Resilience-Based Design of Buildings with Accelerated Post-Earthquake Functional Recovery

C. Franco Mayorga[1], Sena Mursel[2], Georgios Tsampras[3], and Paolo Bocchini[4]

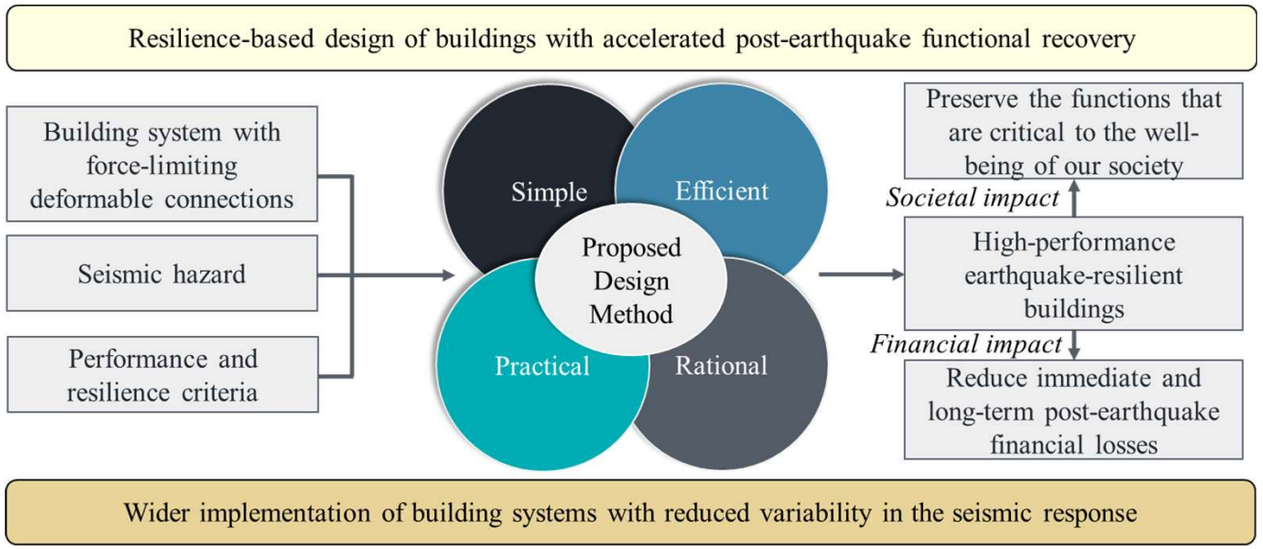
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[2]Graduate Student Researcher, Lehigh University, PA, USA
[3]PI, Assistant Professor, University of California San Diego, CA, USA
[4]Co-PI, Professor, Lehigh University, PA, USA

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2025 Virtual Disaster Resilience Research Grants (DRRG) Symposium

Vision

Project Vision

- Vision:
  - to advance the fundamental knowledge that will democratize the simple, efficient, rational, and practical design of high-performance buildings that even after strong earthquakes preserve the functions that are critical for the well-being of our society and reduce the immediate and long-term financial losses.

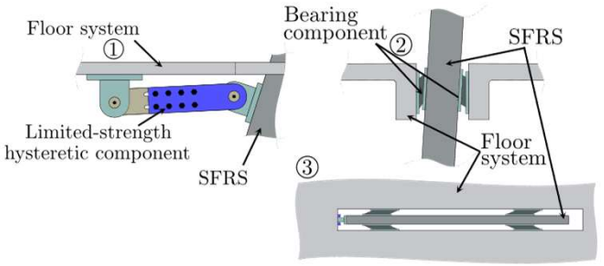


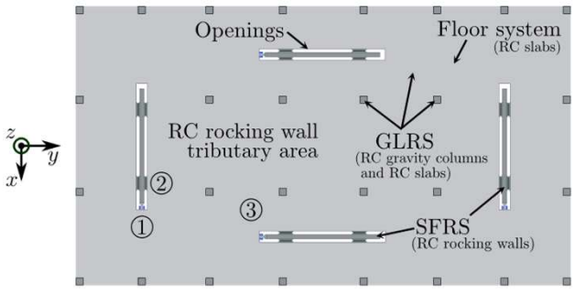
  - We expect that the proposed design method will popularize the use of high-performance earthquake-resilient building systems designed to meet specific performance and resilience criteria.

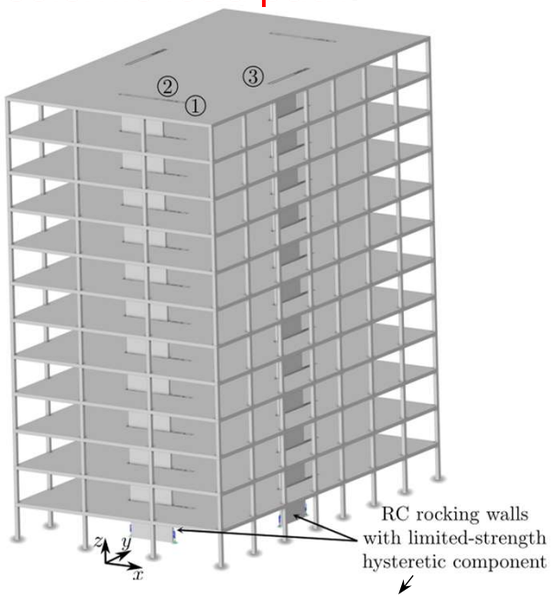
Buildings with Force-Limiting Deformable Connections

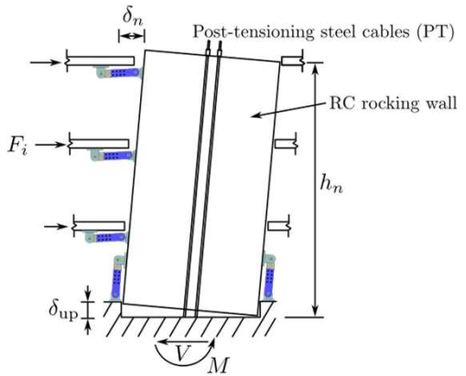
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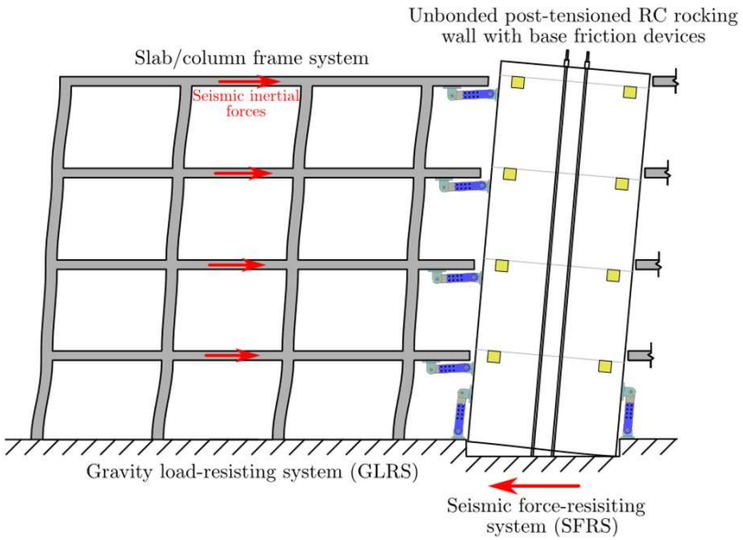
- The proposed design methodology focuses on buildings that utilize practical reusable force-limiting deformable connections efficiently placed in the seismic load path.









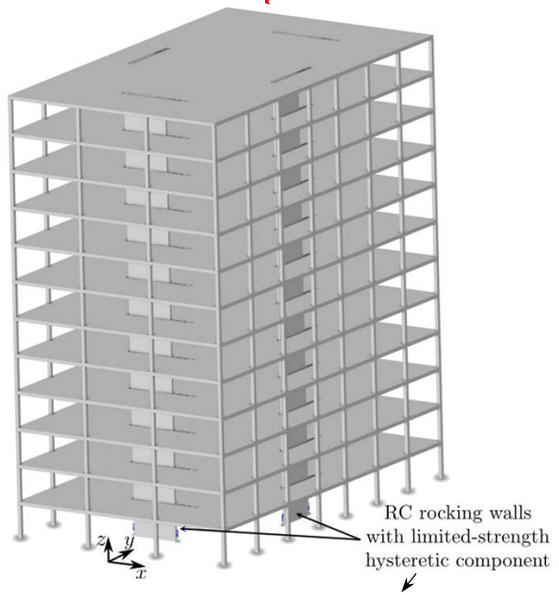


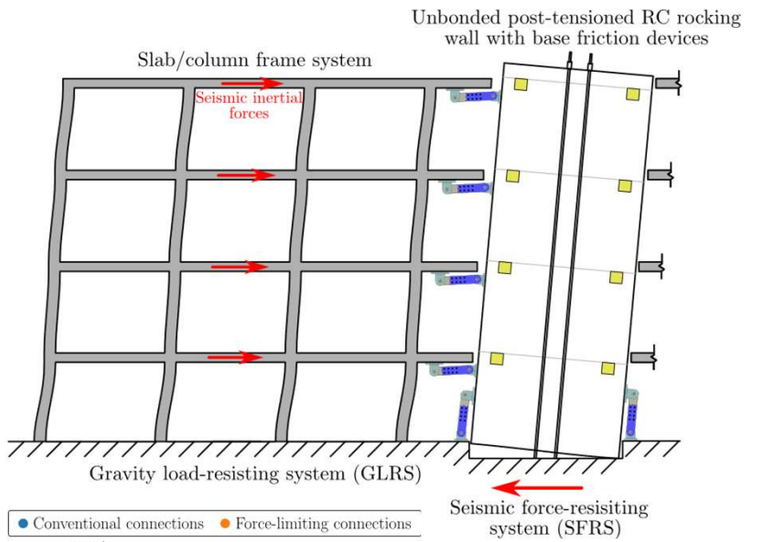
1. Tsampras, G. 2016. "Force-Limiting Deformable Floor Diaphragm Connection for Earthquake Resistant Buildings," PhD Dissertation, Lehigh University, Bethlehem, PA, USA, https://preserve.lib.lehigh.edu/islandora/object/preserve%3Abp-10369972
2. Tsampras, G., R. Sause, D. Zhang, R.B. Fleischman, J.I. Restrepo, D. Mar, J. Maffei. 2016, Development of deformable connection for earthquake-resistant buildings to reduce floor accelerations and force responses, Earthquake Engineering & Structural Dynamics, 45 (9), 1473–1494, https://doi.org/10.1002/eqe.2718.
3. Mayorga, C.F., G. Tsampras. 2024. "Reinforced concrete wall buildings with force-limiting connections: Modeling effects and uncertainty propagation." Earthquake Engineering & Structural Dynamics, 53(4):1465-1491. https://doi.org/10.1002/eqe.4073.
4. Lee K, Tsampras G, Mayorga CF 2025. "Reinforced Concrete Core Wall Buildings with Modified Friction-Based Force-Limiting Connections: Connection Design Considerations and Three-Dimensional Response to Bidirectional Ground Motions. Journal of Structural Engineering 151 (2): 04024203. https://doi.org/10.1061/JSENDH.STENG-13609.

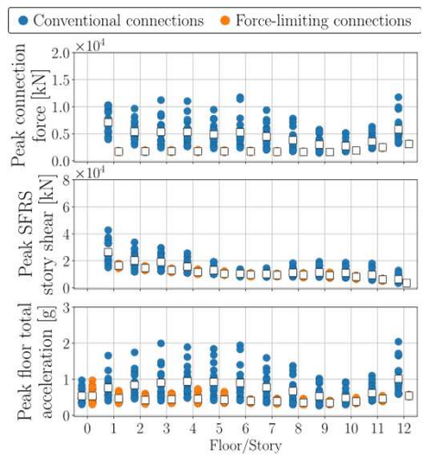
Buildings with Force-Limiting Deformable Connections

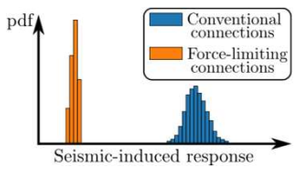
- The proposed design methodology focuses on buildings that utilize practical reusable force-limiting deformable connections efficiently placed in the seismic load path.

