UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Development of fragility functions and seismic design procedure for automatic fire sprinkler systems

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Outline

- Introduction
- Motivation & Problem Statement
- Research Questions
- Objectives
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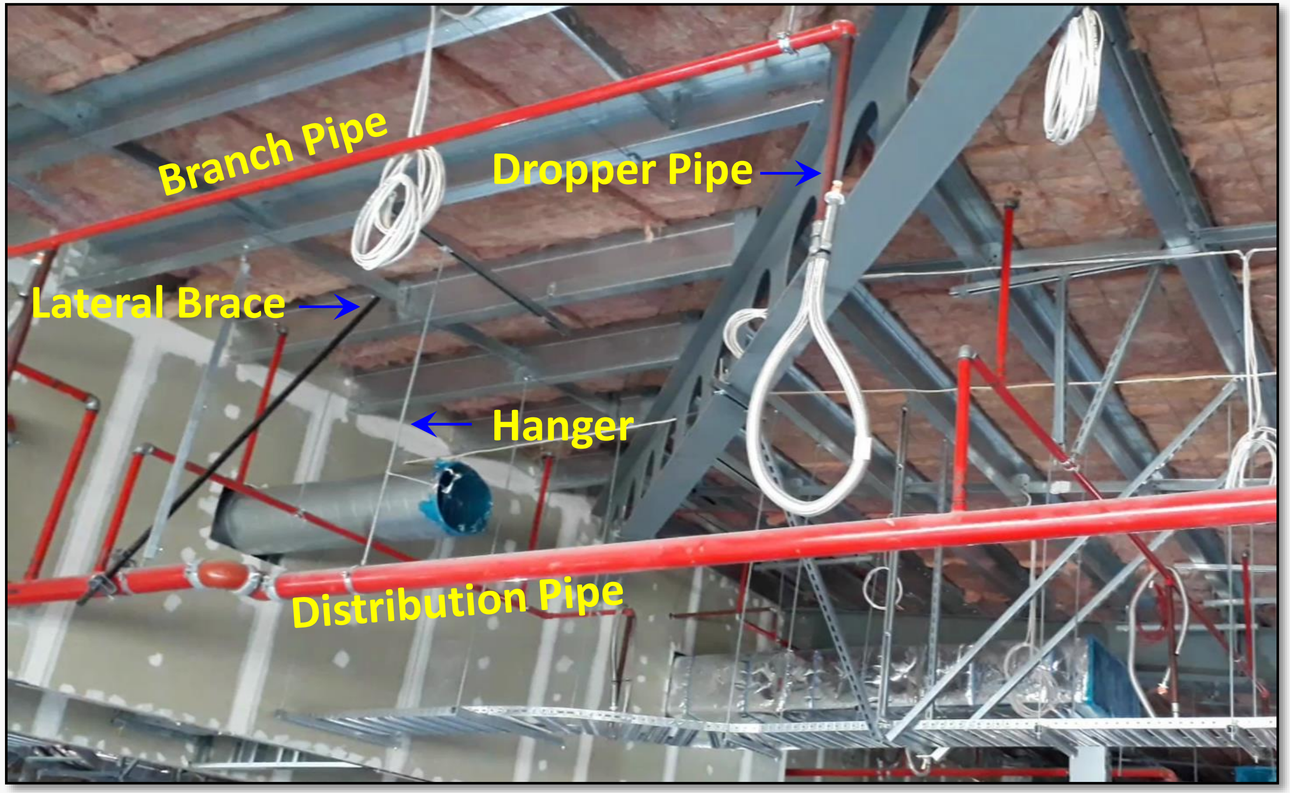
Introduction

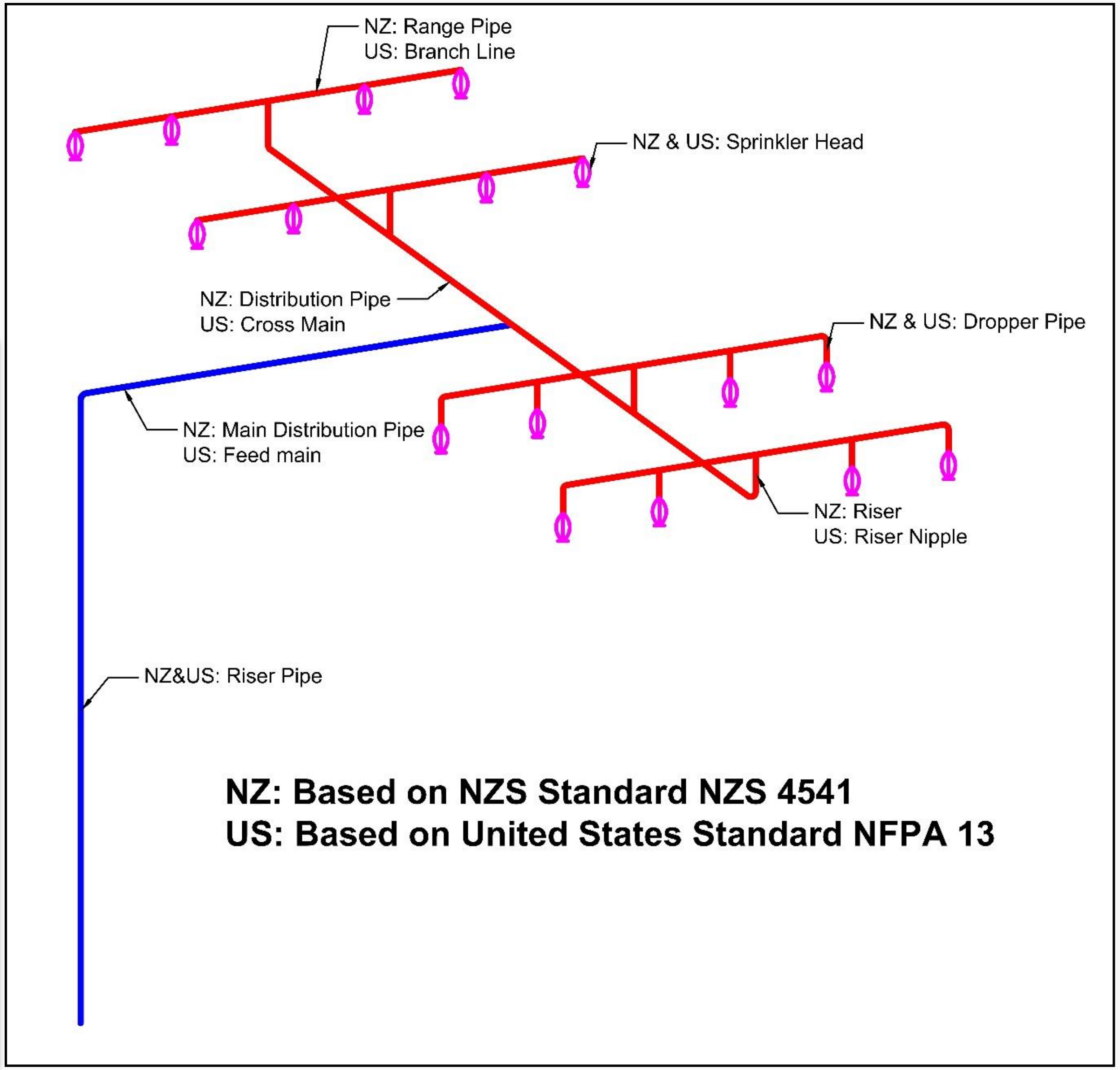
- **Automatic Fire Sprinkler System**
- Primarily, an acceleration – sensitive NSE and one of the most important because of its role in suppressing fires.
- Presently, almost 40 million sprinkler heads are fitted each year.

(Automatic Fire Systems, INC.)

