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Resilience-based design of buildings with accelerated post-earthquake functional recovery

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June 5, 2025

UC San Diego

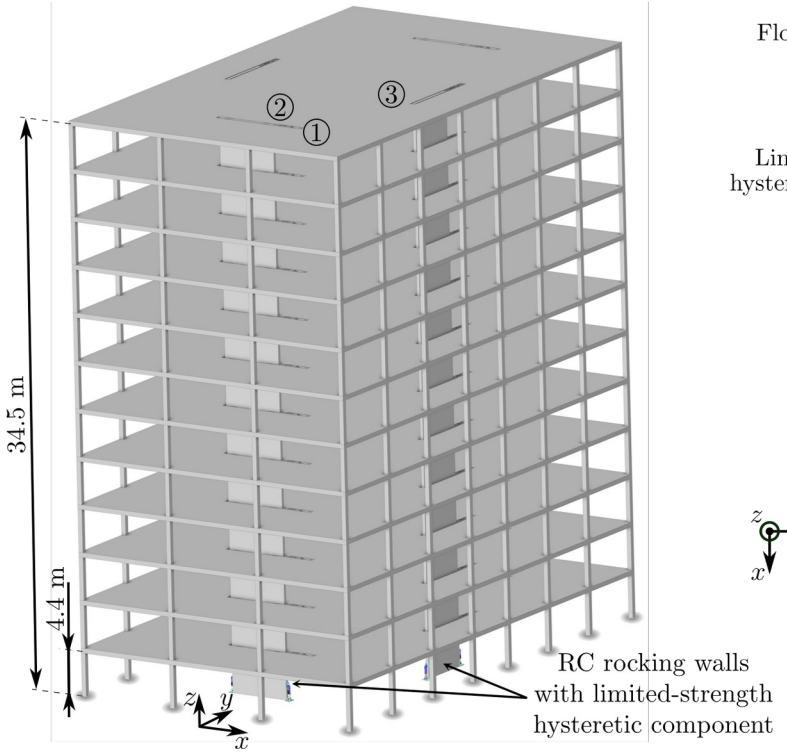
Project Overview & Motivation

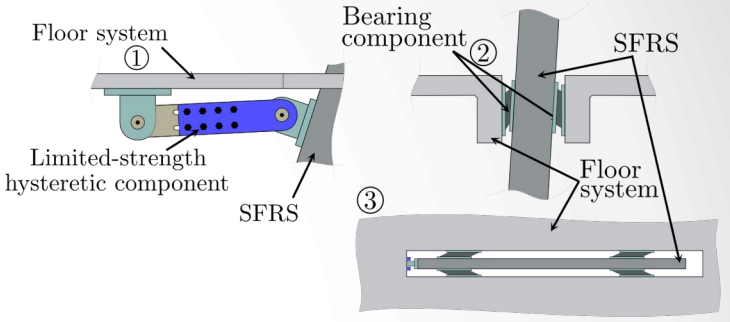
- Earthquakes continue to cause devastating losses, not only in lives but also in long-term disruptions.
- While most building codes protect life safety, they do not ensure rapid post-disaster functionality.
- After major earthquakes, even structurally safe buildings can be unusable due to nonstructural damage or delayed repairs.
- This project develops a practical design method for buildings with force-limiting connections that enable faster and more reliable functional recovery.

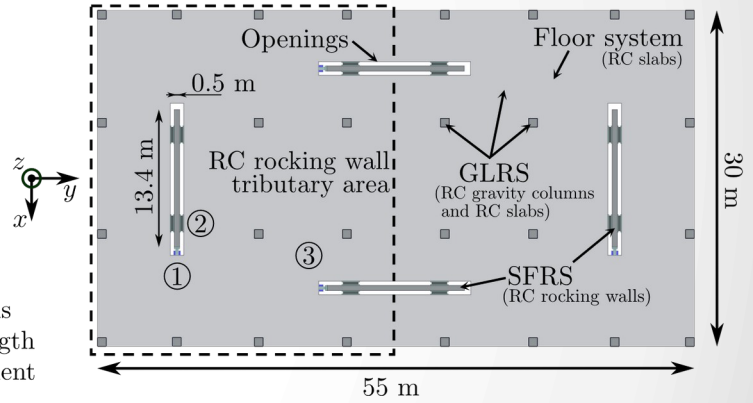


Background

- Traditional seismic design often leads to excessive force demands and costly nonstructural damage.
- Force-limiting connections mitigate seismic forces transferred from diaphragms to structural walls.
- This strategy reduces acceleration-sensitive damage and higher-mode effects, enhancing resilience.
- The concept aligns with modern resilience objectives and functional recovery targets.



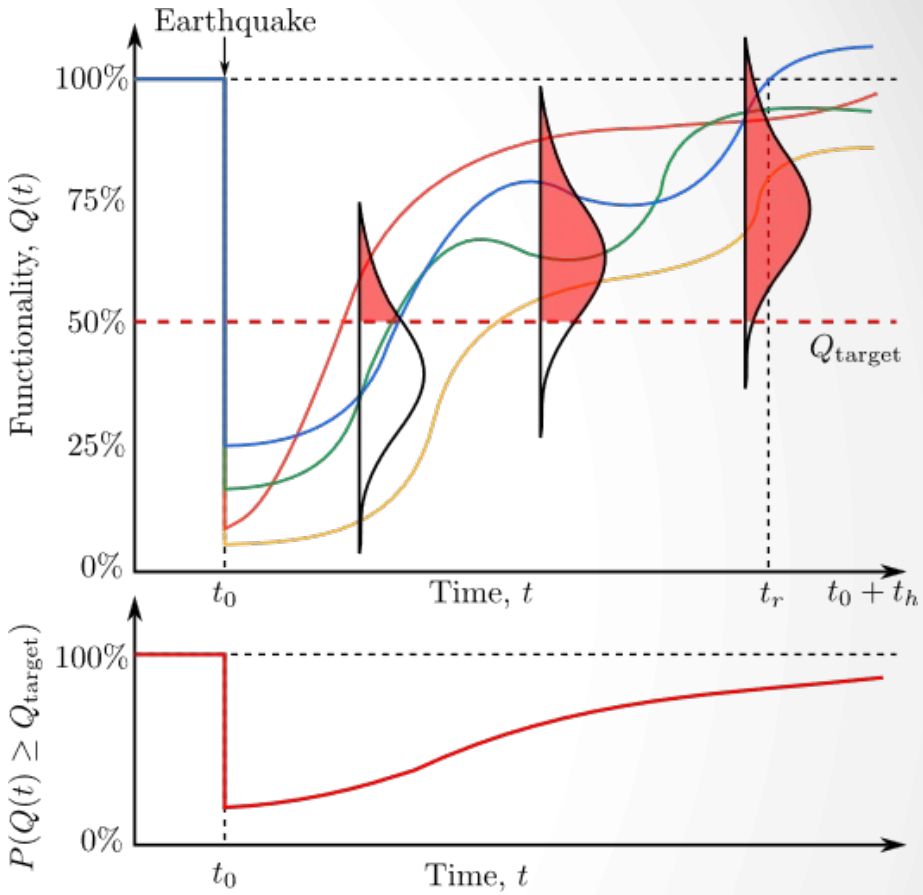




Source: Mayorga and Tsampras, 2024

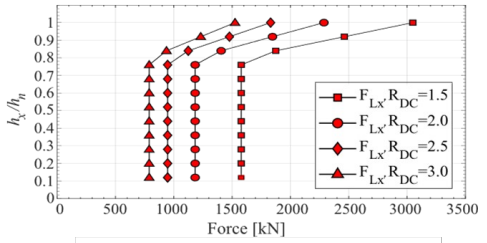
Research Gap & Objectives

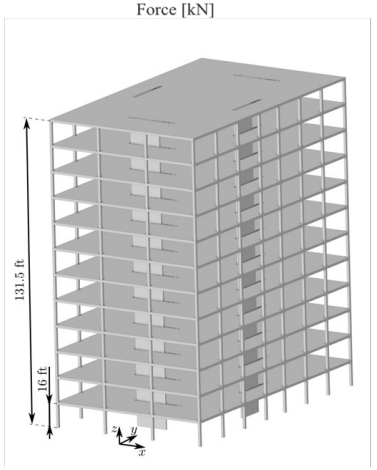
- Existing codes usually target life safety, not functional recovery.
- Lack of design methods that explicitly consider downtime or variability in seismic response.
- Need to integrate probabilistic design with recovery-based performance goals.

