Project Introduction

Resilience-Based Design of Buildings with Accelerated Post-Earthquake Functional Recovery [2024 – 2027]

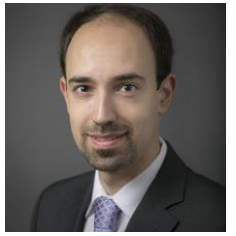
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August 21, 2024
NIST | NSF | Disaster Resilience Research Grant Symposium

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



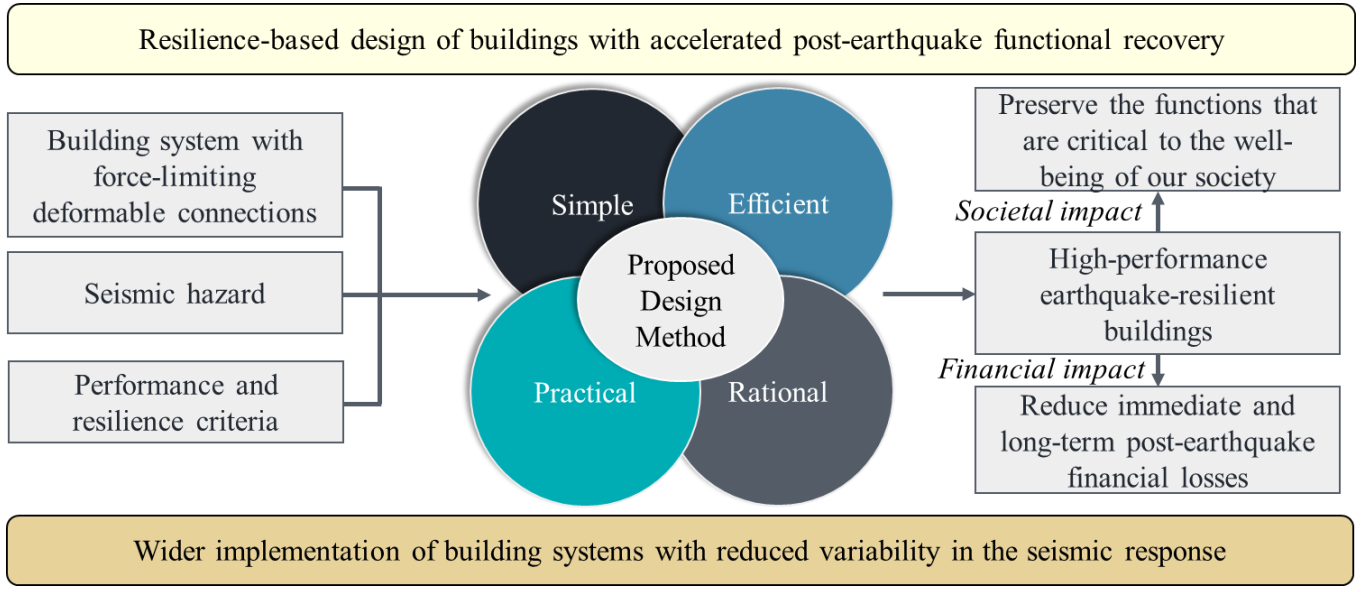






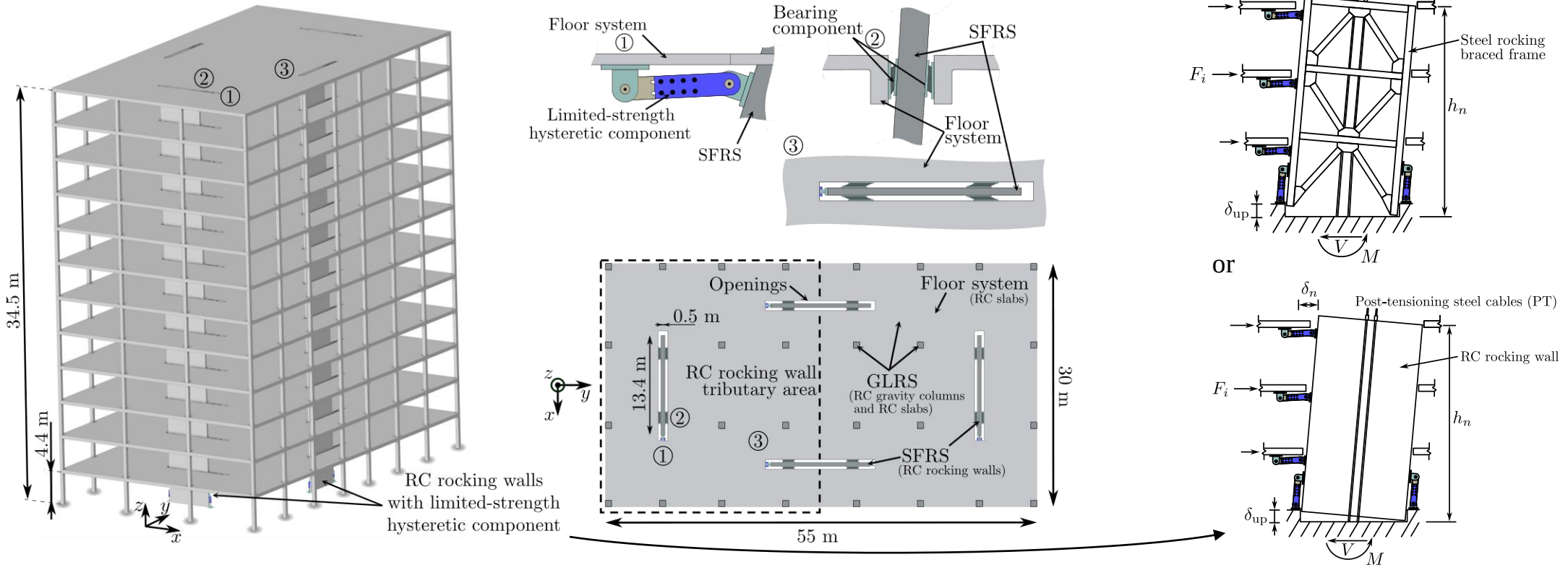

Vision and Goal

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



Vision and Goal (Cont'd)

- The proposed research focuses on **building systems** that utilize **practical reusable force-limiting deformable connections** efficiently placed in the building seismic load path.

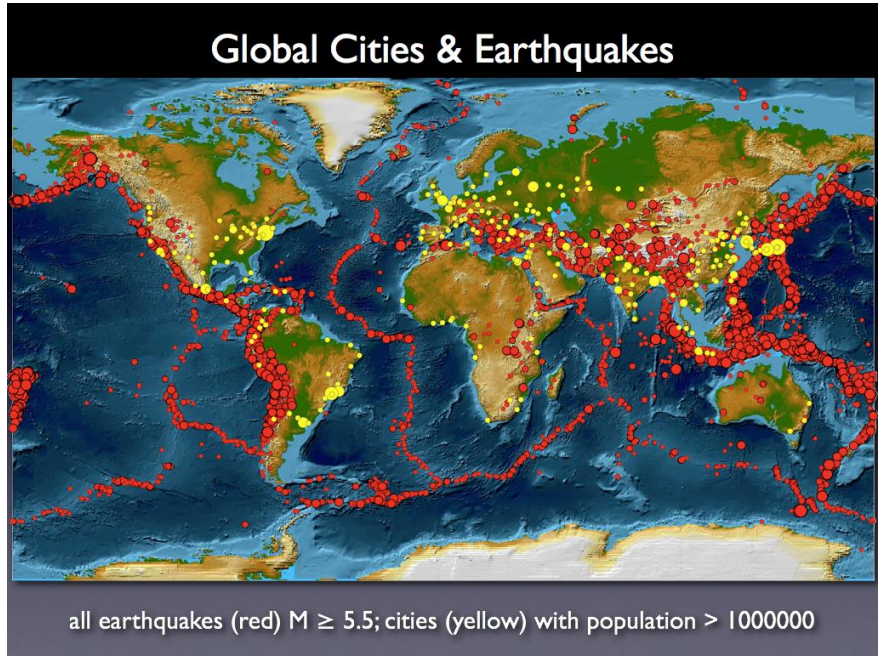


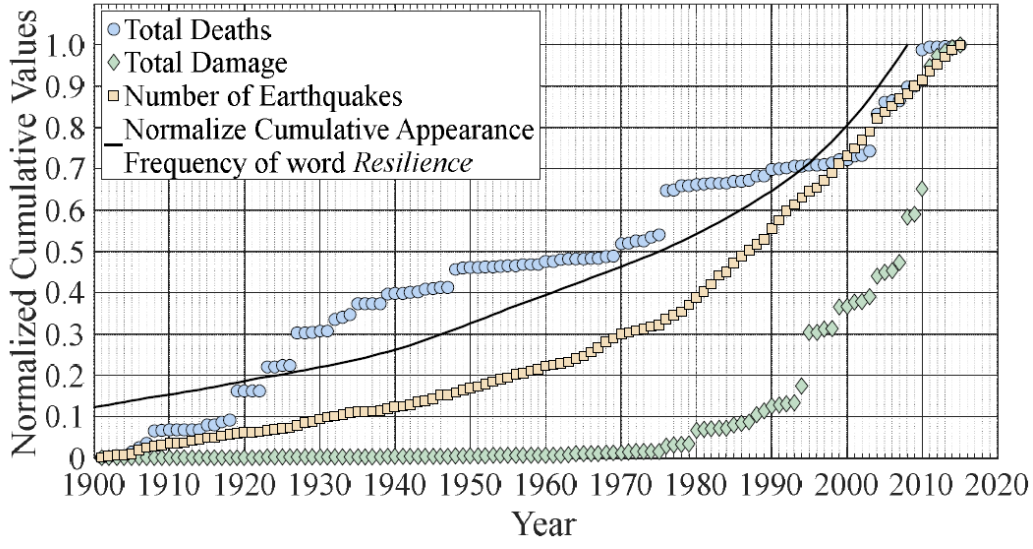
- These building systems have the potential to achieve **faster** and **more reliably** a target **post-earthquake functionality level** because of their **limited seismic responses** and **reduced sensitivity of their seismic response** to the variability of the characteristics of strong earthquake ground motions.

Motivation & Background

Motivation: Societal Impact

- 2011 Christchurch, New Zealand (Mw 6.2) → 182 fatalities, 18 billion USD total damage, 1,240 demolished buildings.
- 2011 Tohoku, Japan (Mw 9.1) → 19,848 fatalities, 210 billion USD total damage.
- 2015 Lamjung, Nepal (Mw 7.8) → 8,969 fatalities, 3.86 billion USD total damage.





1. Guha-Sapir D, Below R, Hoyois P. EM-DAT | The international disasters database 2022. https://www.emdat.be/ [accessed February 7, 2022].
2. Wikipedia. 2011 Christchurch earthquake. 2022.
3. Tsampras G. Force-Limiting Floor Diaphragm Connection for Earthquake-Resistant Buildings. PhD. Lehigh University, USA, 2016.
4. Google Books Ngram Viewer 2022. https://books.google.com/ngrams/info [accessed February 7, 2022].
5. http://www.geo.cornell.edu/geology/faculty/RWA/research/current_research/chile-m-88-earthquake-page/global-earthquakes-and-citi.html [accessed November 15, 2023].

