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Rapid earthquake loss assessment through digital twins: A machine learning and sensor-based approach

A. Taherian, V. Silva, A. Nafeh, G. O'Reilly, R. Vicente

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Smart City Digital Twins (SCDT) in Disaster Management

Smart City Digital Twins (SCDT)

Definition: "Realistic digital representations with data connection between real world and digital representation" *(UK National Digital Twin Program)*

Key Characteristics:

Living simulation models that learn and update

Real-time data integration

Predictive capabilities

Continuous synchronization through bidirectional updating

Proven Large-Scale Implementations:

•Houston Flood Alert System

- 20+ years operational
- 99.17% accuracy in peak flow prediction

•China Yangtze River Digital Twin

- $82 million investment
- Entire river basin coverage

•Singapore Digital Urban Climate Twin (DUCT)

- $73 million climate-focused applications
- Building Energy + Urban Canopy Modeling

Our Definition: "Structural Digital Twin"

"Structural Digital Twin"

Definition: Data-driven system for continuous virtual representation of building structural states

Our Scope:

Location: Lisbon Alvalade District

Scale: 2,600 buildings

Method: ML models trained on 5M+ NLTHA

Purpose: Real-time structural response prediction

Deliberate Constraints:

- **NOT** comprehensive city-scale integration
- **Focused on:** Structural response prediction
- **Focused on:** Real-time seismic loss assessment
- **Focused on:** Sensor-to-model integration validation

Key Innovation:

- **Reduce prediction bias** in portfolio-level seismic loss estimation
- **Fundamental building block** for broader SCDT systems
- **Contribution:**
- Essential validation for sensor-to-model integration processes
- Foundation for comprehensive urban seismic digital twin implementation

Issues in current rapid loss assessment

Ground shaking

- Large uncertainty in definition of earthquake rupture and magnitude
- Delays in understanding the rupture geometry
- Large uncertainty in ground motion models

Exposure

- Lack of information about the vulnerability of each building
- Poor spatial resolution of the models
- No information about the dynamic properties of the building
- Lack of information regarding where population is at different times of the day

Vulnerability

- Large epistemic and aleatory uncertainty in fragility and vulnerability models
- Functions are defined in terms of insufficient and inefficient IMs
- Lack of vulnerability functions for some building classes

Seismicity in Western Iberia

Major Historical Earthquakes in Western Iberia:
1755 Lisbon Earthquake (November 1, 1755)
•Magnitude: ~8.5-9.0

