Performance-based Seismic Design of Nonstructural Building Components: The Next Frontier of Earthquake Engineering

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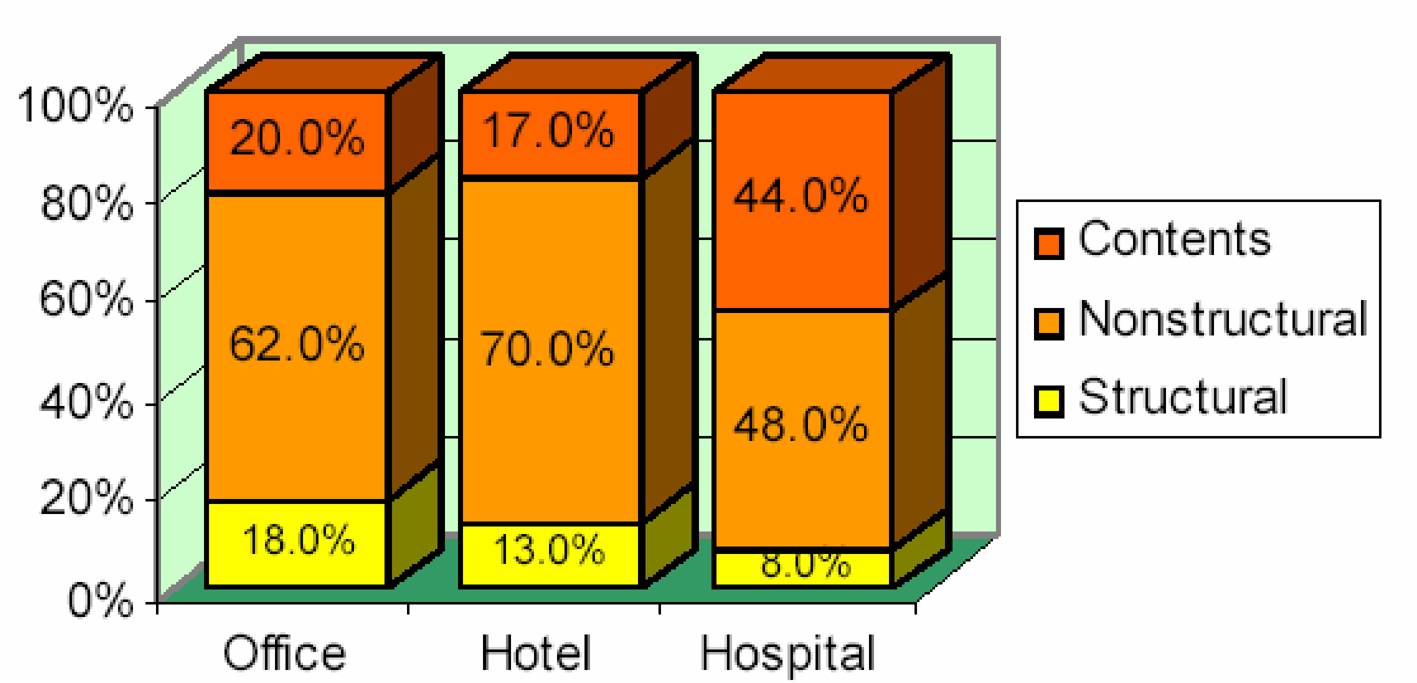
Importance of Considering Nonstructural Components in Seismic Design

- Nonstructural Components represent the major portion of the total investment in typical buildings.



Investments in building construction (Miranda 2003)

Importance of Considering Nonstructural Components in Seismic Design

- Nonstructural damage can limit severely the functionality of critical facilities, such as hospitals.

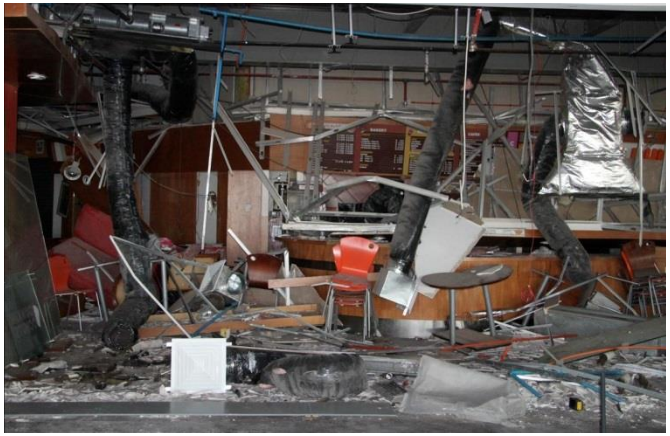
Emergency Room of Veteran Administration Hospital following the 1994 Northridge Earthquake in California

Importance of Considering Nonstructural Components in Seismic Design

- Failure of Nonstructural Components can become a safety hazard or can hamper the safe movement of occupants evacuating or of rescuers entering buildings.

Performance of Nonstructural Components in Recent Earthquakes

- 2010 Maule, Chile Earthquake
  - Impact of Nonstructural damage on airports
    - US$40 million for repairs of Nonstructural damage at SCL.
    - US$10 million loss to Lan Airlines.
    - Two thirds of the Chilean air traffic interrupted for several days.


Challenges Associated with the Seismic Design of Nonstructural Building Components

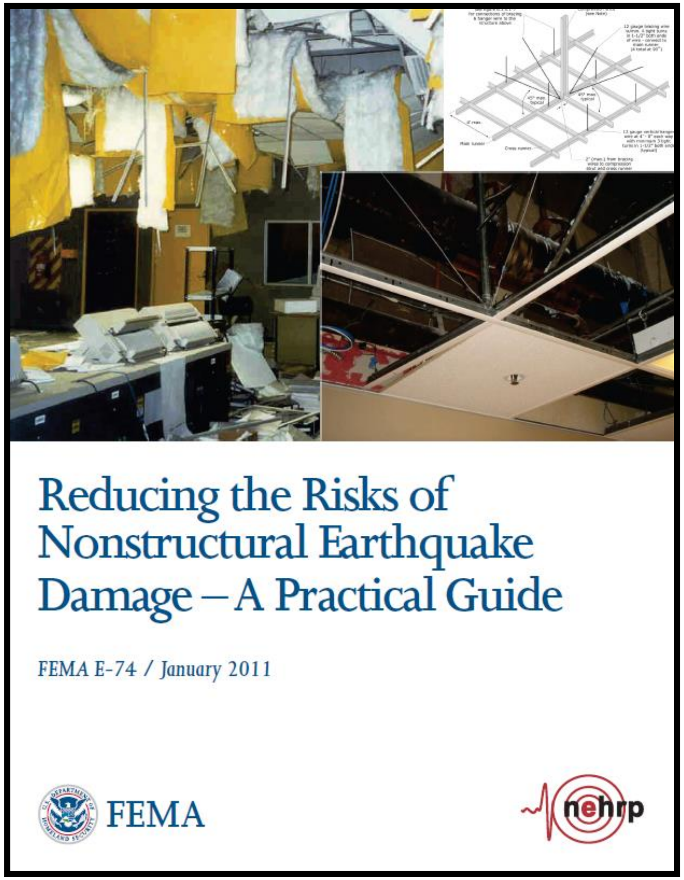
– Few information available giving specific guidance on the seismic design of nonstructural building components for multiple-performance levels.

– Limited basic research results available.

- Empirical seismic regulations and guidelines for Nonstructural Components.
- Design information for the most part is based on judgment and intuition rather than on experimental and analytical results.

The FEMA E-74 Methodology

- Intended Audience:
  - Non-engineer audience located within the US.
  - Design professionals not experienced with the seismic protection of nonstructural components.
- Main Objectives:
  - Explain the sources of nonstructural earthquake damage.
  - Describe methods for reducing the potential risks in simple terms.



Available free online at:
http://www.fema.gov/library/viewRecord.do?id=4626

The FEMA E-74 Methodology

- Retrofit/Design Methods
  - Non-Engineered Design

    - Mitigation details that do not require engineering design.
  - Prescriptive Design
    - Relies on published standards for specific types of Nonstructural Components without the need for an engineer.

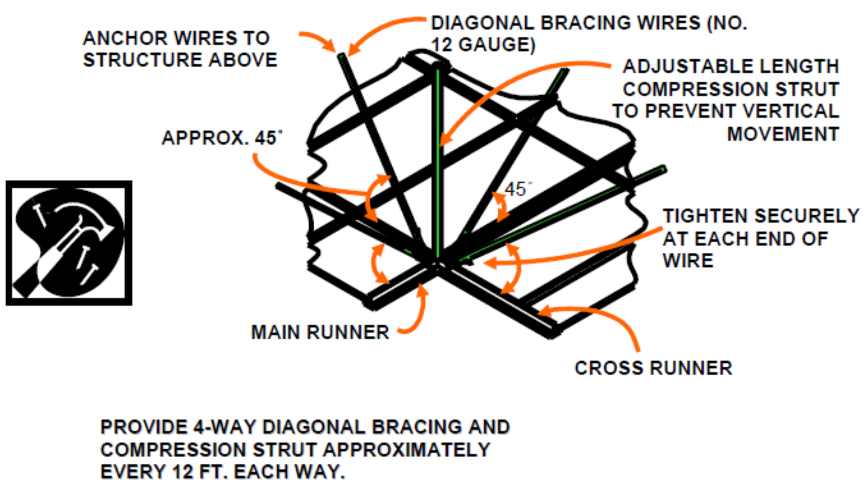
  - Engineering Design
    - Relies on building codes and standards and requires design by an engineer.

