12th National Conference on Earthquake Engineering
Salt Lake City, Utah

Practical force-limiting deformable connections in buildings with rocking base mechanism and limited higher-mode responses

Georgios Tsampras[1], Richard Sause[2], Robert B. Fleischman[3], José I. Restrepo[4], Arpit Nema[5], Zhi Zhang[6]

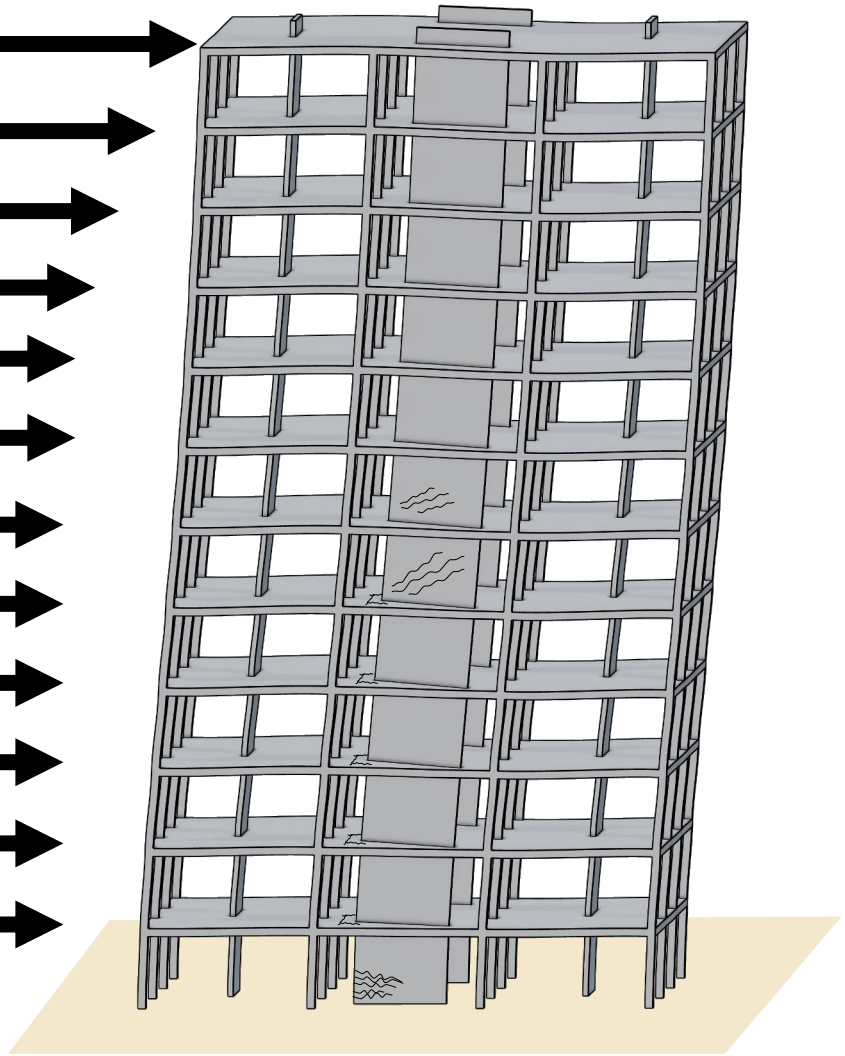
[1]Assistant Professor, University of California San Diego
[2]Professor, Lehigh University
[3]Professor, University of Arizona
[4]Professor, University of California San Diego
[5]Postdoctoral Researcher, University of California Berkeley
[6]Senior Engineer, Thornton Tomasetti

June 29, 2022

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Buildings with flexural yielding base mechanism

Seismic induced horizontal forces

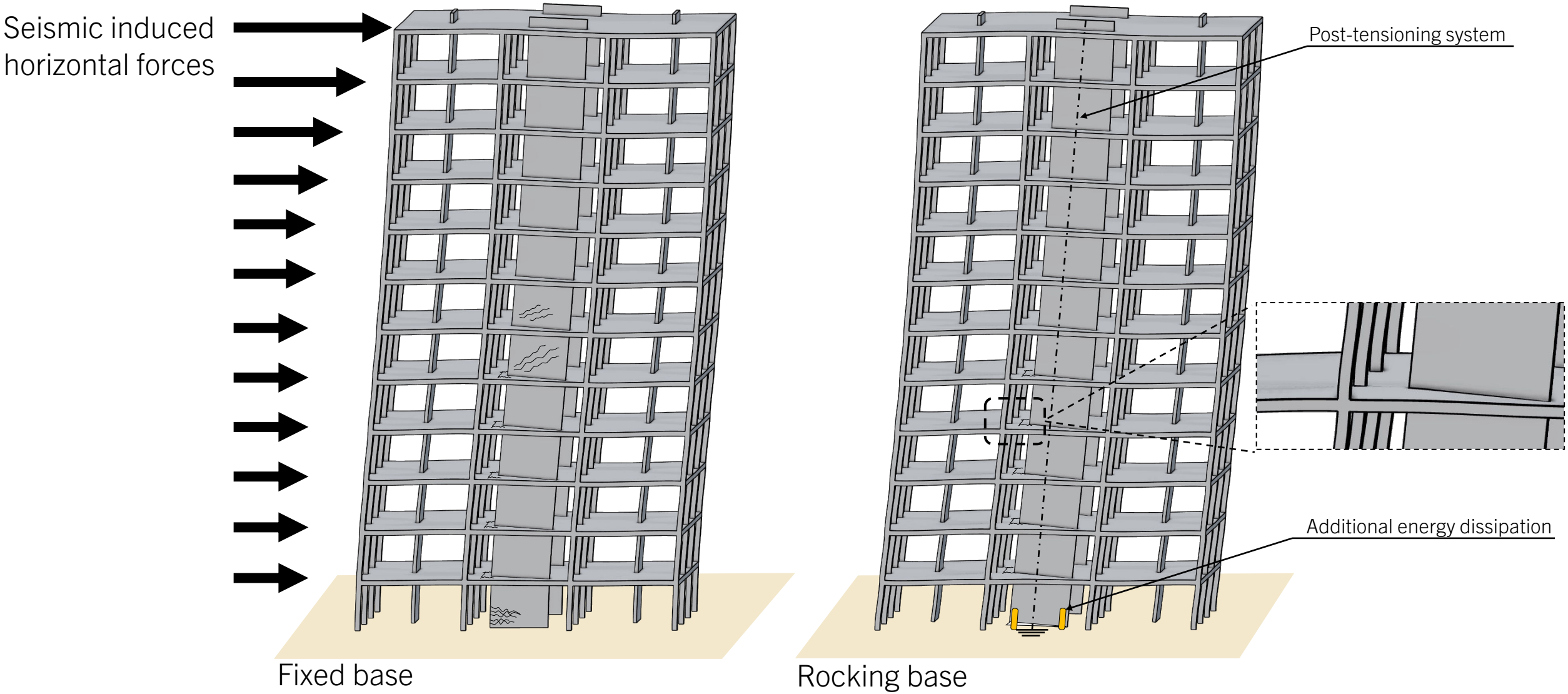


Fixed base

Core wall building construction at UC San Diego



Buildings with rocking base mechanism

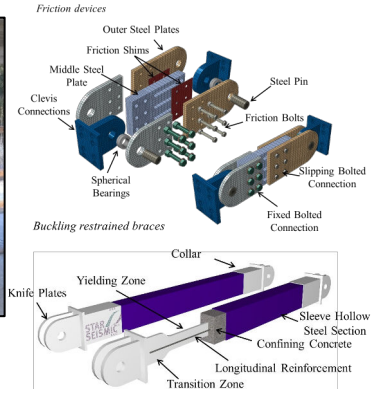


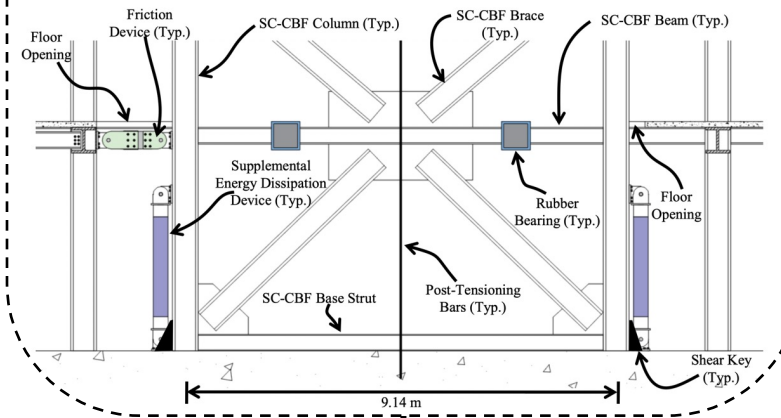
Practical force-limiting deformable connections in buildings structures