1969 Offshore Cape São Vicente Earthquake (February 28, 1969)
•Magnitude: 7.8

1909 Benavente Earthquake (April 23, 1909)
•Magnitude: 6.0

2007 Southwest Iberia Earthquake (December 17, 2007)
•Magnitude: 5.9
•Offshore southwest Portugal

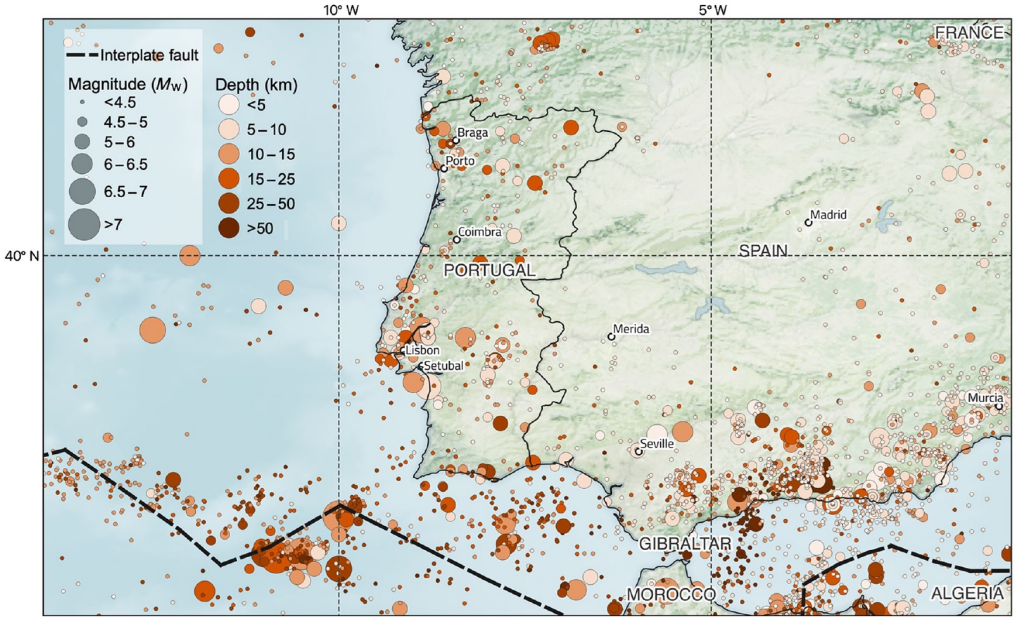
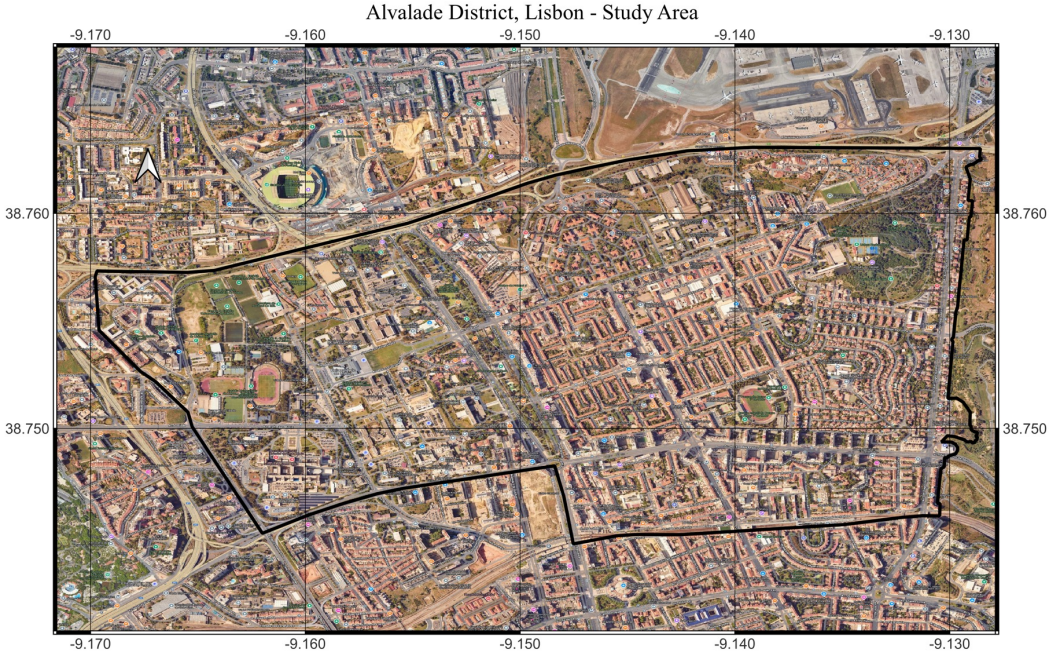


Figure 1. Instrumental and historical earthquake catalog for southwest Iberia (Danciu *et al.*, 2021). The color version of this figure is available only in the electronic edition.

Study Area: Alvalade District, Lisbon

- **Study Area Selection**
  Alvalade District
- **Location:** Central Lisbon, Portugal
- **Building Stock:** 2,600 buildings representing diverse typologies
- Well-documented building inventory from previous seismic studies
- **Seismic vulnerability range:**
  From older masonry to modern RC buildings



Simulation-Based Methodology for Digital Twin Validation

The Challenge:

- **Limited real earthquake data** for structural response validation
- **Need for comprehensive testing** of digital twin frameworks across multiple scenarios

Our Solution: Large-Scale NLTHA Framework:

- **Multiple earthquake scenarios** spanning various magnitudes and source mechanisms
- **Stochastic-based ground motion simulation** accounting for local site effects
- **2,600 building-specific MDOF models** representing actual Alvalade structures
- **5+ million nonlinear time history analyses** across scenario matrix

