18th World Conference on Earthquake Engineering
Technical Session SDM-5

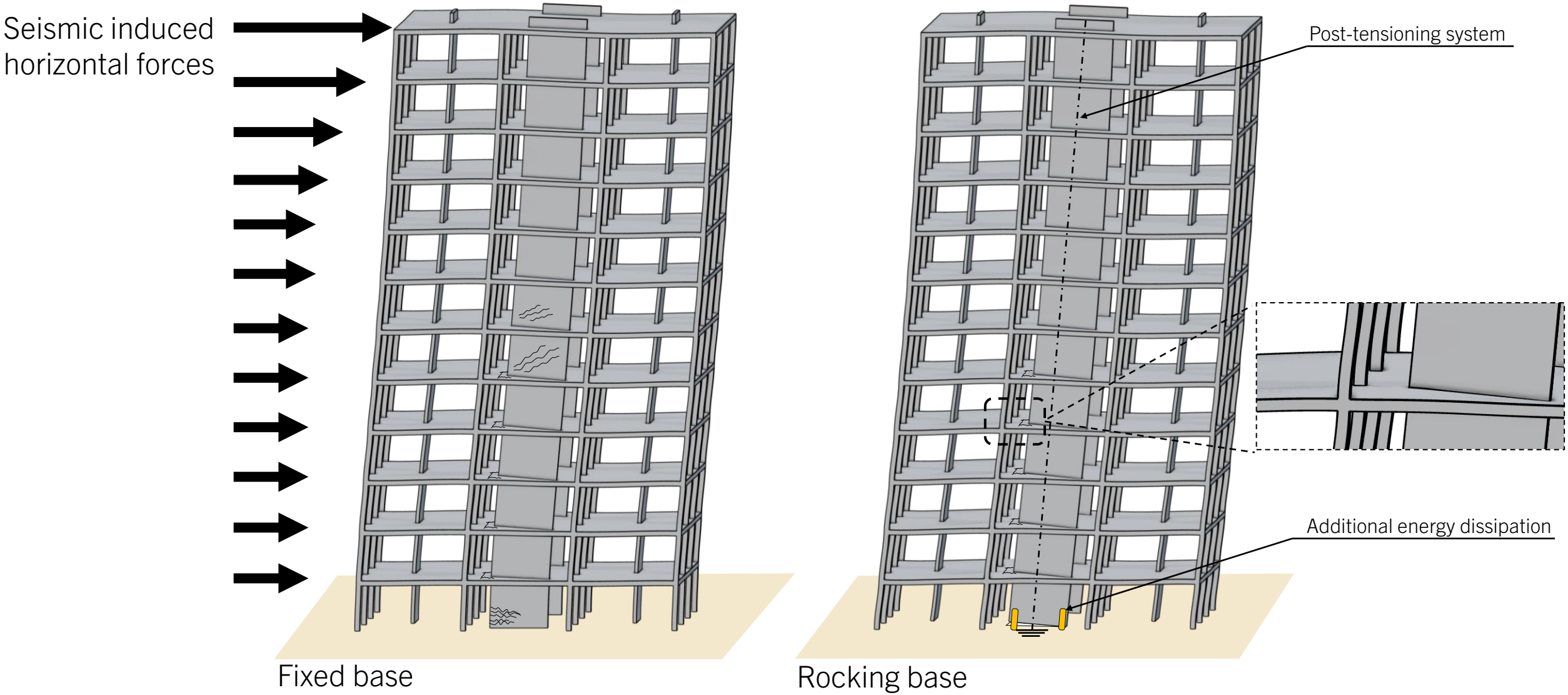
Practical design of force-limiting connections for buildings with reduced higher-mode responses

Georgios Tsampras, Ph.D.
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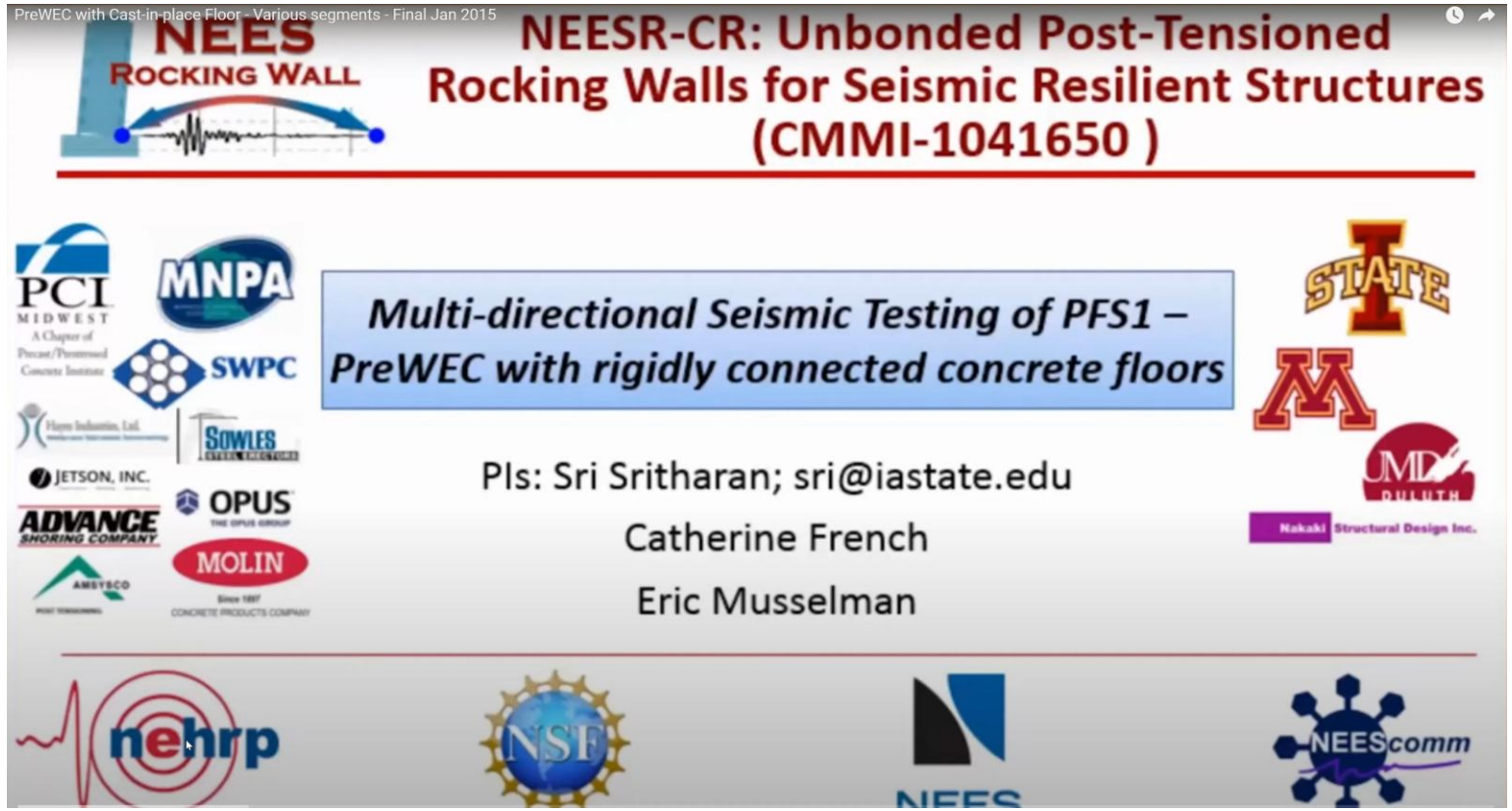
July 3, 2024
Milan, Italy

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Buildings with flexural yielding and rocking base mechanism



Damage in floor diaphragms due to kinematics



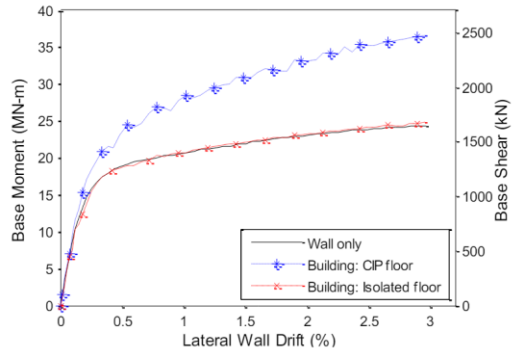


Figure 6 – Calculated response of the prototype building FEM with both cast-in-place and isolated floors

Wall-to-floor interaction in concrete buildings with rocking wall systems

R.S. Henry & J.M. Ingham

Department of Civil and Environmental Engineering, University of Auckland, New Zealand.