Connections between structural components

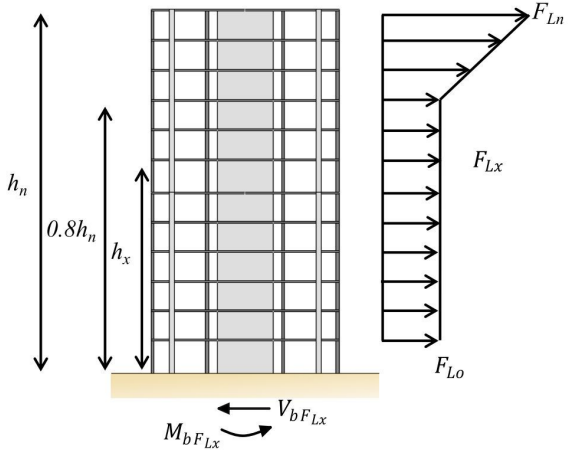


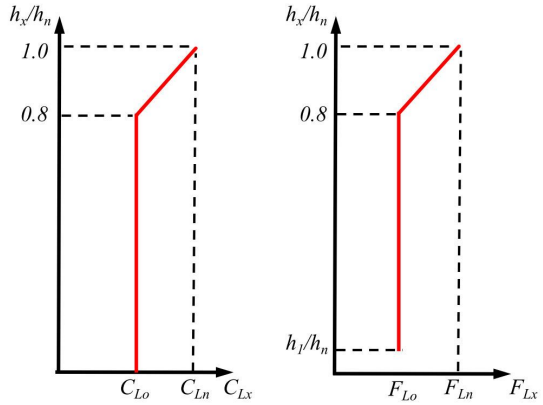
NHERI experimental facility at UCSD



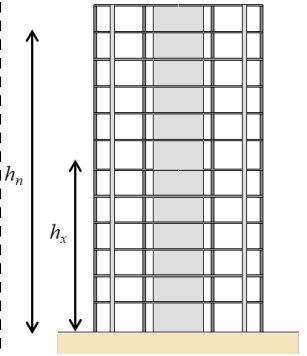


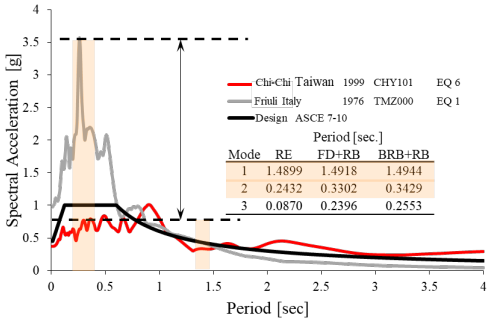
Design of connections

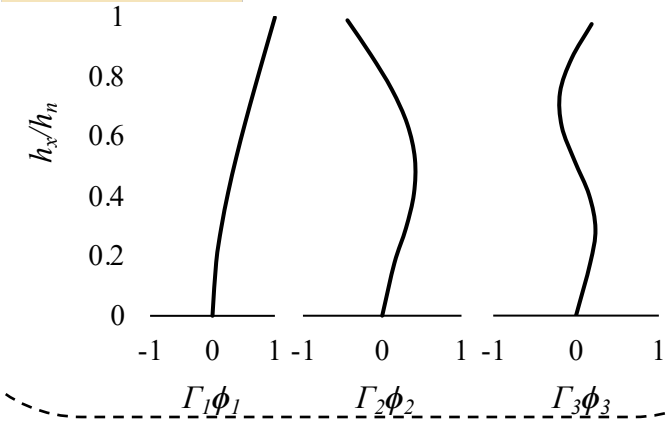




Higher mode effects, ground motion characteristics and variability of seismic responses







Engineering education

UC San Diego
JACOBS SCHOOL OF ENGINEERING
Computer Science and Engineering

NEESR: Inertial Force-limiting Floor Anchorage Systems For Seismic Resistant Building Structures (2011-2016)

- National Science Foundation (Award No. CMMI-1135033)
- George E. Brown, Jr. Network for Earthquake Engineering Simulation Research (NEESR) program (Award No. CMS-0402490)
- PI Robert Fleischman
- Co-PI José I. Restrepo
- Co-PI and advisor Richard Sause
- Industry experts Joe Maffei, David Mar
- Dichuan Zhang (Post-Doc), Zhi Zhang (GSR), Ulina Shakya (GSR), Arpit Nema (GSR), Gabriele Guerrini (GSR), Georgios Tsampras (GSR)
- NEES@UCSD staff
- NEES@Lehigh staff and ATLSS Center staff

NEES @ UCSD



NEES @ Lehigh



Force-Limiting Connection for Earthquake-Resistant Buildings

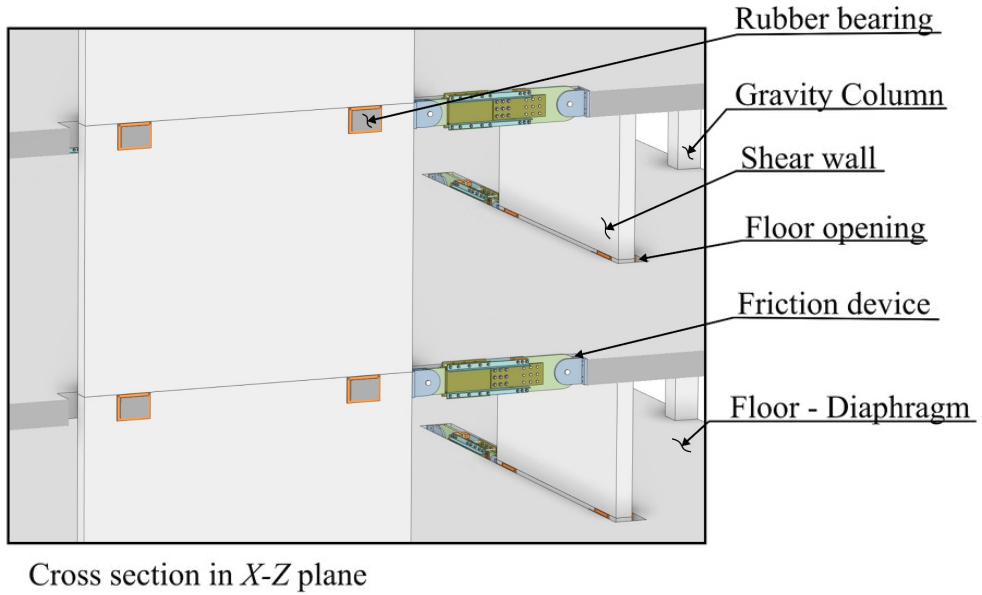
Openings in the Floor Systems
Force-limiting connections between Floor – LFRS with two types of components:

1. Limited-Strength Hysteretic components
2. Bearing Components

<u>Objectives</u>

- Limit the transferred forces by using deformable connections
- Reduce the floor accelerations and force responses