Link to OQ-VMTK

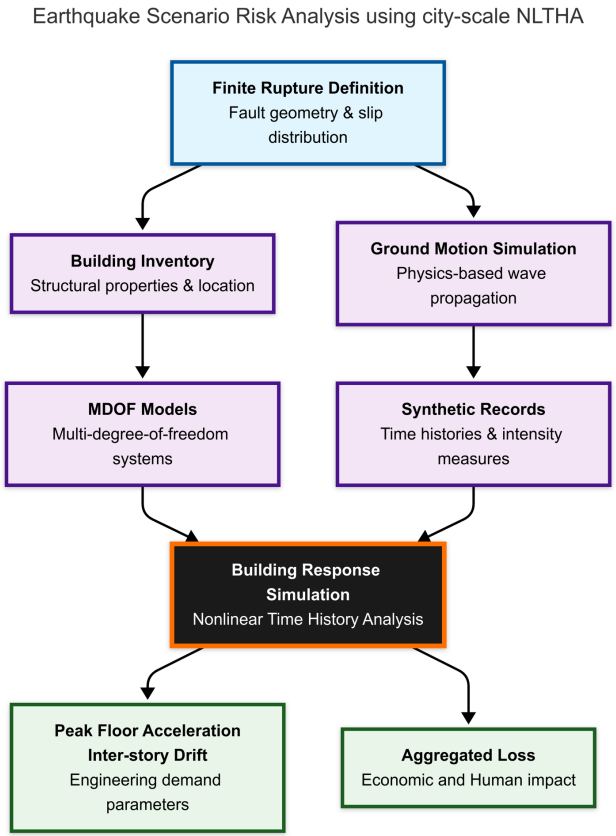
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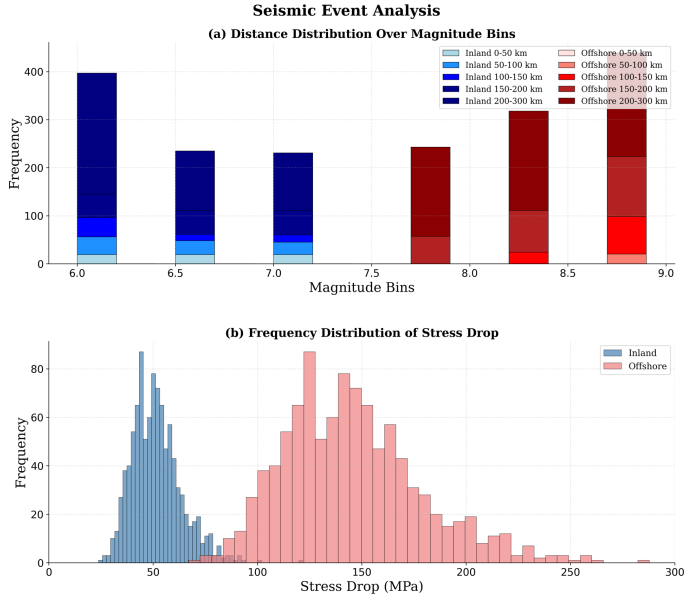
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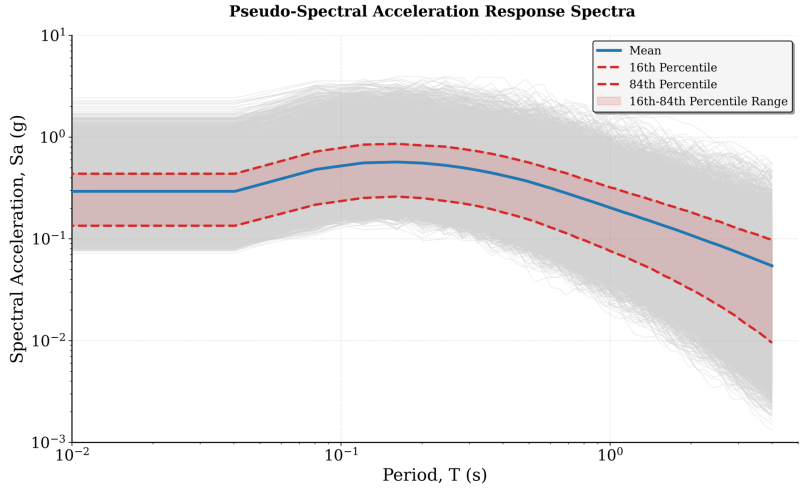
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Stochastic Earthquake Ground Motion Simulation