Introduction

- **Components of a Fire Sprinkler System**

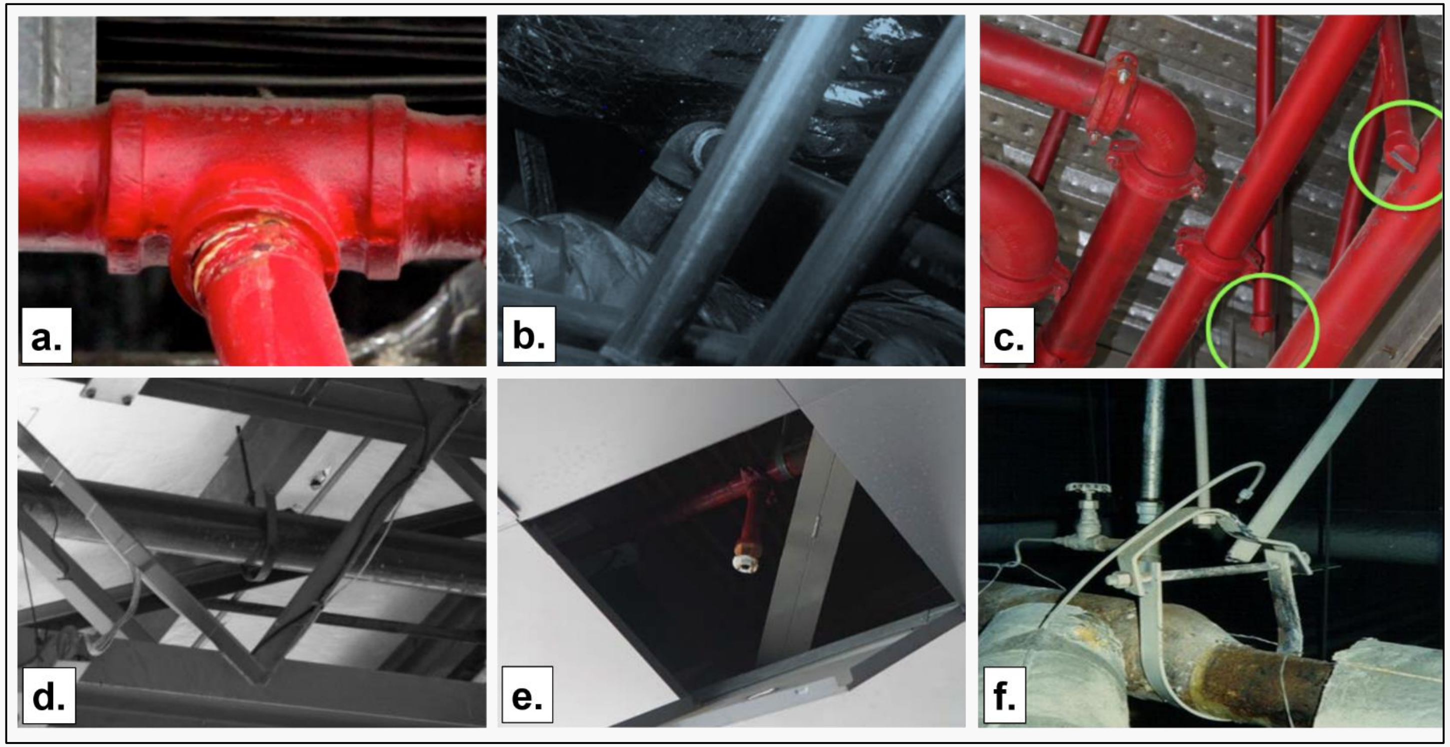




Past Seismic Performance

- The consequential damage, in the form of flooding of a floor(s), from sprinkler systems is disproportionately large in comparison to the damage to itself.

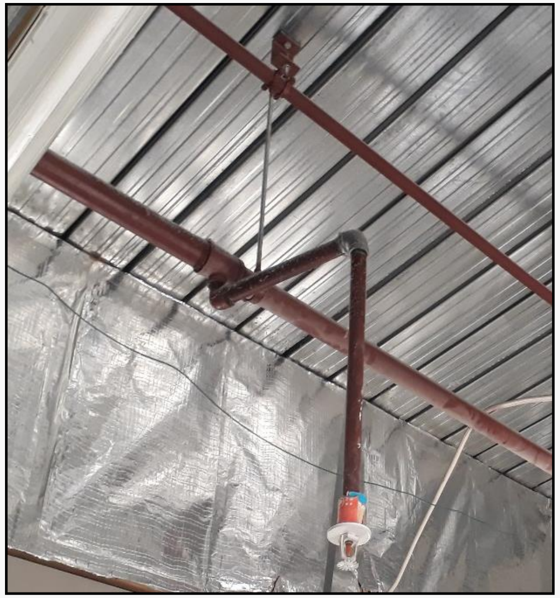
- ***50% of hospitals with sprinkler systems were affected due to leakage in sprinkler pipes in the 2010 Chile earthquake.***
- ***Shutting down of airport terminals at Santiago, Chile, and at the San Francisco airport during the in 2010 Chile earthquake and 1989 Loma Prieta earthquake, respectively.***

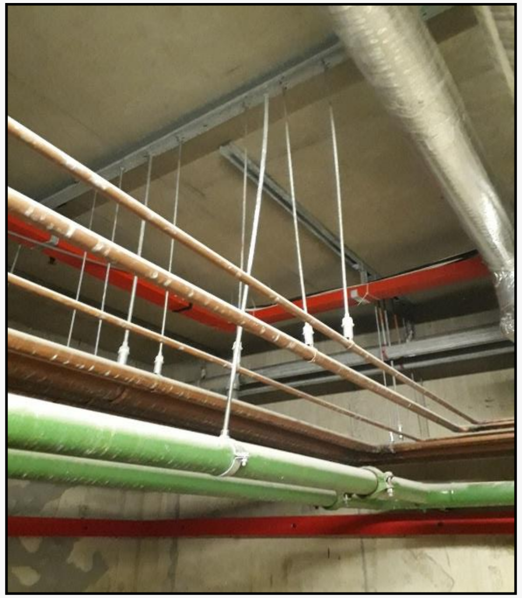


(a) Fractured Tee Joint; (b) Fractured Elbow Joint; (c) Braces Sheared Off; (d) Failure of Hanger; (e) Sprinkler Head Sheared Off; (f) Failure of Brace (Baker et al. 2012)(Miranda et al. 2010)(Taghavi and Miranda 2003)(Tian 2013)

Introduction

- **Old Sprinkler Systems in Christchurch**





Unbraced Pipes & Long Hanger Depths (> 1m)

Weak Hanger Anchorage to Floor

Lack of Clearance around Riser Pipes

Introduction

- New Sprinkler Systems in Christchurch

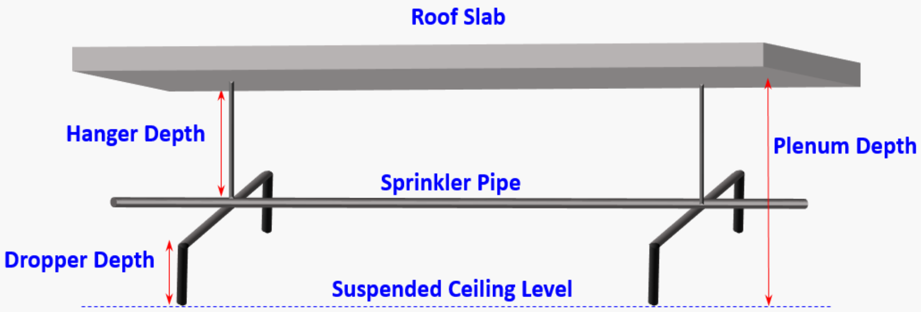
Improper Bracing of Riser

Introduction

- **Design Standards**
- **NZS 4541:** *All sprinkler components shall be designed, detailed and installed so as to remain operational at the ULS earthquake loading for the sprinkler-protected building structure as specified in NZS 1170.5* (NZS4541 2013)
- **Detailed Analysis Method:** It requires the design to be based on analysis of the complete piping support system under loads set by section 8 of NZS 1170.5.
- **Simplified Analysis Method:** It requires the pipework to be designed for a seismic demand of 1.0 g in any direction in addition to the gravity loads.
- Additionally, empirical spacing requirements for bracing pipes are provided. For example, lateral braces on pipes are to be spaced 12 m apart.

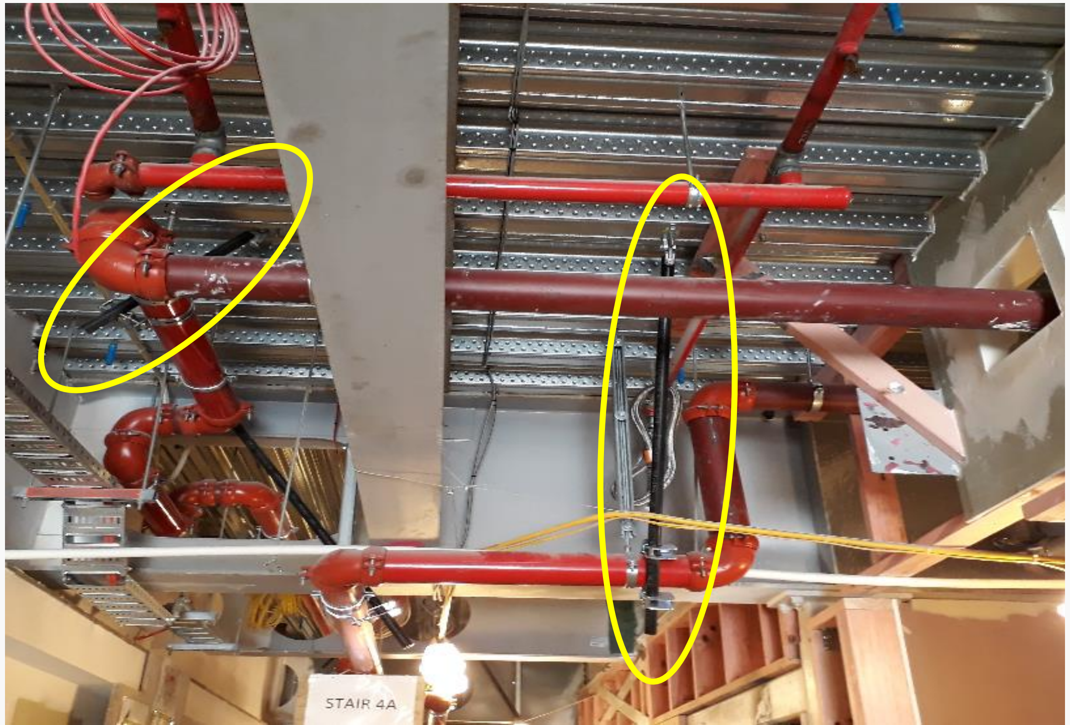
Motivation

- **Randomness in Installation**
- Piping systems have elaborate and complex configurations.
- The installation details, such as the hanger depth of pipes, vary even across a single floor.



