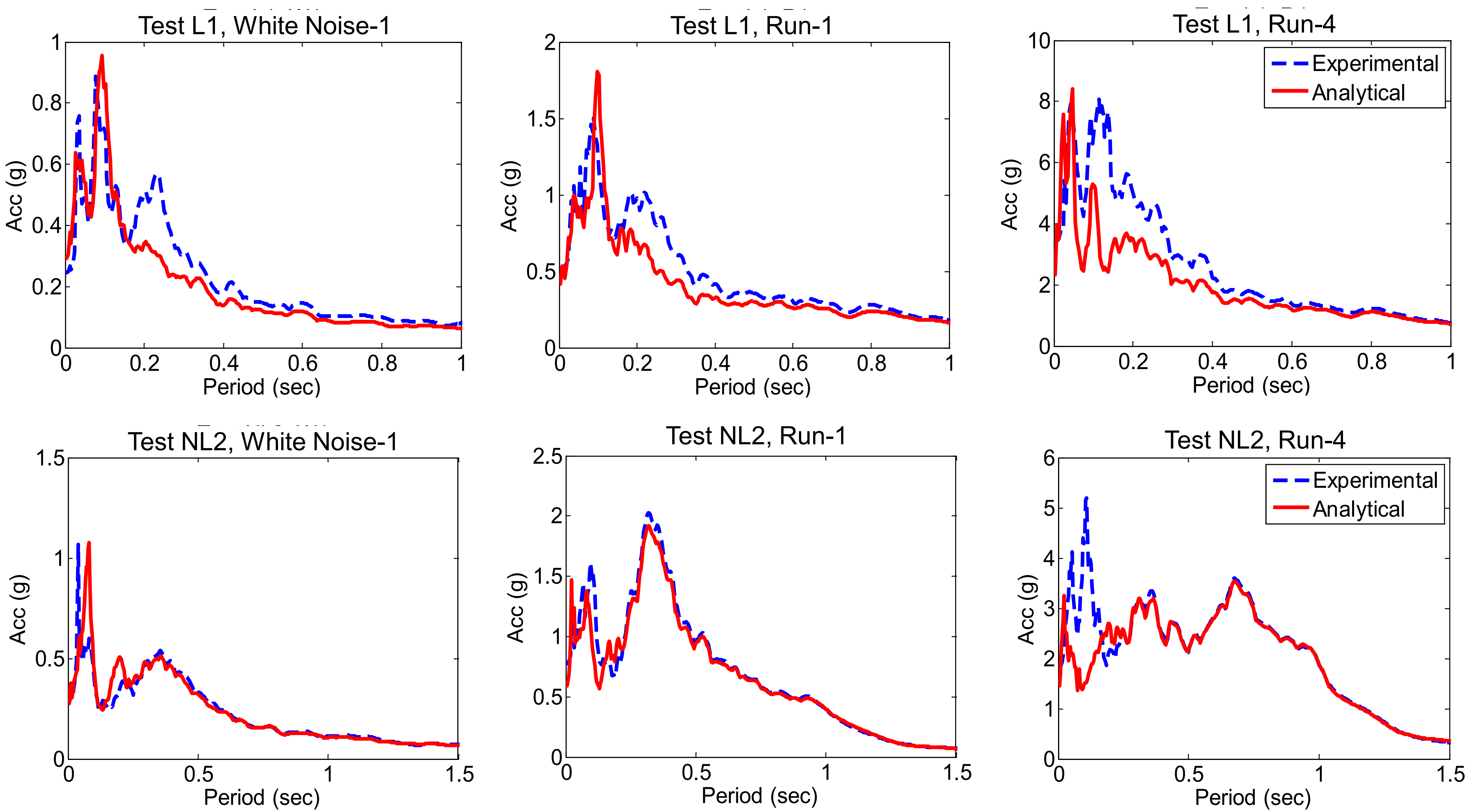


Validation – UNR Experiments

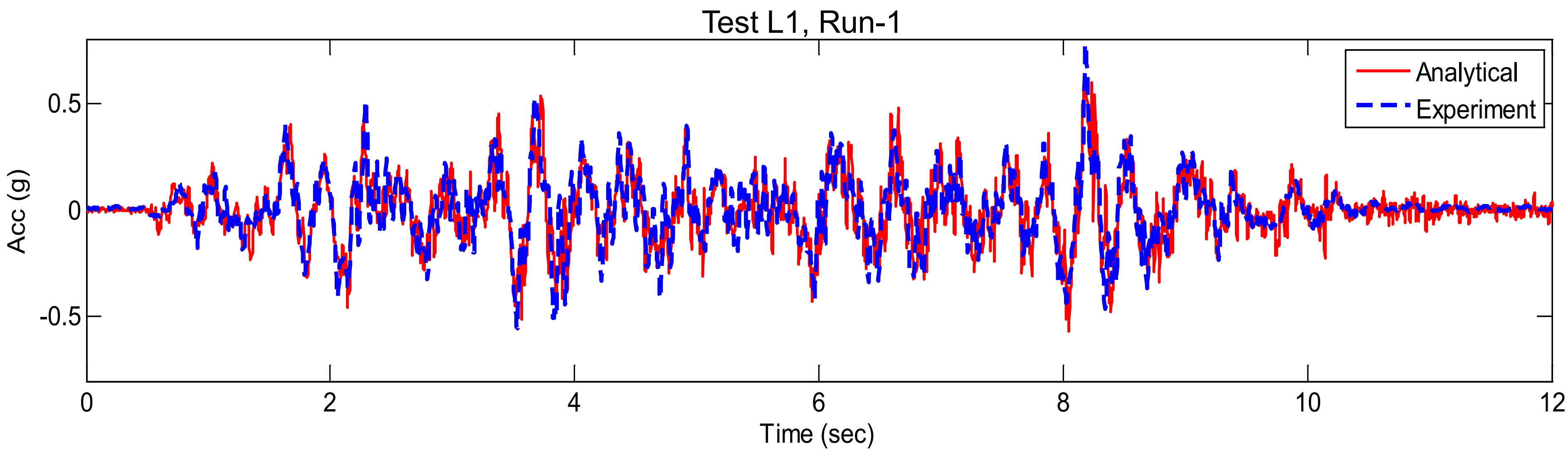
- A C-shaped wall system
- The first linear and second nonlinear tests (test L1 and test NL2)
- In test L1, the gypsum boards were screwed to the top tracks while in test NL2 they were not.



Validation, Out-of-Plane Response



Validation, Out-of-Plane Response

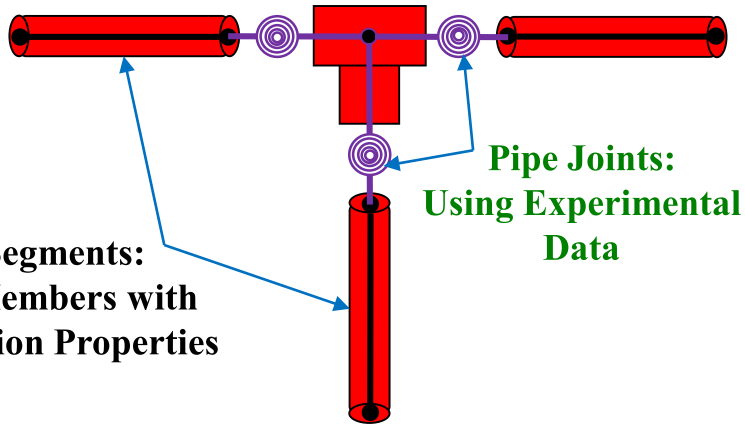


➢ Damage Prediction

- ✓ The predicted damage mechanisms in the analytical model consisted of damage to partition corners, damage to the top tracks of return walls, damage to gypsum-to-tracks screw connections, crushing of gypsum boards, and slight damage to track-to-concrete PAF connections.