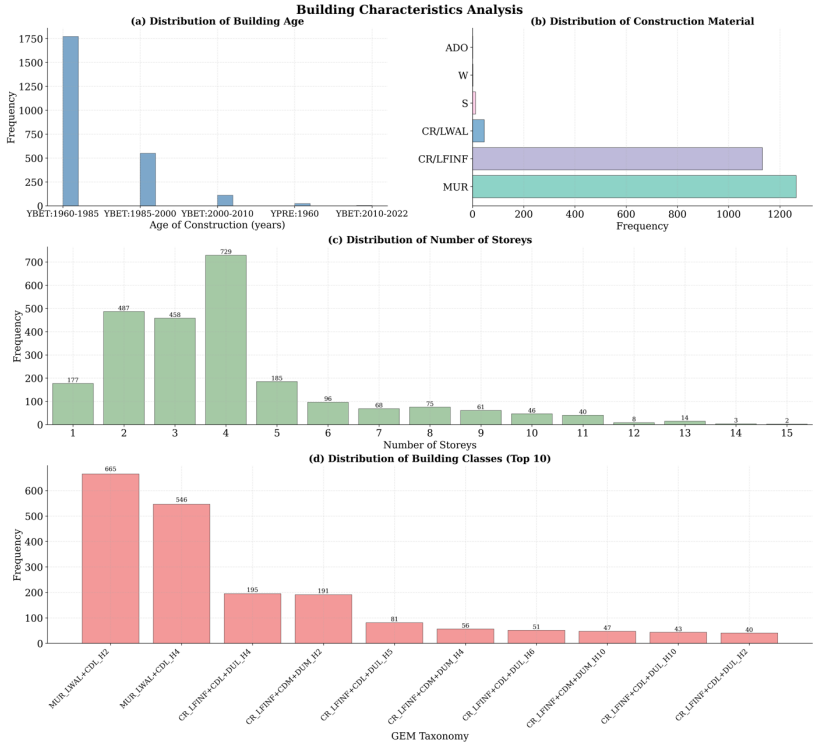
- To address the scarcity of recorded data, we generated **2000 hypothetical earthquake ruptures** with realistic fault geometry and slip distributions.
- Using stochastic ground motion simulation, each scenario was propagated across the region, producing **200,000 synthetic ground motion records**.





Building Stock Distribution in Alvalade District, Lisbon

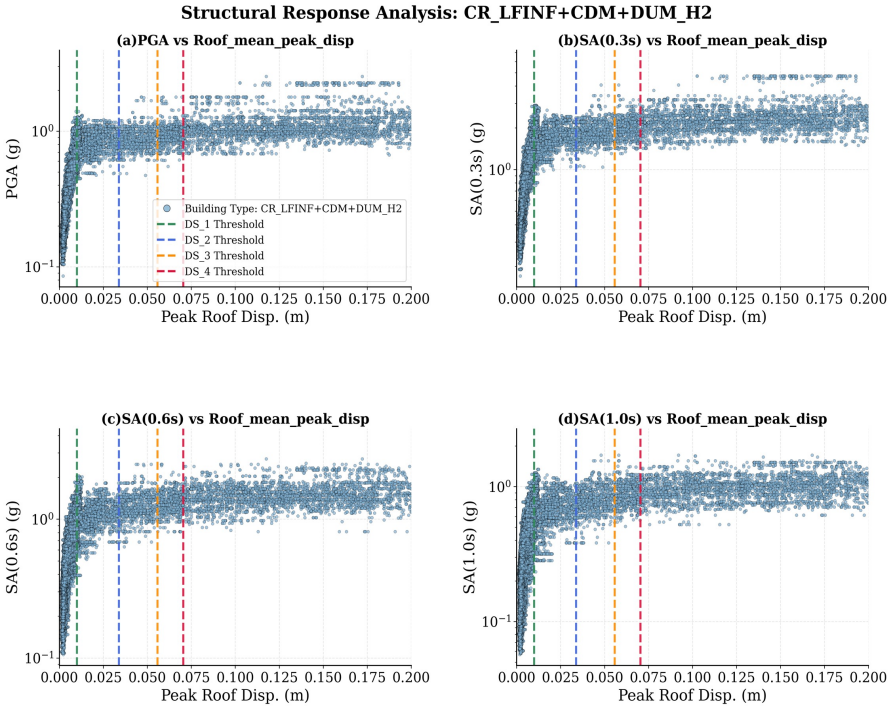
- The figure displays building characteristics like age, material, and story count.
- **Most common building types:** Unreinforced masonry and infilled RC buildings