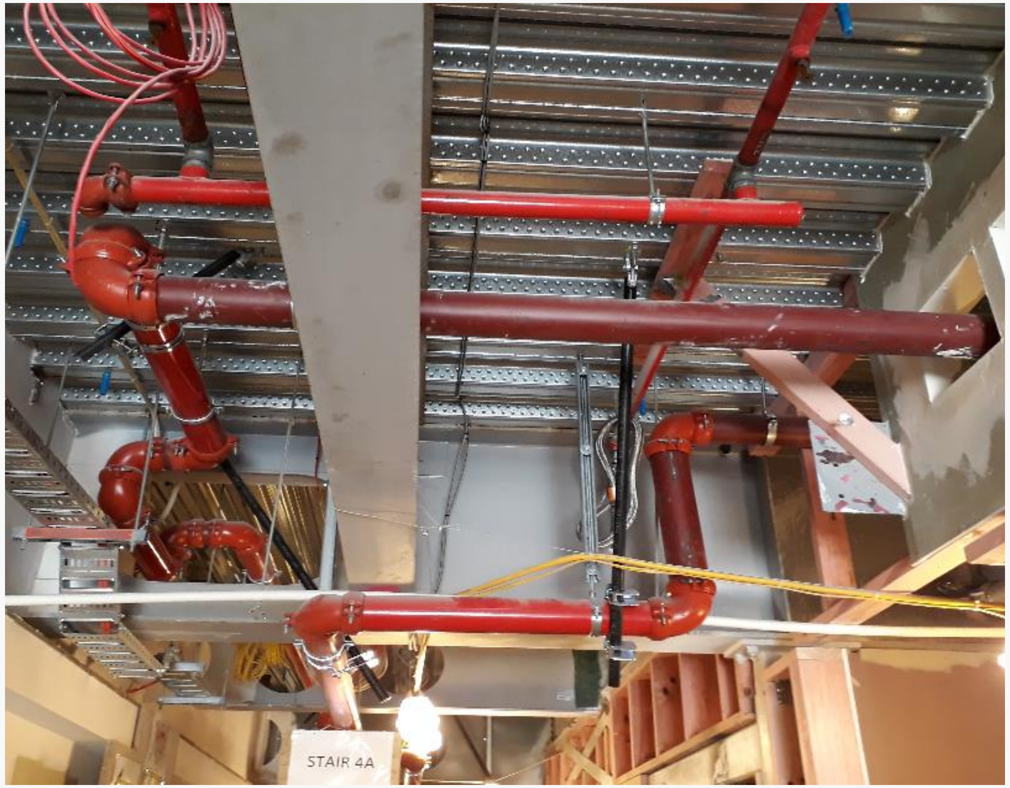
Motivation

- **Randomness in Design**
- Seismic design, in actual practice, primarily means bracing the pipes using empirical spacing requirements.
- Secondly, brace length is simply adjusted to the hanger depth irrespective of its capacity or the anticipated seismic demand.



Problem Statement

"Which component of a sprinkler system, with such an array of design and installation details, and despite being braced, is going to fail in a future seismic event?"



Research Questions

The randomness in the installation details cannot be reduced due to the large number of services in the plenum space; however, the seismic design of such systems can be made more rational be addressing the following questions:

1. *How does pipe size, fitting type and loading type affect the onset and mechanism of piping connection damage?*
2. *How to establish a strength hierarchy between different components of a sprinkler system in order for it to fail in a preferable mode under seismic forces?*
3. *How do different design & installation details affect the seismic force distribution and deformation demands on different components of a sprinkler system?*
4. *What damping shall be used in the determination of seismic force demand on sprinkler systems?*
5. *How to evaluate the time period of sprinkler systems for the determination of seismic force demand on sprinkler systems?*

Objectives

1. Development of fragility curves for piping connections of fire sprinkler systems.
2. Development of a capacity design procedure for fire sprinkler systems.
3. Investigate and quantify the influence of different design and installation details on the force distribution and displacement response of fire sprinkler systems.
4. Evaluation of dynamic characteristics of a fire sprinkler system.

Objective 1: Connection Fragility Curves

- Quasi-Static cyclic tests on piping connections to understand the damage mechanisms and measure the rotation demand at the onset of leakage and fracture.
- The tests need to be conducted for:
    1. Different diameters of pipes
    2. Elbow and tee connections with:
        - Threaded
        - Groove-fit
        - Press-fit
    3. Bending & torsion

Threaded TEE

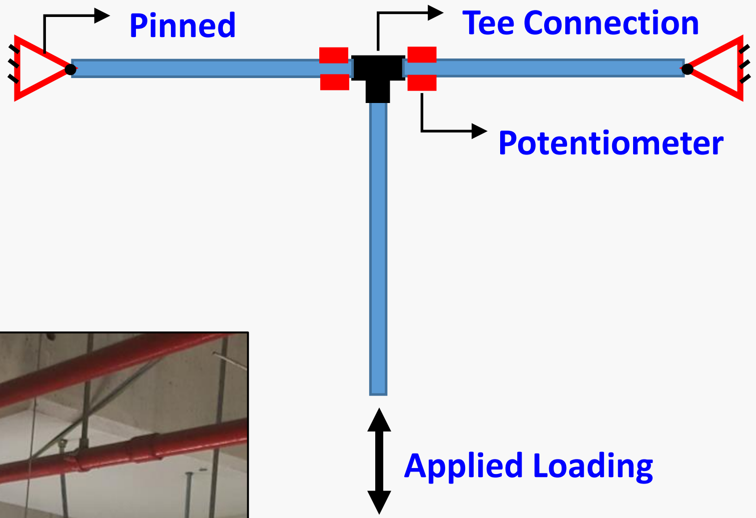
Press-Fit TEE

Groove-Fit

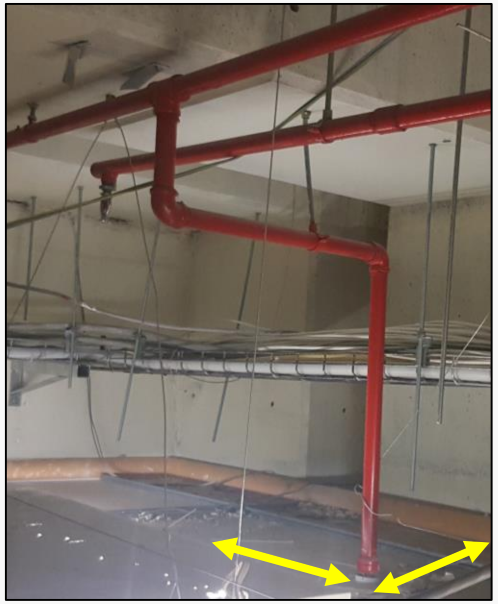
Groove-Fit ELBOW

Objective 1: Component Fragility Curves

Material	Connection Type	Diameter	Fitting	Bending Tests	Torsion Tests	Total
Steel						
	Tee Connection	25	Threaded	3	---	3
		50	Threaded	3	---	3
	Elbow Connection	25	Threaded	3	3	6
		50	Threaded	3	3	6
	Tee Connection	65	Groove-fit	3	---	3
		100	Groove-fit	3	---	3
	Elbow Connection	65	Groove-fit	3	3	6
		100	Groove-fit	3	3	6
	Tee Connection	25	Press-Fit	2	---	2
		50	Press-Fit	2	---	2
	Elbow Connection	25	Press-Fit	2	2	4
		50	Press-Fit	2	2	4
						48



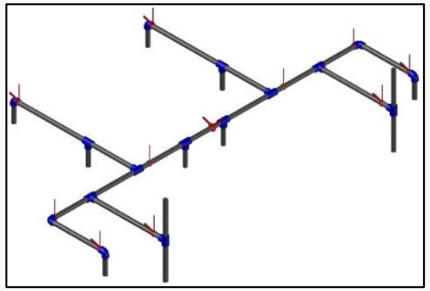
(Tian 2013)

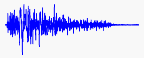


Objective 2: Capacity Design Procedure

- A mechanics-based approach to establishing a strength hierarchy between the components of a sprinkler system to avoid the critical failure modes of connections leakage or failure of brace connections.