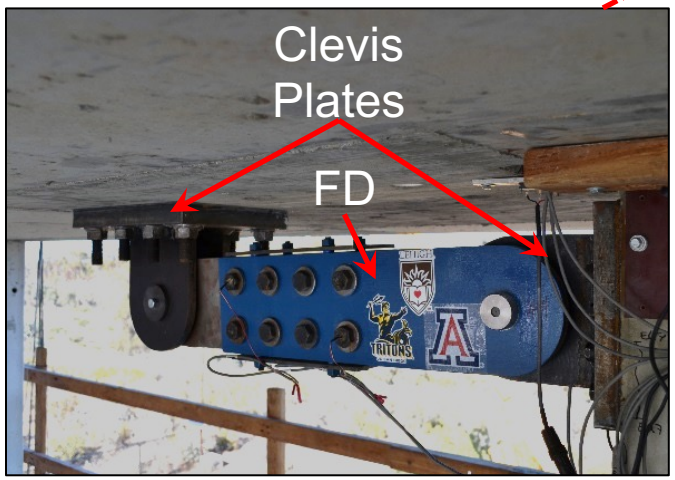


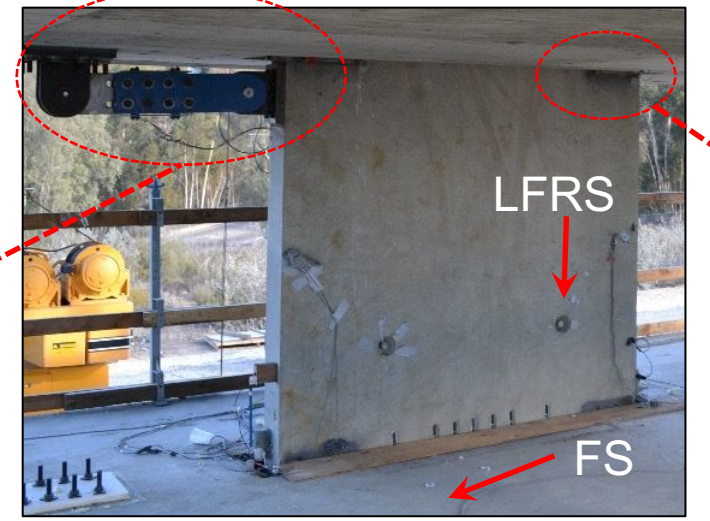
Cross section in *X-Z* plane

1. Zhang, D, R Fleischman, J Restrepo, R Sause, J Maffei, D Mar, and G Monti. "Development of a Floor Inertial Force Limiting Anchorage System Building Seismic Response." In 10th U.S. National Conference on Earthquake Engineering, 11. 10th U.S. National Conference on Earthquake Engineering, 2014.
2. Fleischman, Robert, Jose Restrepo, Arpit Nema, Dichuan Zhang, Ulina Shakya, Zhi Zhang, Richard Sause, Georgios Tsampras, and Giorgio Monti. "Inertial Force-Limiting Anchorage System for Seismic Resistant Building Structures." In Structures Congress, 1302–13. Portland, Oregon: Structures Congress, 2015. https://doi.org/10.1061/9780784479117.111.
3. Tsampras, Georgios, Richard Sause, Dichuan Zhang, Robert B. Fleischman, Jose I. Restrepo, David Mar, and Joseph Maffei. "Development of Deformable Connection for Earthquake-Resistant Buildings to Reduce Floor Accelerations and Force Responses." Earthquake Engineering & Structural Dynamics 45, no. 9 (July 25, 2016): 1473–94. https://doi.org/10.1002/eqe.2718.
4. Tsampras, Georgios, Richard Sause, Robert B. Fleischman, and Jose I. Restrepo. "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, no. 8 (July 10, 2017): 1287–1305. https://doi.org/10.1002/eqe.2856.
5. Tsampras Georgios, Richard Sause, Robert B. Fleischman, and José I. Restrepo. "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, no. 4 (April 10, 2018): 1032–53. https://doi.org/10.1002/eqe.3004.
6. Zhang, Z. el al. (2018) Shake table test performance of an inertial force-limiting floor anchorage system, Earthquake Engineering & Structural Dynamics, 47 (10), 1987-2011, doi: 10.1002/eqe.3047

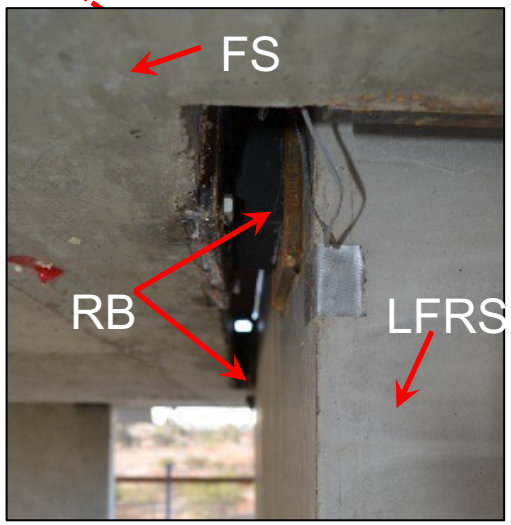
Example Installation of Force-Limiting Connection

Half-Scale 4-story Precast Rocking Shear Wall Structure at NEES @ UCSD



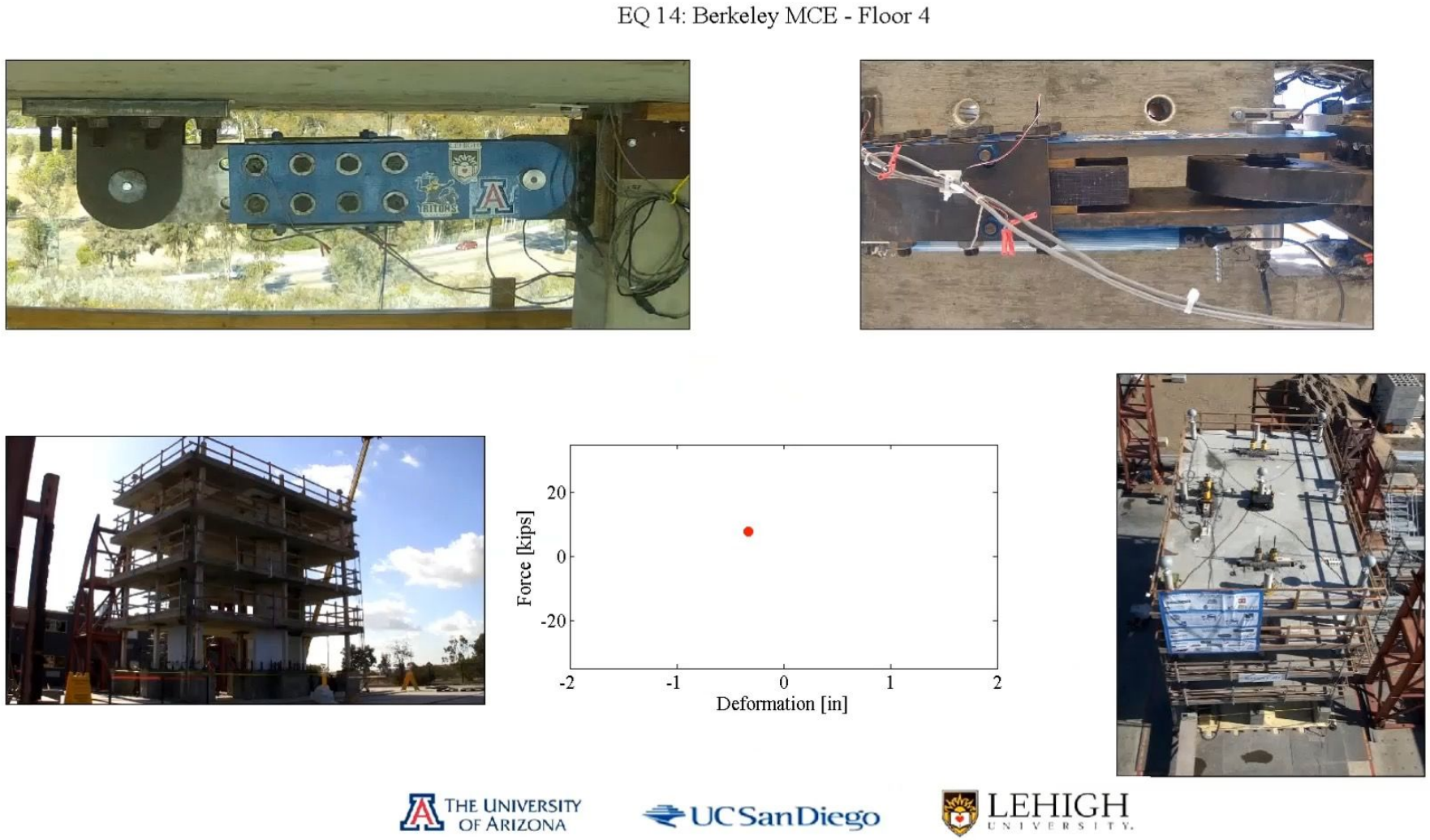






Zhi Zhang, Robert B. Fleischman, José I. Restrepo, Gabrielle Guerrini, Arpit Nema, Dichuan Zhang, Ulina Shakya, Georgios Tsampras, Richard Sause (2018), Shake table test performance of an inertial force-limiting floor anchorage system, Earthquake Engineering & Structural Dynamics, 47 (10), 1987-2011, doi: 10.1002/eqe.3047

