18th U.S.-Japan-New Zealand
Workshop on the Improvement of Structural Engineering and Resilience

Overview of a Project on Resilience-Based Design of Buildings with Accelerated Post-earthquake Functional Recovery

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

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

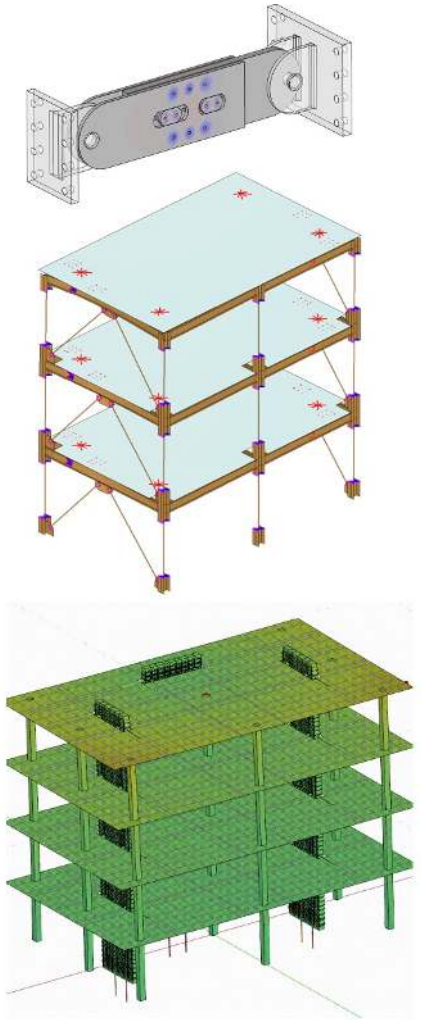
December 2, 2024
San Diego, CA

Overall, our research group at UC San Diego aims to contribute to the improvement of safety and resilience of our built environment

Experimental

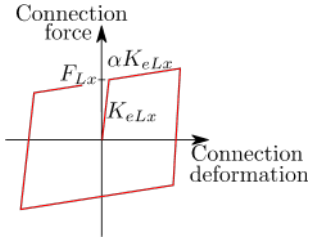


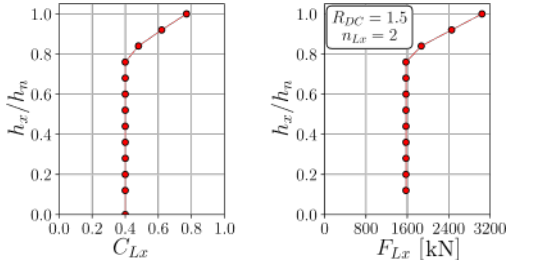
Computational

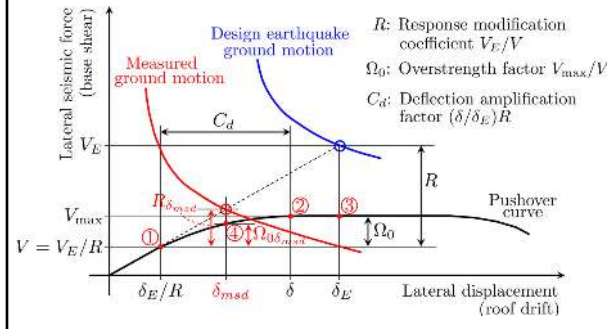


Design

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





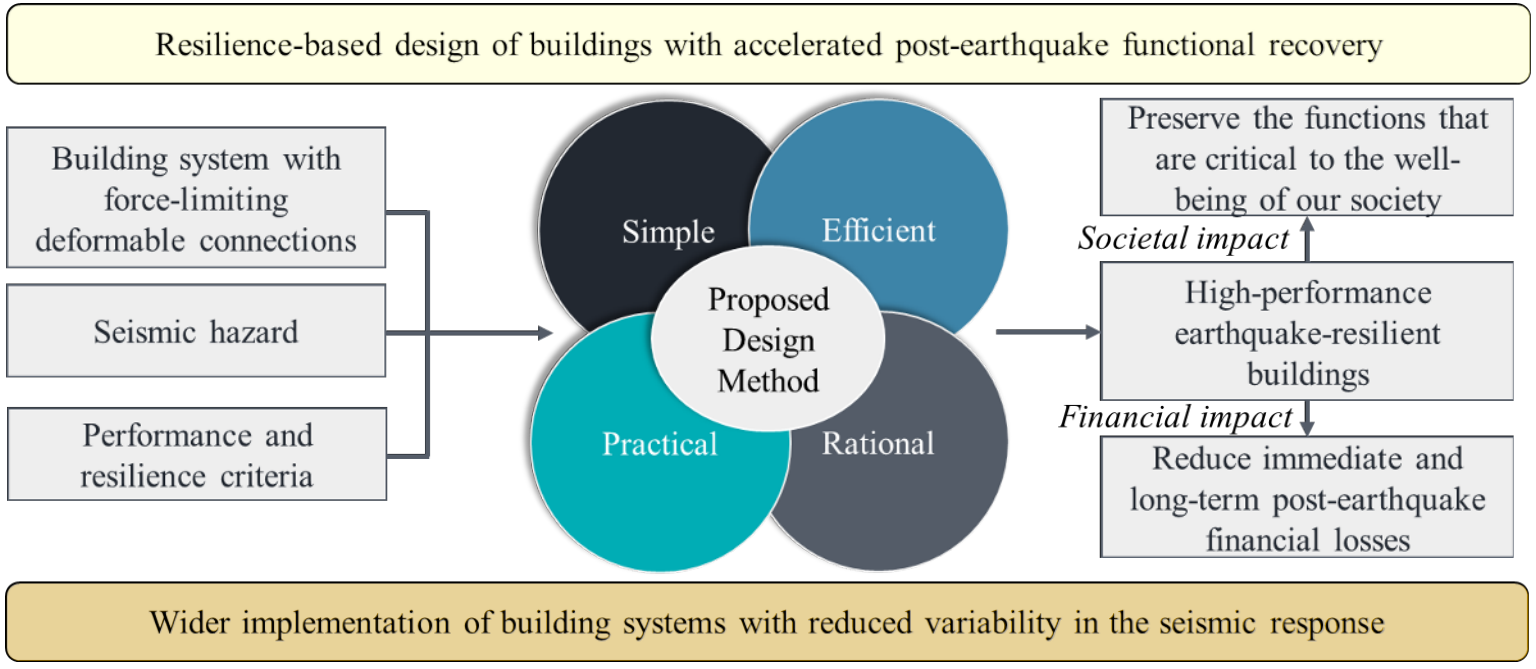


Hybrid Manufacturing



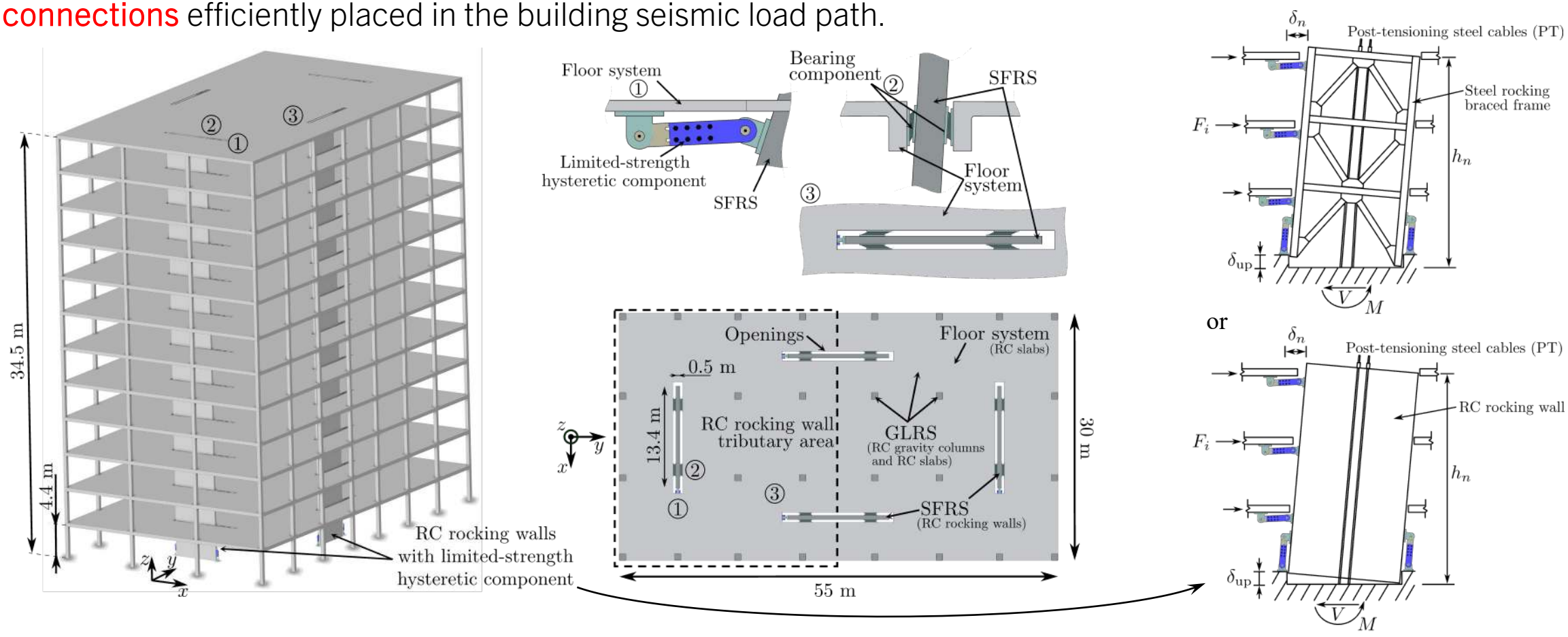
Project Vision and Goal

- 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.



Project Vision and Goal (continued)

- 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.

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

U.S. National Science Foundation | NIST

Disaster Resilience Research Grant













Motivation & Background

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)

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

1. 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.
2. Congressional Research Service. The National Earthquake Hazards Reduction Program (NEHRP): Issues in Brief. Washington, D.C.: 2021.
3. FEMA. NEHRP Recommended Seismic Provisions for New Buildings and Other Structures. FEMA; 2020.
4. National Research Council. National Earthquake Resilience: Research, Implementation, and Outreach. Washington, D.C.: National Academies Press; 2011. DOI: 10.17226/13092.
5. McAllister, T.P., R. Walker, A. Baker. 2022. "Assessment of Resilience in Codes, Standards, Regulations, and Best Practices for Buildings and Infrastructure Systems." Gaithersburg, MD: National Institute of Standards and Technology.