Analytical Model of Fire Sprinkler Systems

Pipe Runs

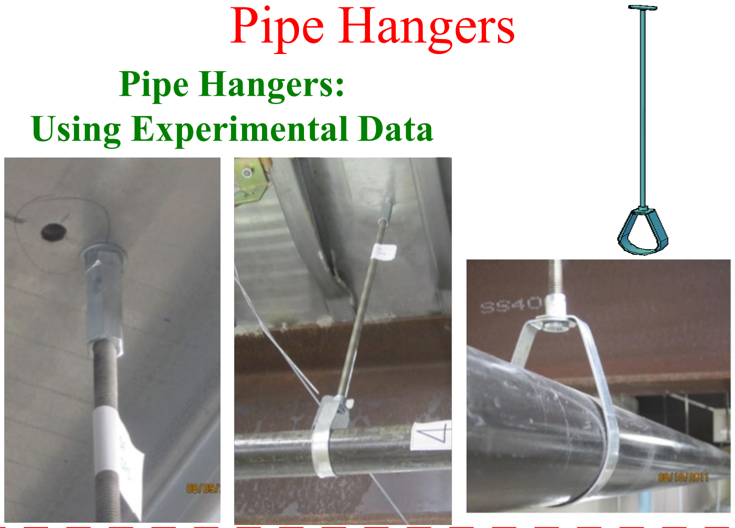


Pipe Joints: Using Experimental Data

Pipe Segments: Elastic Members with Cross Section Properties

Pipe Hangers

Pipe Hangers: Using Experimental Data



Braces

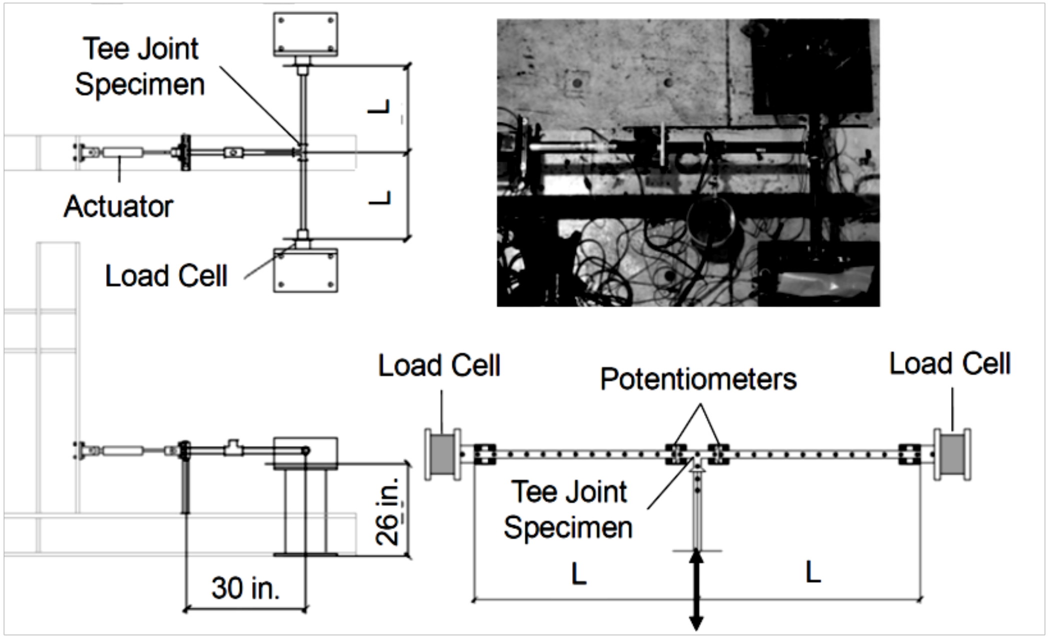
Solid Braces Elastic Members with Cross Section Properties

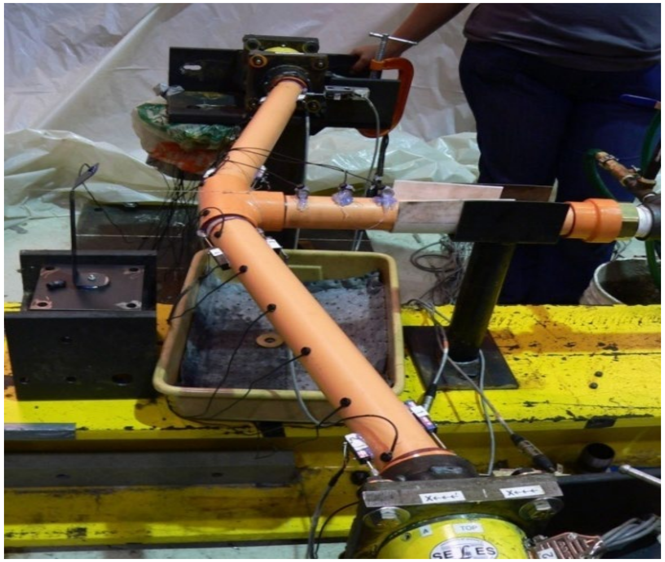
Wire Restrainer

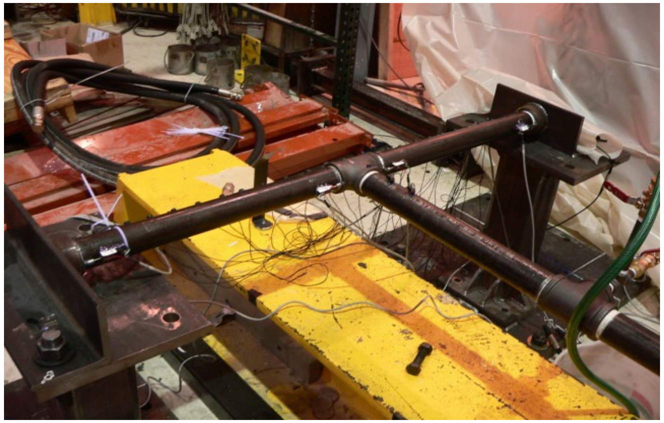
Wire Restrainers: Using Experimental Data

Piping Tee-Joint Tests at the University at Buffalo

✓ 48 T-Joint Specimens Tested Under Cyclic Loading



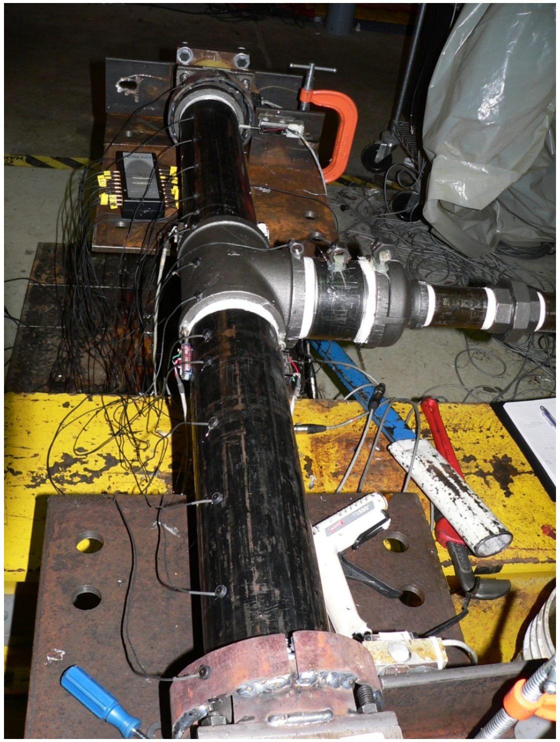




Figures from University of Buffalo

Piping Tee-Joint Tests at the University at Buffalo

Threaded

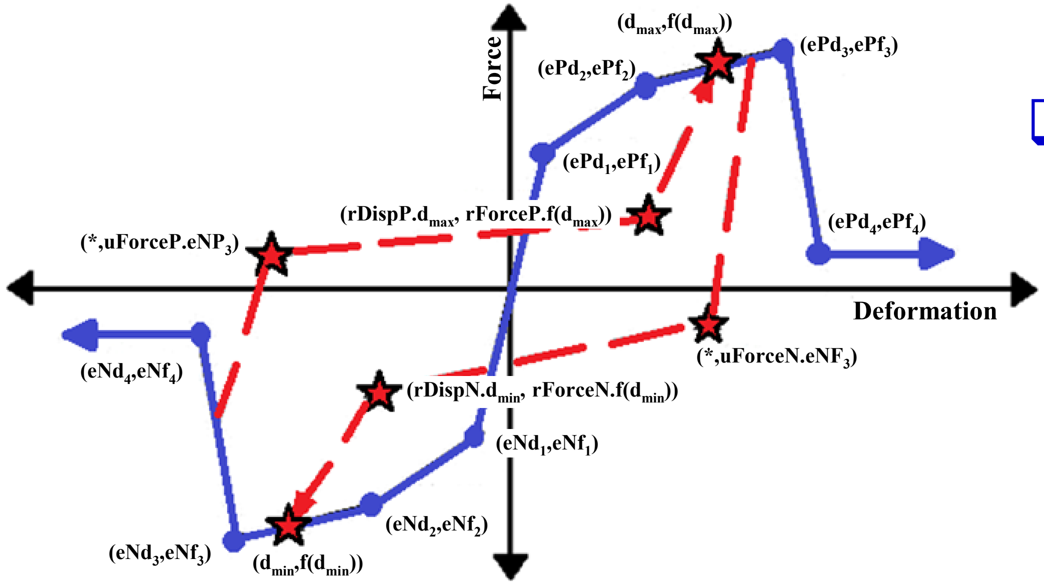


Grooved

Figures from University of Buffalo

Development of an Analytical Model For Piping Tee-Joint

- The “Pinching4" uniaxial material along with a "zeroLength" element was used to simulate the moment-rotation response of tee joints (OpenSees)