S. Sritharan

Department of Civil, Construction and Environmental Engineering, Iowa State University, Ames, IA, USA.

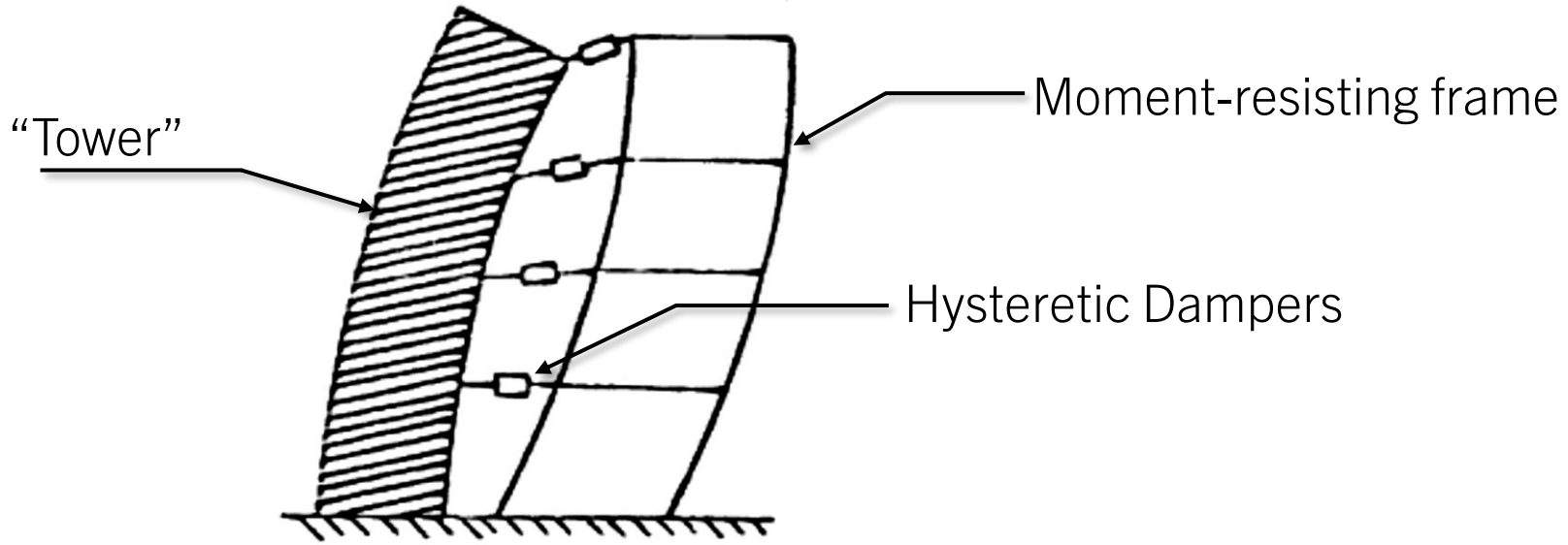
2012 NZSEE Conference

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

Alternative system



R.I. Skinner, J. Kelly and A. Heine (1975) "Hysteretic dampers for earthquake resistant structures," Earthquake Engineering and Structural Dynamics, pp. 287-296



A building which combines a moment-resisting frame with a central tower may utilize hysteretic dampers if the tower is left separate from the floors and beams. Under lateral loads there would be large relative movements between the tower and the frame, with moderate interfloor translations. Hysteretic dampers may be connected between the tower and nearby floor beams

For system level literature review: Tsampras et al. (2016)

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

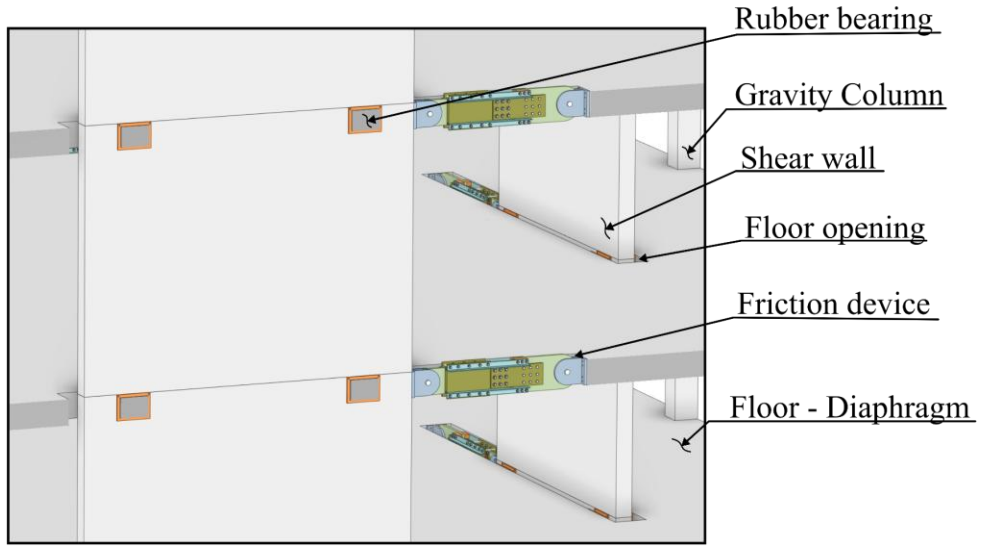
Openings in the Floor Systems
Force-limiting connections between Floor – LFRS with two types of components:

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

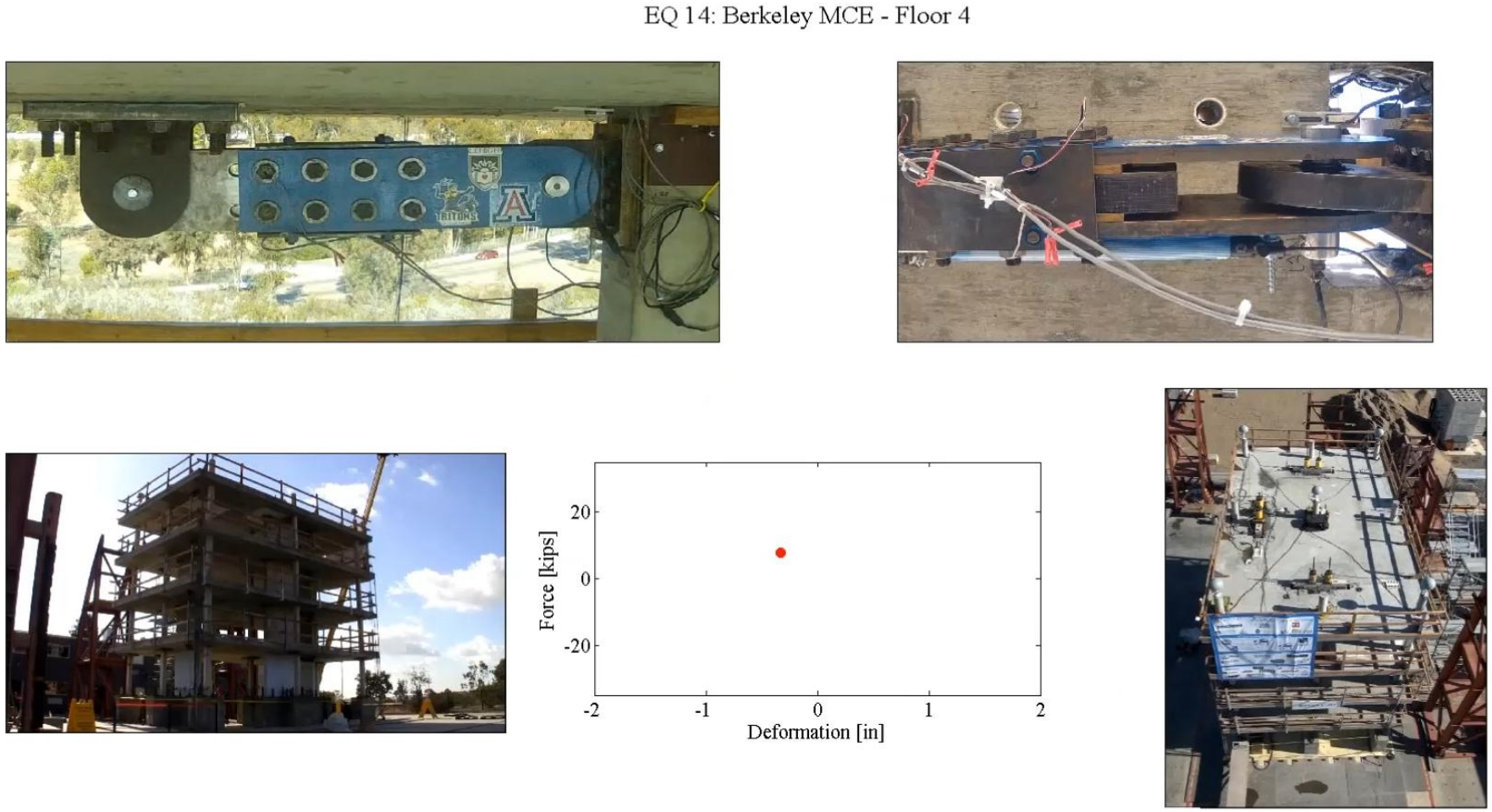




Cross section in *X*-*Z* plane

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

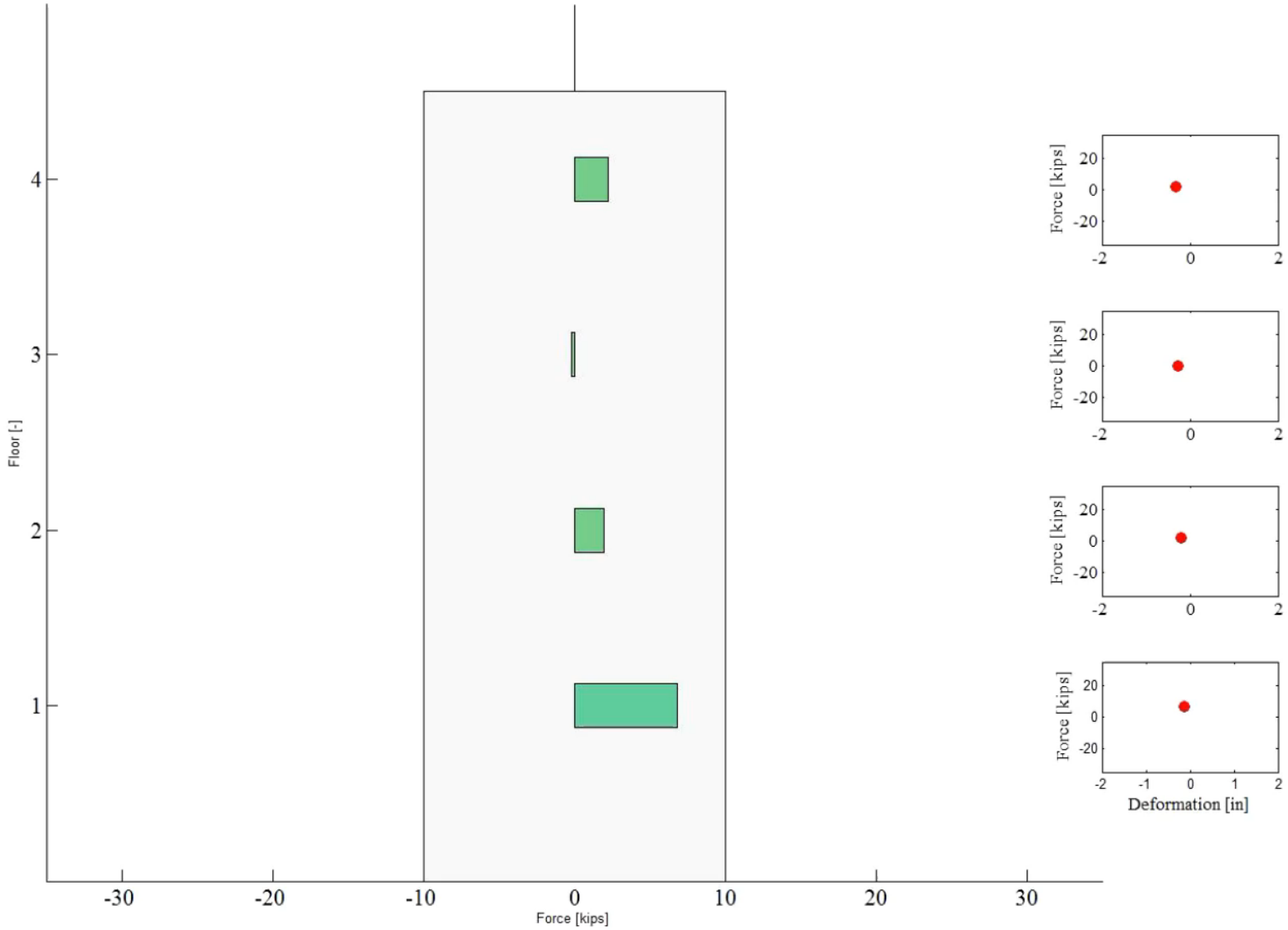
Example Installation at NEES @ UCSD



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

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

Example Installation at NEES @ UCSD

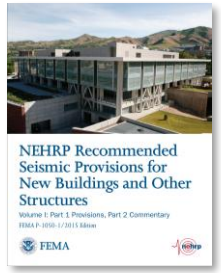


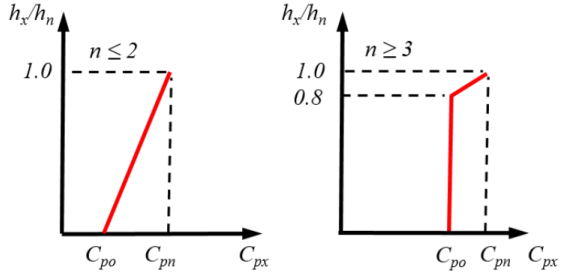
Georgios Tsampras, Richard Sause, Robert B. Fleischman, José I. Restrepo (2017) Experimental study of deformable connection consisting of friction device and rubber bearings to connect floor system to lateral force resisting system, Earthquake Engineering & Structural Dynamics, 47 (4), 1032-1053, doi: 10.1002/eqe.3004

Can we determine the forces that can be used for the preliminary design of the connections without large parametric earthquake numerical simulations?

Force-Based Design Method for Force-Limiting Connections

Alternative design provisions for diaphragms adopted by ASCE 7-22







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

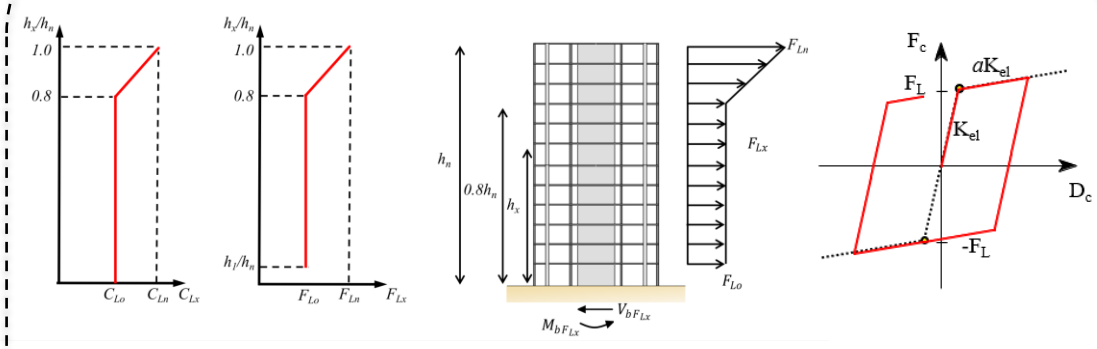
$$C_{p0} = 0.4 S_{DS} I_e \qquad C_{pn} = \sqrt{(\Gamma_{m1}\Omega_0 C_s)^2 + (\Gamma_{m2} C_{s2})^2} \ge C_{pi}$$

