Are Our Buildings Safe Enough?
– Case Studies for a Region of Lower Seismicity

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Do we know…

1. How likely our buildings will collapse in earthquakes?

2. What is our risk of dying in earthquakes?

M6.3 Christchurch, NZ, Earthquake 2011 (no. of deaths = 185)

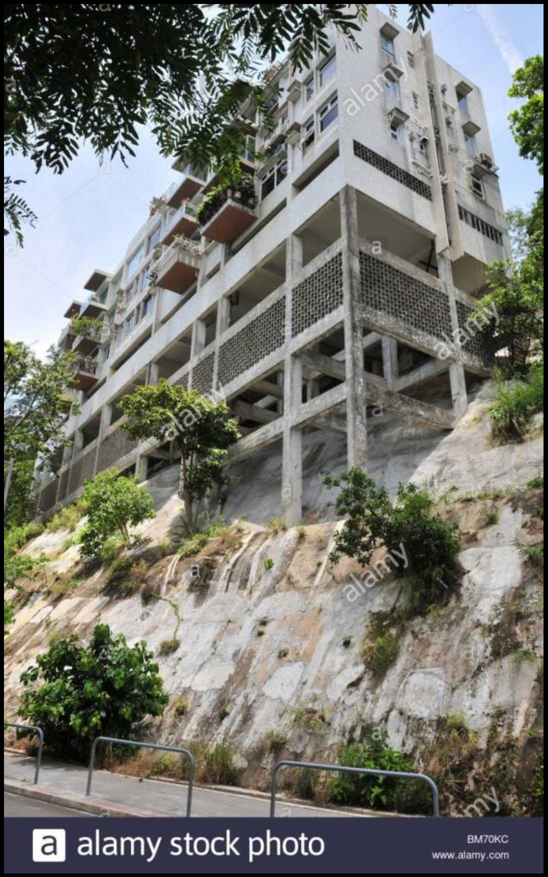
(Photo: Mark Mitchell/AP)

Which Types of Buildings are More Vulnerable?

1. **Aged buildings, especially with insufficient maintenance**
   → Low-to-mid-rise frame

2. **Buildings on slope with columns of different length**
   → Different lateral stiffness
   → *Short Column Effect*
   → Torsional effect

Aged building in Hong Kong



Building on slope in Hong Kong

Factors Affecting Seismic Vulnerability of Columns

1. **Poor joint detailing:**
   → Inadequate shear strength or deformability of joints

2. **Smaller section size**
   → higher axial load
   → smaller drift capacity

3. **Higher strength concrete**
   → smaller drift capacity

M8 Wenchuan Earthquake 2008

QUESTION

How much a column can deform?

Effects of Axial Load Ratio (ALR)

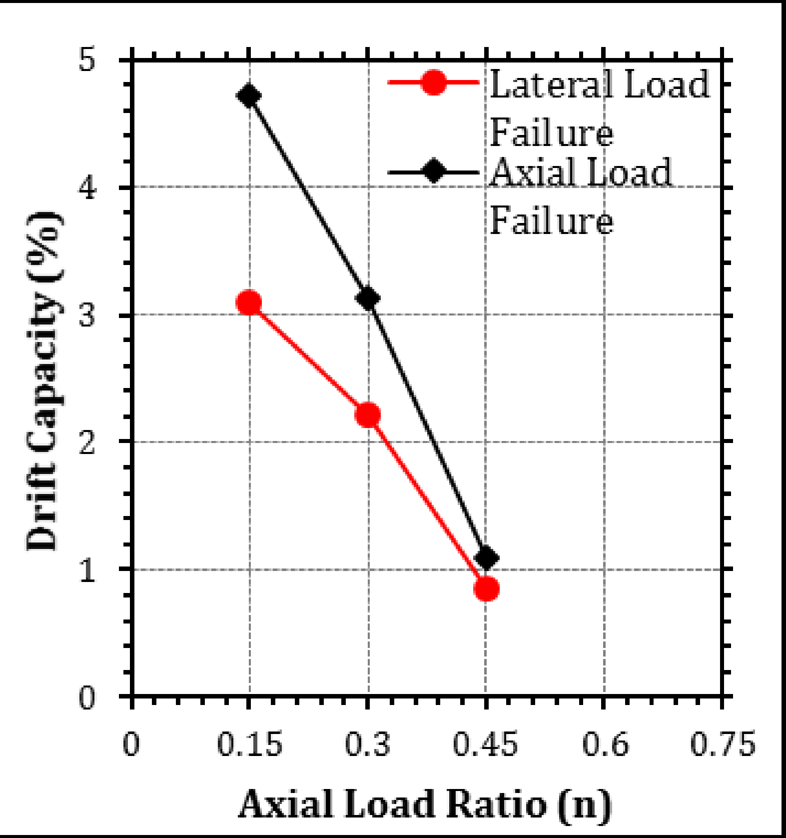
Definition of ALR:

$n = P \,/\, A_g f_c'$

- Actual Axial Load (P)
- Gross Area of Section (A_g)
- Concrete Compressive Strength (f_c')

ALR × 2, drift ↓ 40%

ALR × 3, drift ↓ 80%



Definitions

Lateral Load Failure Drift:

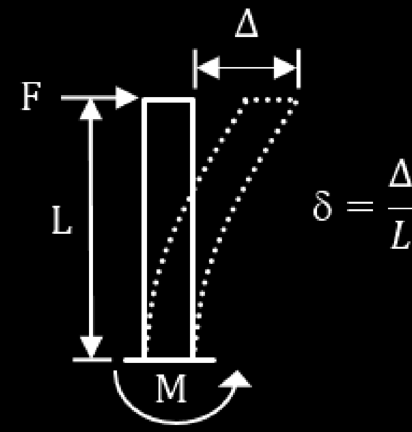
20% reduction from peak lateral strength