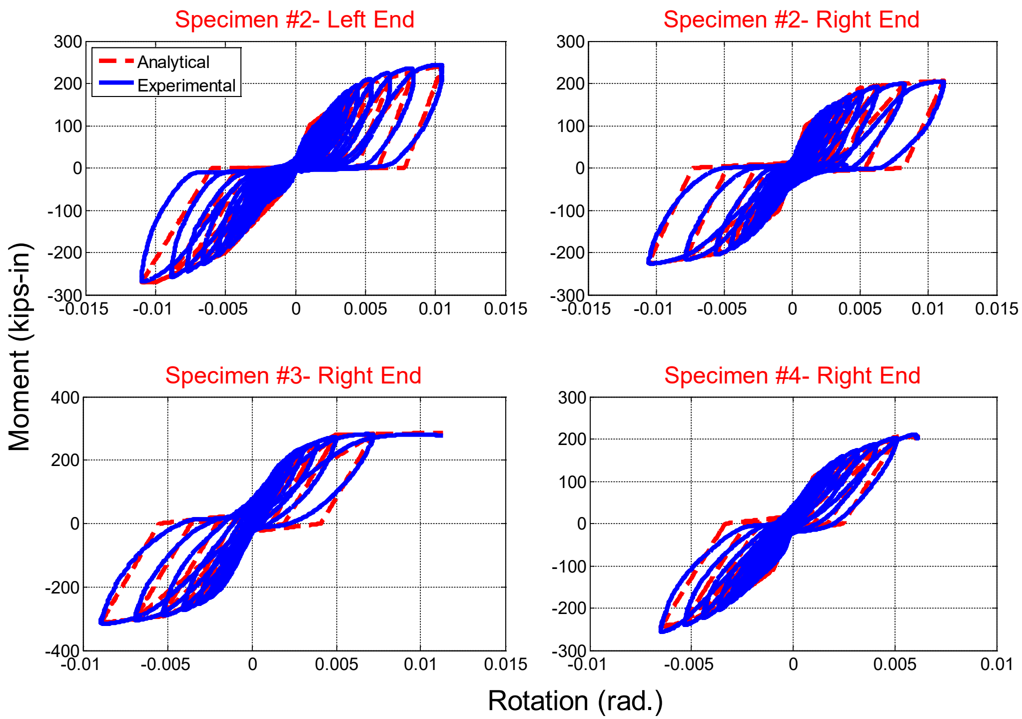


- Total number of 39 parameters were defined

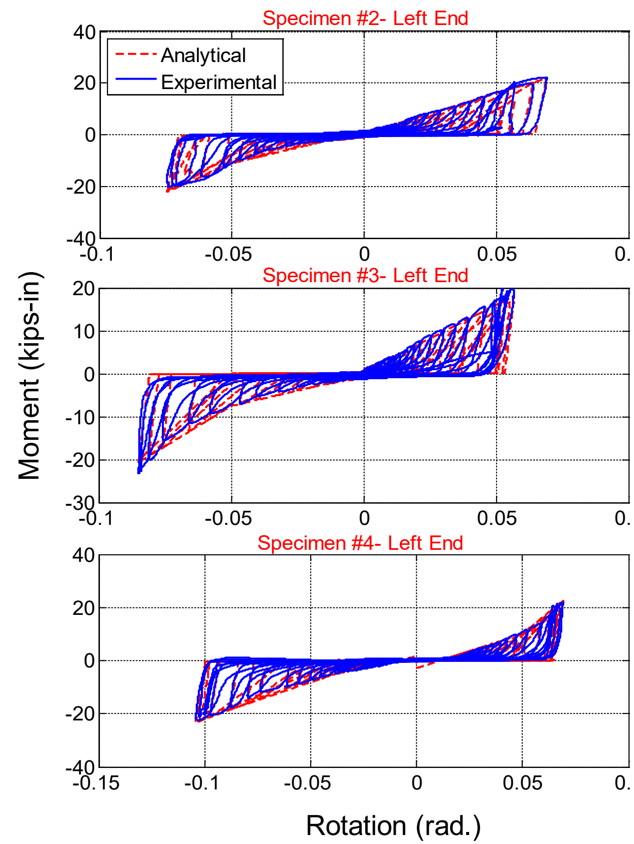
Validation of Analytical Model with Experimental Data for Pipe Tee Joint Components – Examples

- Total number of **29** joint components (Threaded/Grooved) were calibrated

Threaded (6 in.)

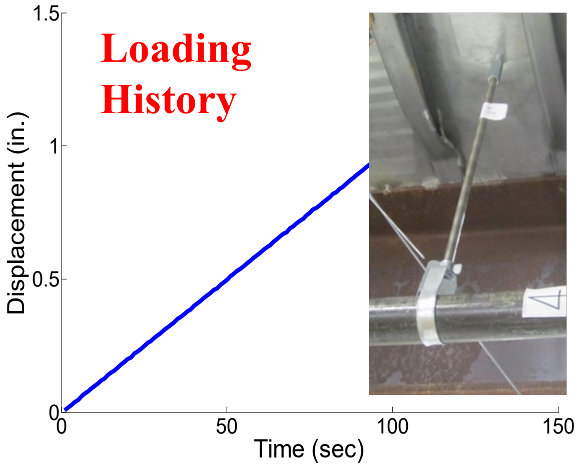


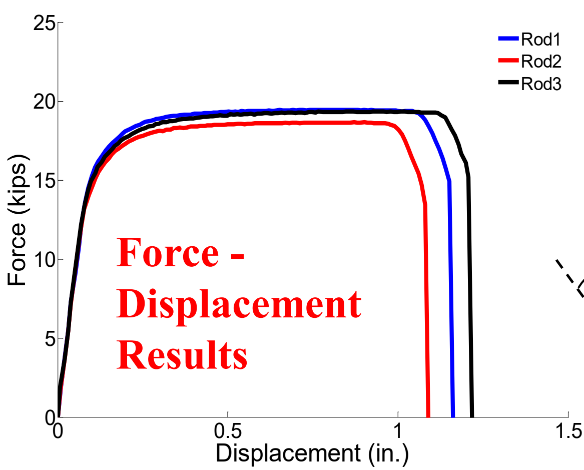
Grooved (2 in.)



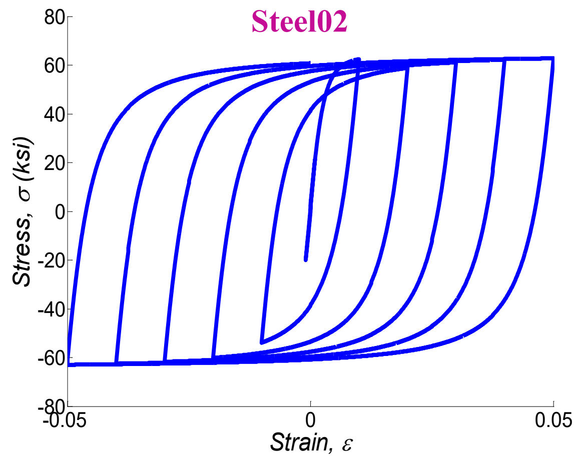
Generation of Analytical Model for Supporting Elements – Pipe Hangers

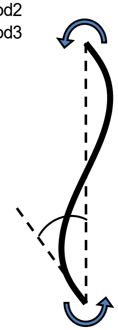
Threaded Rod Tests at the University of Nevada, Reno

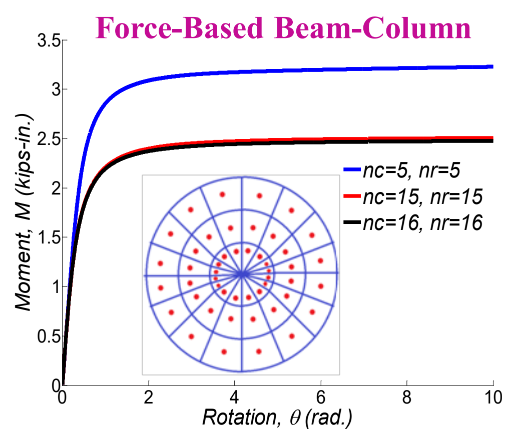




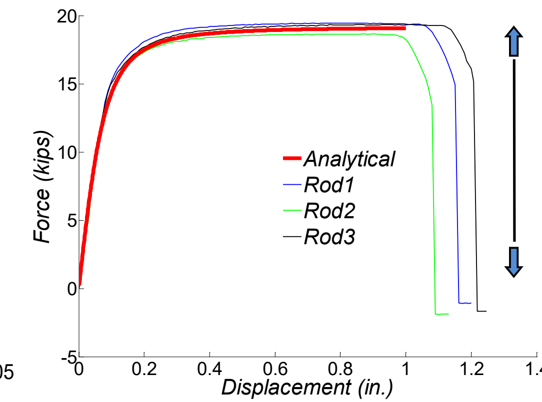
Analytical Model of Threaded Rods (OpenSees)

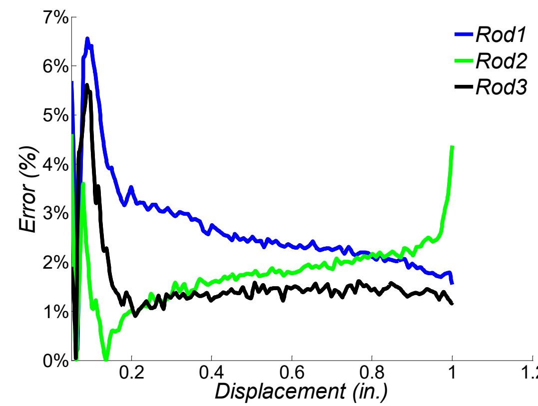






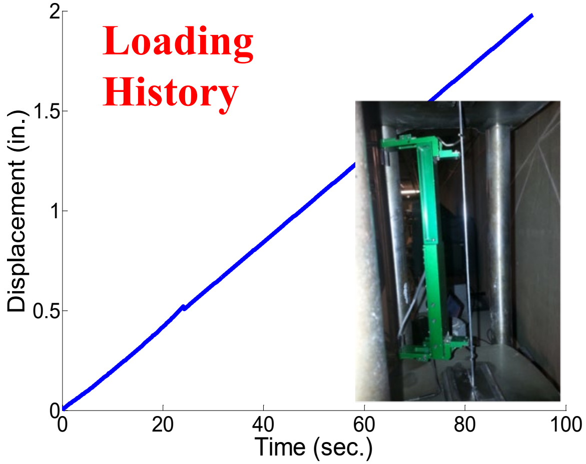
Calibration of Analytical Model for Threaded Rods

