Issues in the fragility analysis of non-structural elements and the role of structural health monitoring

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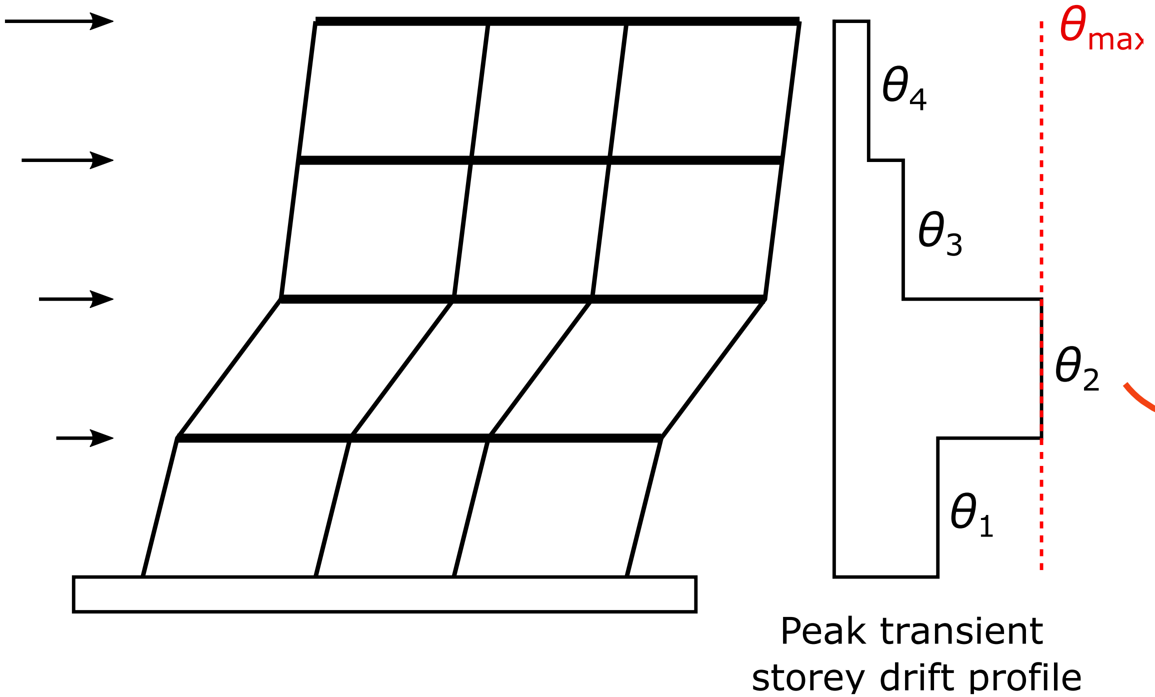
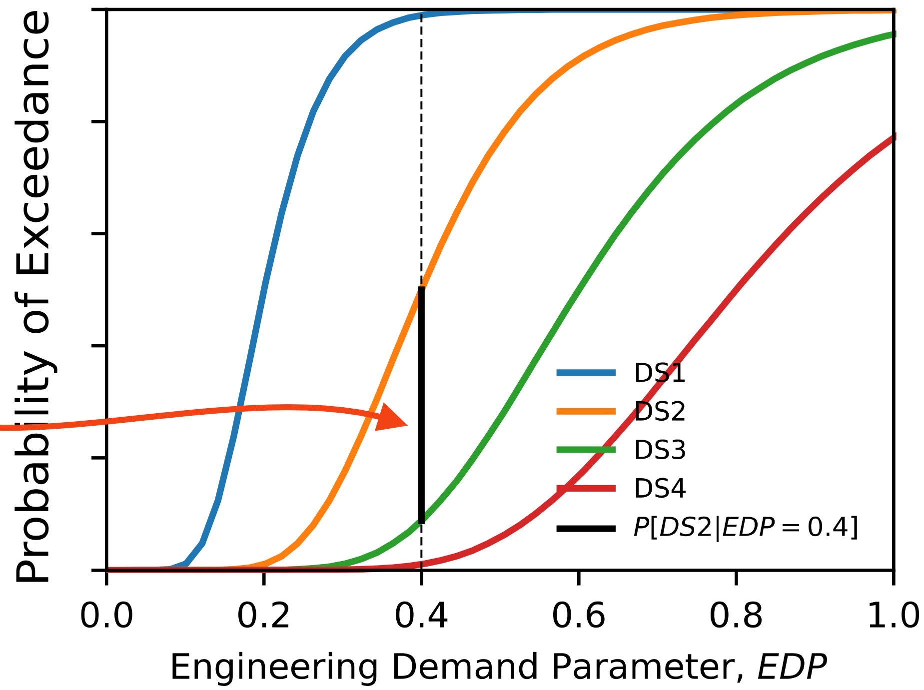
SPONSE INTERNATIONAL ASSOCIATION FOR THE SEISMIC PERFORMANCE OF NON-STRUCTURAL ELEMENTS

Damage and loss estimation of NSEs





1. Experimental data
2. In-situ measurements
3. Numerical simulations
4. Expert opinion

$$L_{n,i,k} = N_n \sum_{j=1}^{N_{DS}} L_{n,k}[DS_j] \underbrace{P[DS_j|EDP_i]}_{\text{Probability of damage}}$$

Experimental testing

- Following on from the tradition of structural element testing, the same approach has been applied to NSEs

Experimental testing

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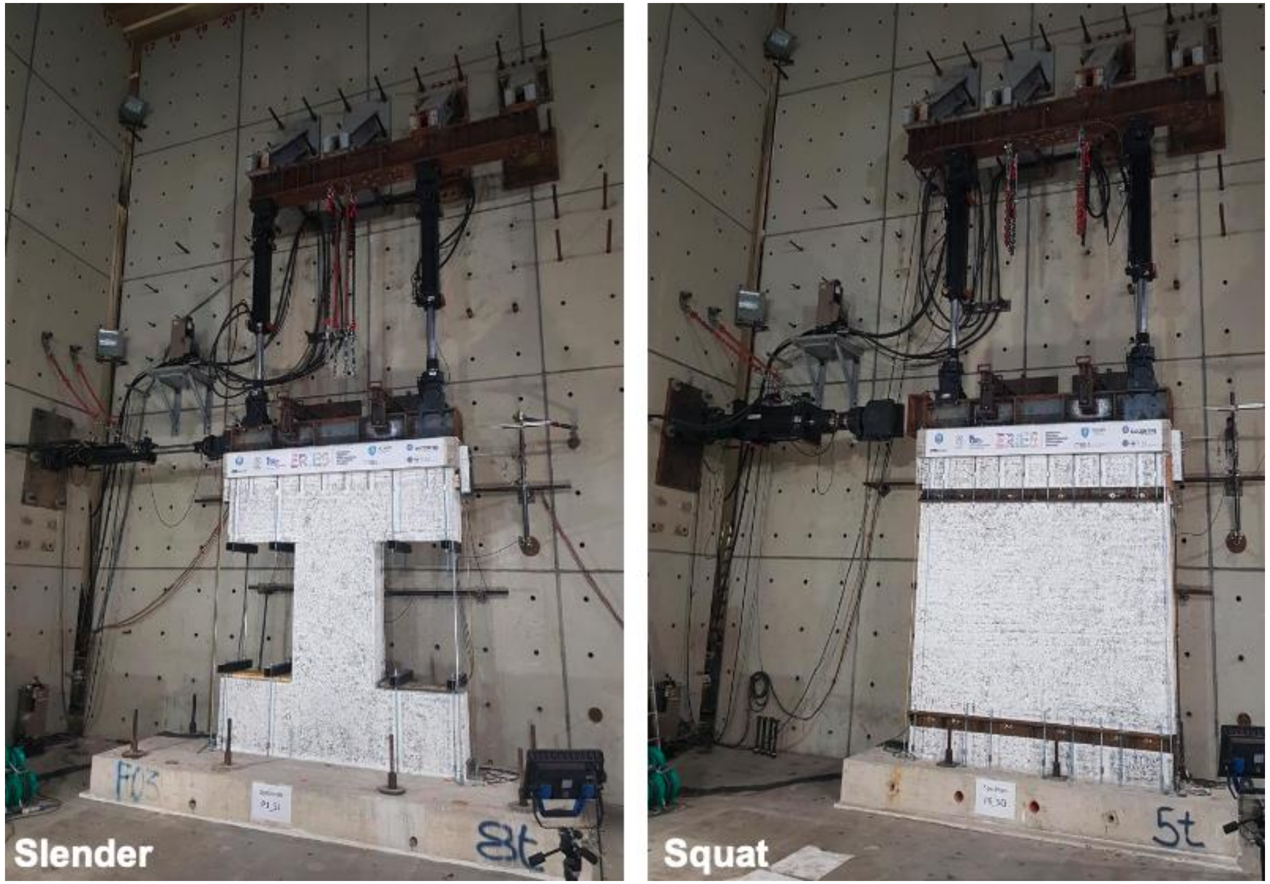
ERIES-RESTORING: Retrofitting of STOne masonRy using INnovative Grid-based composites



Images from: Ponte, M., Guerrini, G., Garcia-Ramonda, L., Lanese, I., Rizzo Parisi, E., O'Reilly, G. J., Graziotti, F., Tsiavos, A., Pelà, L., Penna, A., Magenes, G., & Bento, R. (2024). Retrofitting of stone masonry using innovative grid-based composites: the ERIES-RESTORING project. 18th World Conference on Earthquake Engineering, Milan, Italy.