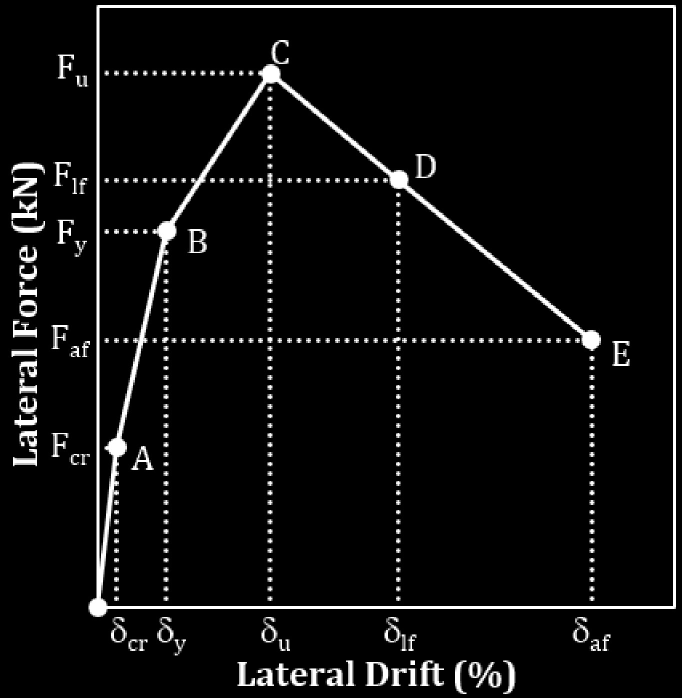
Axial Load Failure (Real Collapse) Drift:

10% loss in axial load carrying capacity

Drift Capacity of RC Columns

– Design Equations





Raza S, Tsang HH, Wilson JL (2018)

Magazine of Concrete Research 70:1081–1101

Lateral Load Failure Drift:

$$\delta_{lf} = 3(1 - 2n) + \left(\rho_h \sqrt{\frac{f_{yh}}{f_c'}}\right)$$

Axial Load Failure (Real Collapse) Drift:

$$\delta_{af} = 5(1 - 2n) + \left(\rho_h \sqrt{\frac{f_{yh}}{f_c'}}\right)$$

n = axial load ratio

ρ_h = transverse reinforcement ratio by area (in %)

f_{yh} = transverse reinforcement yield strength

f_c' = concrete compressive strength

CASE STUDY

Soft-Storey Buildings in Melbourne, Australia

Low-to-mid-rise buildings with column size ~ 300 – 600 mm

Column lengths of 3 – 4 m, Slenderness ratio up to 10

(photos taken by the speaker)

2008 Wenchuan Earthquake
- Soft-Storey Effects

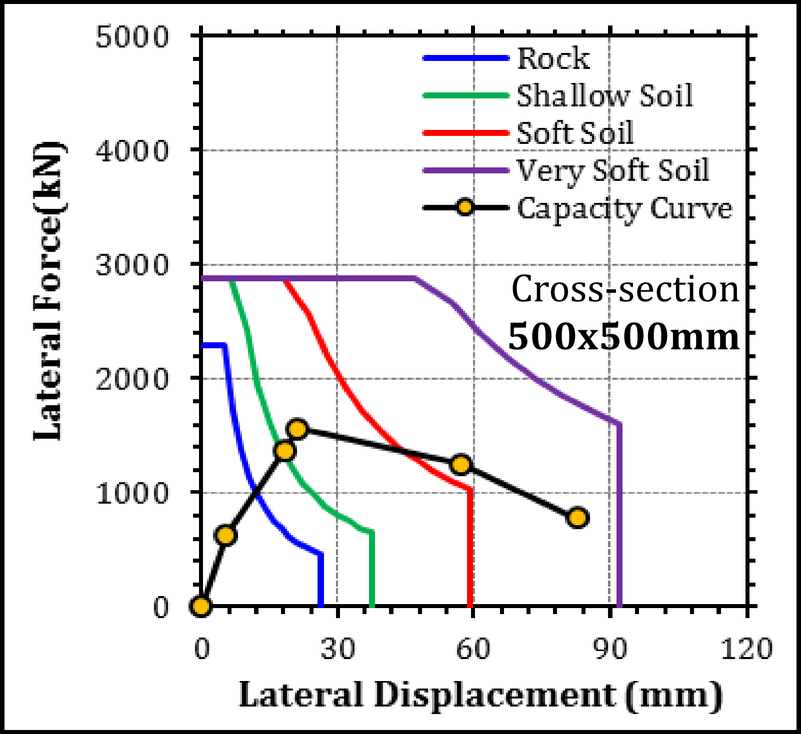
(photos taken by the speaker on July 1, 2008)

Soft-Storey Collapse of an Office Building with an Unsymmetrical Structural Configuration in 1995 Kobe, Japan Earthquake

Source: http://www.ngdc.noaa.gov/

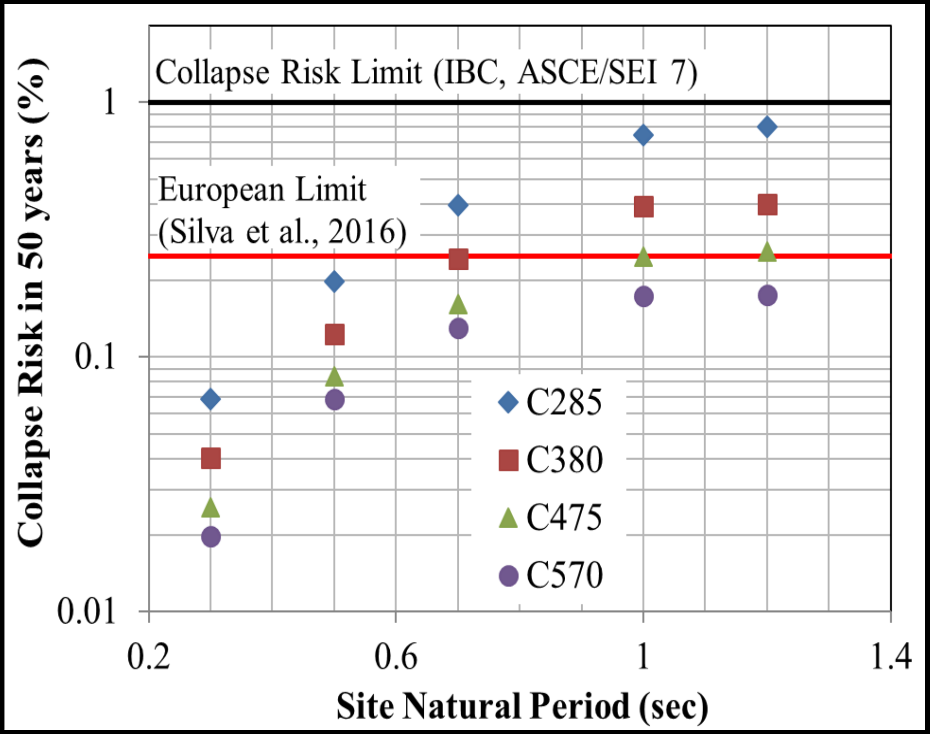
Collapse Risk of RC Soft-Storey Buildings in Melbourne, Australia

Capacity Spectrum Method
(Design Return Period = 500 yr)



Raza S, Tsang HH, Menegon SJ, Wilson JL (2019)
Chapter in *Resilient Structures and Infrastructure*
Springer, p. 269-286

Probabilistic Risk Analysis



Tsang et al. (2016)
Proceedings of 24th ACMSM

Risk-based Performance Objective

Aim: Uniform Collapse Risk for All Structures

Target Collapse Risk, P(C), in 50 yr (ordinary buildings):

U.S. International Building Code (2012): **1%**

Europe – Silva et al. (2016): **0.25%**

Tsang & Wenzel (2016): **0.5%** (0.25% - 1%, depending on building type)

Europe - Dolšek et al. (2017): **0.5%**

Leading the "Performance Objectives" chapter in the EAEE Working Group 1: Future directions for Eurocode 8

Drift Capacity of RC Columns
– seems to be sufficient?