Determination of Part Design Seismic Force, F_{ph} (NZS 1170.5, Sec. 8)





Proprietary Hangers & braces installed as per the spacing requirements of NZS 4541.

Force Distribution

- Capacity of brace & its connections > Force demand

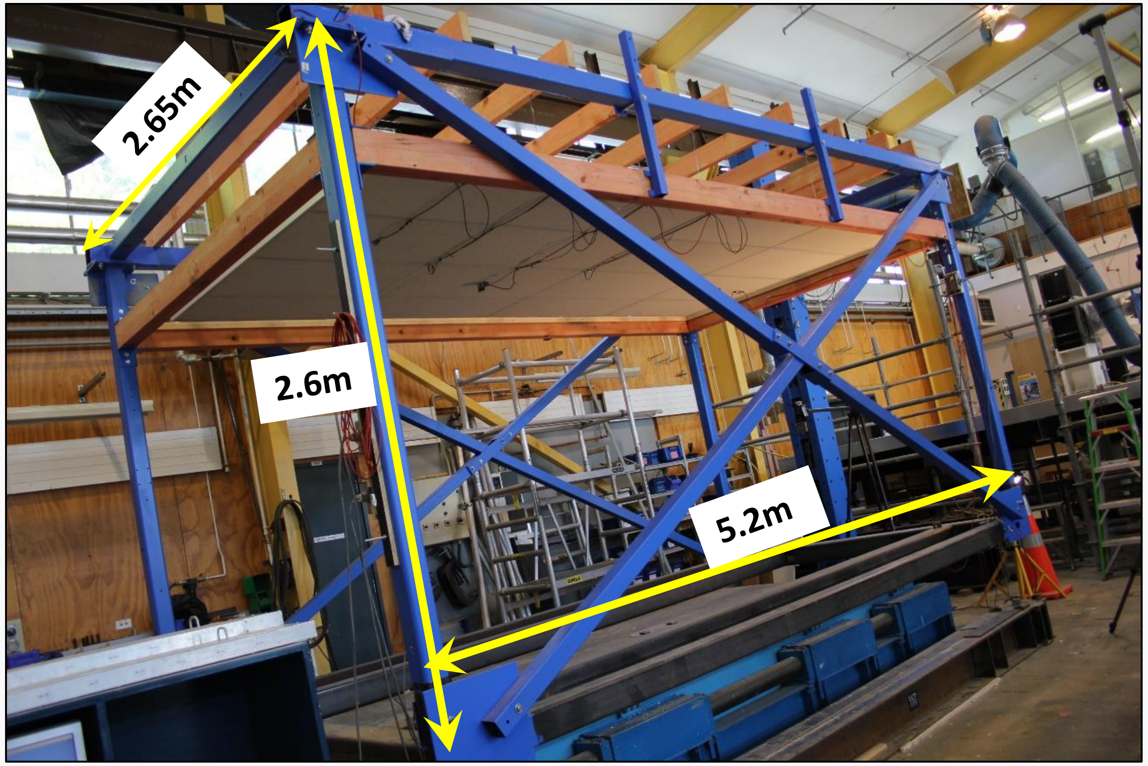
- The strength of connections should be > over-strength capacity of the brace

Displacement Demand

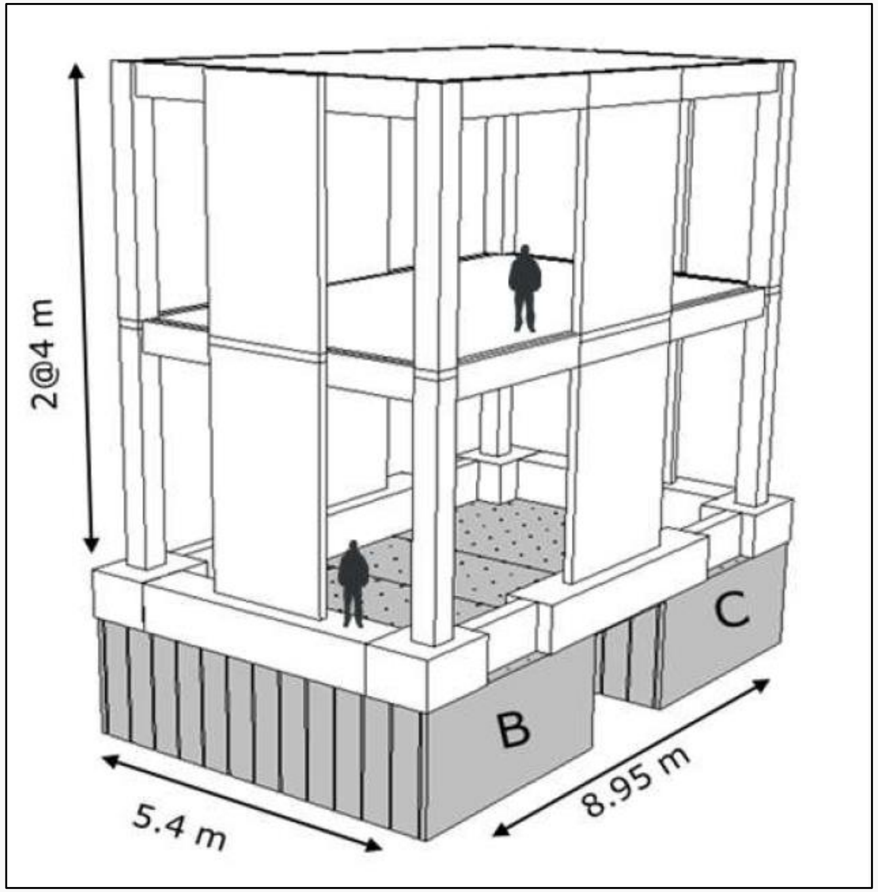
- The deformation demands on connections should be below the leakage limit state.

Objective 3: System-Level Performance

- **Part a**: Shake table tests on sprinkler systems will be conducted at the University Of Canterbury (UC) & Tongji University.