The FEMA E-74 Methodology

- Retrofit/Design Methods
  - Prescriptive Design

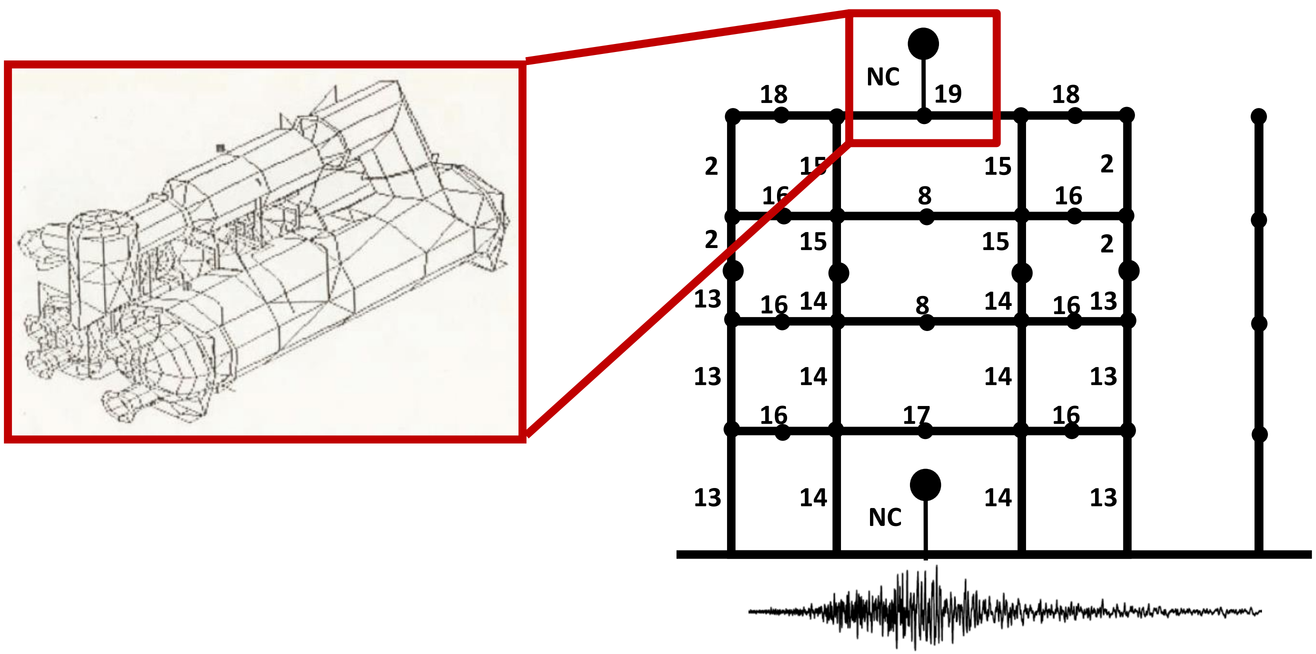
Ceilings (acoustic tile, gypsumboard, plaster)

- ☐ Does the suspended ceiling have adequate diagonal bracing wires and compression struts?
- ☐ Are decorative ceiling panels and/or latticework securely attached?
- ☐ For plaster ceilings, is the wire mesh or wood lath securely attached to the structural framing above?
- ☐ Are partitions and lighting restrained independently and do not rely on the ceiling to provide lateral support?



Direct and Cascading Analysis Methods

- Direct Analysis Method
  - Modeling of structural and Nonstructural Components.
  - Ground input motions.

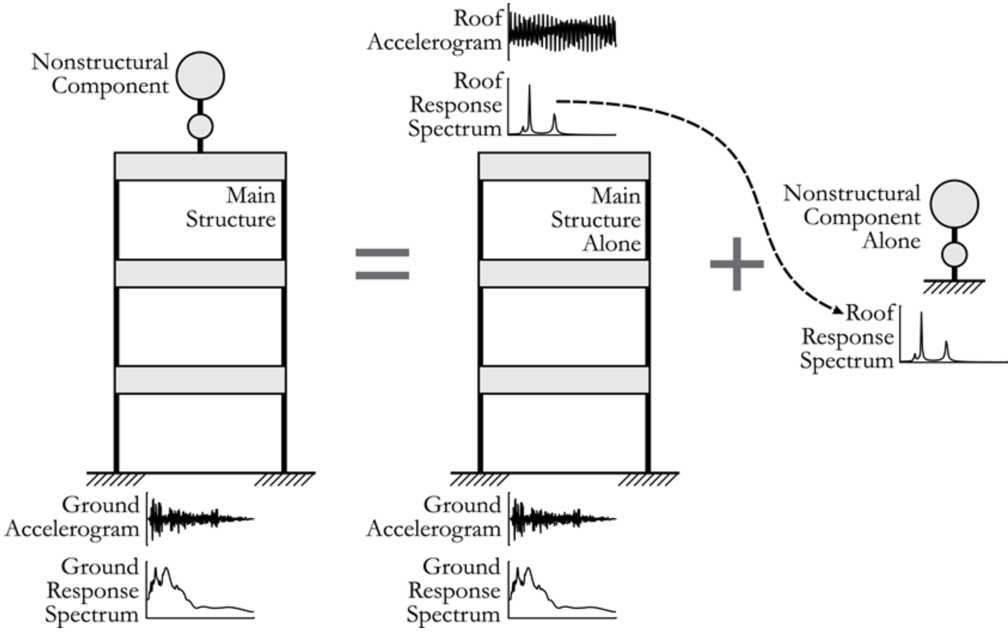


Direct and Cascading Analysis Methods

- Challenges with Direct Analysis Method
  - Differences in order of magnitudes of properties of structural and Nonstructural Components often makes numerical models ill-conditioned.
  - Natural frequencies of Nonstructural Components can coincide with natural frequencies of the structure causing closely spaced modes and highly correlated modal responses.
  - Non-classical damping modes.
  - Structural system and the Nonstructural Components typically not selected and designed at the same time in a construction project making a combined analysis difficult from a scheduling point of view.
  - Limited application to very simple Nonstructural building Components.

Direct and Cascading Analysis Methods

- Floor Response Spectrum (FRS) Method
  - First obtain the response spectrum at the location in the structure where a Nonstructural element is attached (the floor response spectrum) and then using this spectrum to estimate its seismic response.

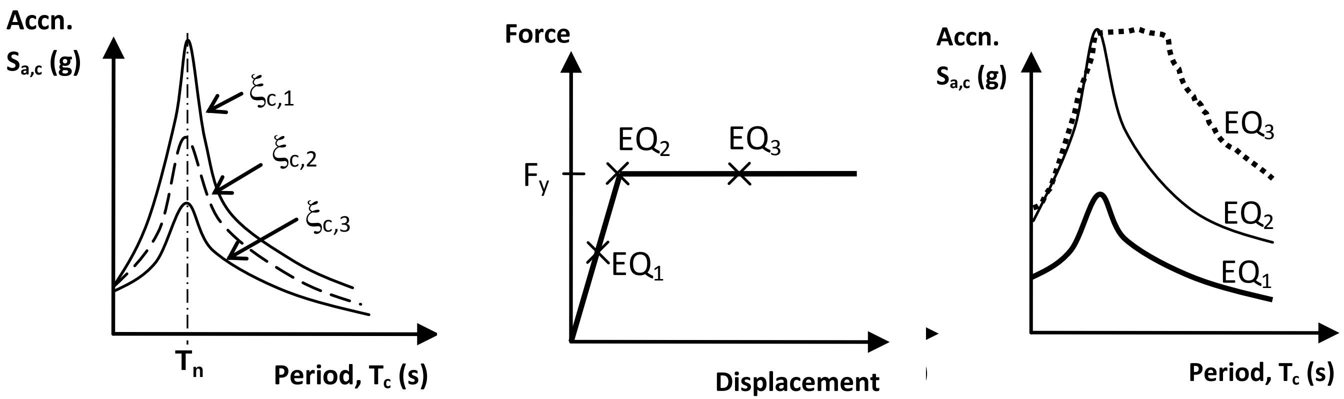


Direct and Cascading Analysis Methods

- Generation of a Floor Response Spectrum
  - Conduct a dynamic analysis of the structure by itself under a ground motion to calculate the horizontal acceleration time-history of the floor on which the Nonstructural element is attached.
  - Compute the response spectrum of this floor acceleration to obtain the floor response spectrum.
  - If a simplified floor design spectrum needs to be constructed for a given structure, then the process needs to be repeated for an ensemble of ground motions representative of the selected design seismic hazard level at the construction site.

Direct and Cascading Analysis Methods

- Generation of a Floor Response Spectrum
  - Direct generation of floor response spectrum using approximate methods.
  - Recent procedure proposed by Sullivan et al. (2013); Calvi et al. (2014):
    - Consider effects of:
      - Dynamic filtering; Elastic damping; Earthquake intensity



Seismic Design Requirements for Nonstructural Building Components in Europe

- Equivalent Static Design Forces
  - Horizontal equivalent static design forces, F_a, to be applied at the element’s center of gravity:

$$F_a = \frac{\alpha S}{\left(\frac{q_a}{\gamma_a}\right)}\left[3\frac{\left(1+\frac{z}{H}\right)}{\left(1+\left(1-\frac{T_a}{T_1}\right)^2\right)}-0.5\right]W_a$$

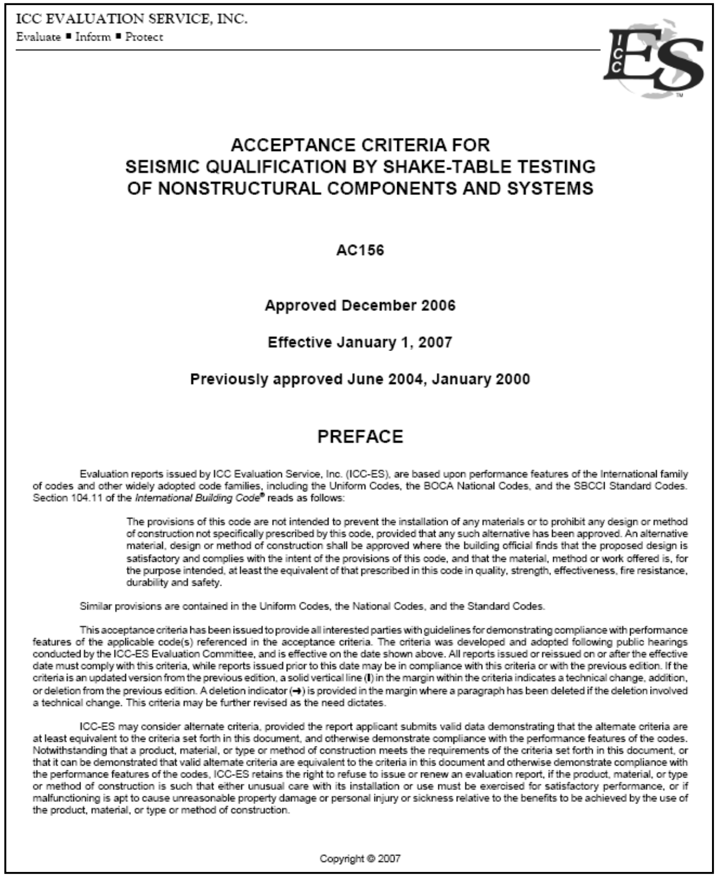
W_a = Weight of the element.
α = Design ground acceleration ratio.
S = Soil factor.
T_a = Fundamental period of the element.
T_1 = Fundamental period of the building.
z = Height of the element above the base.
H = Building height from the base.
γ_a = Importance factor of the element.
q_a = Behavior factor of the element.

Seismic Qualification Testing of Nonstructural Components

- Special seismic qualification requirements for designated seismic systems included in Chapter 13 of ASCE 7-10 Standard in the United States.
  - A designated seismic system is a Nonstructural element with an importance factor $I_p = 1.5$ that is required to remain functional after a design earthquake.
- Three possible qualification methods:
  - Analysis (difficult)
  - Experience Data (limited data available)
  - Testing (easy but can be expensive)

Seismic Qualification Testing of Nonstructural Components

- ICC-ES AC-156 Test Protocol
  - Referred by Section 13.2 of ASCE 7-10
  - Components with fundamental frequencies ≥ 1.3 Hz
  - Post-test functional verification:
    - I_p = 1.0: Life Safety
    - I_p = 1.5: Continued Operation
  - To be converted into an ASCE Standard.