Example Installation at NEES @ UCSD



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Georgios Tsampras, Richard Sause, Robert B. Fleischman, José I. Restrepo (2017) 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, doi: 10.1002/eqe.3004

Shake table test at NEES @ UCSD

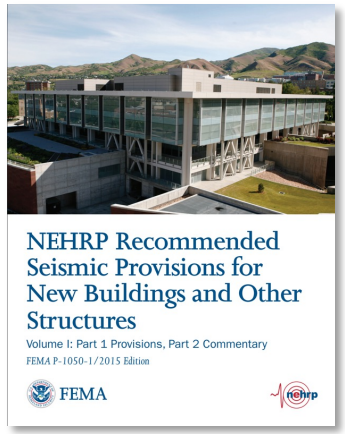
Force-limiting connections

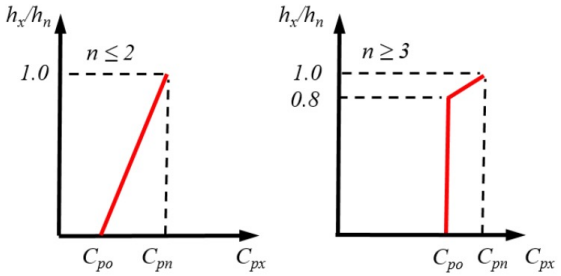
Rigid-Elastic connections



Zhi Zhang, Robert B. Fleischman, José I. Restrepo, Gabrielle Guerrini, Arpit Nema, Dichuan Zhang, Ulina Shakya, Georgios Tsampras, Richard Sause (2018), Shake table test performance of an inertial force-limiting floor anchorage system, Earthquake Engineering & Structural Dynamics, 47 (10), 1987-2011, doi: 10.1002/eqe.3047

Force-Based Design Method for Force-Limiting Connections





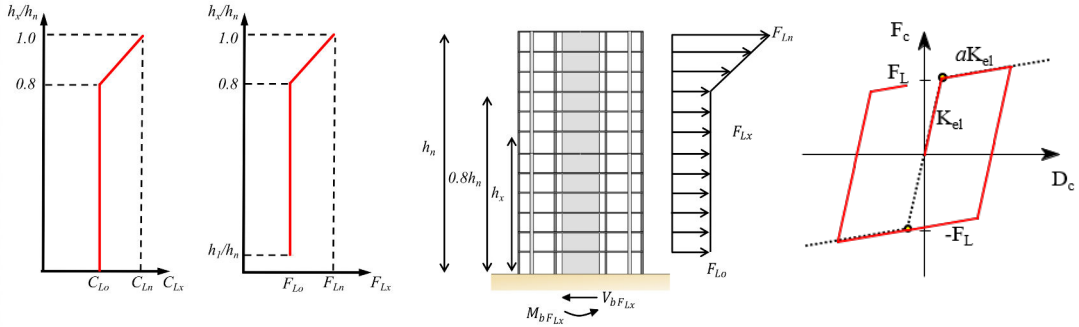
$$F_{px} = \frac{C_{px}}{R_s} w_{px} \geq 0.2 S_{DS} I_e w_{px}$$

$$\Gamma_{m1} = 1 + \frac{z_s}{2}(1 - \frac{1}{n})$$

$$\Gamma_{m2} = 0.9 z_s (1 - \frac{1}{n})^2$$

$$C_{p0} = 0.4 S_{DS} I_e \qquad C_{pn} = \sqrt{(\Gamma_{m1} \Omega_0 C_s)^2 + (\Gamma_{m2} C_{s2})^2} \geq C_{pi}$$

$$C_s = \frac{S_{DS}}{R/I_e} \qquad C_{s2} = \begin{cases} \min\left(\frac{I_e S_{D1}}{0.03(N-1)}, (0.15N + 0.25) I_e S_{DS}, I_e S_{DS}\right) & \text{for } N \geq 2 \\ 0 & \text{for } N = 1 \end{cases}$$



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

$$C_{Ln} = \sqrt{(\Gamma_{m1} C_s)^2 + (\Gamma_{m2} C_{s2})^2}$$

$$C_{L0} = 0.4 S_{DS} I_e$$

$$1.0 \leq \frac{M_{bFLx}}{M_{by}}$$

$$1.0 \leq \sum_{x=1}^{n} \frac{F_{Lx} h_x}{M_{by}}$$

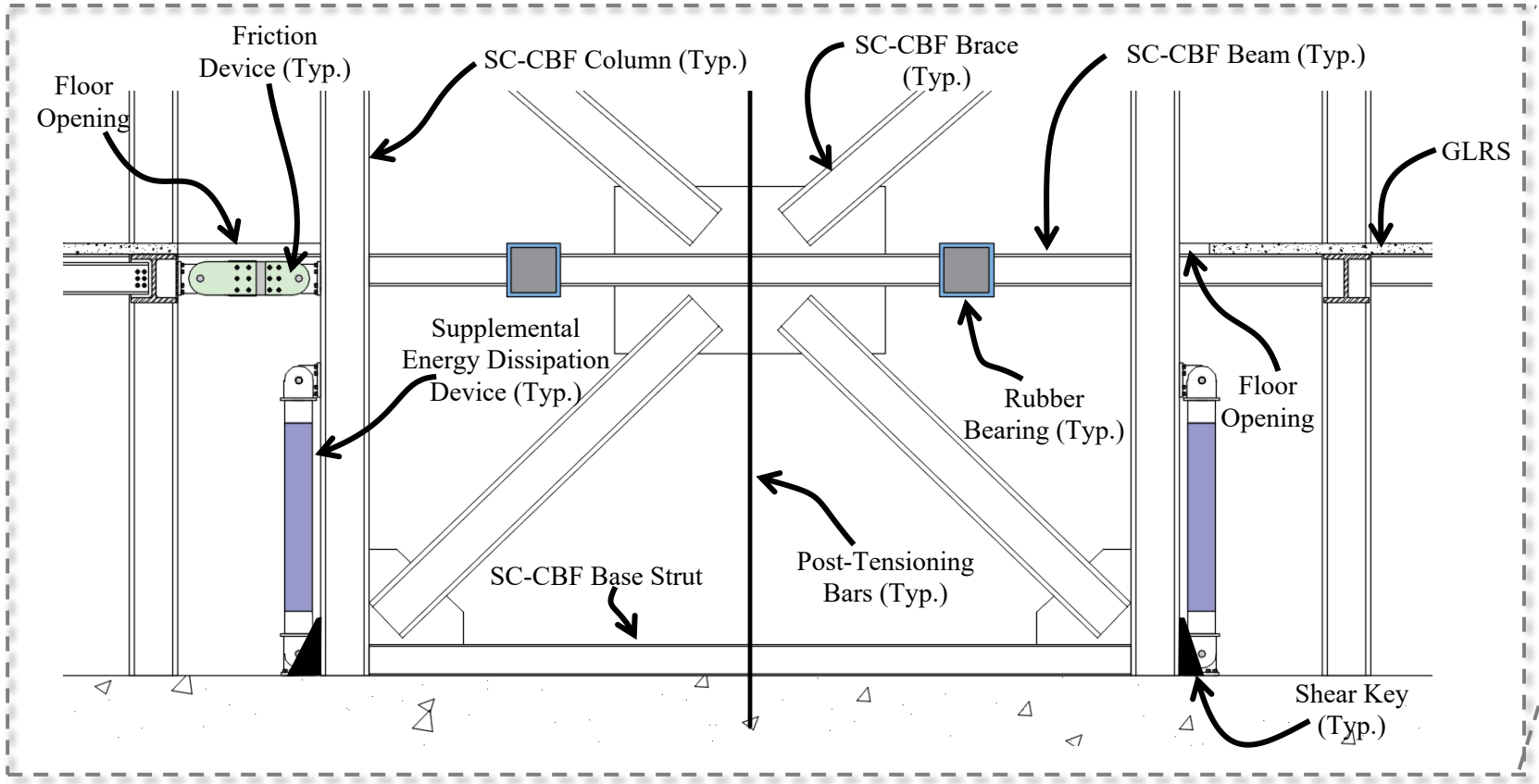
$$1.0 \leq \sum_{x=1}^{n} \frac{\frac{C_{Lx}}{R_{DC}} \frac{w_{px}}{n_{Lx}} h_x}{M_{by}}$$