National Earthquake Resilience (continued)



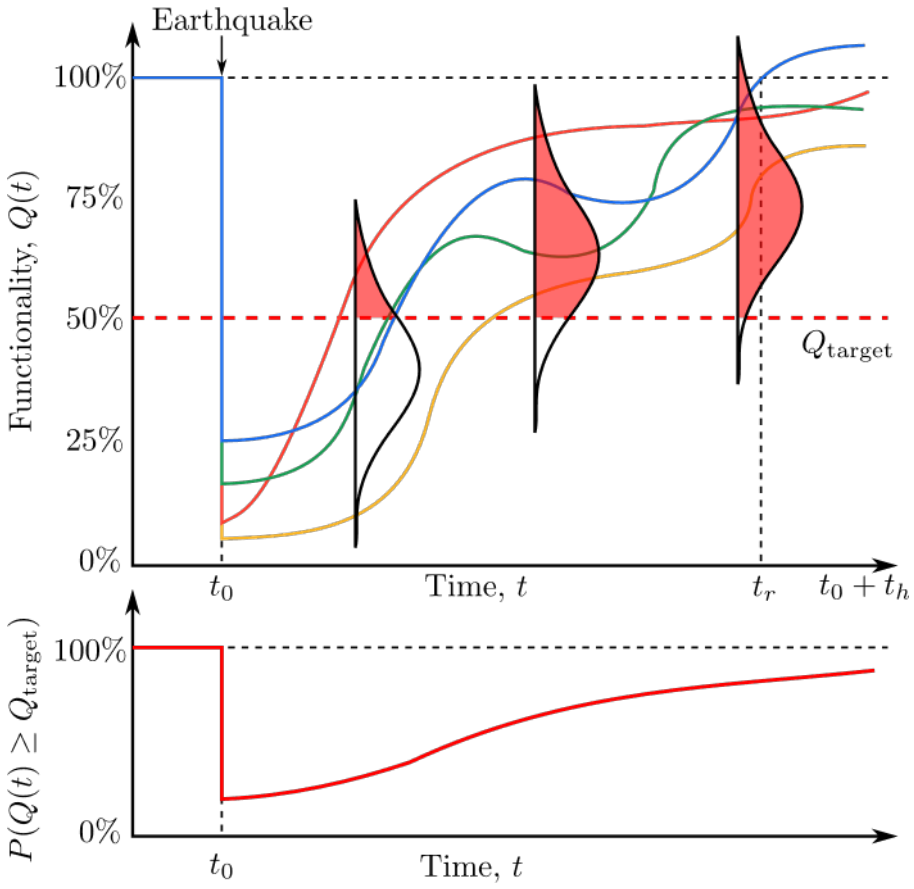
"How can we **reduce** the **risks of life and property** from future earthquakes and **increase** the **resilience of communities** in the United States?"

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

FEMA/BSSC/PUC 2024. "Functional Recovery Task Committee Recommended Scope, Organization and Deliverables." 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 earthquake 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., D.M. Frangopol, T. Ummenhofer, T. Zinke 2014. "Resilience and Sustainability of Civil Infrastructure: Toward a Unified Approach". Journal of Infrastructure Systems, 20(2): 04014004..
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. 2022. "Assessment of Resilience in Codes, Standards, Regulations, and Best Practices for Buildings and Infrastructure Systems." Gaithersburg, MD

Building Design Challenges

Current Prescriptive Design Methods

- Force-based methods:
  - Practical.
  - Easy to implement.
  - Use of seismic modification factors and design response spectra to represent the seismic demand.



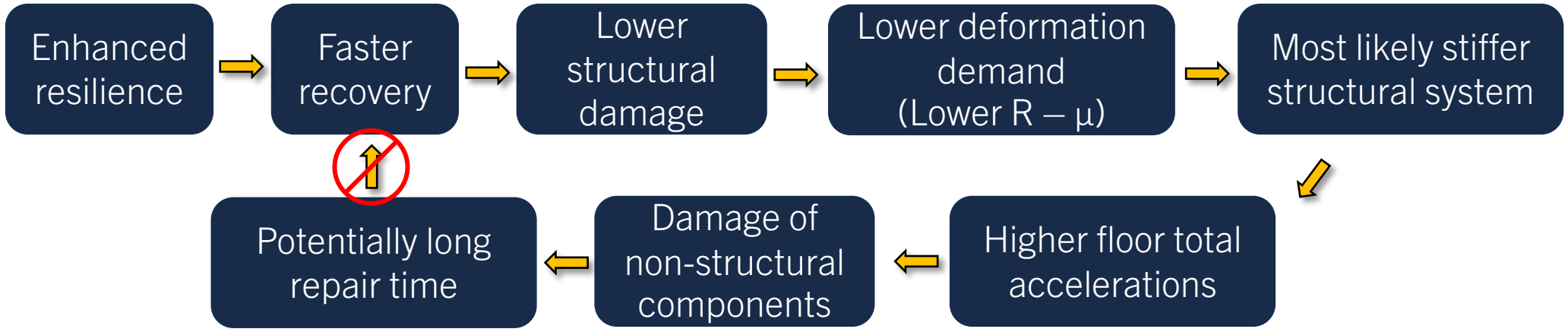
- Displacement-based methods:
  - Performance oriented.
  - Accounts for the nonlinear evolution of stiffness of equivalent single degree of freedom systems.

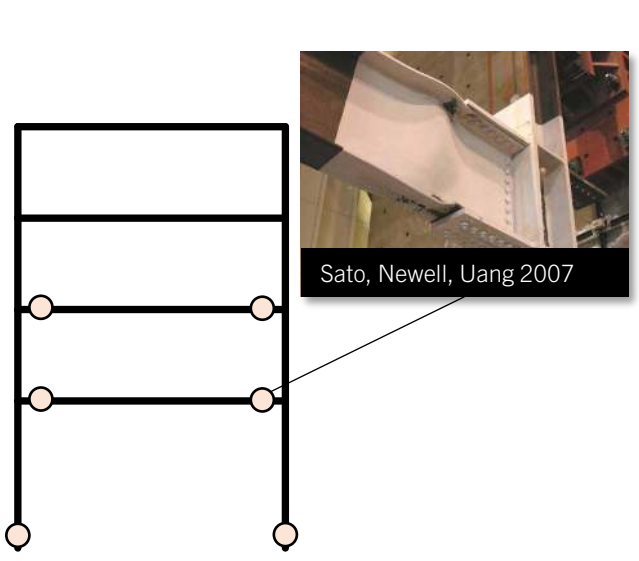
- Hybrid Force/Displacement methods:
  - Performance-orientated displacement-based design principles framed in the context of force-based design.
  - Use of performance-based seismic response modification factors along with design response spectra.

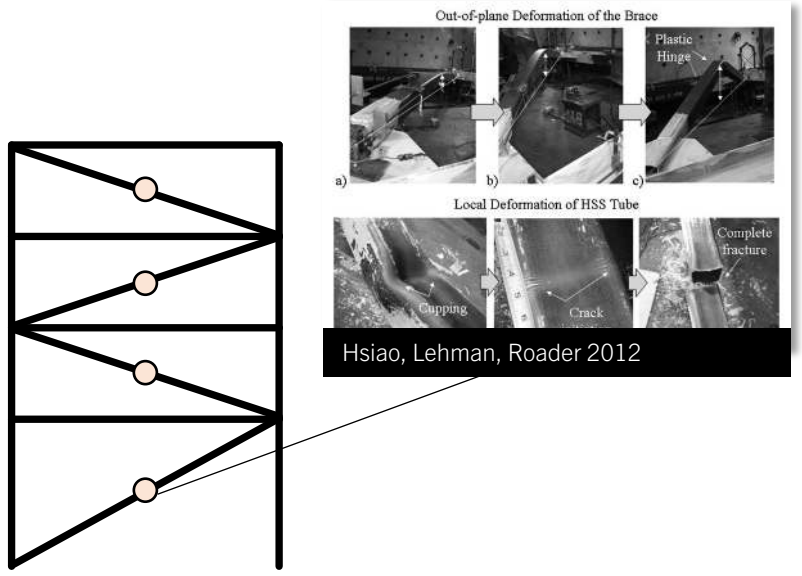
All methods include assumptions to approximate the seismic design demands

1. ASCE/SEI 7-22. 2021, "Minimum Design Loads and Associated Criteria for Buildings and Other Structures (7-22)."
2. 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.
3. Fardis, M. N. 2018, "From Force- to Displacement-Based Seismic Design of Concrete Structures and Beyond." Recent Advances in Earthquake Engineering in Europe: 16th European Conference on Earthquake Engineering-Thessaloniki 2018, 101–22.
4. 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.
5. Moehle, J. P., 1992, "Displacement-Based Design of RC Structures Subjected to Earthquakes." Earthquake Spectra, 8:403–28. https://doi.org/10.1193/1.1585688.
6. Priestley, M.J.N., G.M. Calvi (Author), M.J. Kowalsky. 2007. "Displacement-Based Seismic Design of Structures."
7. Tsampras, G. 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,
8. 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.
9. Uang, C.-M., 1991, "Establishing R (or Rw) and Cd Factors for Building Seismic Provisions." Journal of Structural Engineering, 117,(1): 19–28. https://doi.org/ 10.1061/(ASCE)0733-9445(1991)117:1(19).

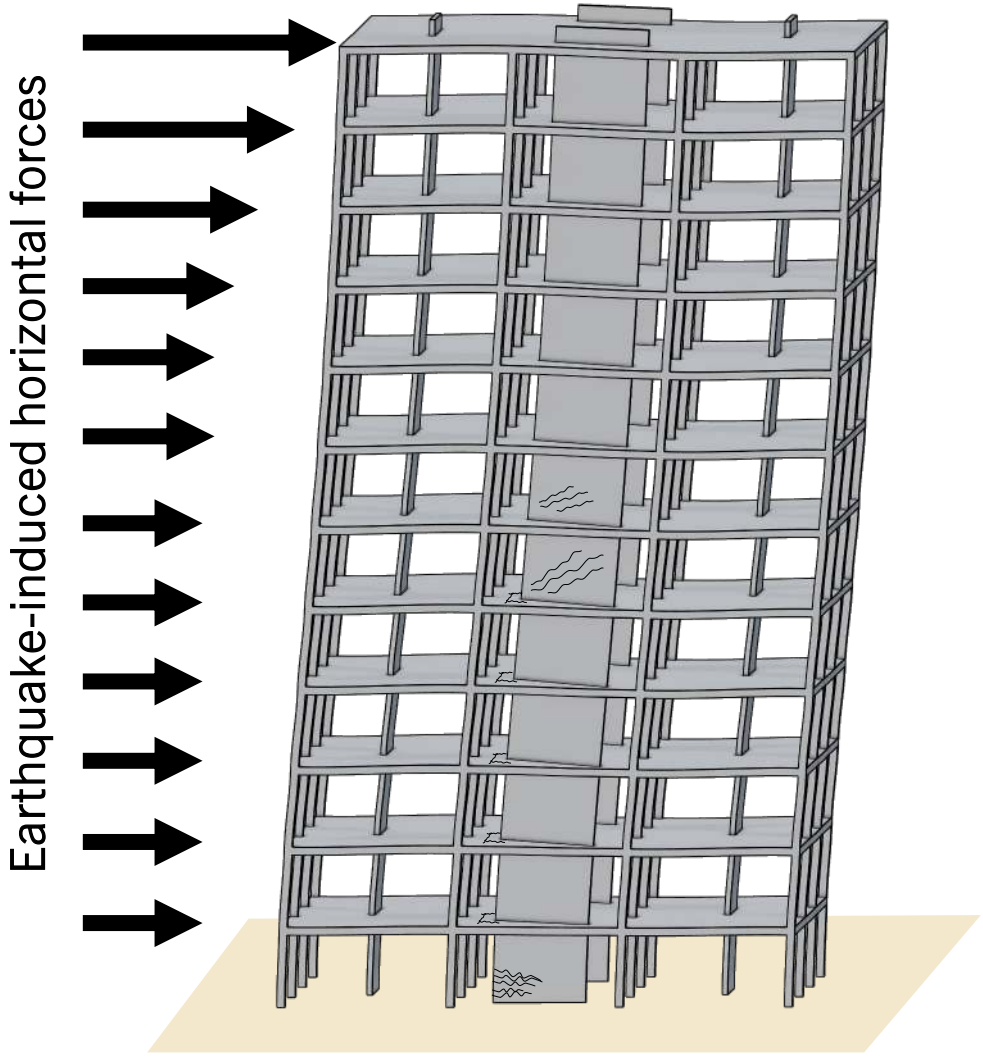
Challenge with Conventional Building Systems