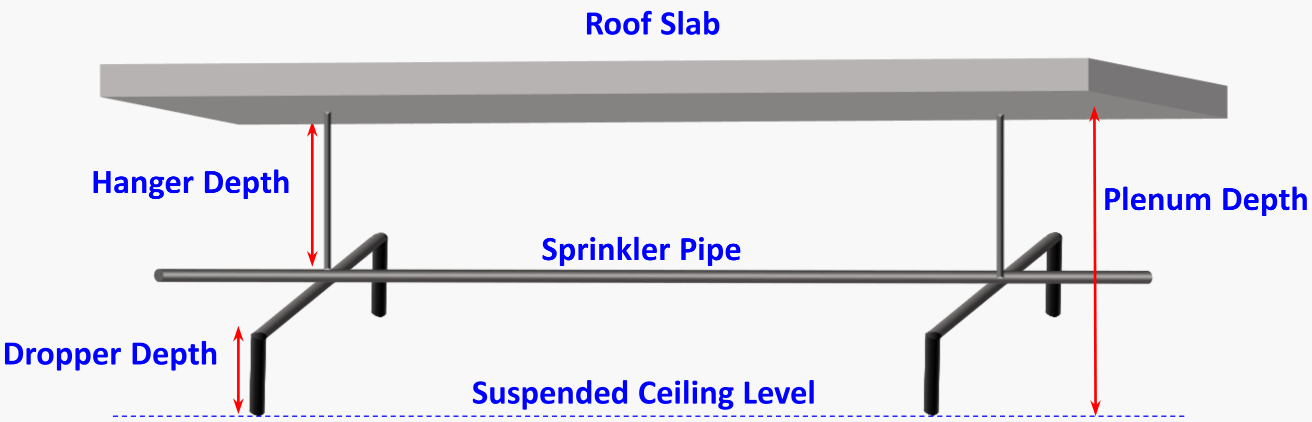
Test Frame at UC



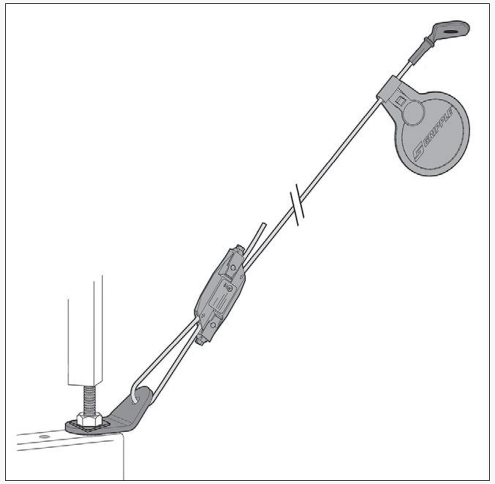
Test Building at Tongji University

Objective 3: System-Level Performance

- **Shake Table Tests**
- Variables:
    - Hanger Depth
    - Brace Design



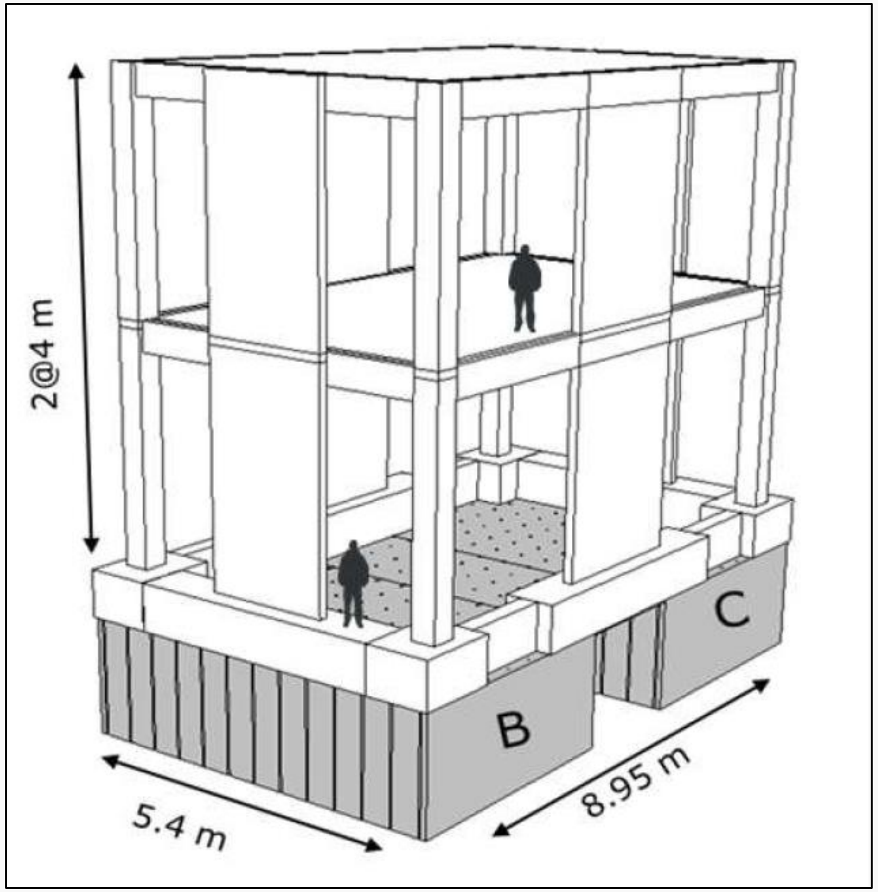
Rigid Lateral Brace



Flexible (Cable or Wire) Brace

Objective 3: System-Level Performance

- **Shake Table Test at Tongji University**

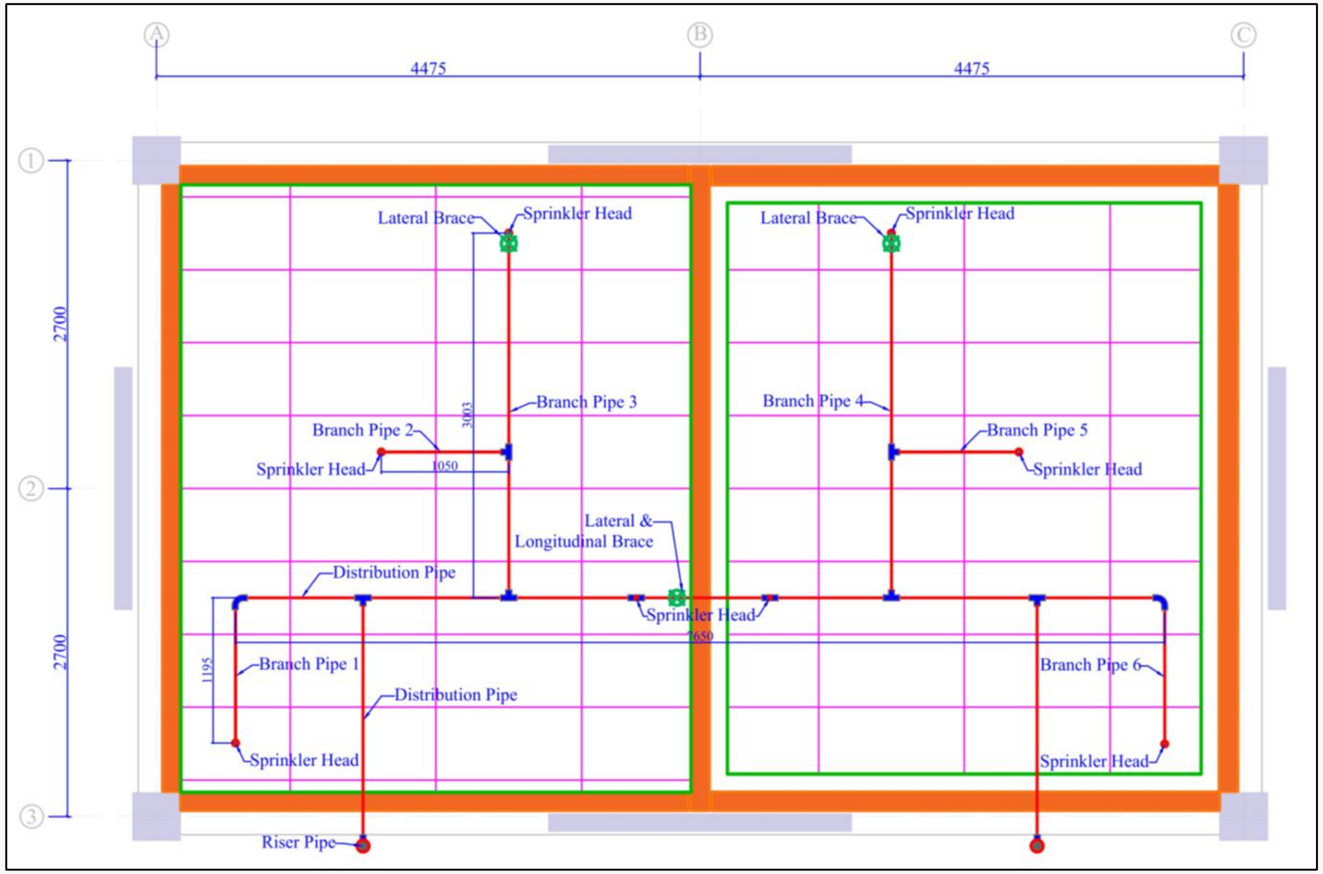


Test Building at Tongji University

Floor No.	Description	Remarks
1.	Sprinkler system with a hanger depth of 350 mm and braced by lateral and longitudinal braces.	To assess the influence of different hanger depths on the force distribution and displacement response of sprinkler systems.
	Perimeter fixed and fully floating ceilings	To compare the seismic performance of perimeter-fixed and fully floating ceilings under the same demand and their interaction with sprinkler system
2.	Sprinkler system with a hanger depth of 1 m and braced by lateral and longitudinal braces.	To assess the influence of different hanger depths on the force distribution and displacement response of sprinkler systems.
	Perimeter fixed and fully floating ceilings	To compare the seismic performance of perimeter-fixed and fully floating ceilings under the same demand and their interaction with sprinkler system