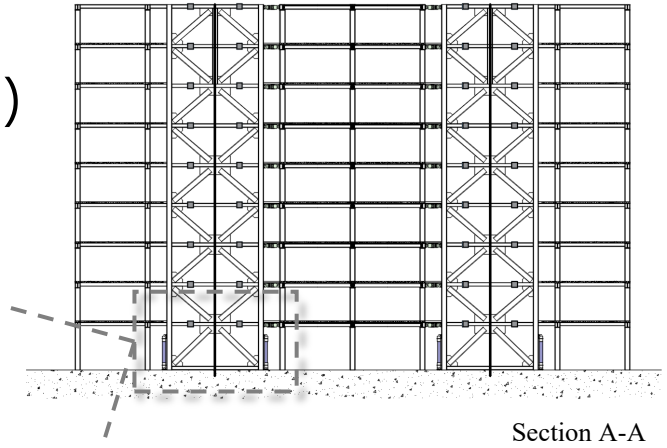
$$R_{DC} \leq \sum_{x=1}^{n} \frac{C_{Lx} \frac{w_{px}}{n_{Lx}} h_x}{M_{by}}$$

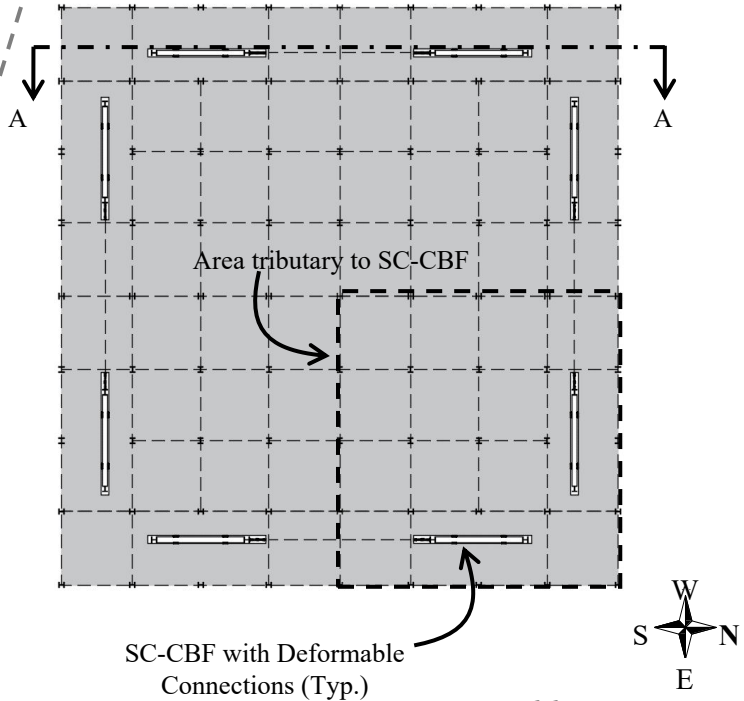
Tsampras, Georgios, Richard Sause, Forthcoming, "Force-Based Design Method for Force-Limiting Deformable Connections in Earthquake-Resistant Buildings." Journal of Structural Engineering, 10.1061/(ASCE)ST.1943-541X.0003456

Kyoungyeon Lee, Kaixin Chen, Georgios Tsampras, (2022) Seismic Response of Core Wall Building with Friction-Based Force-Limiting Connections, 3rd European Conference on Earthquake Engineering & Seismology, Bucharest, Romania (Accepted)