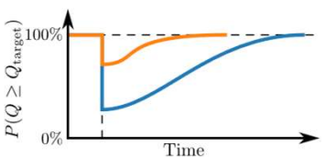
- These nonconventional buildings have:
  - limited seismic-induced force responses.
  - reduced seismic-induced acceleration responses.
  - reduced sensitivity of their seismic responses to the variability of the characteristics of strong earthquake ground motions.
  - reduced sensitivity of their seismic responses to the uncertainty in model parameters.
  - potential to achieve faster and more reliably a target post-earthquake functionality level.









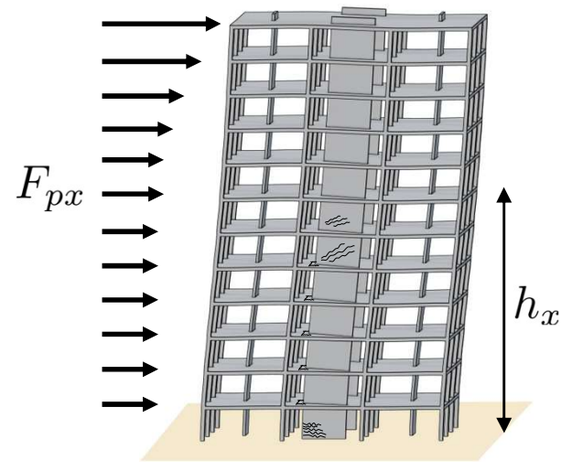


1. Tsampras, G. 2016. "Force-Limiting Deformable Floor Diaphragm Connection for Earthquake Resistant Buildings," PhD Dissertation, Lehigh University, Bethlehem, PA, USA, https://preserve.lib.lehigh.edu/islandora/object/preserve%3Abp-10369972
2. Tsampras, G., R. Sause, D. Zhang, R.B. Fleischman, J.I. Restrepo, D. Mar, J. Maffei. 2016, Development of deformable connection for earthquake-resistant buildings to reduce floor accelerations and force responses, Earthquake Engineering & Structural Dynamics, 45 (9), 1473–1494, https://doi.org/10.1002/eqe.2718.
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4. Lee K, Tsampras G, Mayorga CF 2025. "Reinforced Concrete Core Wall Buildings with Modified Friction-Based Force-Limiting Connections: Connection Design Considerations and Three-Dimensional Response to Bidirectional Ground Motions. Journal of Structural Engineering 151 (2): 04024203. https://doi.org/10.1061/JSENDH.STENG-13609.

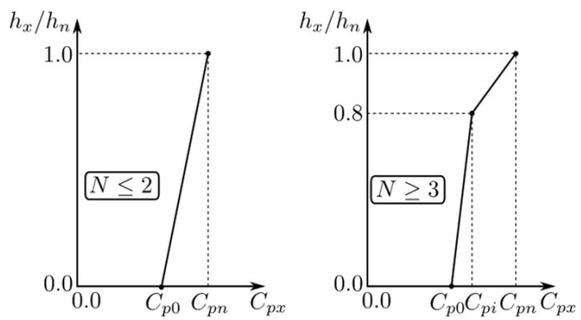
Force-Based Design for Force-Limiting Deformable Connections

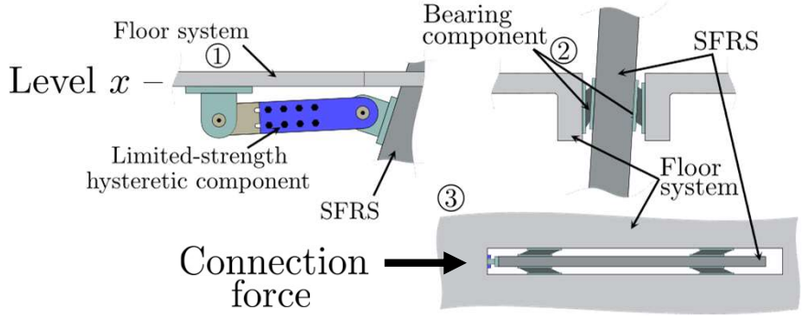
- A force-based method has been developed based on the alternative design provisions for floor diaphragms per ASCE/SEI 7-22 §12.10.3. (Tsampras and Sause (2022))



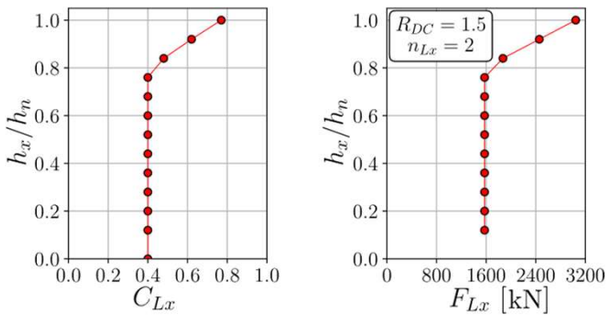


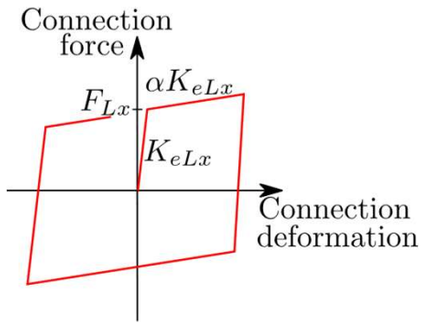
$$F_{px} = \frac{C_{px}}{R_s} w_{px}$$





$$F_{Lx} = \frac{C_{Lx}}{R_{DC}} \frac{w_{px}}{n_{Lx}}$$





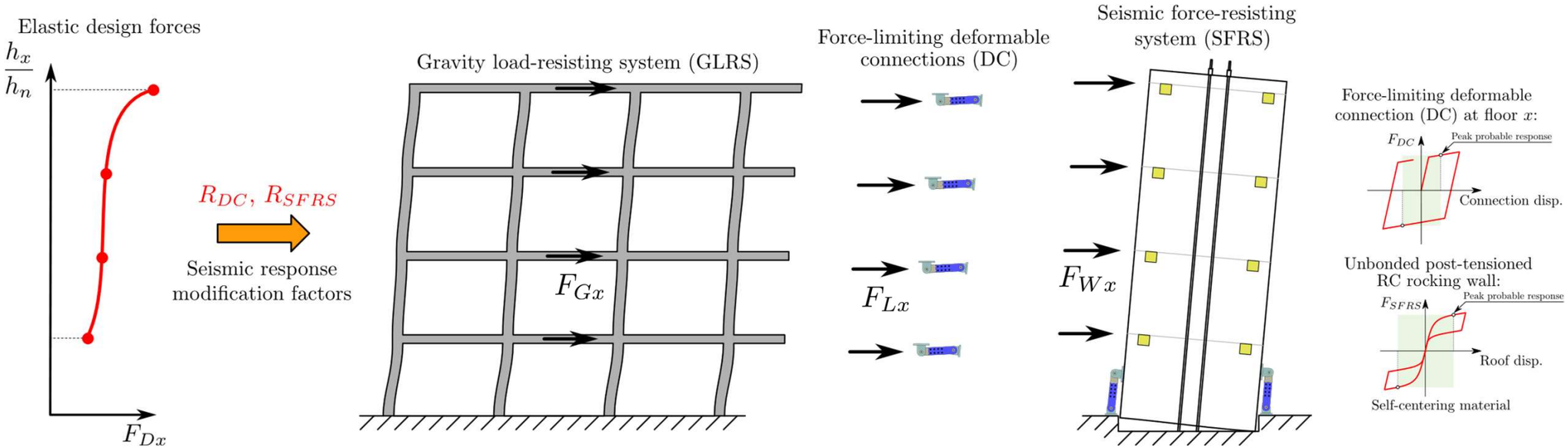
<u>Alternative floor diaphragm design provisions</u>: Estimates of horizontal earthquake-induced inertial floor forces

1. ASCE/SEI 7-22 2021. "Minimum design loads and associated criteria for buildings and other structures." American Society of Civil Engineers. https://doi.org/10.1061/9780784415788.
2. Tsampras, G., R. Sause. 2022. "Force-Based Design Method for Force-Limiting Deformable Connections in Earthquake-Resistant Buildings." Journal of Structural Engineering, 148(10): 04022150. https://doi.org/10.1061/(ASCE)ST.1943-541X.0003456.

Goal

Goal

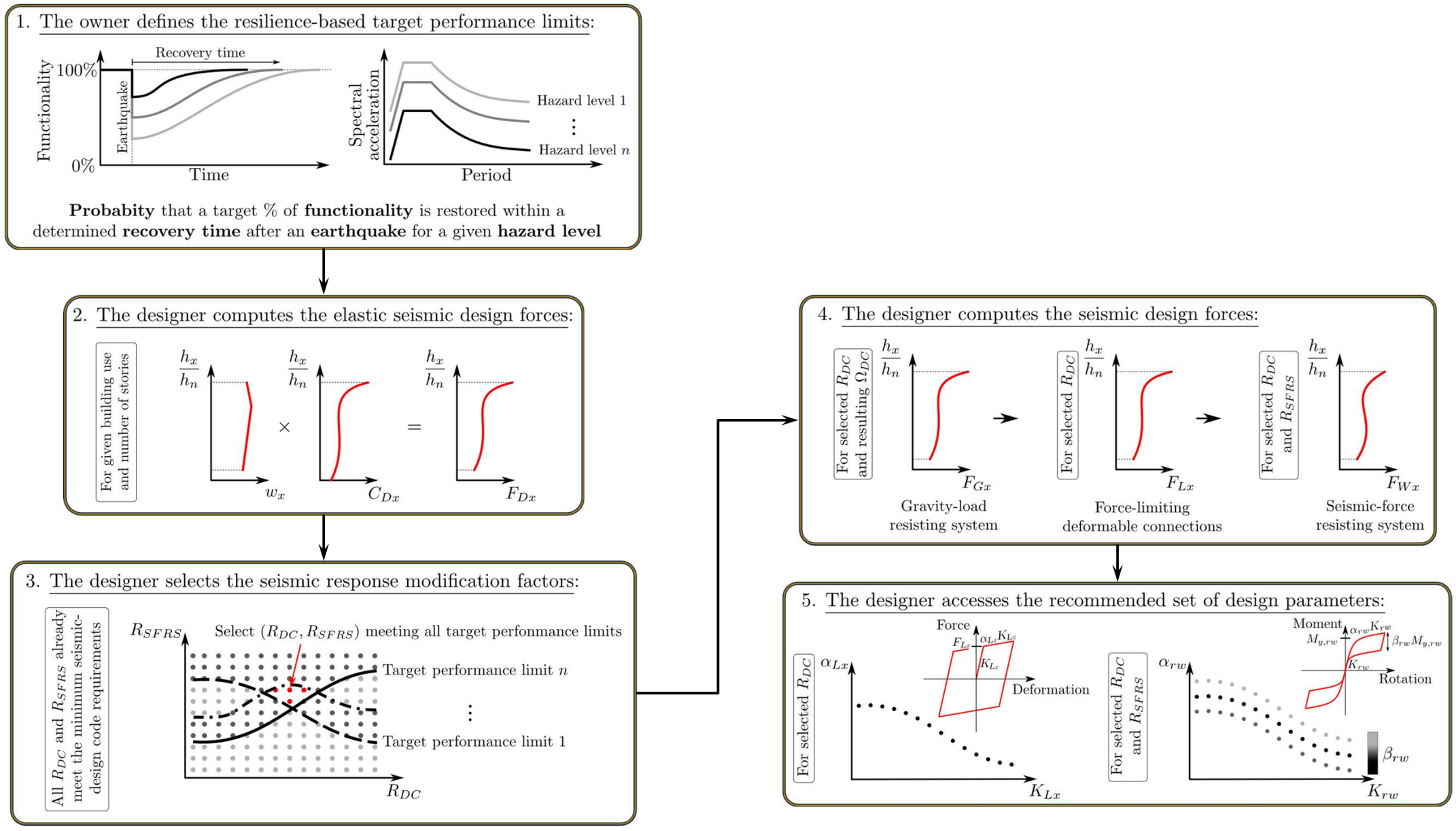
- To develop and validate a design method that will integrate performance and resilience criteria.
  - Buildings will be designed with a simple and practical methodology, but they are expected to perform better than conventional buildings designed using current code requirements.
  - Design forces for all components are consistent with the seismic load path.
  - Design meets the performance and resilience criteria.