Experimental testing

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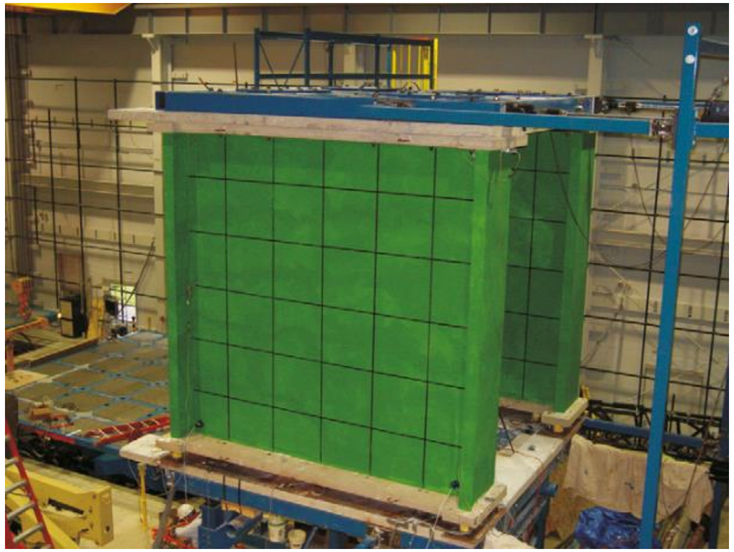
Silos

Transmission towers

Gypsum partitions



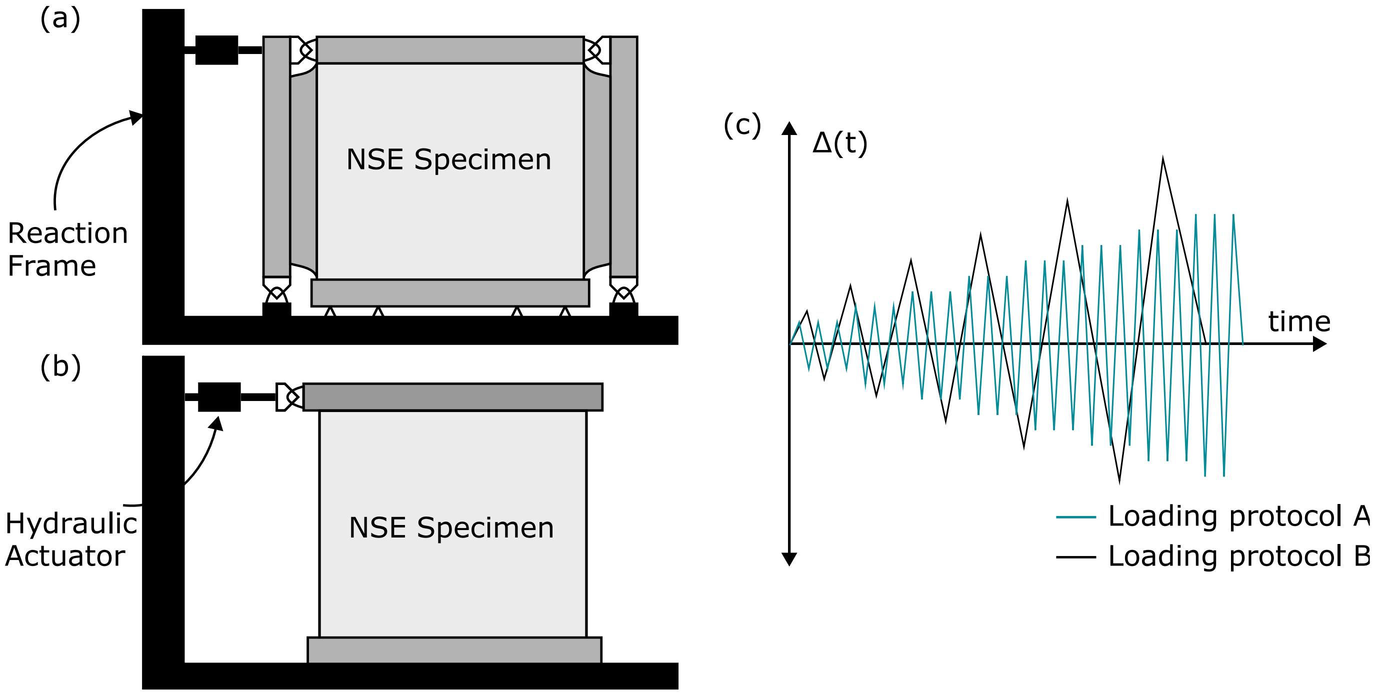
Images from www.eucentre.it and Retamales, R., Davies, R., Mosqueda, G., & Filiatrault, A. (2013). Experimental Seismic Fragility of Cold-Formed Steel Framed Gypsum Partition Walls. Journal of Structural Engineering, 139(8), 1285–1293. https://doi.org/10.1061/(asce)st.1943-541x.0000657

Experimental testing: potential discrepancies

- While a logical approach, several situations may arise in which the experimental testing of NSEs in a laboratory setting may not adequately represent reality:

  - Bianchi and Pampanin [2022] note how fragility functions derived from experimental testing of NSEs are significantly influenced by their **connection** details

  - Which loading protocols should be applied?



Bianchi, S., & Pampanin, S. (2022). Fragility Functions for Architectural Nonstructural Components. Journal of Structural Engineering, 148(10). https://doi.org/10.1061/(ASCE)ST.1943-541X.0003352

Experimental testing: potential discrepancies

- While a logical approach, several situations may arise in which the experimental testing of NSEs in a laboratory setting may not adequately represent reality:

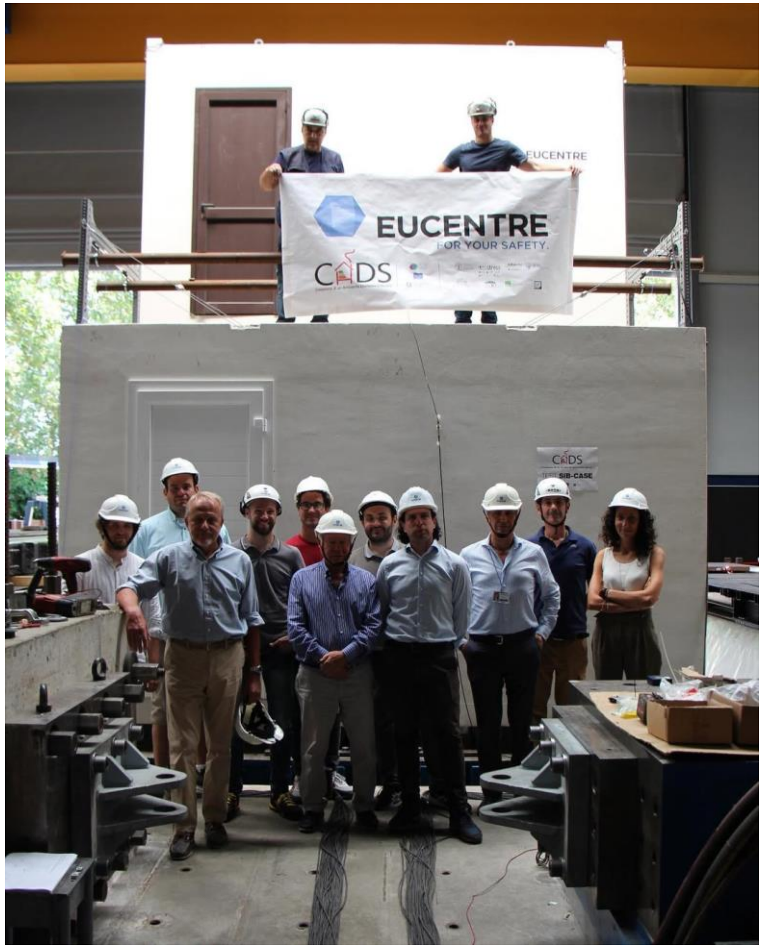
    - Interaction with other elements

Experimental testing: potential discrepancies

- While a logical approach, several situations may arise in which the experimental testing of NSEs in a laboratory setting may not adequately represent reality:

  - Quality of workmanship during installation

Tested specimen



Experimental testing: potential discrepancies

- While a logical approach, several situations may arise in which the experimental testing of NSEs in a laboratory setting may not adequately represent reality:
  - Quality of workmanship during installation

Actual construction

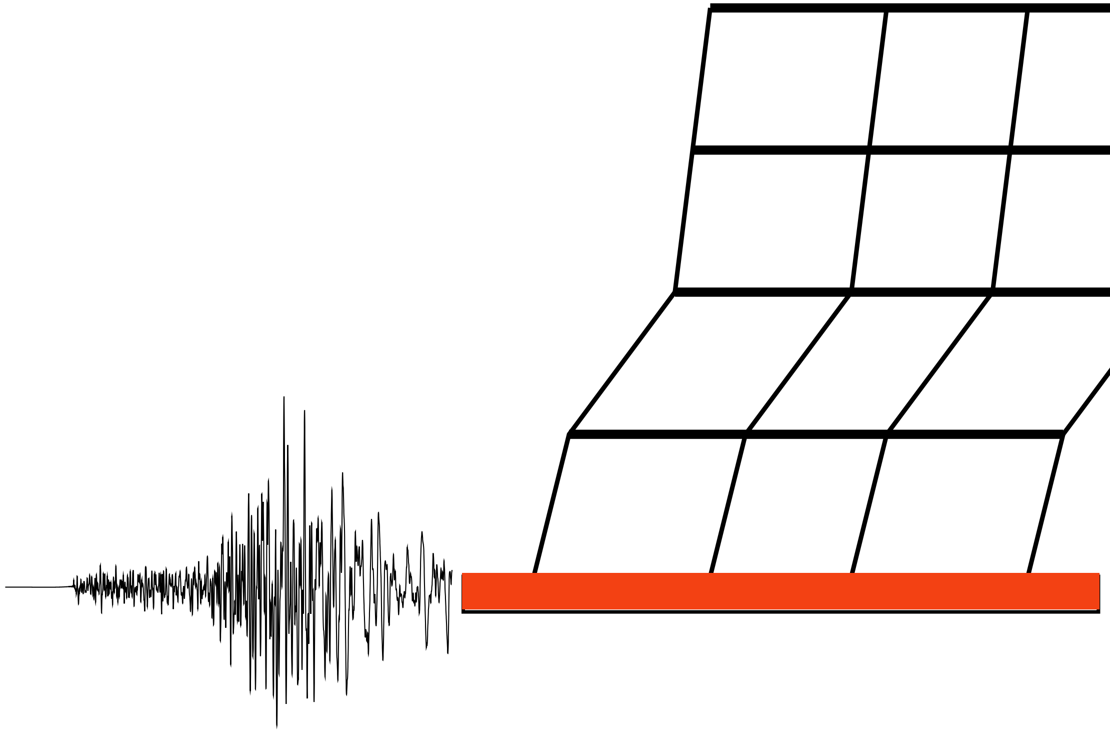
Experimental testing: potential discrepancies

- While a logical approach, several situations may arise in which the experimental testing of NSEs in a laboratory setting may not adequately represent reality:
    - Wear, tear and unanticipated interventions

Wear and tear

Experimental testing: possible solutions?