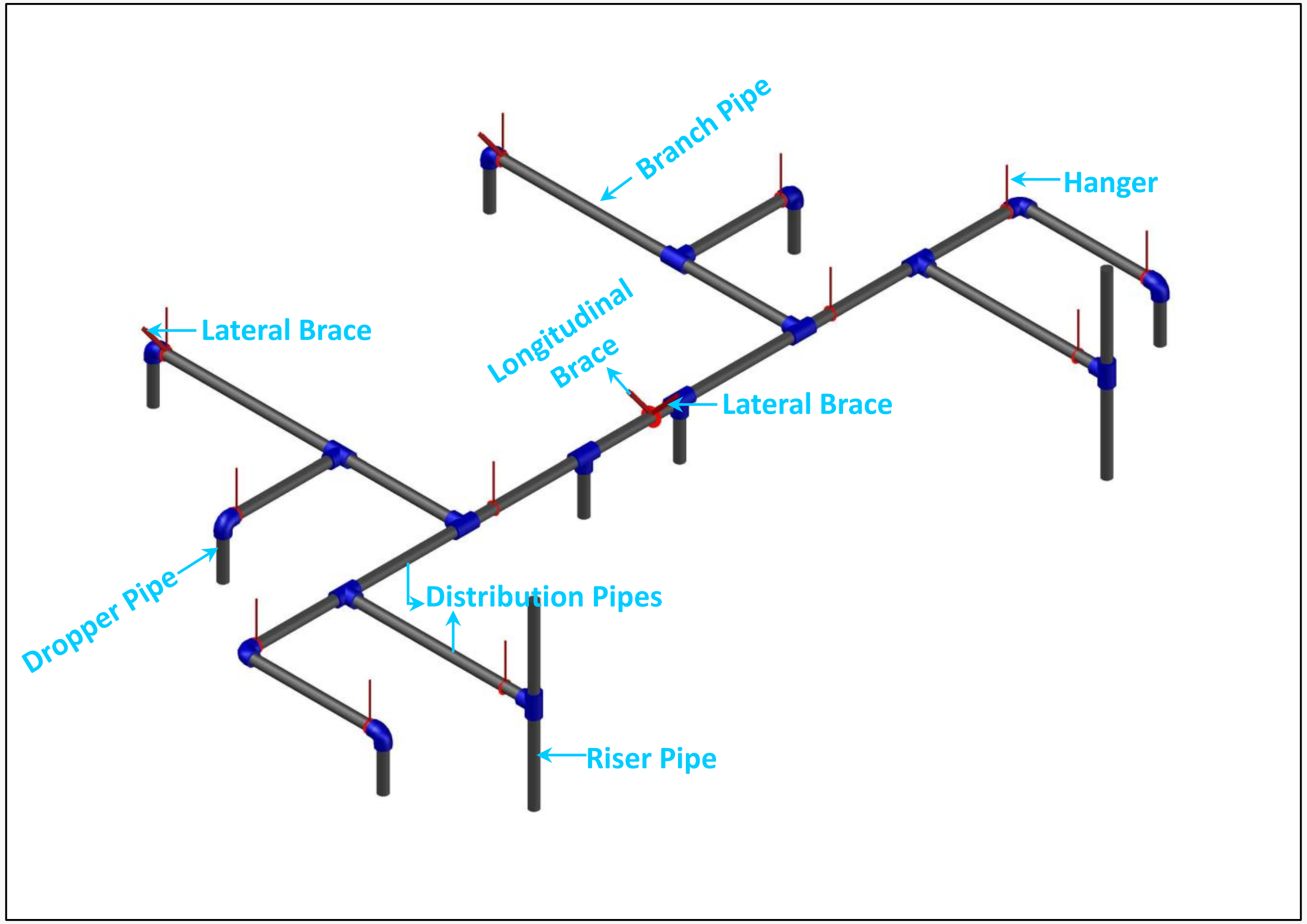
Objective 3: System-Level Performance

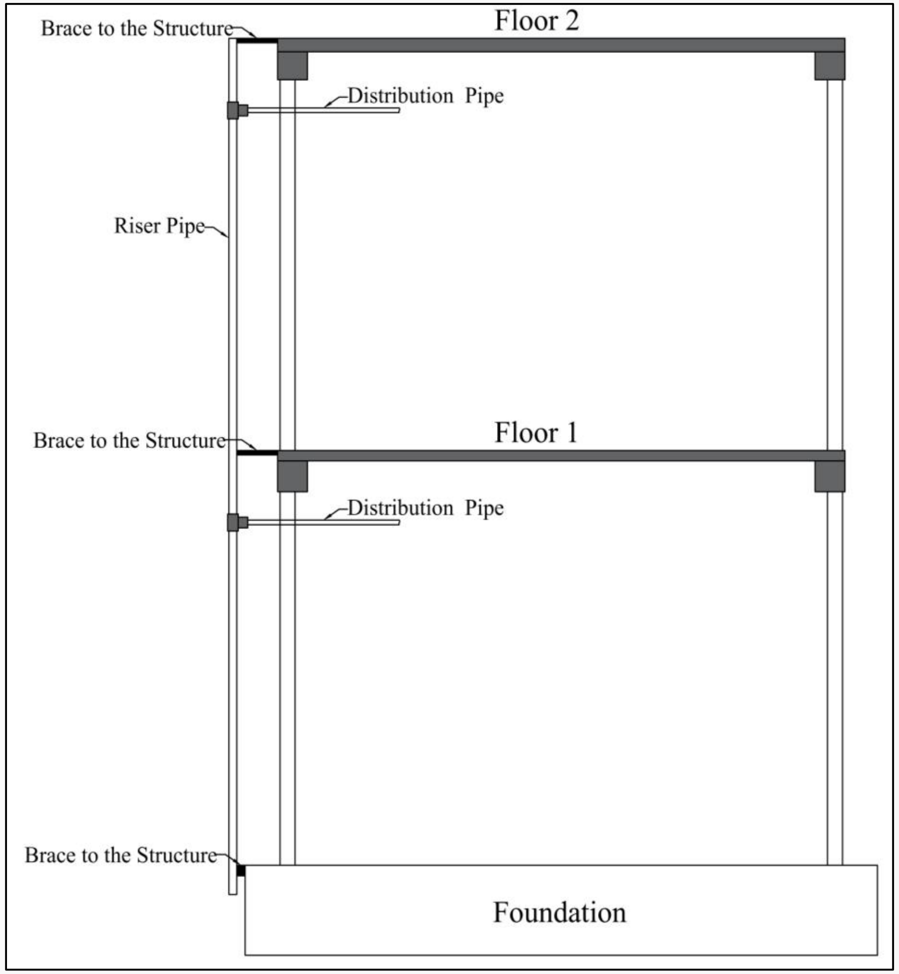
- **Shake Table Test at Tongji University**



(Pourali et al. 2017)