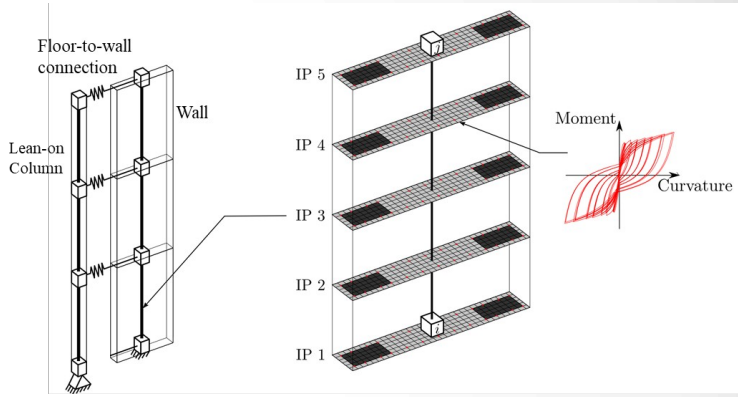


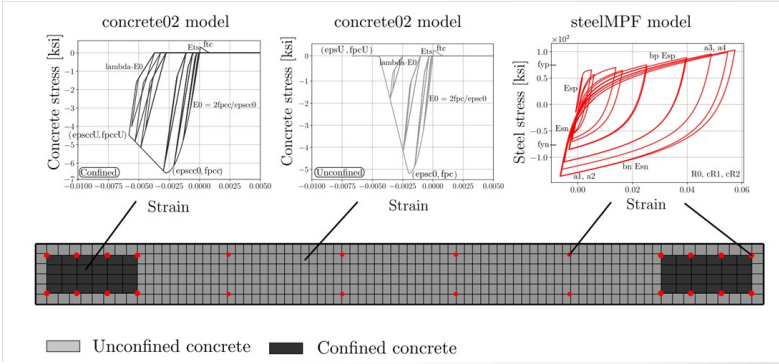
Preliminary Studies: Numerical Earthquake Simulations

- RC wall building numerical models with force-limiting connections designed using the proposed force-based method.
- 18 ground motions scaled to the design-basis earthquake-intensity level.
- Reduction in the peak acceleration and force responses and their dispersion due to ground motion-to-ground motion variability.
- Evaluate peak and residual responses, including:
  - Floor accelerations
  - Connection forces
  - Interstory drift





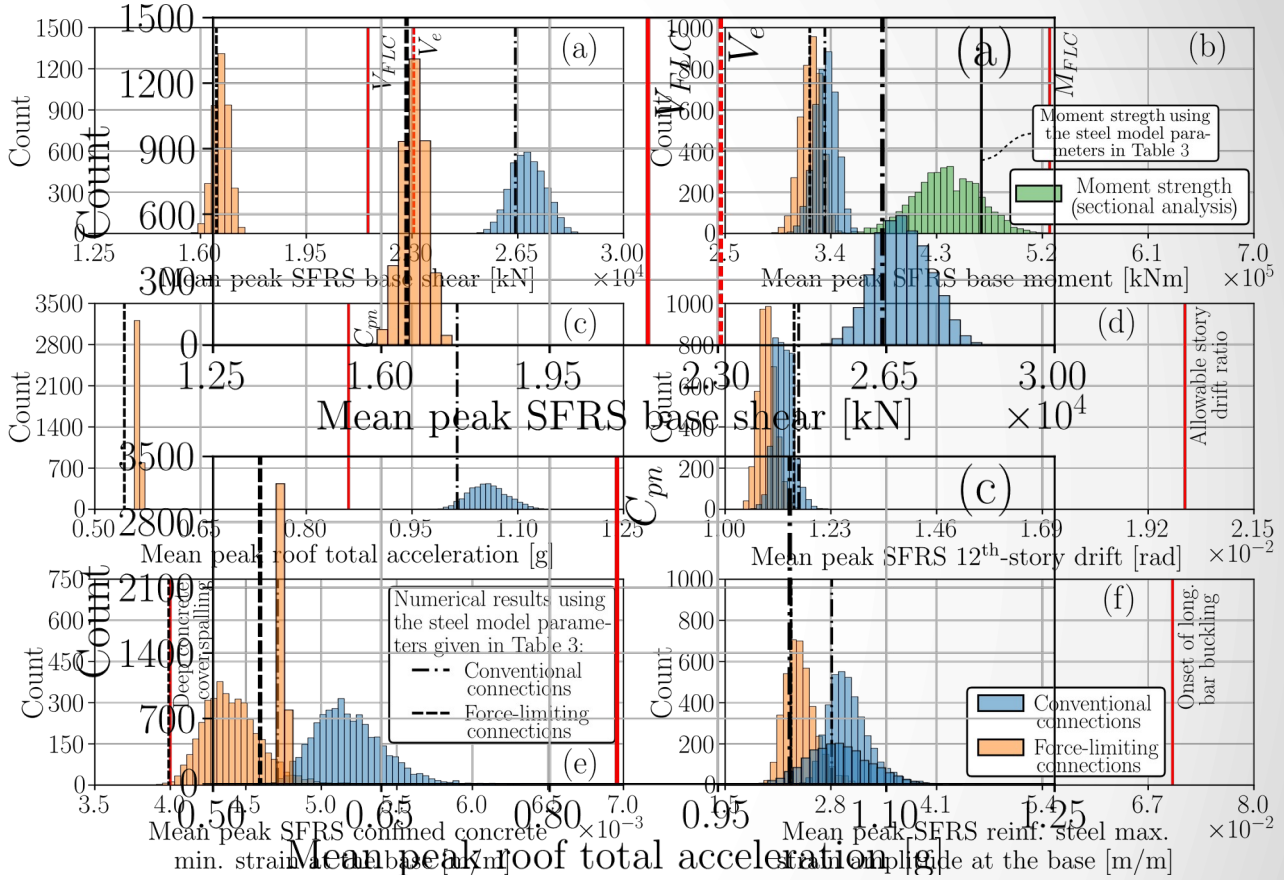




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Preliminary Studies: Numerical Earthquake Simulations

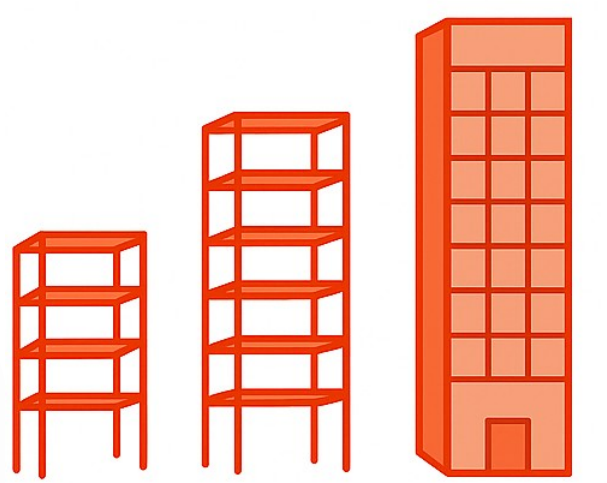
- Buildings with force-limiting connections showed:
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  - Reduced dispersion in EDPs across ground motions
  - Lowered sensitivity to higher-mode effects
- Consistent performance across multiple hazard levels



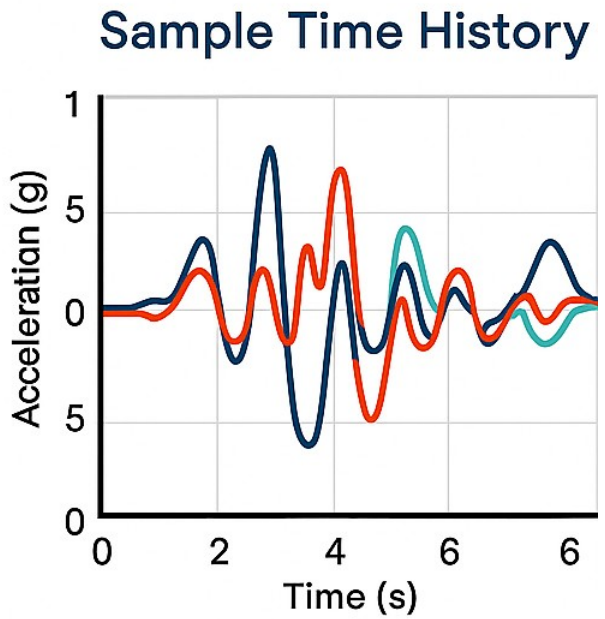
Source: Mayorga and Tsampras, 2024

Some Challenges: Incompatible Intensity Measures

- We do not intend to develop fragility functions for nonstructural components, but their inclusion is essential for the functional recovery model.
- However, the IMs used for nonstructural components in Performance Assessment Calculation Tool (PACT) are not directly compatible with those derived in this study.
- To bridge this gap, a model to map ground shaking IMs to floor-specific IMs used by PACT is needed.