- Traditionally, dynamic testing has been via shaking table tests to replicate the ground shaking



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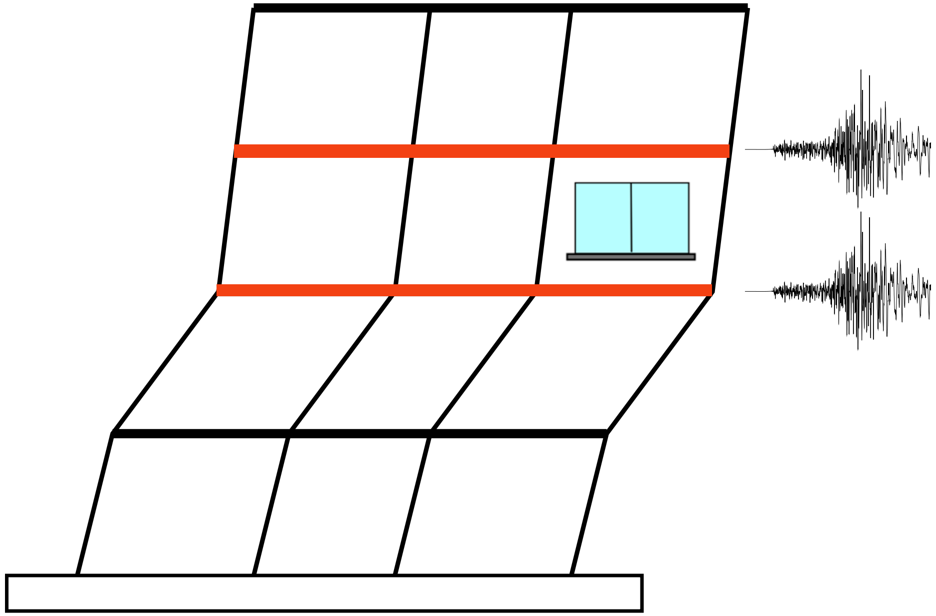
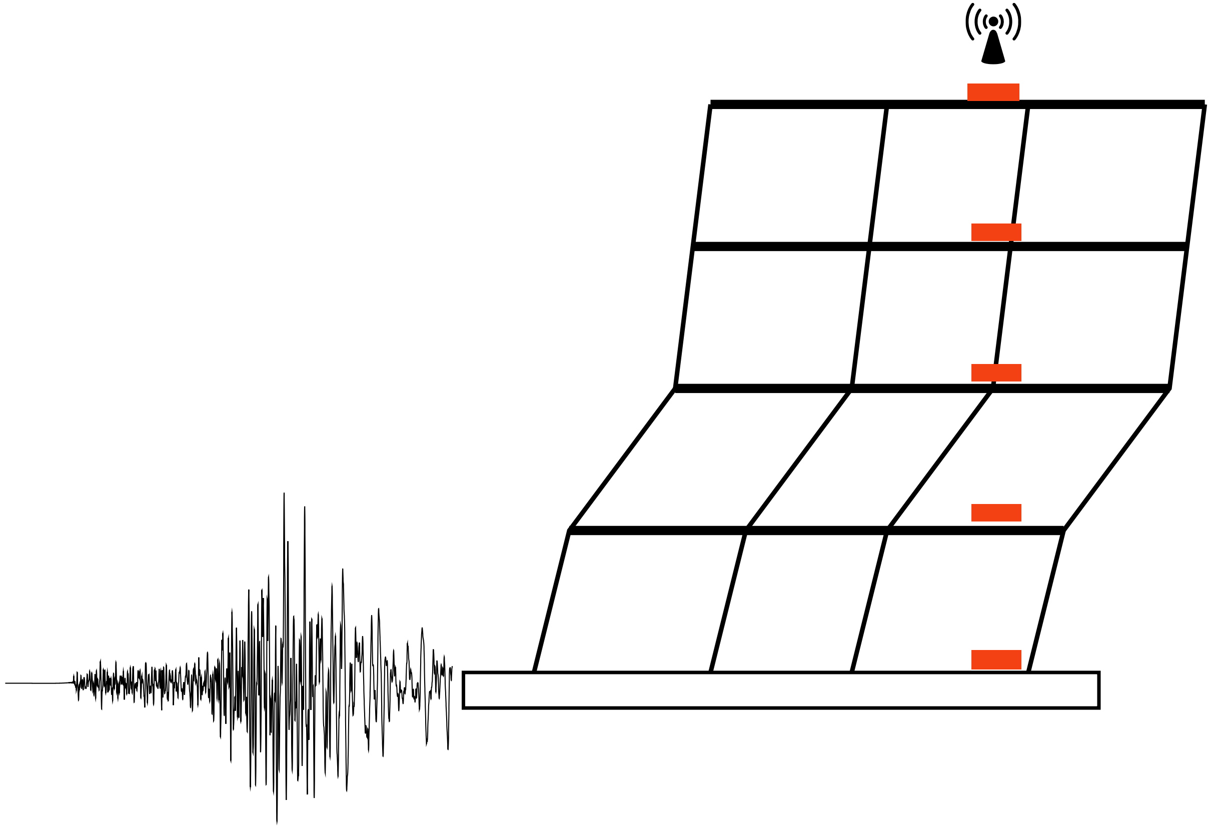
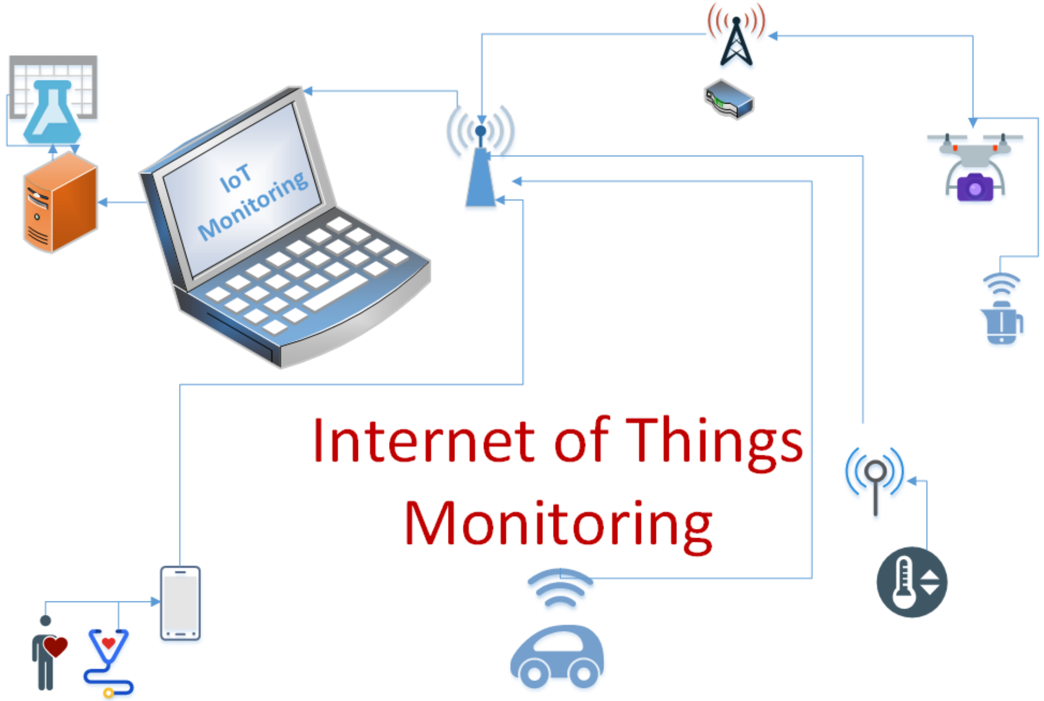


Structural health monitoring (SHM)

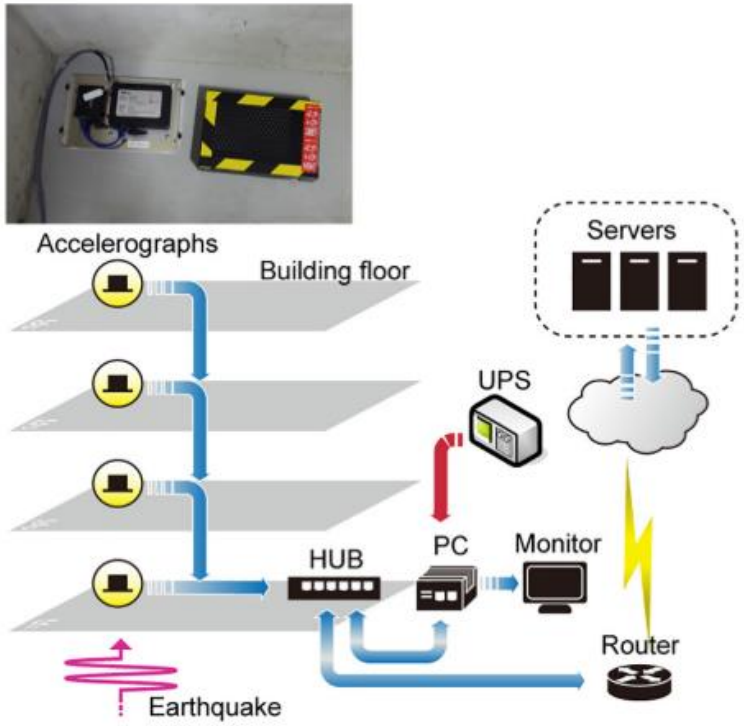
- Another solution is to monitor existing buildings