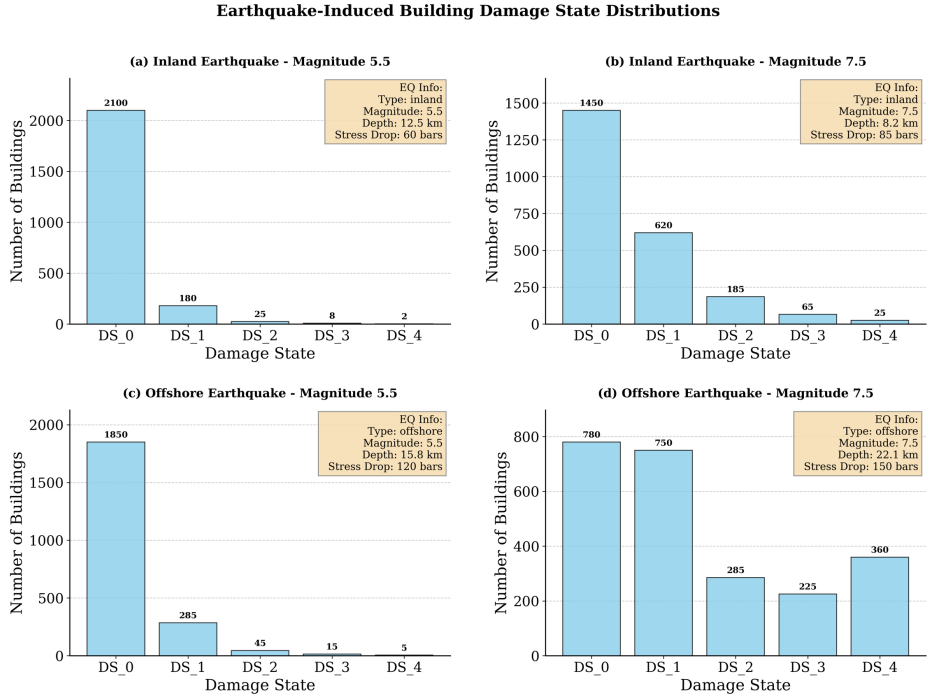




Summary of NLTHA and Damage Analysis Results

- **Damage states** defined by GEM were applied.
- **IM-EDP** data for each building class were gathered.





Earthquake Shaking and Impact Footprint

For each earthquake rupture: Visualization of shaking and damage footprint generated

Earthquake Impact Assessment Example
Rupture Scenario 950:

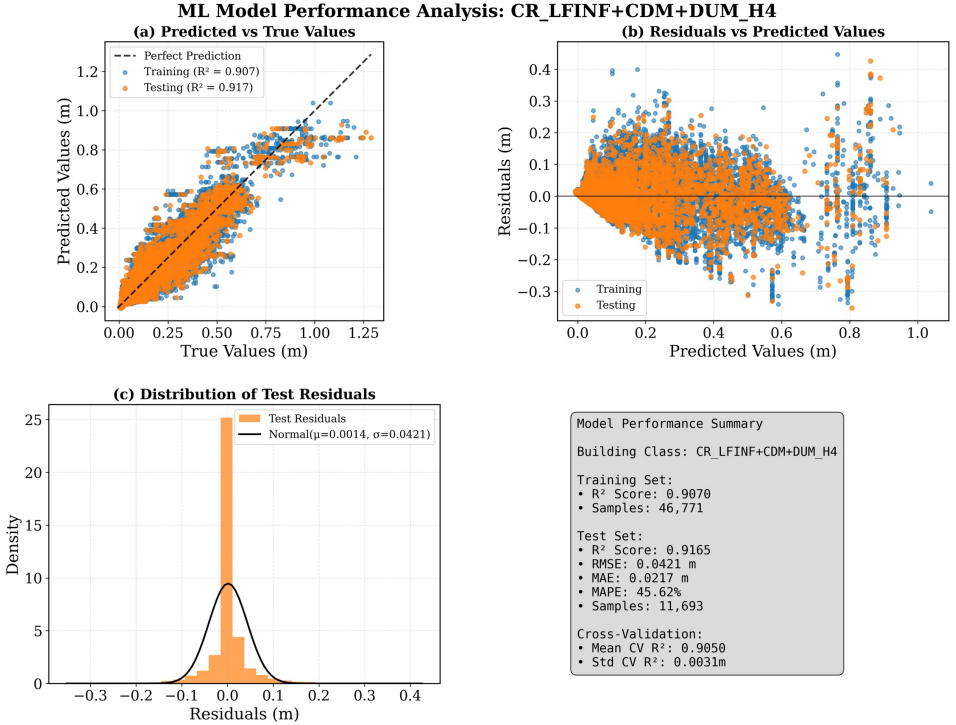
- **Ground shaking variability:** PGA ranges from 0.35 g to 0.5 g across district
- **Spatial damage prediction:** Building-by-building damage state assessment
- **Portfolio-level results:** 1,515 undamaged, 1,085 damaged buildings predicted



ML Based Building Response Model

- **Using NLTHA results for each building class:** A Machine Learning model is developed to predict structural response as a function of earthquake IMs

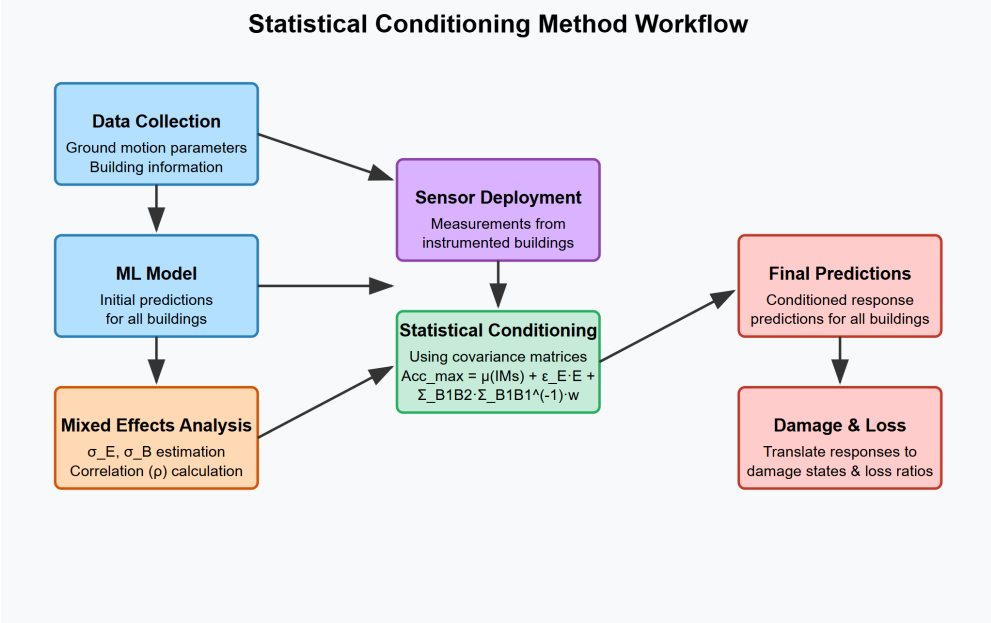
- By measuring ground shaking after an earthquake, we can run this ML models to predict damage and total loss.