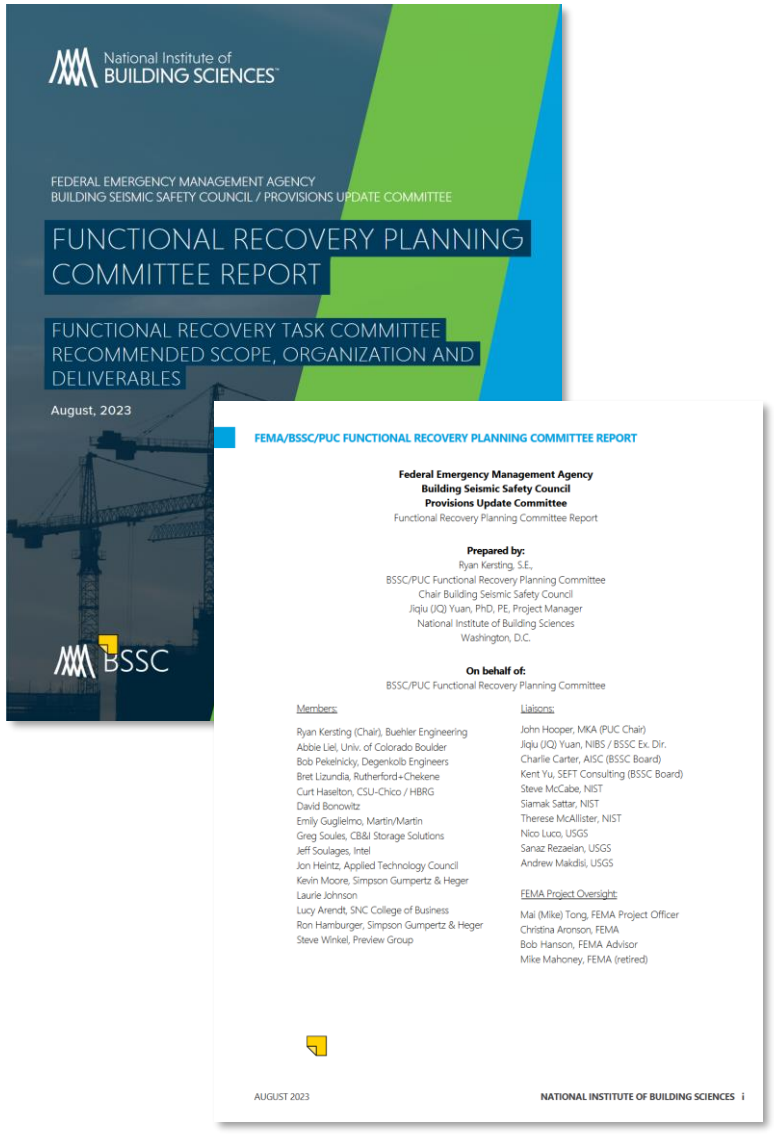
Motivation: National Earthquake Resilience

- "*A **disaster-resilient nation** is one in which its communities, through mitigation and pre-disaster preparation, develop the **adaptive capacity to maintain important community functions** and **recover quickly when major disasters occur.**"* According to National Research Council of the National Academies.

- "*Even if a community enforces and adopts all **current codes and standards**, the **performance of the built environment** is not expected to result in a **resilient community**. This is because **prescriptive and performance requirements** in current codes and standards primarily focus on **life safety objectives** for buildings and transportation, and on **reliability** for electric and water."* McAllister et al. (2022)

- **National earthquake resilience** is one of the priorities of the National Earthquake Hazards Reduction Program (**NEHRP**).

1. Congressional Research Service. The National Earthquake Hazards Reduction Program (NEHRP): Issues in Brief. Washington, D.C.: 2021.
2. FEMA. NEHRP Recommended Seismic Provisions for New Buildings and Other Structures. FEMA; 2020.
3. National Research Council. National Earthquake Resilience: Research, Implementation, and Outreach. Washington, D.C.: National Academies Press; 2011. DOI: 10.17226/13092.
4. McAllister TP, Walker R, Baker A. Assessment of Resilience in Codes, Standards, Regulations, and Best Practices for Buildings and Infrastructure Systems. Gaithersburg, MD: National Institute of Standards and Technology; 2022.
5. Chen, K., G. Tsampras, and K. Lee. 2023. "Structural connection with predetermined discrete variable friction forces." Resilient Cities and Structures, Resilience of Structures to Earthquakes, 2 (1): 1–17. https://doi.org/10.1016/j.rcns.2023.02.006.

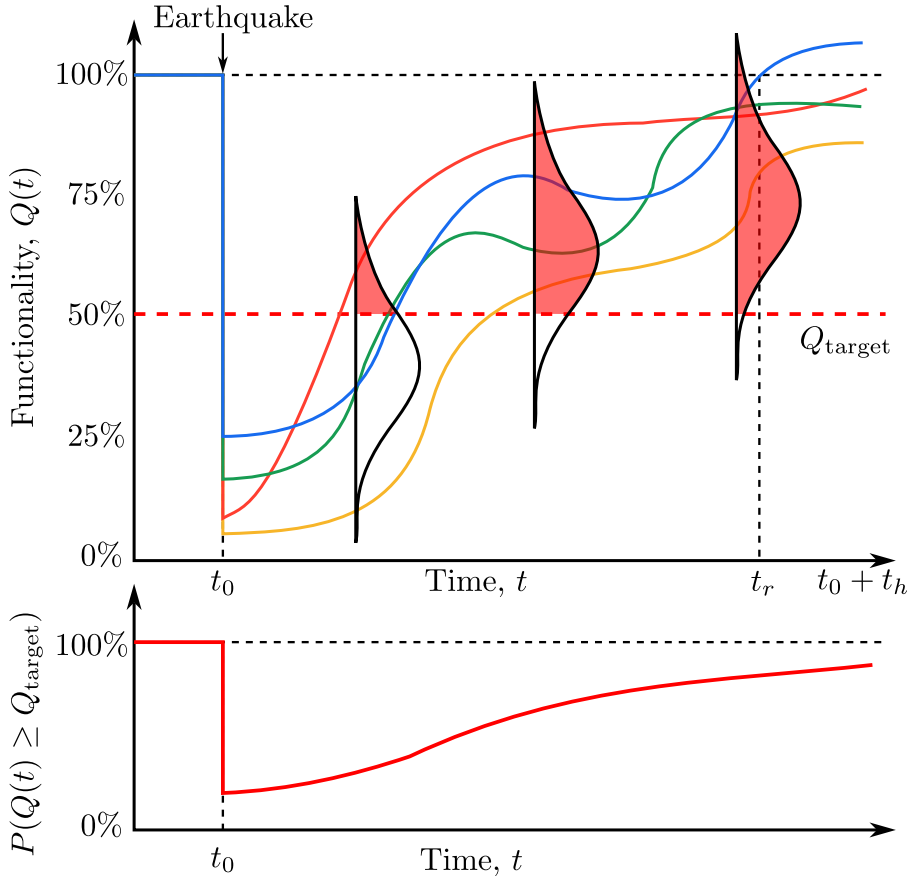


"How can we reduce the risks of life and property from future earthquakes and increase the resilience of communities in the United States?"

FEMA/BSSC/PUC FUNCTIONAL RECOVERY PLANNING COMMITTEE REPORT (2024), https://www.nibs.org/reports/functional-recovery-planning-committee-report

Design for Functional Recovery

- The engineering community is shifting the **seismic design criteria** for buildings from **life safety** to pursue **immediate occupancy**.
- **Occupancy** and **functionality** are two concepts directly related.
- Most of the **resilience metrics** are built on **functionality recovery curves**.
- The **immediate effects** of a strong seismic event on the **building functionality** ($Q(t_0)$) and how it is **recovered** over time ($Q(t)$) are two **complex** and **uncertain** problems.
- **Probabilistic assessment** of resilience.



1. Bocchini P, Frangopol DM, Ummenhofer T, Zinke T. Resilience and Sustainability of Civil Infrastructure: Toward a Unified Approach. Journal of Infrastructure Systems 2014; 20(2): 04014004. DOI: 10.1061/(ASCE)IS.1943-555X.0000177.
2. FEMA. NEHRP Recommended Seismic Provisions for New Buildings and Other Structures. FEMA; 2020.
3. National Research Council. National Earthquake Resilience: Research, Implementation, and Outreach. Washington, D.C.: National Academies Press; 2011. DOI: 10.17226/13092.
4. McAllister TP, Walker R, Baker A. Assessment of Resilience in Codes, Standards, Regulations, and Best Practices for Buildings and Infrastructure Systems. Gaithersburg, MD: National Institute of Standards and Technology; 2022.

Challenges Associated with Conventional Building Systems

Current Design Practice

Force-based methods:

- Practical
- Easy to implement
- Use of the design response spectra

All methods include assumptions to approximate the seismic response and seismic design demands

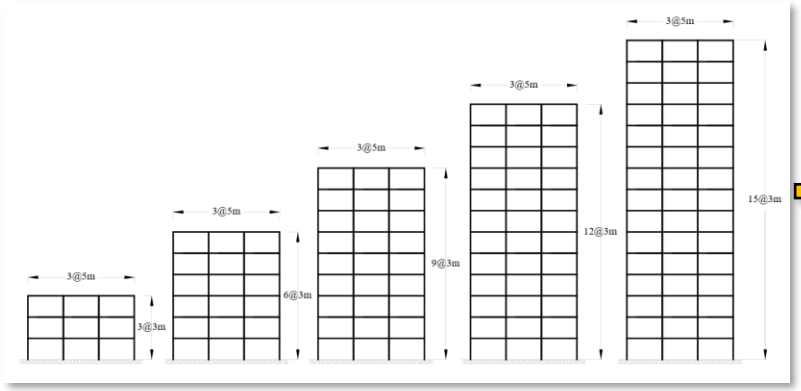
Displacement-based methods :

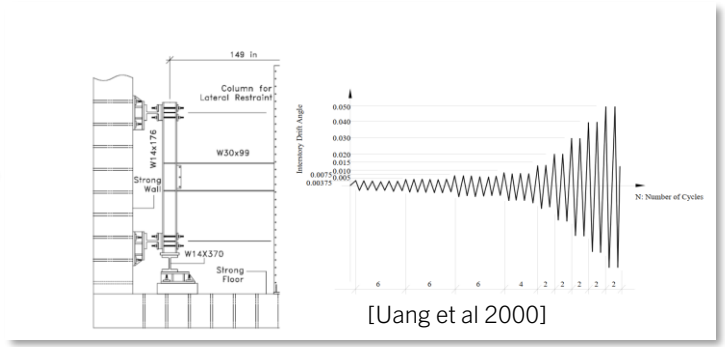
- Performance oriented
- Accounts for the nonlinear evolution of stiffness of equivalent single degree of freedom systems

Hybrid Force/Displacement methods:

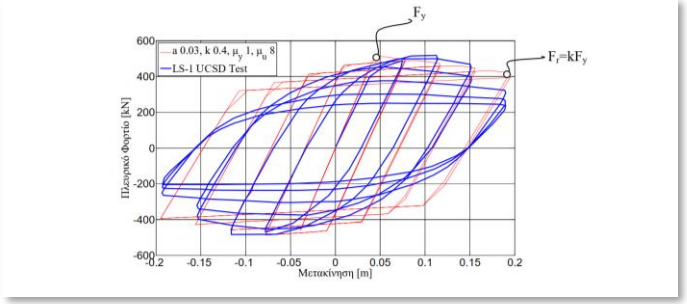
- Performance orientated displacement-based design principles framed in the context of force-based design by using performance-based seismic response modification factors along with design response spectra.