Structural health monitoring: Japanese experience

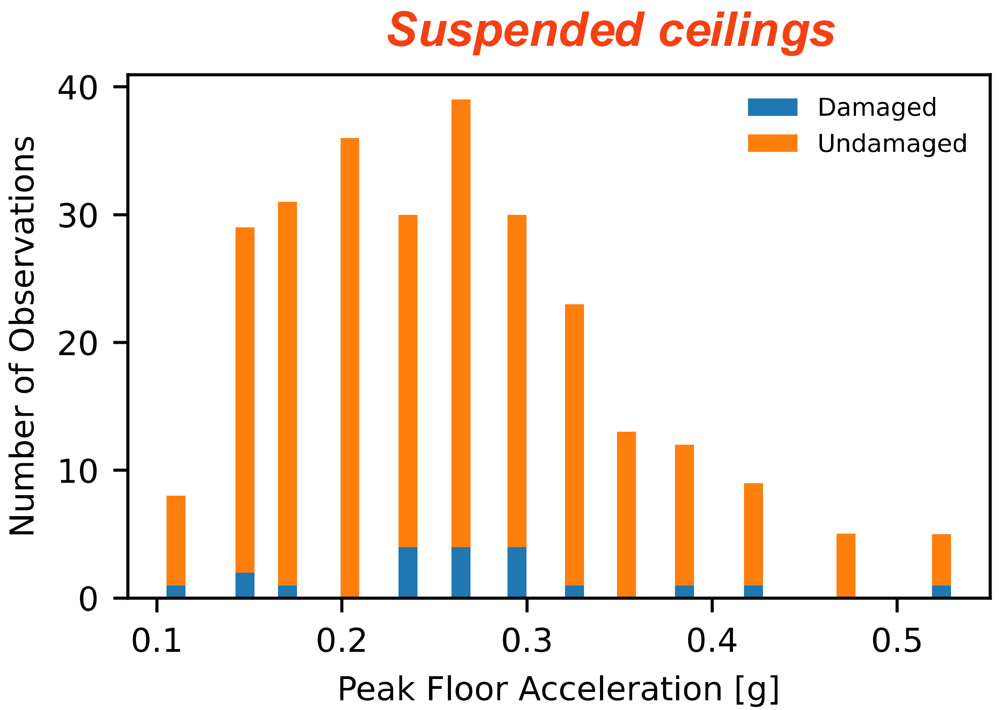
- SHM began in the 1950s, around 150 instrumented buildings before 2011
- Following the 2011 Tohoku earthquake, the urgent need to inspect many buildings in Tokyo showed SHM to be a pragmatic solution
- Japan saw a steady increase in implementation, with around 500 instrumented buildings in 2016 and 850 as of 2018

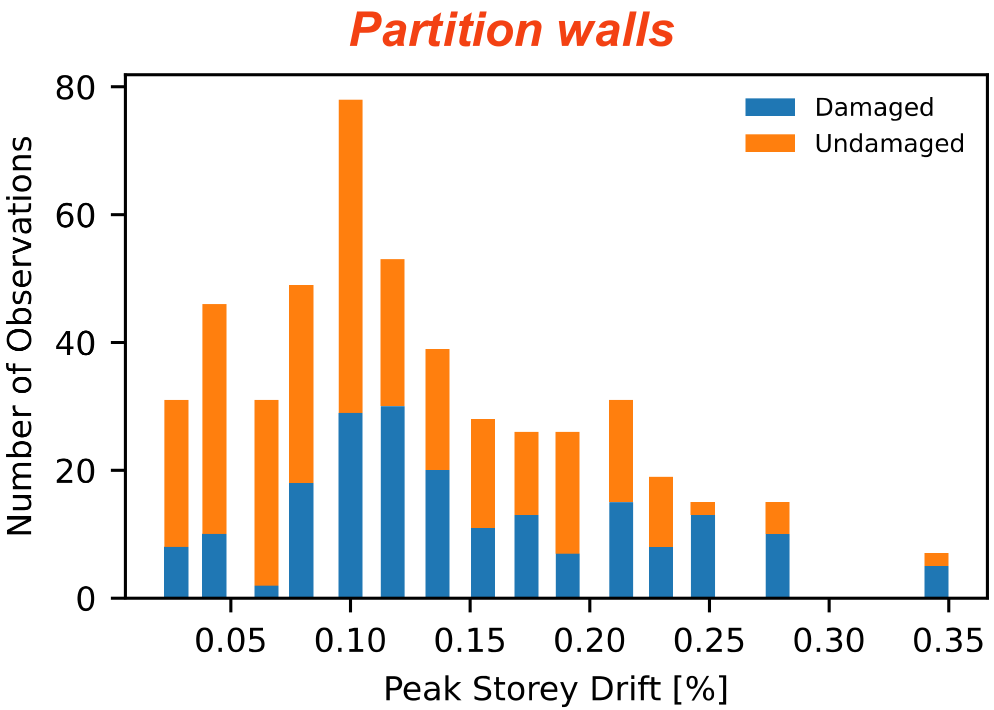


Kanda, K., Nakashima, M., Suzuki, Y., & Ogasawara, S. (2021). "q-NAVI": A case of market-based implementation of structural health monitoring in Japan. Earthquake Spectra, 37(1), 160–179. https://doi.org/10.1177/8755293020935884

Structural health monitoring: Japanese experience

- Following the 2018 Osaka and 2018 Hokkaido Eastern Iburi earthquakes, vast amounts of data have been recorded
- Post-earthquake damage surveys have also provided rich data on damage to NSEs





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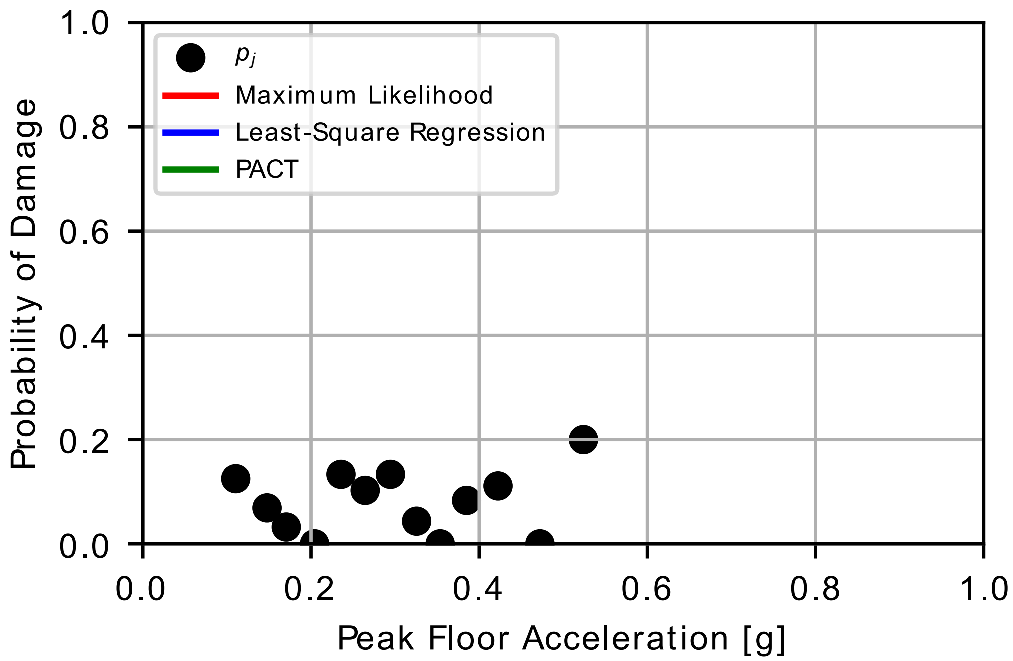
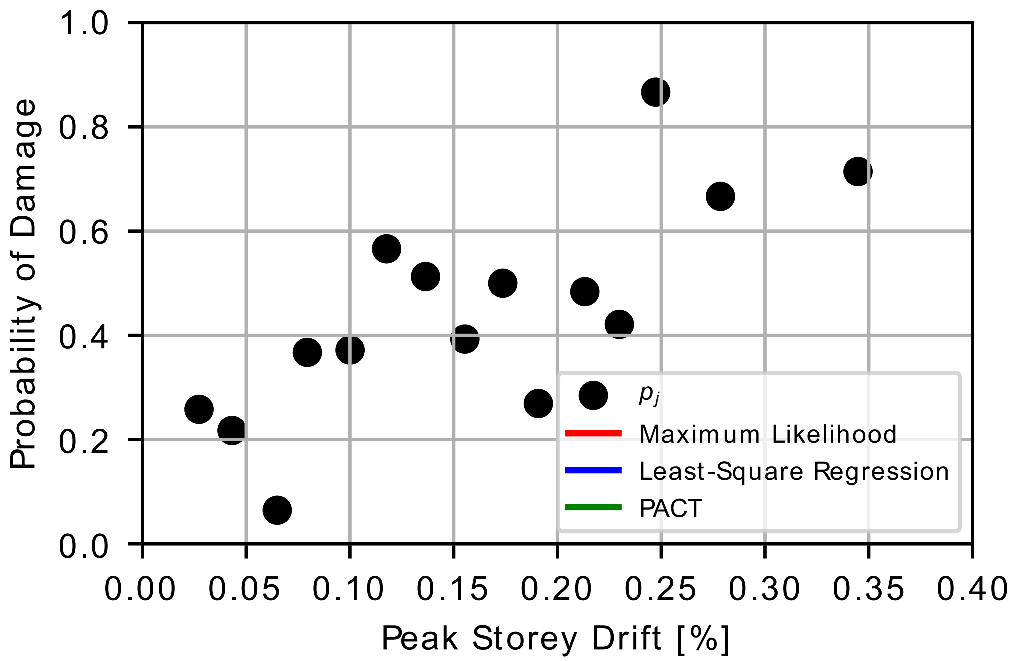
Structural health monitoring: Japanese experience