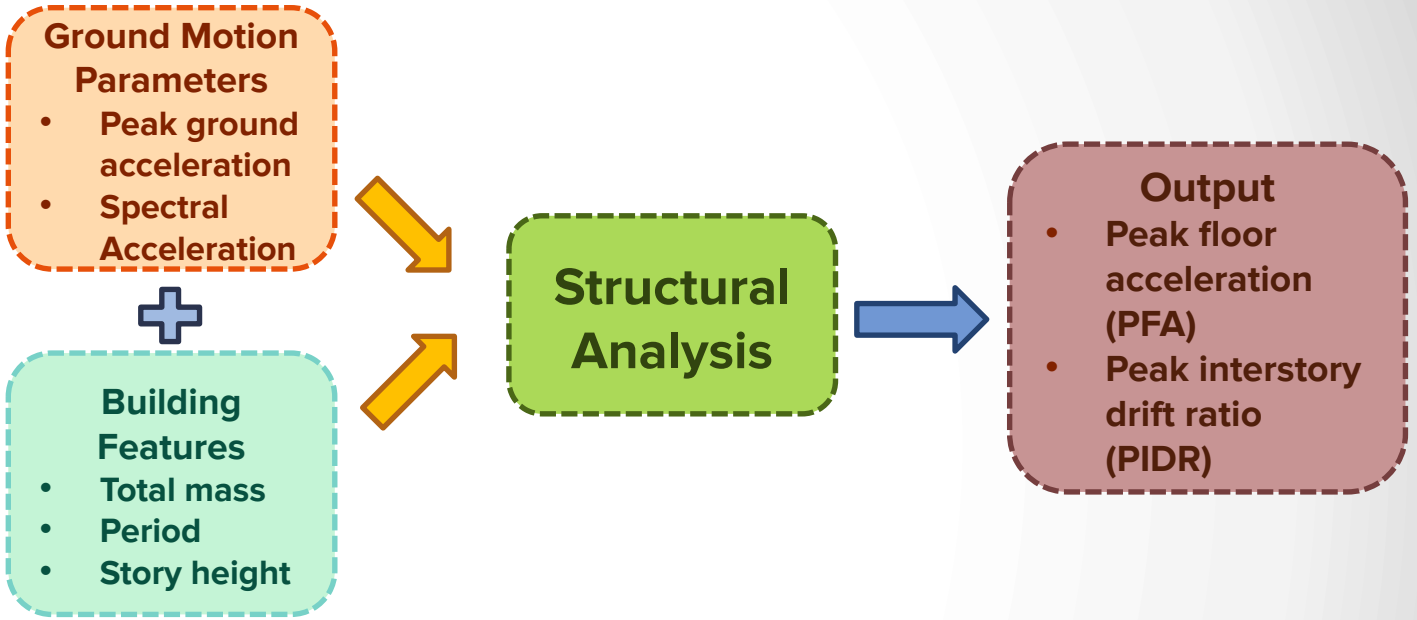


Varied Building Geometries



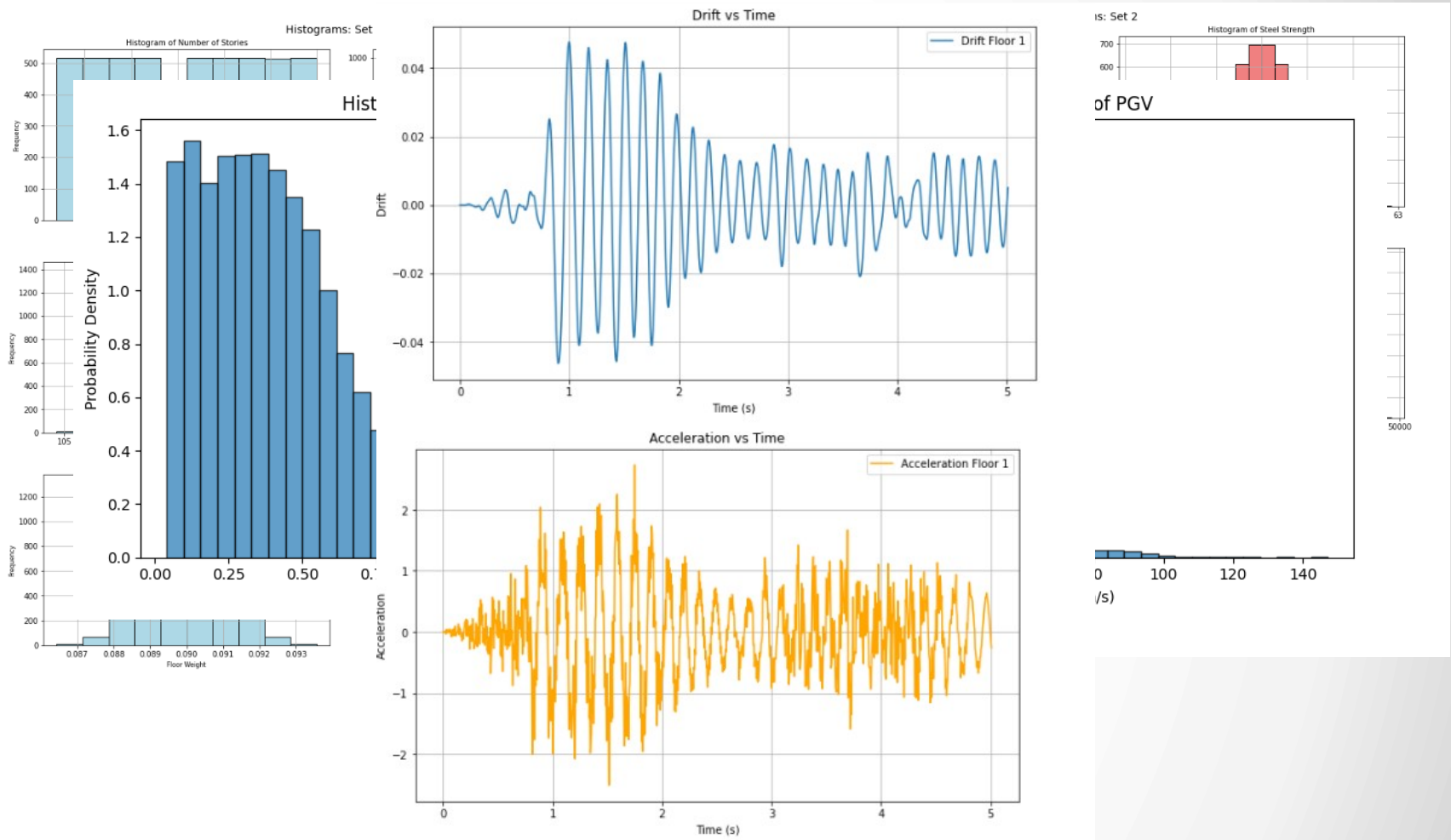
Some Challenges: Incompatible Intensity Measures

- The model was trained on 5,000 building configurations generated by varying structural parameters (e.g., number of stories, bays, story heights, bay widths, floor weights), material properties (e.g., concrete compressive strength, steel tensile strength), and column design features (e.g., cross-sectional area, moment of inertia, reinforcement area).
- Each configuration was subjected to a distinct ground motion record with varying PGA values.



Incompatible Intensity Measures

- For each building:
- Extract its design and material properties (e.g., height, number of storeys, column dimensions).
- Simulate its behavior under predefined ground motion scenarios using a structural analysis function.
- Calculate key metrics like floor drifts, accelerations, and tip displacements which are the intensity measures used in PACT.