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

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

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

Design Method for Force-Limiting Connections



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

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

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

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

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

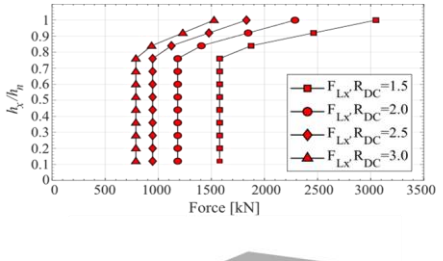
$$1.0 \le \sum_{x=1}^{n} \frac{\frac{C_{Lx}}{R_{DC}} \frac{w_{px}}{n_{Lx}} h_x}{M_{by}}$$

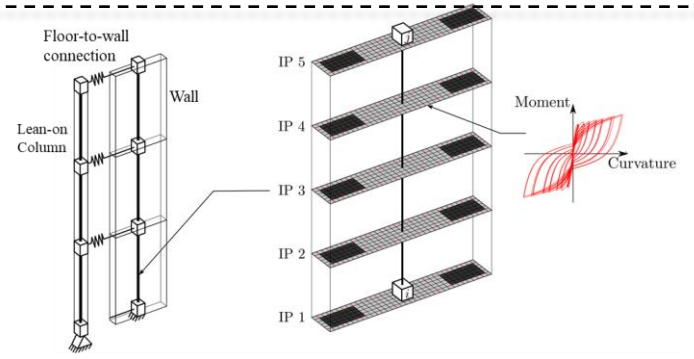
$$R_{DC} \le \sum_{x=1}^{n} \frac{C_{Lx} \frac{w_{px}}{n_{Lx}} h_x}{M_{by}}$$

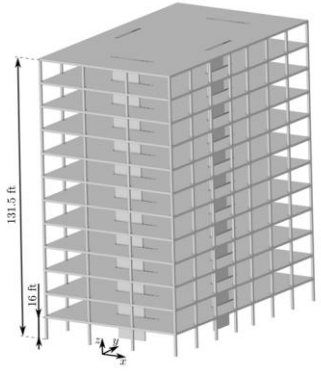
Georgios Tsampras, Richard Sause (2022), "Force-Based Design Method for Force-Limiting Deformable Connections in Earthquake-Resistant Buildings." Journal of Structural Engineering, https://doi.org/10.1061/(ASCE)ST.1943-541X.0003456.