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

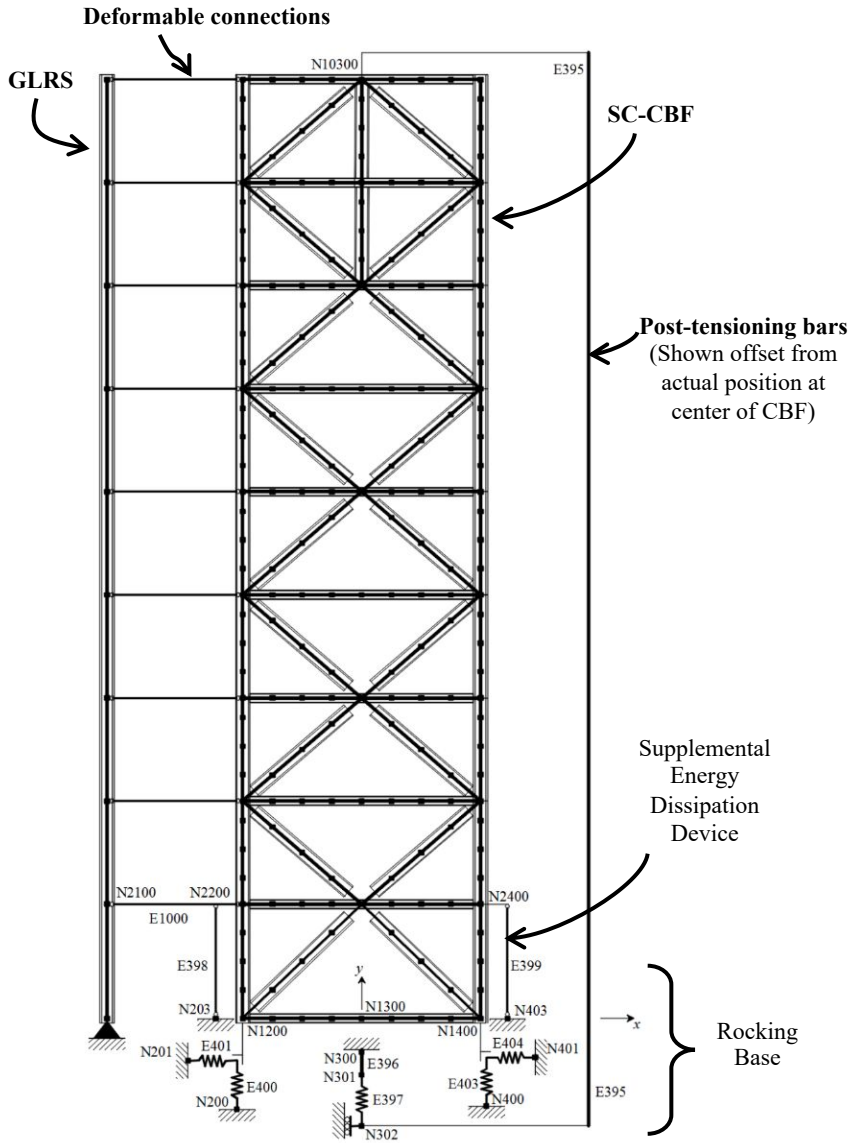




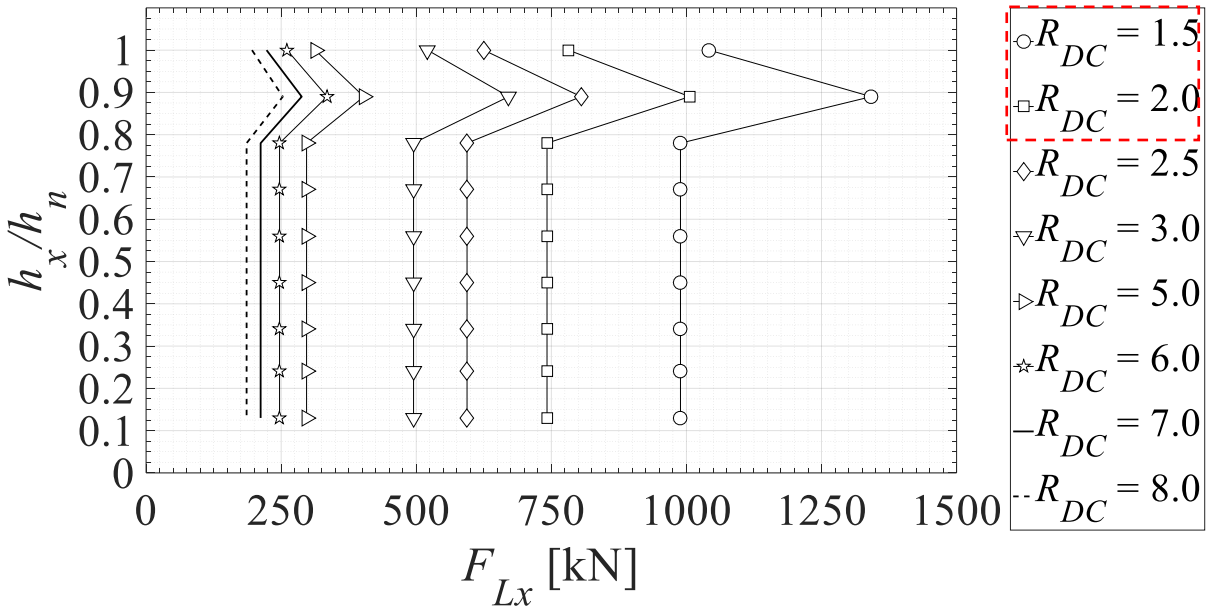


Georgios Tsampras (2016), Force-Limiting Deformable Floor Diaphragm Connection for Earthquake Resistant Buildings, PhD Dissertation, Lehigh University, Bethlehem, PA, USA, DOI: https://preserve.lib.lehigh.edu/islandora/object/preserve%3Abp-10369972

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



$$\frac{Seismic\ Mass\ at\ floor\ 9}{Seismic\ Mass\ at\ floor\ 8} = 0.6$$

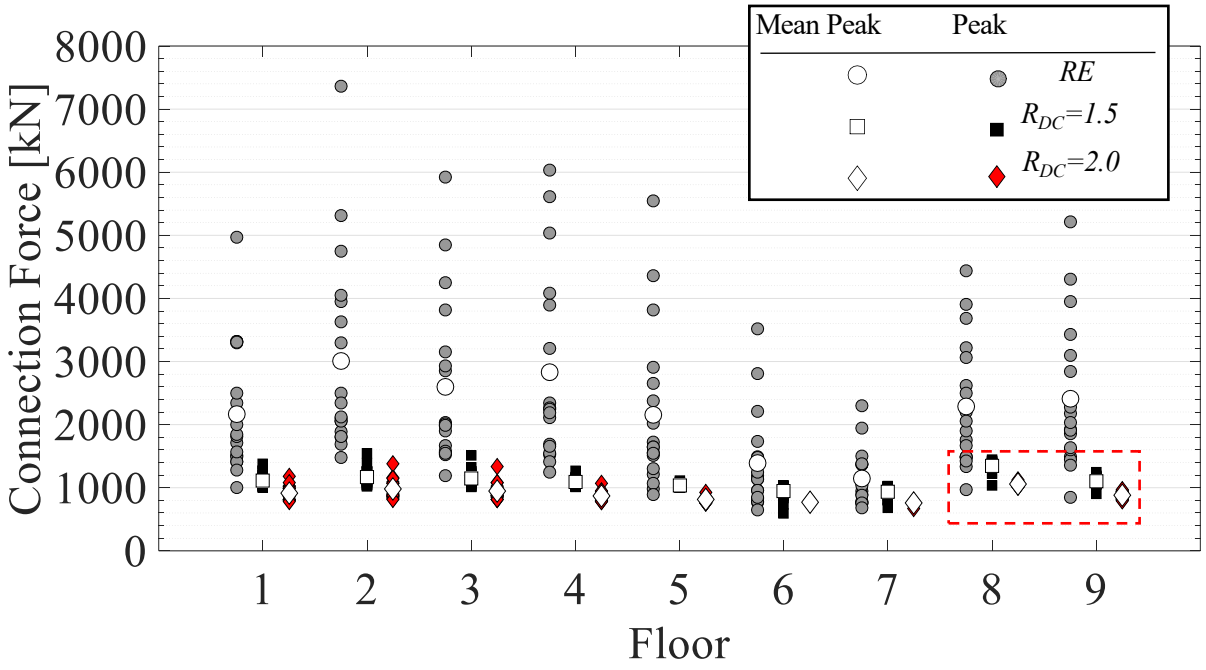


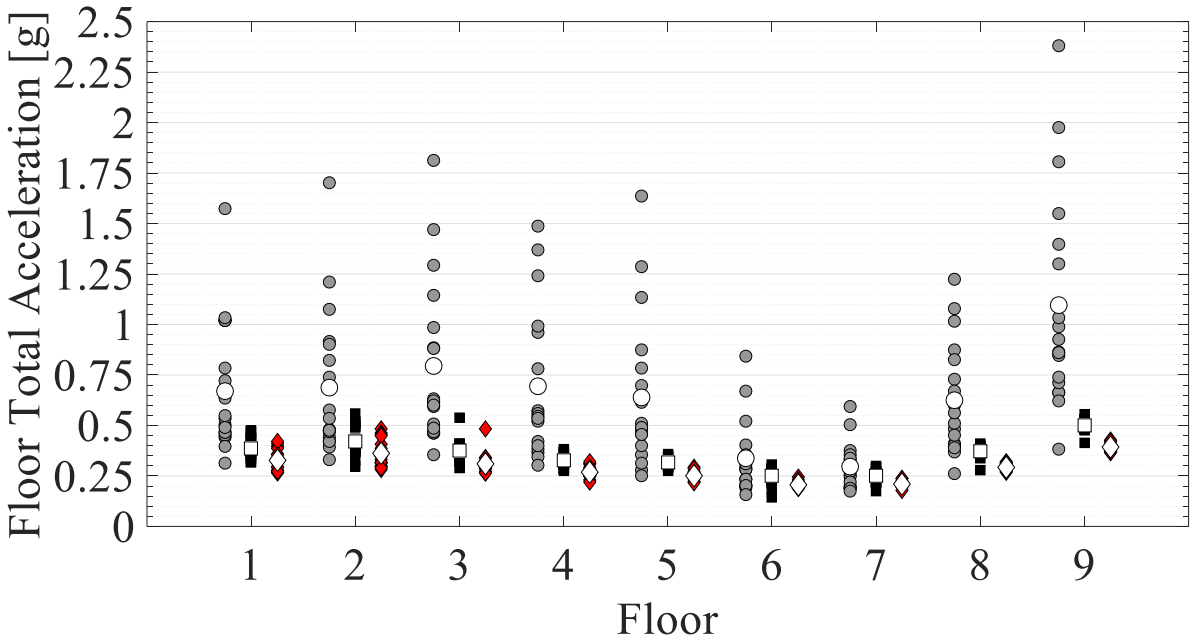
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9-Story Self-Centering Concentrically Braced Frame (SC-CBF)