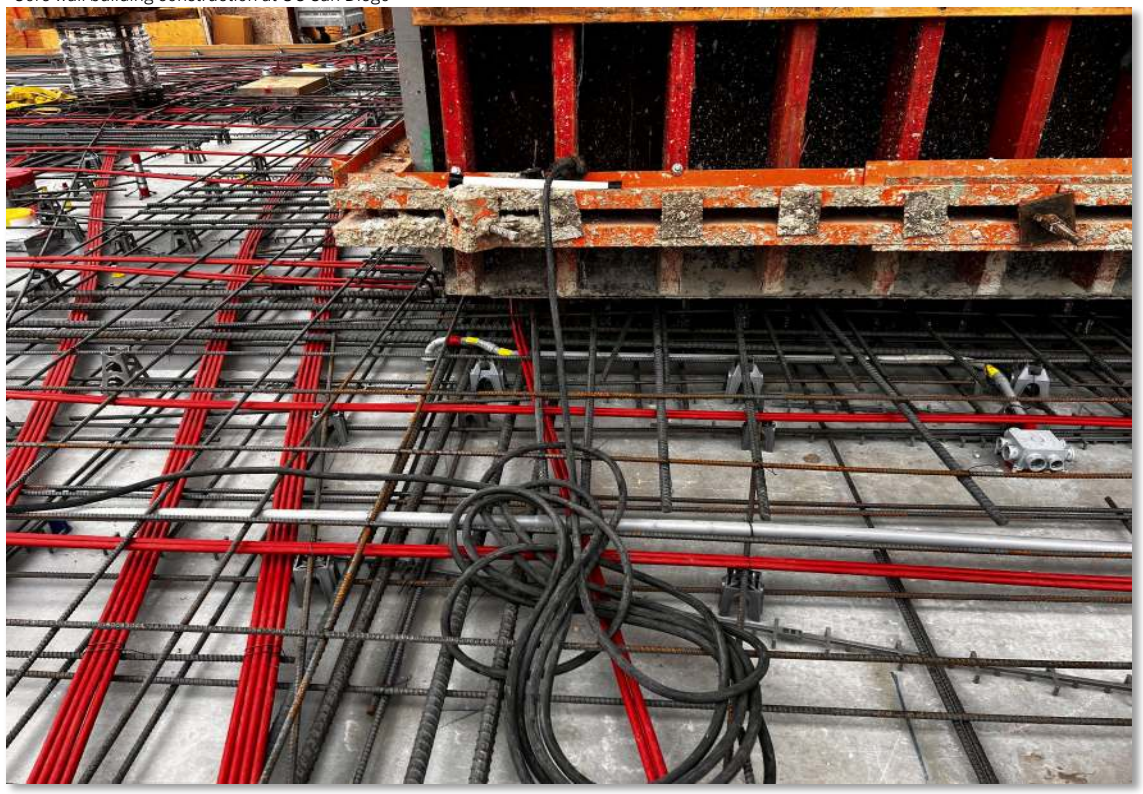




Buildings with Flexural Yielding Base Mechanism

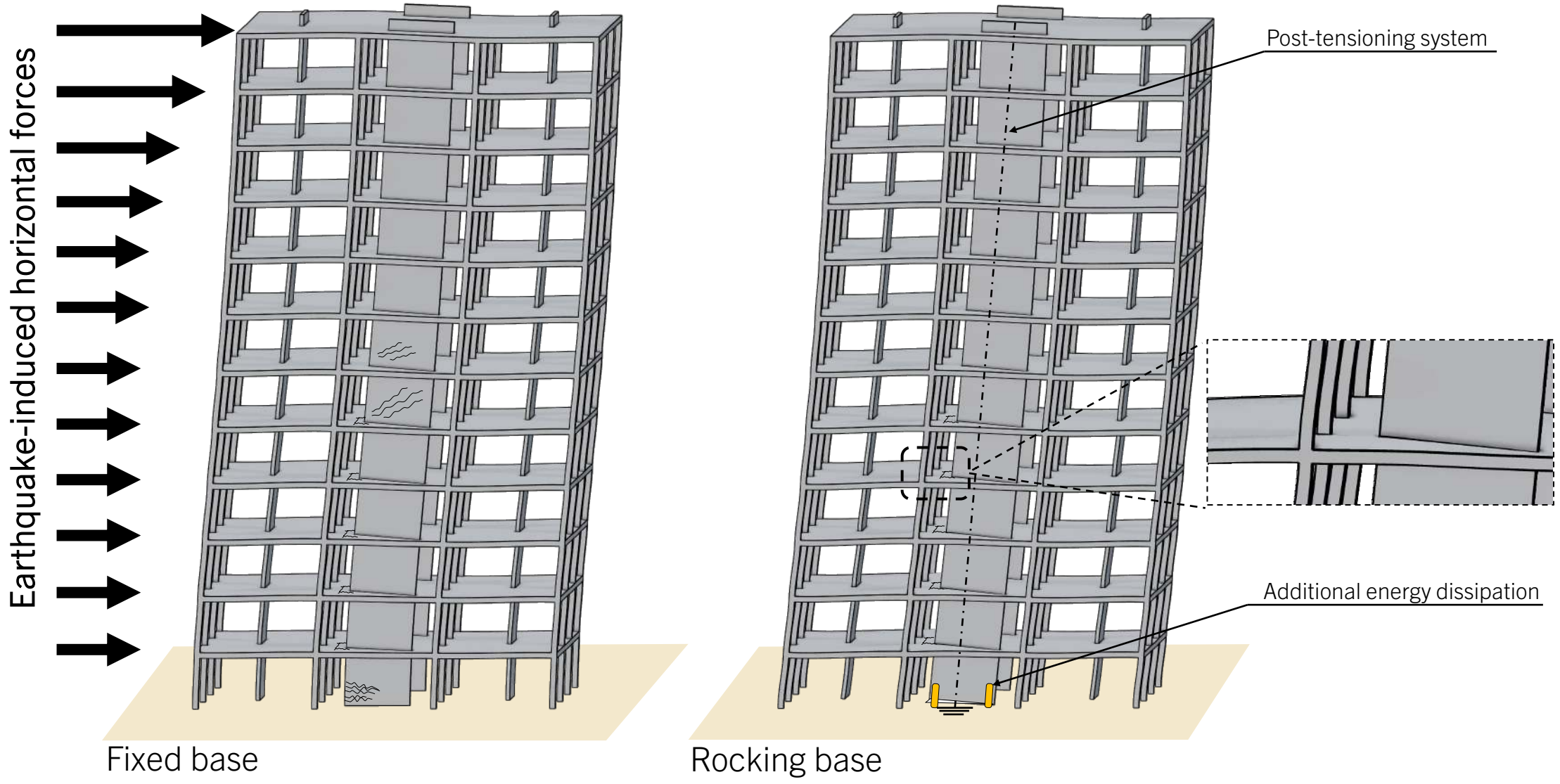


Core wall building construction at UC San Diego

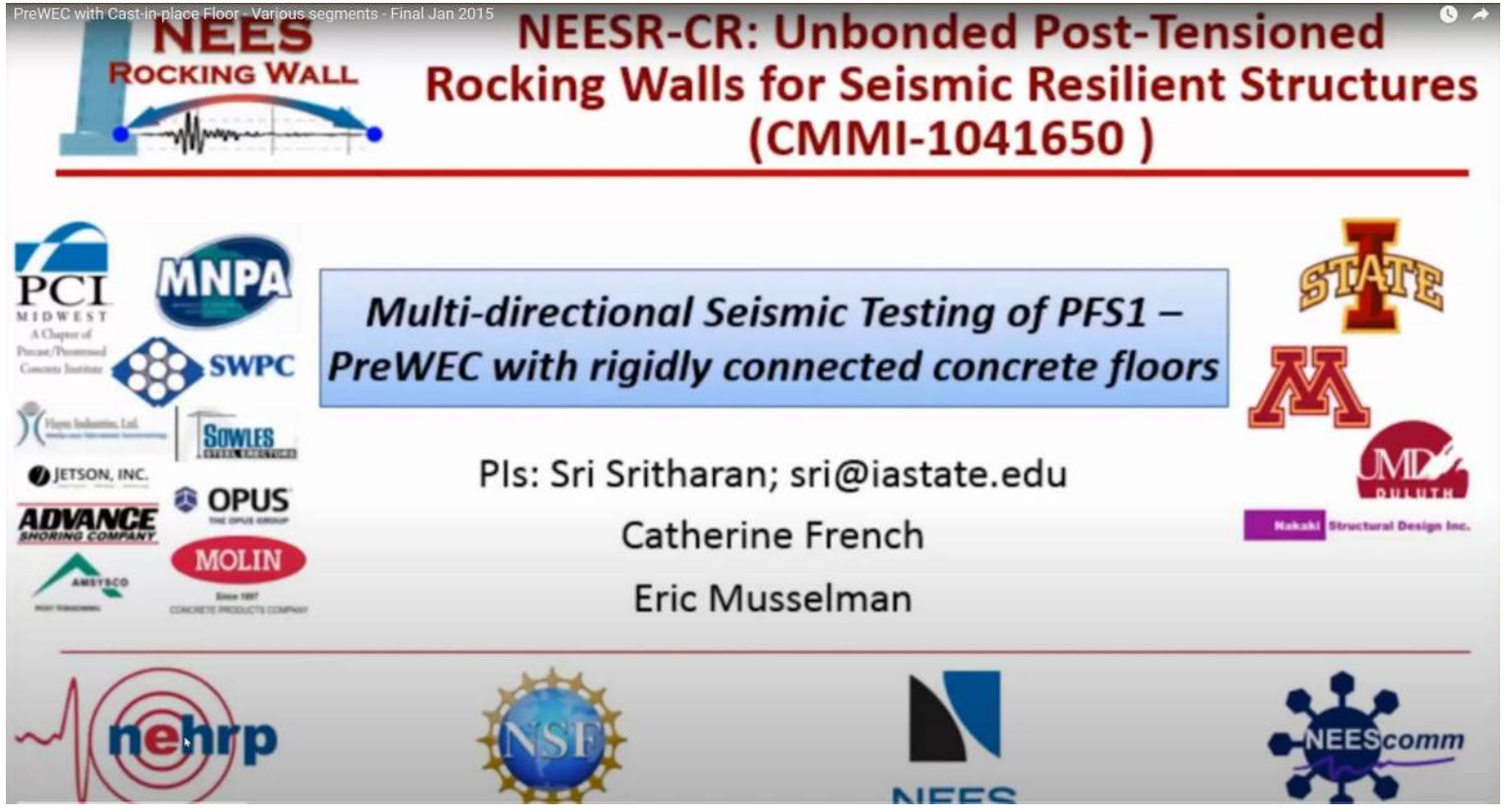


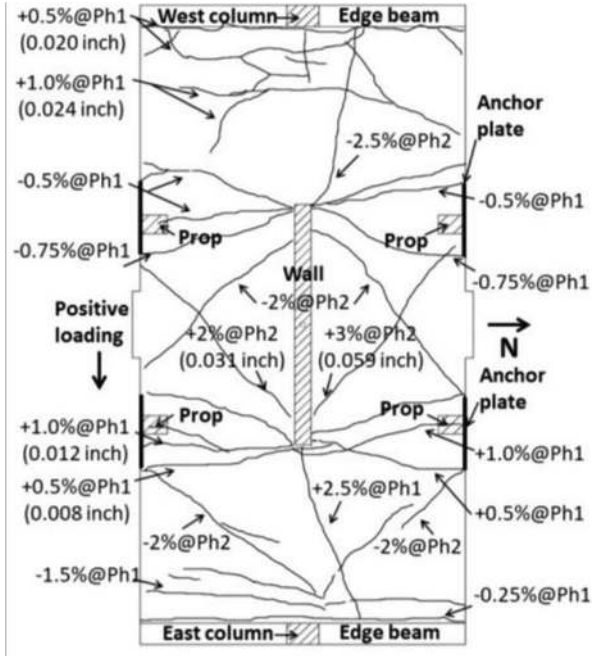
Floor diaphragm: Reinforcing steel of collectors