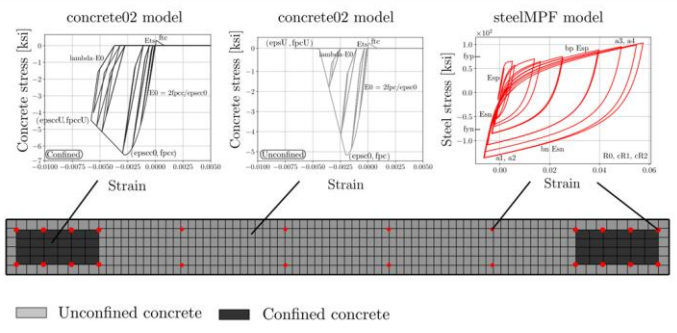
Application of design method

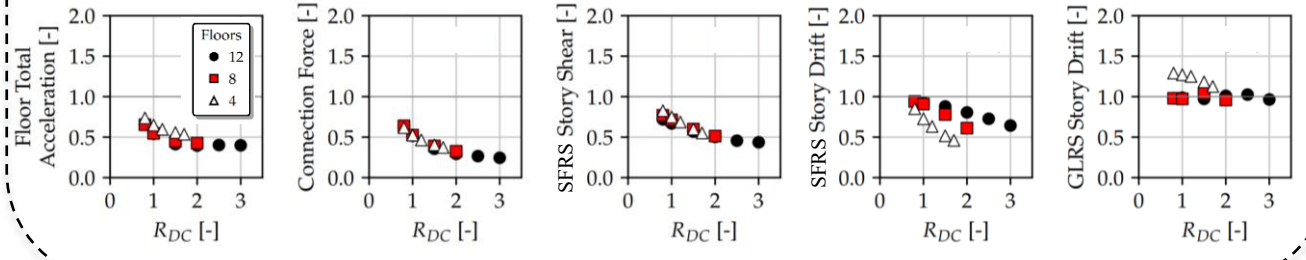
RC planar wall buildings



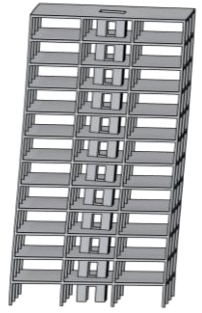


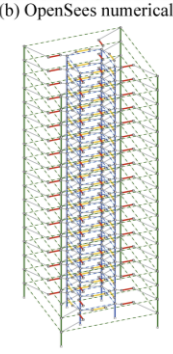


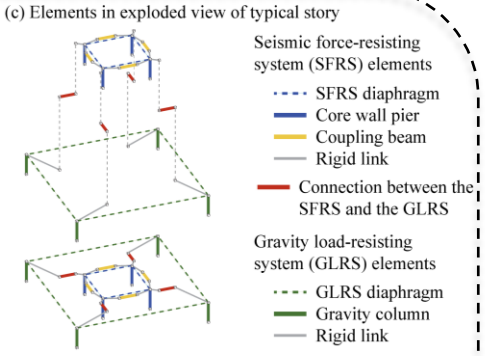


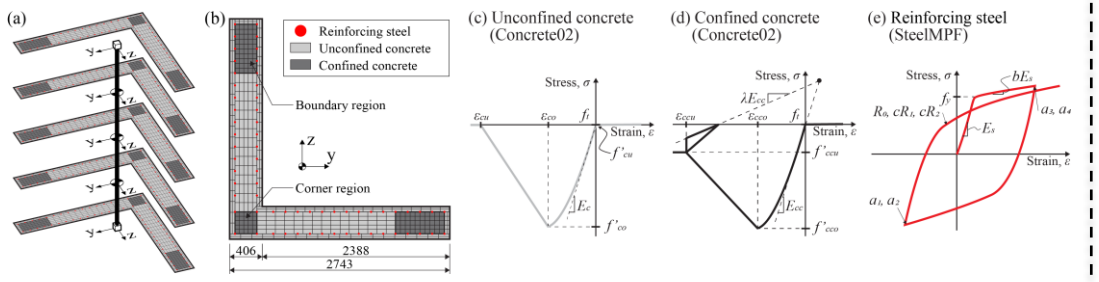


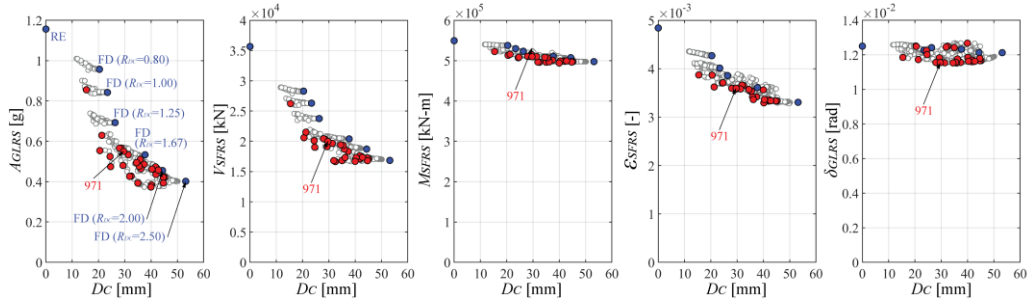
RC core wall building





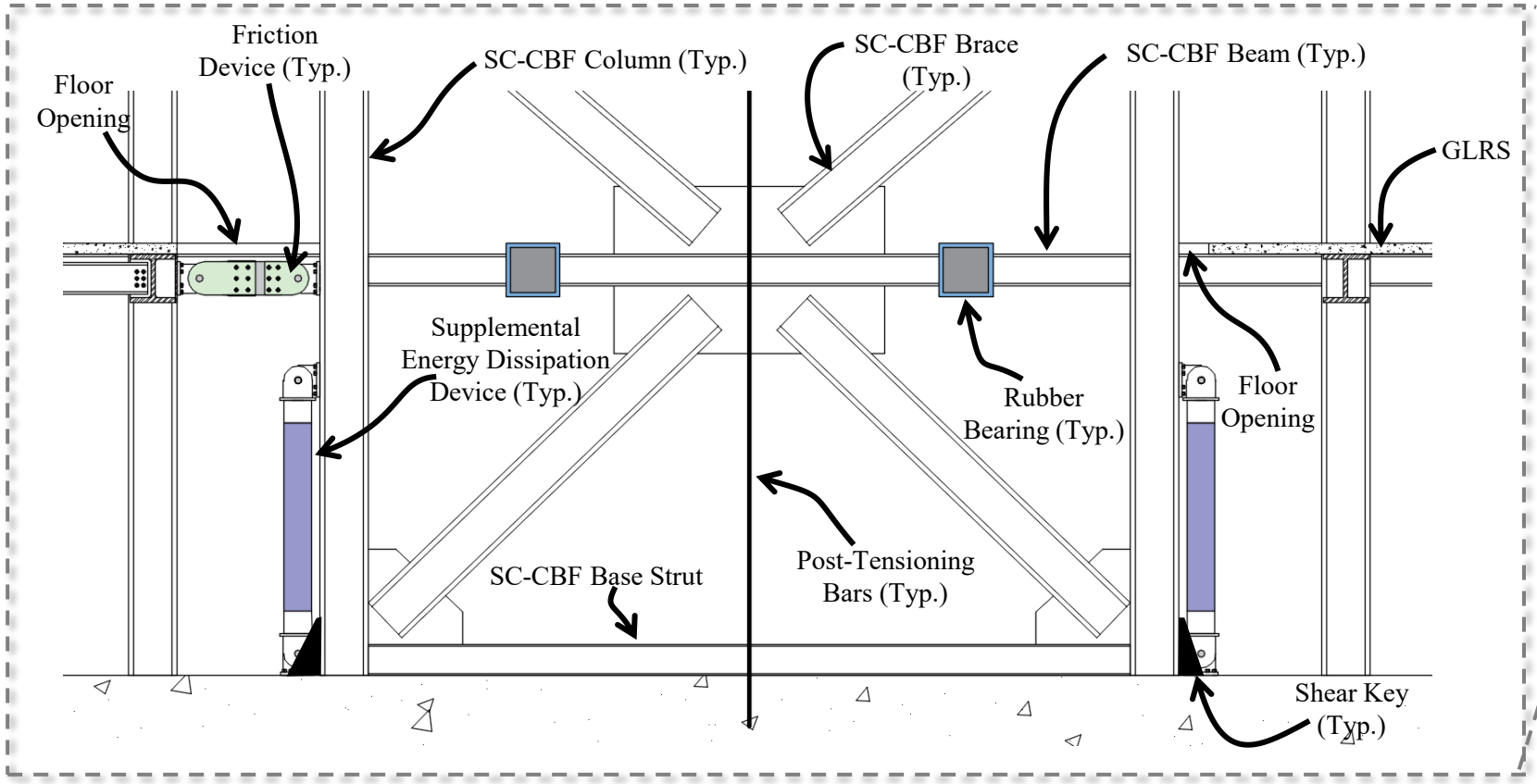


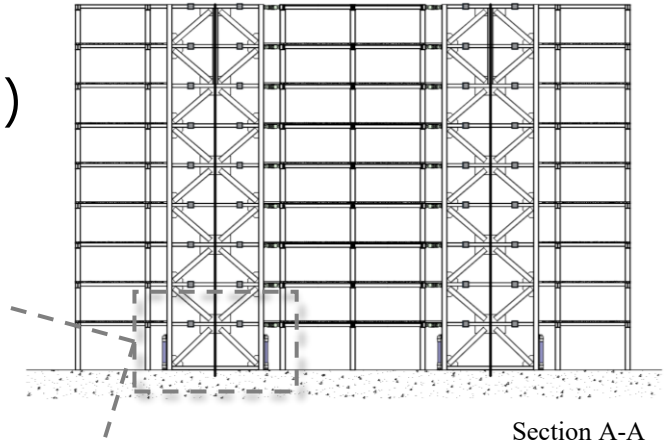


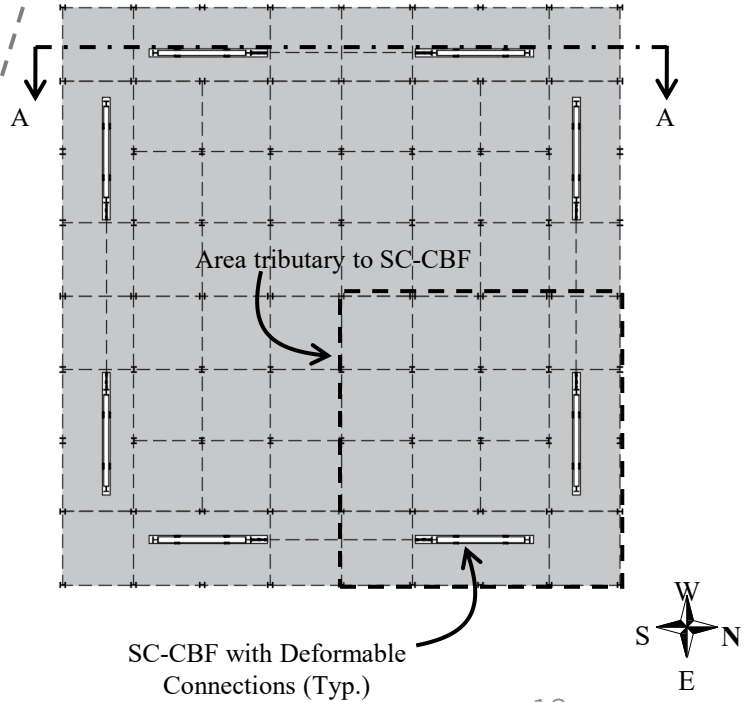


1. Tsampras G, Sause R. Force-Based Design Method for Force-Limiting Deformable Connections in Earthquake-Resistant Buildings. Journal of Structural Engineering 2022; 148(10): 04022150. DOI: 10.1061/(ASCE)ST.1943-541X.0003456.
2. Mayorga CF, Tsampras G. Reinforced concrete wall buildings with force-limiting connections: Modeling effects and uncertainty propagation. Earthquake Engineering & Structural Dynamics 2024. DOI: 10.1002/eqe.4073.
3. Kyoungyeon Lee; Georgios Tsampras; C. Franco Mayorga (Forthcoming), "Reinforced Concrete Core Wall Buildings with Modified Friction-Based Force-Limiting Connections: Connection Design Considerations and Three-Dimensional Response to Bidirectional Ground Motions " ASCE Journal of Structural Engineering, DOI: 10.1061/JSENDH/STENG-13609