Reduction in **mean** peak connection forces and floor total accelerations

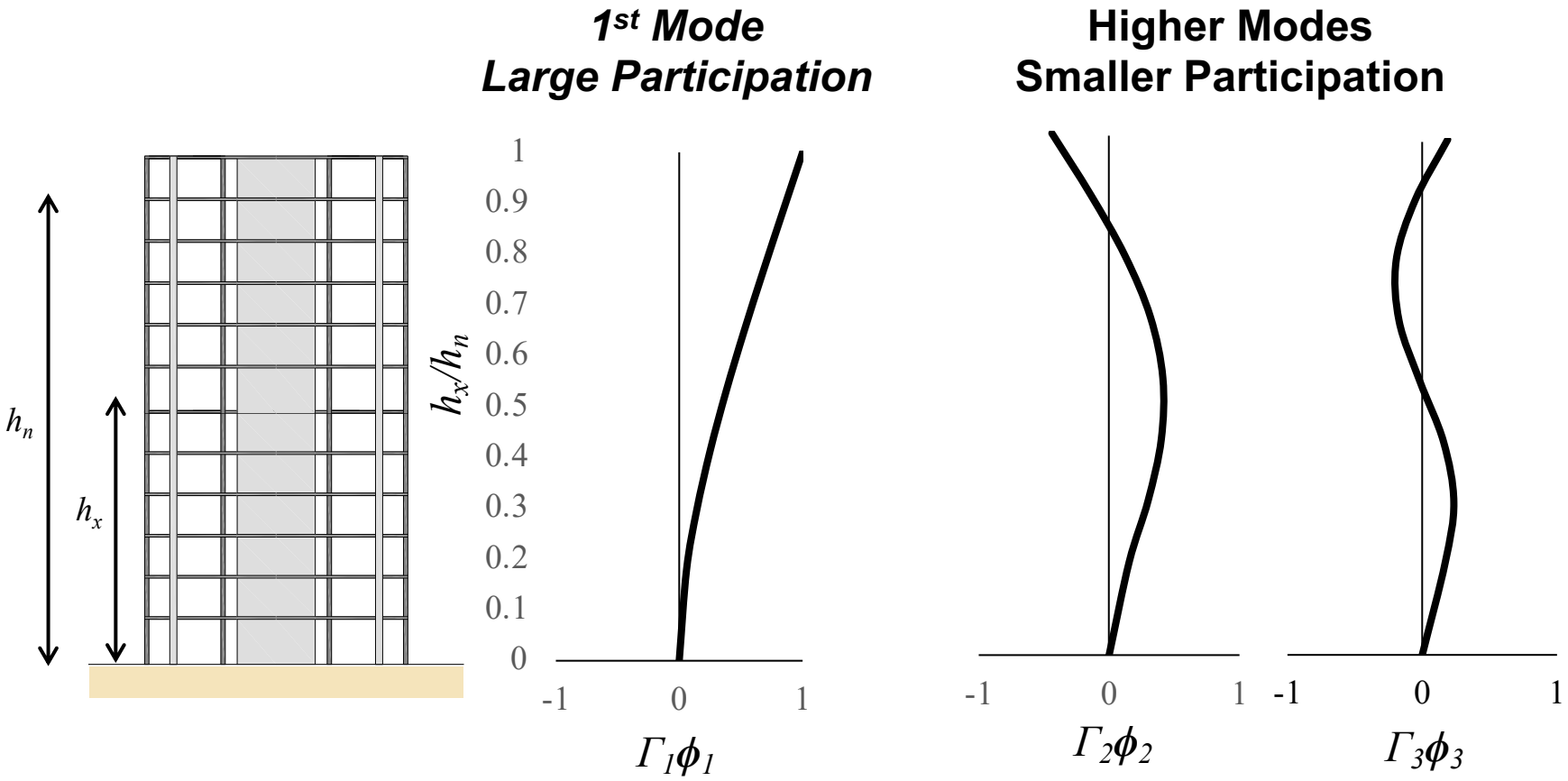
Reduction in **dispersion** of peak connection forces and floor total accelerations





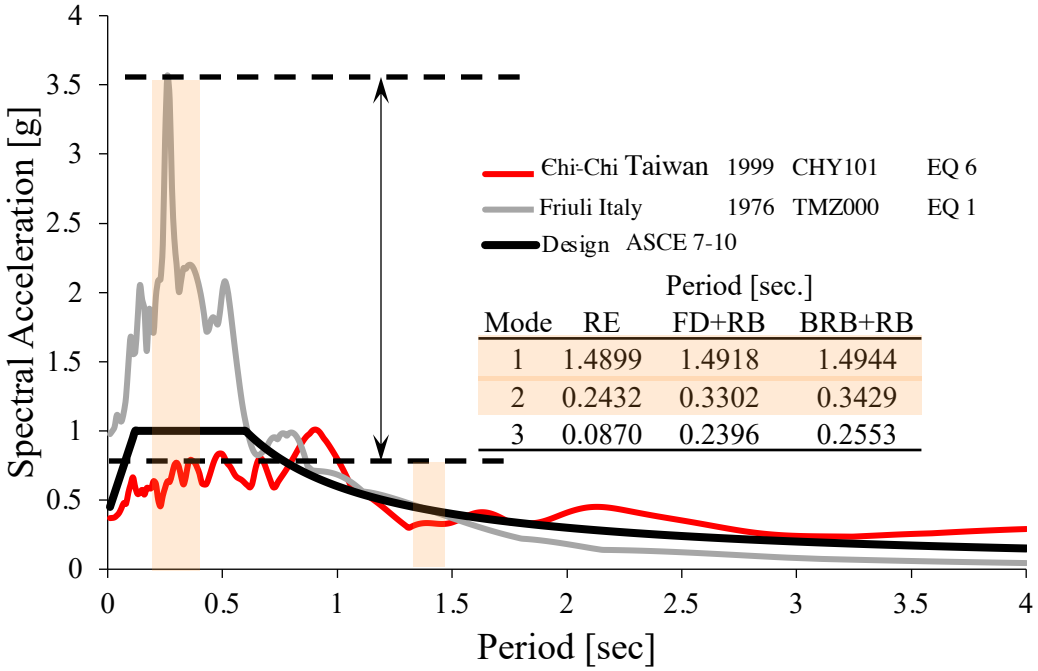
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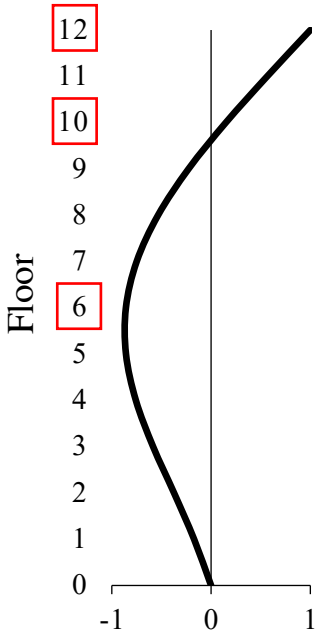
Higher Mode Responses



Tsampras, G., Sause, R., Zhang, D., Fleischman, R. B., Restrepo, J. I., Mar, D., and Maffei, J. (2016) Development of deformable connection for earthquake-resistant buildings to reduce floor accelerations and force responses. *Earthquake Engng Struct. Dyn.*, 45: 1473–1494. doi:10.1002/eqe.2718.