ICC EVALUATION SERVICE, INC.
Evaluate ▪ Inform ▪ Protect

ACCEPTANCE CRITERIA FOR
SEISMIC QUALIFICATION BY SHAKE-TABLE TESTING
OF NONSTRUCTURAL COMPONENTS AND SYSTEMS

AC156

Approved December 2006

Effective January 1, 2007

Previously approved June 2004, January 2000

PREFACE

Evaluation reports issued by ICC Evaluation Service, Inc. (ICC-ES), are based upon performance features of the International family of codes and other widely adopted code families, including the Uniform Codes, the BOCA National Codes, and the SBCCI Standard Codes. Section 104.11 of the *International Building Code®* reads as follows:

> The provisions of this code are not intended to prevent the installation of any materials or to prohibit any design or method of construction not specifically prescribed by this code, provided that any such alternative has been approved. An alternative material, design or method of construction shall be approved where the building official finds that the proposed design is satisfactory and complies with the intent of the provisions of this code, and that the material, method or work offered is, for the purpose intended, at least the equivalent of that prescribed in this code in quality, strength, effectiveness, fire resistance, durability and safety.

Similar provisions are contained in the Uniform Codes, the National Codes, and the Standard Codes.

This acceptance criteria has been issued to provide all interested parties with guidelines for demonstrating compliance with performance features of the applicable code(s) referenced in the acceptance criteria. The criteria was developed and adopted following public hearings conducted by the ICC-ES Evaluation Committee, and is effective on the date shown above. All reports issued or reissued on or after the effective date must comply with this criteria, while reports issued prior to this date may be in compliance with this criteria or with the previous edition. If the criteria is an updated version from the previous edition, a solid vertical line (I) in the margin within the criteria indicates a technical change, addition, or deletion from the previous edition. A deletion indicator (➜) is provided in the margin where a paragraph has been deleted if the deletion involved a technical change. This criteria may be further revised as the need dictates.

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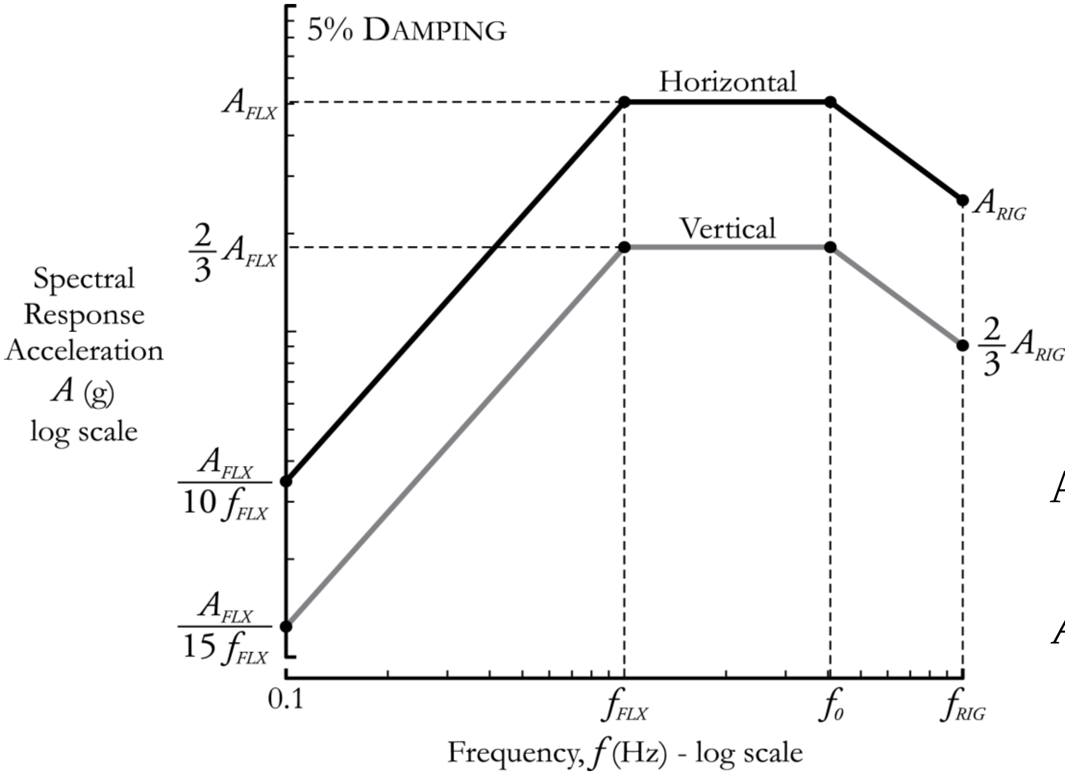
Seismic Qualification Testing of Nonstructural Components

- ICC-ES AC-156 Required Response Spectrum (RRS)

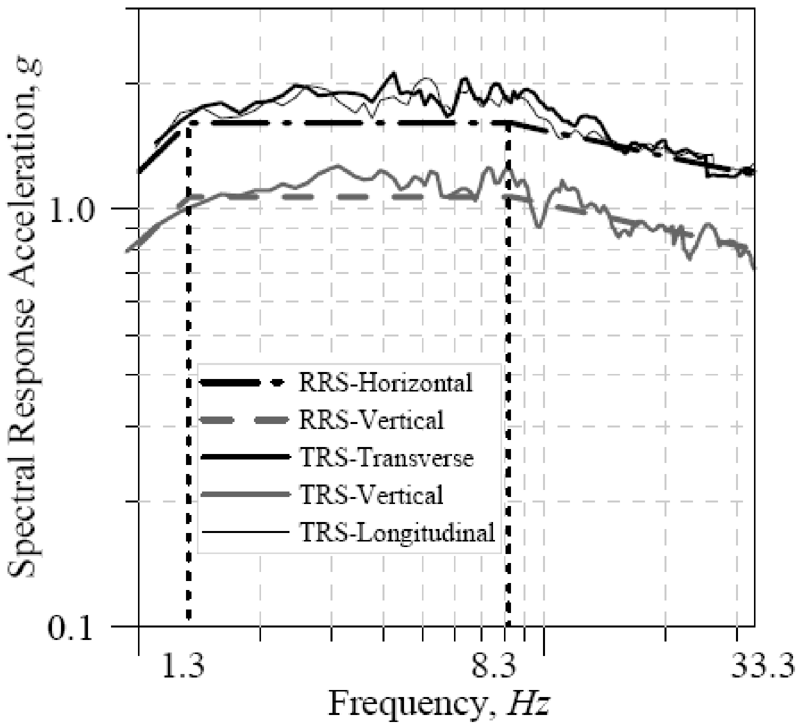


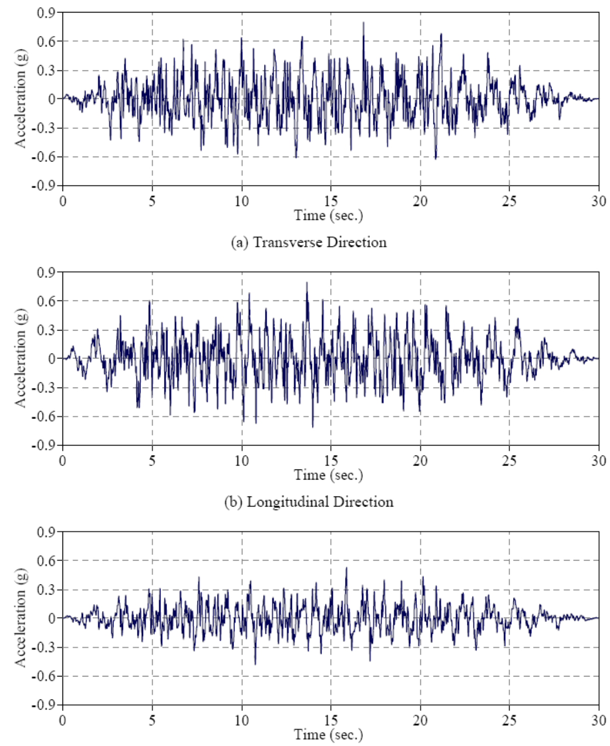
$$A_{RIG} = 0.4 S_{DS}\left(1 + 2\frac{z}{h}\right)$$

$$A_{FLX} = S_{DS}\left(1 + 2\frac{z}{h}\right)$$

Seismic Qualification Testing of Nonstructural Components

- ICC-ES AC-156 Test Input Motions





Seismic Qualification Testing of Nonstructural Components

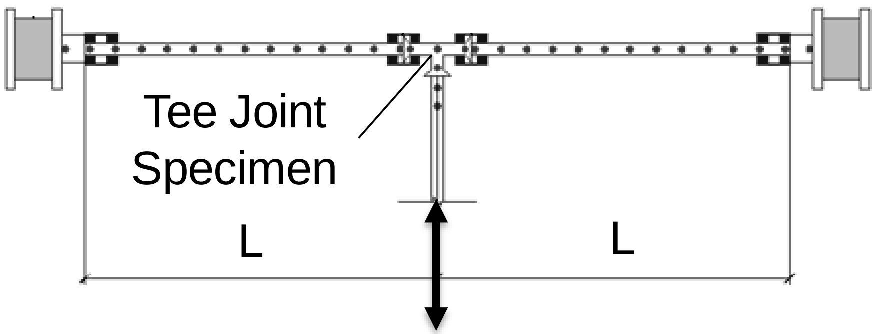
- ICC-ES AC-156 Qualification of Suspended Ceilings