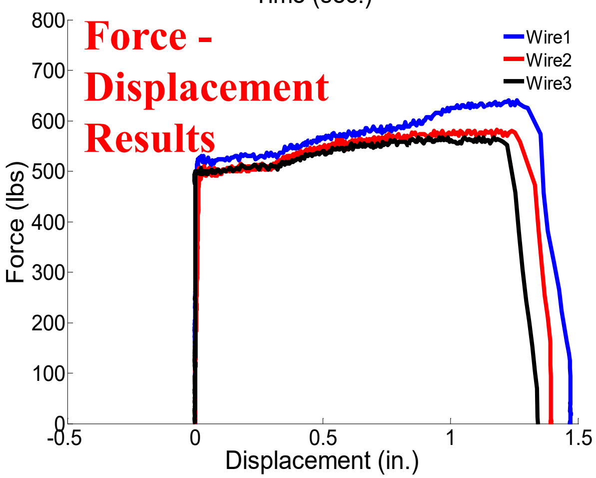




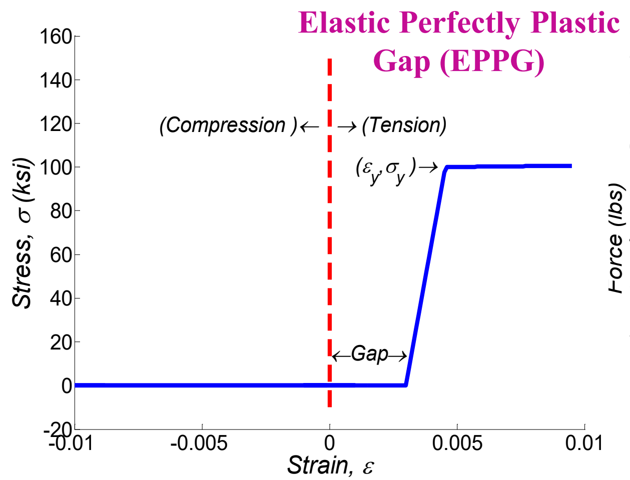
Generation of Analytical Model for Supporting Elements – Pipe Restrainers and Ceiling Hangers

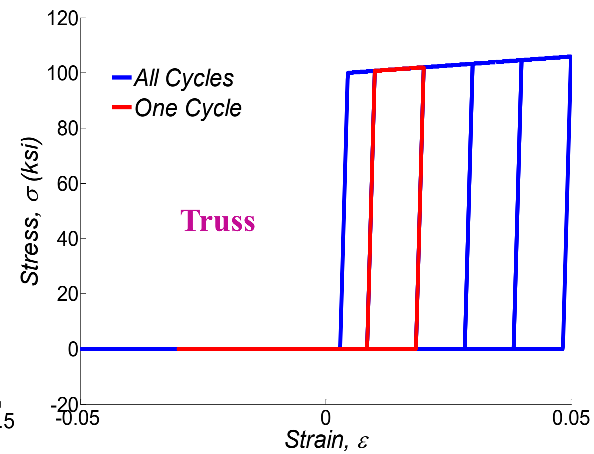
Wire Tests at the University of Nevada, Reno



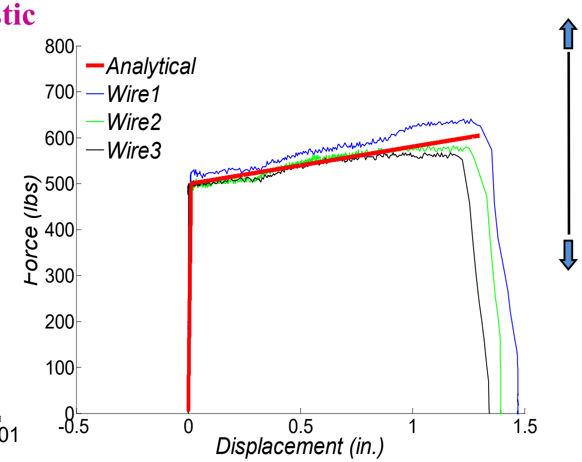


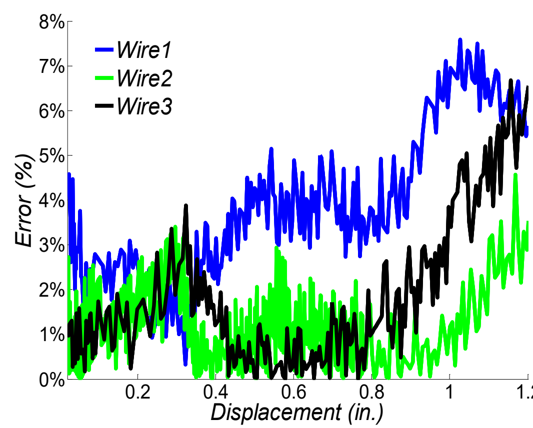
Analytical Model of Wires (OpenSees)





Calibration of Analytical Model for Wires

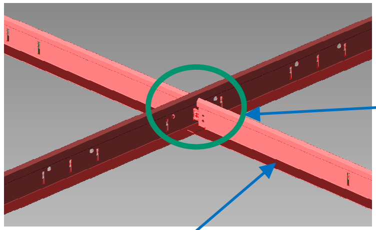




Host Institution Funded by

Analytical Model of Suspended Ceiling Systems

Grid Sections

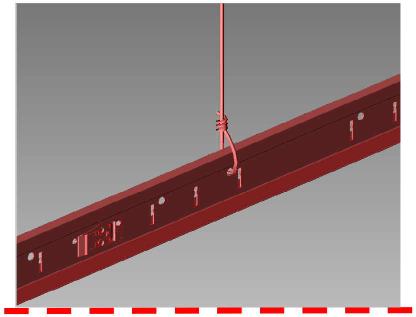


Grid Joints: Using Experimental Data

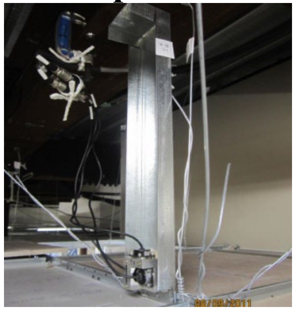
Grid Segments: Elastic Members with Cross Section Properties