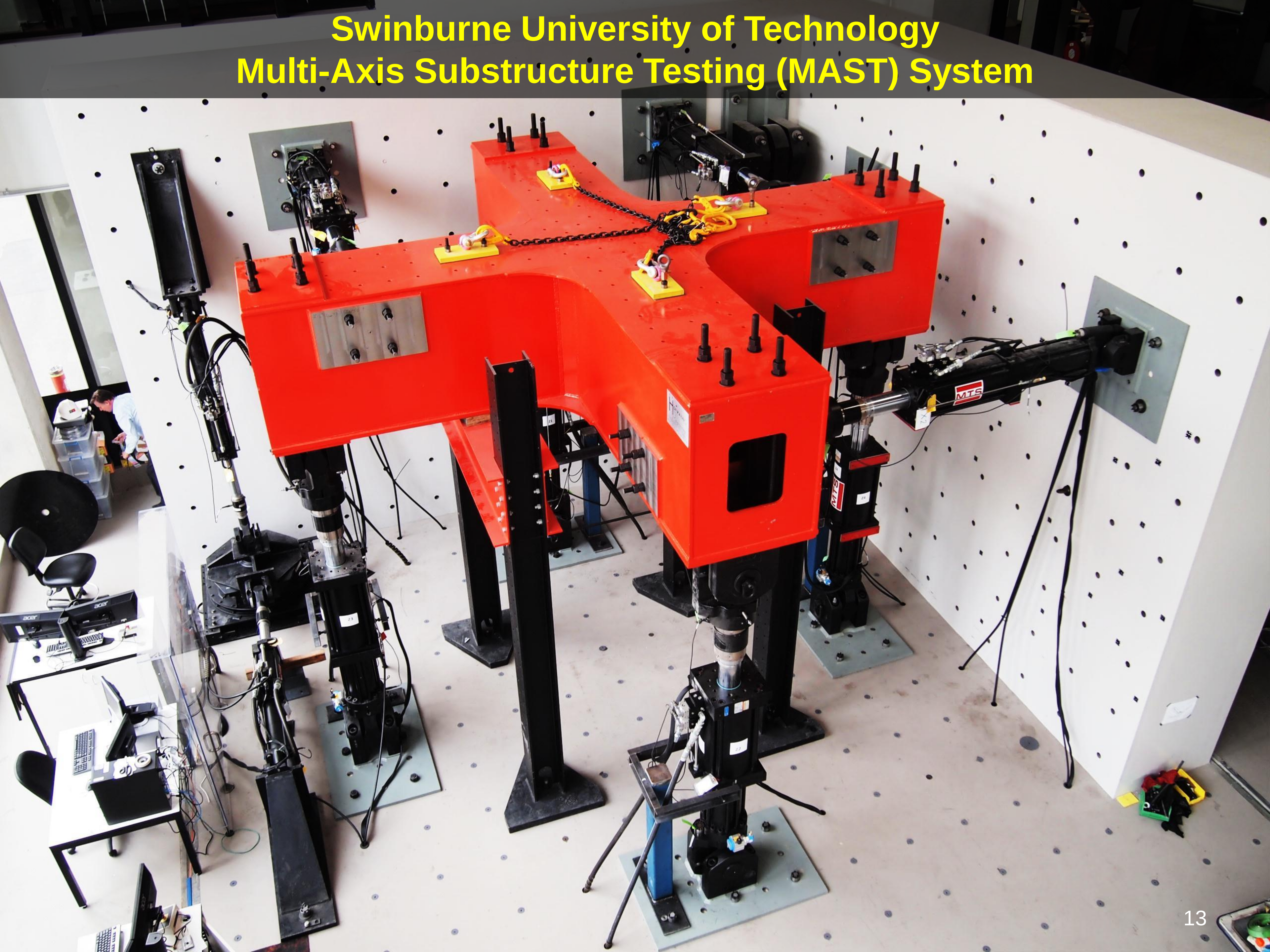
Existing Studies:

1. **Mostly uni-directional loading**
2. **Axial load is constant**

Real Earthquakes:

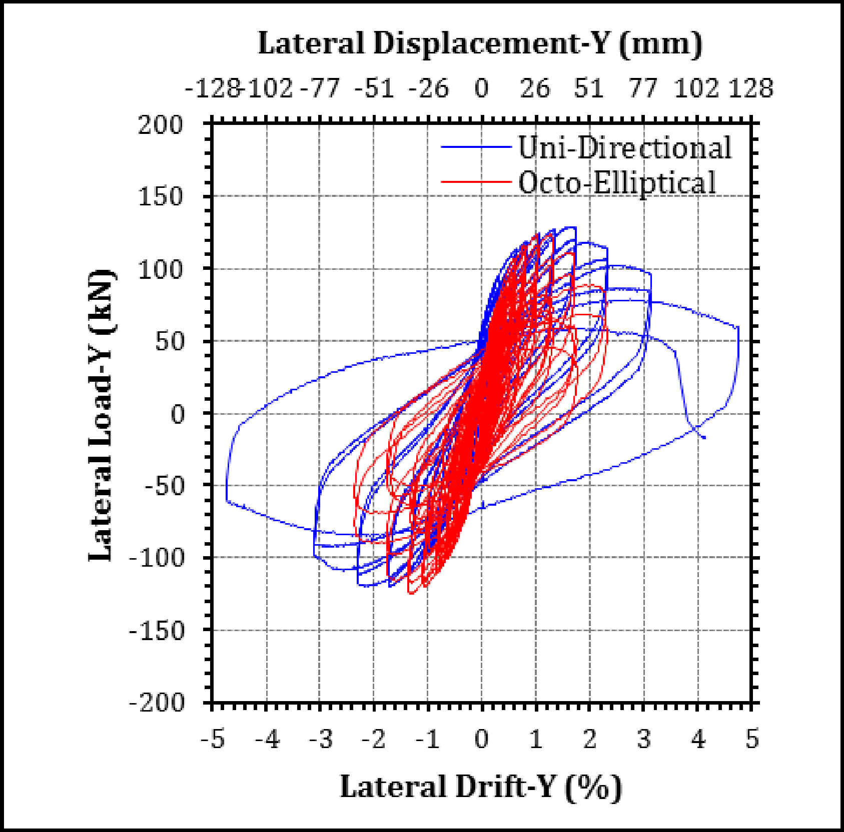
1. **Shakings are multi-directional**
2. **Axial load is varying**