$*$ F_{Lx}, F_{Wx}, and F_{Gx} as a function of F_{Dx}, R_{DC}, and R_{SFRS}.

Proposed Design Methodology

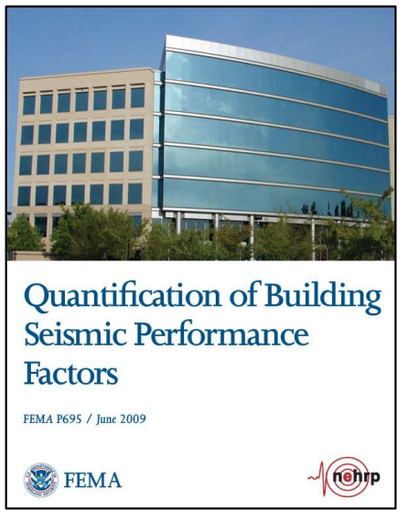
Proposed Design Methodology

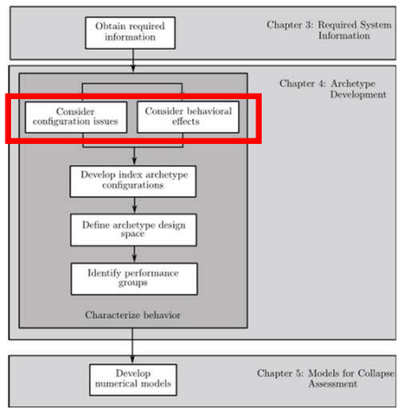


Building Archetypes

Building Archetypes

Number of stories, in-plane SFRS distribution, and building use.





Performance Group No.	Building Type	No. of Stories	Use	SFRS Distribution	Period domain	SDC
PG1	Reinforced Concrete	3	Residential	Perimeter	Short	Dmax
			Office			
			Medical			
			Data Center			
PG2		6	Residential			
			Office			
			Medical			
			Data Center			
PG3		9	Residential			
			Office			
			Medical			
			Data Center			
PG4		12	Residential	Perimeter	Long	
			Office			
			Medical			
			Variable			
PG5		12	Residential	Core		
			Office			
			Medical			
			6 Residential/6 Office			
			6 Medical/6 Office			
			10 Office/2 Data Center			
PG6		18	Residential			
			Office			
			Medical			
			Variable			
PG7		24	Residential			
			Office			
			12 Residential/12 Office			
			6 Medical/18 Office			
			22 Office/2 Data Center			
PG8		30	Residential			
			Office			

Performance Group No.	Building Type	No. of Stories	Use	SFRS Distribution	Period domain	SDC
PG9	Steel	3	Residential	Perimeter	Short	Dmax
			Office			
			Medical			
			Data Center			
PG10		6	Residential			
			Office			
			Medical			
			Data Center			
PG11		9	Residential			
			Office			
			Medical			
			Data Center			
PG12		12	Residential	Perimeter	Long	
			Office			
			Medical			
			Variable			
PG13		12	Residential	Core		
			Office			
			Medical			
			6 Residential/6 Office			
			6 Medical/6 Office			
			10 Office/2 Data Center			
PG14		18	Residential			
			Office			
			Medical			
			Variable			
PG15		24	Residential			
			Office			
			12 Residential/12 Office			
			6 Medical/18 Office			
			22 Office/2 Data Center			
PG16		30	Residential			
			Office			

Index archetype configurations: 68 Building Archetypes.

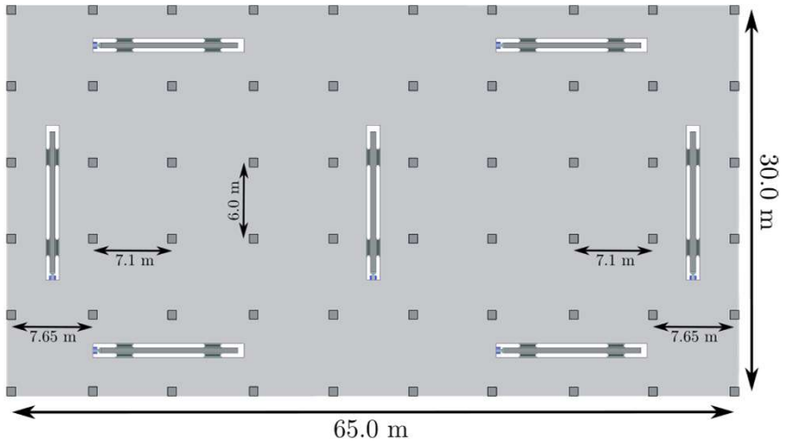
1. FEMA P695. Quantification of Building Seismic Performance Factors. June 2009.

Building Archetypes

In-plane dimensions and story heights of the building archetypes

For the Development of the Design Methodology:

Average of median building plan dimensions

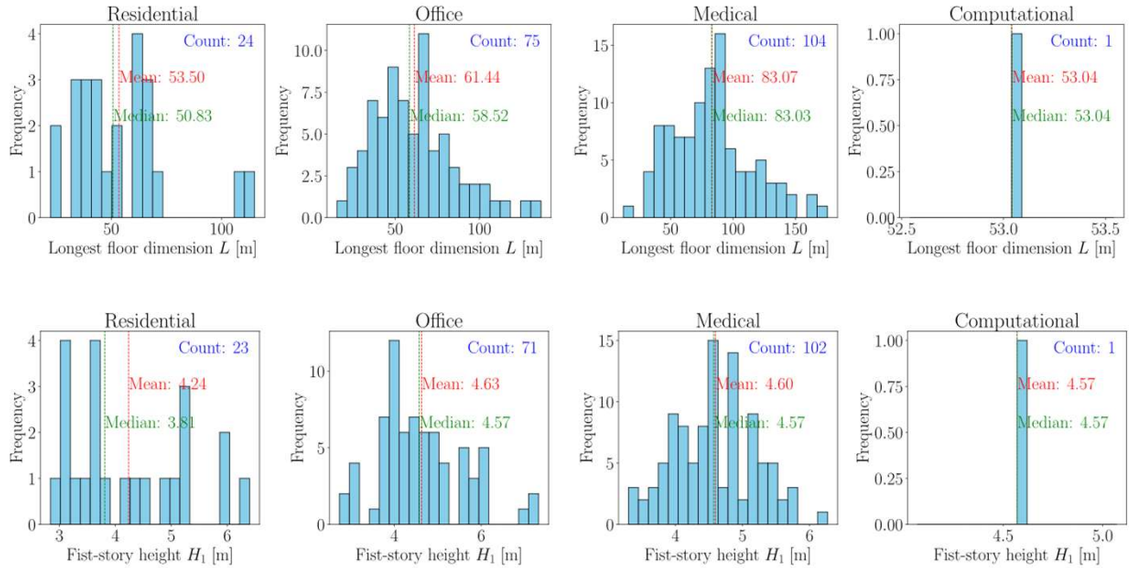


(Same plan dimensions for all uses)

Median story heights

Use	h_1 m	h_{upper} m
Residential	3.8	2.9
Office	4.6	4.0
Medical	4.6	4.4
Data center	–	–

Statistics from buildings monitored by the California Strong-Motion Instrumentation Program

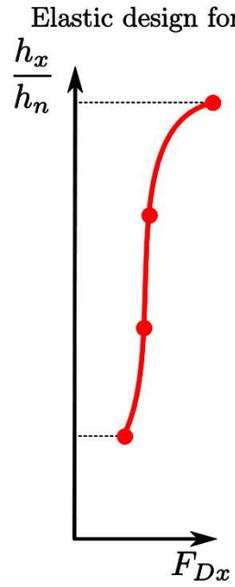


California Department of Conservation



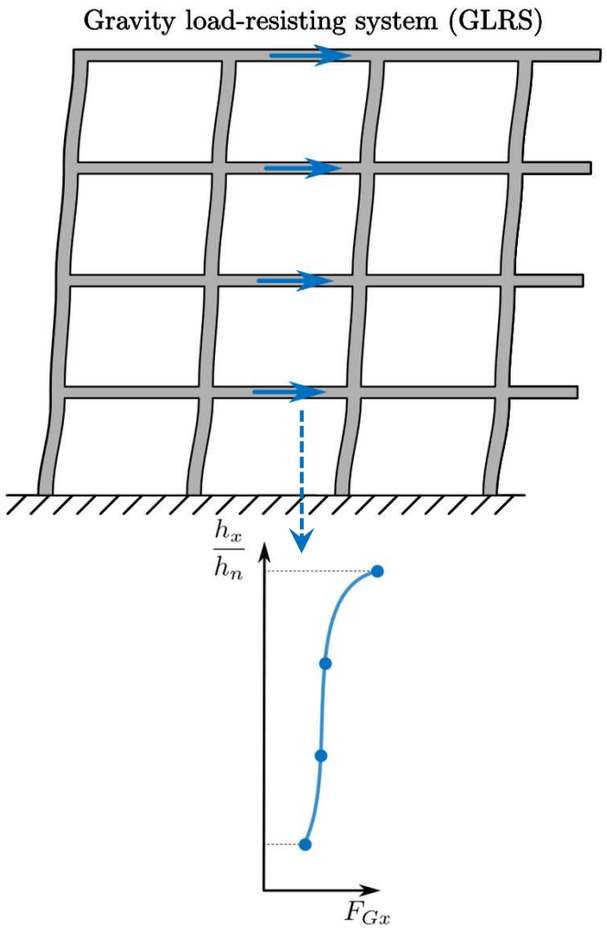
Seismic Design Forces

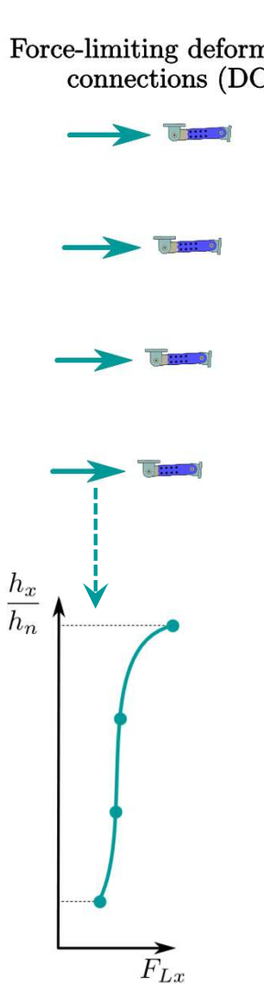
Seismic Design Forces

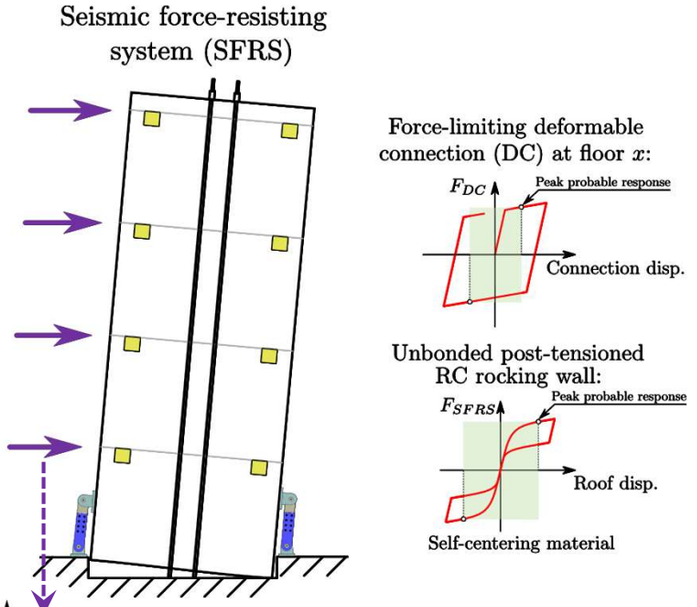


R_{DC}, R_{SFRS}

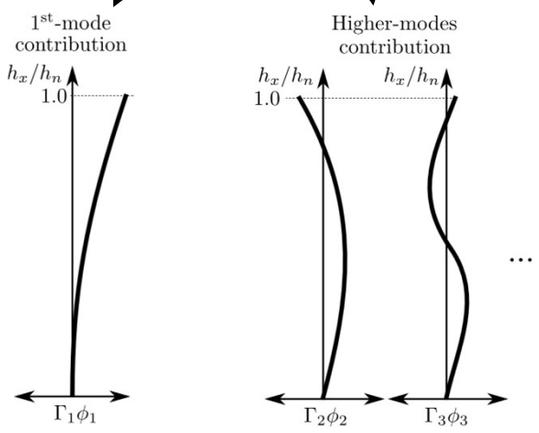
Seismic response modification factors







$$F_{Dx} = \sqrt{(F_{Dx,1m})^2 + (F_{Dx,hm})^2}$$



$$F_{Gx} = n_{DC} \cdot \Omega_{DC} \cdot F_{Lx}$$

(capacity design forces)