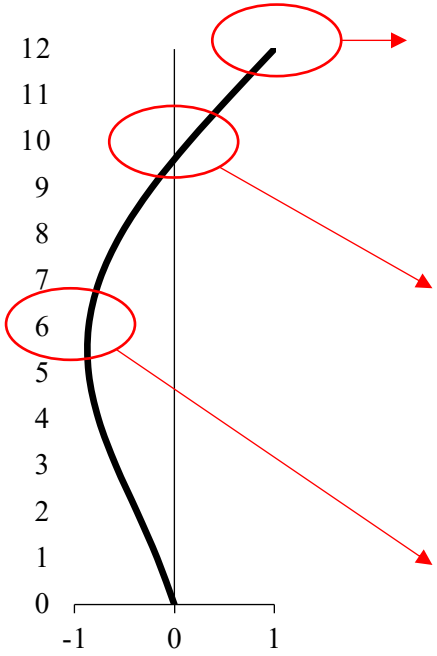
Higher Mode Responses



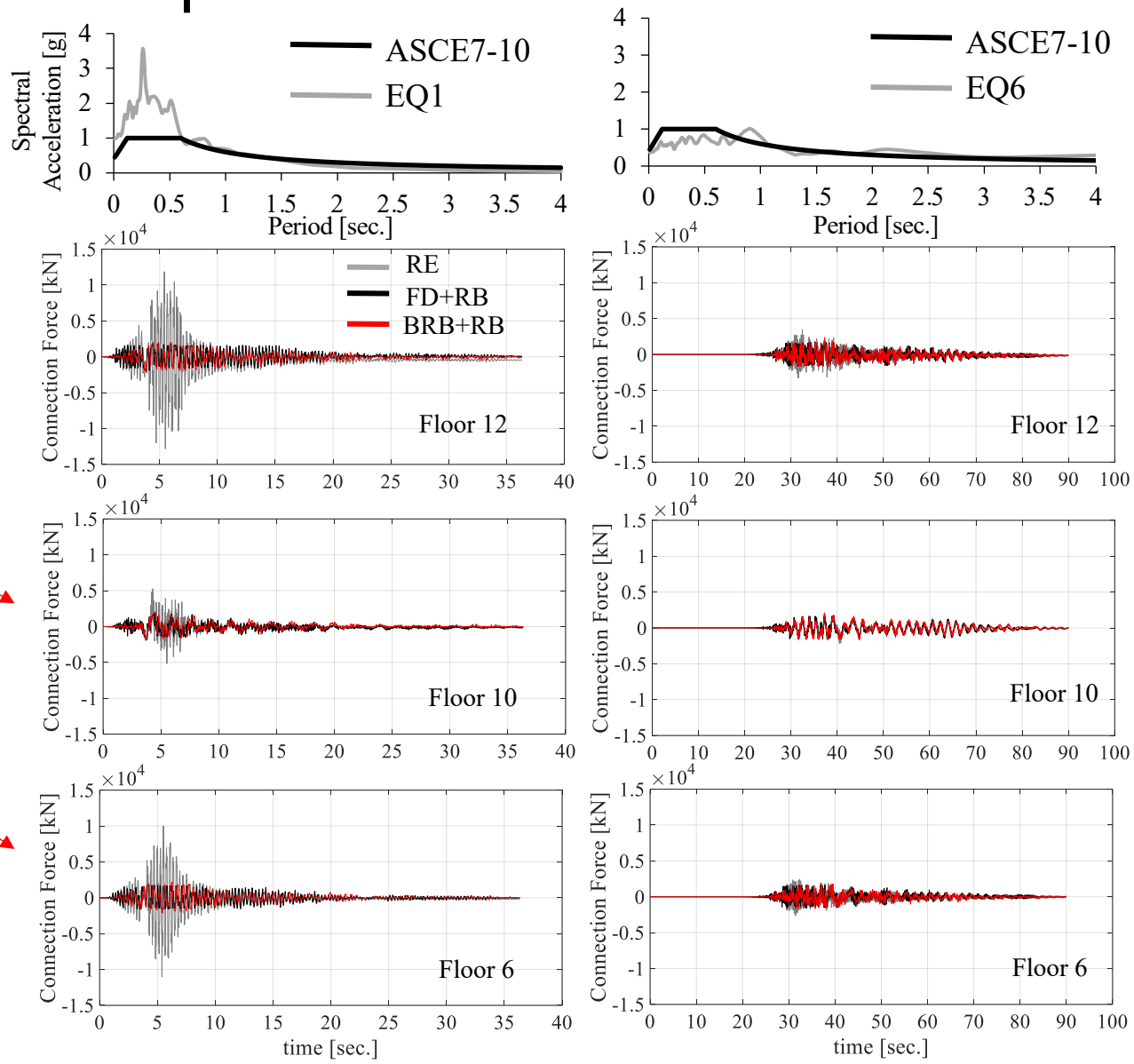


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Higher Mode Responses

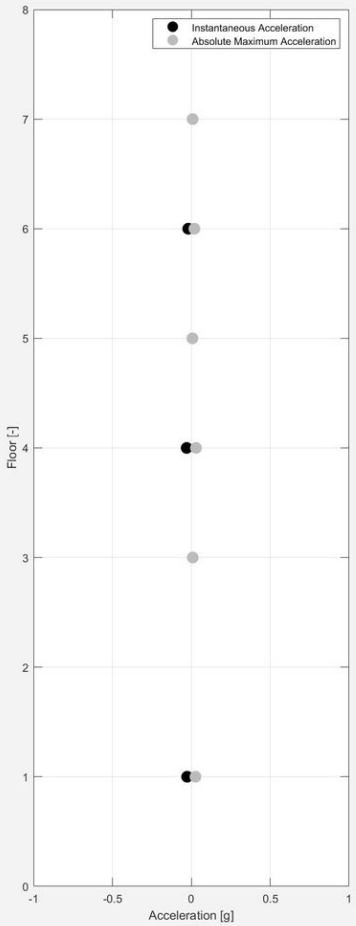


Second Mode
Displacement Shape

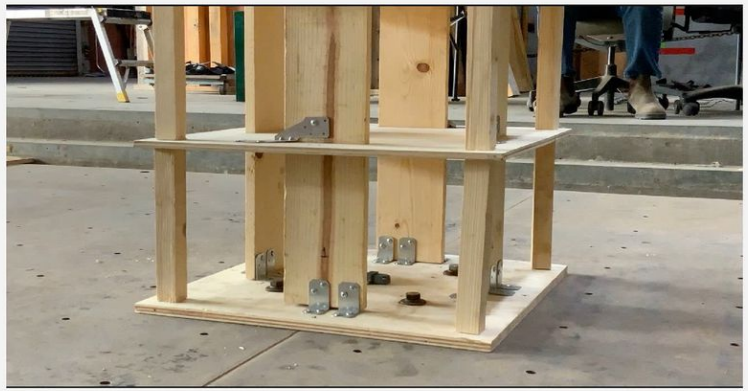


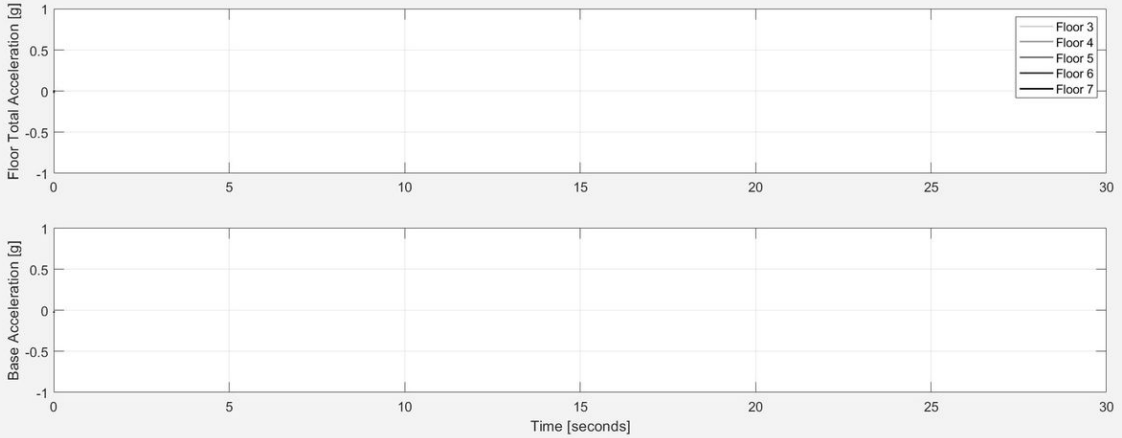
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Engineering Education









https://tsampras.eng.ucsd.edu/education#h.3ffhs5cbn0gg

1. Zhang, D, R Fleischman, J Restrepo, R Sause, J Maffei, D Mar, and G Monti. “Development of a Floor Inertial Force Limiting Anchorage System Building Seismic Response.” In *10th U.S. National Conference on Earthquake Engineering*, 11. 10th U.S. National Conference on Earthquake Engineering, 2014.

2. Fleischman, Robert, Jose Restrepo, Arpit Nema, Dichuan Zhang, Ulina Shakya, Zhi Zhang, Richard Sause, Georgios Tsampras, and Giorgio Monti. “Inertial Force-Limiting Anchorage System for Seismic Resistant Building Structures.” In *Structures Congress*, 1302–13. Portland, Oregon: Structures Congress, 2015. https://doi.org/10.1061/9780784479117.111.

3. Tsampras Georgios, Richard Sause, Dichuan Zhang, Robert B. Fleischman, Jose I. Restrepo, David Mar, and Joseph Maffei. “Development of Deformable Connection for Earthquake-Resistant Buildings to Reduce Floor Accelerations and Force Responses.” *Earthquake Engineering & Structural Dynamics* 45, no. 9 (July 25, 2016): 1473–94. https://doi.org/10.1002/eqe.2718.

4. Tsampras Georgios, Richard Sause, Robert B. Fleischman, and Jose I. Restrepo. “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, no. 8 (July 10, 2017): 1287–1305. https://doi.org/10.1002/eqe.2856.

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7. Tsampras Georgios, Richard Sause, “Force-Based Design Method for Force-Limiting Deformable Connections in Earthquake-Resistant Buildings.” *Journal of Structural Engineering*, 10.1061/(ASCE)ST.1943-541X.0003456 (Forthcoming)

8. Kyoungyeon Lee, Kaixin Chen, Georgios Tsampras, (2022) “Seismic Response of Core Wall Building with Friction-Based Force-Limiting Connections”, 3rd European Conference on Earthquake Engineering & Seismology, Bucharest, Romania