Performance-based seismic reduction factors for conventional building systems





[Uang et al 2000]



1. Estimate roof displacement at target drift ratio: $\mathbf{u_{r,max} = b_1 IDR_{target}^{b_2} \rho^{b^3} (f_{y,b}/235)^{b^4} =}$

$$= 22.18 * 0.016^{1.18} 0.47^{0.00} (275/235)^{-0.02} = 16.9cm$$

2. Estimate yield roof displacement : $u_{r,y} = b_1 IDR_{yield}^{b_2} \rho^{b^3} (f_{y,b}/235)^{b^4} =$

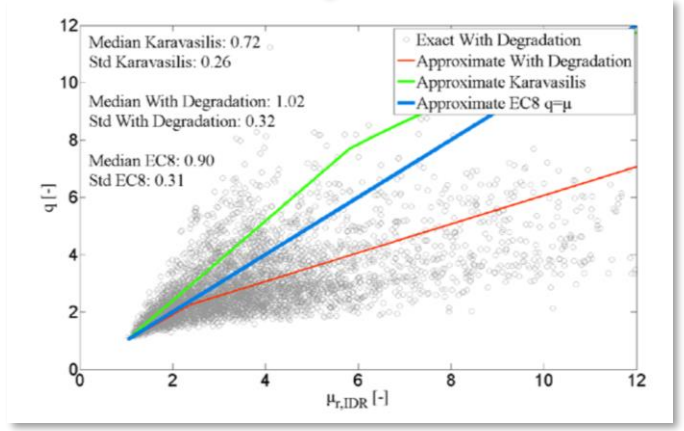
$$= 22.18 * 0.01^{1.18} 0.47^{0.00} (275/235)^{-0.02} = 9.7cm$$

3. Estimate global ductility demands at target drift ratio : $\mu_{r,IDR} = u_{r,max}/u_{r,y} = 17.5/10 = 1.75$

$$\mu_{r,\theta} = 0.43\mu_\theta + 1.14 = 0.43 * 3.0 + 1.14 = 2.43$$

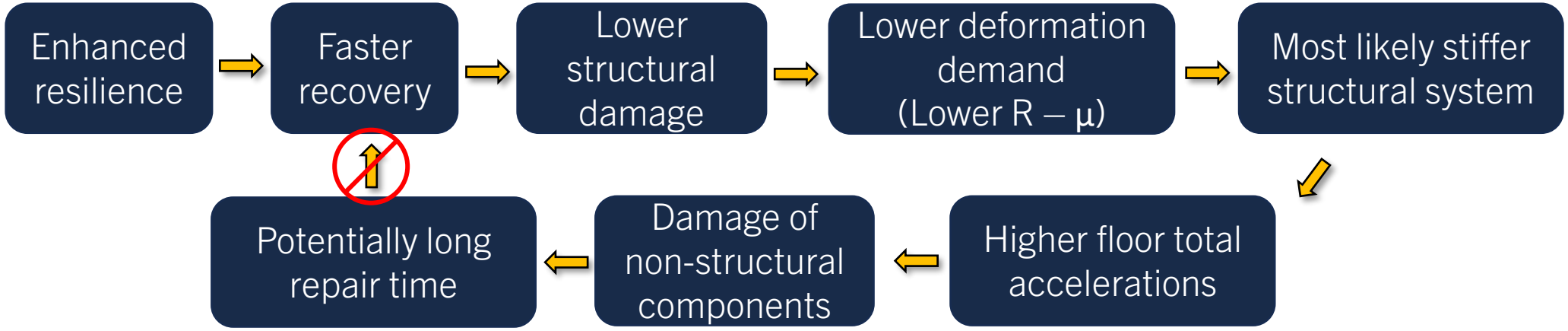
$\mu_{r,d} = min\{\mu_{r,IDR}\ ;\ \mu_{r,\theta}\} = 1.75.$

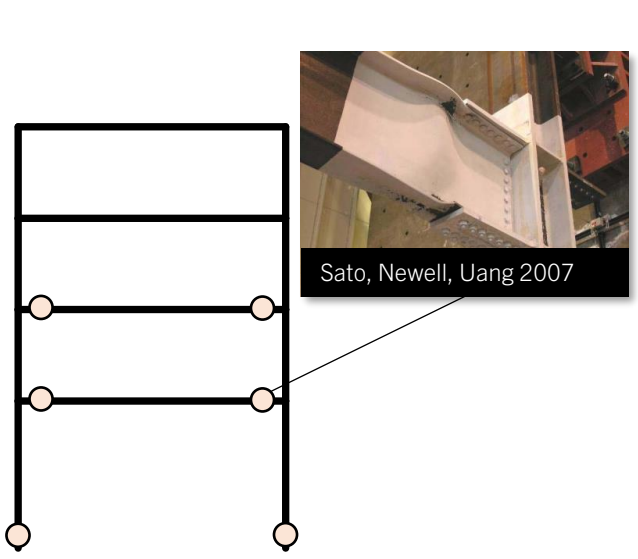
4. Estimate seismic response modification factor: $q = 0.9\mu_{r,IDR} + 0.1 = 0.9 * 1.75 + 0.1 = 1.7$



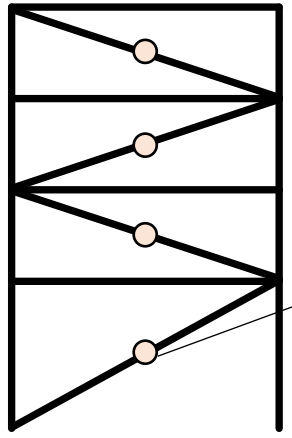
- Bazeos, N. and D. E. Beskos (2003). 29(3): 553-562. New Seismic Design Method for Building Framed Structures, Proceedings of ICCES '03, Corfu, Greece.
- Karavasilis, T. L., N. Bazeos, and D. E. Beskos. 2007. "Behavior Factor for Performance-Based Seismic Design of Plane Steel Moment Resisting Frames." Journal of Earthquake Engineering, 11 (4): 531–559. https://doi.org/10.1080/13632460601031284.
- Georgios Tsampras (2011), Parametric Inelastic Response and Performance-Based Seismic Response Modification Factors of Planar Steel Moment Resisting Frames, M.Sc. Thesis, Department of Civil Engineering, University of Patras, Greece, https://nemertes.library.upatras.gr/items/3d12fde6-dc93-4e95-96e5-469d5608ba1b/full
- Tzimas, A. S., T. L. Karavasilis, N. Bazeos, and D. E. Beskos. 2013. "A hybrid force/displacement seismic design method for steel building frames." Engineering Structures, 56: 1452–1463. https://doi.org/10.1016/j.engstruct.2013.07.014.

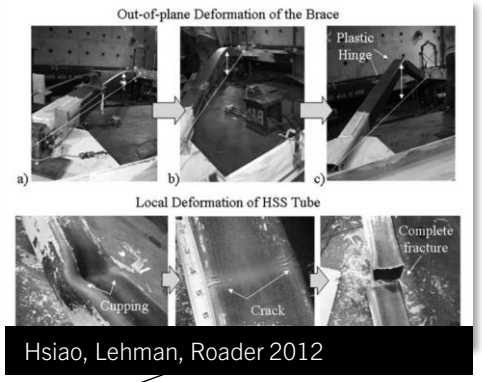
Challenge with conventional systems





Sato, Newell, Uang 2007

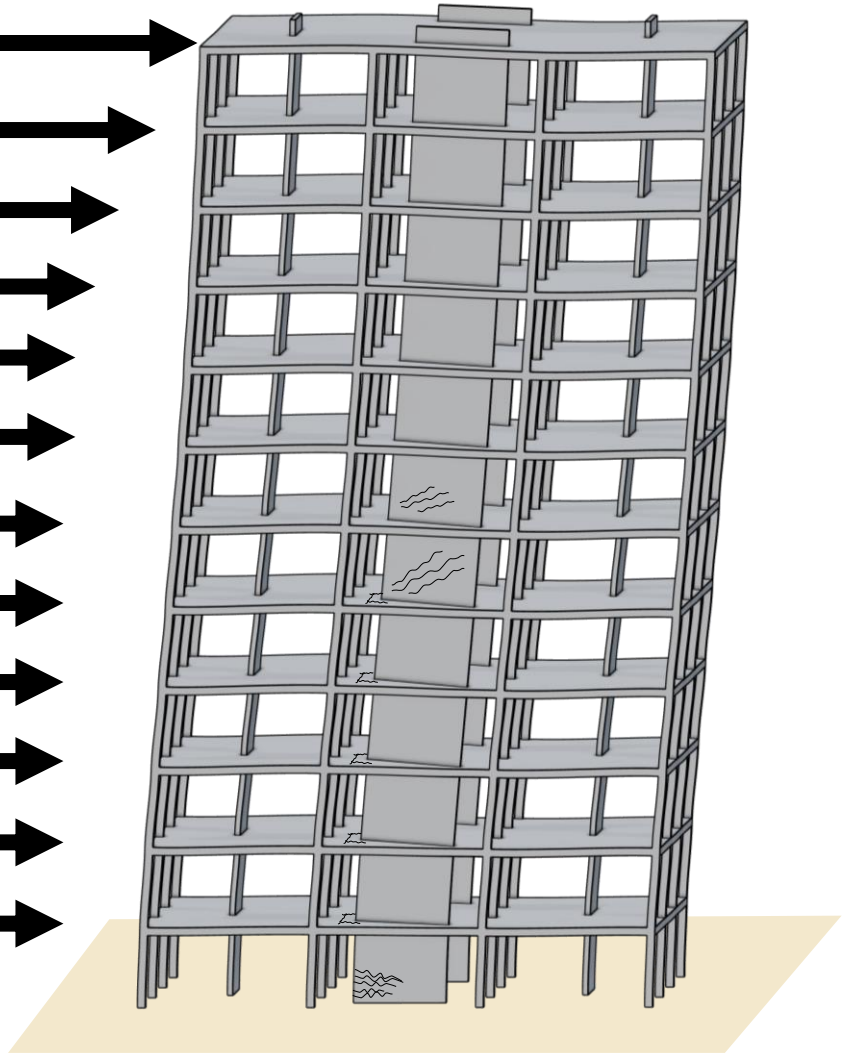




Hsiao, Lehman, Roader 2012

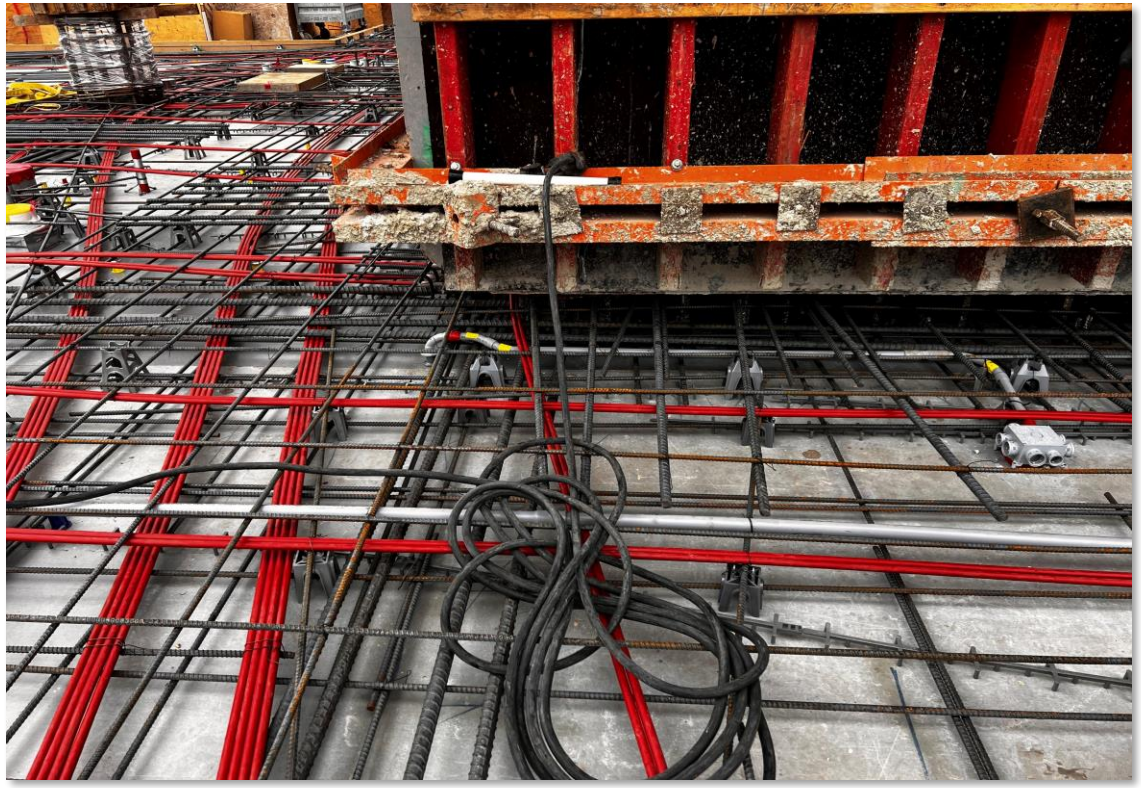
Buildings with flexural yielding base mechanism