Swinburne University of Technology
Multi-Axis Substructure Testing (MAST) System

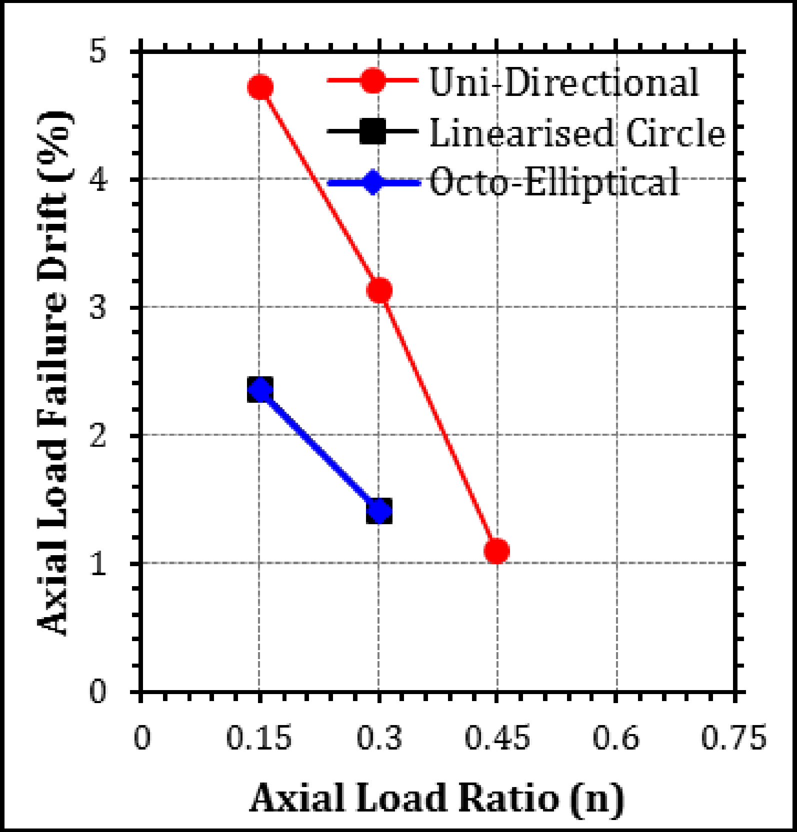


Effects of Bi-Directional Motions

e.g. Axial Load Ratio = 0.15



Collapse Drift reduced by 50%



Drift Capacity of RC Columns is halved under Bi-directional Loading !!