Hangers and Braces

Ceiling Hangers and Diagonal Wires: Using Experimental Data

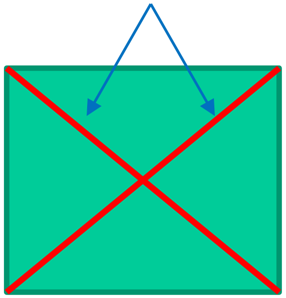


Compression Posts: Elastic Members with Cross Section Properties

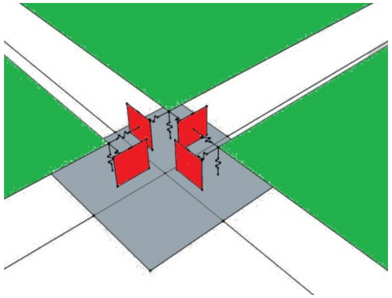


Panels

Ceiling Panels: X- Shape Rigid Link Assembly



Ceiling Panel Movement: 12 zeroLengthImpact3D Elements

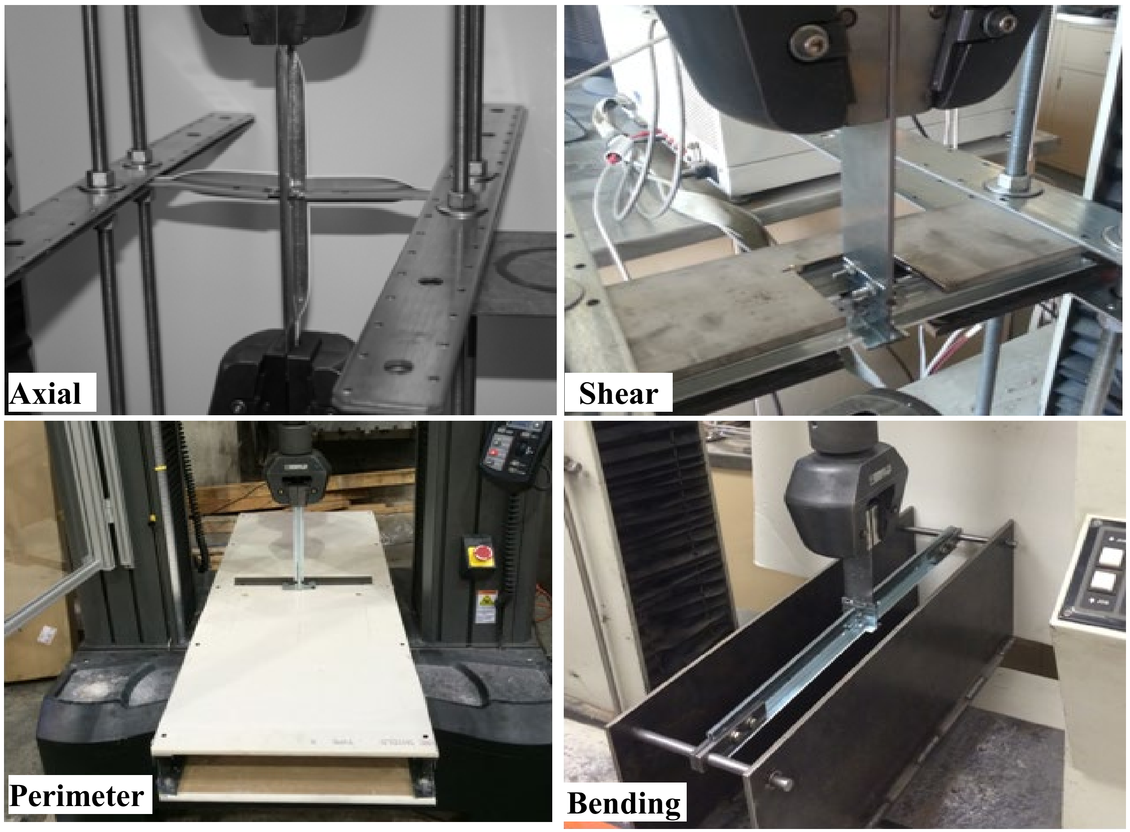


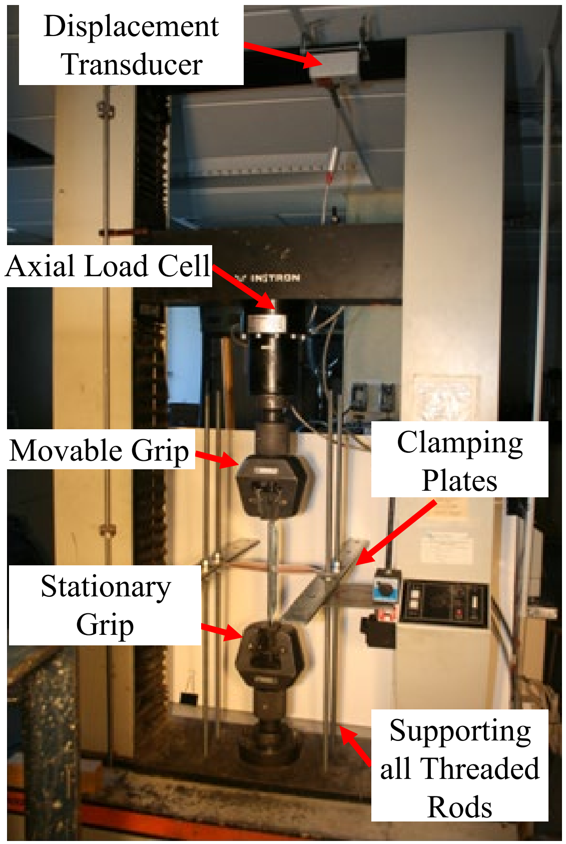
Panel/Sprinkler Interaction

Interactions: Using Experimental Data

Ceiling Joint Tests at the University of Nevada, Reno

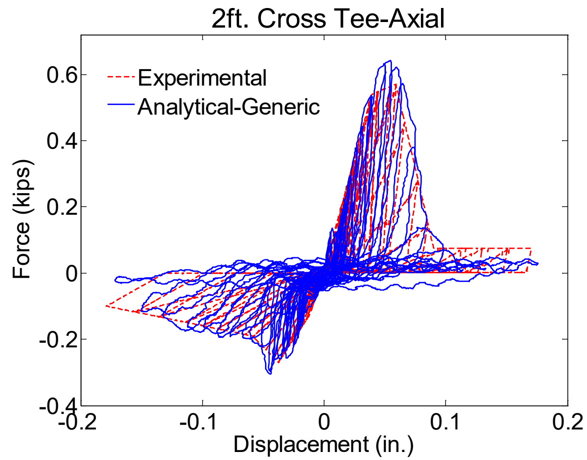
✓ More than 100 Ceiling Joint Specimens Tested Under Monotonic and Cyclic Loading

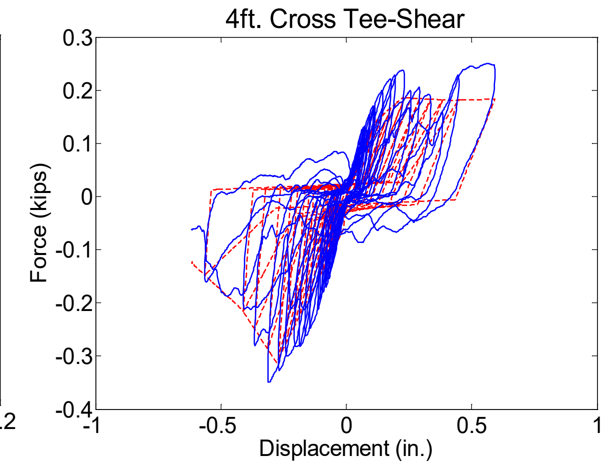


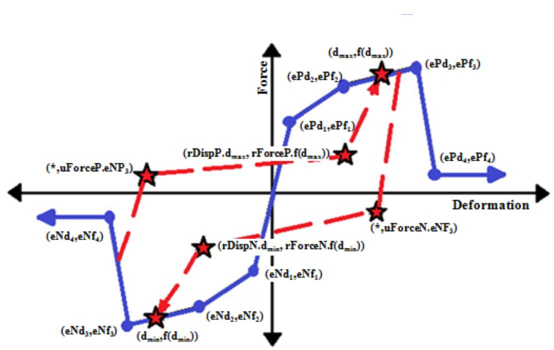


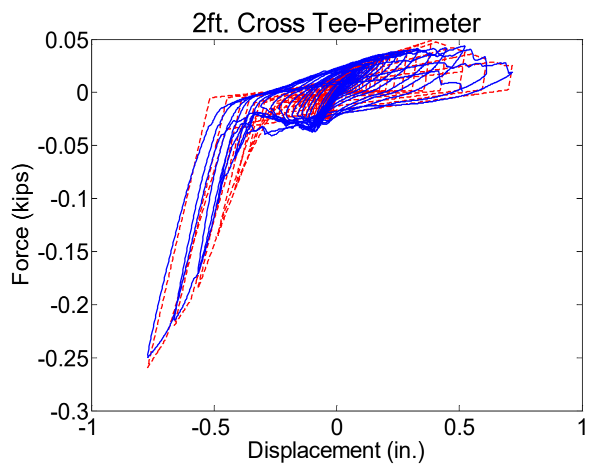
Development of an Analytical Model for Ceiling Joints

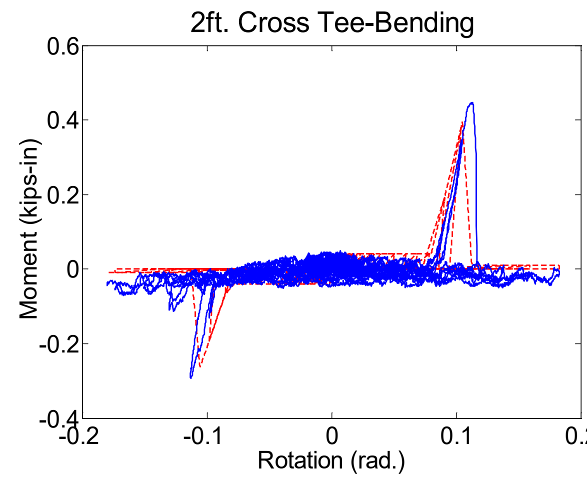
- The "Pinching4" uniaxial material along with a "zeroLength" element was used to simulate the force-displacement response of the joints (OpenSees)