Seismic induced horizontal forces

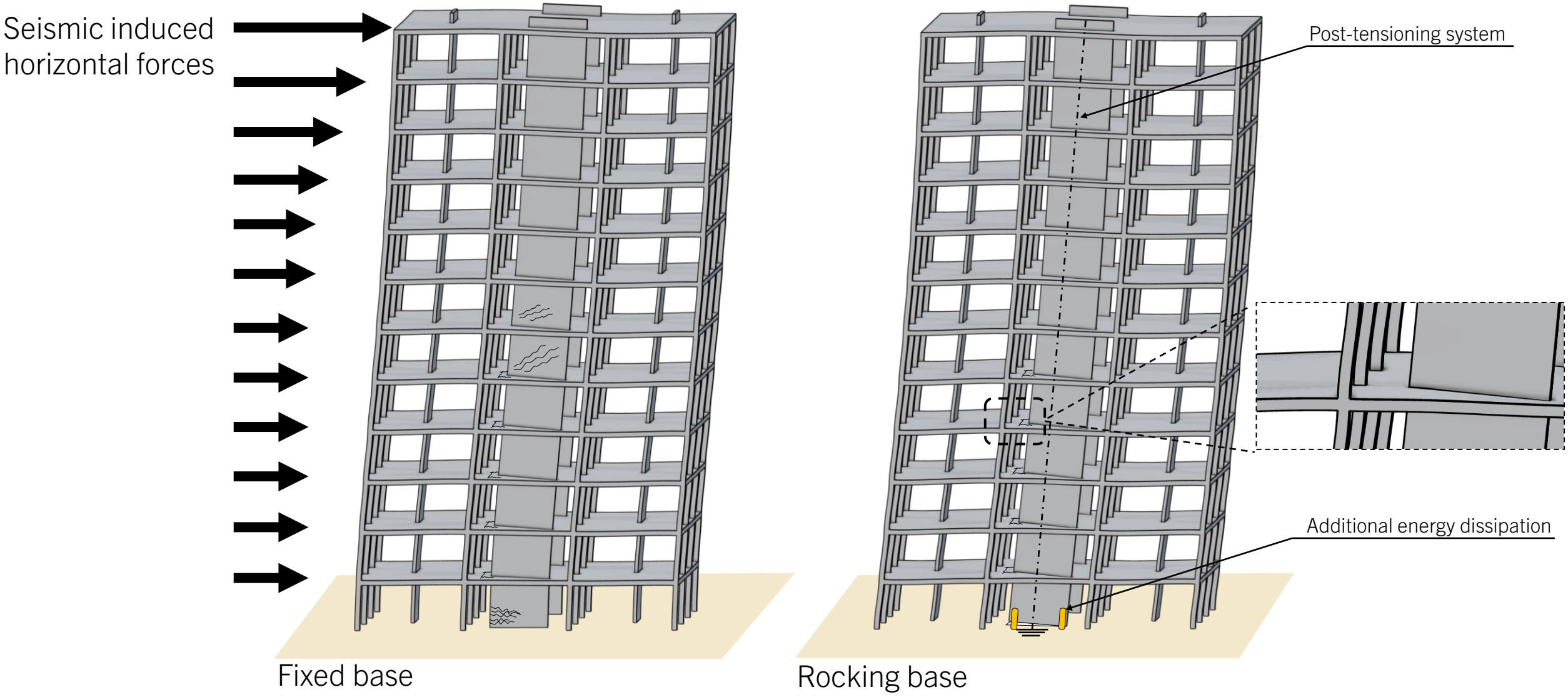


Fixed base

Core wall building construction at UC San Diego

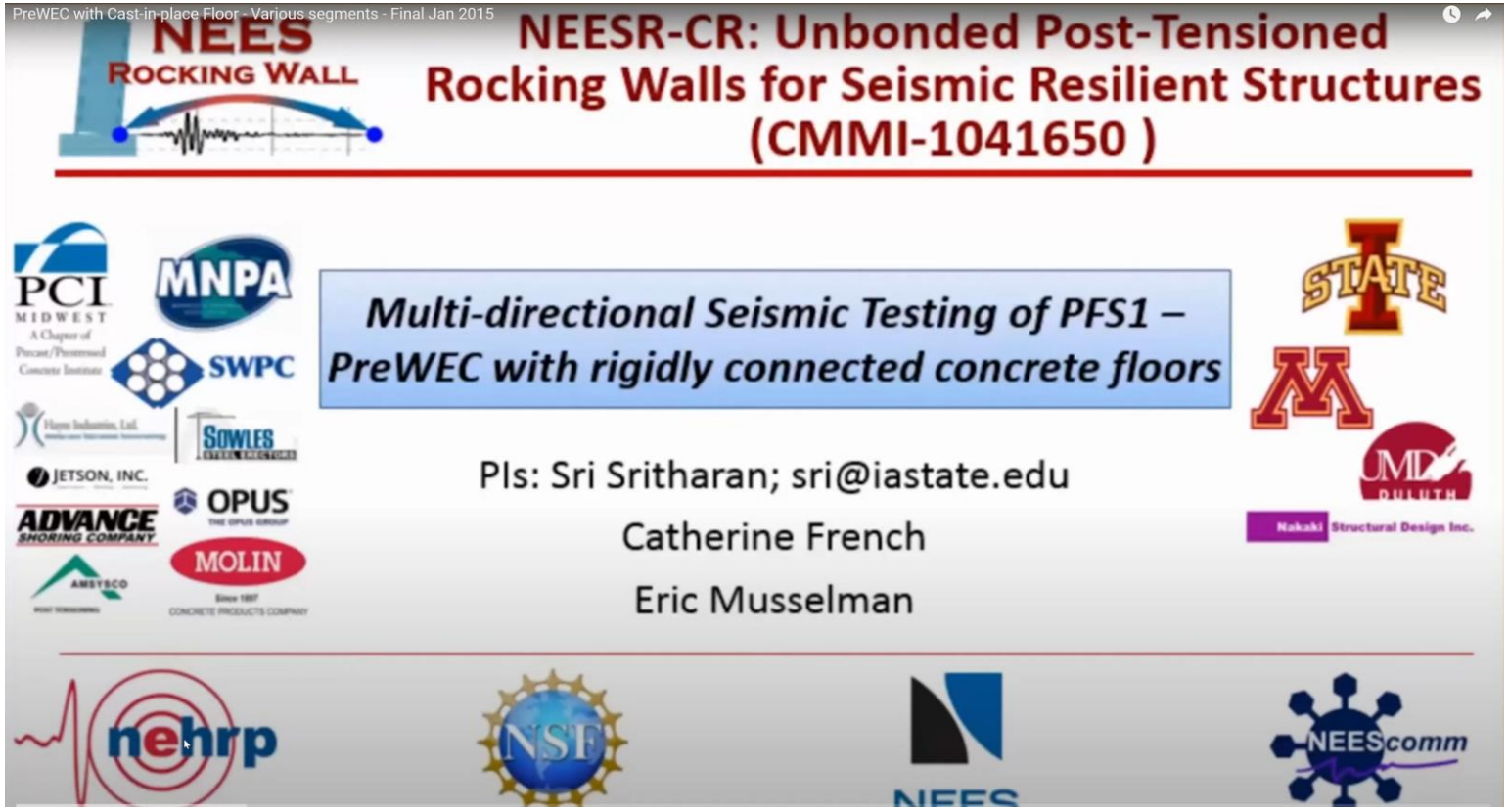


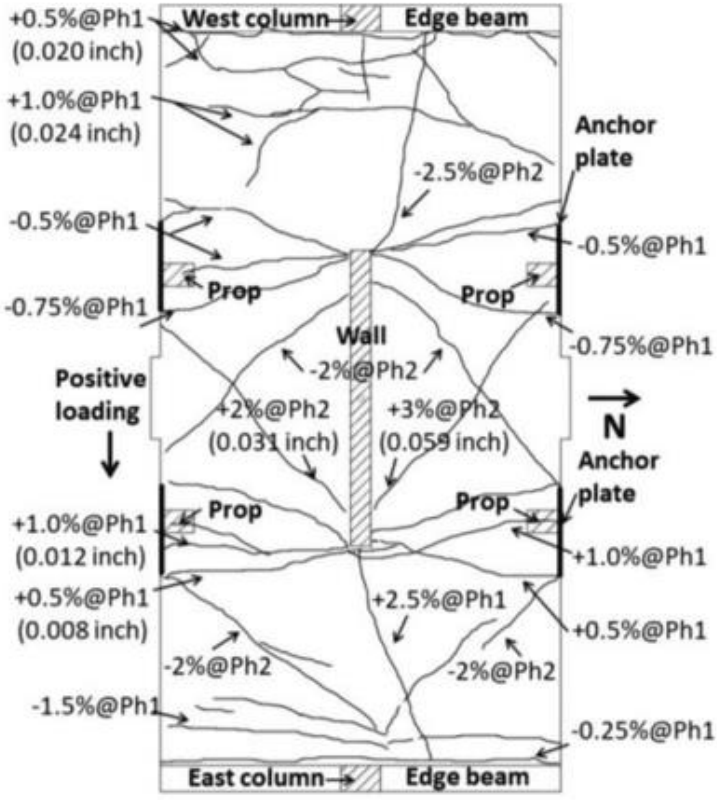
Buildings with rocking base mechanism



Motivation: Damage of Structural Components

- e.g., damage in floor diaphragms to ensure kinematic compatibility.





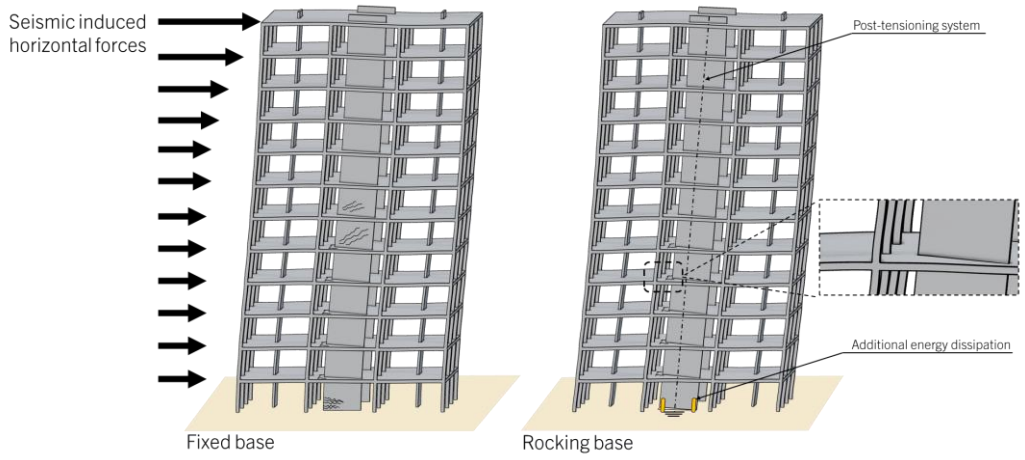
1. Liu Q, French CW, Sritharan S. Study of Interaction between a PreWEC System and Surrounding Structure. Structural Journal 2018; 115(5): 1407–1418. DOI: 10.14359/51702248.
2. Sri Sritharan (2015), PreWEC Project, Iowa State University, https://sri.cce.iastate.edu/NEES-Rocking-Wall/index.htm.
3. Online video https://www.youtube.com/watch?v=iNOZFpj6QGQ

Challenges Lead to Uncertain Seismic Response

Uncertainty in the characteristics of the earthquake ground motion.