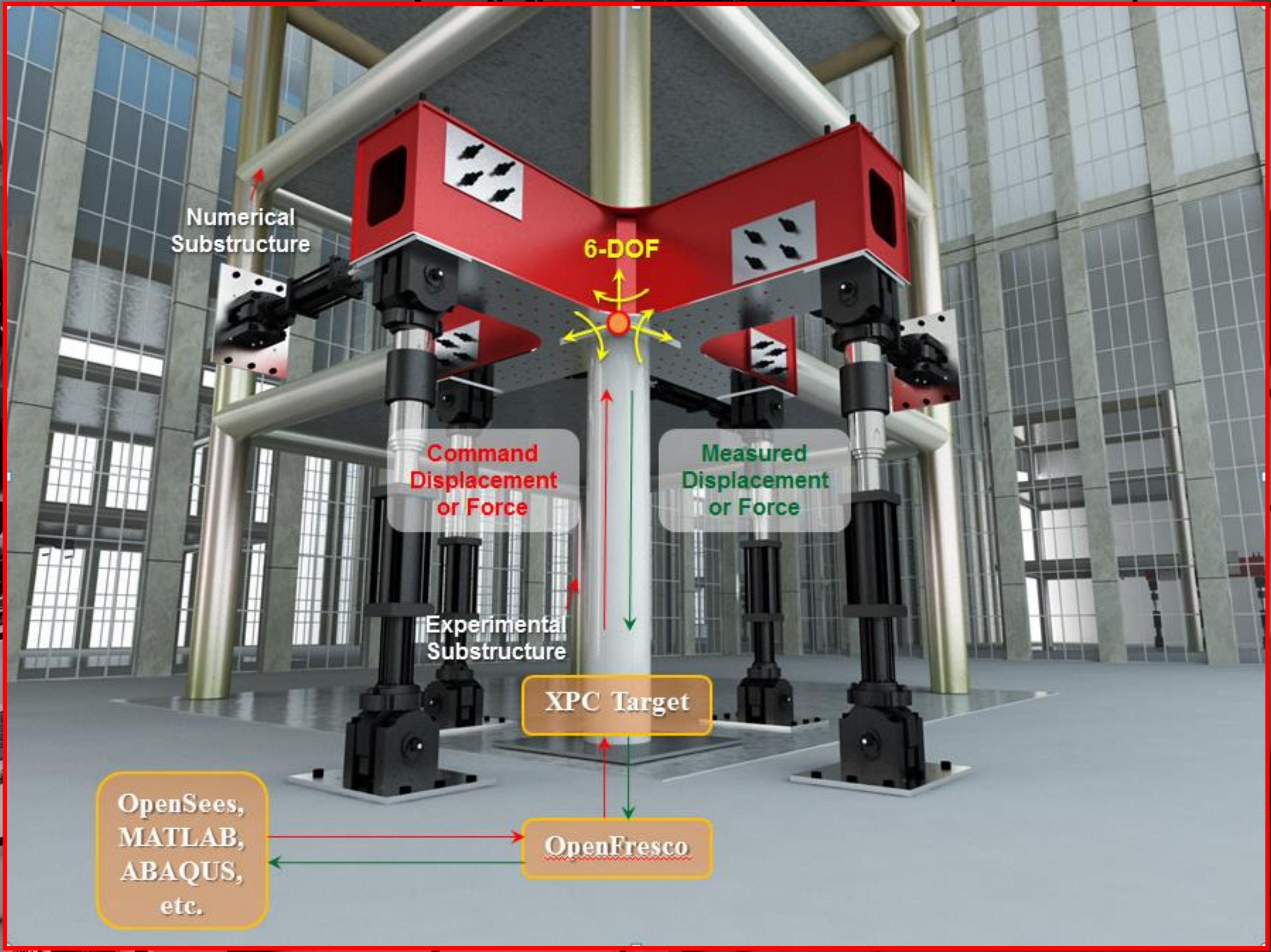
ANOTHER PROBLEM

Existing Studies: Axial load is <u>constant</u>

Real Earthquakes: Axial load is <u>varying</u>

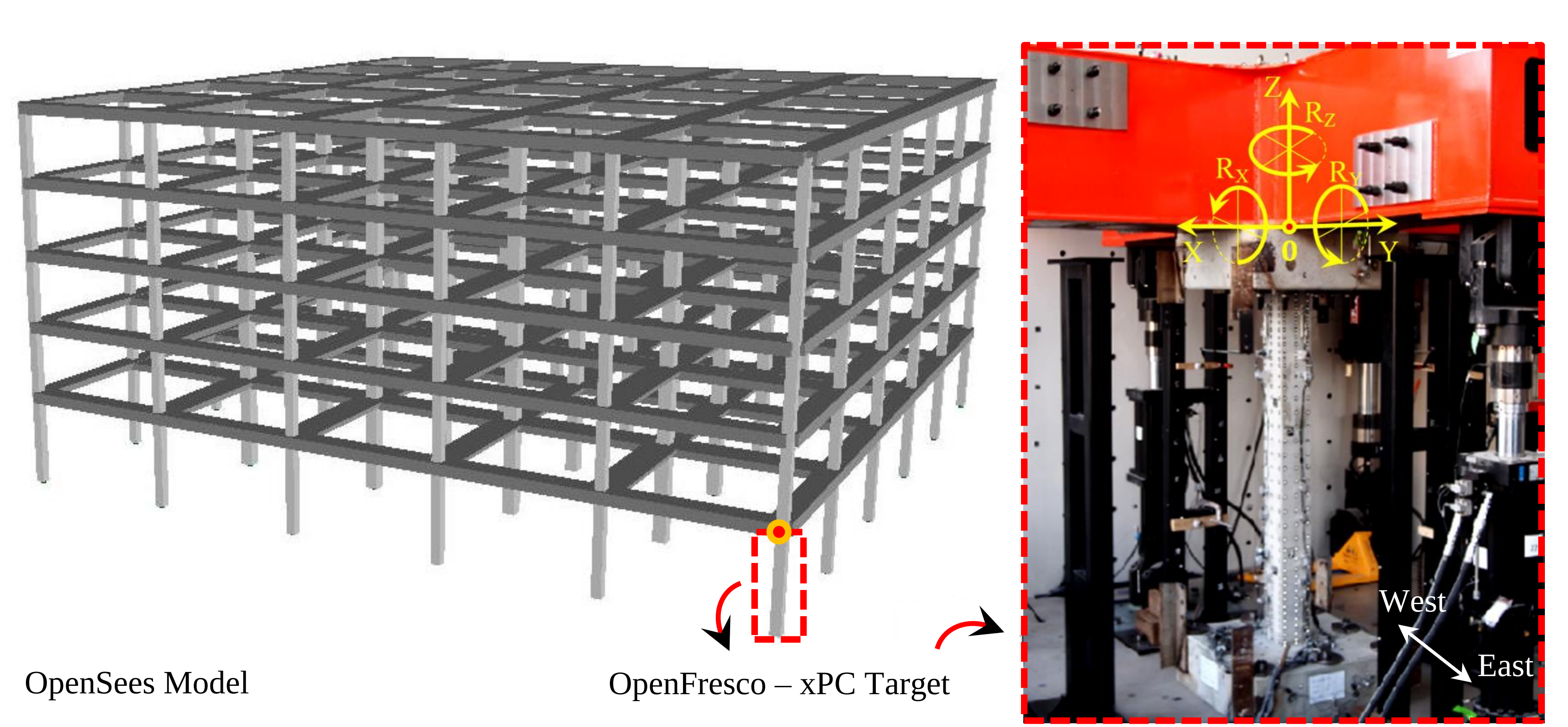
How can we investigate
real earthquake response ?

Hybrid Simulation (a.k.a. pseudo-dynamic testing)



Effects of Varying Axial Loads in Real Earthquakes

Moment Frame Structures with In-situ RC Columns



a) Numerical substructure b) Experimental substructure

Hashemi, Tsang et al. (2017)