Use of Advanced Technologies

- Seismic Isolation of Steel Storage Racks

Seismic Fragility Analysis of Sprinkler Piping Systems: A Case Study

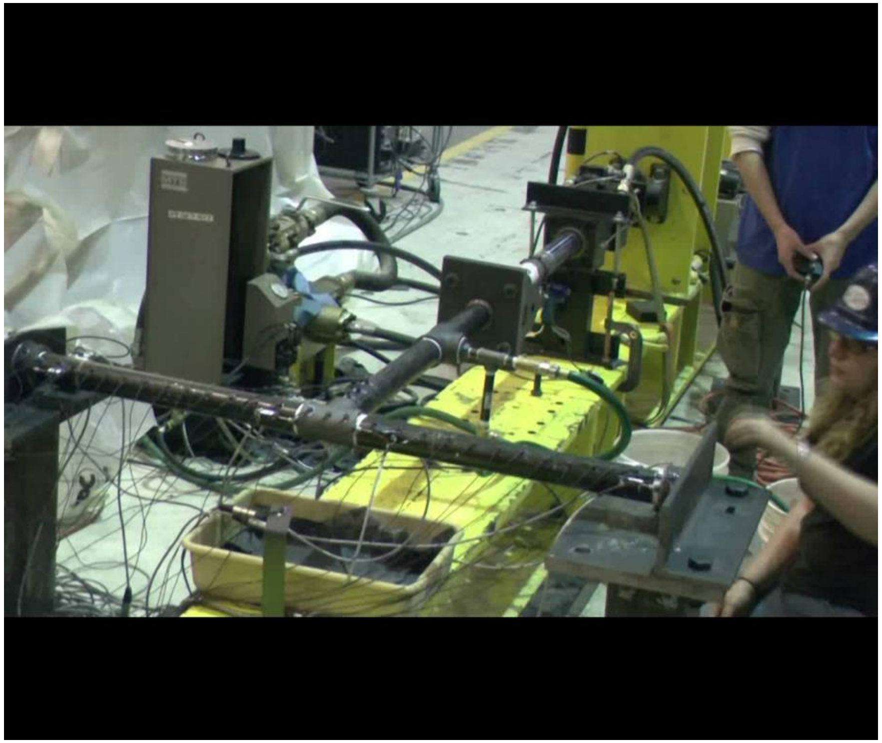
1. Cyclic testing of sprinkler piping joints



Black iron with threaded joints

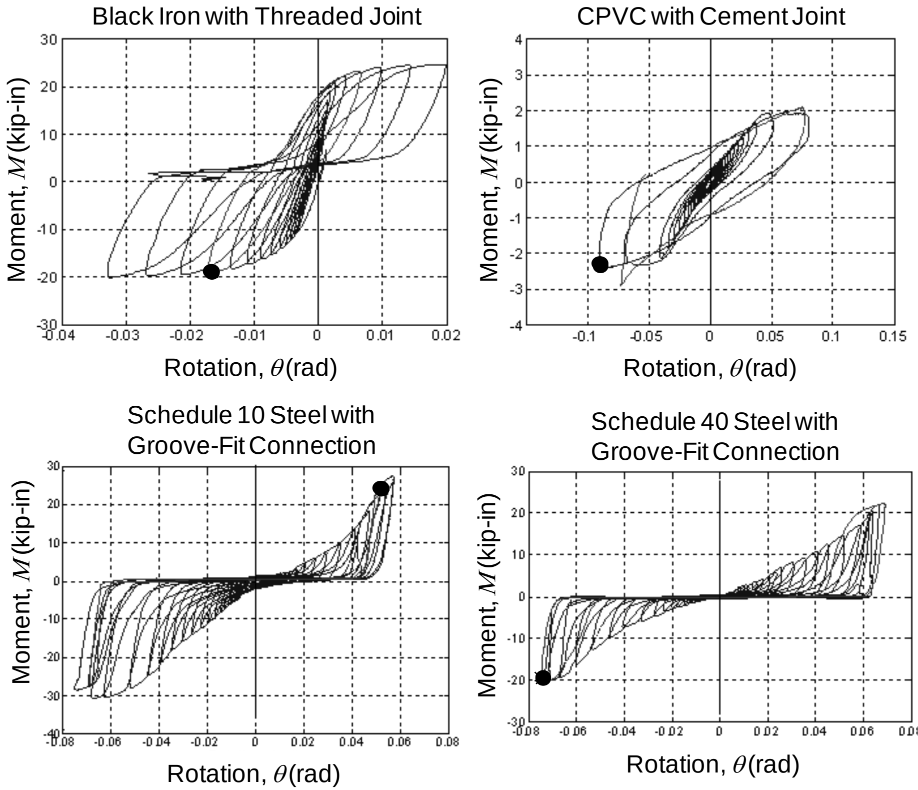
CPVC with cement joints

Steel with grooved joints



Seismic Fragility Analysis of Sprinkler Piping Systems: A Case Study

1. Cyclic testing of sprinkler piping joints
   – Cyclic response – 50 mm (2 in.) diameter pipes

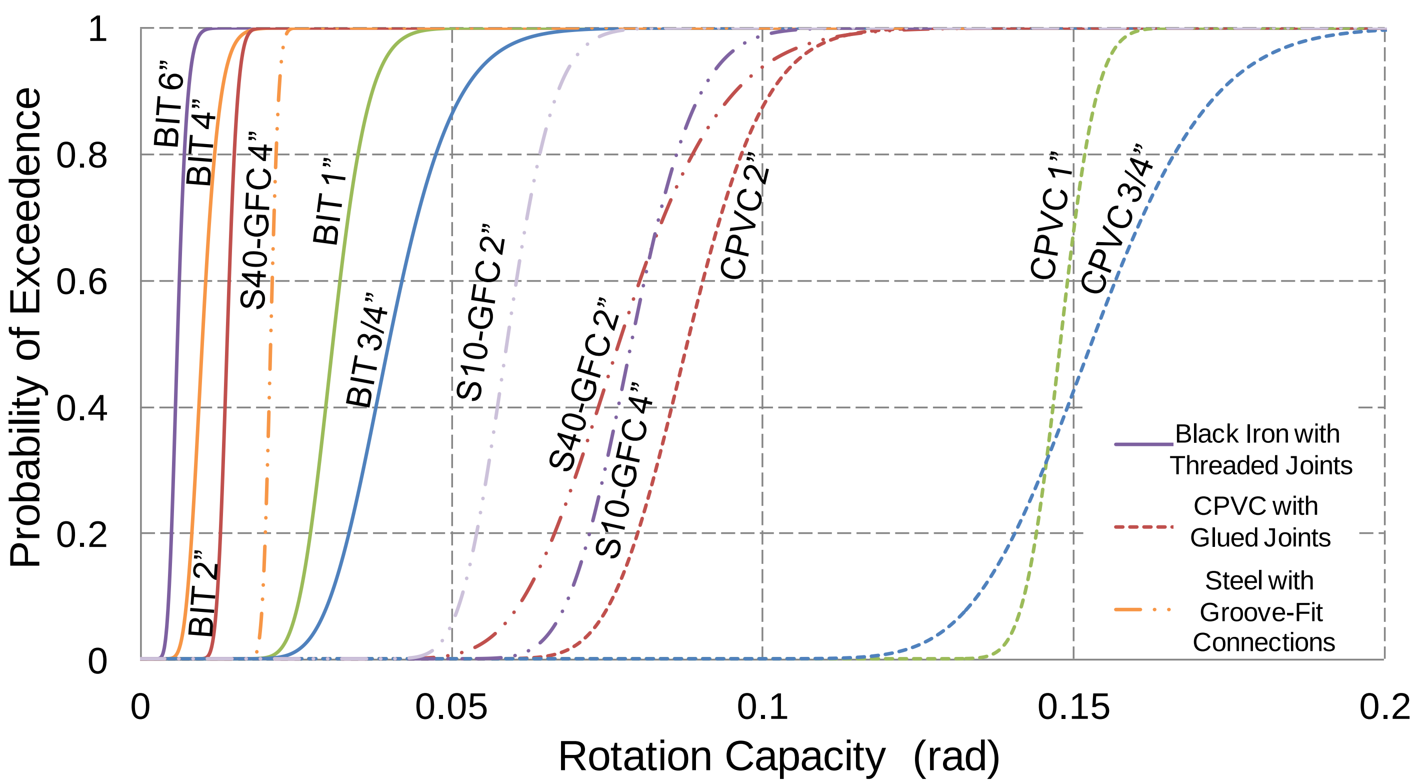


- First leakage

Note:
1 in. = 25.4 mm
1 kip = 4.45 kN

Seismic Fragility Analysis of Sprinkler Piping Systems: A Case Study

2. Fragility analysis of sprinkler piping joints

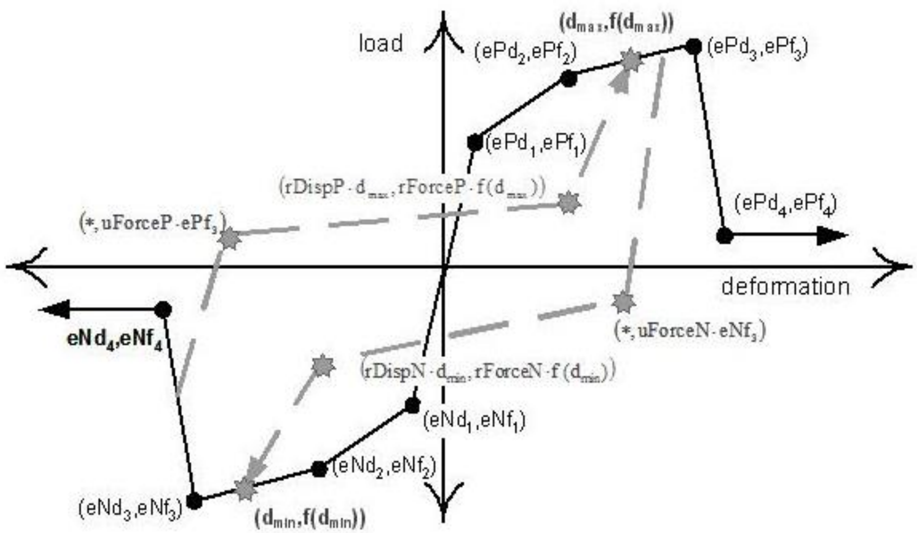


Note:
1 in. = 25.4 mm

BIT: Black Iron Threaded, CPVC: Thermoplastic, S10-GFC: Schedule 10 Groove-Fit, S40-GFC: Schedule 40 Groove-Fit.