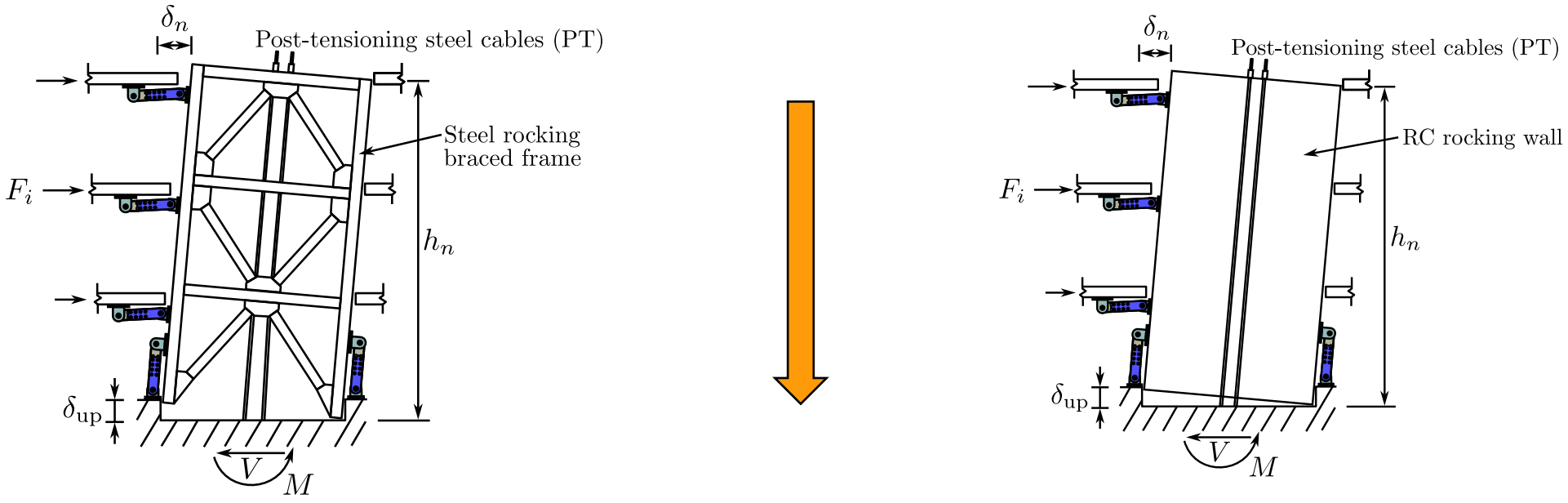
Uncertainty in the structural characteristics of the buildings, their material properties, and their evolution in time.

Variability in the simulated nonlinear response of buildings subjected to earthquake ground motions.



1. FEMA. Seismic Performance Assessment of Buildings, Volume 1 -- Methodology, Second Edition. Federal Emergency Management Agency; 2018.
2. FEMA. Guidelines for nonlinear structural analysis and design of buildings. part I - general. Gaithersburg, MD: National Institute of Standards and Technology; 2017. DOI: 10.6028/NIST.GCR.17-917-46v1.
3. Segura Jr. CL, Sattar S. Uncertainty in the seismic response of reinforced concrete structures due to material variability, 2020.National Research Council. National Earthquake Resilience: Research, Implementation, and Outreach. Washington, D.C.: National Academies Press; 2011. DOI: 10.17226/13092.
4. Georgios Tsampras, Richard Sause, Dichuan Zhang, Robert B. Fleischman, José I. Restrepo, David Mar, Joseph 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, doi:10.1002/eqe.2718
5. Mayorga CF, Tsampras G. Reinforced concrete wall buildings with force-limiting connections: Modeling effects and uncertainty propagation. Earthquake Engineering & Structural Dynamics 2024. DOI: 10.1002/eqe.4073.

Buildings with force-limiting connections can help us overcome these challenges



Potential for accelerated post-earthquake functional recovery

Why?

Building systems with force-limiting connections:

- Limit the seismic-induced horizontal forces transferred from the floor diaphragms to the vertical elements of the seismic force-resisting system.
- Reduce the seismic-induced horizontal floor accelerations.
- Reduce the acceleration and force responses and their ground motion-to-ground motion variability.
- Mitigate the higher-mode effects.

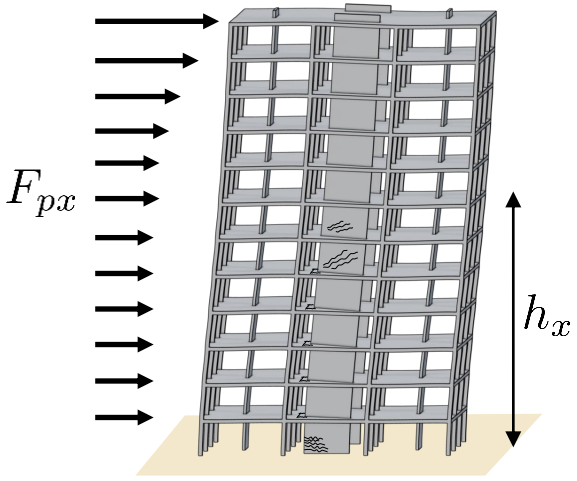


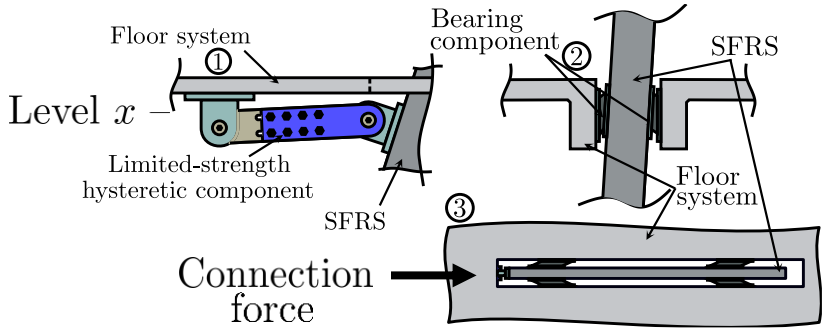
1. Skinner R, Kelly J, Heine A. Hysteretic dampers for earthquake resistant structures. Earthquake Engineering and Structural Dynamics 1975; 3:287–296.
2. Crane ST. Influence of energy dissipation connections between floors and the lateral force resisting system. UC San Diego, USA, 2004.
3. Tsampras G. Force-Limiting Floor Diaphragm Connection for Earthquake-Resistant Buildings. PhD. Lehigh University, USA, 2016.
4. Tsampras G, Sause R, Zhang D, Fleischman RB, Restrepo JI, Mar D, et al. Development of deformable connection for earthquake-resistant buildings to reduce floor accelerations and force responses. Earthquake Engineering & Structural Dynamics 2016; 45(9): 1473–1494. DOI: 10.1002/eqe.2718.
5. Zhang Z, Fleischman RB, Restrepo JI, Guerrini G, Nema A, Zhang D, et al. Shake-table test performance of an inertial force-limiting floor anchorage system. Earthquake Engineering & Structural Dynamics 2018; 47(10): 1987–2011. DOI: 10.1002/eqe.3047.
6. Tsampras G, Sause R, Fleischman RB, Restrepo JI. Experimental study of deformable connection consisting of buckling-restrained brace and rubber bearings to connect floor system to lateral force resisting system. Earthquake Engineering & Structural Dynamics 2017; 46(8): 1287–1305. DOI: 10.1002/eqe.2856.
7. Tsampras G, Sause R, Fleischman RB, Restrepo JI. Experimental study of deformable connection consisting of friction device and rubber bearings to connect floor system to lateral force resisting system. Earthquake Engineering & Structural Dynamics 2018; 47(4): 1032–1053. DOI: 10.1002/eqe.3004.

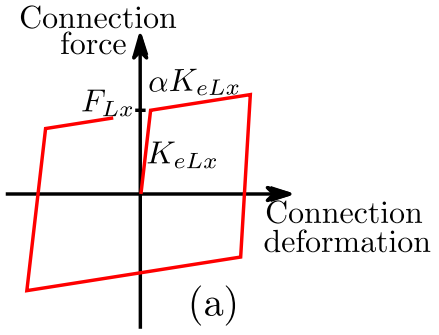
Force-Based Design of Force-Limiting Connections

- A **force-based method** per **ASCE 7 Section 12.10.3** has been developed.

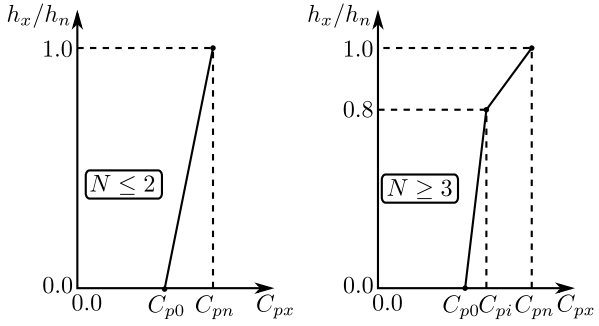




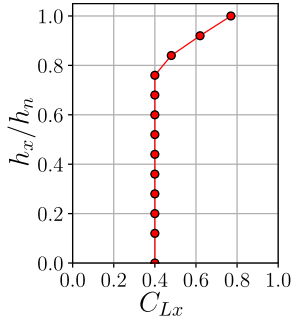


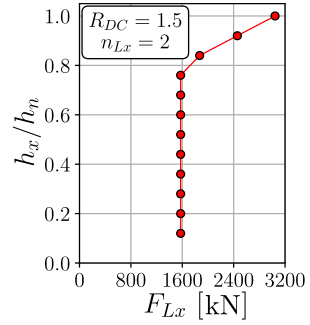


$$F_{px} = \frac{C_{px}}{R_s} w_{px}$$



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

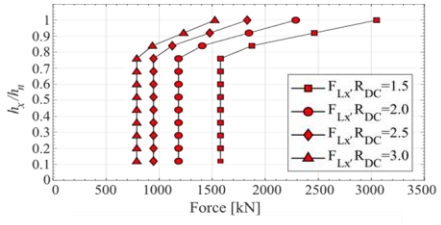


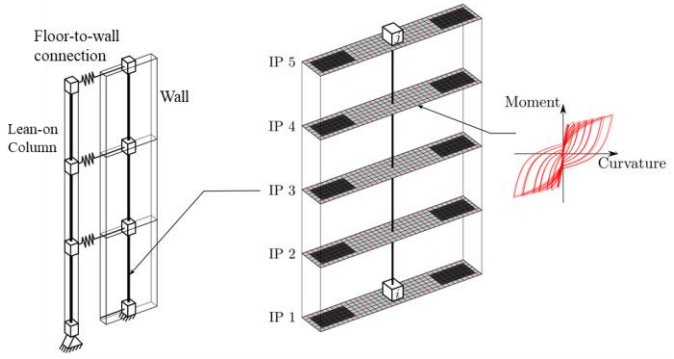


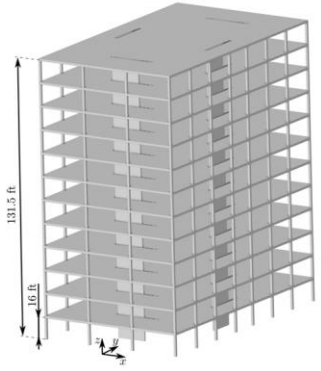
1. Georgios Tsampras (2016), Force-Limiting Deformable Floor Diaphragm Connection for Earthquake Resistant Buildings, PhD Dissertation, Lehigh University, Bethlehem, PA, USA, DOI: https://preserve.lib.lehigh.edu/islandora/object/preserve%3Abp-10369972
2. Tsampras G, Sause R. Force-Based Design Method for Force-Limiting Deformable Connections in Earthquake-Resistant Buildings. Journal of Structural Engineering 2022; 148(10): 04022150. DOI: 10.1061/(ASCE)ST.1943-541X.0003456.
3. 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.
4. Mayorga CF, Tsampras G. Reinforced concrete wall buildings with force-limiting connections: Modeling effects and uncertainty propagation. Earthquake Engineering & Structural Dynamics 2024. DOI: 10.1002/eqe.4073.
5. Lee K, Tsampras G, Mayorga CF. 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 2024: (Accepted).