$$F_{Lx} = \frac{F_{Dx}}{R_{DC}}$$

$$F_{Wx} = \sqrt{(F_{Wx,1m})^2 + (F_{Wx,hm})^2}$$

$$F_{Lx} = \sqrt{(F_{Lx,1m})^2 + (F_{Lx,hm})^2}$$

$$= \sqrt{\left(\frac{F_{Dx,1m}}{R_{DC}}\right)^2 + \left(\frac{\frac{F_{Lx,1m}}{F_{Dx,hm}}}{R_{SFRS}}\right)^2 + (F_{Lx,hm})^2}$$

$$= \sqrt{\left(\frac{F_{Dx,1m}}{R_{DC} \cdot R_{SFRS}}\right)^2 + \left(\frac{F_{Dx,hm}}{R_{DC}}\right)^2}$$

$$= \frac{F_{Dx}}{R_{DC}}$$

$$F_{Wx} = \sqrt{\left(\frac{F_{Lx,1m}}{R_{SFRS}}\right)^2 + (F_{Lx,hm})^2}$$

Seismic Design Forces – Elastic Design Forces

1. Based on ASCE/SEI 7-22

$$\Gamma_{m1} = 1 + z_s(1 - 1/N)/2$$

$$\Gamma_{m2} = 0.9 z_s (1 - 1/N)^2$$



2. Based on continuum models

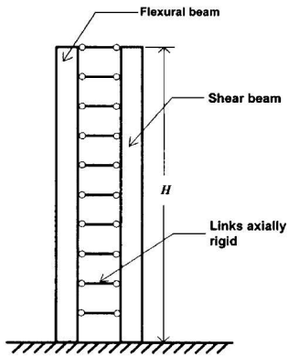
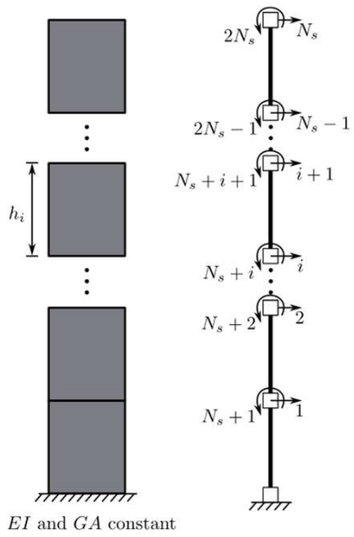
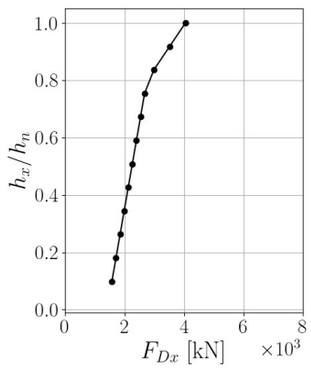


Fig. 1. Simplified model to estimate dynamic properties of multistory buildings

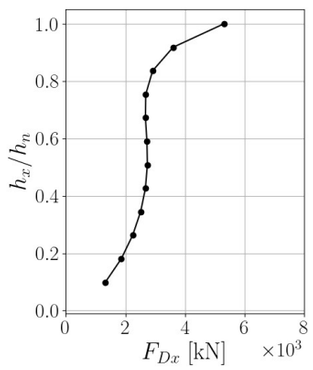
3. Based on discrete models



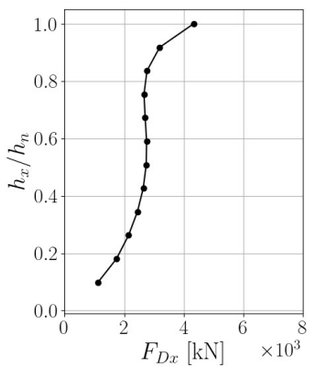
F_{Dx1}



F_{Dx2}

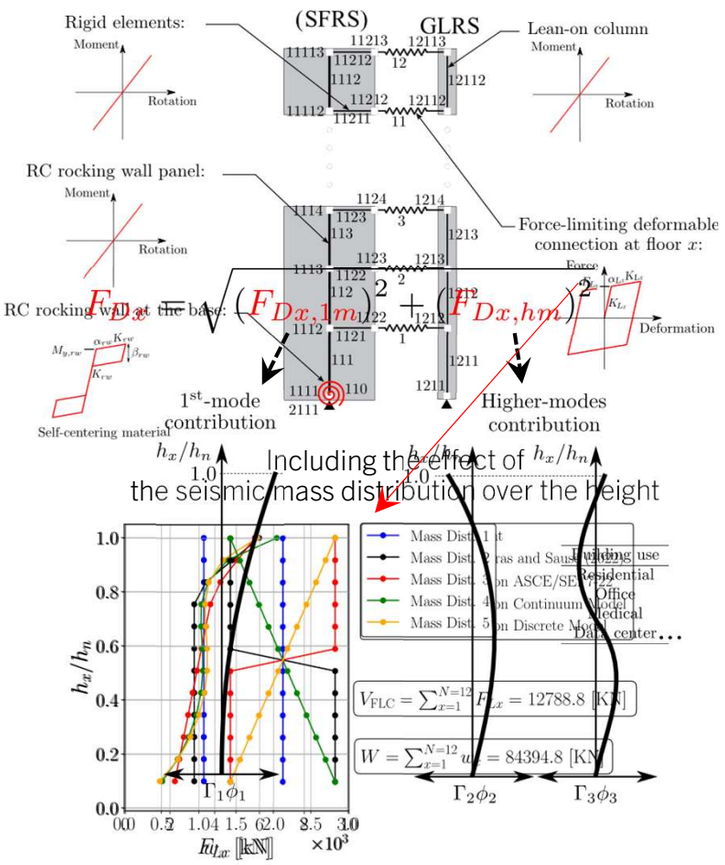


F_{Dx3}



Different ways to estimate the modal contribution factors ($\Gamma_{1m,x}$ and $\Gamma_{hm,x}$)

Numerical comparison between different approaches



on the seismic responses of building archetypes.

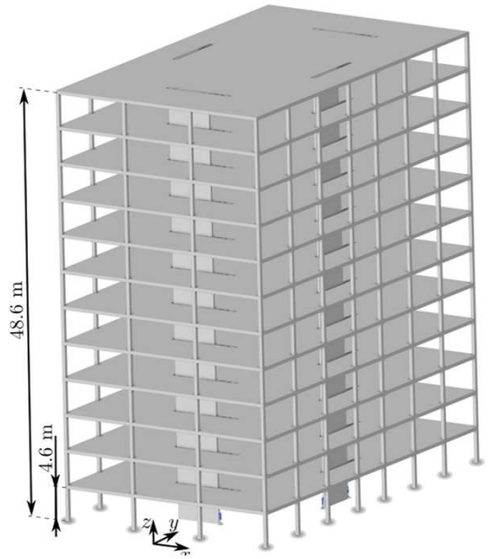
1. Miranda, E. and S. Taghavi. 2005. "Approximate Floor Acceleration Demands in Multistory Buildings. I:Formulation." Journal of Structural Engineering, 131:203–211. https://doi.org/10.1061/(ASCE)0733-9445(2005)131:2(203).
2. Mayorga, C.F. and G. Tsampras 2025. "Assessment of Seismic Design Provisions for Floor Diaphragms and Higher-Mode Responses Using Data from Instrumented Buildings in California." Earthquake Spectra, Accepted.

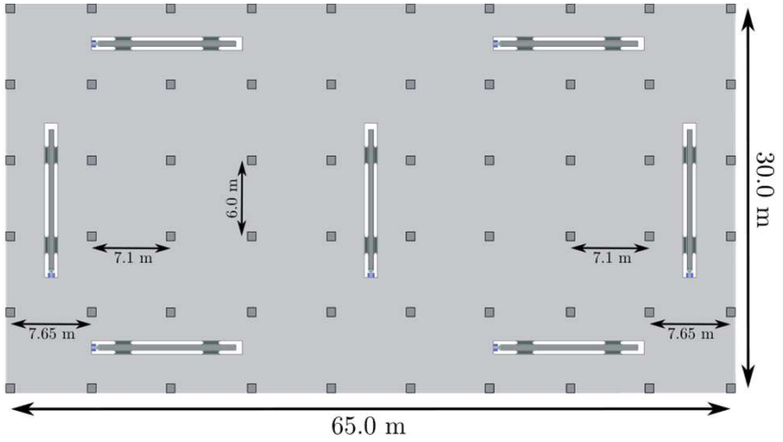
Nonlinear Numerical Models

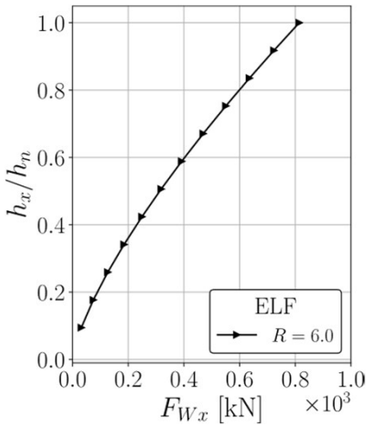
Nonlinear Numerical Models

Unbonded post-tensioned RC rocking wall with base friction devices.

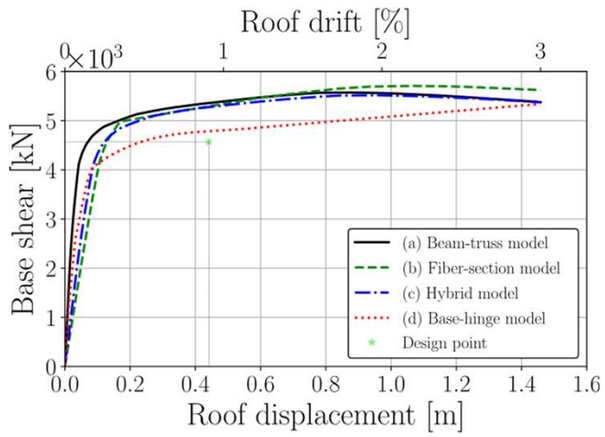
- 12-Story Office Building archetype designed using the equivalent lateral force (ELF) method.