Real Earthquake Response of RC Column

- Higher Flexural Strength
- Steeper Post-Peak Strength Degradation

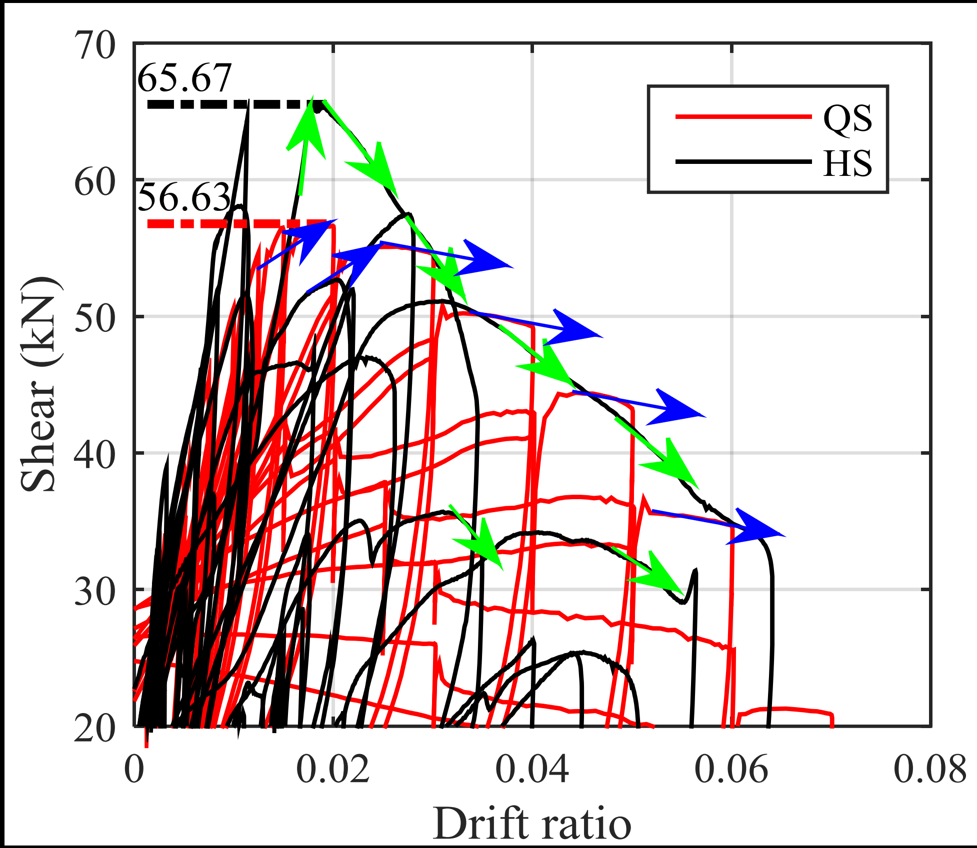
Quasi-Static (QS) Test

*(with **constant** axial load)*

Hybrid Simulation (HS)

*(with **varying** axial load)*

Hashemi, Tsang et al. (2017).
ACI Structural Journal



Collapse Risk is Much Higher in Real Earthquakes

than that implied by results from most Laboratory Tests

Quasi-Static (QS) Test

*(with **constant** axial load)*

Hybrid Simulation (HS)

*(with **varying** axial load)*

Hashemi, Tsang et al. (2017).
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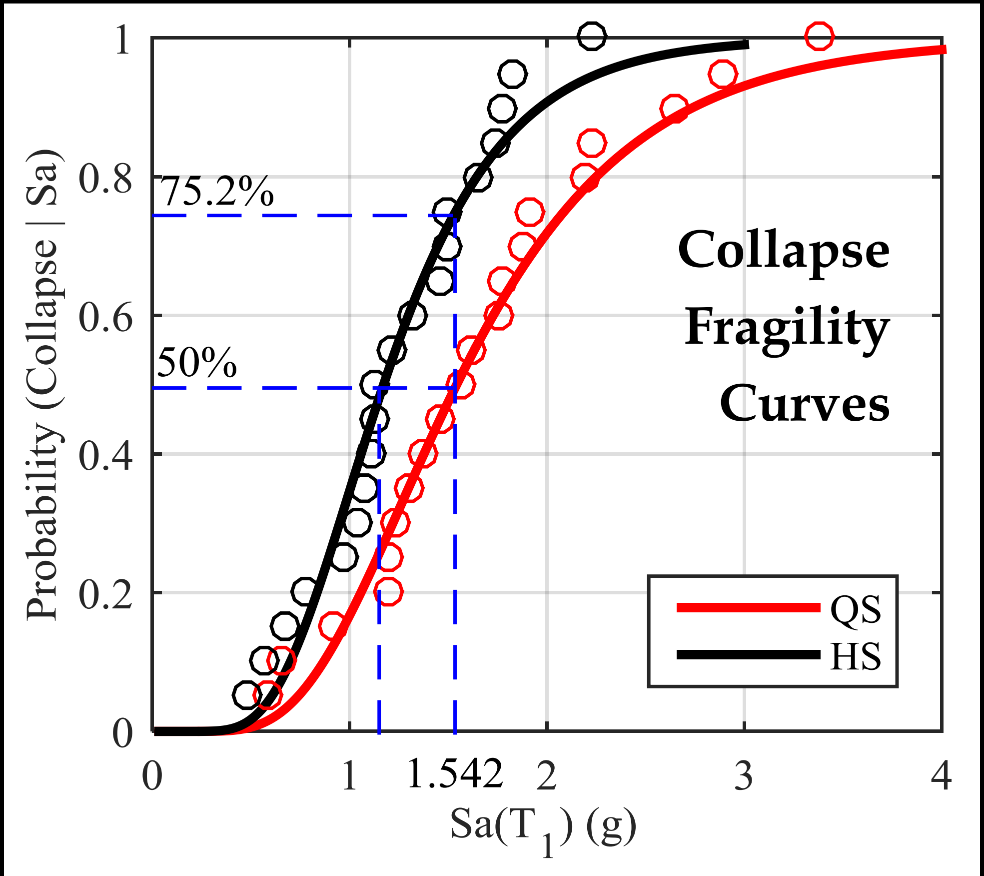


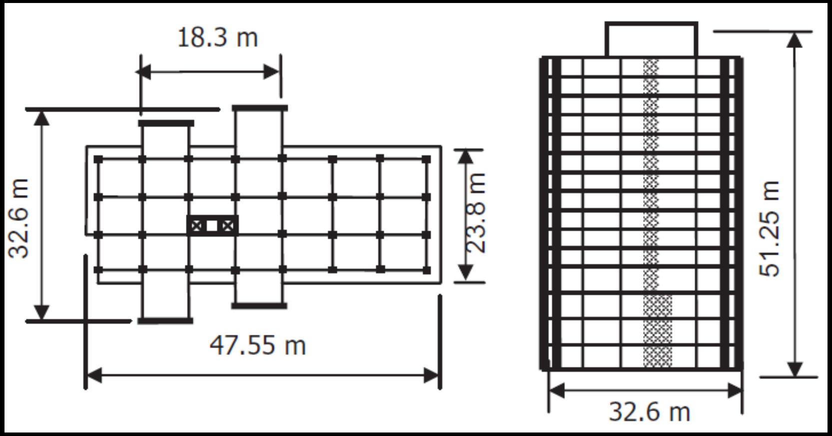
HYPOTHETICAL CASE STUDY

Lateral Load Failure Drift Capacity = 1.1%

(Experiment: axial load ratio = 0.3, bi-directional)

Reference Drift Demand =

0.4–0.5% (2%/50yr) (Tsang et al. 2009)



15-Storey Swire Building, HKU
(no soft-storey)

What if there is…

Short Column Effect

→ Column length halved, drift **doubled**

→ Drift increased by **~50%** due to torsional effect

→ **Drift Demand = 1.2–1.5%**

Question:

Is it adequate for mortality control?