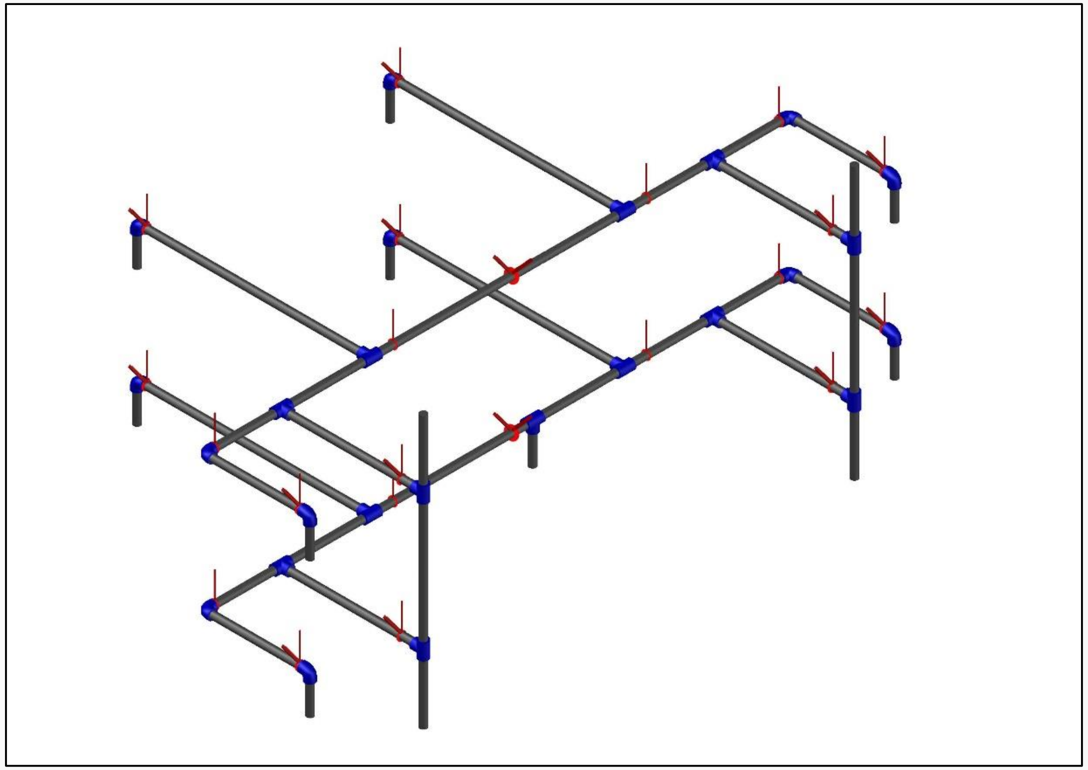
Objective 3: System-Level Performance





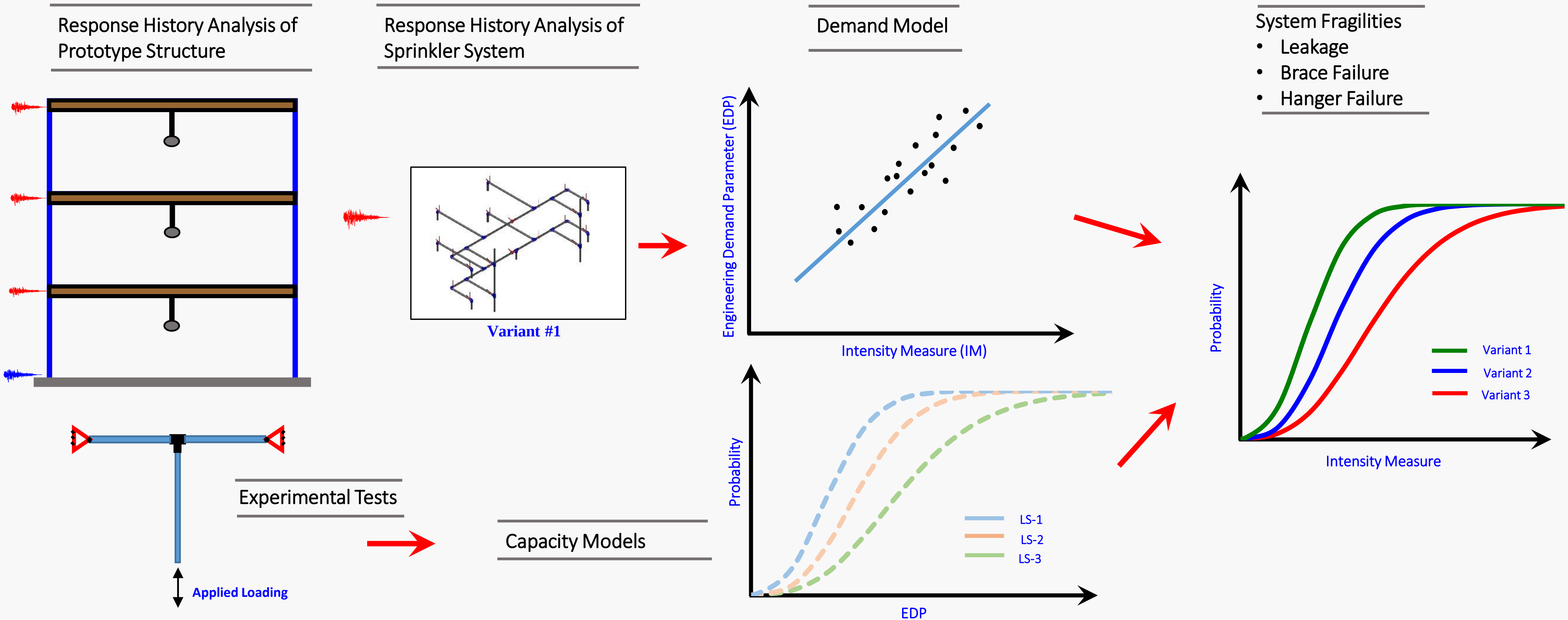
Objective 3: System-Level Performance

- **Part b:** System fragility curves for a sprinkler system with a configuration based on a real-life sprinkler system.
- The system fragilities will be developed for:
  - Different hanger depths.
  - Different brace design.
    - Rigid vs. flexible
    - Spacing
- To assess how varying these details affect the vulnerability of:
  - Connection leakage
  - Brace failure
  - Hanger failure



Objective 3: System-Level Performance

- **Part b:** System fragility curves for a real-life sprinkler system

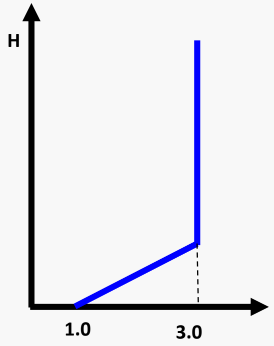


Objective 4: Dynamic Characteristics

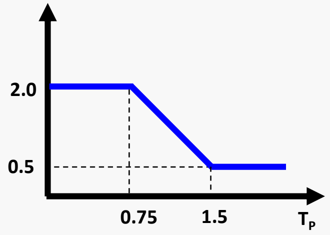
- The time period and damping of a part (component), attached to a building, are needed to determine the seismic force demand on it.

According to NZSE 1170.5, Section 8:

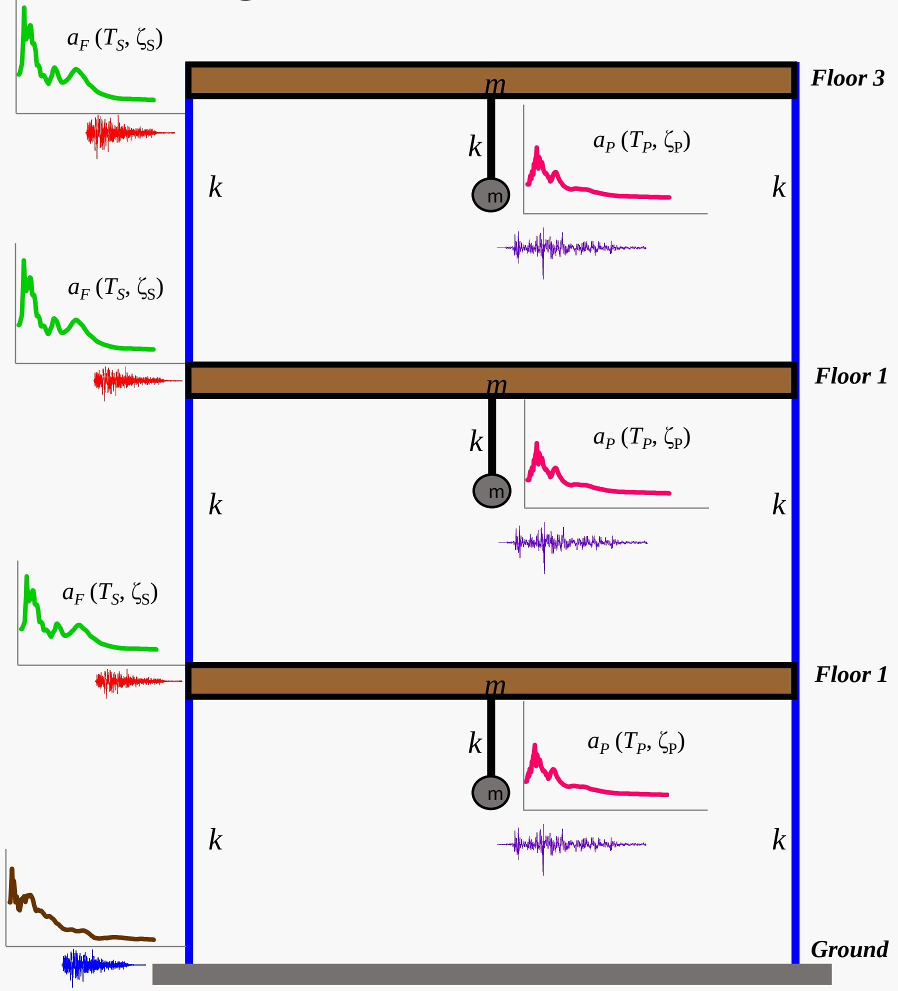
$$C_{Hi}\left(\frac{a_F}{a_G}\right) =$$



$$C_{i}(T_p)\left(\frac{a_P}{a_F}\right) =$$

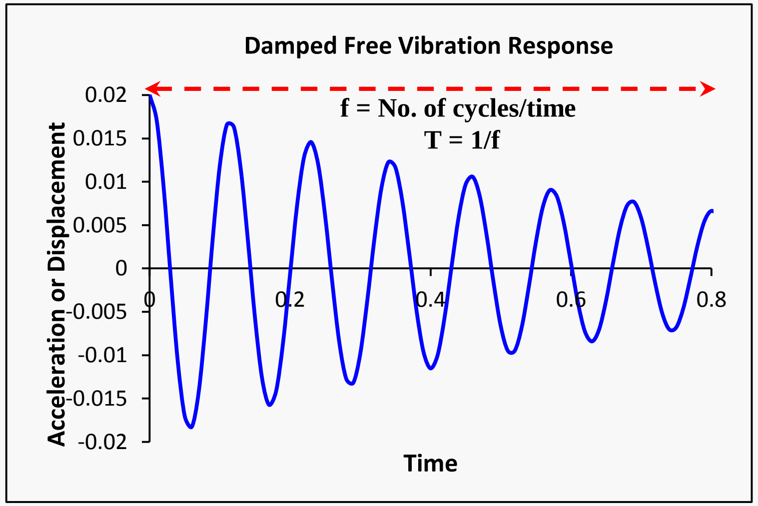


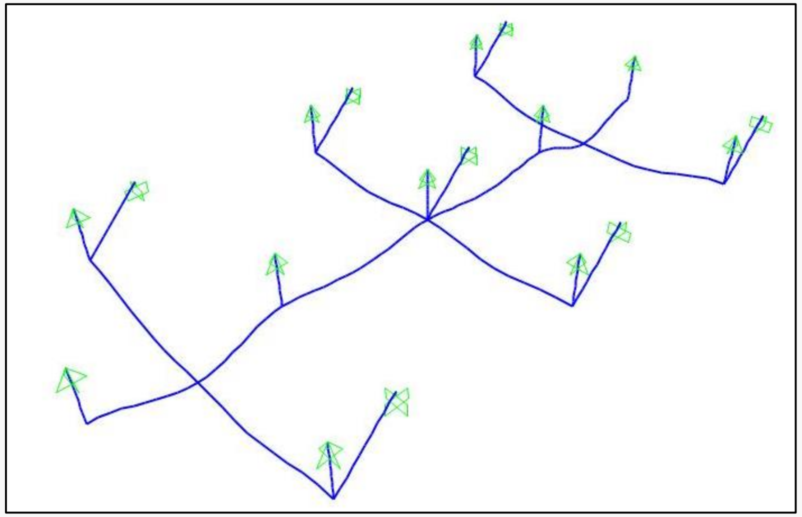
Where:
a_G = Input ground acceleration
a_F = Floor acceleration
T_S = Time period of structure
ζ_S = Damping of structure
a_P = Part (Component) acceleration
T_P = Time Period of part
ζ_P = Damping of part



Objective 4: Dynamic Characteristics

- **Time period:**
- To determine time period of a system from an analytical model, the modelling approach needs to be verified first.
- Once verified, the modelling approach can be used for any generic system.