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

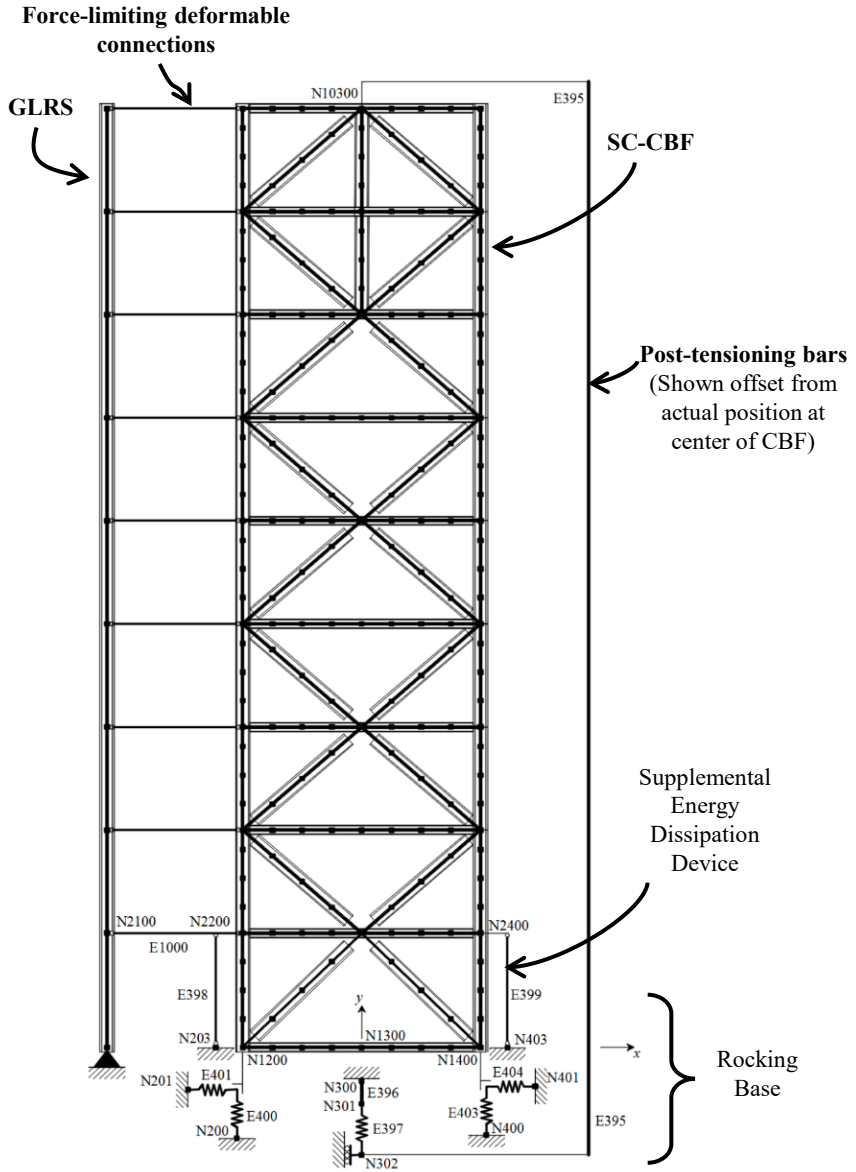




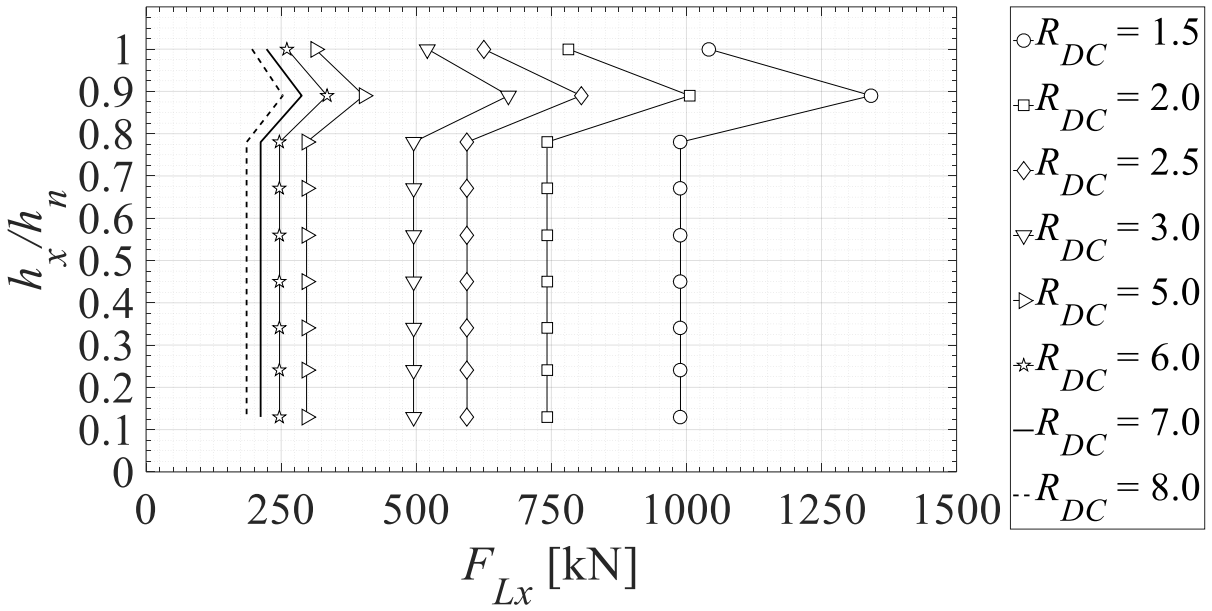


Georgios Tsampras (2016), Force-Limiting Deformable Floor Diaphragm Connection for Earthquake Resistant Buildings, PhD Dissertation, Lehigh University, Bethlehem, PA, USA, DOI: https://preserve.lib.lehigh.edu/islandora/object/preserve%3Abp-10369972

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



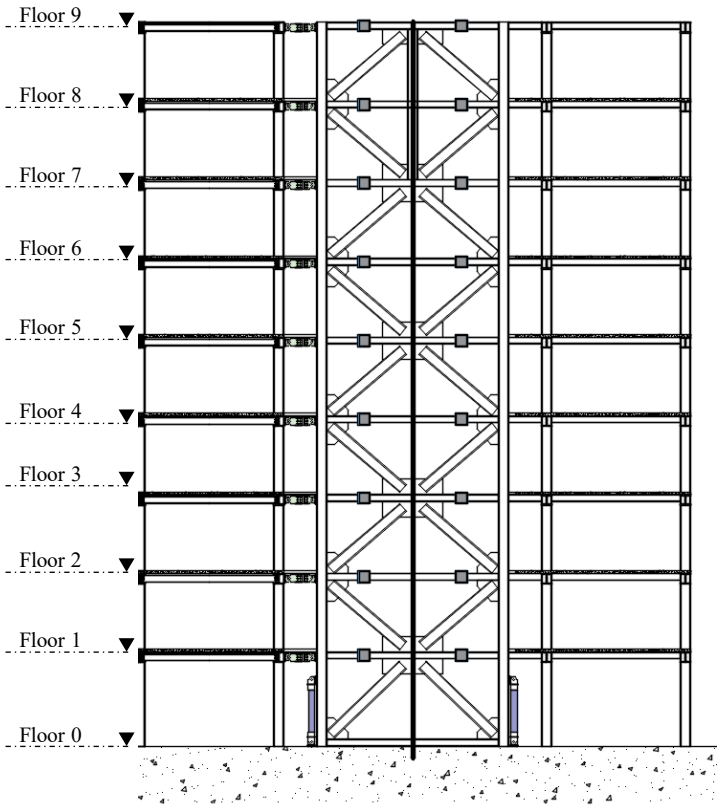
$$\frac{Seismic\ Mass\ at\ floor\ 9}{Seismic\ Mass\ at\ floor\ 8} = 0.6$$