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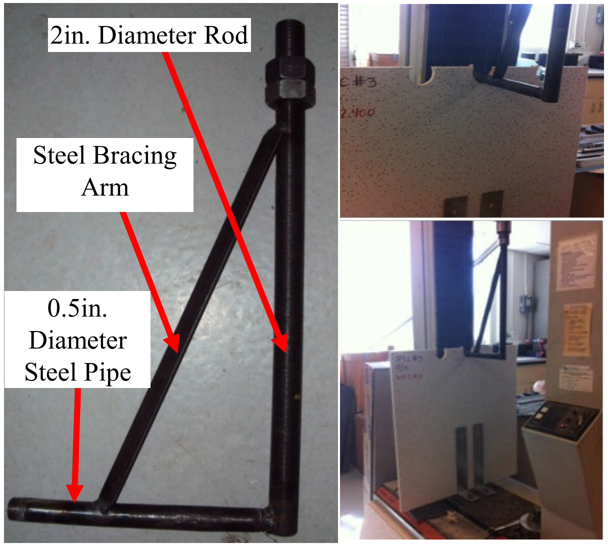
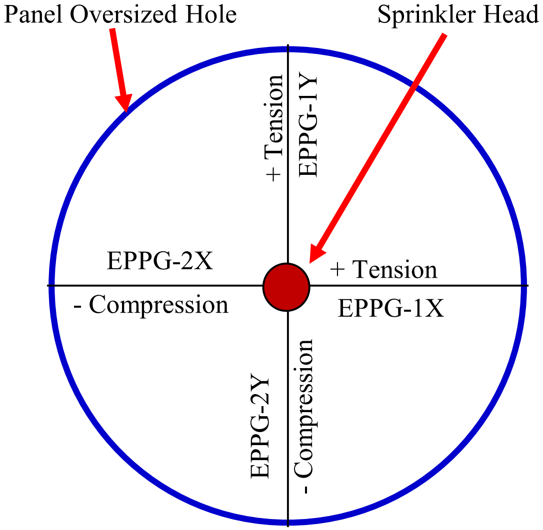
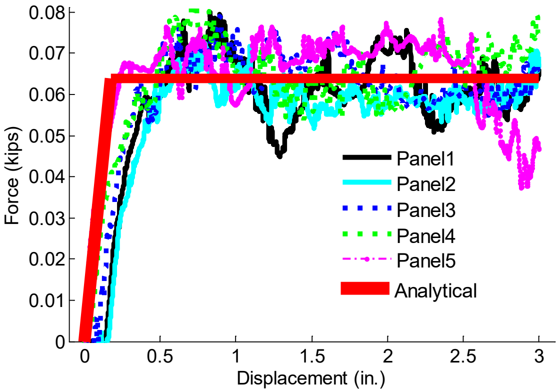
Generation of Analytical Model for Capturing Ceiling Panel-Sprinkler Head Interaction

Panel-Sprinkler Tests at the University of Nevada, Reno

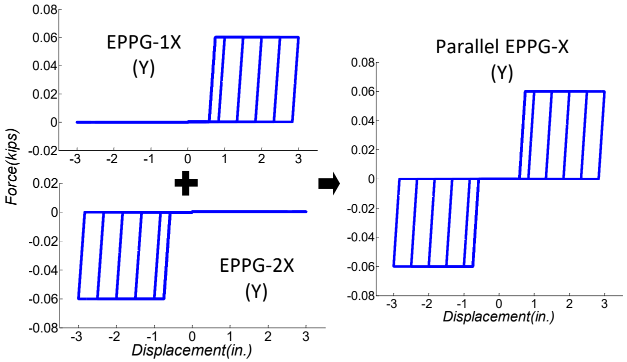




Elastic Perfectly Plastic Gap (EPPG) + zeroLengthElement



5 Monotonic Ceiling Panel-Sprinkler head Tests



NEES Nonstructural

Simulation of the Seismic Performance of Nonstructural Systems

Host Institution

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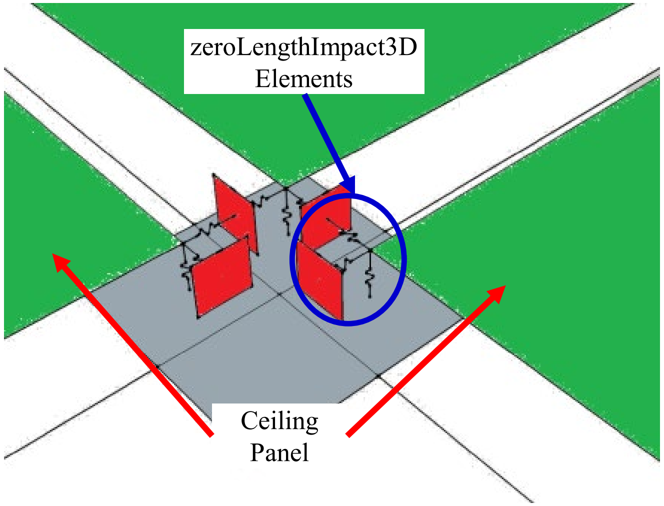
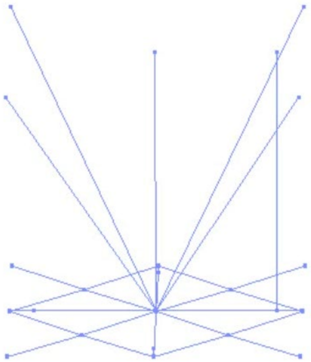
Generation of Analytical Model for Ceiling Panel Movement

- 12 zeroLengthImpact3D elements were used:
  - **Initial normal gap**
  - **In-plane friction transfer after gap closure**
  - **Energy dissipation due to impact (Hertz Model)**



Dancing of Ceiling Panels
(Example Provided by UCONN)

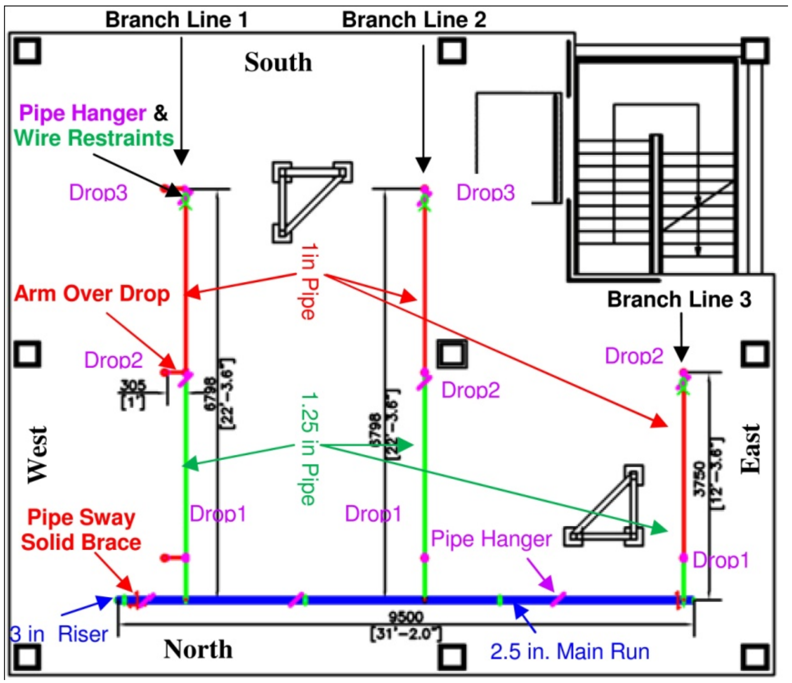


Location of CPP Nonstructural Systems

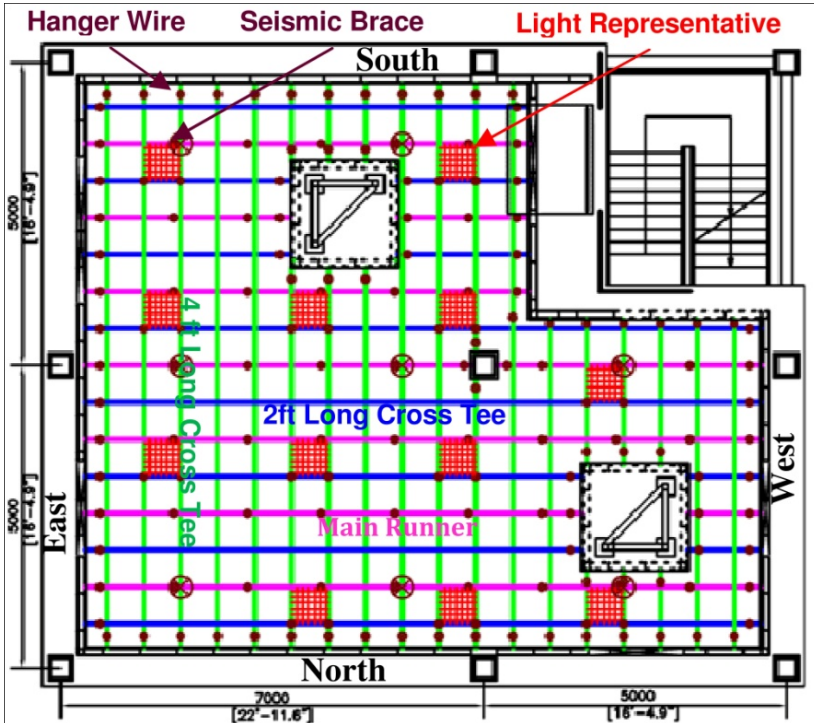
- Ceilings, Partition Walls, and Sprinkler Piping installed on 4th and 5th floors
- Nearly identical configurations over two complete floors