Sensor-Based Conditioning Approach

- Assuming we have some sensors installed on top of some buildings we can update predicted response through conditioning approach

- Relies on pre-calculated correlation coefficient (ρ)
- Uses covariance matrices to condition predictions



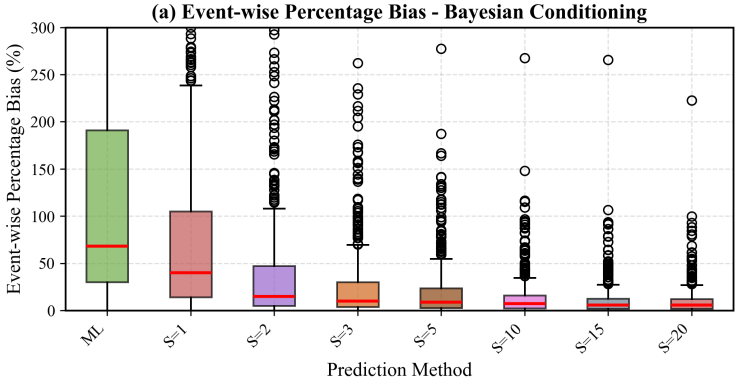
$$\Sigma_{BB} = \begin{bmatrix} 1 & 0.6 \cdot B \cdot B & 0.6 \cdot B \cdot B \\ 0.6 \cdot B \cdot B & 1 & 0.6 \cdot B \cdot B \\ 0.6 \cdot B \cdot B & 0.6 \cdot B \cdot B & 1 \end{bmatrix}$$

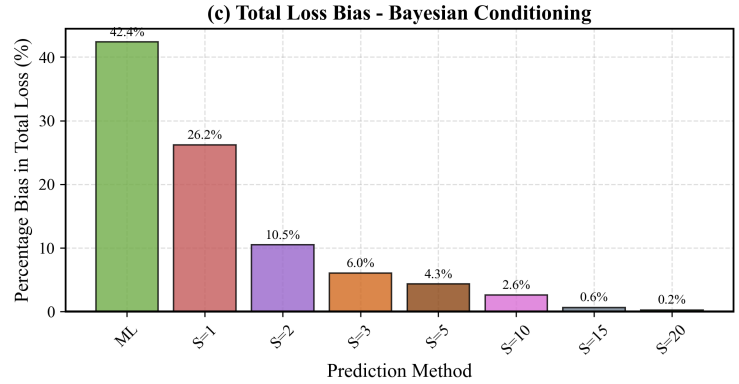
$$Disp_{max}|\mu_{E} = \mu(IMs) + \varepsilon_{E} E + \Sigma_{B1B2}\Sigma_{B1B1}^{-1} w$$

Impact of Sensors in Reducing Bias in Loss Assessment

Key Results:

- **Dramatic bias reduction:** From 68% baseline error to 5.6% with optimal sensor deployment
- **Sensor efficiency:** 5 sensors per building class achieve 90% improvement over ML predictions
- **Progressive improvement:** Each additional sensor reduces bias systematically
- **Real-time capability:** conditioning approach enables immediate loss assessment refinement as sensor data arrives
- **Cost-effective solution:** Significant accuracy gains achievable with moderate sensor deployment





Concluding Remarks

Key Innovation Achieved:

- **First comprehensive validation** of sensor-integrated digital twins for rapid earthquake loss assessment using large-scale NLTHA simulation framework
- **conditioning approach** demonstrates exceptional bias reduction (68% → 5.6%) with strategic sensor deployment
- **Real-time capability** enables immediate post-earthquake loss refinement as sensor data becomes available

Practical Impact:

- **Cost-effective solution:** Significant accuracy improvements with moderate sensor investment (5 sensors per building class)
- **Scalable methodology**: Framework applicable to other urban districts and building portfolios worldwide
- Emergency response enhancement: Rapid, accurate loss estimates critical for disaster management and resource allocation

Broader Implications:

- Foundation for comprehensive SCDTs: Validates essential sensor-to-model integration processes for broader urban digital twin systems
- Paradigm shift: From static vulnerability assessments to dynamic, sensor-informed structural health monitoring

Thank you!

Please attribute to the GEM Foundation with a link to:
https://www.globalquakemodel.org



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