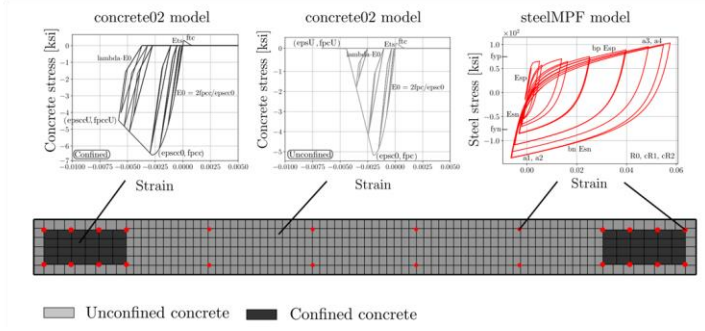
Application of force-based design on RC Wall Buildings

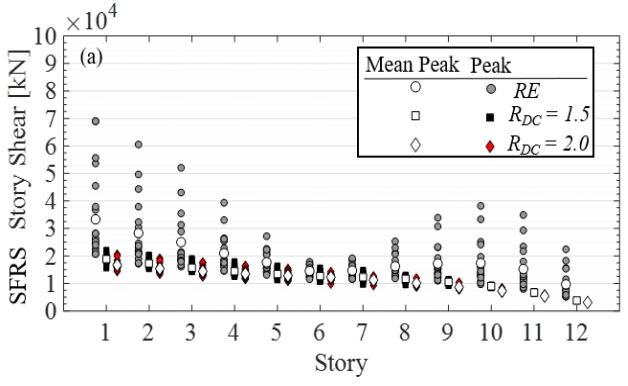
- **Reduction** in the peak **acceleration and force responses** and their **dispersion** due to **ground motion-to-ground motion variability**.
- R_{DC} modifies the distribution of engineering demands.

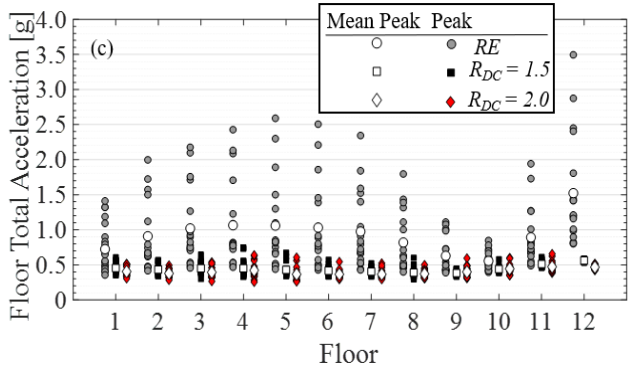


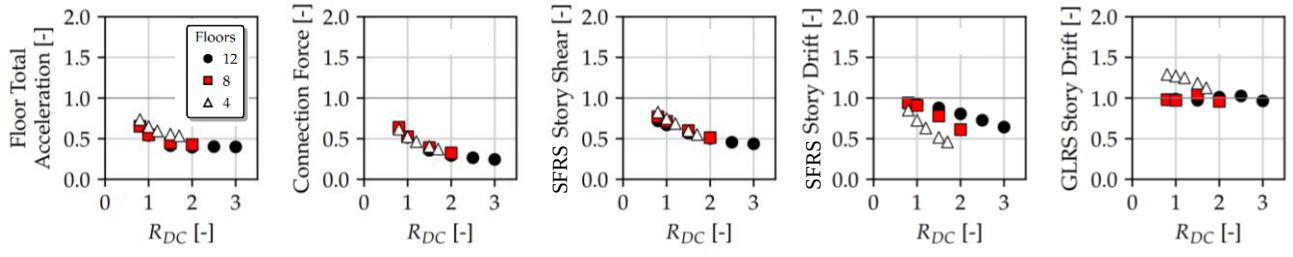








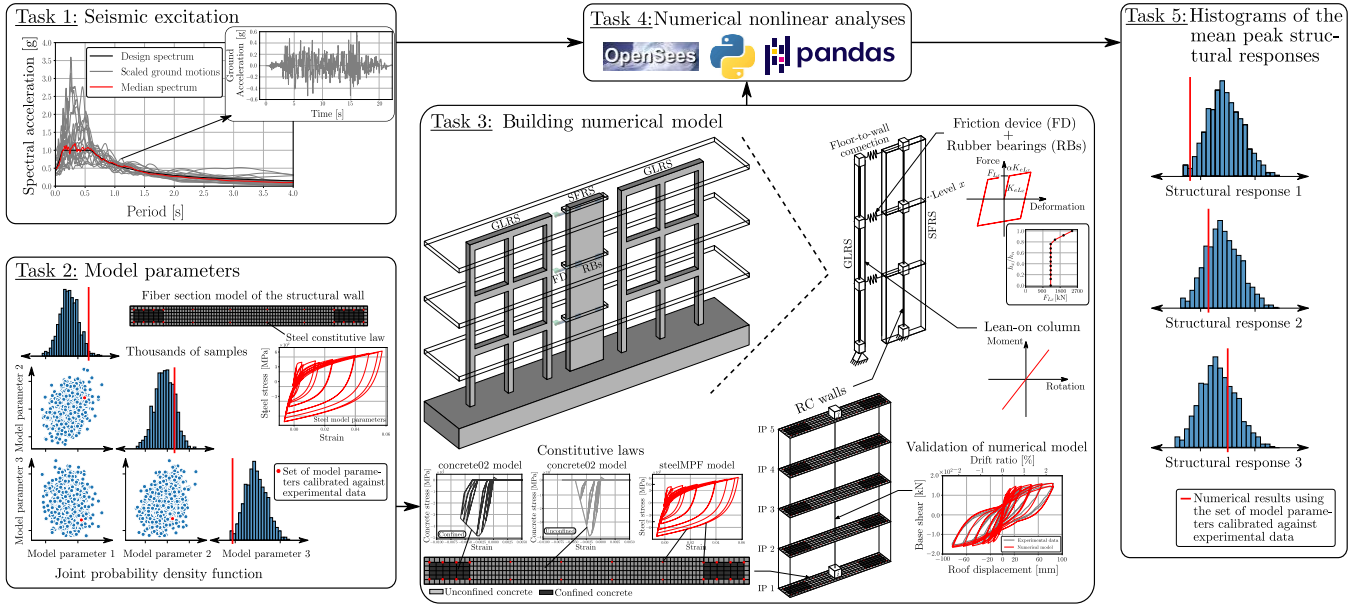


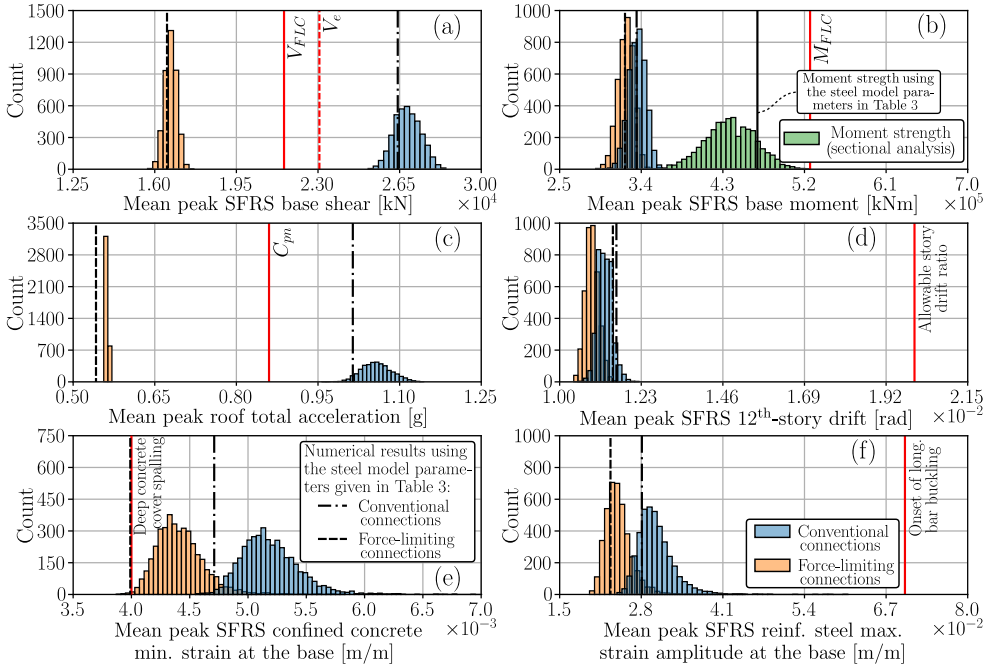


1. Tsampras G, Sause R, Zhang D, Fleischman RB, Restrepo JI, Mar D, et al. Development of deformable connection for earthquake-resistant buildings to reduce floor accelerations and force responses. Earthquake Engineering & Structural Dynamics 2016; 45(9): 1473–1494. DOI: 10.1002/eqe.2718.
2. Tsampras G, Sause R. Force-Based Design Method for Force-Limiting Deformable Connections in Earthquake-Resistant Buildings. Journal of Structural Engineering 2022; 148(10): 04022150. DOI: 10.1061/(ASCE)ST.1943-541X.0003456.
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Uncertainty Propagation

- **Reduction** in the **dispersion** of the **distribution** of the mean peak **acceleration and force responses** due to **uncertainty** in the **material properties** of the longitudinal reinforcing steel bars.