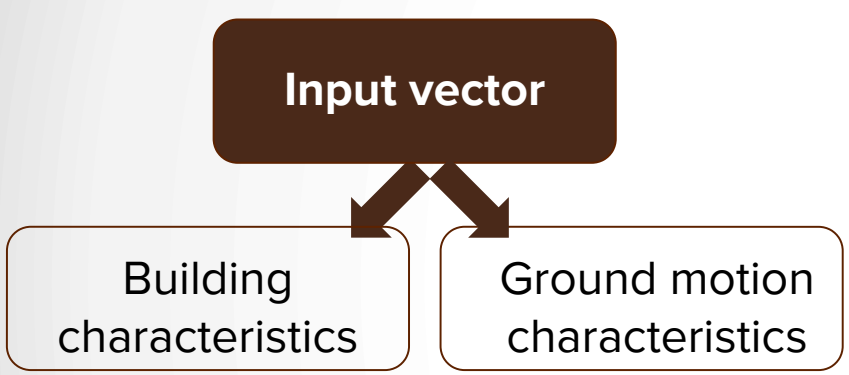


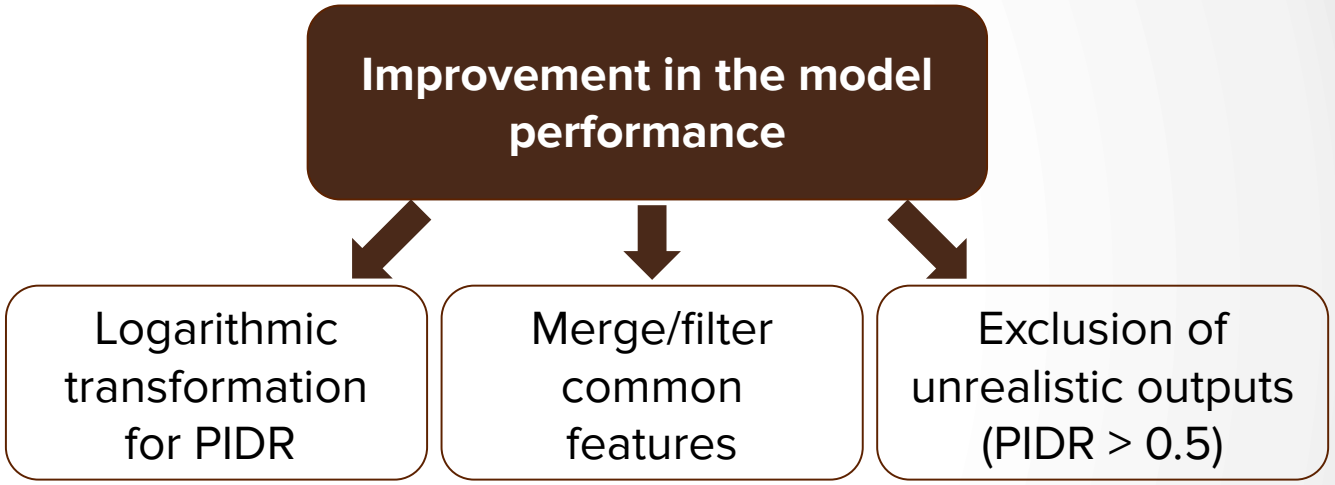
Features

Catergory	Input Parameter
Building characteristics	Number of stories
Building characteristics	Number of bays
Building characteristics	Story height
Building characteristics	Bay width
Building characteristics	Floor weight
Building characteristics	Concrete compressive strength
Building characteristics	Steel tensile strength
Building characteristics	Column area
Building characteristics	Column moment of inertia
Building characteristics	Reinforcement area
Building characteristics	Total mass
Building characteristics	Total stiffness
Building characteristics	Period of the first mode
Building characteristics	Period of the second mode
Building characteristics	Period of the third mode
Ground motion characteristics	PGA
Ground motion characteristics	PGV
Ground motion characteristics	PGD
Ground motion characteristics	Spectral acceleration at short periods
Ground motion characteristics	Spectral acceleration at long periods
Ground motion characteristics	Spectral acceleration at the first mode
Ground motion characteristics	Spectral acceleration at the second mode
Ground motion characteristics	Spectral acceleration at the third mode

Model

- Supervised neural network to predict critical seismic response parameters for buildings:

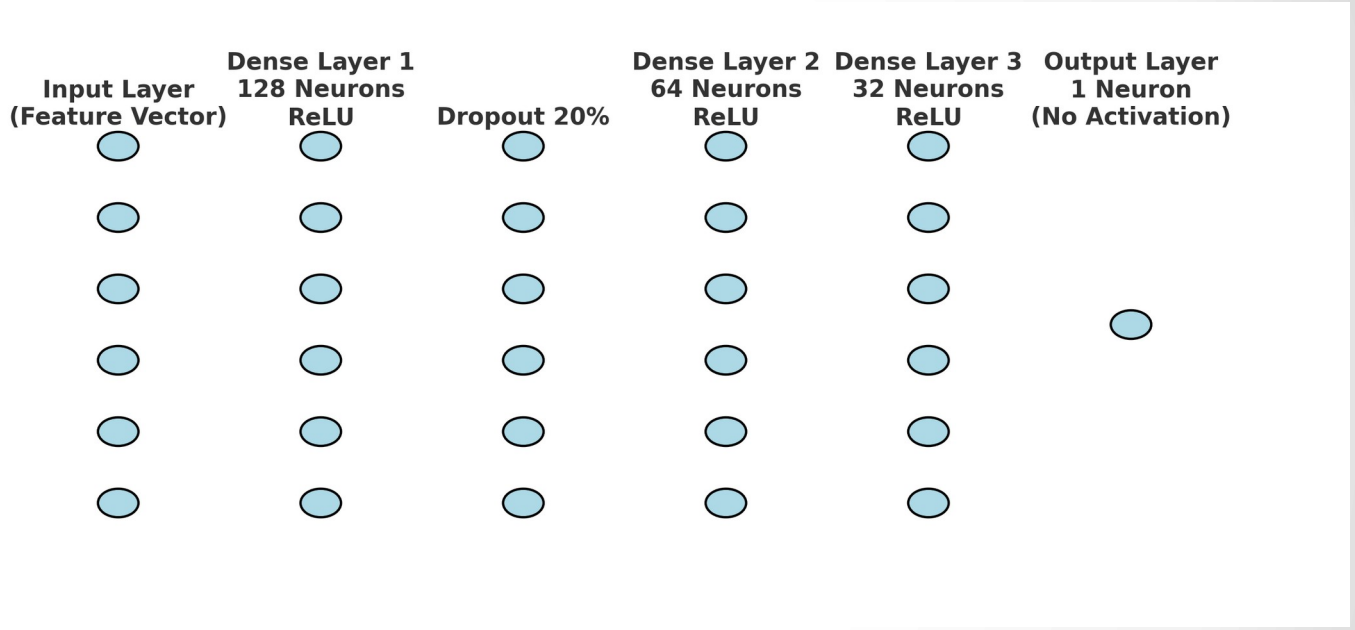




Model

A feedforward neural network was used with the following configuration:

- **Input Layer**: 18 features
- **Hidden Layer 1**: 128 neurons, ReLU activation
- **Dropout Layer**: 20% dropout
- **Hidden Layer 2**: 64 neurons, ReLU activation
- **Dropout Layer**: 20% dropout
- **Hidden Layer 3**: 32 neurons, ReLU activation
- **Output Layer**: 1 neuron (PIDR) **linear activation**