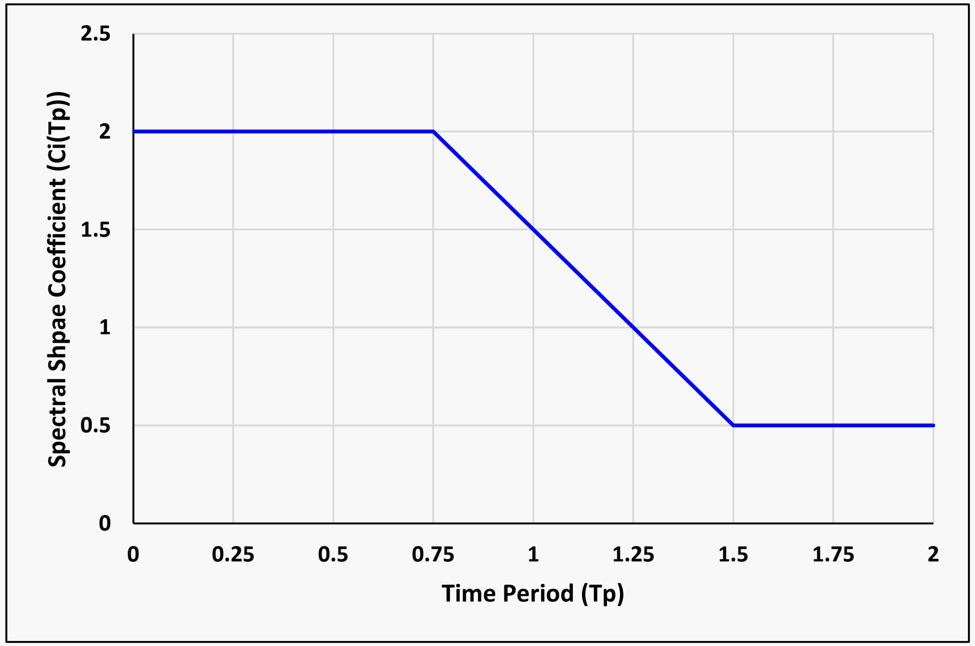




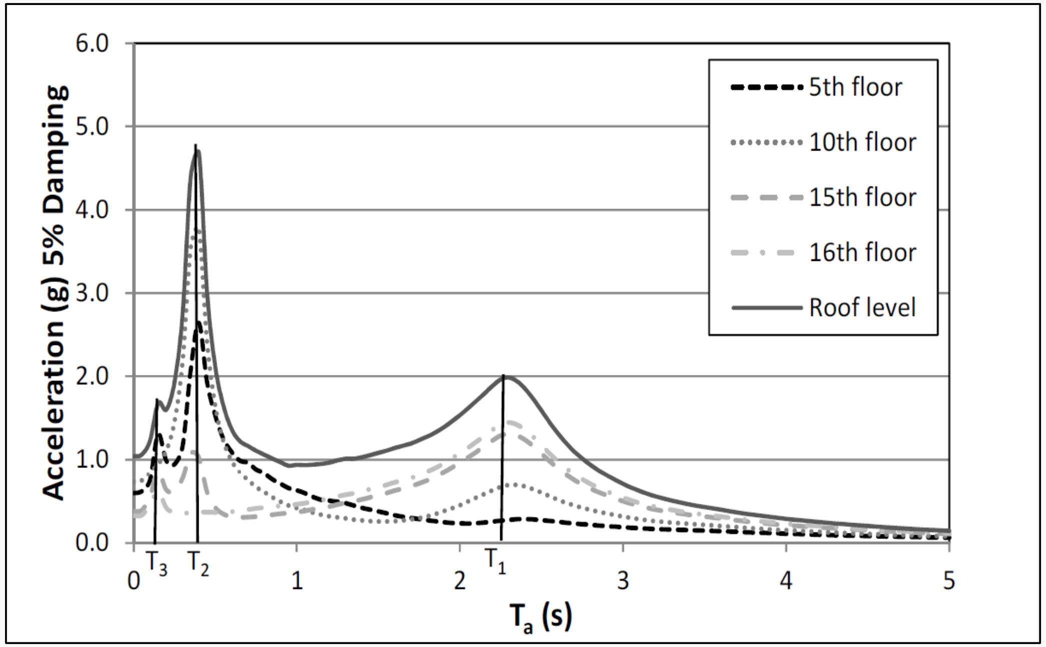
Modal Analysis of Sprinkler System

Objective 4: Dynamic Characteristics

- **Damping**
- The floor spectra method, can give better and realistic estimates of the seismic demands on a component attached to a building as it can account for the dynamic characteristics of the structure and the component (T, ζ).



Spectral Shape Coefficient

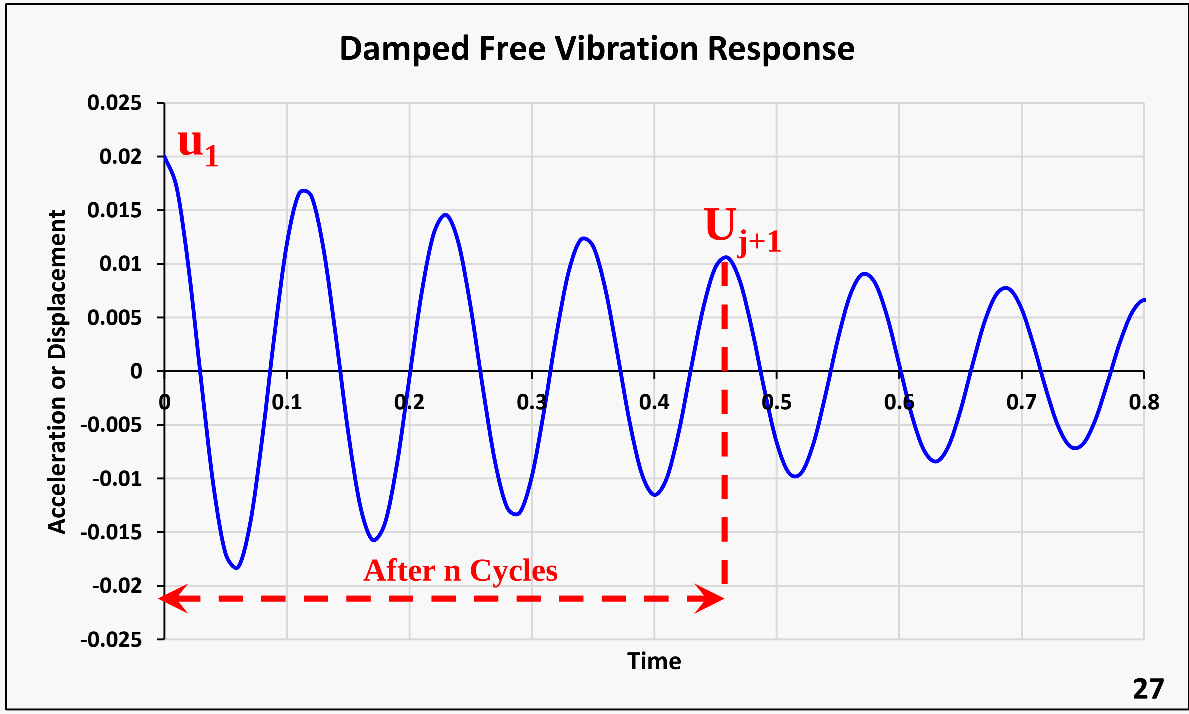


(Calvi et al. 2014) Floor Spectra

Objective 4: Dynamic Characteristics

- **Damping**
- However, damping values for sprinkler system are based on a few experiments and needs validation.
- The damping ratio will be determined from the shake table tests using the free vibration response by the application of logarithmic decrement method.

$$\zeta = \frac{1}{2\pi n} \ln\left(\frac{u_i}{u_{i+j}}\right)$$



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Thank You !