Seismic Fragility Analysis of Sprinkler Piping Systems: A Case Study

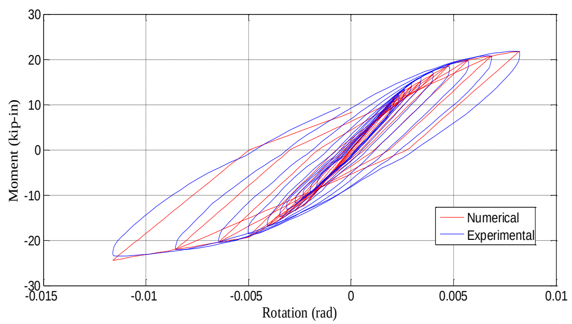
3. Hysteretic modeling of sprinkler piping joints
   - Pinching4 Material Model (OpenSees)
   - 36 parameters for definition



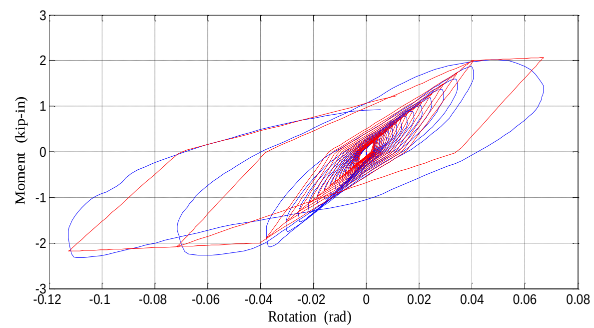
Seismic Fragility Analysis of Sprinkler Piping Systems: A Case Study

3. Hysteretic modeling of sprinkler piping joints

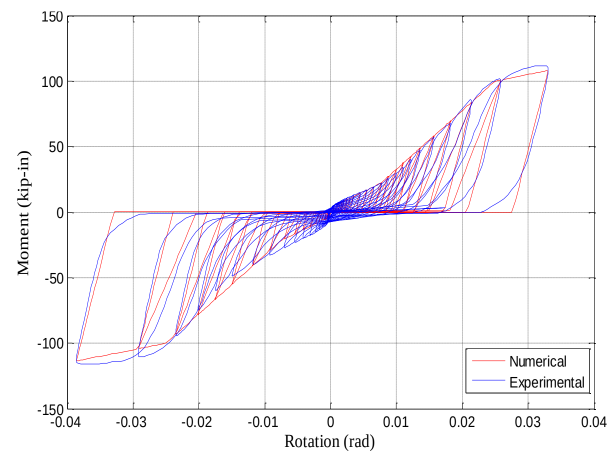
2'' Black iron pipes w. threaded joints

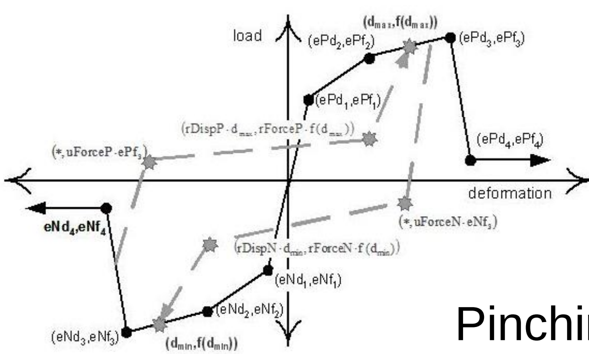


2'' CPVC pipes w. cement joints



Schedule 10 4'' steel pipe w. grooved-fit connections





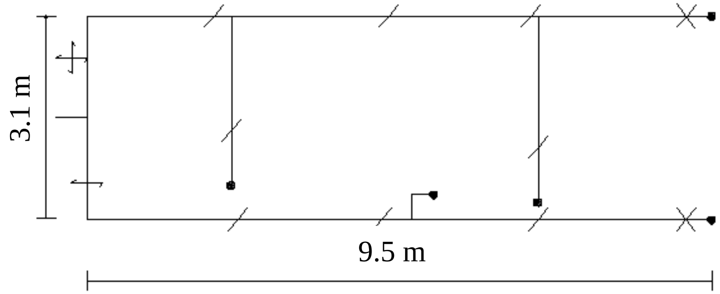
Note:
1 in. = 25.4 mm
1 kip = 4.45 kN

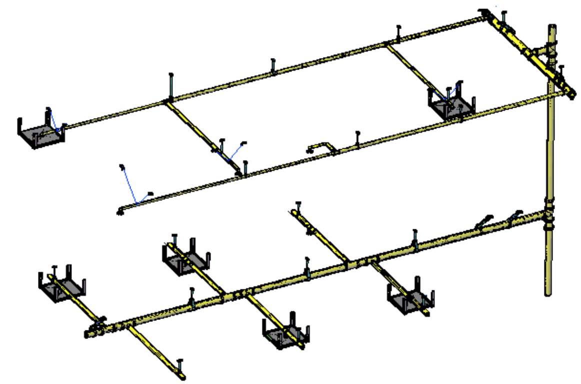
Pinching4 Material Model (OpenSees)

Seismic Fragility Analysis of Sprinkler Piping Systems: A Case Study

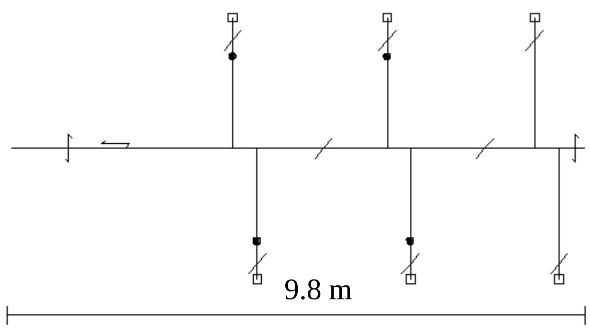
4. Seismic testing of sprinkler piping subsystems

- Long Branch Lines – Level 2





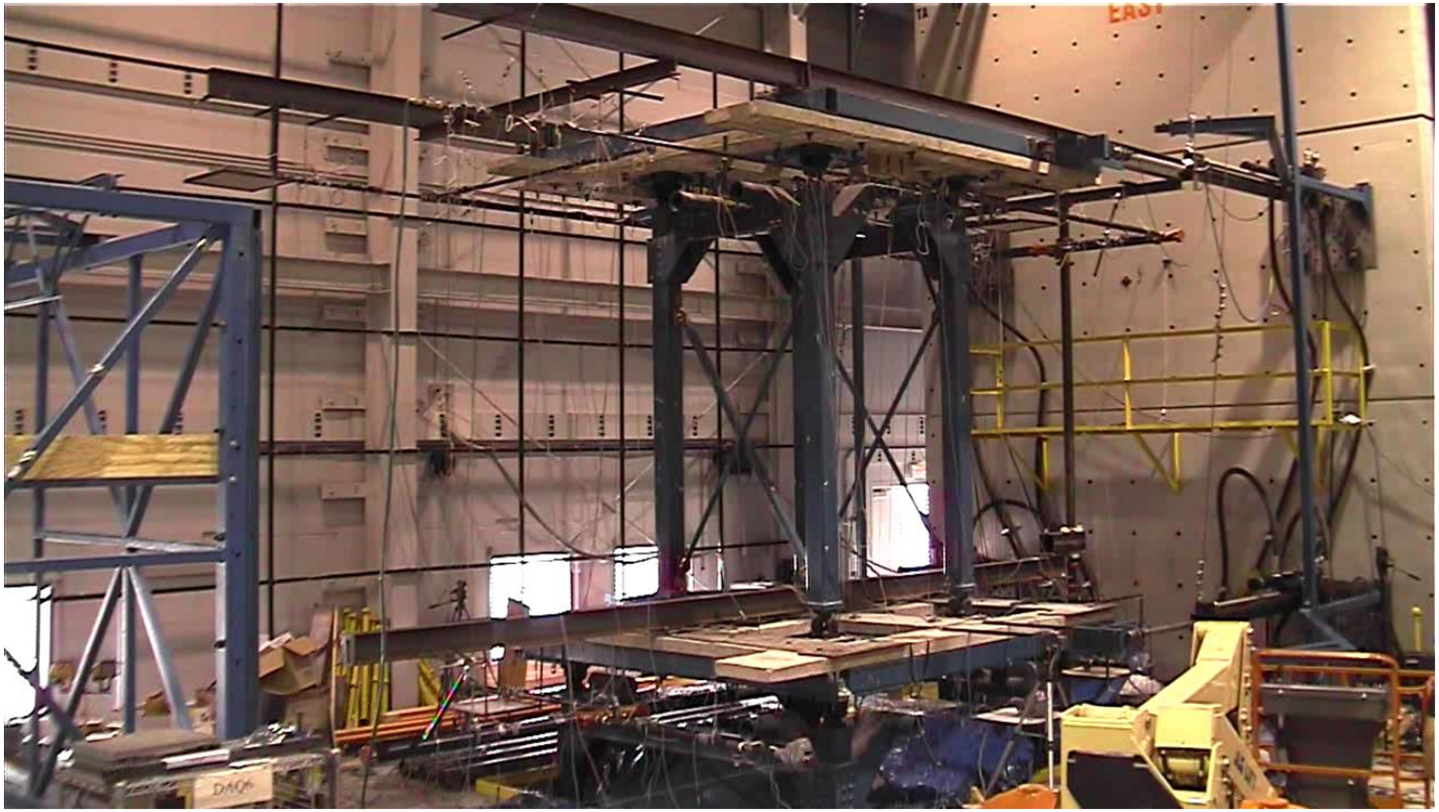
- Main Line and Riser – Level 1

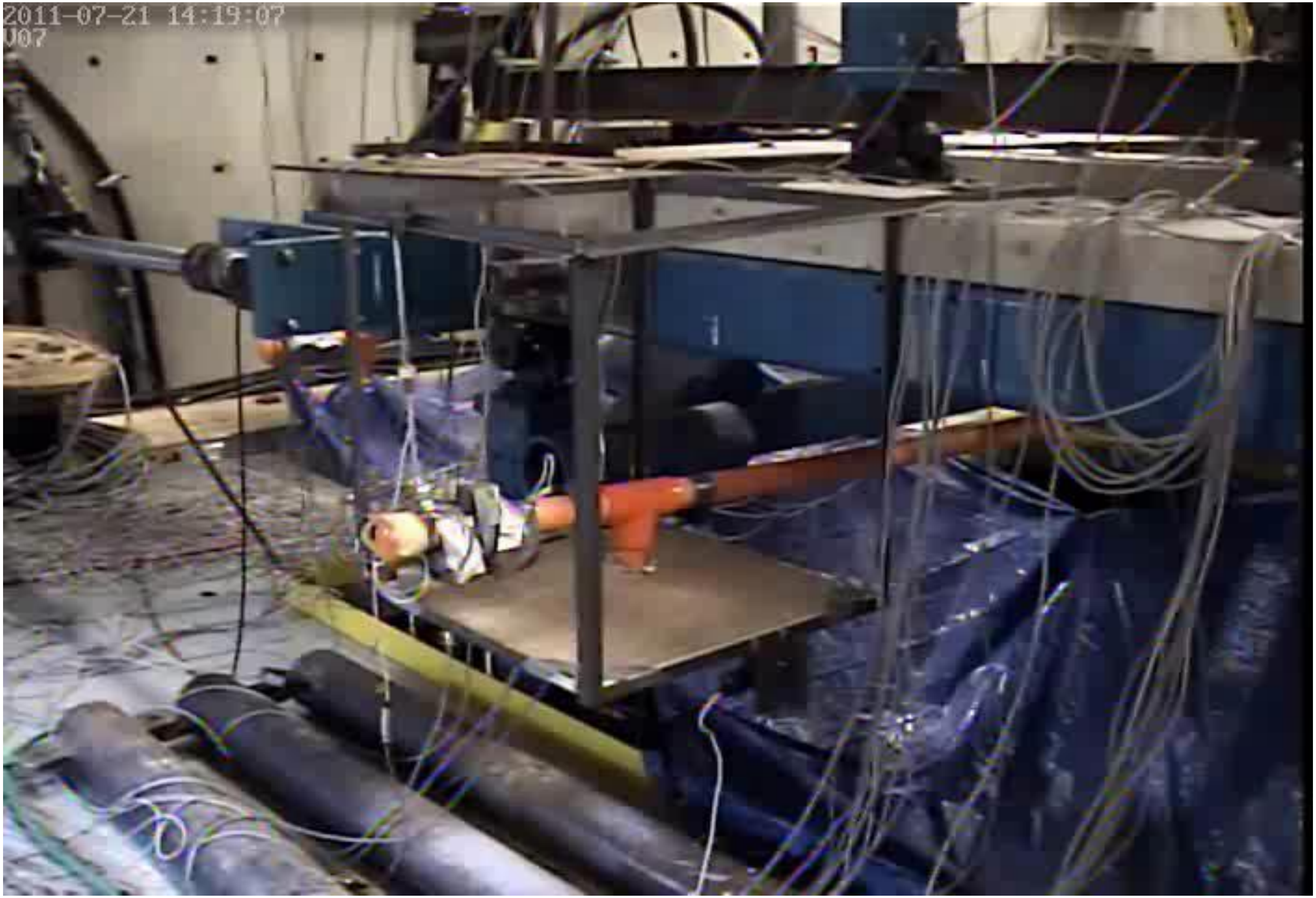


Legend	Note
	4-way seismic brace
	Sprinkler pipe run
	Sprinkler head
	Vertical hanger
	Lateral bracing
	Wire restraint
	Mass block