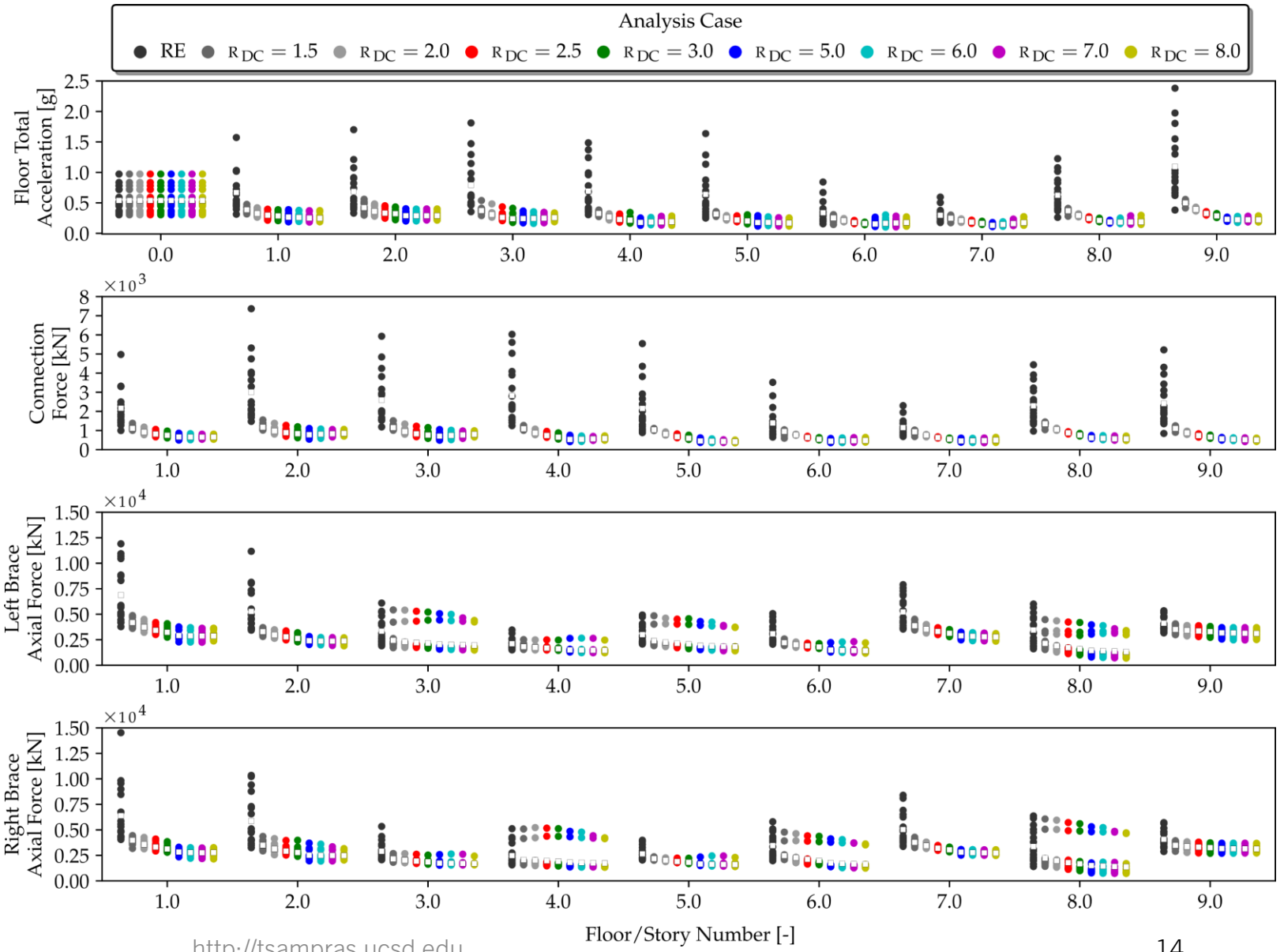


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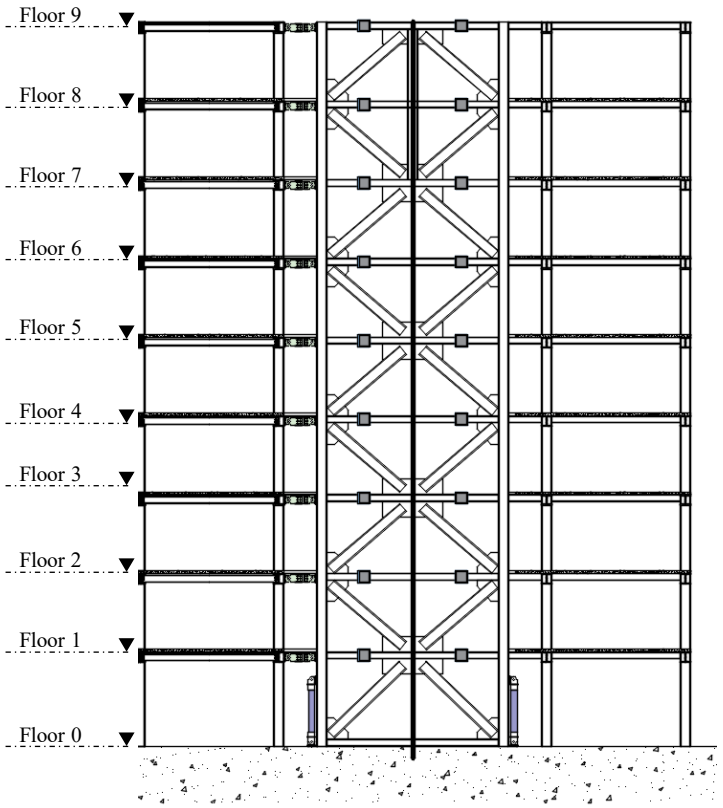
Reduction in **mean** peak responses and their **dispersion**

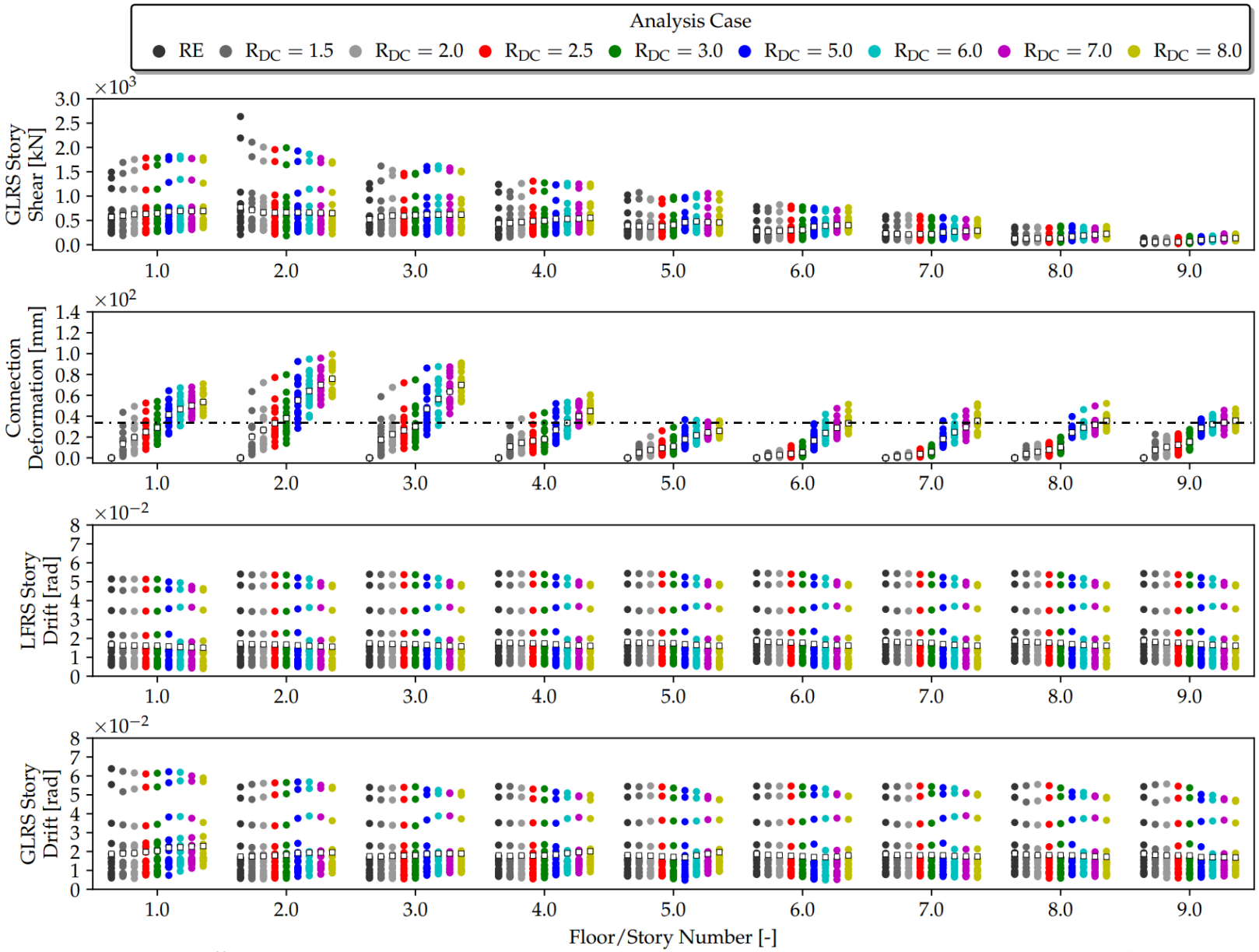




9-Story Self-Centering Concentrically Braced Frame (SC-CBF)