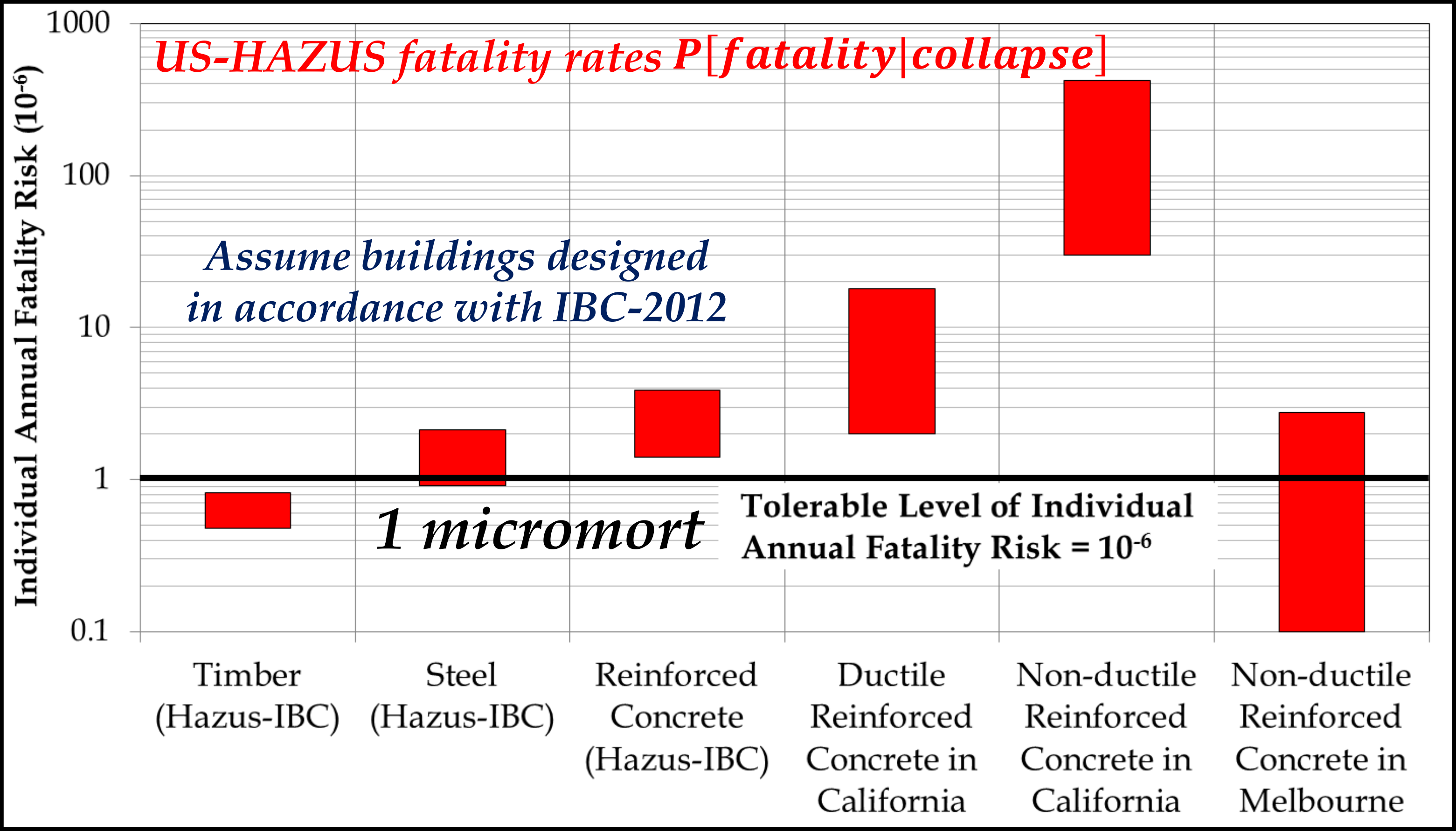
Tolerable Level of Individual Annual Fatality Risk

Maximum Allowable Annual Fatality Risk ~ 10^{-6}

"micromort"

- ISO 2394:1998 "General Principles on Reliability for Structures"
- Eurocode – Basis of Structural Design EN 1990:2002
- The Ministry of Housing, Spatial Planning and the Environment (VROM) of the Netherlands
- The Long Beach City Council, California, U.S. (1971)
- Historical mortality data caused by natural hazards (Starr, 1969, 1972)

Estimated individual annual fatality risk



Tsang, Wenzel, Daniell (2017) *Haselton, Liel, Deierlein (2007-08)* *Tsang et al. (2016) (uni-directional)*

Is the risk limit 10^{-6} Safe Enough ??

Probably YES as an individual risk limit.

However, for a city with ***5 millions*** *population*,

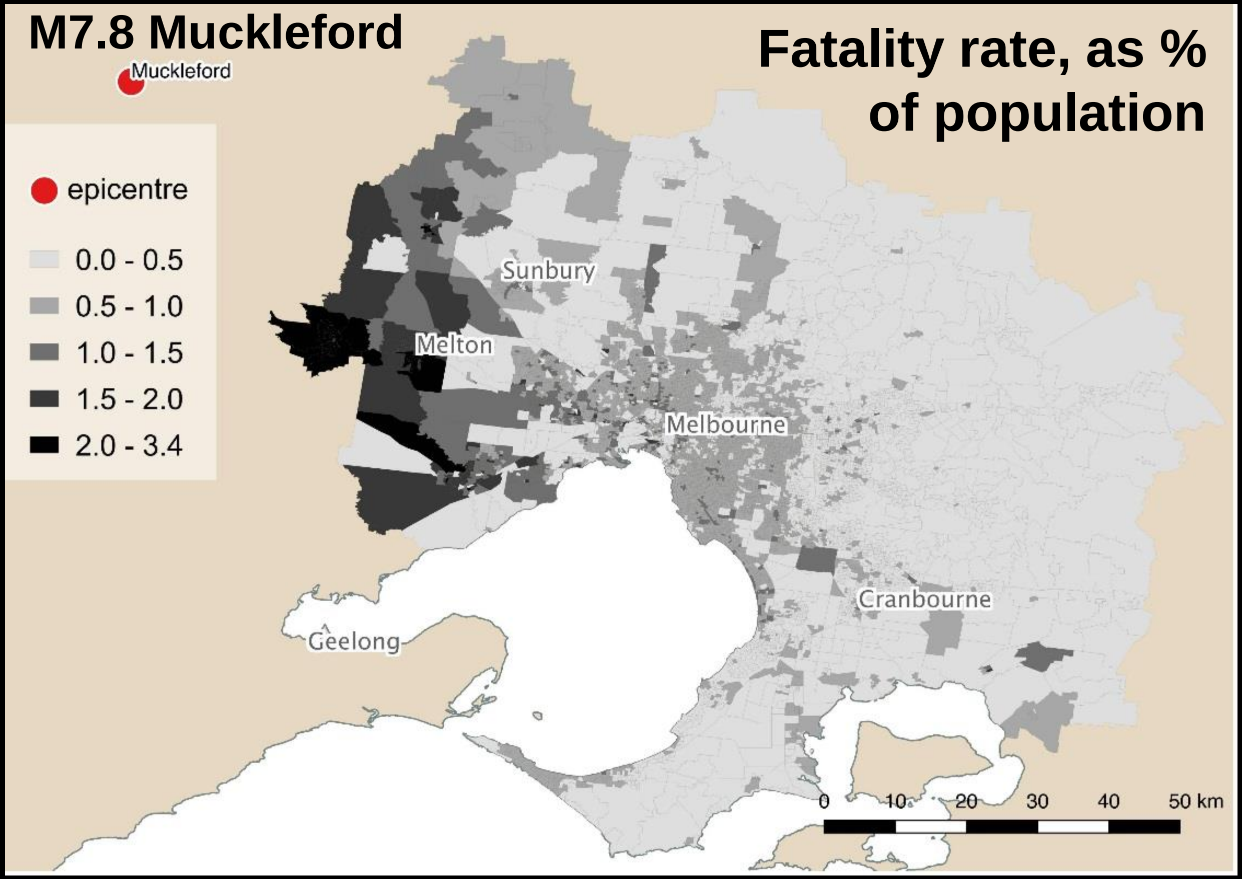
it is **'expected', 'designed' and 'allowed'** to have an average of