- These damage observations can be translated to fragility functions
- These can be considered much more representative that other experimentally derived ones





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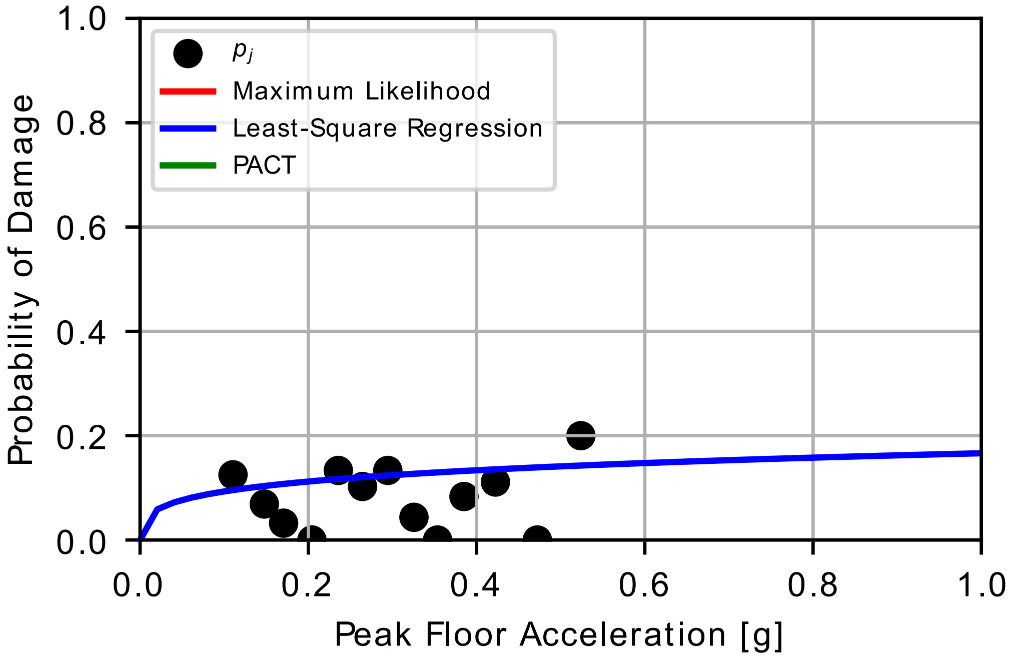

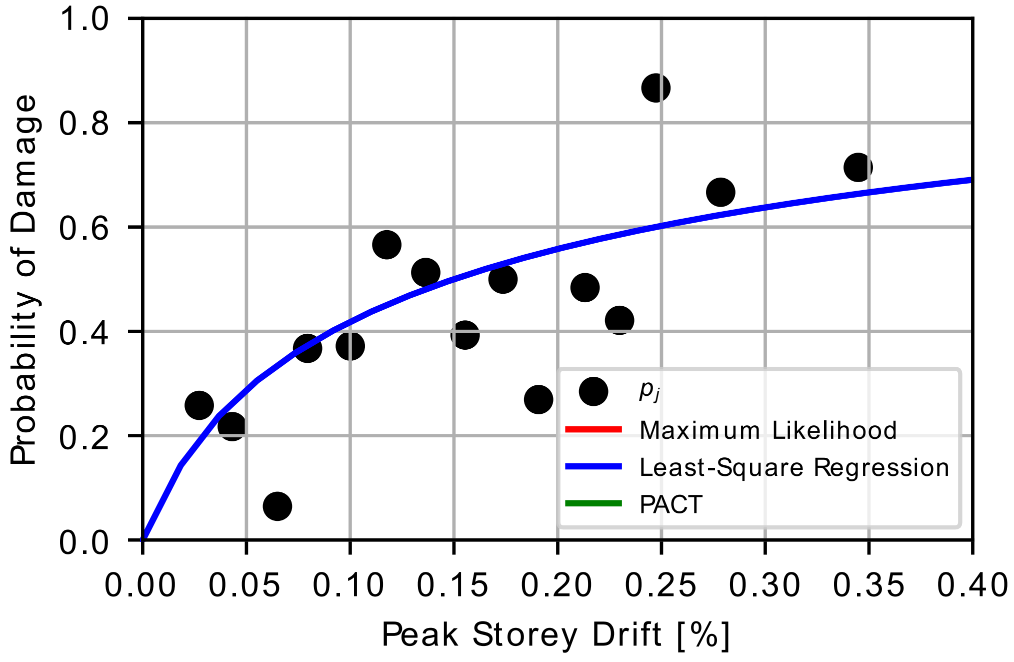

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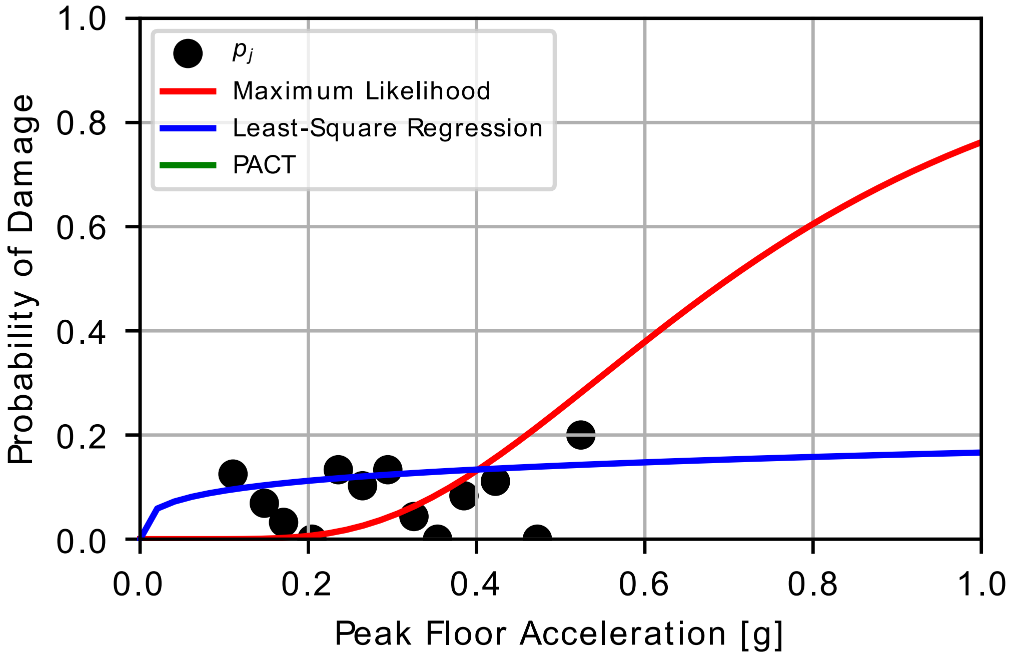

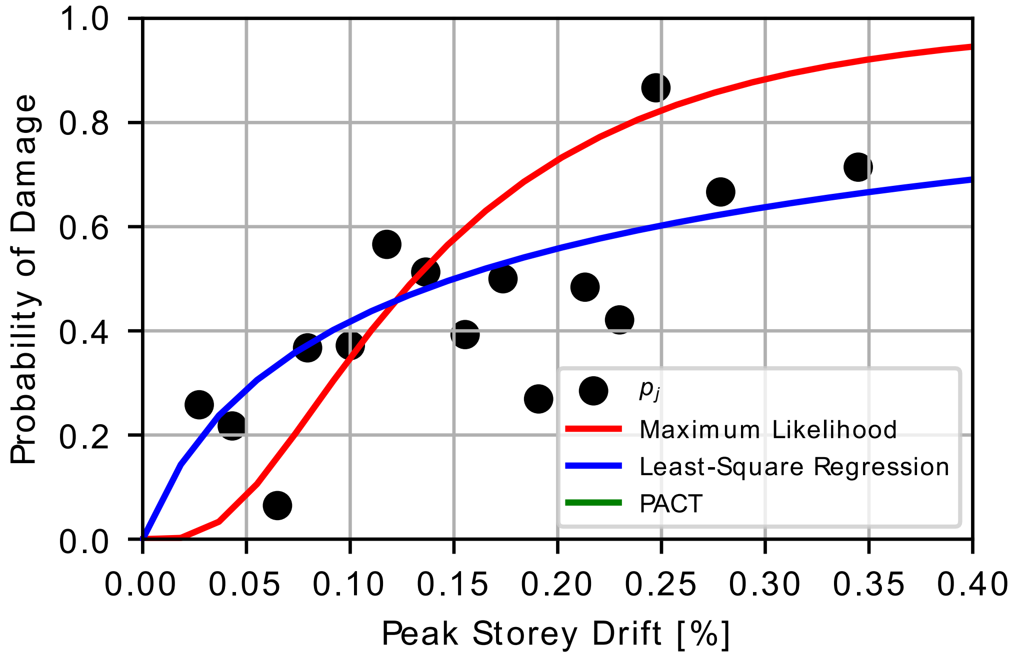

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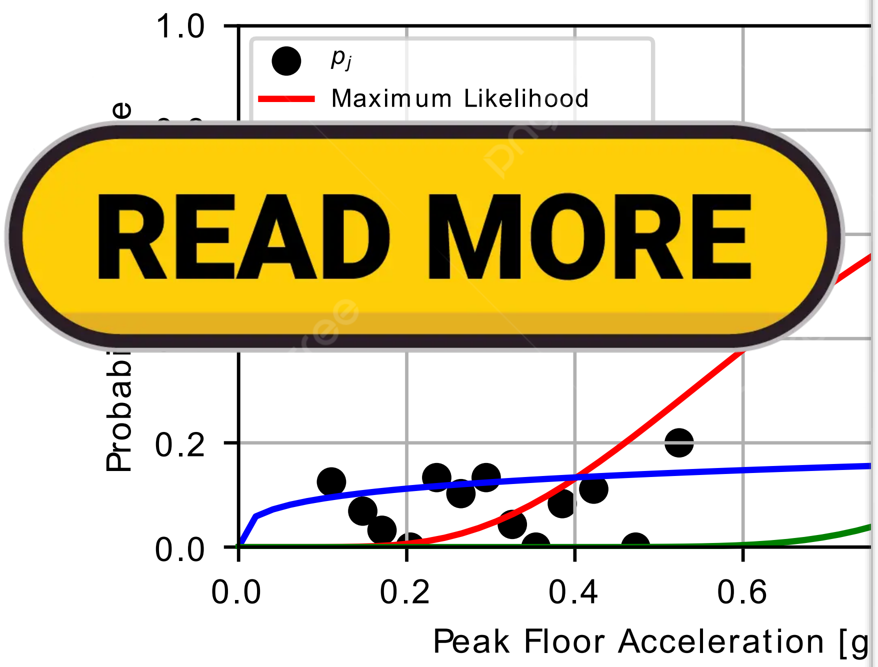