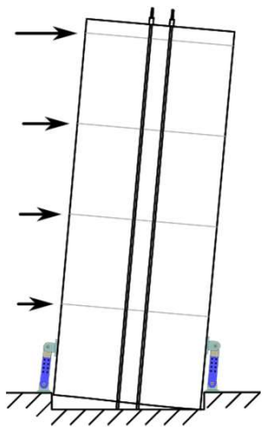


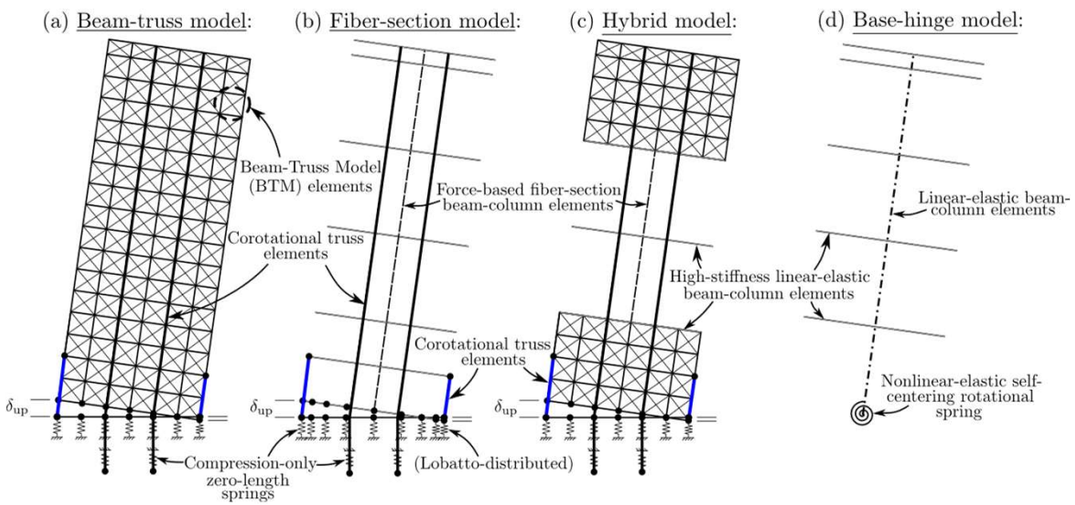




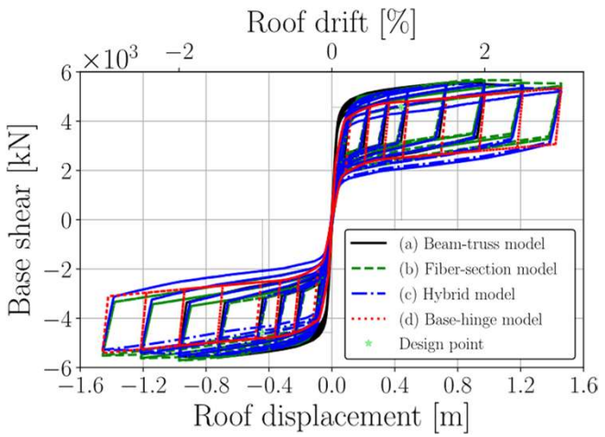
Pushover







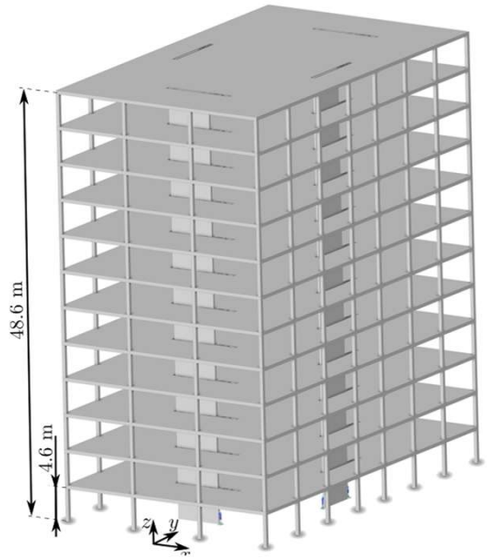
Cyclic quasi-static

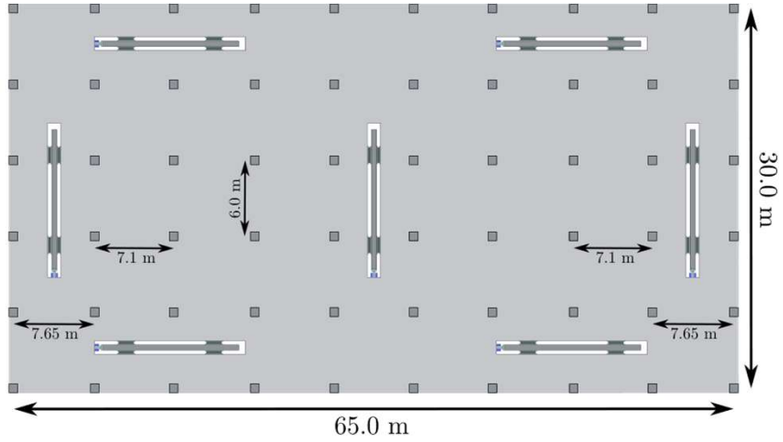


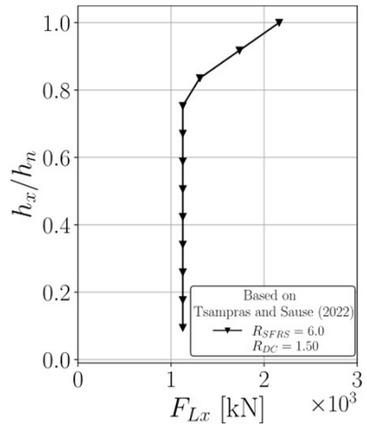
Nonlinear Numerical Models

Unbonded post-tensioned RC rocking wall with base friction devices.

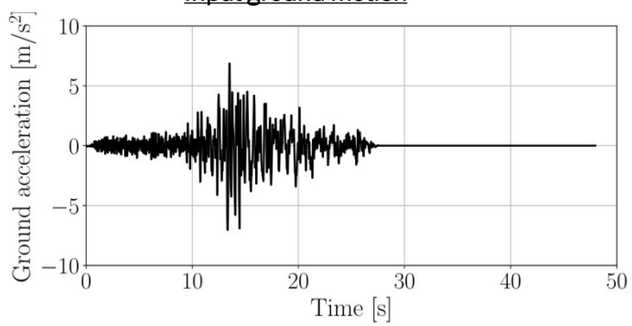
- Force-limiting connections over the height designed using force-base method proposed by Tsampras and Sause (2022).