Seismic Fragility Analysis of Sprinkler Piping Systems: A Case Study

4. Seismic testing of sprinkler piping subsystems

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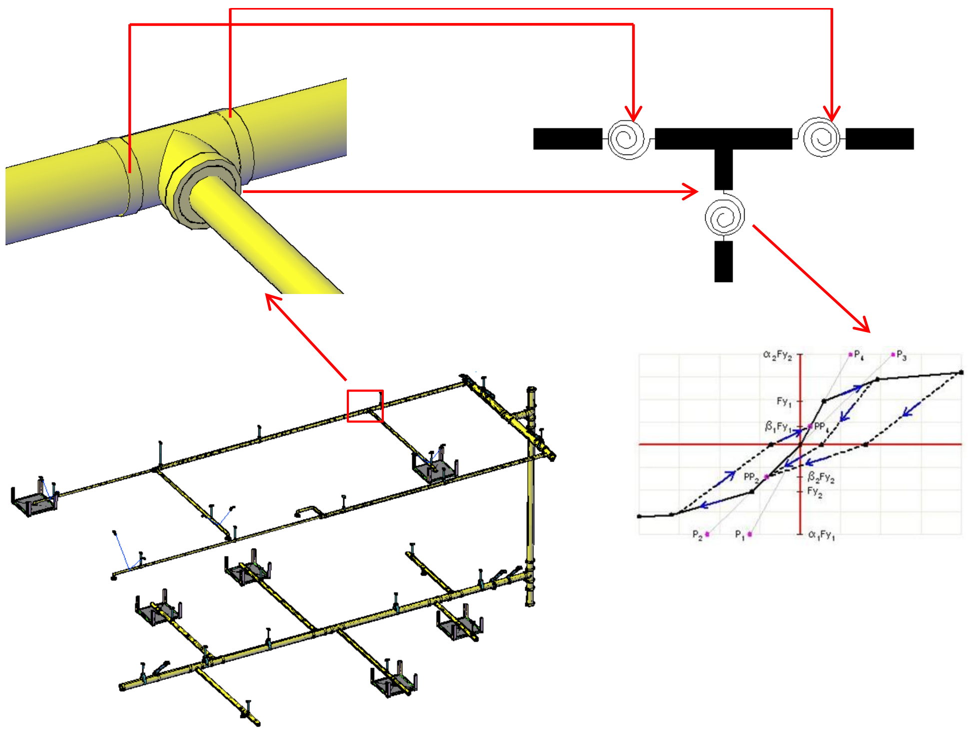
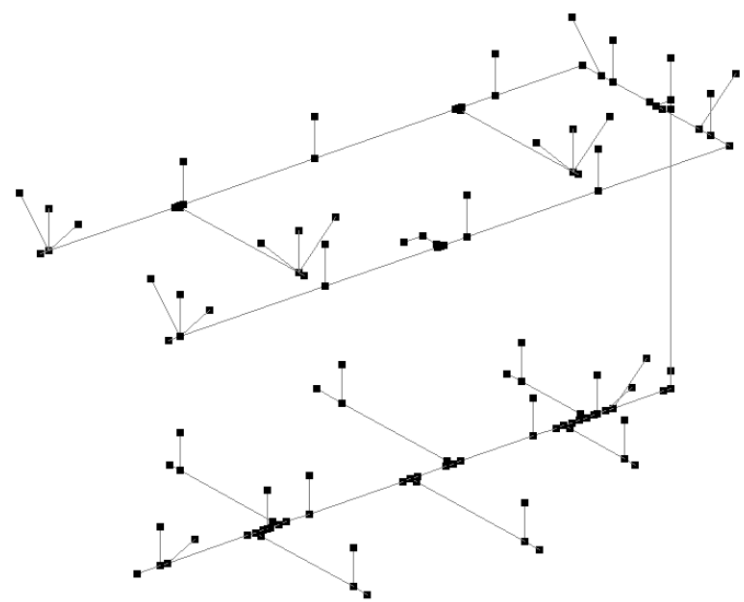
Seismic Fragility Analysis of Sprinkler Piping Systems: A Case Study

5. Numerical modeling of sprinkler piping subsystems

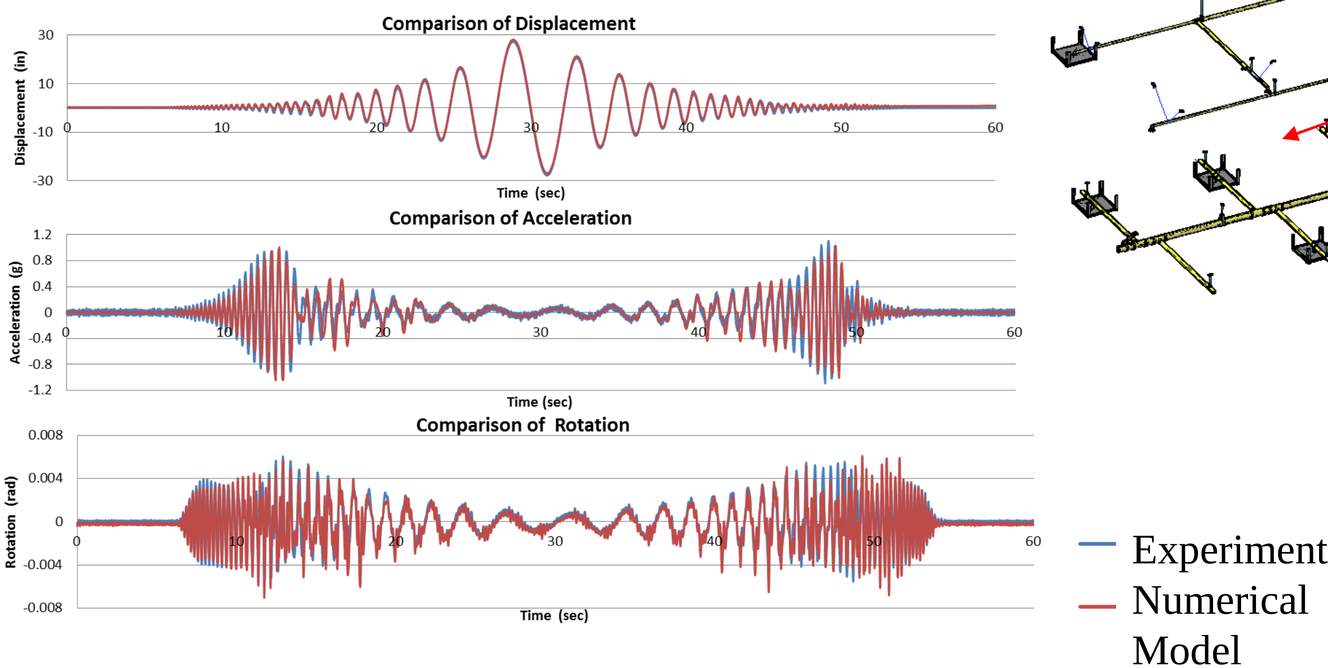


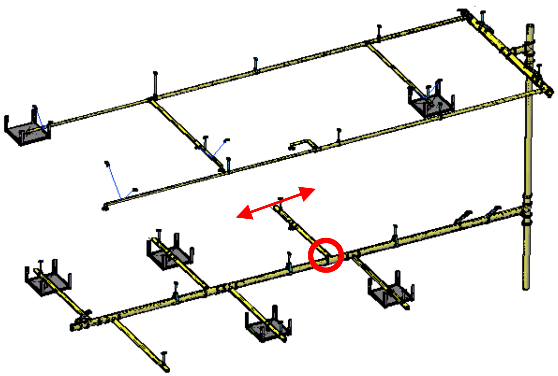
OpenSees model



Seismic Fragility Analysis of Sprinkler Piping Systems: A Case Study

5. Numerical modeling of sprinkler piping subsystems
   - OpenSees numerical analysis - black iron threaded - NFPA-13 bracing - MCE intensity.





Seismic Fragility Analysis of Sprinkler Piping Systems: A Case Study

6. Fragility analysis of sprinkler piping systems

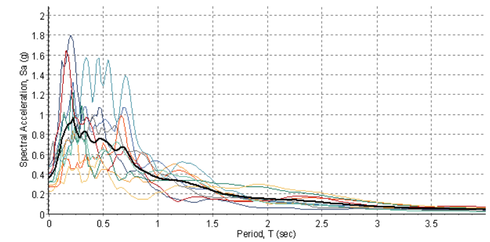
Scaling of Earthquake Ground Motion Records

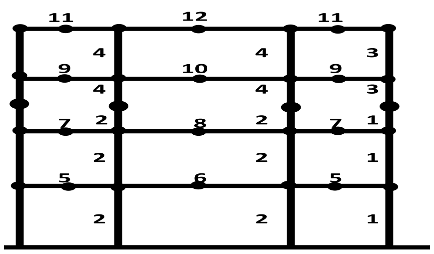
↓

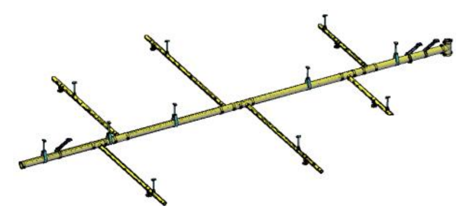
Seismic Fragility Analyses of Building Models (RUAUMOKO)

↓

Seismic Fragility Assessment of Fire Sprinkler Piping Systems (OpenSees)