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RESEARCH ARTICLE

WILEY

On the fragility of non-structural elements in loss and recovery: Field observations from Japan

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[4]Disaster Prevention Research Institute,

Abstract

The role of non-structural elements (NSEs) in the seismic performance of buildings has been highlighted in past years. Research studies following state-of-the-art methodologies generally find that when the structural collapse is not of significant concern, NSEs tend to dominate the repair costs and financial investment required in a building. This paper examines field observations from interviews and data collected from commercial buildings via structural

O'Reilly, G. J., Hasegawa, K., Shahnazaryan, D., Poveda, J., Fukutomi, Y., Kusaka, A., & Nakashima, M. (2024). On the fragility of non-structural elements in loss and recovery: Field observations from Japan. Earthquake Engineering & Structural Dynamics, 53(3), 1125–1144. https://doi.org/10.1002/eqe.4066

Decision-making post-earthquake

- This SHM network was installed in Japan to help with post-earthquake inspection delays
- Thresholds were set to allow occupants to receive one of the following responses:
  - Safe (Green Alert)
  - Caution (Yellow Alert)
  - Danger (Red Alert)

Structure Type	**Safe → Caution**	**Caution → Danger**
RC & SRC Frame	0.40% – 0.67%	0.67% – 1.7%
RC with Shear Walls	0.29% – 0.50%	0.40% – 0.83%
Steel Frame	0.45% – 1.0%	1.0% – 1.7%
Steel with Braces	0.33% – 0.56%	0.67% – 1.3%

Fukutomi, Y., O'Reilly, G., Nakashima, M., Kanda, K., Kusaka, A., & Ogasawara, S. (2025). Three benefits of "Caution (Yellow Tag)" in SHM-driven condition assessment of buildings: Eight years experience with market-based SHM. Earthquake Spectra, 41(1), 979–994. https://doi.org/10.1177/87552930241296377

Lessons learned

Damage thresholds should be adaptable rather than fixed

- Experience from past earthquakes shows that SHM threshold values for Green (Safe), Yellow (Caution), and Red (Danger) tags can be refined using real earthquake response data
- Observations from site inspections confirmed that initially conservative thresholds could be safely relaxed
- Demonstrate that continuously updating criteria based on measured building behaviour is beneficial

Lessons learned

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- Demonstrate that continuously updating criteria based on measured building behaviour is beneficial

SHM is highly valuable for understanding non-structural damage

- NSEs often experience damage before structural elements and can significantly disrupt building operations
- Behaviour depends heavily on connection details and installation quality - collecting fragility data is difficult
- SHM systems help address this gap by providing real-time and representative response data

Lessons learned

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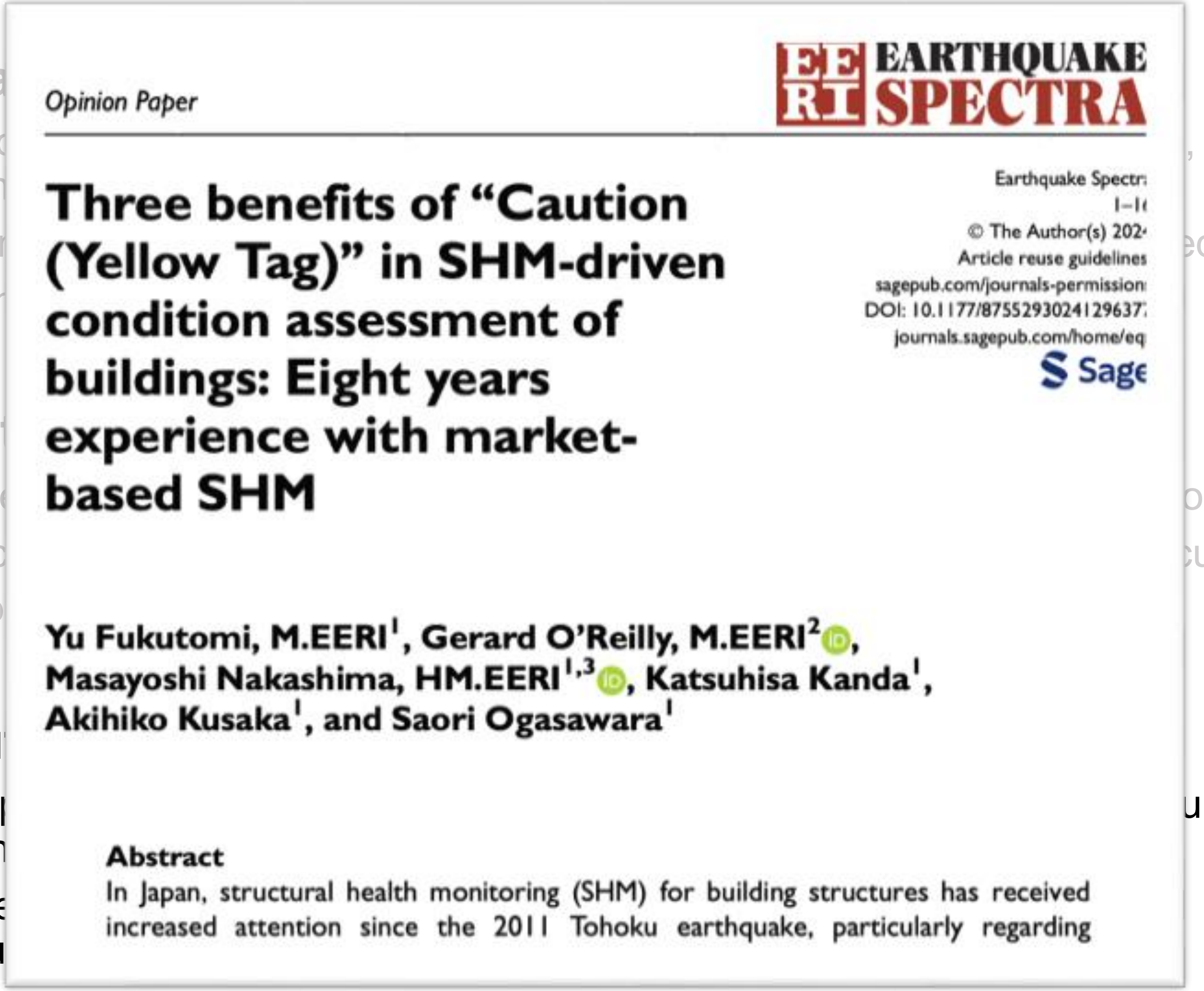

Opinion Paper

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Earthquake Spectra
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Three benefits of "Caution (Yellow Tag)" in SHM-driven condition assessment of buildings: Eight years experience with market-based SHM

Yu Fukutomi, M.EERI[1], Gerard O'Reilly, M.EERI[2], Masayoshi Nakashima, HM.EERI[1,3], Katsuhisa Kanda[1], Akihiko Kusaka[1], and Saori Ogasawara[1]

Abstract

In Japan, structural health monitoring (SHM) for building structures has received increased attention since the 2011 Tohoku earthquake, particularly regarding

The usefulness of the Yellow (Cau

- For building owners with contingency p upport, a Yellow status provides an early warn
- For owners without such support syste adoption, as it highlights potential issu