Suspended Ceiling and Sprinkler Piping Plan Views

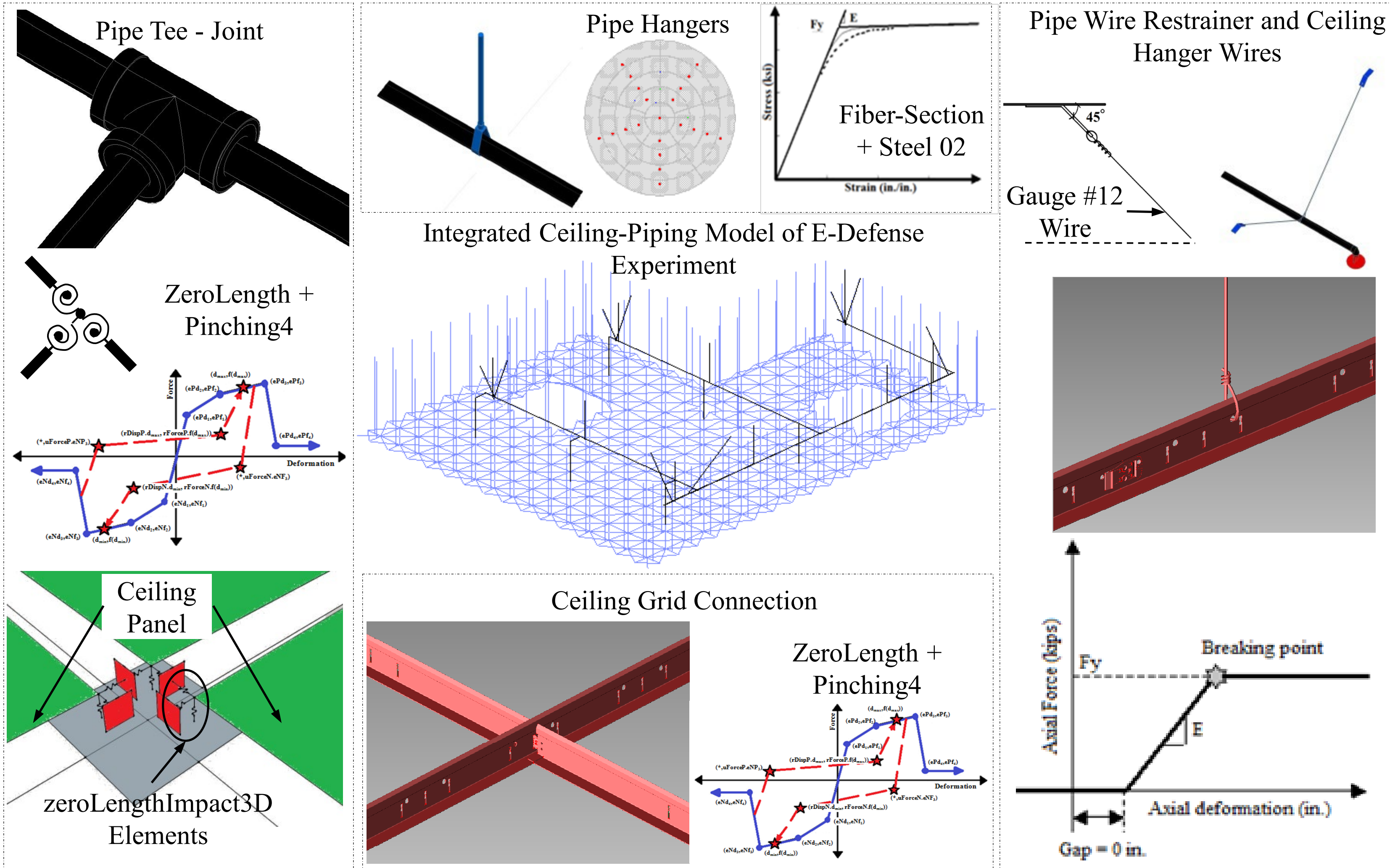
Fire Sprinkler Piping System



Suspended Ceiling System

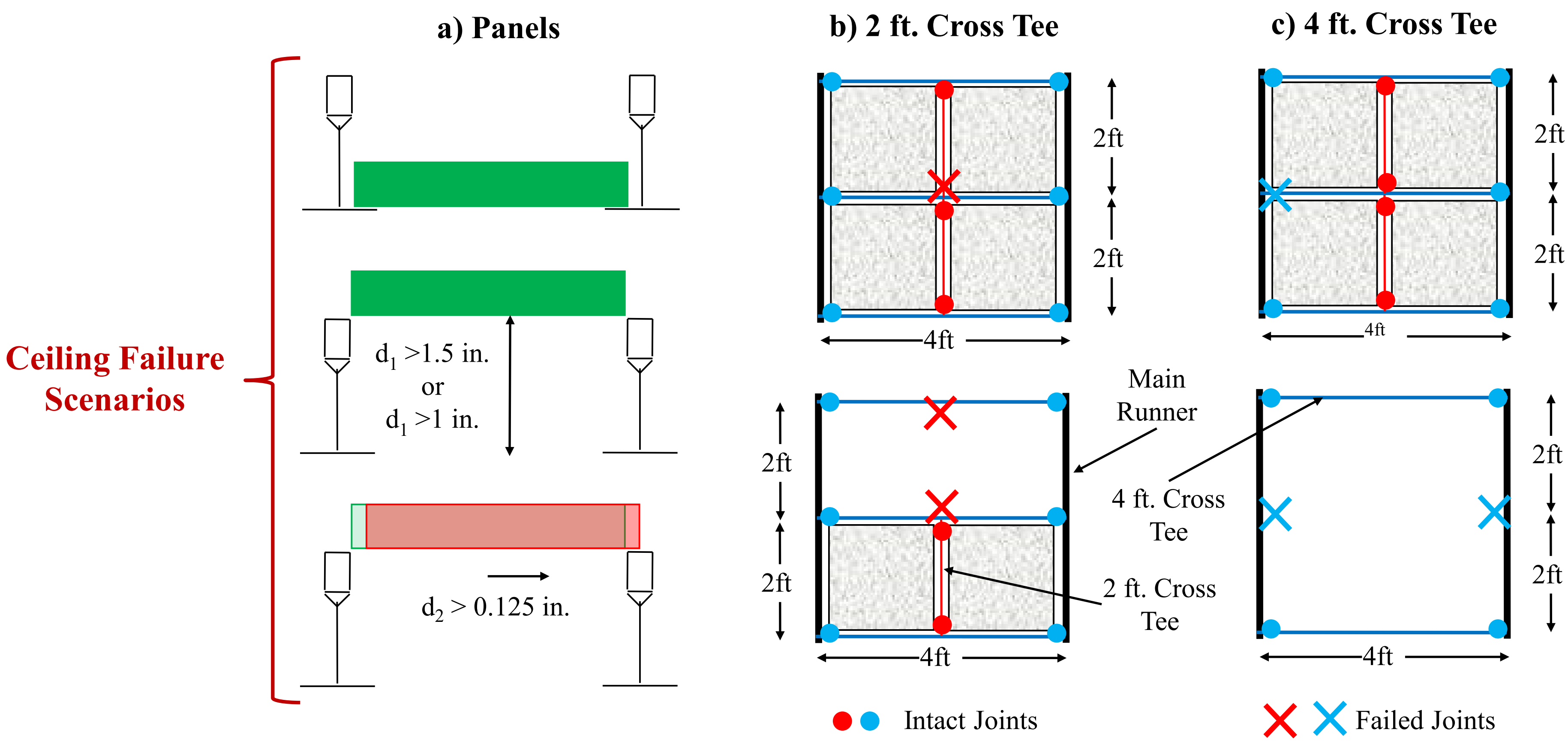


Integrated Analytical Model



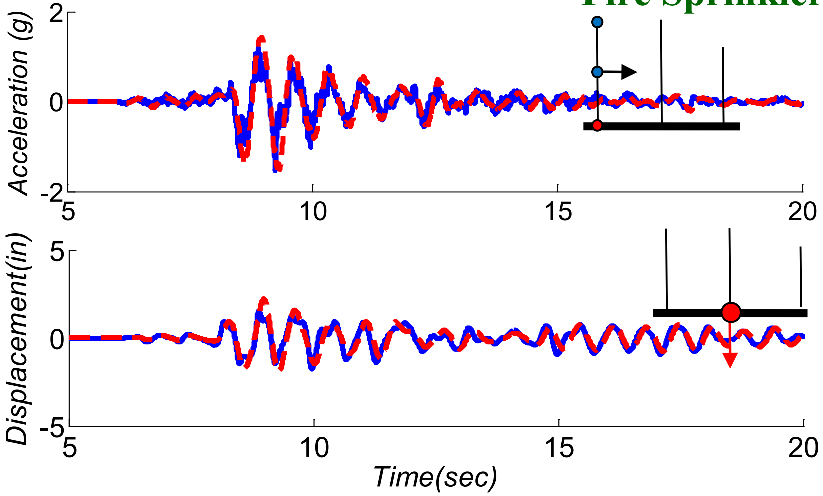
Remove Element Algorithms

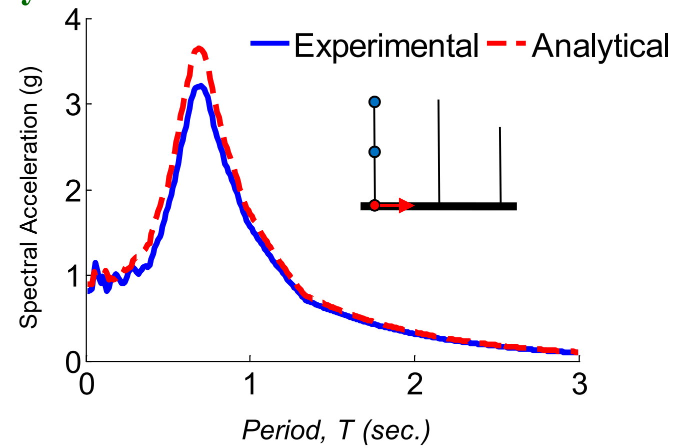
- **All of the ceiling and piping supporting elements were removed during the time history analysis when they reached their predefined capacity values.**