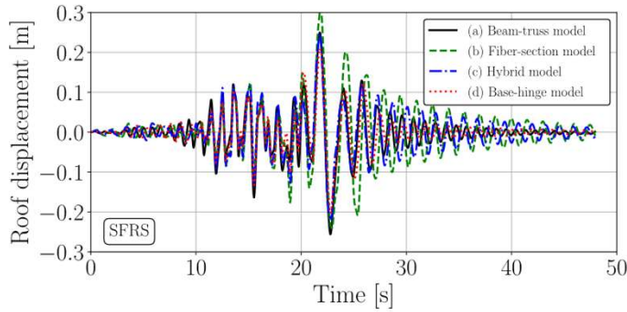


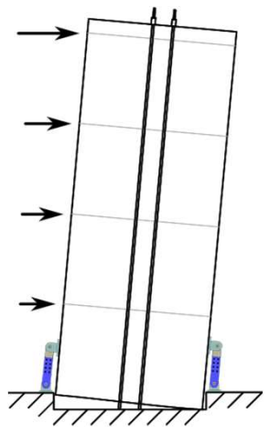


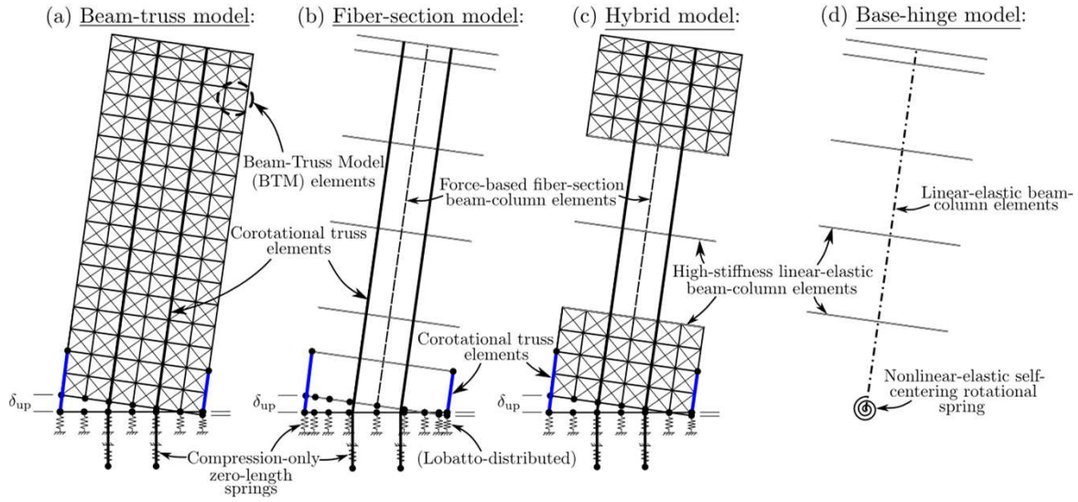
Input ground motion

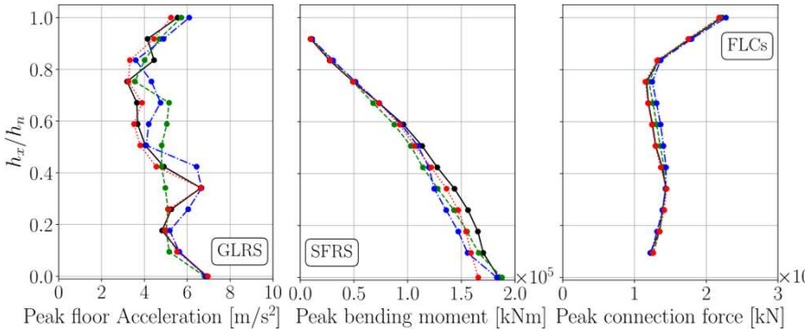


Numerical Earthquake Simulation





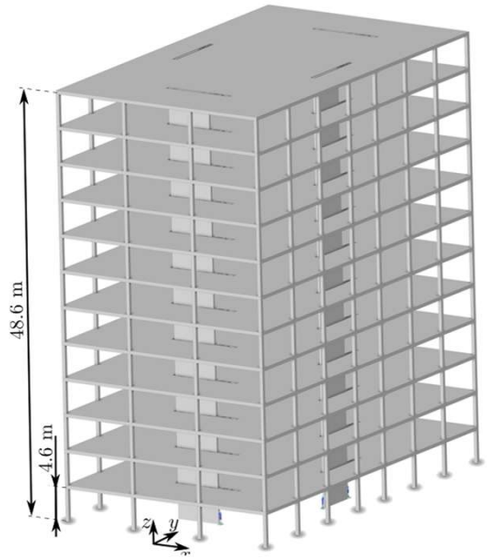


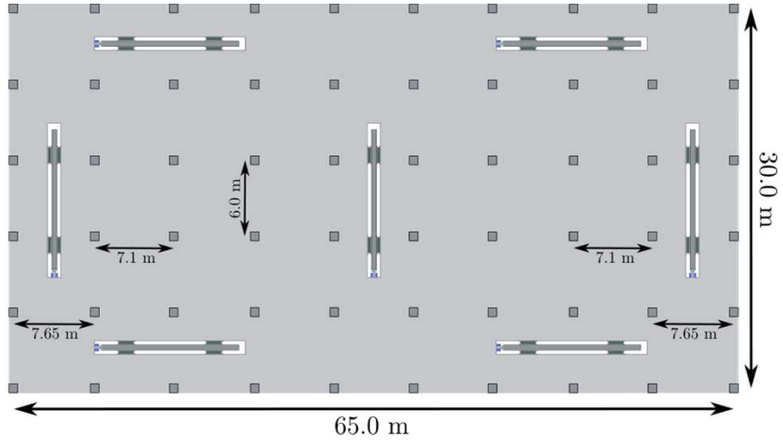


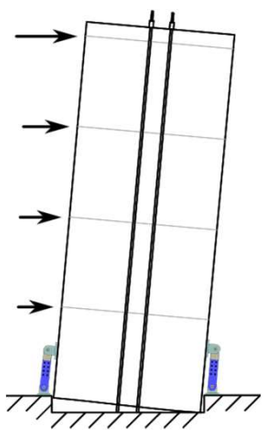
Damage Limit States

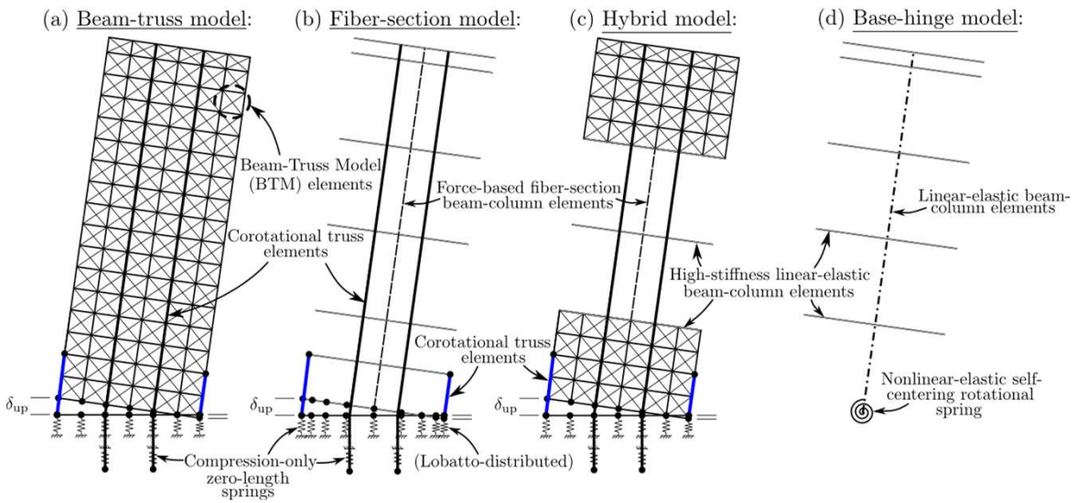
Unbonded post-tensioned RC rocking wall with base friction devices.

- 12-Story Office Building archetype designed using the equivalent lateral force (ELF) method.

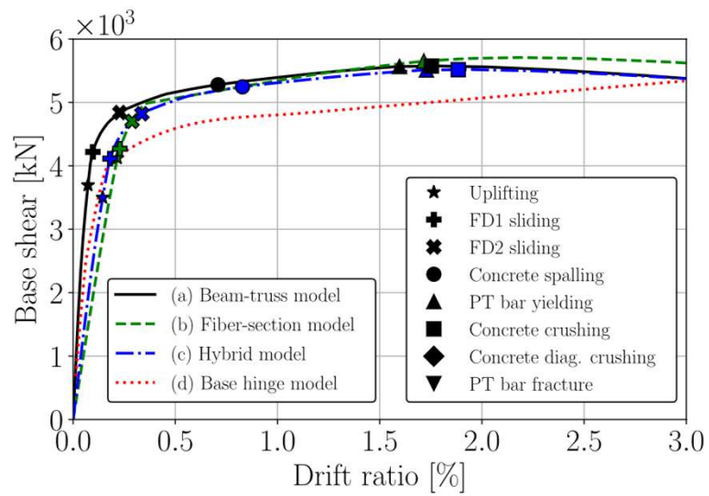






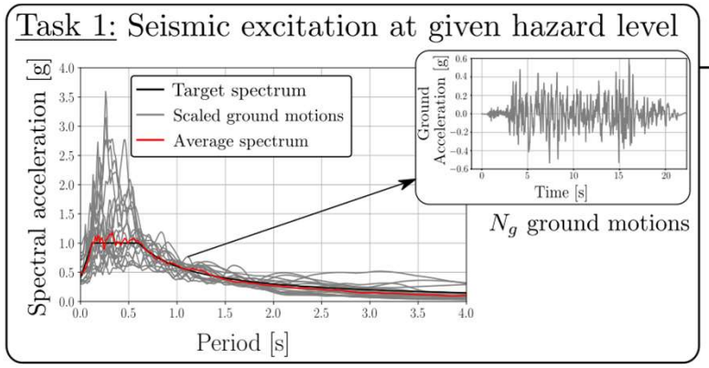


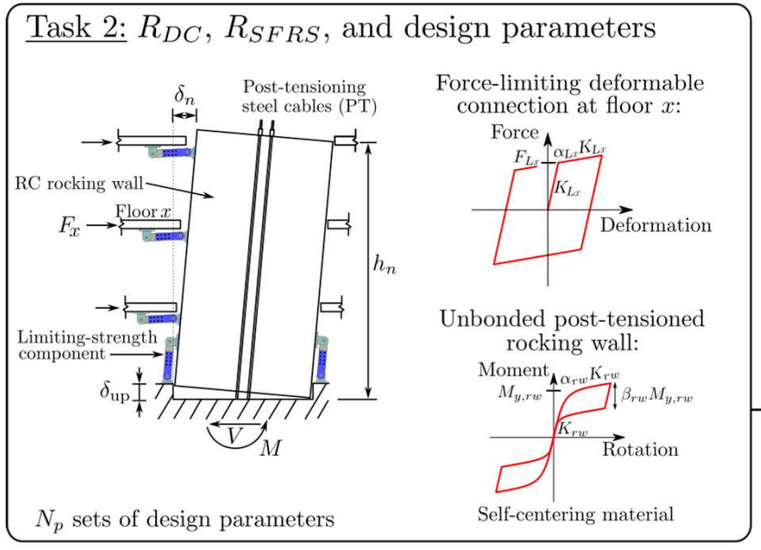
Critical Point	Numerical Model			
	Beam-truss	Fiber-section	Hybrid	Base-hinge
Uplifting	0.0727%	0.2166%	0.1446%	–
FD1 sliding	0.0967%	0.2286%	0.1806%	–
FD2 sliding	0.2287%	0.2886%	0.3366%	–
Concrete spalling	0.7087%	Not reached	0.8286%	–
Concrete crushing	1.7527%	Not reached	1.8844%	–
Concrete diag. crushing	Not reached	Not reached	Not reached	–
PT bar yielding	1.5967%	1.7158%	1.7284%	–
PT bar fracture	Not reached	Not reached	Not reached	–

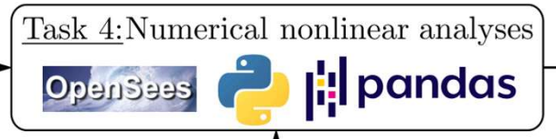


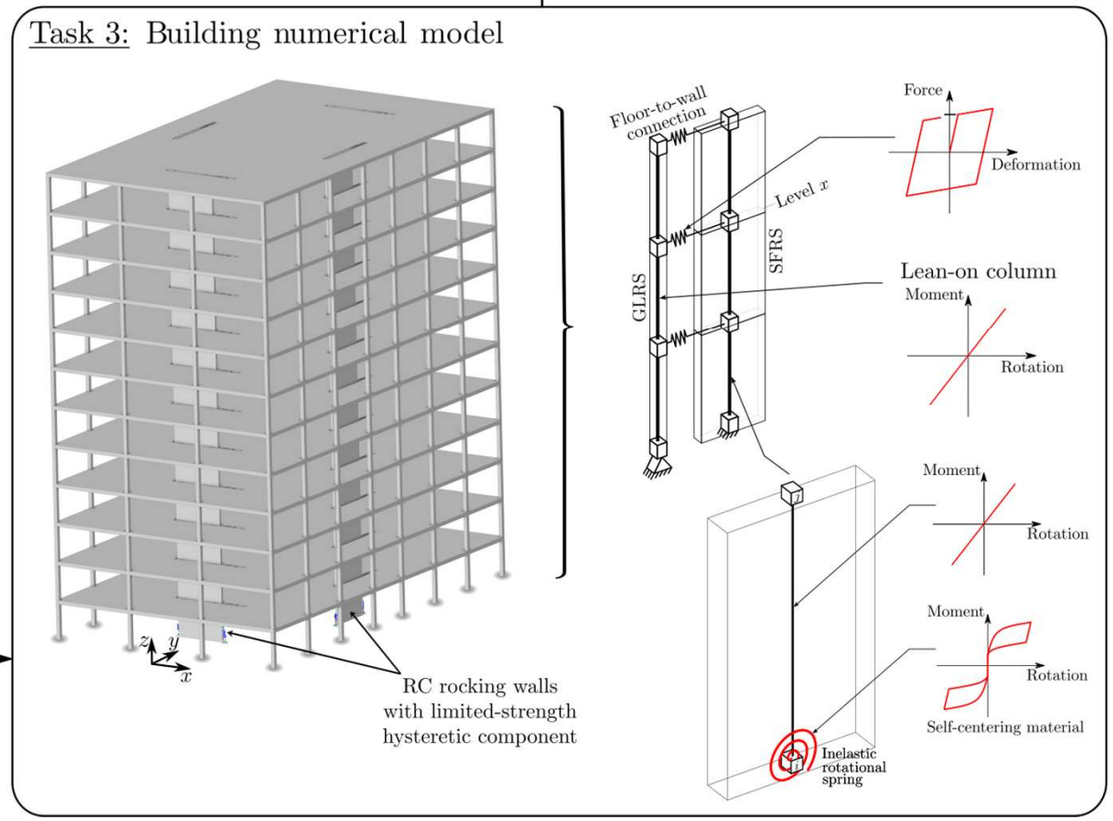
Parametric Analysis

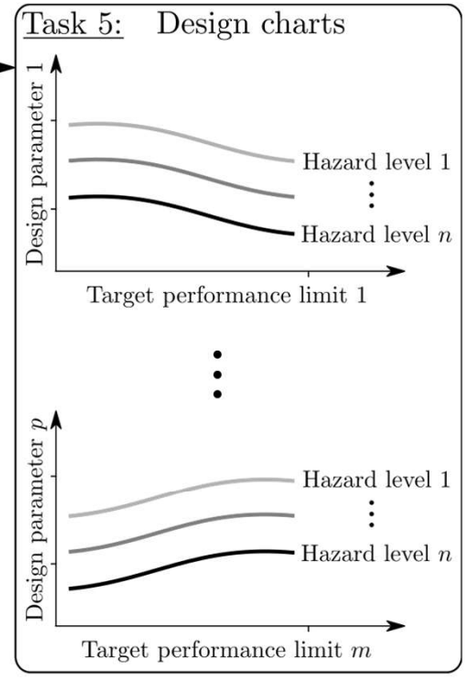
Extensive parametric analysis to relate the expected performance of building archetypes to different combinations of seismic response modification factors R_{DC} and R_{SFRS}.