SONATA Project

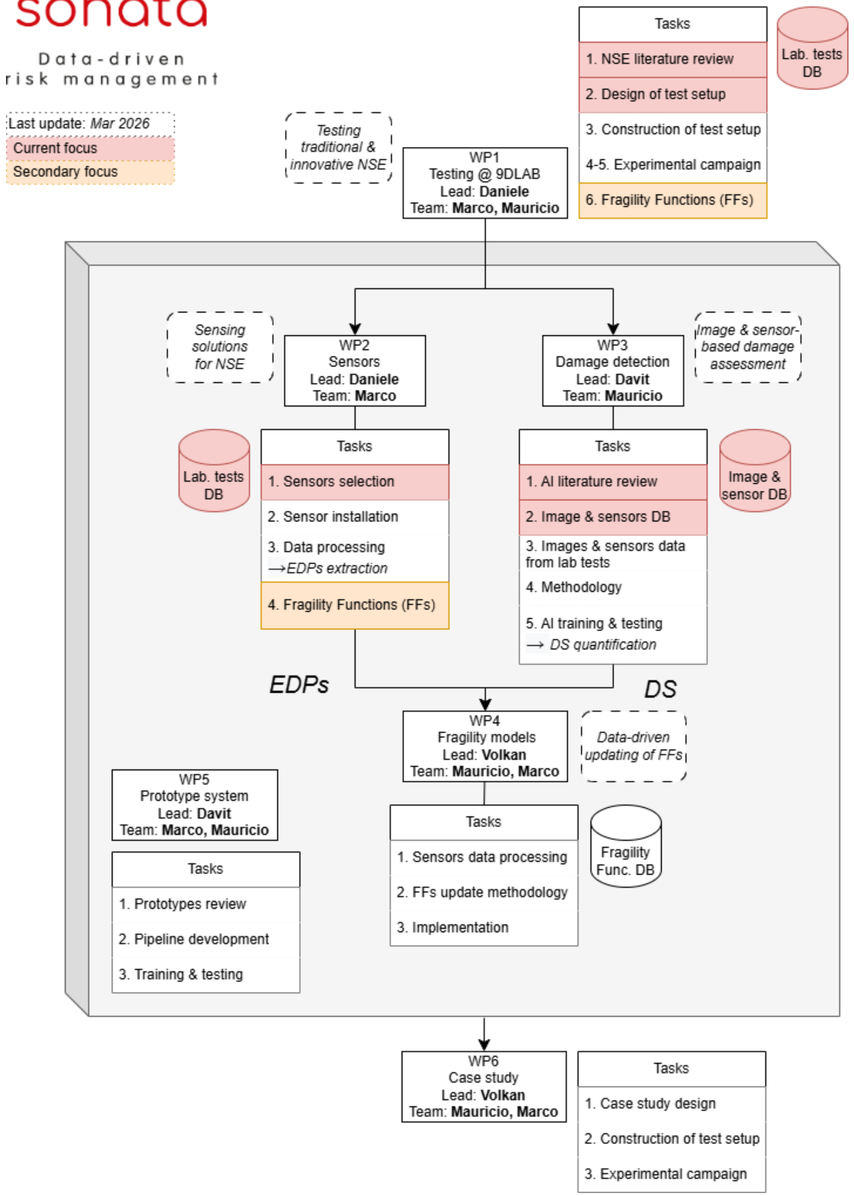
- ***S**ens**O**r-drive**N** statistic**A**l tools to evalua**T**e risks and manage s**A**fety in the built environment*
- The project is organized in **6 Working Packages** (WP):
  - WP1: Experimental testing
  - WP2: Sensors
  - WP3: Damage detection
  - WP4: Fragility models
  - WP5: Prototype system
  - WP6: Case study

- Currently focusing on:
  - **designing shaking table tests for NSEs @ Eucentre 9DLAB** (Pavia, Italy)
  - exploring **advanced sensing instrumentation** and **vision-based technologies** (WP2/WP3) for demand and damage monitoring
  - **collecting NSE fragility data and damage images** from previous experimental campaigns (WP3) to train AI-models

Sensor-driven statistical tools to evaluate risks and manage safety in the built environment

sonata

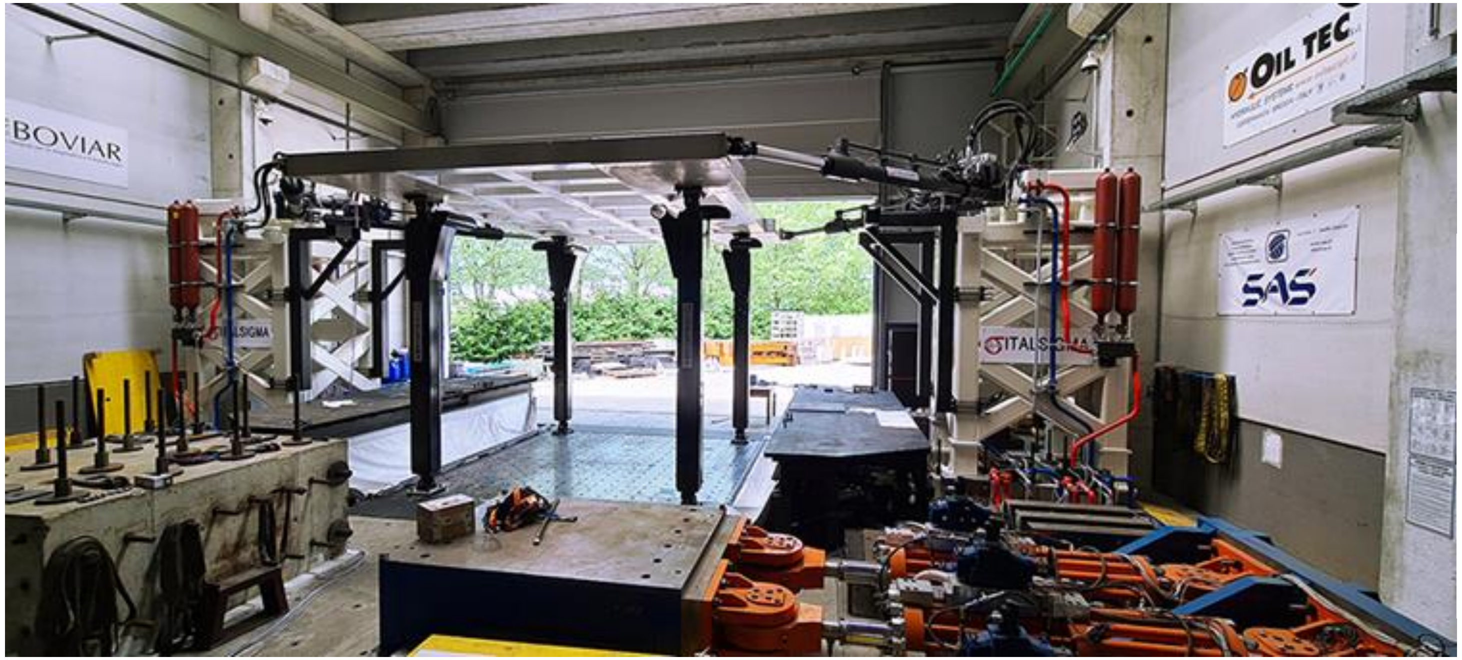
Data-driven risk management

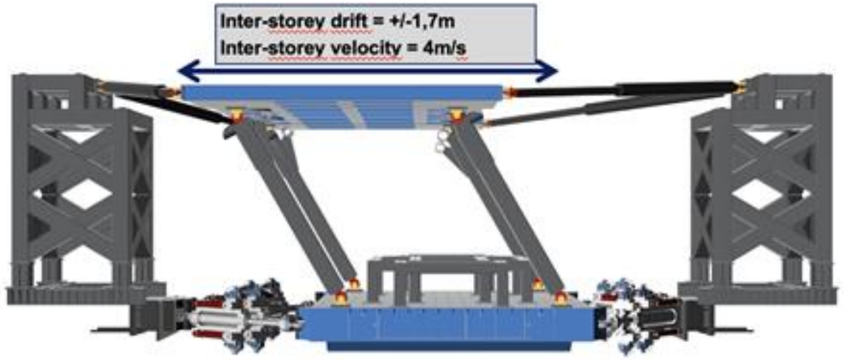


WP1: Experimental testing

- WP1 aims at developing more representative and reliable fragility data for Non-Structural Elements (NSEs) through innovative experimental testing

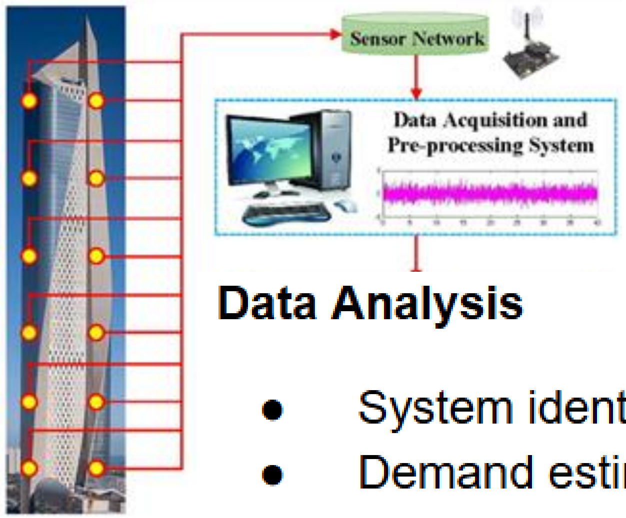
Degrees of freedom (upper table)	3
Degrees of freedom (lower table)	6
Upper table dimensions	5.00 m × 7.00 m
Lower table dimensions	4.80 m × 4.80 m
Maximum displacement in x and y	1 m
Maximum displacement in z	0.140 m
Maximum speed (upper table)	3 m/s
Maximum speed (lower table)	2 m/s
Interstory drift in longitudinal direction	± 1.7 m
Interstory drift in transverse direction	± 1.1 m
Actuators	14





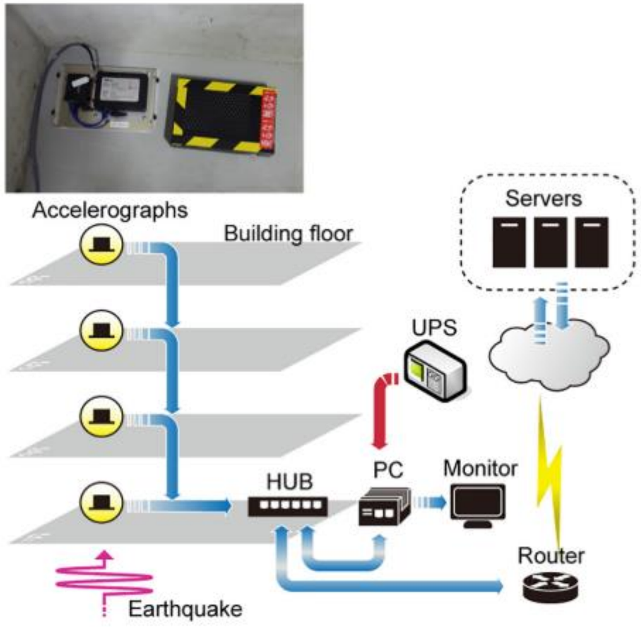
WP2: Demand measurement via sensors

- WP2 aims to use and test smart sensor systems to:
  - Measure seismic demands (EDPs) during earthquakes
  - Identify system properties sensitive to damage
- The goal is to move toward a **smart built environment** where sensors continuously provide performance data that can be employed to support **damage assessment**