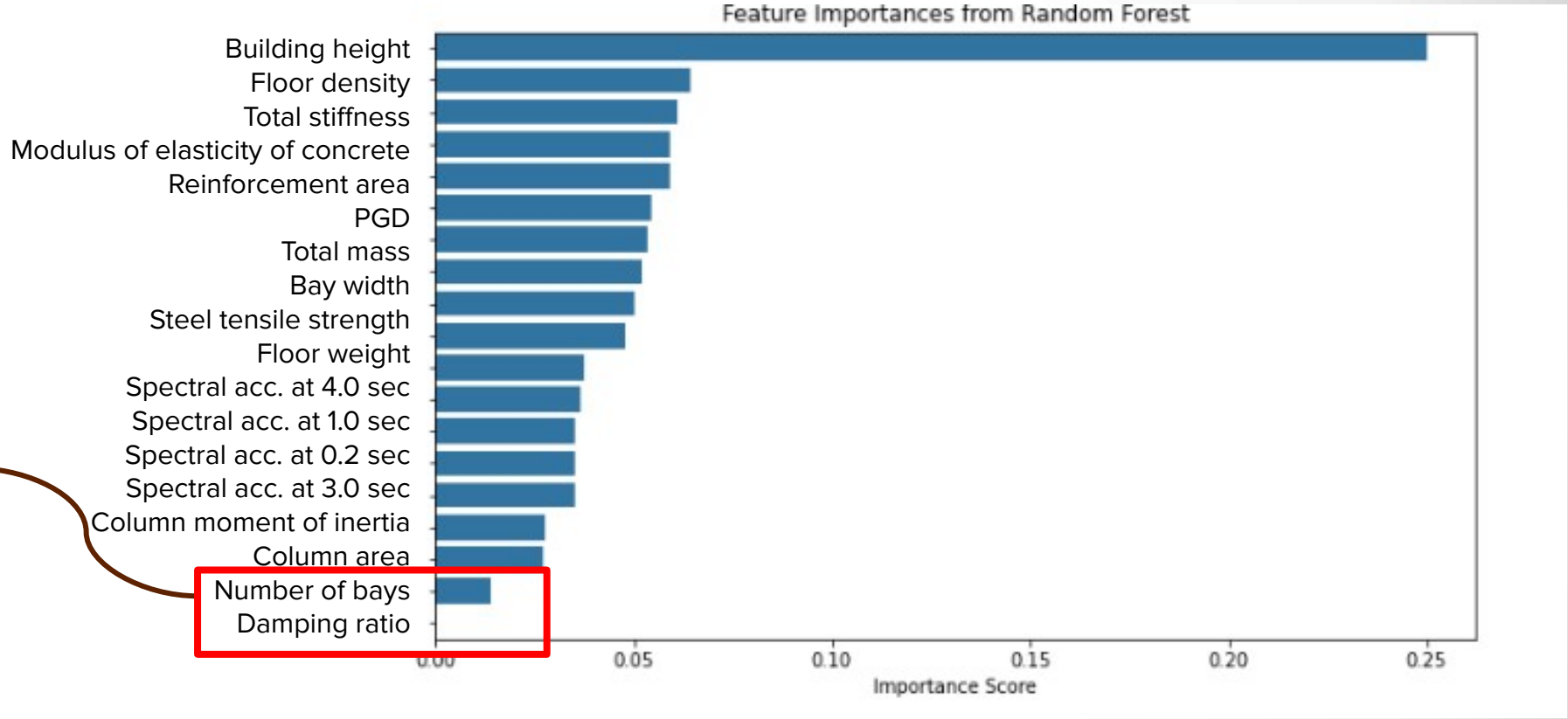


Loss Function: Mean Squared Error (MSE) on both outputs
Optimizer: Adam (adaptive learning rate)
Epochs: Increased iteratively until convergence
Regularization: Dropout + Feature selection to control overfitting
Stopping criteria?

Model Performance

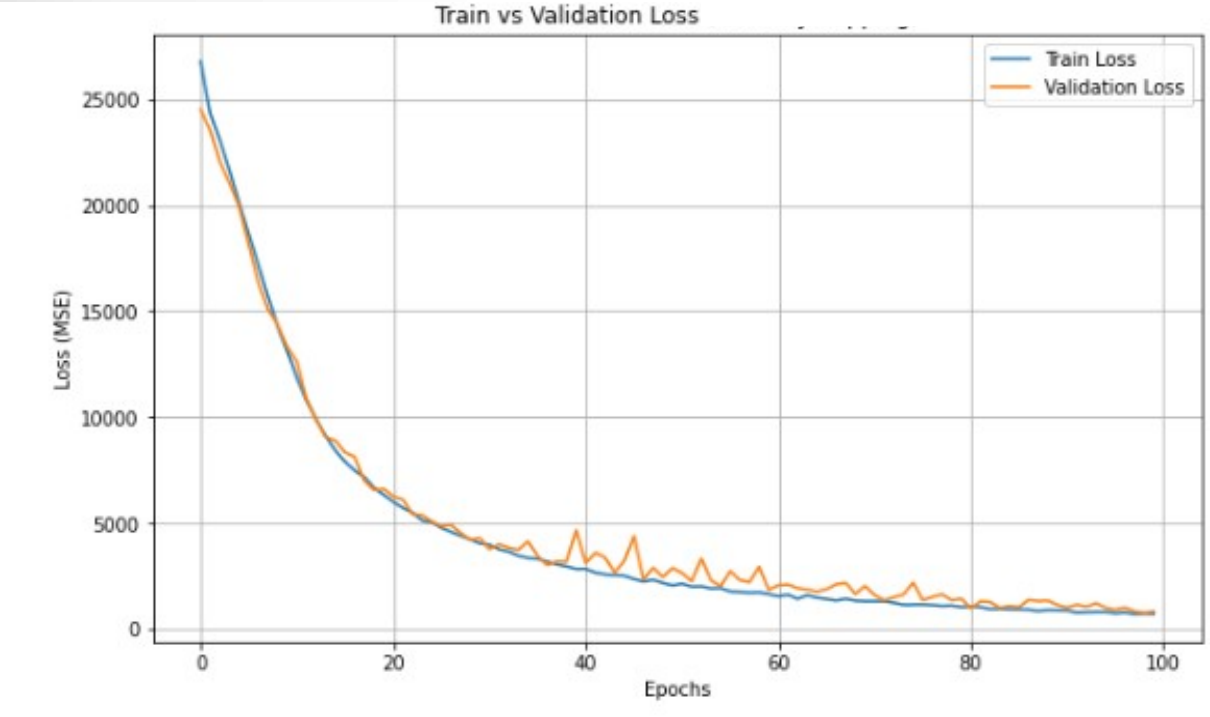
- Before training, we used a Random Forest model to rank features by importance.

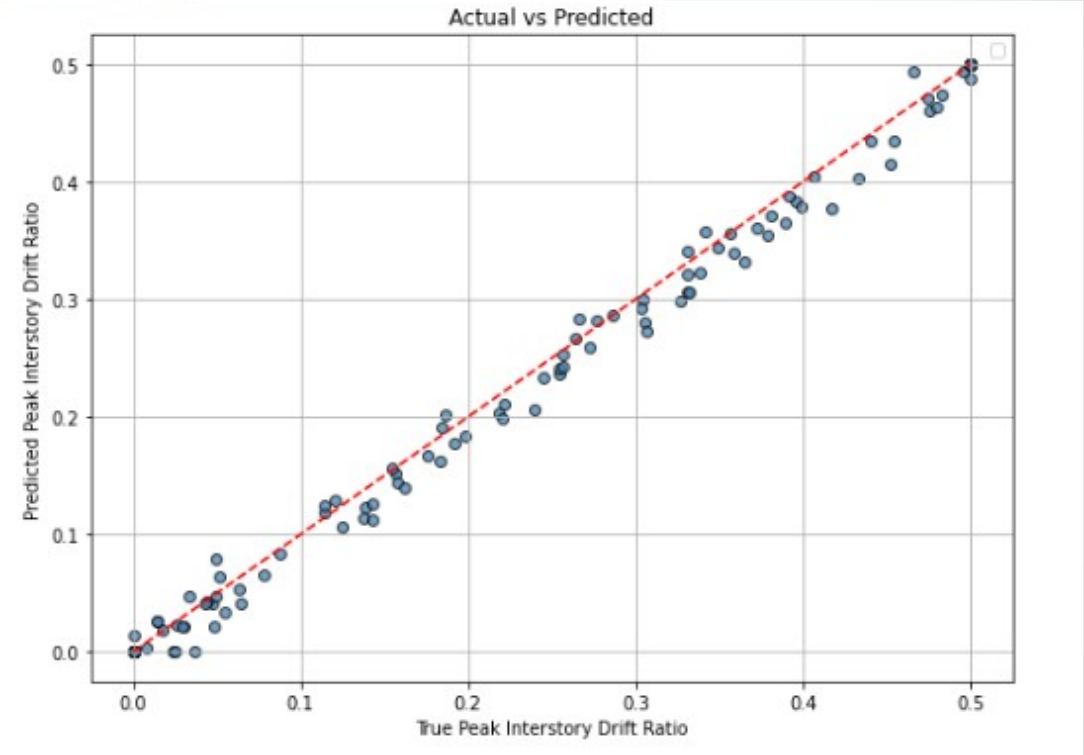
Low-impact or redundant features were filtered out to improve training stability.