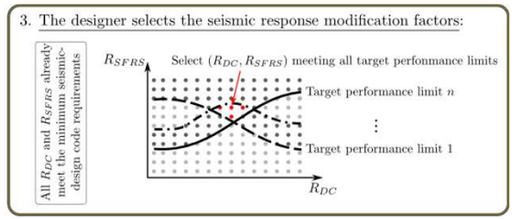








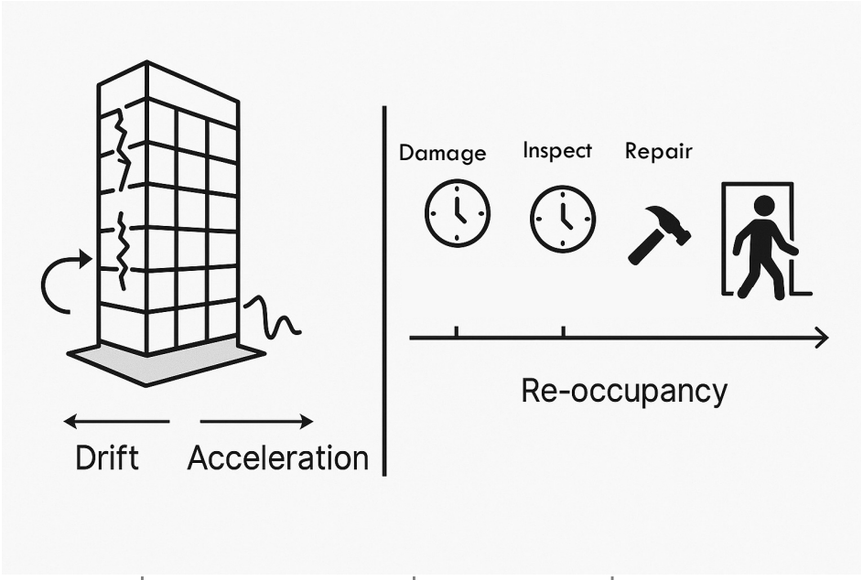


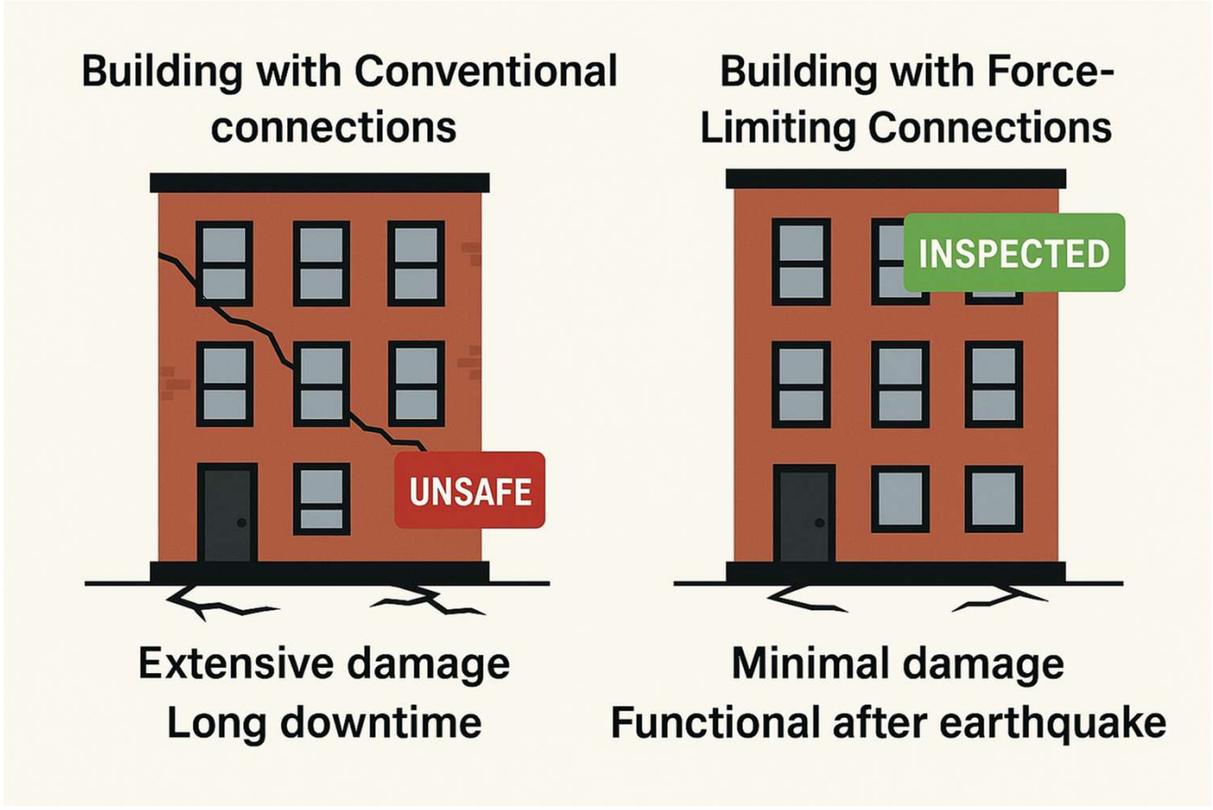


From Structural Response to Functional Recovery

From Structural Response to Functional Recovery: A Unified Framework

- In the first part of this study, we developed a detailed numerical model to simulate building responses under seismic loading.
- Now, we transition to the second part: integrating these outputs into a resilience-based framework. This step focuses on evaluating the functional recovery of buildings, incorporating component-level damage, downtime, and re-occupancy timelines.

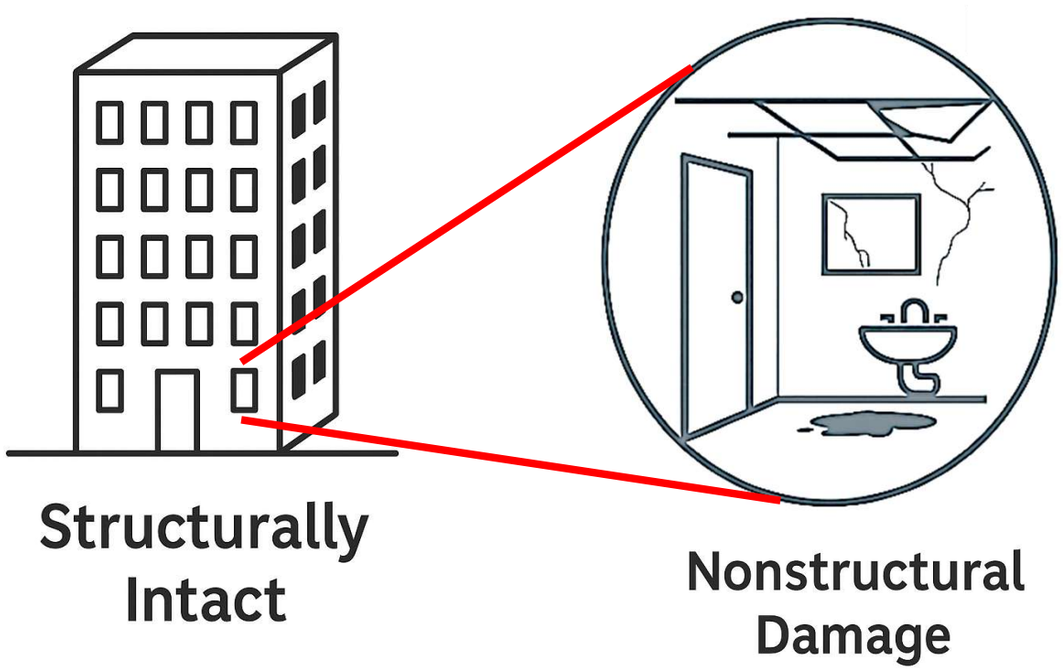


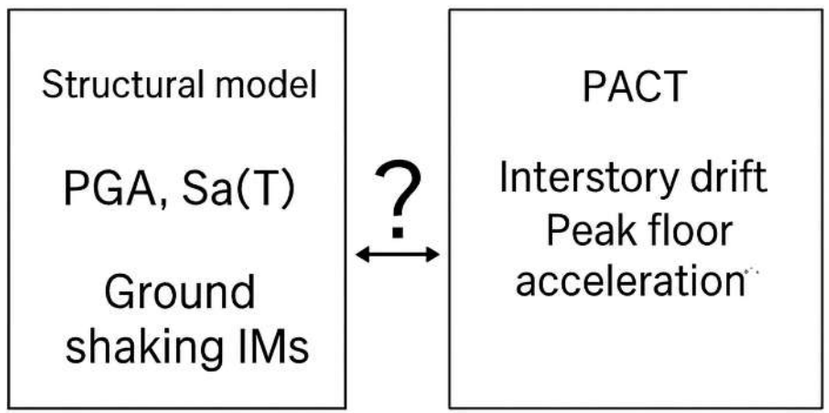


Challenges

Some Challenges

- Fragilities needed for nonstructural components
- PACT provides fragilities → requires floor-specific intensity measures (IMs)
- Our model: ground shaking IMs (e.g., PGA, Sa)
- Goal: Consistent IMs across structural & nonstructural systems

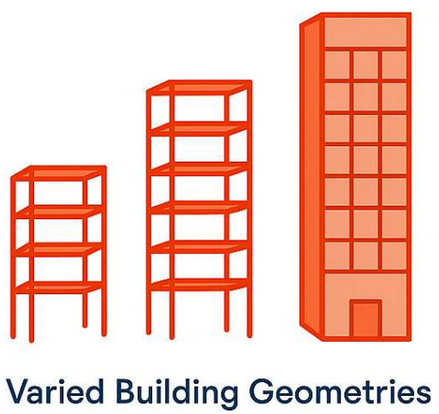




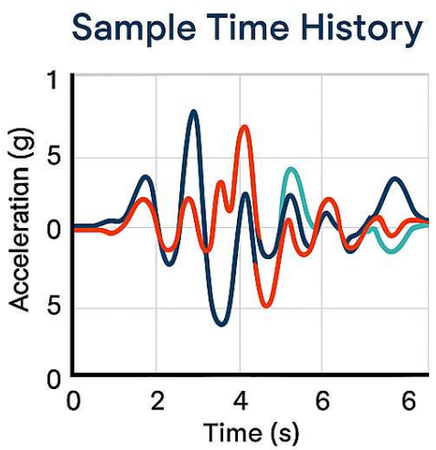
Need for a *mapping model*

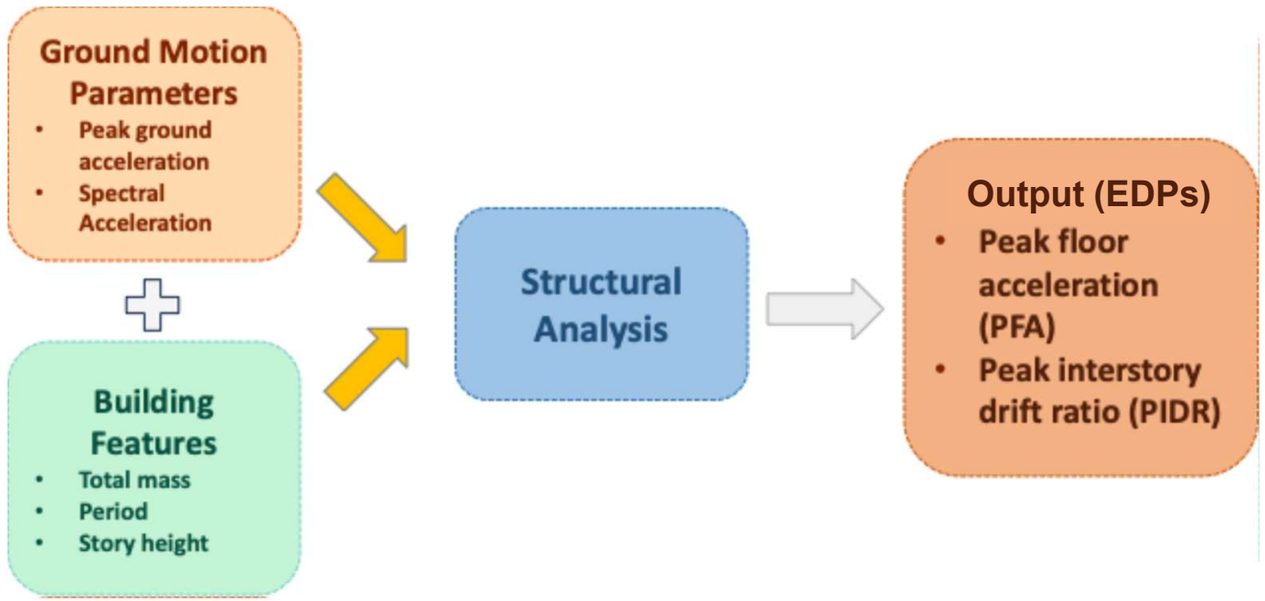
Consistent Intensity Measures

- The model was trained on 5,000 building configurations generated by varying structural parameters, material properties, and column design features.
- Each configuration was subjected to a distinct ground motion record with varying PGA values.