Data Analysis

- System identification
- Demand estimation



Learning from the q-NAVI experience in Japan

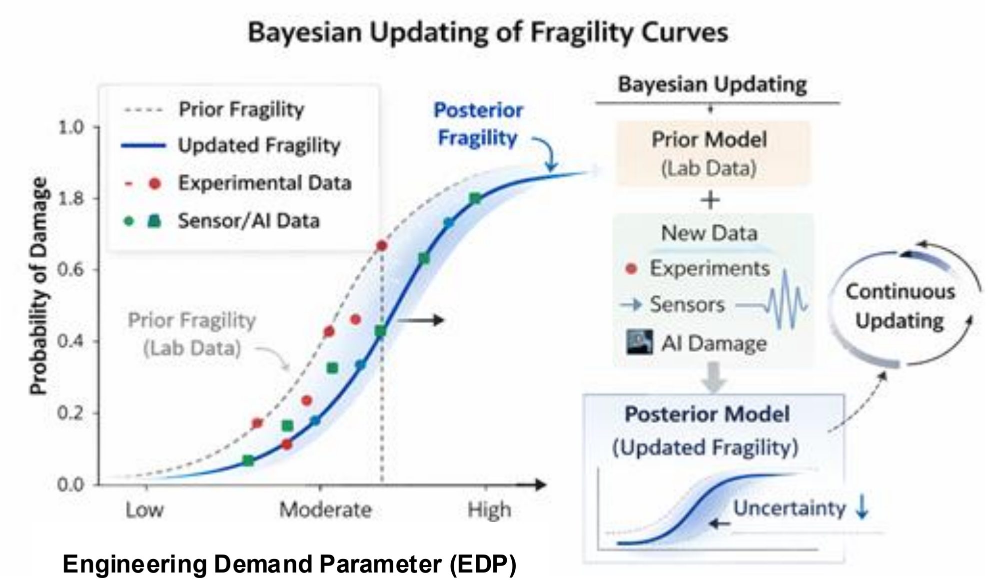
WP3: Damage detection via AI

- WP3 develops image-recognition-based artificial intelligence models to:
  - Detect damaged NSEs (partitions, ceilings, etc.)
  - Automatically classify damage states from images
  - Reduce reliance on manual post-earthquake inspections

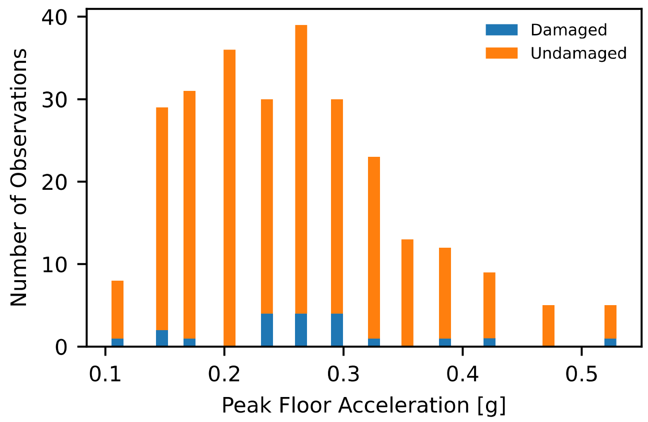
Reduce need for human intervention to reduce waits and also address labour shortages

WP4: Calibration of fragility models

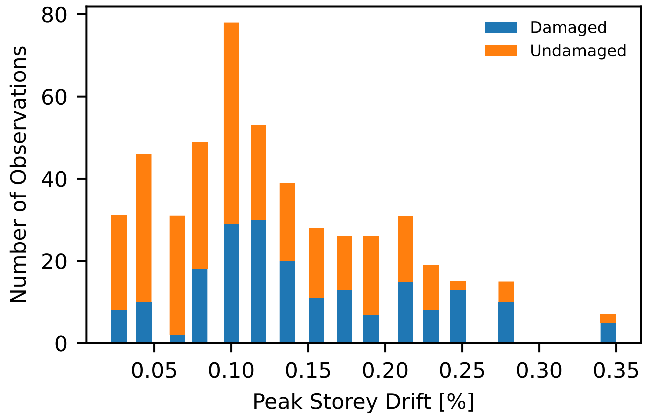
- WP4 Implements advanced statistical techniques (e.g., Bayesian updating) to:
    - Integrate sensor data (EDPs) and AI inference (damage states)
    - Update fragility models of NSEs
    - Improve probabilistic seismic risk estimation
- This bridges structural engineering with modern data-driven assessment



Suspended ceilings

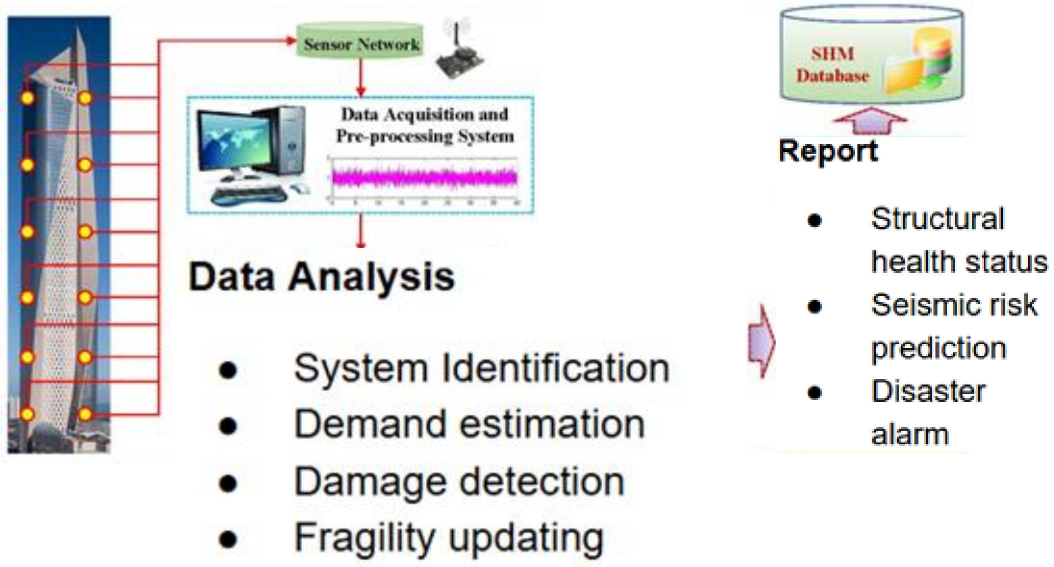


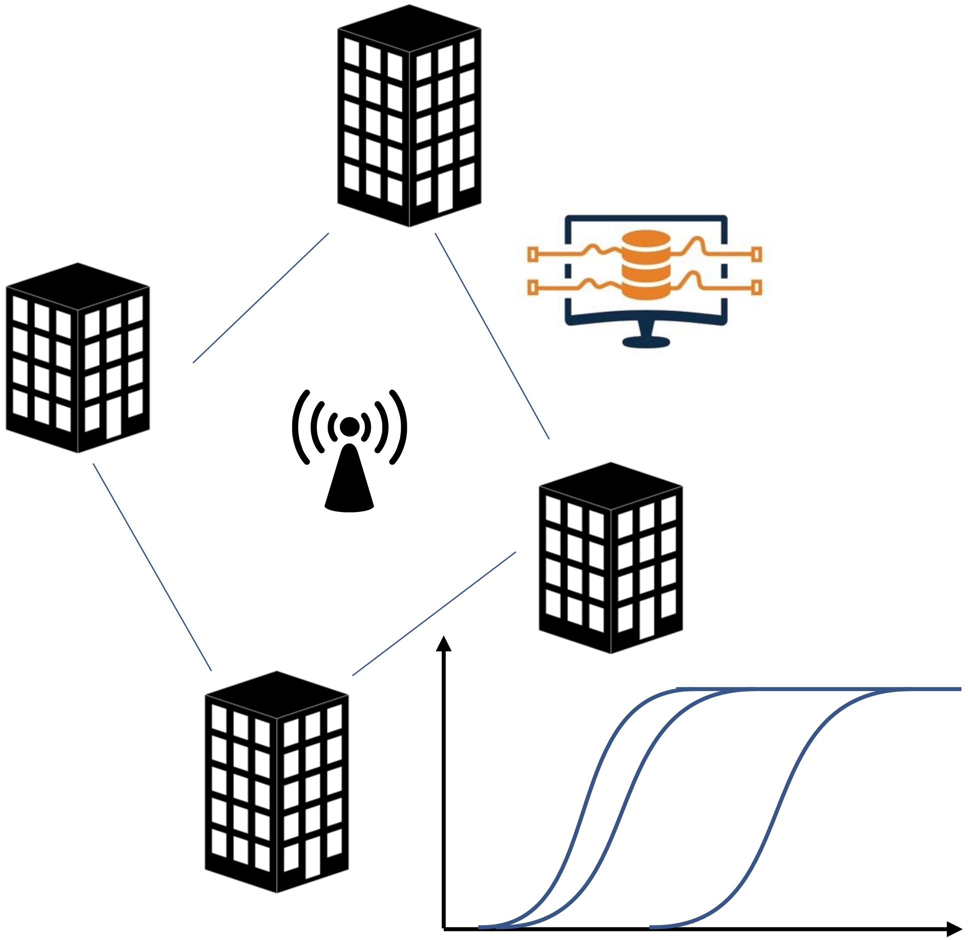
Partition walls



WP5: Development of a prototype system

- WP5 develops a working integrated system that:
  - Receives sensor data
  - Detect damage with AI
  - Updates fragility models
  - Supports decision-making (damage alert with sensor data and fragilities)
- This is not just theoretical research -- it aims at technology transfer





Updating fragility and risk models

Questions?

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