Model Performance

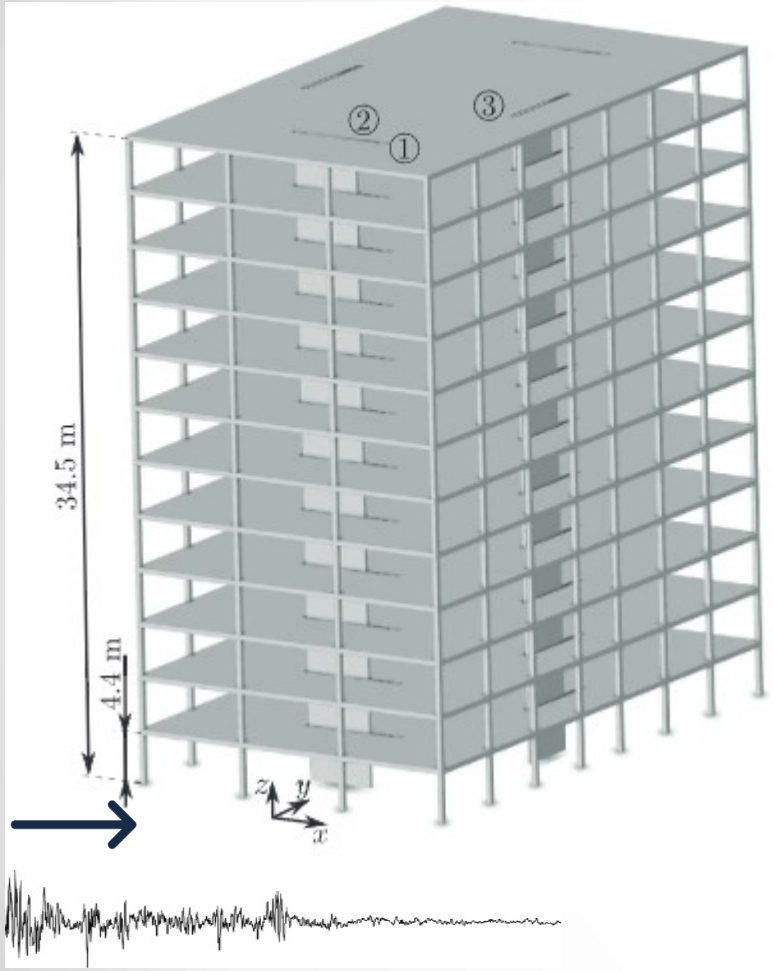
- Reduced loss and convergence using over 100 epochs
- High level of accuracy between predicted and actual PIDR values





Test Set R^2 Score: 0.9370

Numerical Example



Source: Mayorga and Tsampras, 2024

12-story RC wall building

- **RC walls:** Curvature demand at the base
- **Beams/slabs:** Maximum moment demand
- **Capacities for each component:** based on empirical and code-based distributions
- **Randomness** in materials for variability
- **Independent capacities and demands** as a conservative estimation in absence of known correlation.
- **Output:** Component-level damage state (DS) classification as output for resilience assessment.

Numerical Example

RC Wall Curvature at Base

Limit State	Description	Thresholds	Values (1/m)
Slight Damage	First cracking or minor yielding	$0.5\phi_y$	0.0042
Moderate Damage	Full yielding, residual drift starts	ϕ_y to $2\phi_y$	0.0084
Extensive Damage	Concrete cover spalling, bar buckling	$2\phi_y$ to $3\phi_y$	0.0168
Collapse	Near loss of lateral load capacity	$3\phi_y$ to ϕ_u	0.0252

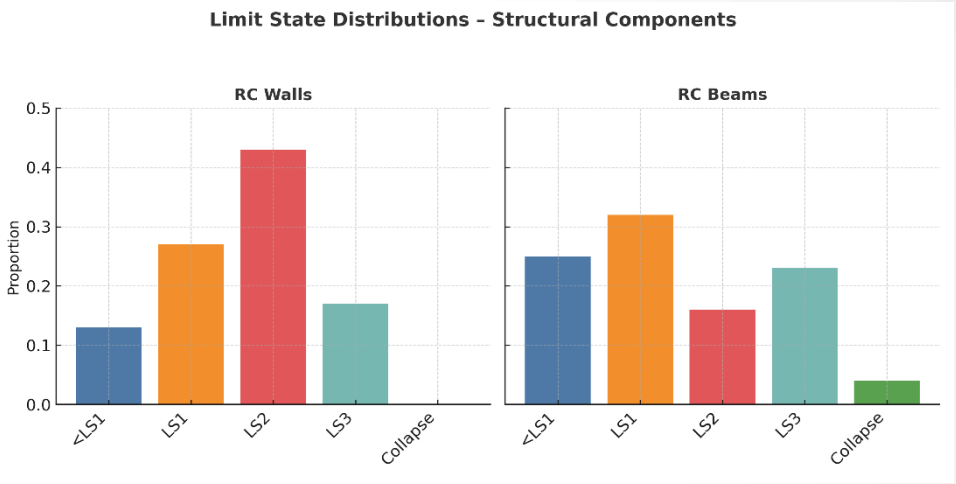
Maximum Beam Moment Capacity

Limit State	Description	Thresholds	Values (kN·m)
Slight Damage	First yielding of longitudinal reinforcement	$0.25M_p$	437.5
Moderate Damage	Full plastic hinge formation	$0.5M_p$	875
Extensive Damage	Significant rotation and reinforcement strain	$0.5M_p$ to $0.75M_p$	1312.5
Collapse	Rotation capacity exceeded	M_p	1750

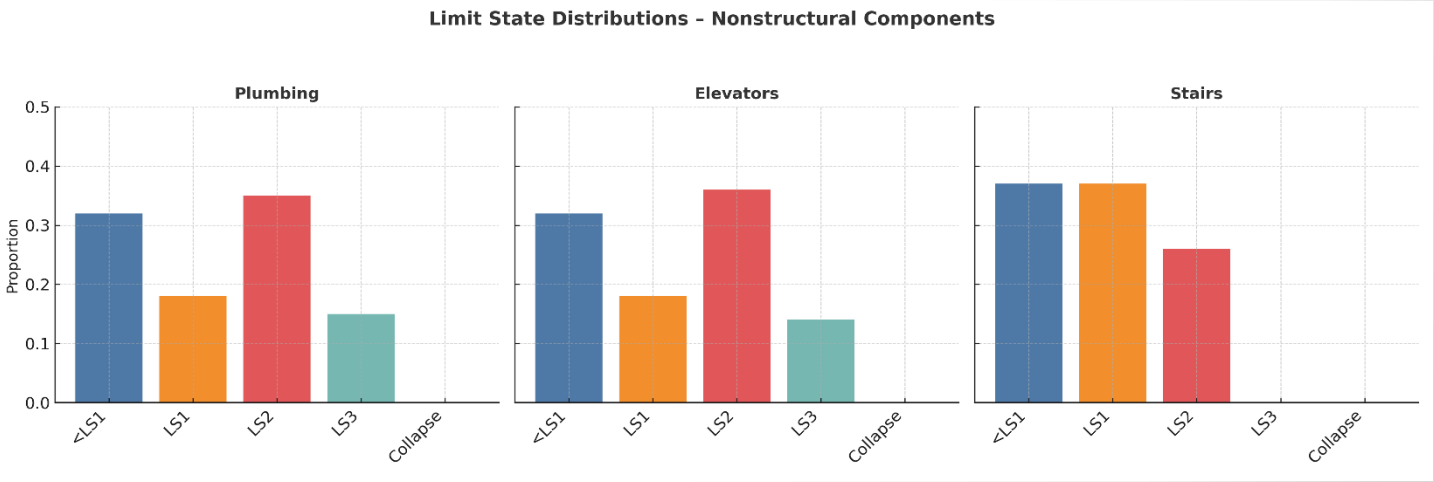
Numerical Example

- The plot shows how curvature demand at RC wall bases compares to their assigned capacity distributions.
- A similar analysis is done for moment demand in beams.
- The surrogate model was used to assign damage states to nonstructural components.
- The resulting demand-to-capacity ratios are categorized into damage states for each element.
- These damage states are used as inputs for functional recovery assessment.