Varied Building Geometries

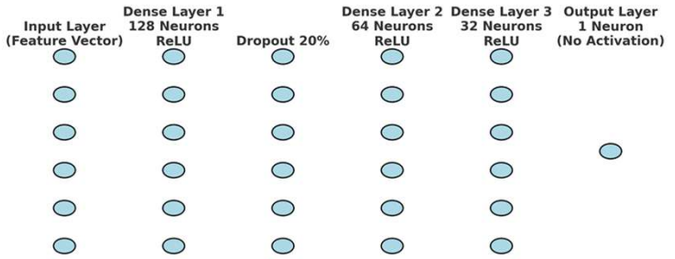


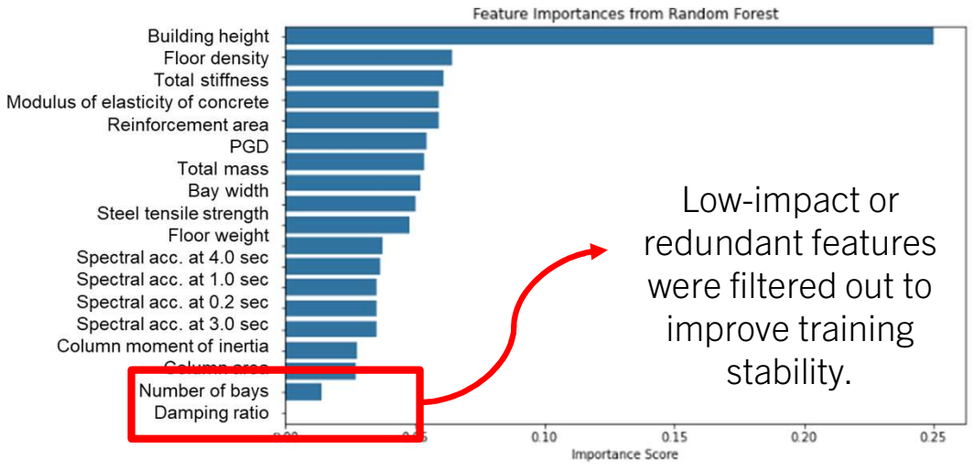


Surrogate Model

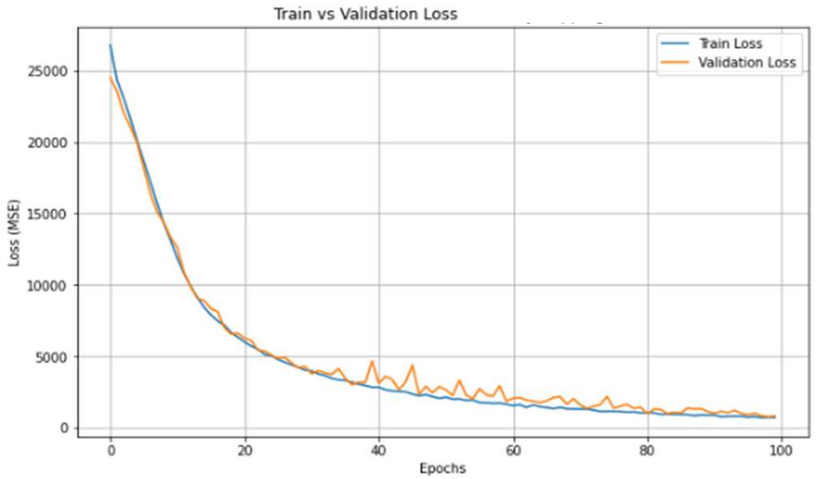
Model

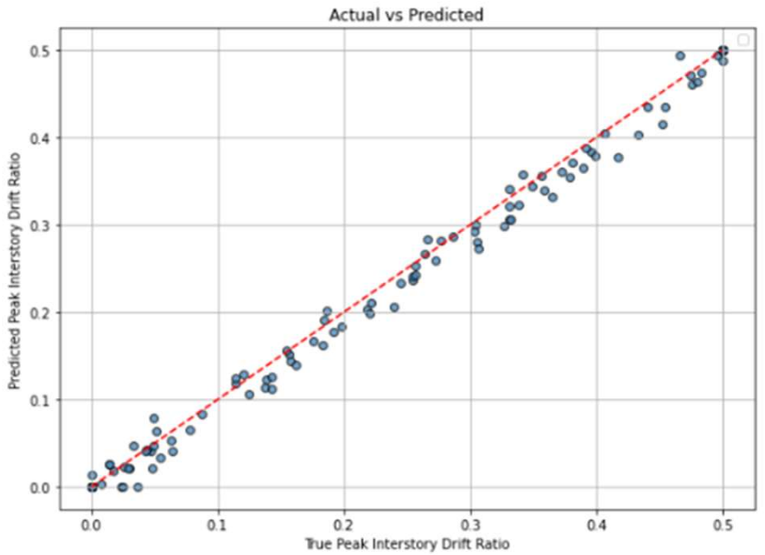
A neural network with three hidden layers was used





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



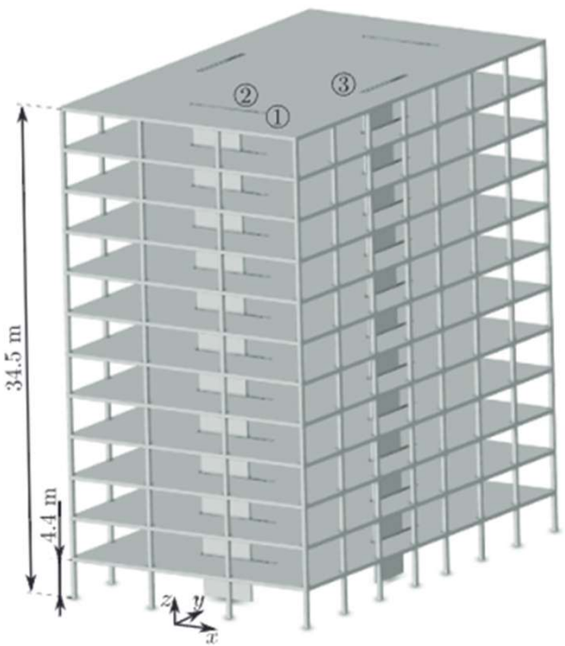


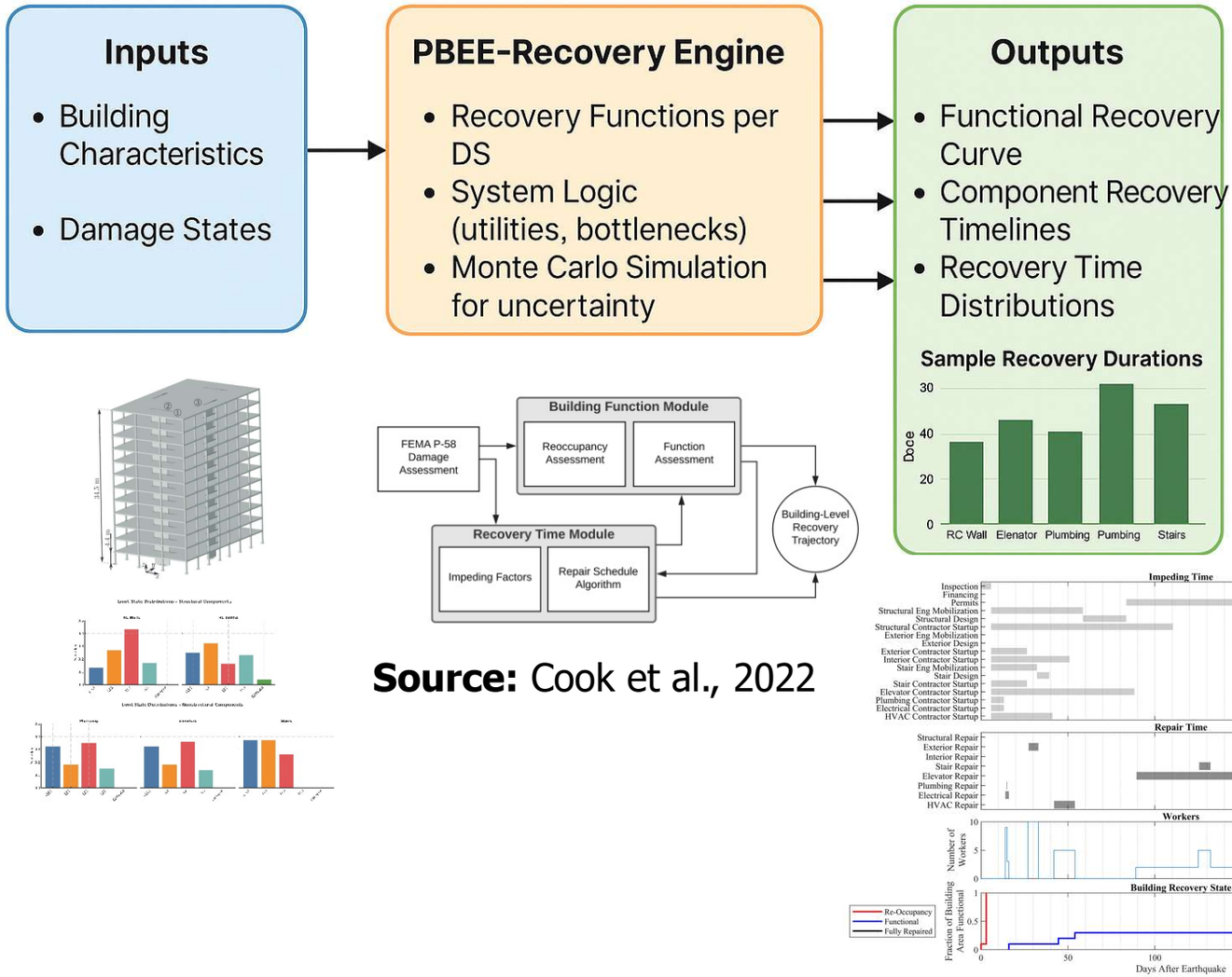
Test Set R^2 Score: 0.9370

Numerical Example

Numerical Example

- Structural and nonstructural elements
- Output: Component level damage state classification





Source: Cook et al., 2022

Summary of Contributions

Summary of Contributions

- Tsampras, Georgios, Paolo Bocchini, C. Franco Mayorga, Sena Mursel. 2024. “Project Introduction: Resilience-Based Design of Buildings with Accelerated Post-Earthquake Functional Recovery [2024–2027].” In *NIST/NSF Disaster Resilience Research Grant Symposium*, Aug 20–21, Virtual.

- Mayorga, C. Franco, Georgios Tsampras, Paolo Bocchini, and Sena Mursel. 2024. “Overview of a Project on Resilience-Based Design of Buildings with Accelerated Post-Earthquake Functional Recovery.” In *18th U.S.-Japan-New Zealand Workshop on the Improvement of Structural Engineering and Resilience (ATC-15-17)*, Dec 2–4, 2024, San Diego, CA.

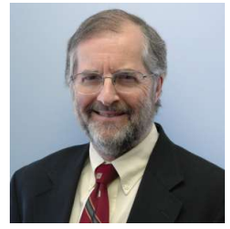
- Mursel, Sena, C. Franco Mayorga, Georgios Tsampras, and Paolo Bocchini. 2025. “Resilience-based design of buildings with accelerated post-earthquake functional recovery.” In *14th International Conference on Structural Safety and Reliability (ICOSSAR’25)*, Jun 1–6, 2025, Los Angeles, CA.

Project Team

Project	Group/Board	Organization	Member
Resilience-based design of buildings with accelerated post-earthquake functional recovery	Research Group	UC San Diego	PI, Georgios Tsampras
			GSR, Franco Mayorga
		Lehigh University	Co-PI, Paolo Bocchini
			GSR, Sena Mursel
	Educational Outreach Group	Walgrove Elementary School	Coordinator, Andrea Kittelson
			STEAM Teachers
	Academic Advisory Board	Colorado State University	Advisor, Bruce R. Ellingwood
	Practicing Engineering Advisory Board	Maffei Structural Engineering	Advisor, Lawrence Burkett
		Magnusson Klemencic Associates	Advisor, John D. Hooper
		Mar Structural Design	Advisor, David Mar
		Skidmore, Owings & Merrill (SOM)	Advisor, Mark Sarkisian
	Industry Advisory Board	Gripple Inc.	Advisor, Prasad Naik










Questions?

Thank you