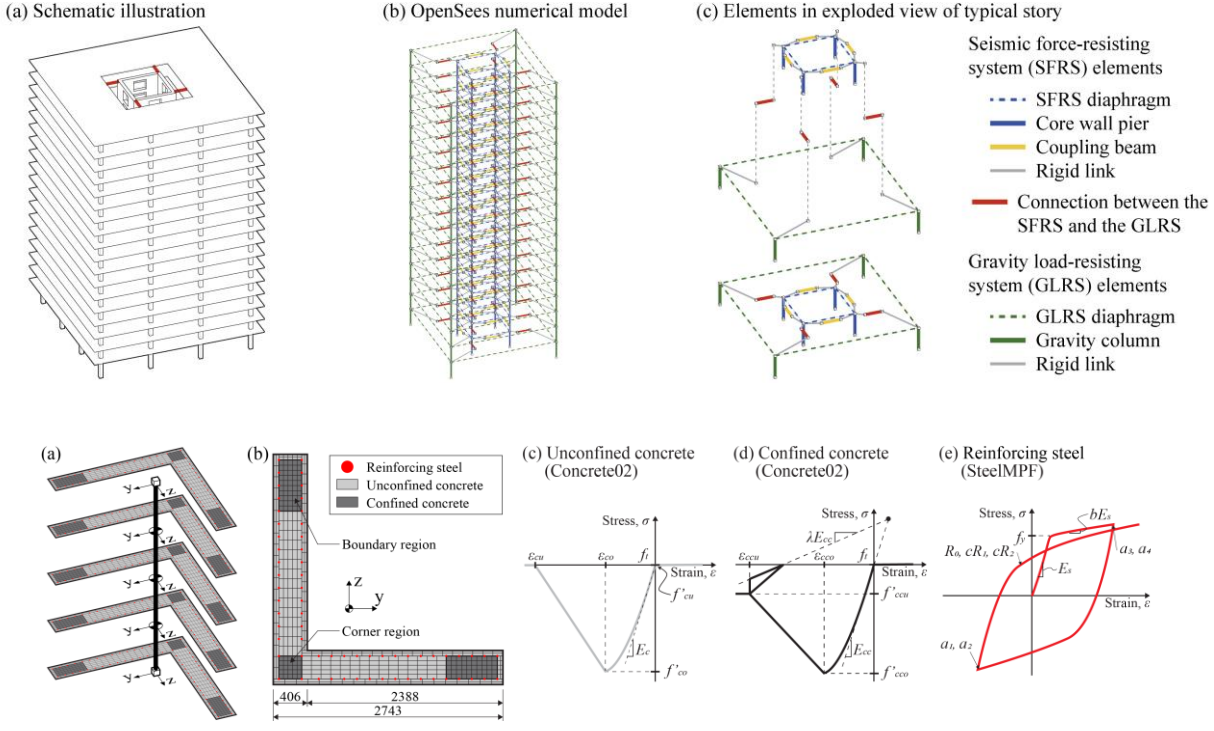


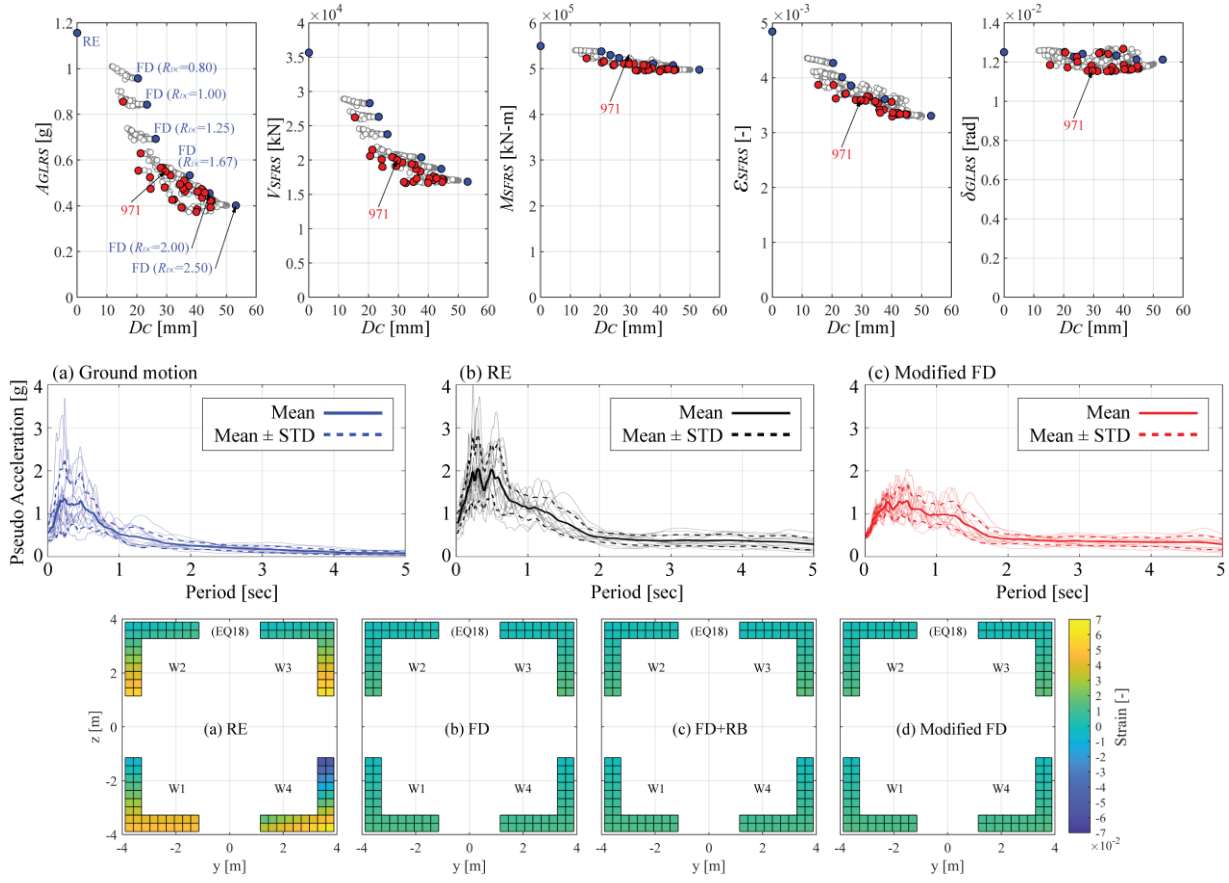
4000 realizations

1. Tsampras G, Sause R, Zhang D, Fleischman RB, Restrepo JI, Mar D, et al. Development of deformable connection for earthquake-resistant buildings to reduce floor accelerations and force responses. Earthquake Engineering & Structural Dynamics 2016; 45(9): 1473–1494. DOI: 10.1002/eqe.2718.
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RC Core Wall Buildings

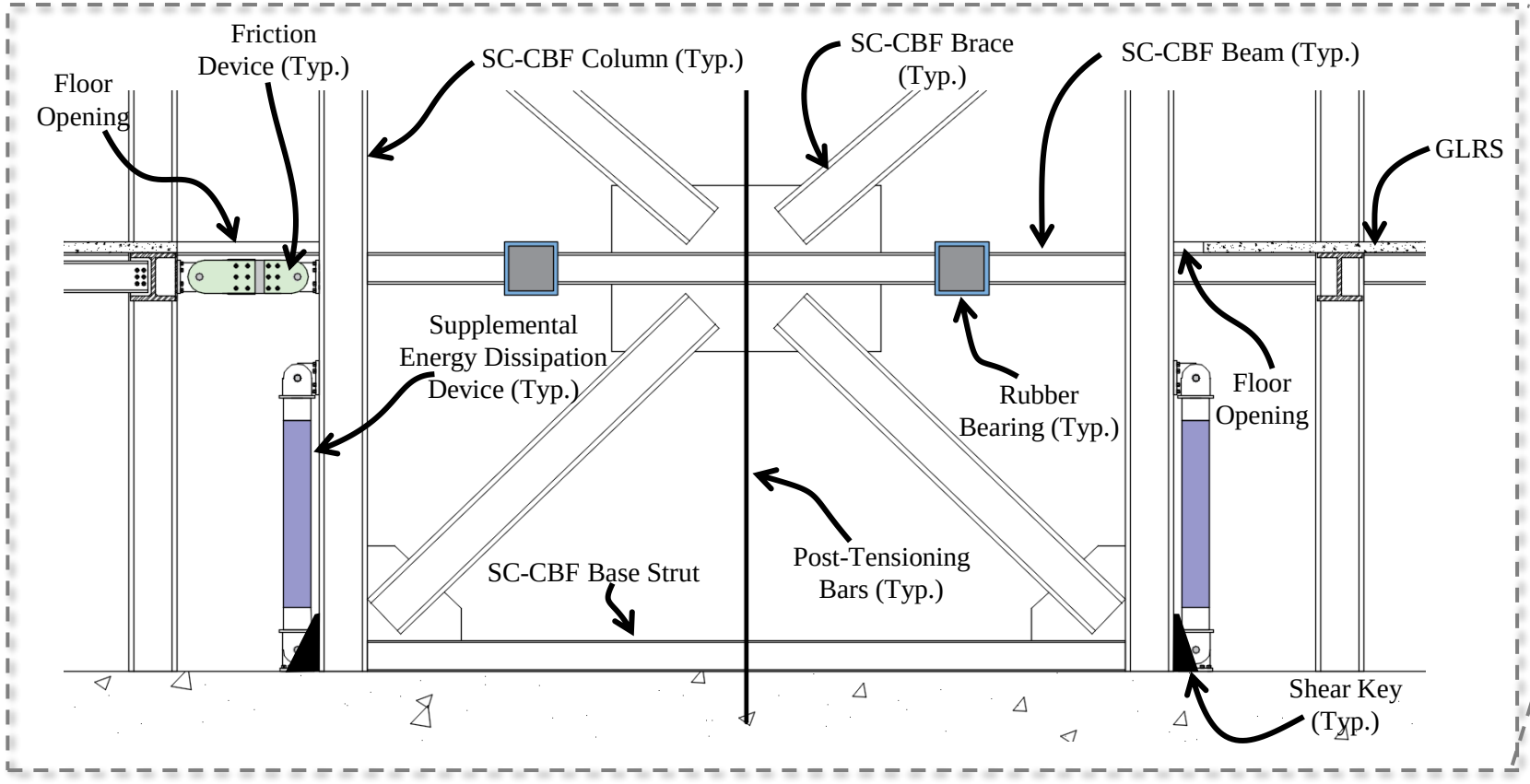
- **RC core wall** building numerical model with force-limiting connections designed using the proposed force-based method. **Pareto-front analysis to determine R_{DC}.**
- Reduction in the floor **total accelerations, torsional moments and strain demand** in the longitudinal steel reinforcement at the base of the core wall.

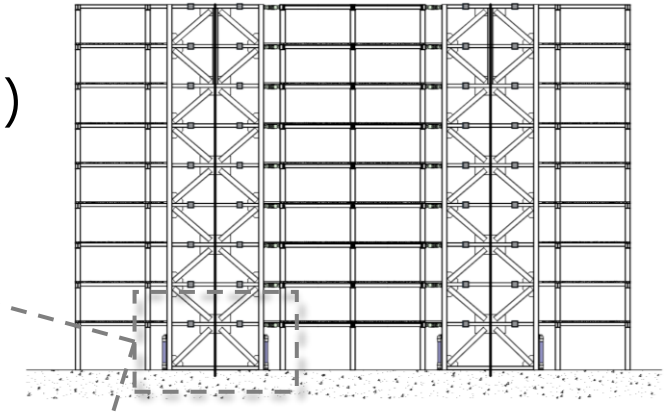


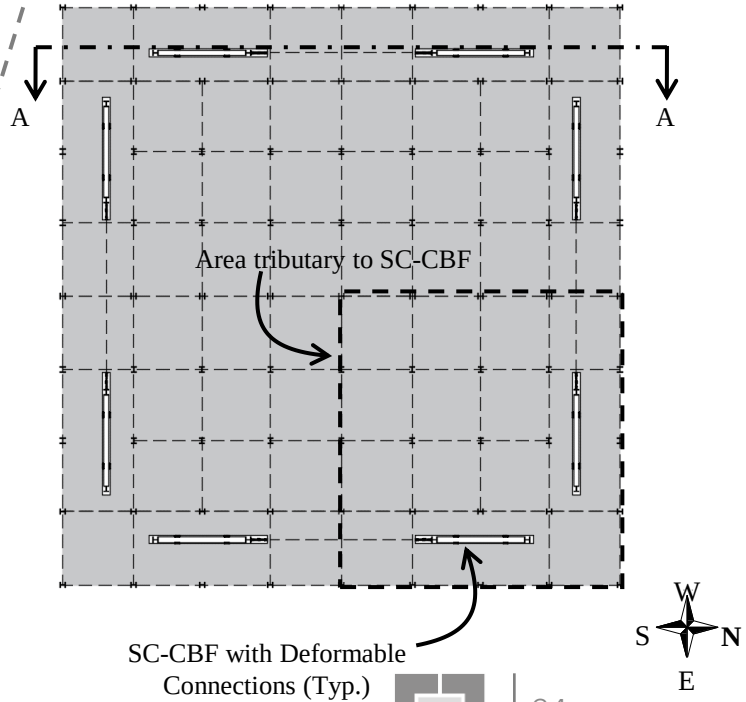


1. Lee K, Tsampras G, Mayorga CF. Reinforced Concrete Core Wall Buildings with Modified Friction-Based Force-Limiting Connections: Connection Design Considerations and Three-Dimensional Response to Bidirectional Ground Motions. Journal of Structural Engineering 2024; (In Production).