Buildings with Rocking Base Mechanism



Damage in diaphragms due to wall-to-floor interactions





Liu et al. (2018)

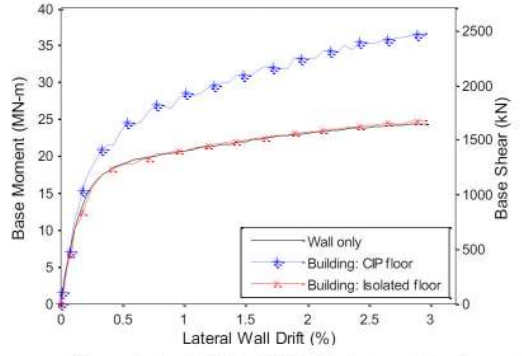


Figure 6 – Calculated response of the prototype building FEM with both cast-in-place and isolated floors

Henry et al. (2012)

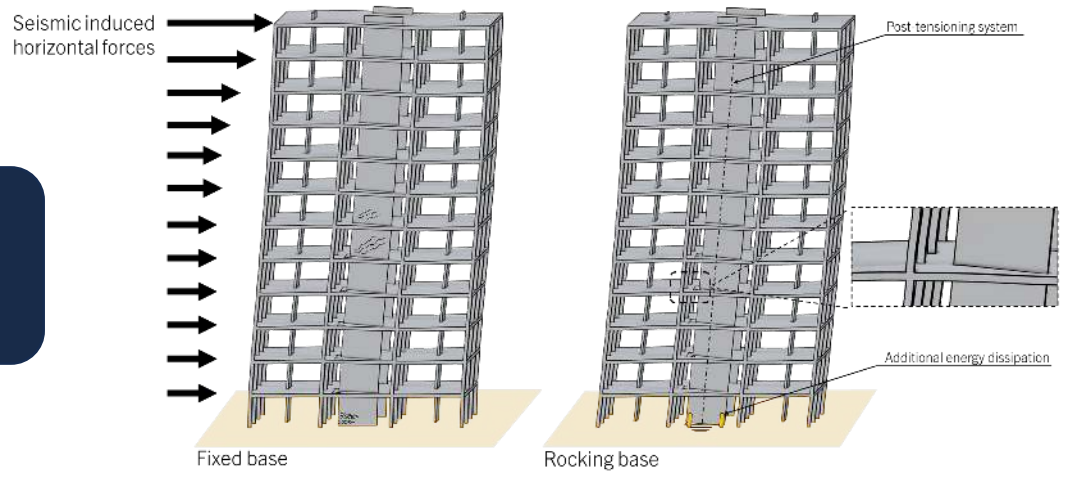
1. Liu, Q., C.W. French, S. Sritharan. 2018. "Study of Interaction between a PreWEC System and Surrounding Structure." Structural Journal, 115(5): 1407–1418. . https://doi.org/10.14359/51702248.
2. Sritharan, S. 2015. PreWEC Project, Iowa State University, https://sri.cce.iastate.edu/NEES-Rocking-Wall/index.htm.
3. Online video https://www.youtube.com/watch?v=iNOZFpj6QGQ
4. Henry, Richard, Jason Ingham, and S. Sritharan. "Wall-to-Floor Interaction in Concrete Buildings with Rocking Wall Systems," 2012. https://researchspace.auckland.ac.nz/handle/2292/17241.

Challenges Lead to Uncertain Seismic Response

Uncertainty in the characteristics of the earthquake ground motion.

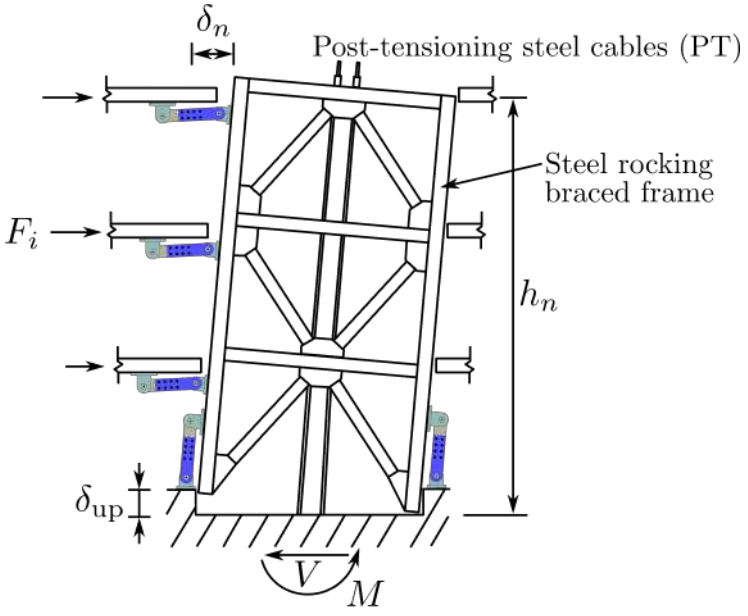
Uncertainty in the structural characteristics of the buildings, their material properties, and their evolution in time.

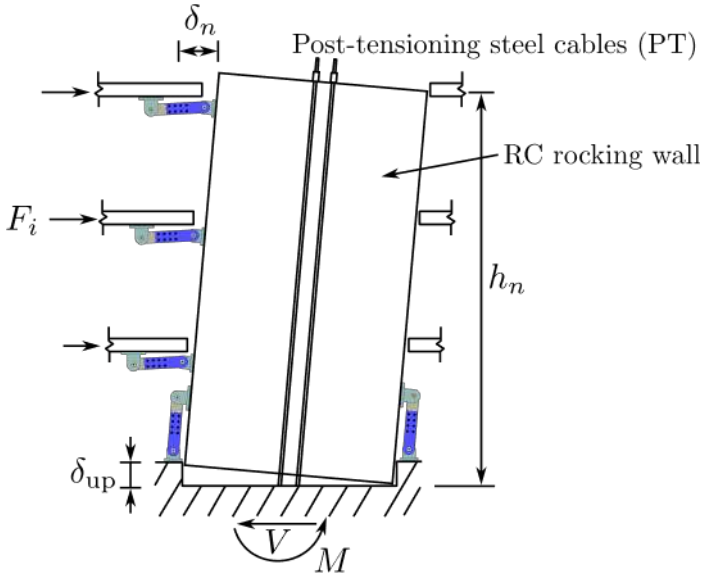
Variability in the simulated nonlinear response of buildings subjected to earthquake ground motions.



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. https://doi.org/10.6028/NIST.GCR.17-917-46v1.
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.
4. Segura Jr., C.L., S. Sattar. 2020. "Uncertainty in the seismic response of reinforced concrete structures due to material variability." National Research Council. National Earthquake Resilience: Research, Implementation, and Outreach. Washington, D.C.: National Academies Press. https://doi.org/10.17226/13092.
5. 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.

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





Potential for accelerated post-earthquake functional recovery

Buildings with Force-Limiting Connections - Why?

- Limit the earthquake-induced horizontal forces transferred from the floor diaphragms to the vertical elements of the seismic force-resisting system.
- Reduce the higher-mode shear-dominant acceleration and force responses and their dispersion due to ground motion-to-ground motion variability.
- Modify the distribution of the ductility demand and global seismic responses based on the connection design.
- Reduce the dispersion of the higher-mode shear-dominant acceleration and force responses cause by the uncertainty in the numerical model parameters.

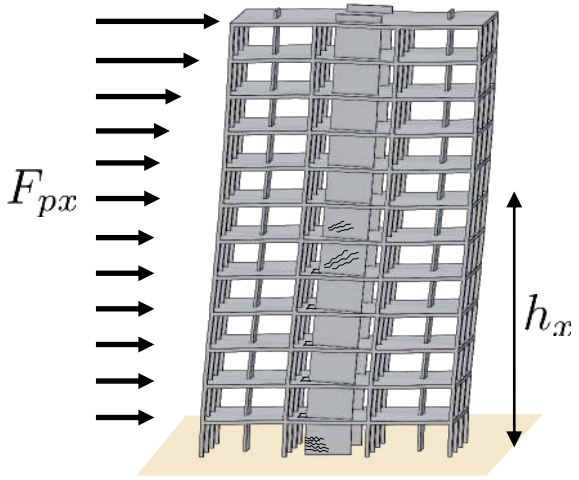


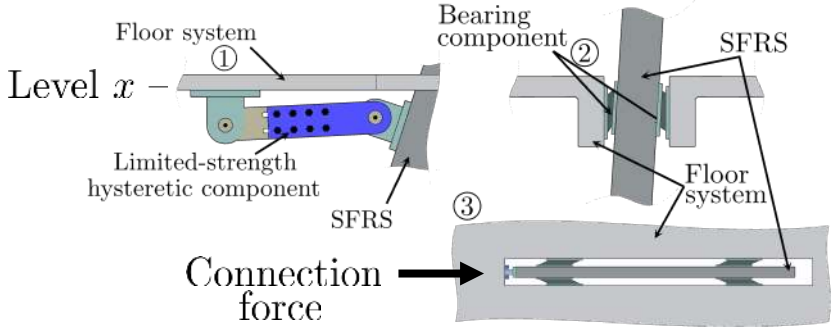
1. Crane, S.T. 2024. “Influence of energy dissipation connections between floors and the lateral force resisting system.” PhD Dissertation. UC San Diego, USA.
2. Skinner, R., J. Kelly, A. Heine. 1975. “Hysteretic dampers for earthquake resistant structures.” Earthquake Engineering and Structural Dynamics; 3:287–296. https://doi.org/10.1002/eqe.4290030307.
3. Tsampras, G. 2016. “Force-Limiting Deformable Floor Diaphragm Connection for Earthquake Resistant Buildings,” PhD Dissertation, Lehigh University, Bethlehem, PA, USA
4. 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.
5. Tsampras, G., R. Sause, R.B. Fleischman, J.I. Restrepo. 2017. “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, 46(8): 1287–1305. https://doi.org/10.1002/eqe.2856.
6. Tsampras, G., R. Sause, R.B. Fleischman, J.I. Restrepo. 2018. “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; 47(4): 1032–1053. https://doi.org/10.1002/eqe.3004.
7. Zhang, Z., R.B. Fleischman, J.I. Restrepo, G. Guerrini, A. Nema, D. Zhang, U. Shakya, G. Tsampras, R. Sause. 2018. “Shake-table test performance of an inertial force-limiting floor anchorage system.” Earthquake Engineering & Structural Dynamics, 47(10): 1987–2011. https://doi.org/10.1002/eqe.3047.

Force-Based Design for Force-Limiting Connections

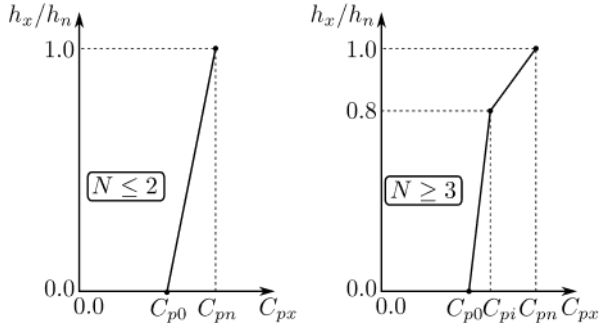
- A force-based method has been developed based on the alternative design provisions for floor diaphragms per ASCE/SEI 7-22 Section 12.10.3.