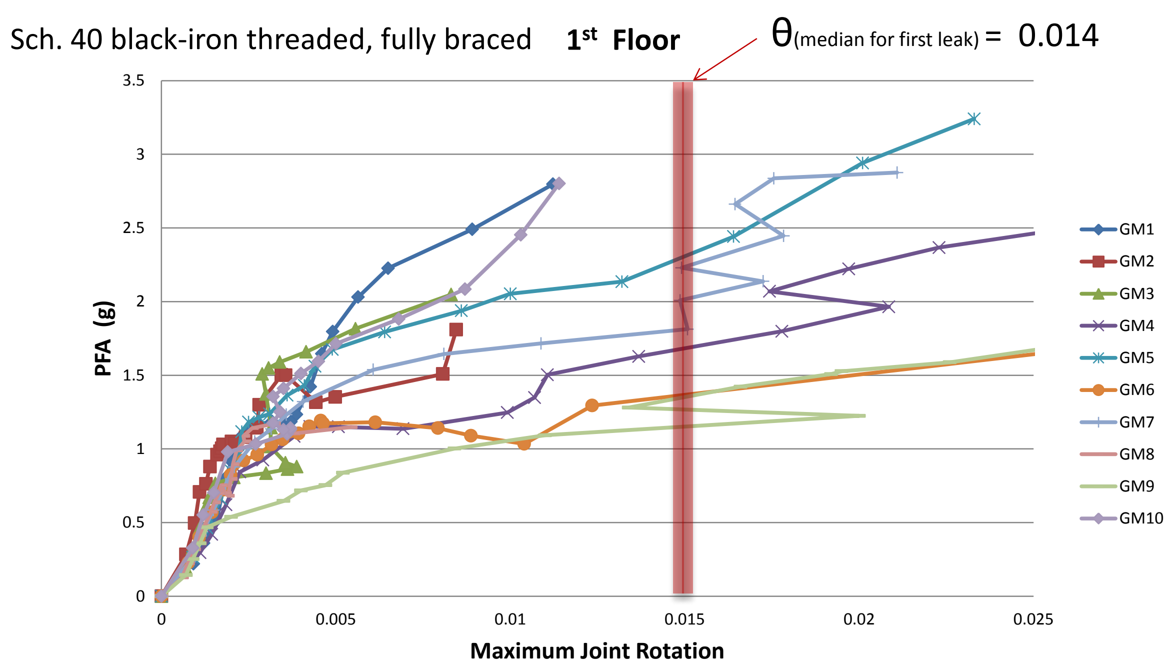






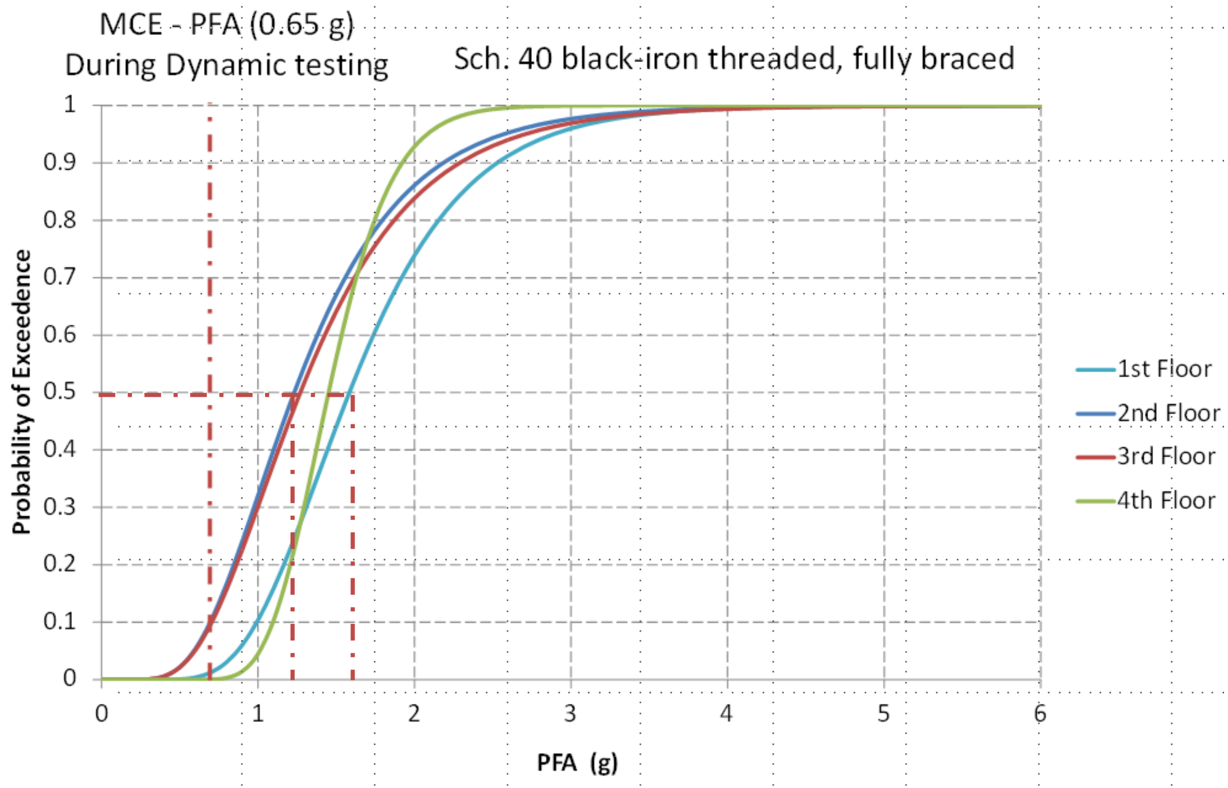
Seismic Fragility Analysis of Sprinkler Piping Systems: A Case Study

6. Fragility analysis of sprinkler piping systems
   - Incremental dynamic analysis curves for sprinkler piping system
   - Intensity measure: Peak Floor Acceleration (PFA)



Seismic Fragility Analysis of Sprinkler Piping Systems: A Case Study

6. Fragility analysis of sprinkler piping systems
   – First leakage fragility curves



Impediments to Incorporating Nonstructural Design into Practice

- The problem
  - Close collaboration between architects and structural engineers understood to be highly desirable and has become practice within Europe and North America.
  - Not the case with design and installation of Nonstructural Components.
  - Often lack of design integration of structural engineering and engineering of Nonstructural Components.
  - Brought to focus in California by SB 1953 in California.

Impediments to Incorporating Nonstructural Design into Practice

- Reasons for lack of integration between Structural and Nonstructural Engineering
  - Traditional roles cloud responsibility
    - Five major stakeholders typically involved in traditional building design process:
      - Architect;
      - Structural engineer;
      - Electrical engineer;
      - Mechanical engineer;
      - Specialty consultants and subcontractors often designing Nonstructural Components.

Nonstructural System or Component	Architect	Structural Engineer	Electrical Engineer	Mechanical Engineer	other design professionals
curtain wall	1	2			consider a specialty consultant
doors / windows	1				
access floors	1				consider a specialty consultant
HVAC systems	2			1	
plumbing systems	2			2	
communication systems	2		1		1 consider a specialty consultant
data systems	2		1		1 consider a specialty consultant
elevator systems	1	2	2	2	2
emergency power supply system	2	2	1	2	2
fire protection systems	2		2	1	1 consider a specialty consultant
kitchen systems	1				2 consider a specialty consultant
lighting systems	2		1		

Nonstructural System or Component	Architect	Structural Engineer	Electrical Engineer	Mechanical Engineer	other design professionals
medical sytems	1	2	2	2	1 consider a specialty consultant
ceiling systems	1	2	2	2	
unbraced walls and parapets	1	2			
interior bearing walls	1	2			
interior non-bearing walls	1				
prefabricated elements (architectural appendages)	1	2			
chimneys	1	2			
signs	1	2			
billboards	2	1	2		2 consider a specialty consultant
storage racks	1				2 consider a specialty consultant
cabinets and book stacks	1				2
wall hung cabinets	1			1	
tanks and vessels	2	2			
electrical equipment	2	2	1		
plumbing equipment	2	2		1	

Note: 1 = Primary Responsibility 2 = Support Responsibility

Source: FEMA 454

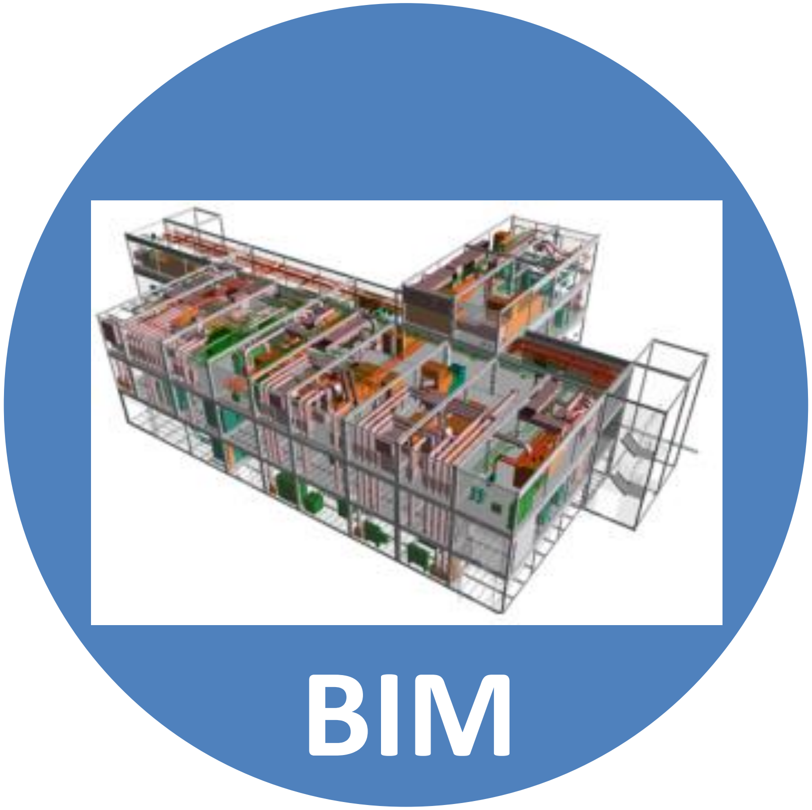
Impediments to Incorporating Nonstructural Design into Practice

- Reasons for lack of integration between Structural and Nonstructural Engineering
  - Traditional roles cloud responsibility
    - Building construction generally under oversight of a project architect responsible for project management.
      - Architects are rarely engineers.
    - Sometimes structural engineer designated responsible for seismic design of Nonstructural Components
      - Rarely structural engineers experienced in specifying appropriate seismic design and installation of plumbing, heating, venting, electrical, and other Nonstructural specialties.
      - Structural engineers do not want to work on Nonstructural design problems.