50 deaths due to ***collapse of structures*** **in every decade …**

Melbourne, Australia

Societal Fatality Risk Case Study

Scenario Loss Modelling using Software SELENA



Tsang, Daniell, Wenzel, Werner (2018). Natural Hazards

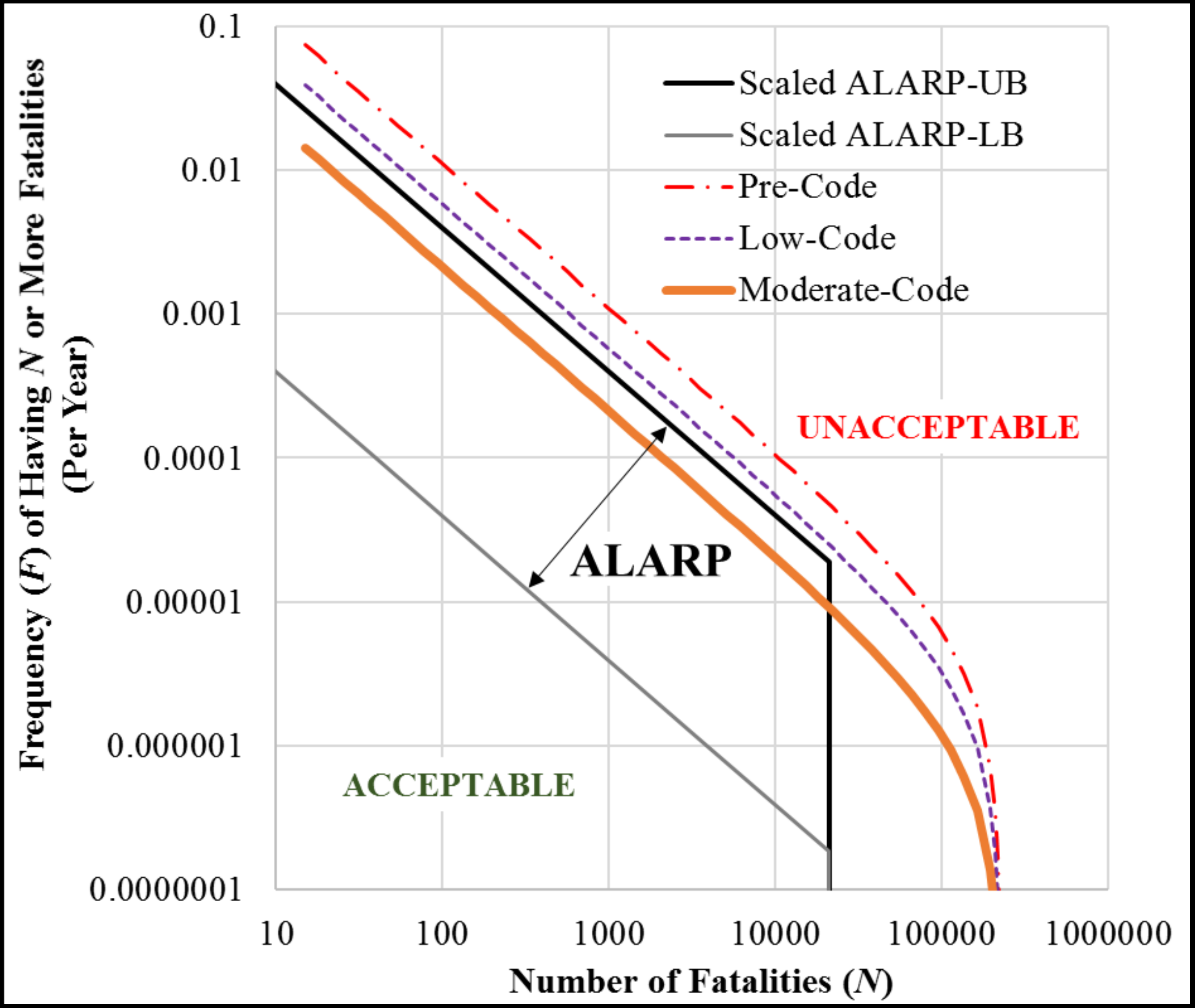
Low-rise Unreinforced Masonry

&

Low-rise RC Frame

*are most fatal (~**4.5% death**)*

Simulated Risk Function vs. Proposed Regulation



Societal fatality risk function

- *HAZUS **Moderate**-code (0.2g) URML & C1L*
- *with remaining Pre-code building stocks*

Tsang, Daniell, Wenzel (2018). 16th ECEE Thessaloniki, Greece

Conclusions

1. ***Our Buildings are considered SAFE, if… …***

   - Axial Load Ratio is relatively low.

   - Bi-directional Action is not significant.

   - They are not sitting on slope or soft / flexible site.

2. ***Individual Micro-Risk of Death*** (***limit to*** $\mathbf{10^{-6}}$ ***/ yr***)

   - P(Collapse)=1%/50yr in US Code leads to higher fatality risk.

3. *Unbearable* ***Societal Risk*** *for Densely-Populated City*

   - may require more stringent design requirements.

Background picture: allandroidanswer.com