9-Story Self-Centering Concentrically Braced Frame (SC-CBF)



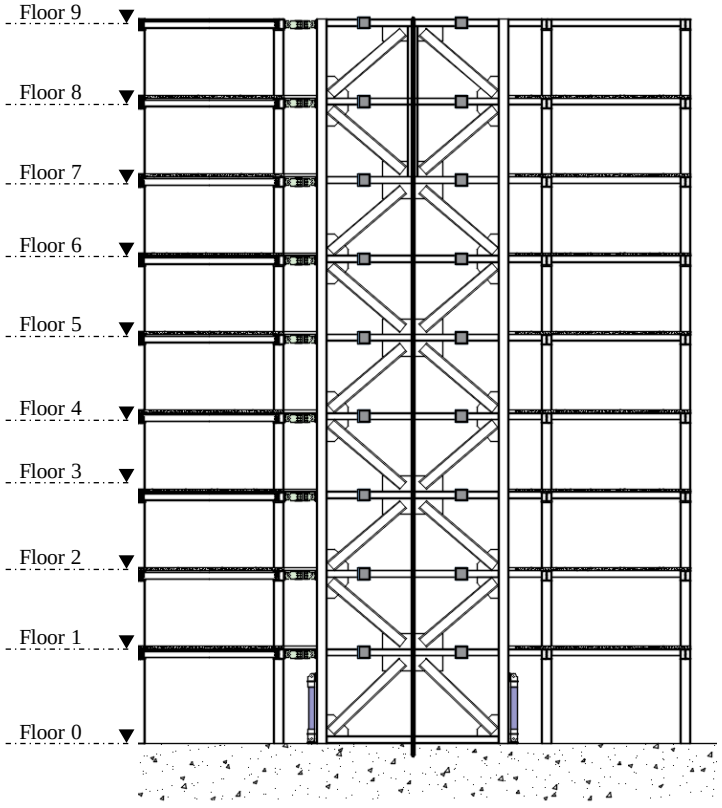


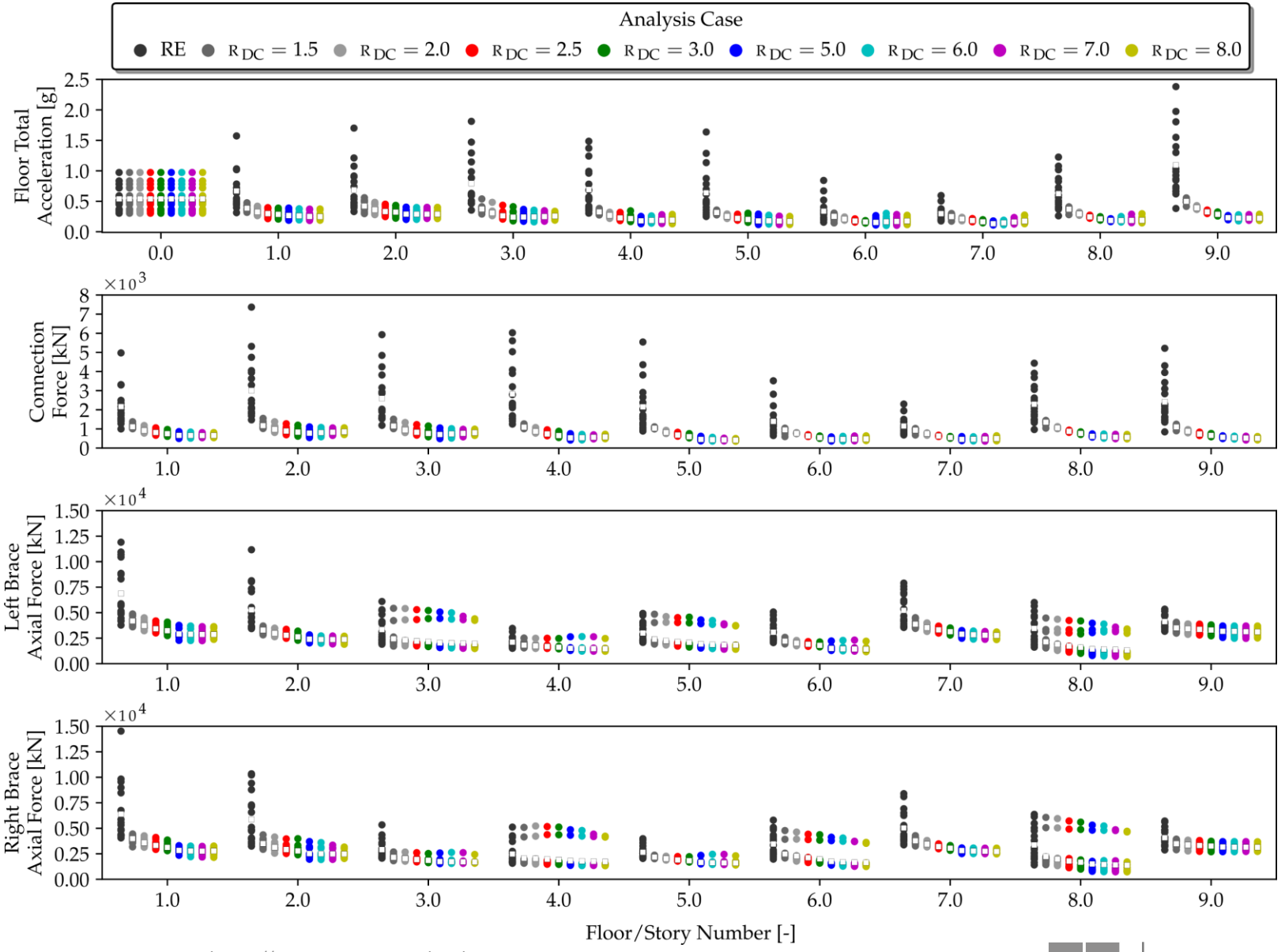


Georgios Tsampras (2016), Force-Limiting Deformable Floor Diaphragm Connection for Earthquake Resistant Buildings, PhD Dissertation, Lehigh University, Bethlehem, PA, USA, DOI: https://preserve.lib.lehigh.edu/islandora/object/preserve%3Abp-10369972

9-Story Self-Centering Concentrically Braced Frame (SC-CBF)

Reduction in **mean** peak responses and their **dispersion**





Conclusions and Limitations

- **Reduced magnitude** of the building **seismic responses** → **Reduced damage** in the **structural** and **nonstructural components** → **Improved post-disaster functionality**.
- **Reduced dispersion** of the building **seismic responses** → **Higher confidence** in the **response prediction** → **Higher confidence** in **building design reliability** → **Higher confidence** in the **design building resilience.**
- The use of **force-limiting connections** is a **practical solution** to **design buildings** with **accelerated post-earthquake functional recovery**.
- **Buildings with force-limiting connections** could contribute to **national earthquake resilience** and **address issues raised by FEMA**.

There is no simple and practical design method that provides the means for the holistic design of buildings with force-limiting connections for target performance and post-earthquake functional recovery levels.

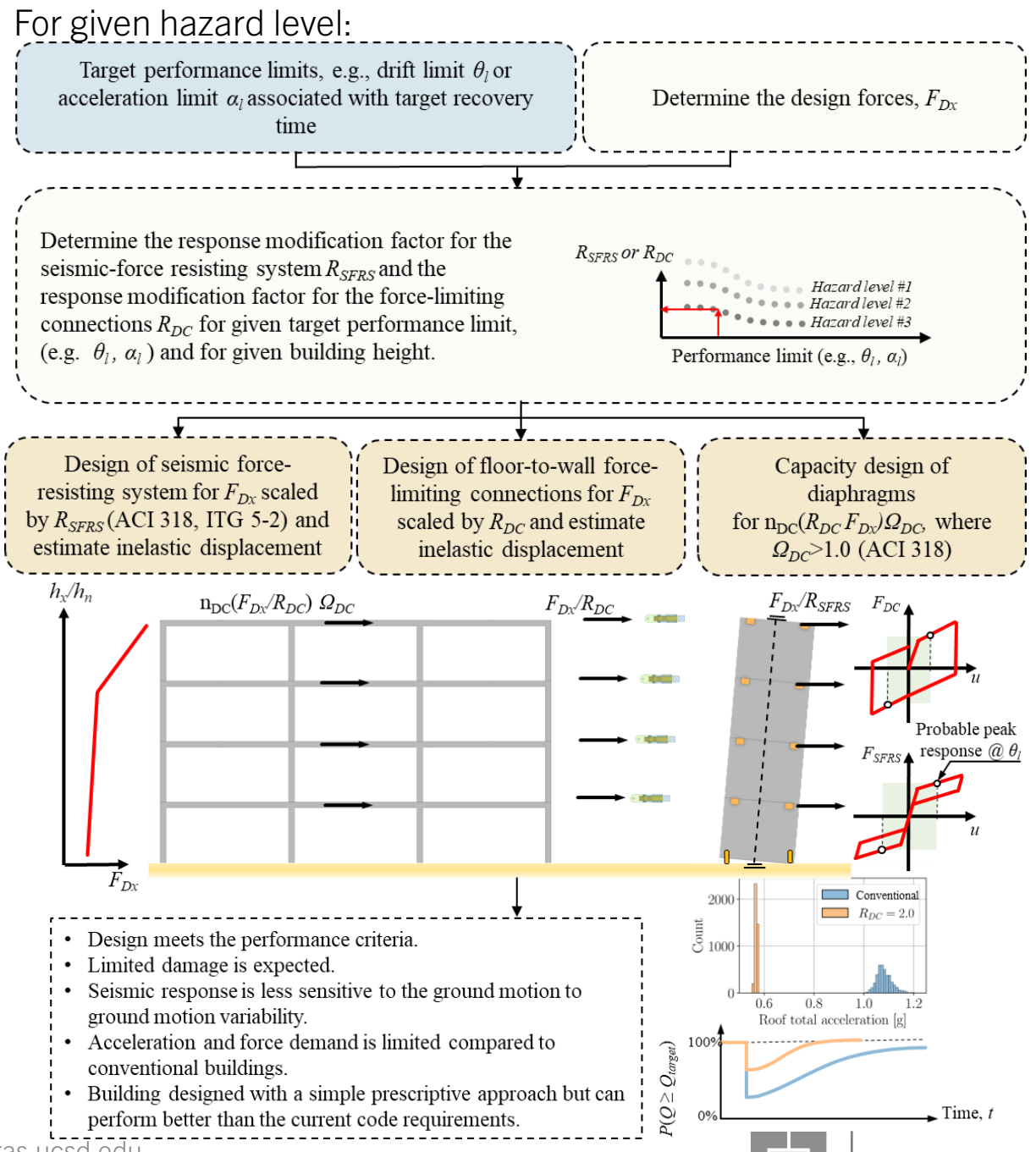
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4. Mayorga CF, Tsampras G. Reinforced concrete wall buildings with force-limiting connections: Modeling effects and uncertainty propagation. Earthquake Engineering & Structural Dynamics 2024. DOI: 10.1002/eqe.4073.

Aims of Research

Our research will:

1. Determine $\boldsymbol{R_{SFRS}}$ and $\boldsymbol{R_{DC}}$.
2. Determine $\boldsymbol{F_{Dx}}$.
3. Determine $\boldsymbol{\Omega_{DC}}$.
4. Determine the expected inelastic demands in the force-limiting connections and seismic force-resisting system.
5. Relate the structural performance limits to the functional recovery limits for given level of hazard.

Tsampras and Bocchini, DRRG Proposals [2020, 2022]



Intellectual Merit

1. A protocol for the integration of functionality and resilience considerations as early as the design phase of building systems able to recover faster than conventional building systems.
2. A probabilistic focus on variability reduction, rather than on analysis of mean values only.

The main advantage of force-limiting deformable connections is **not in the reduction of the mean** engineering demand parameters but in the **reduction of their sensitivity to the ground motion**. For these reasons, **the proposed design and probabilistic resilience-based approach proposed in this project are perfectly synergistic**.

Project Introduction

Resilience-Based Design of Buildings with Accelerated Post-Earthquake Functional Recovery [2024 – 2027]

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Thank you!

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NIST | NSF | Disaster Resilience Research Grant Symposium

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