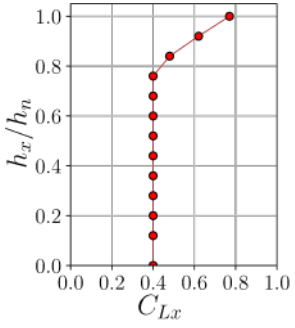


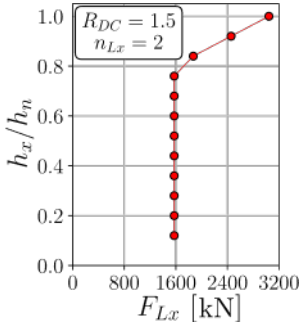


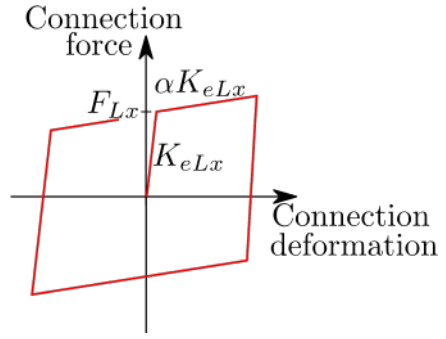
$$F_{px} = \frac{C_{px}}{R_s} w_{px}$$



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





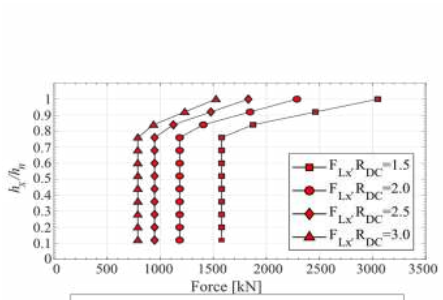


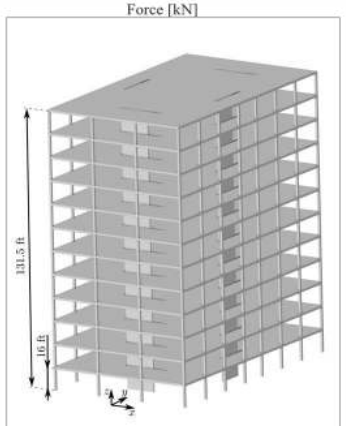
Alternative floor diaphragm seismic design provisions

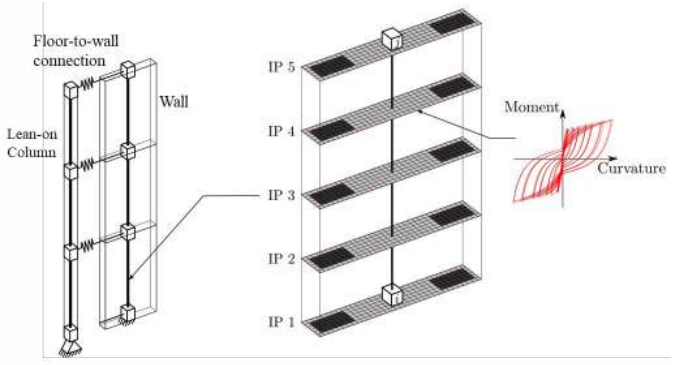
1. ASCE/SEI 7-22 2021. "Minimum design loads and associated criteria for buildings and other structures." American Society of Civil Engineers. https://doi.org/10.1061/9780784415788.
2. Tsampras, G. 2016. "Force-Limiting Deformable Floor Diaphragm Connection for Earthquake Resistant Buildings," PhD Dissertation, Lehigh University, Bethlehem, PA, USA,
3. 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.

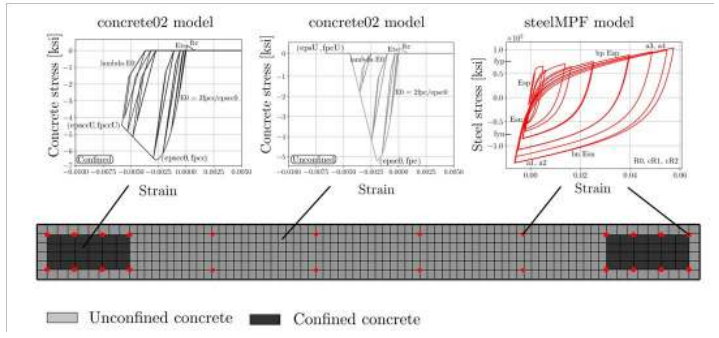
Application of force-based design on RC Wall Buildings

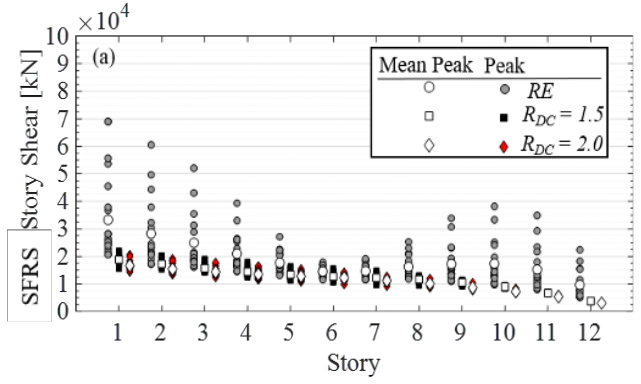
- Reduction in the peak higher-mode shear dominant acceleration and force responses and their dispersion due to ground motion-to-ground motion variability.
- R_{DC} controls the distribution of the ductility demand on the connections. As a result, the global engineering demand parameters can be modified.

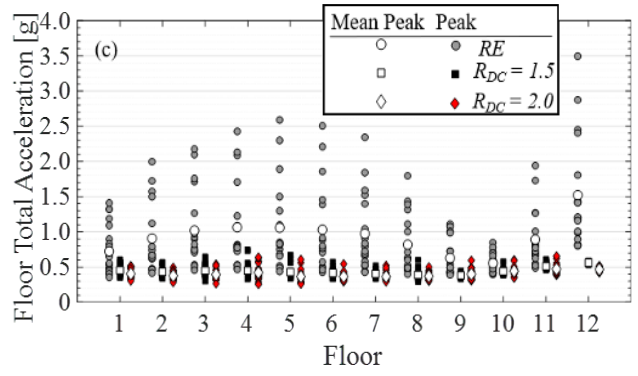


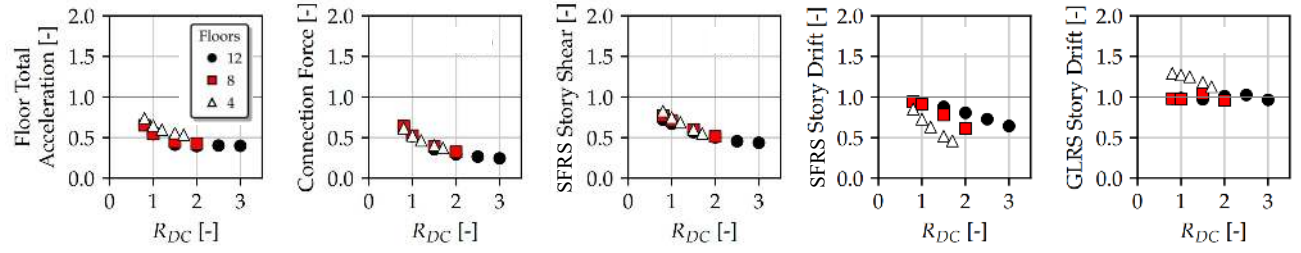








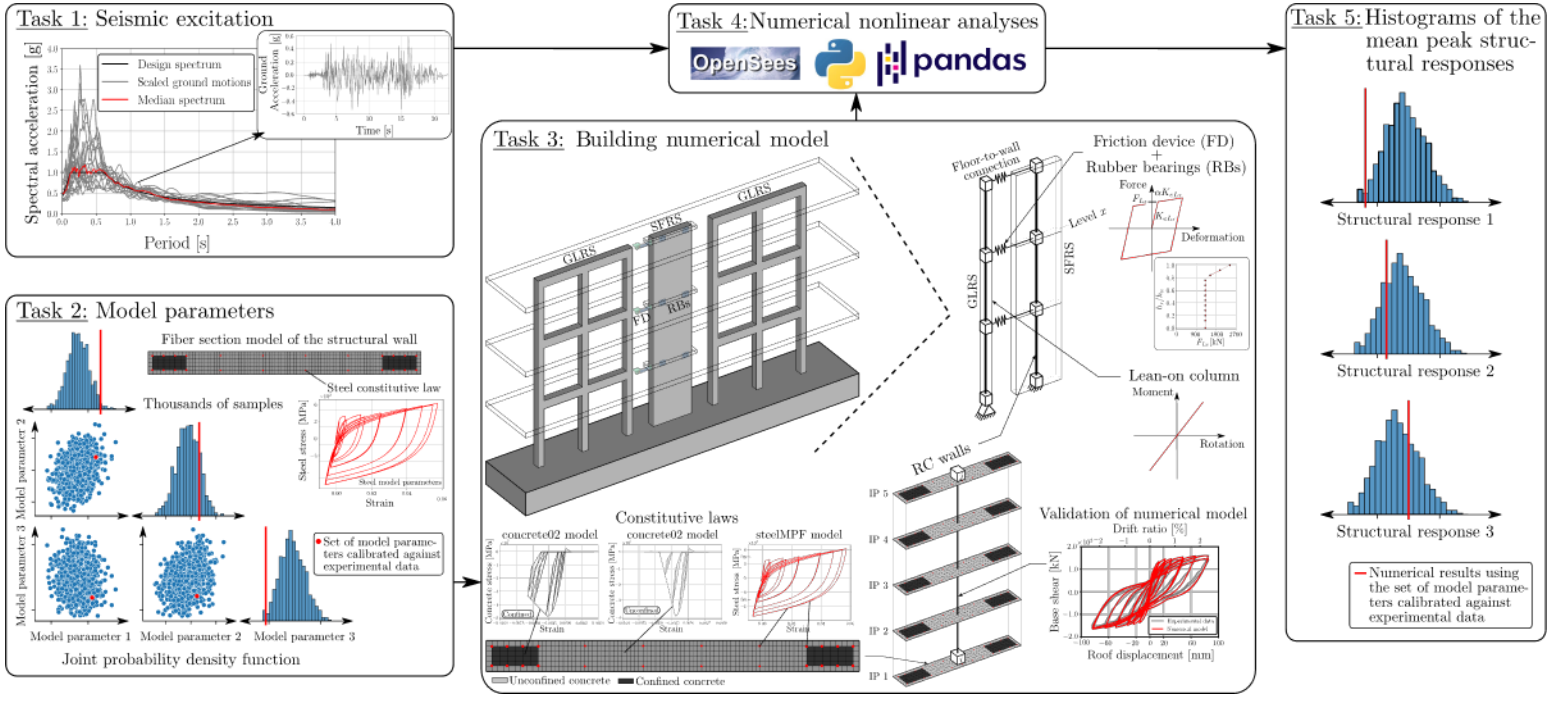


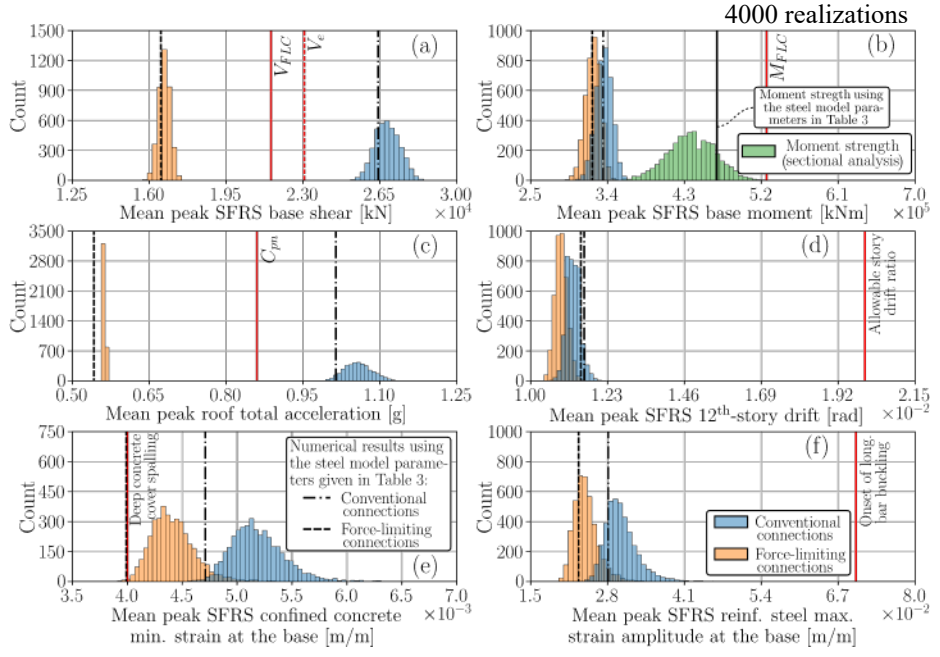


1. Tsampras, G., R. Sause, D. Zhang, R.B. Fleischman, J.I. Restrepo, D. Mar, J. Maffei. 2016, Development of deformable connection for earthquake-resistant buildings to reduce floor accelerations and force responses, Earthquake Engineering & Structural Dynamics, 45 (9), 1473–1494, https://doi.org/10.1002/eqe.2718.
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.