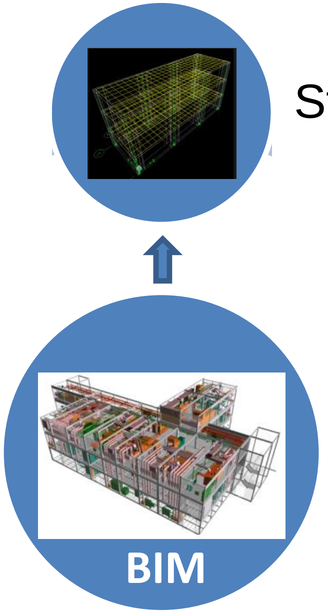
Possible solution: Design Build Contracting — the Master Builder Concept

- Single source has absolute accountability for both design and construction.
- Owner contracts with a single firm to design and build the facility.
- Tools currently available for implementation:
  - Concurrent Engineering;
  - Lean Construction;
  - Building Information Modeling (BIM).

Building Information Modeling (BIM) for Integrated Seismic Assessment and Design

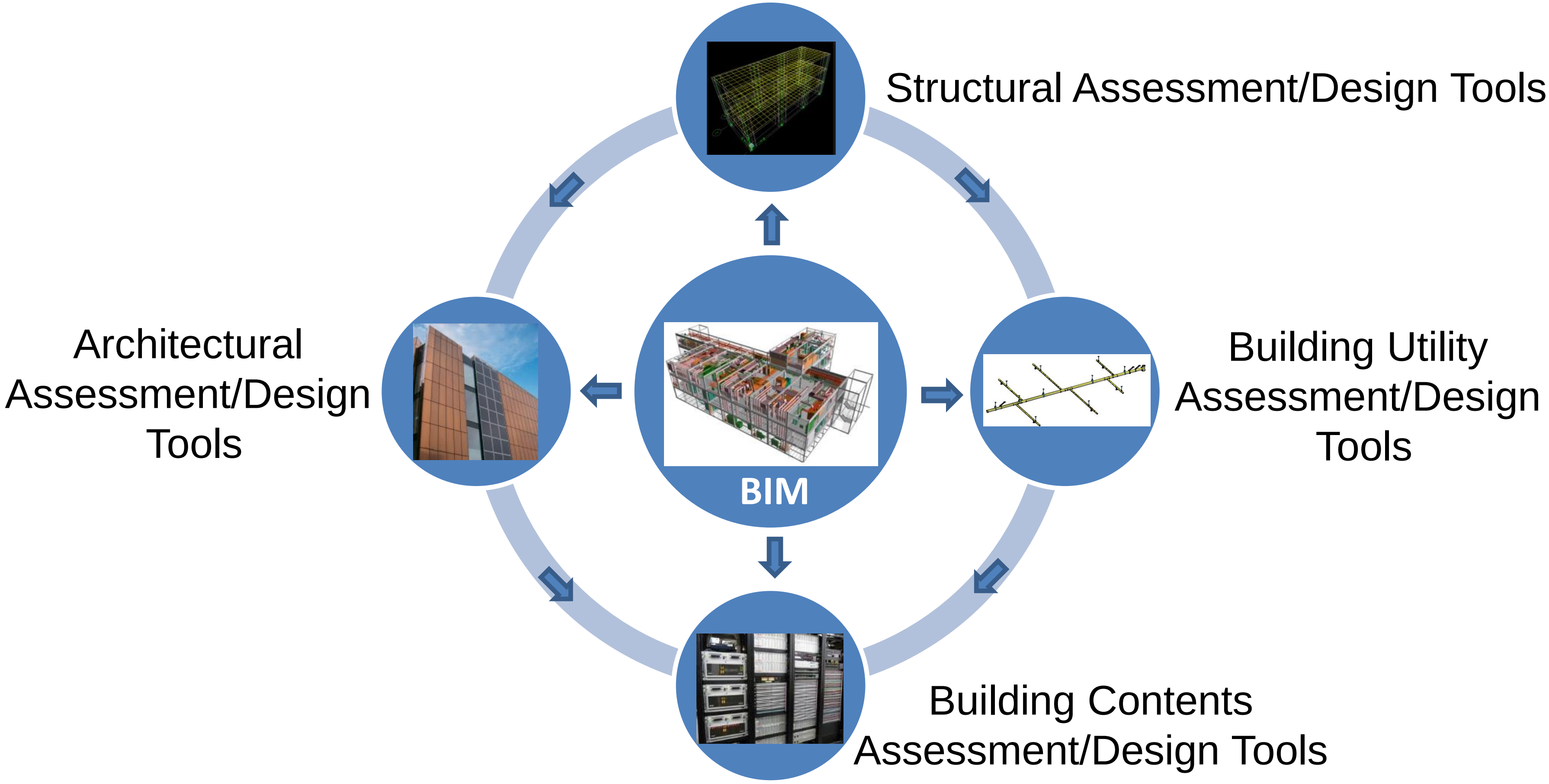


BIM for Integrated Seismic Assessment and Design



Structural Assessment/Design Tools

BIM for Integrated Seismic Assessment and Design



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With the development and implementation of performance-based earthquake engineering, harmonization of performance levels between structural and non-structural elements becomes vital. Even if the structural elements of a building achieve a continuous or immediate occupancy performance level after a seismic event, failure of architectural, mechanical or electrical elements can lower the performance level of the entire building system. This reduction in performance caused by the vulnerability of non-structural elements has been observed during recent earthquakes in Italy and worldwide. Moreover, non-structural damage has limited the functionality of critical facilities, such as hospitals, following major seismic events. The investment in non-structural elements and building contents is far greater than that of structural elements and framing. Therefore, it is not surprising that in many past earthquakes, losses from damage to non-structural elements have exceeded losses from structural damage. Furthermore, the failure of non-structural elements can become a safety hazard or can hamper the safe movement of occupants evacuating buildings, or of rescue workers entering buildings. In comparison to structural elements and systems, there is relatively limited information on the seismic design of non-structural elements. Basic research work in this area has been sparse, and the available codes and guidelines are usually, for the most parts, based on past experiences, engineering judgment and intuition, rather than on objective experimental and analytical results. Often, design engineers must start almost from square one after each earthquake event: to observe what went wrong and to try to prevent repetitions. This is a consequence of the empirical nature of current seismic regulations and guidelines for non-structural elements.


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INTERNATIONAL ASSOCIATION FOR THE SEISMIC PERFORMANCE OF NON-STRUCTURAL ELEMENTS
Second International Workshop on Seismic Performance of Non-Structural Elements
May 13, 2015, Pavia, Italy


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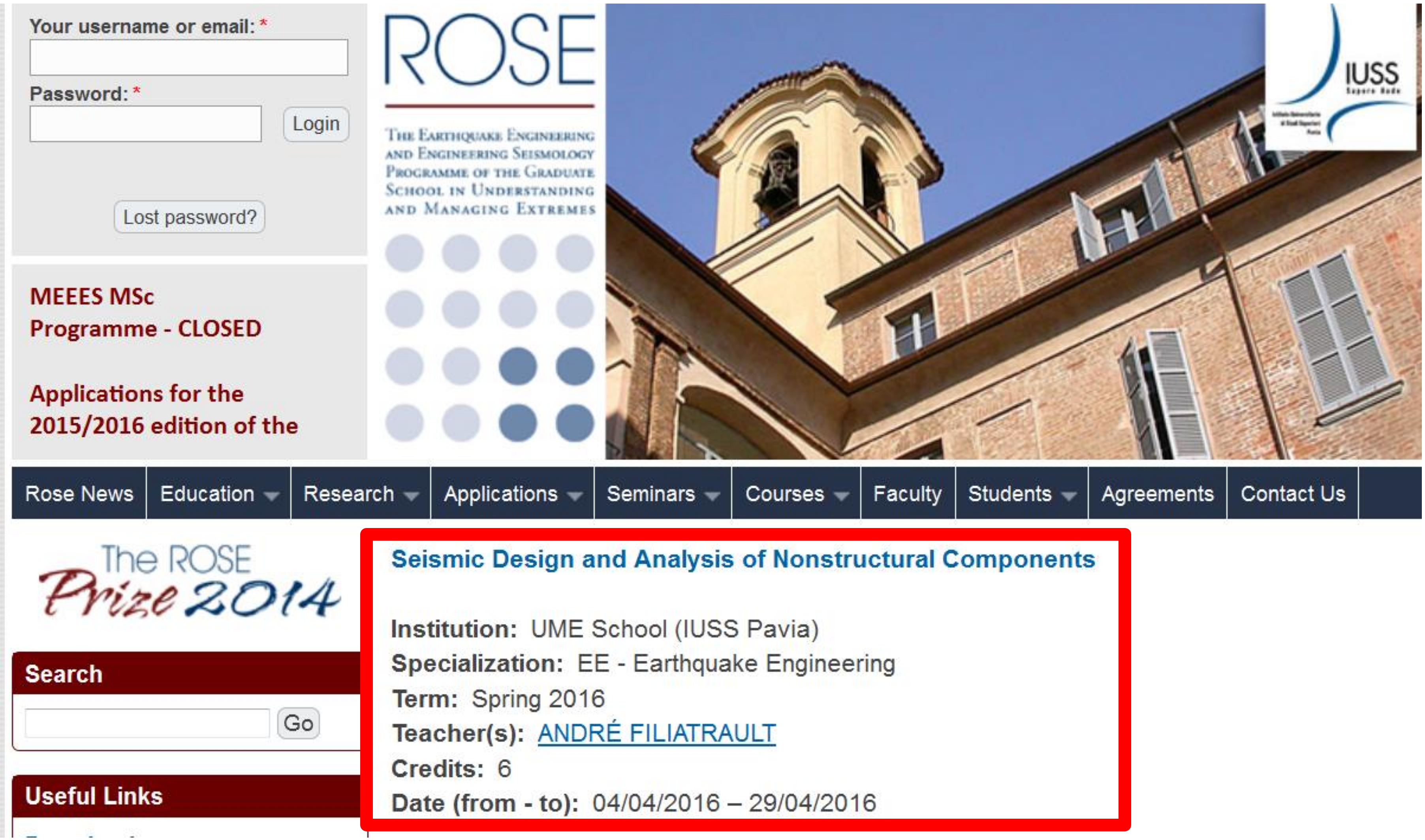
UME Graduate Course on the Seismic Design of Non-structural Elements



Final Thoughts

- In 1914, Professor Modesto Panetti from Istituto Superiore di Torino wrote:
  - *…the effects of earthquakes on structures are in fact a structural dynamics problem, which is much too complicated to address…*
- In 2015, the earthquake engineering community still believes:
  - *…the effects of earthquakes on nonstructural nomponents are in fact a structural dynamics problem, which is much too complicated to address…*
- Today, I believe that we have the tools to develop performance-based seismic design for nonstructural components the same way it was done for structural components. Now is the time for structural engineers to take responsibility and start doing it!

Thank you!

What the client wanted.

The architect's solution.

The structural engineer's solution.

The non-structural engineer's Solution.