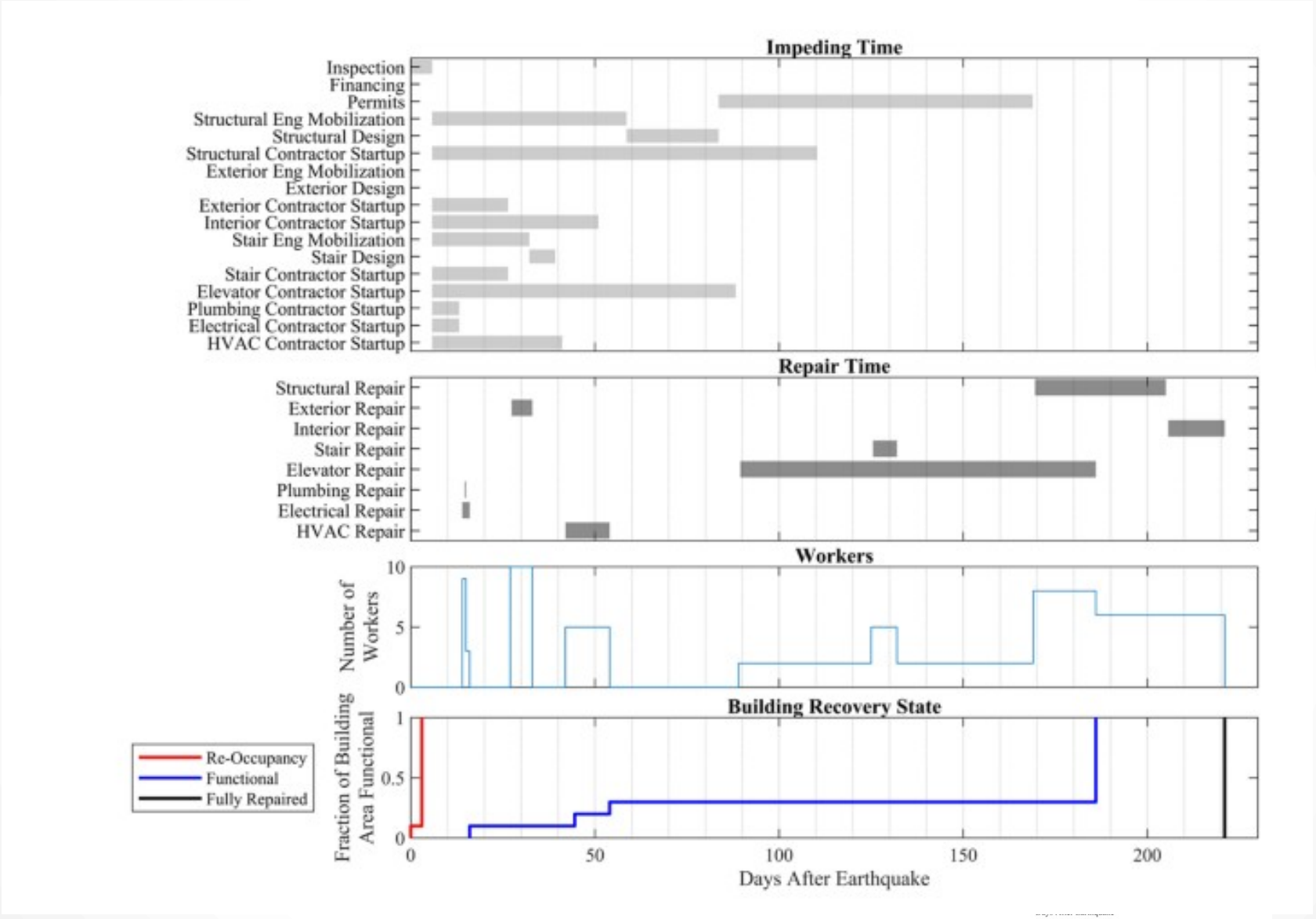
Obtained from our numerical model analyzed in OpenSees



Based on surrogate model and seismic input parameters



Numerical Example



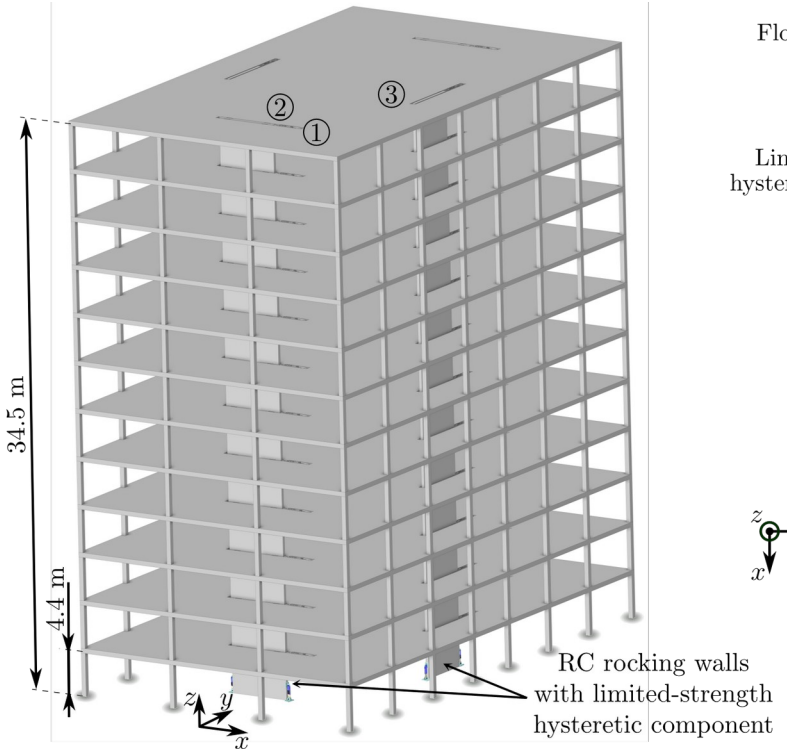
Conclusions and Future Work

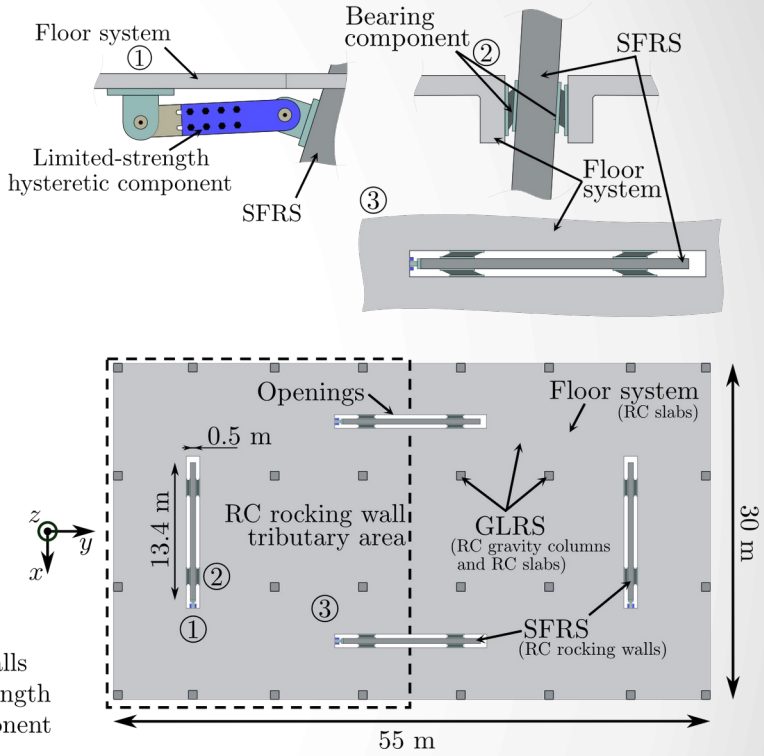
- Developed a resilience-based framework focusing on post-earthquake functional recovery for buildings with force-limiting connections.
- Implemented and validated force-limiting connections, showing reduced floor accelerations and improved response consistency.
- Created a machine learning surrogate model to map input features to floor-level IMs compatible with recovery tools.
- Integrated damage states and recovery functions to estimate system-level recovery trajectories.
- Streamlined the end-to-end workflow, linking structural simulations with resilience metrics by integrating the numerical model outputs into FEMA P-58's functional recovery tool.
- Plan to extend the framework to include varied building archetypes (e.g., different heights, layouts, and functional uses) to evaluate broader applicability.