Uncertainty Propagation Analysis

- Reduction in the dispersion of the distribution of the mean peak acceleration and force responses potentially induced by the uncertainty in the material properties of the longitudinal reinforcing steel bars.

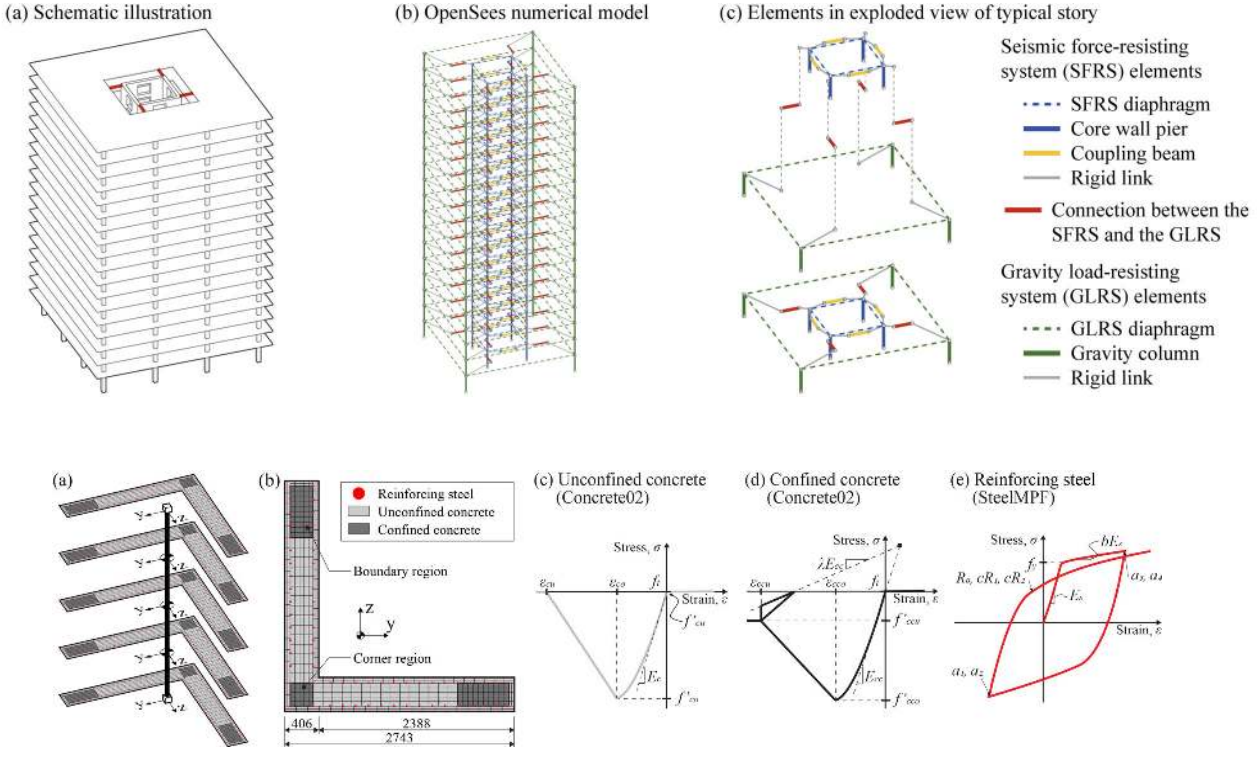


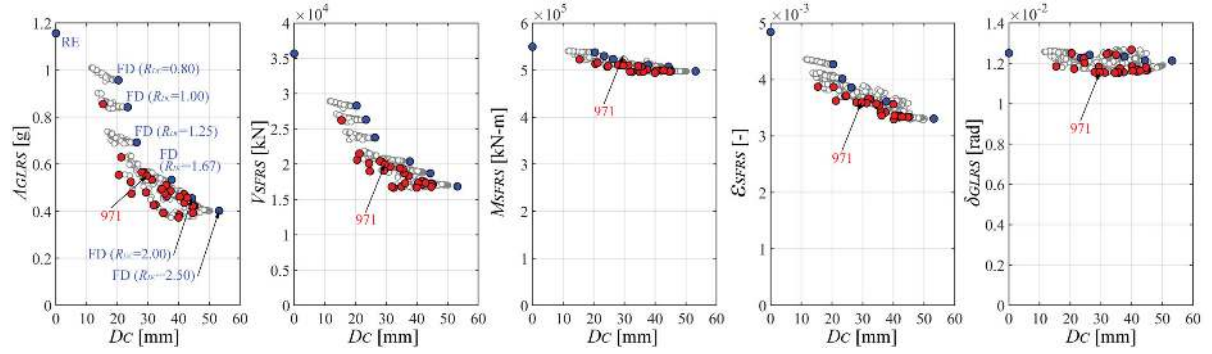


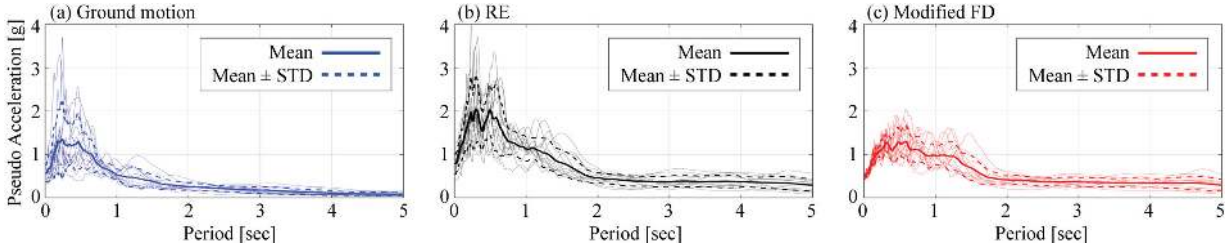
Mayorga, C.F., G. Tsampras. 2024. "Reinforced concrete wall buildings with force-limiting connections: Modeling effects and uncertainty propagation." Earthquake Engineering & Structural Dynamics, 53(4):1465-1491. https://doi.org/10.1002/eqe.4073.

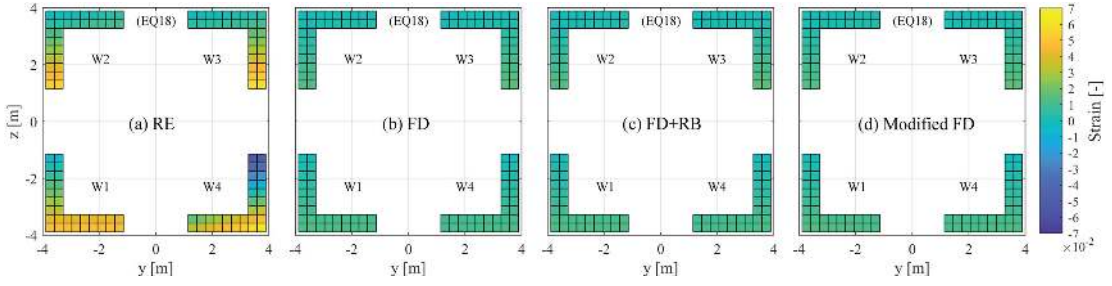
RC Core Wall Buildings

- 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.