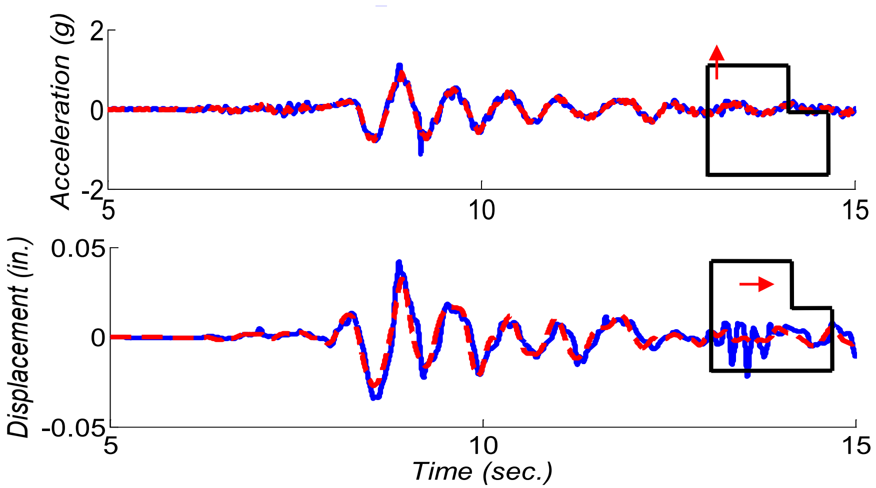
Validation of Integrated Analytical Models (35% RRS – Fixed Base)

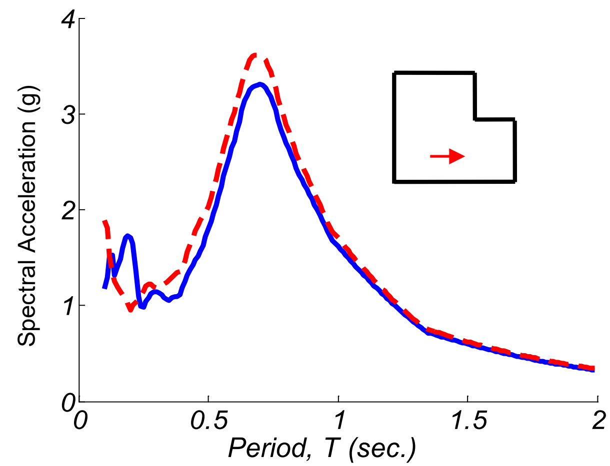
Fire Sprinkler Piping System



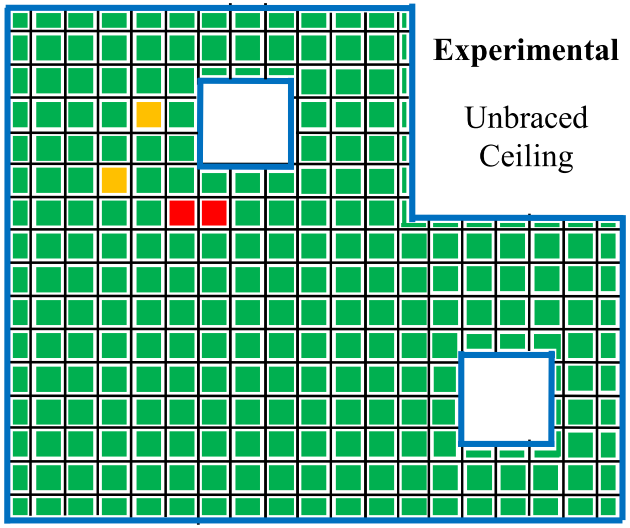


Suspended Ceiling System



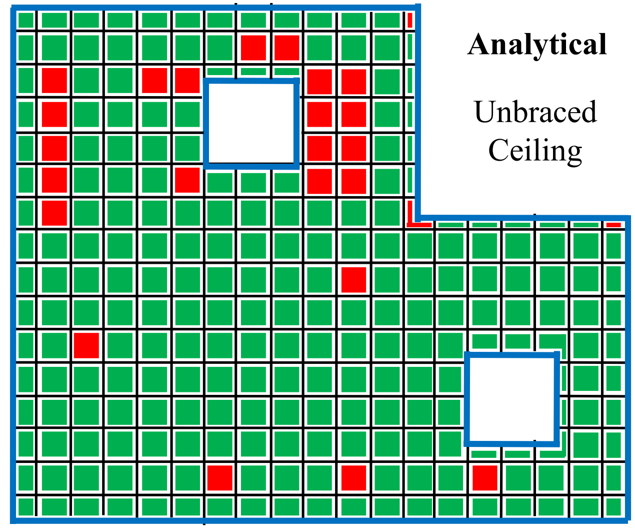


Pattern of Fallen Ceiling Panels (RRS35XY-88Z – Fixed Base)



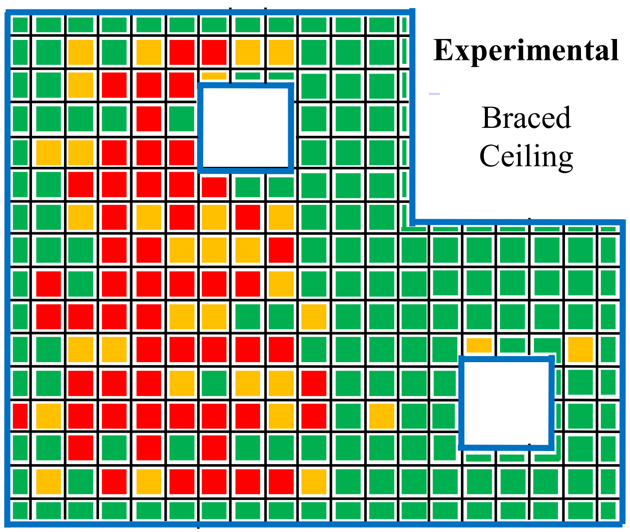
Experimental

Unbraced Ceiling



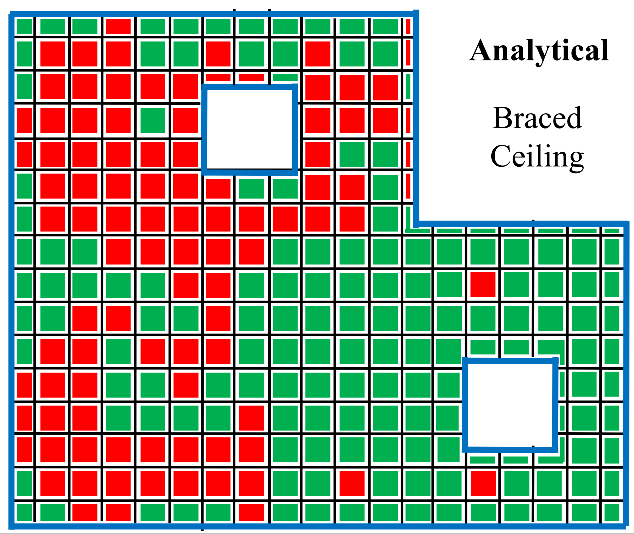
Analytical

Unbraced Ceiling



Experimental

Braced Ceiling



Analytical

Braced Ceiling

Misaligned ceiling panels

In-place ceiling panels

Fallen ceiling panels

Outline

- Introduction
- NEES Nonstructural Grand Challenge Project
- Experimental Studies (GC Projects)
- Analytical Studies
  - Previous Studies
  - Experimentally Integrated Studies
- **Future Directions**

Some Major Contributions

- Several component-level and two major system-level tests.
- Experimentally validated models for ceiling, piping., partition systems and integrated piping/ceiling systems.
- Development of fragility curves.
- Provided FEMAP-58 new fragility sets for partition and ceiling systems.
- Provided ASCE7 code modification on ceiling perimeter attachments

Research Areas that Need Improvements

- Crack mechanisms in partition gypsum boards.
- Out-of-plane behaviour of partition walls.
- Nonlinear bending response of partition studs.
- Torsional behaviour of pipe joints.
- Connection capacity of ceiling and piping supporting elements.
- Nonlinear behaviour of ceiling grid segments.
- Accurate model of ceiling panels.

Research Areas that Need Improvements

- **New Construction practices should be pursued**
- **Other non-structural elements need detailed research, e.g. HVAC systems, facads, stairs, equipment**
- **Building-dependent response spectra are needed**

Thank You!

NEES Nonstructural
Simulation of the Seismic Performance of Nonstructural Systems

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