Thank you

Background

- Traditional seismic design often leads to excessive force demands and costly nonstructural damage.
- Force-limiting connections mitigate seismic forces transferred from diaphragms to structural walls.
- This strategy reduces acceleration-sensitive damage and higher-mode effects, enhancing resilience.
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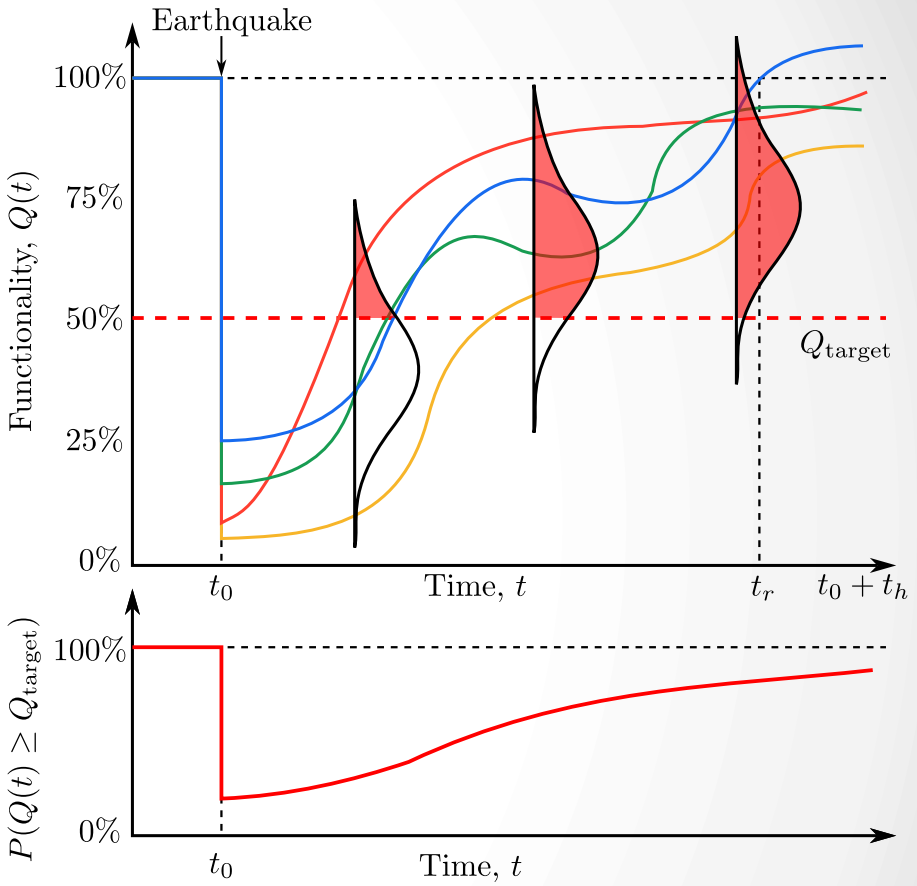




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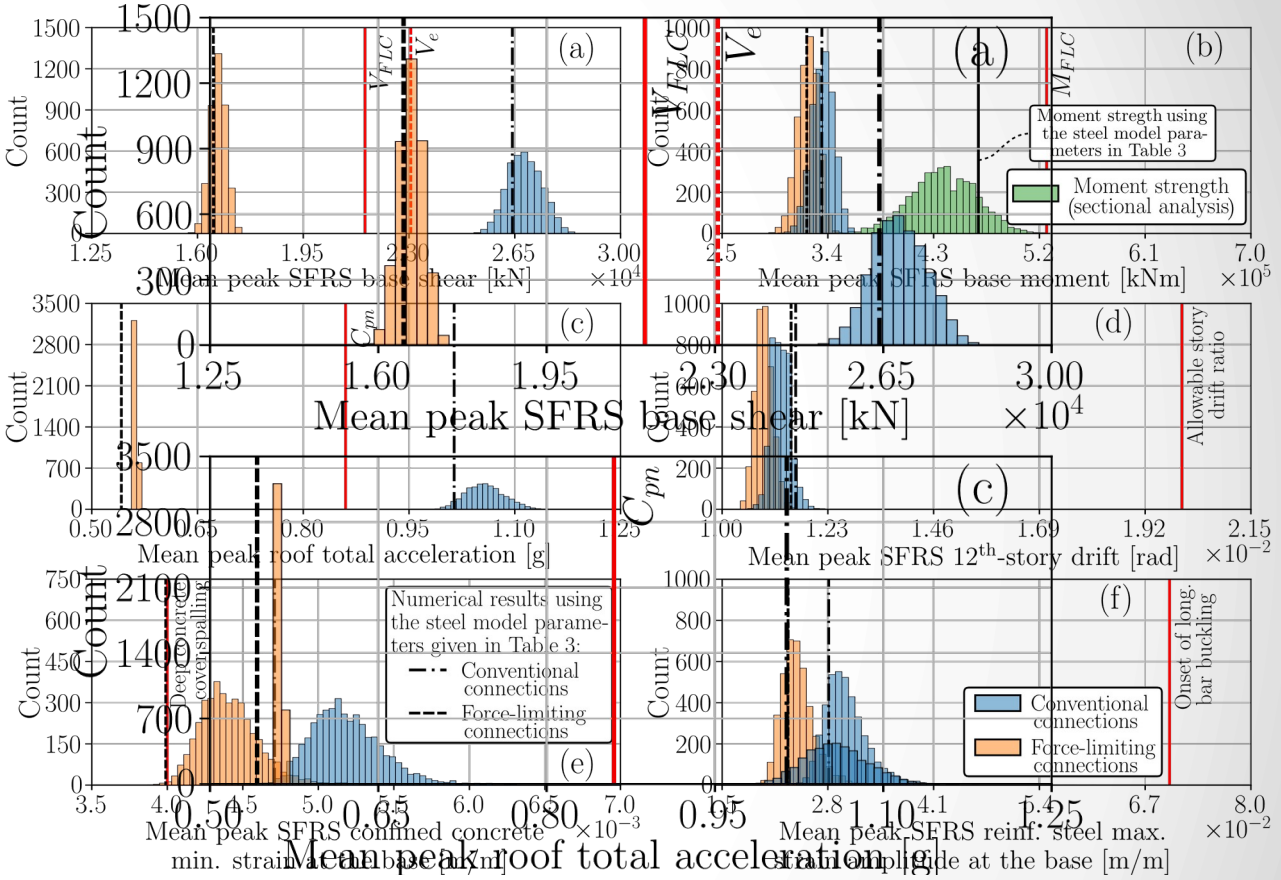
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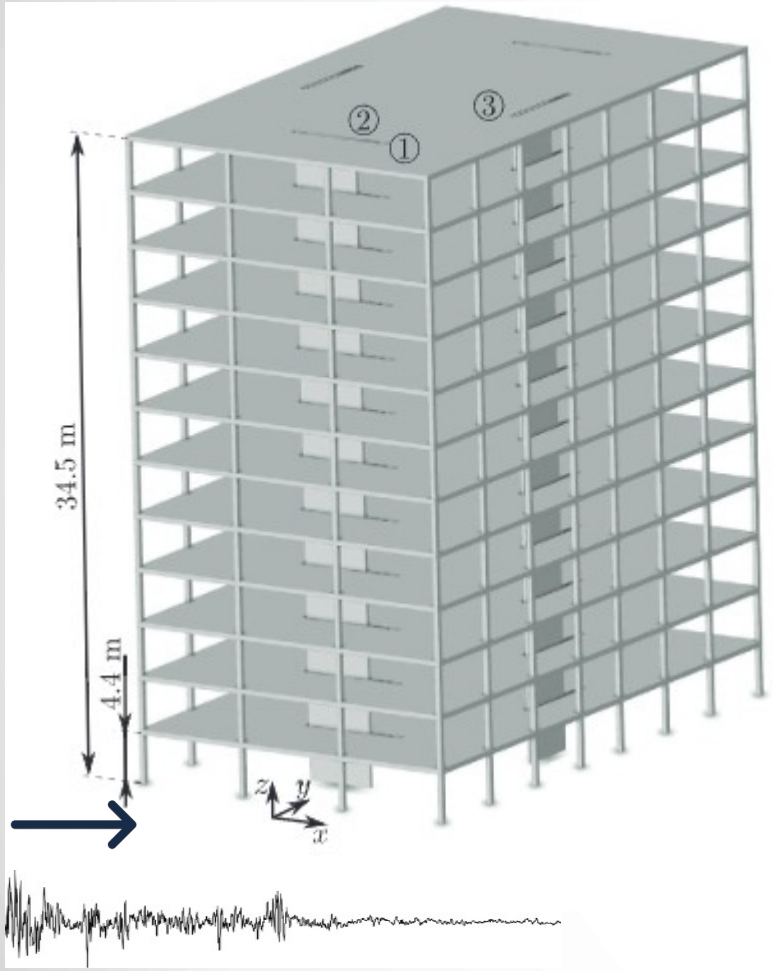
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  - Reduced dispersion in EDPs across ground motions
  - Reduced dispersion in EDPs due to variability in the parameters of the constitutive law of the longitudinal reinforcing steel.
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Numerical Example



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