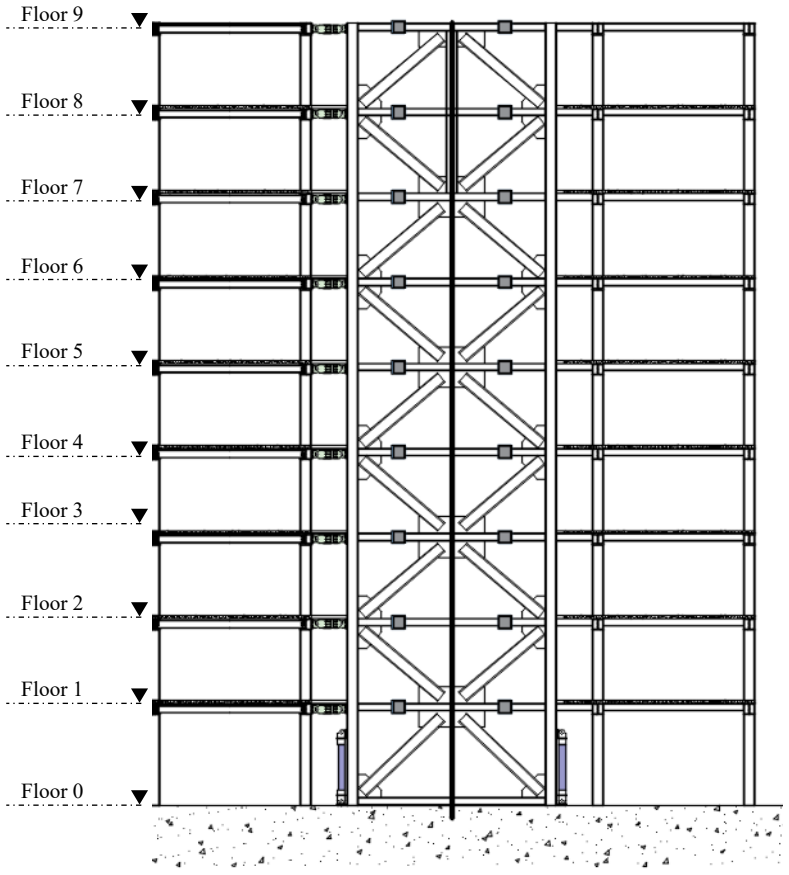


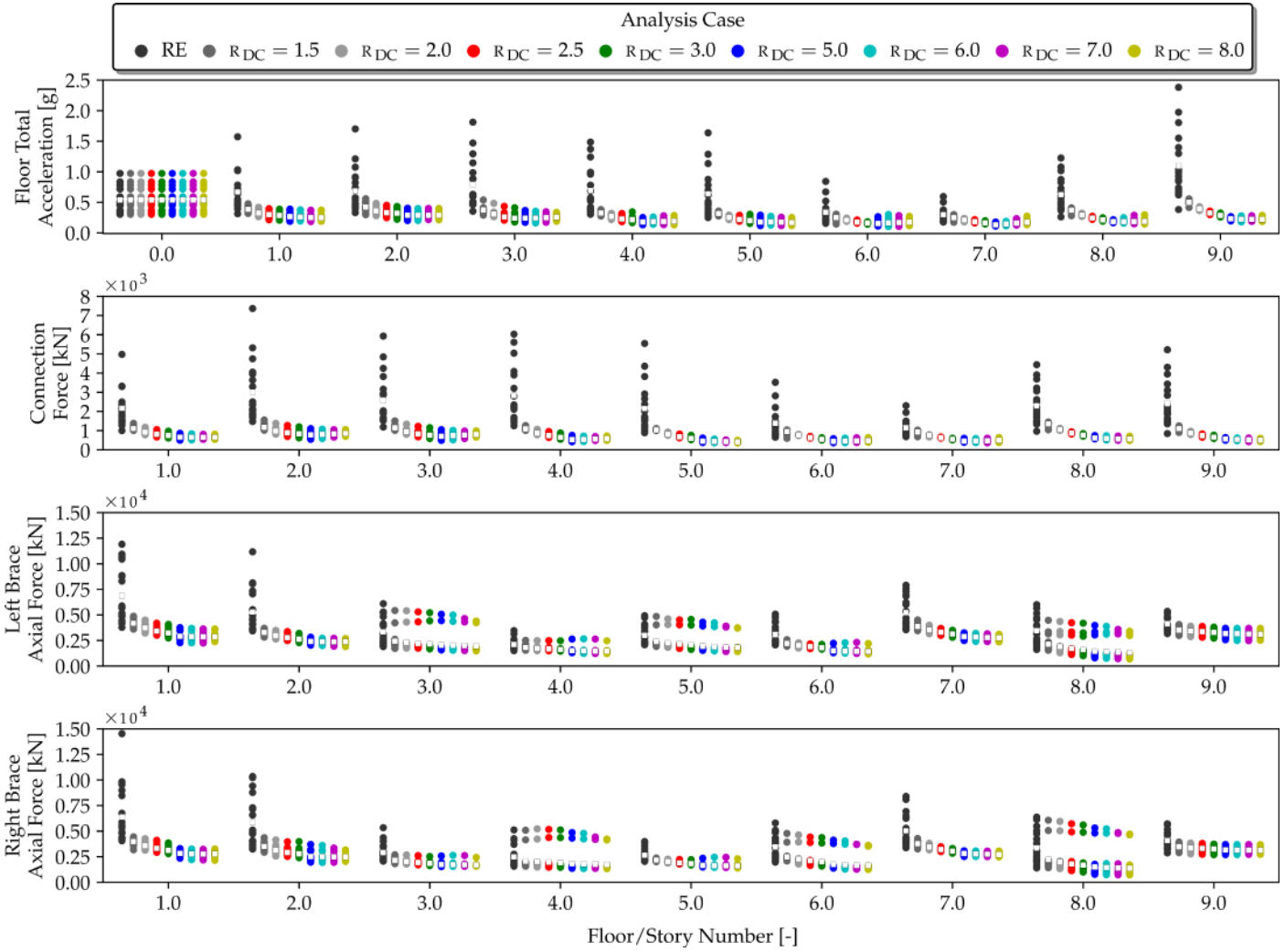


Lee, K., G. Tsampras, C.F. Mayorga. 2025. "Reinforced Concrete Core Wall Buildings with Modified Friction-Based Force-Limiting Connections: Connection Design Considerations and Three-Dimensional Response to Bidirectional Ground Motions." Journal of Structural Engineering, 151(2): 04024203. https://doi.org/10.1061/JSENDH.STENG-13609.

Self-Centering Concentrically Braced Frame Buildings

- Reduction in mean peak responses and their dispersion.





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.

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 achieving resilience-based design objectives.

- Using force-limiting connections is a practical solution for designing buildings with accelerated post-earthquake functional recovery.

- Buildings with force-limiting connections have the potential to contribute to the national earthquake resilience.

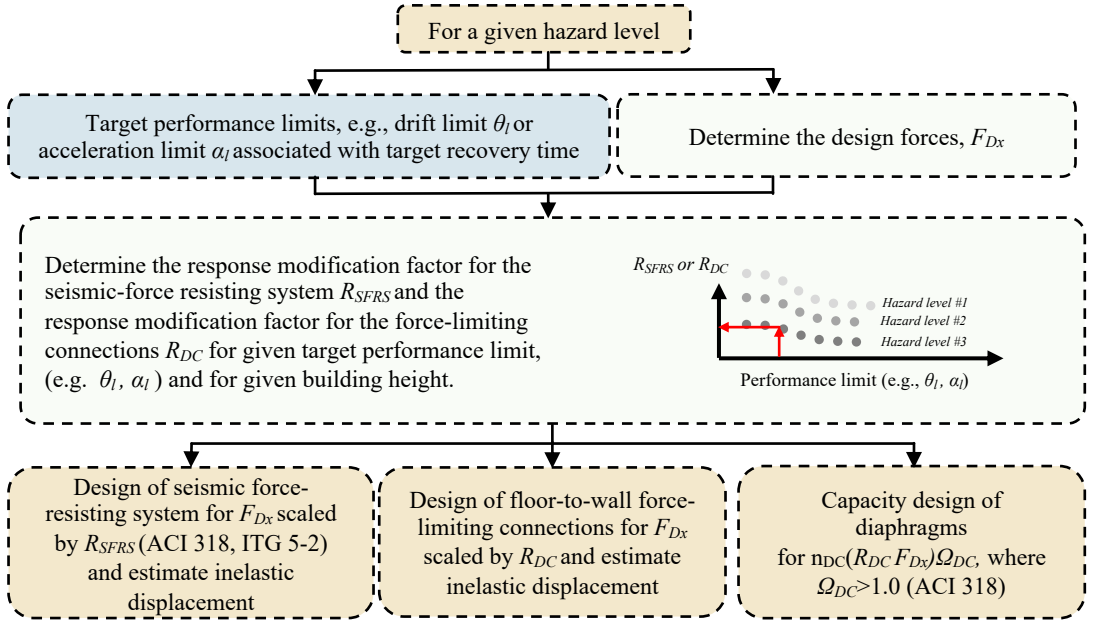
There is no simple and practical design method that provides the means for the holistic design of buildings with force-limiting connections for target performance and post-earthquake functional recovery levels.

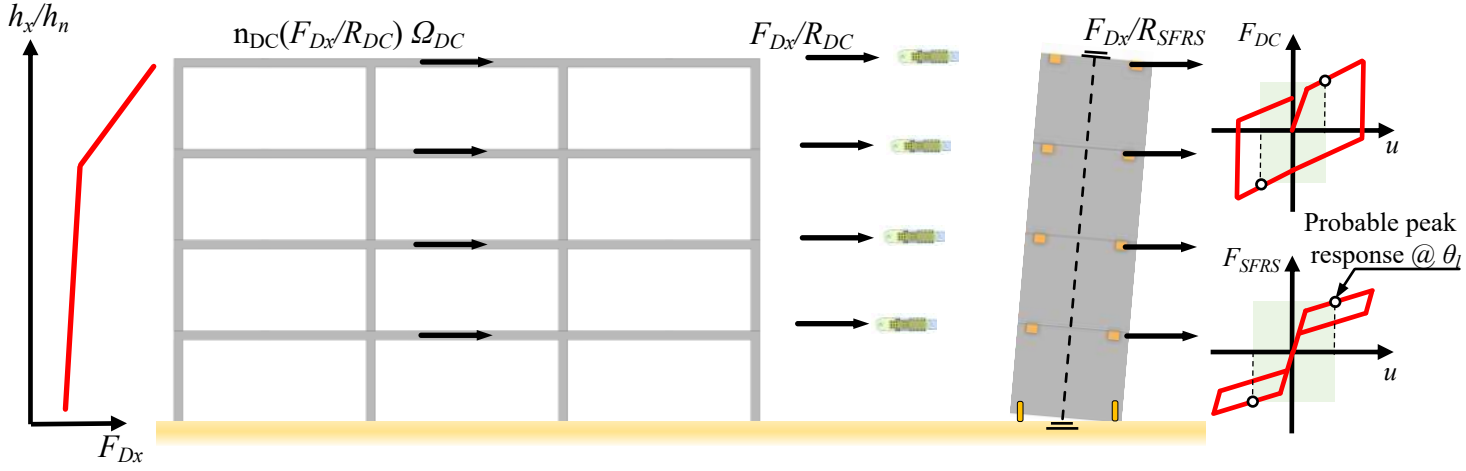
Resilience-Based Design of Buildings with Accelerated Post-earthquake Functional Recovery

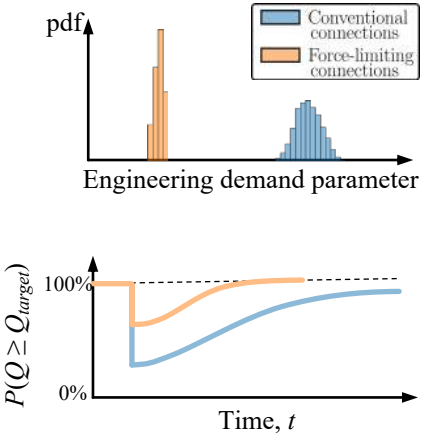
Aims of Research

Our research will:

1. Determine $\boldsymbol{F_{Dx}}$.
2. Determine $\boldsymbol{R_{SFRS}}$ and $\boldsymbol{R_{DC}}$.
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 Georgios and Bocchini Paolo. 2020 & 2022. NSF | NIST DRRG Proposals.

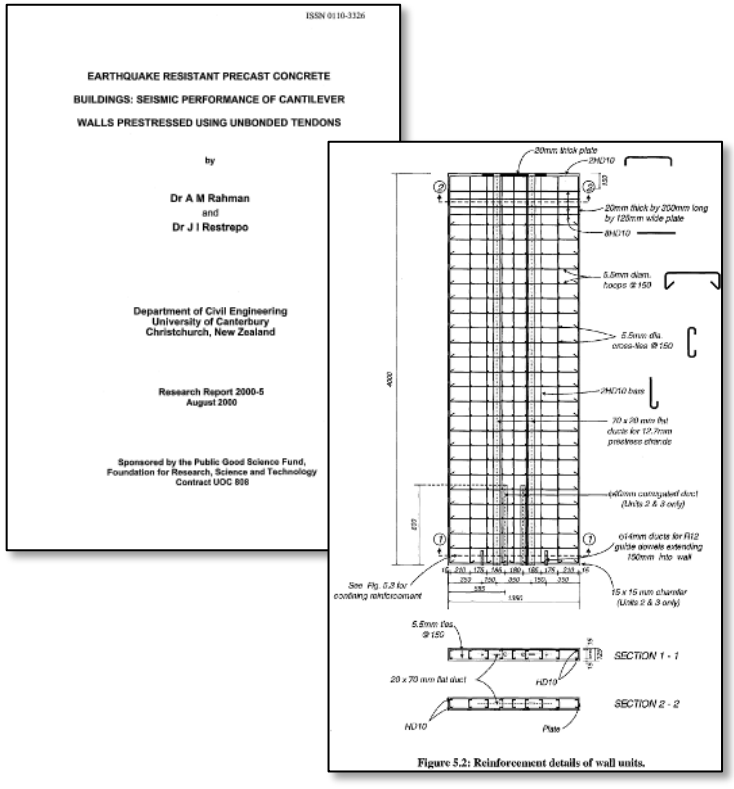
Current Tasks - Definition of Building Archetypes

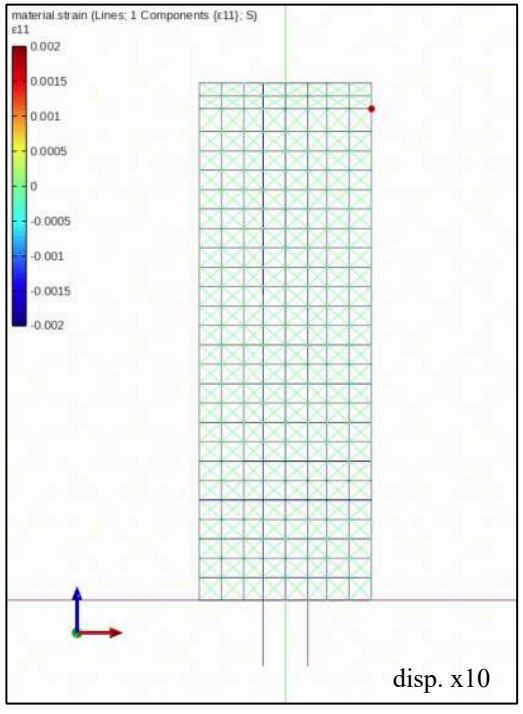
- 68 Building archetypes - Definition based on FEMA P-695 for buildings with rocking system and force-limiting connections.
- The building archetypes are defined considering:
  - Concrete and steel buildings because they are the most frequent materials used in the construction of mid-to-high-rise buildings.
  - 3, 6, 9, 12, 18, 24, and 30 stories to cover a wide range of buildings with different dynamic properties affecting their seismic response under seismic loads.
  - Perimeter and core distributions of the SFRS to include two building types that are typically used in the construction of low-to-mid-rise buildings. They are expected to behave differently under seismic loads, specially in terms of their torsional response.
  - Residential, office, medical, data center, mixed, and variable uses to cover a wide range of building uses encountered in our community. This is a key variable to assess the resilience of the building archetypes.
    - Residential and office buildings are considered because they are two of the most frequent building uses in our community.
    - Medical and data center buildings are considered because of their importance of these buildings to our society, especially after a natural disaster occurs.
    - Mixed- and variable-use buildings are considered to show the flexibility in design that can be provided by including force-limiting connections installed strategically in the seismic load path.

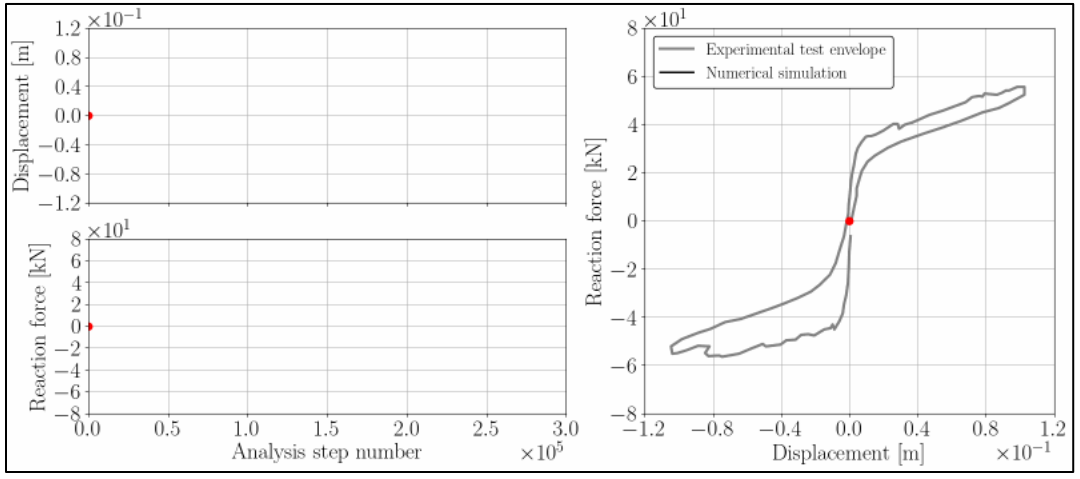
FEMA P695. 2009. Quantification of Building Seismic Performance Factors.

Current Tasks - Development of Building Numerical Models

- Calibration of rocking wall component model.



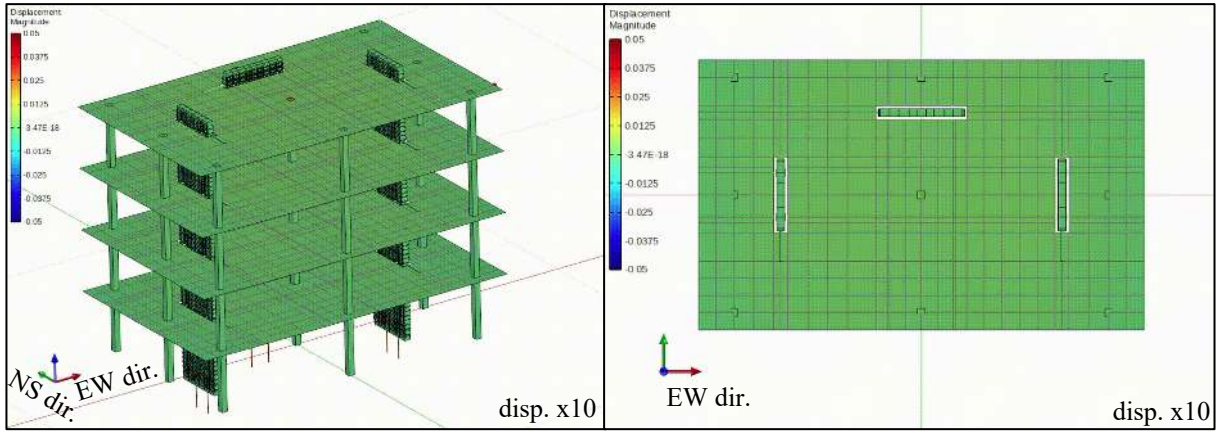


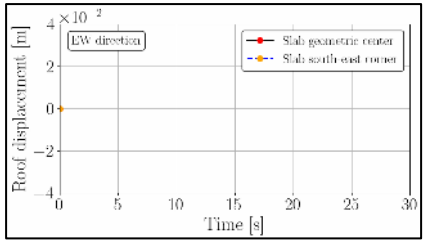


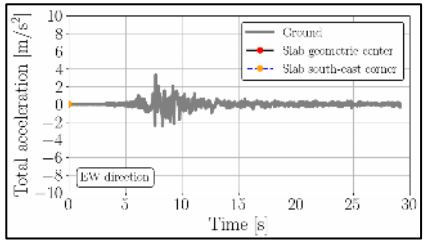
1. Lu, Y., M. Panagiotou, I. Koutromanos. 2016, "Three-dimensional beam-truss model for reinforced concrete walls and slabs – part 1: modeling approach, validation, and parametric study for individual reinforced concrete walls," Earthquake Engineering & Structural Dynamics, 45, (9): 1495–1513. https://doi.org/10.1002/eqe.2719.
2. McKenna, F., M.H. Scott, G.L. Fenves. 2010, "Nonlinear Finite-Element Analysis Software Architecture Using Object Composition," Journal of Computing in Civil Engineering, 24, (1): 95–107. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000002.
3. Petracca, M., F. Candeloro, G. Camata. 2017. "STKO user manual". ASDEA Software Technology, Pescara Italy
4. Rahman, A. M., J.I. Restrepo-Posada. 2000. "Earthquake resistant precast concrete buildings : seismic performance of cantilever walls prestressed using unbonded tendons." Department of Civil Engineering University of Canterbury Christchurch, New Zealand . Technical report

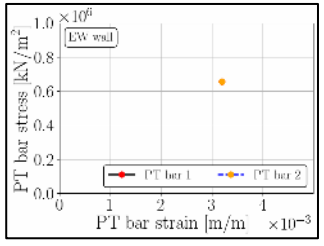
Current Tasks - Development of Building Numerical Models (cont'd)

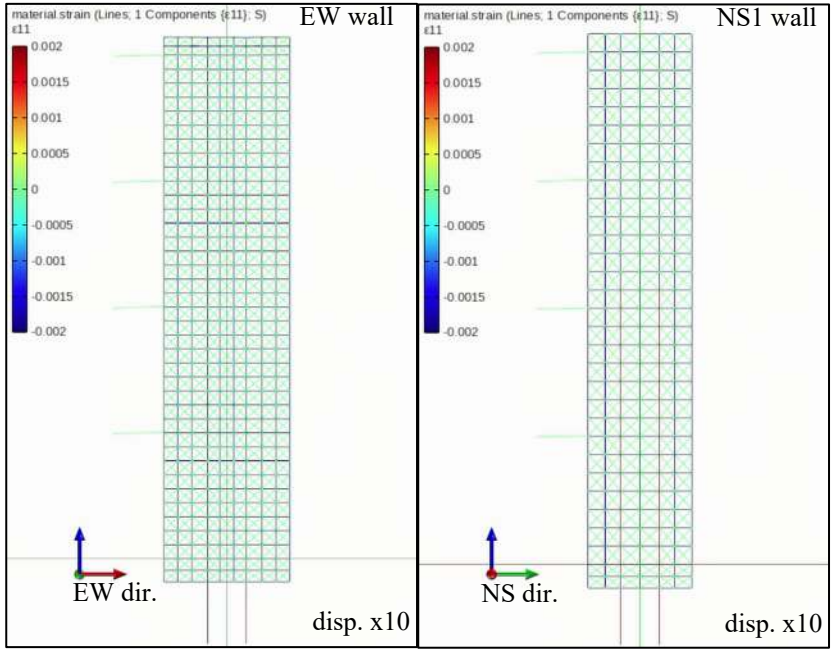
- Calibration of rocking wall building system model with force-limiting connections.

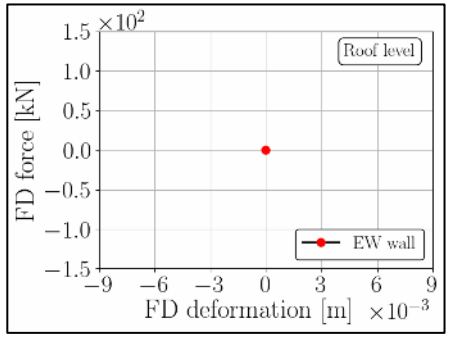


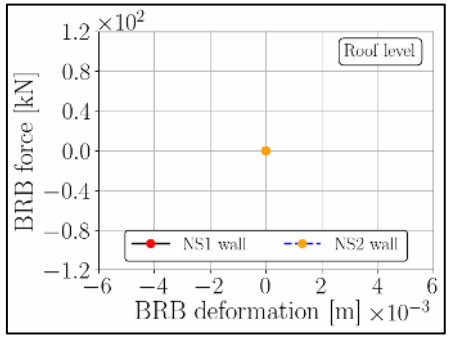












1. McKenna, F., M.H. Scott, G.L. Fenves. 2010, "Nonlinear Finite-Element Analysis Software Architecture Using Object Composition," Journal of Computing in Civil Engineering, 24, (1): 95–107. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000002.
2. Nema, A. 2018. "Development of Low Seismic Damage Structural Systems," PhD Dissertation, UC San Diego.
3. Petracca, M., F. Candeloro, G. Camata. 2017. "STKO user manual". ASDEA Software Technology, Pescara Italy.
4. Zhang, Z., R.B. Fleischman, J.I. Restrepo, G. Guerrini, A. Nema, D. Zhang, U. Shakya, G. Tsampras, R. Sause. 2018. "Shake-table test performance of an inertial force-limiting floor anchorage system." Earthquake Engineering & Structural Dynamics, 47(10): 1987–2011. https://doi.org/10.1002/eqe.3047.

18th U.S.-Japan-New Zealand
Workshop on the Improvement of Structural Engineering and Resilience

Overview of a Project on Resilience-Based Design of Buildings with Accelerated Post-earthquake Functional Recovery

Georgios Tsampras, gtsampras@ucsd.edu
Paolo Bocchini, paolo.bocchini@lehigh.edu
Franco Mayorga, cfmayorg@ucsd.edu
Sena Mursel, sem419@lehigh.edu

Thank you!

December 2, 2024
San Diego, CA

http://tsampras.ucsd.edu
http://www.paolobocchini.com