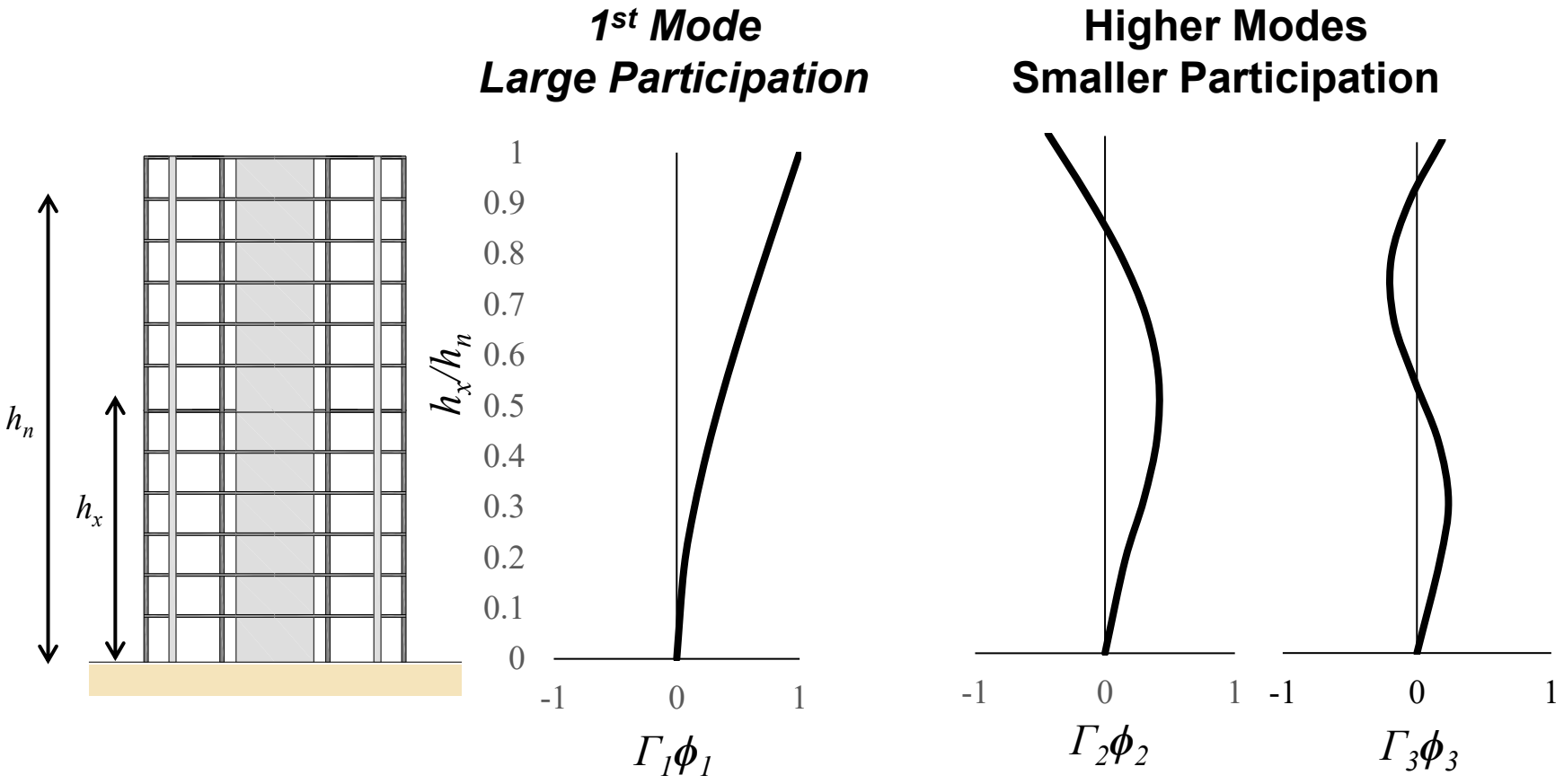
$R_{DC} \leq 2.5$ results in connection deformation demand at design level ground motions below 40 mm without affecting the drift demands





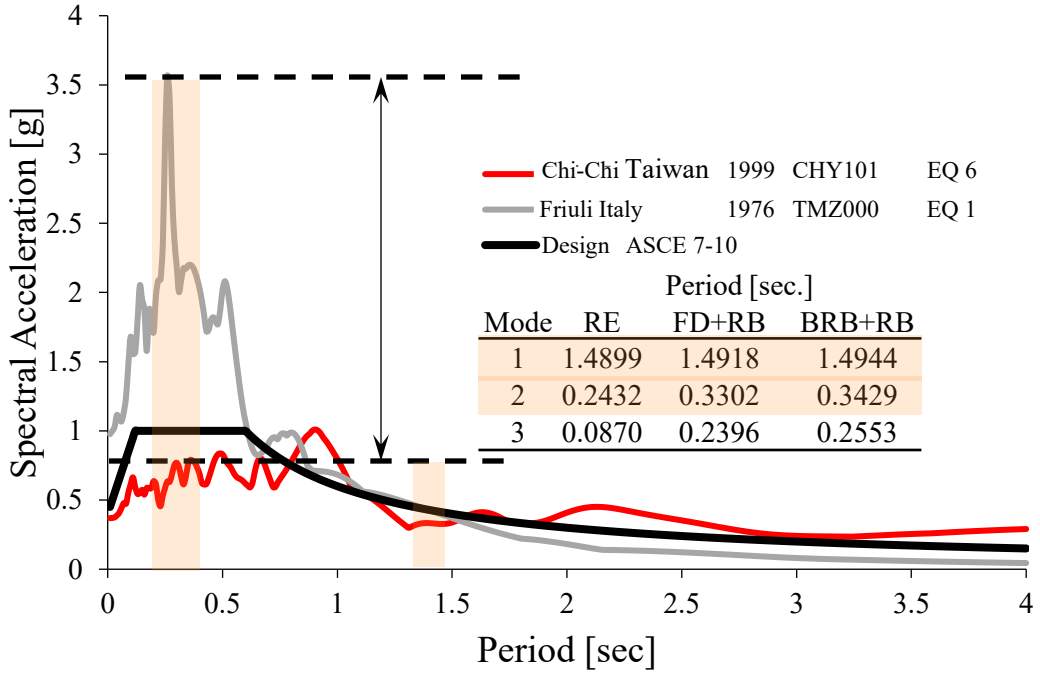
Reductions in seismic responses due to mitigation of higher mode effects

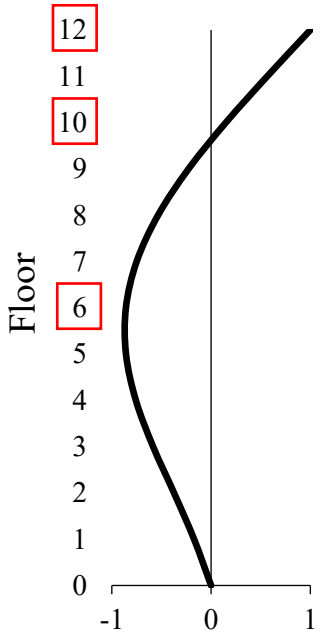
Higher Mode Responses



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.

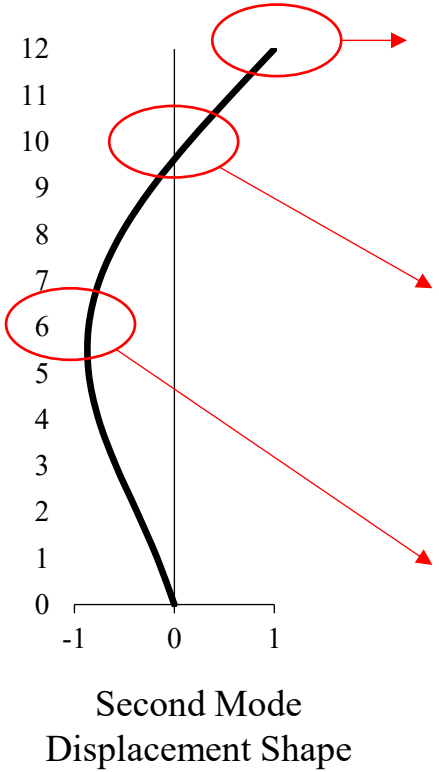
Higher Mode Responses



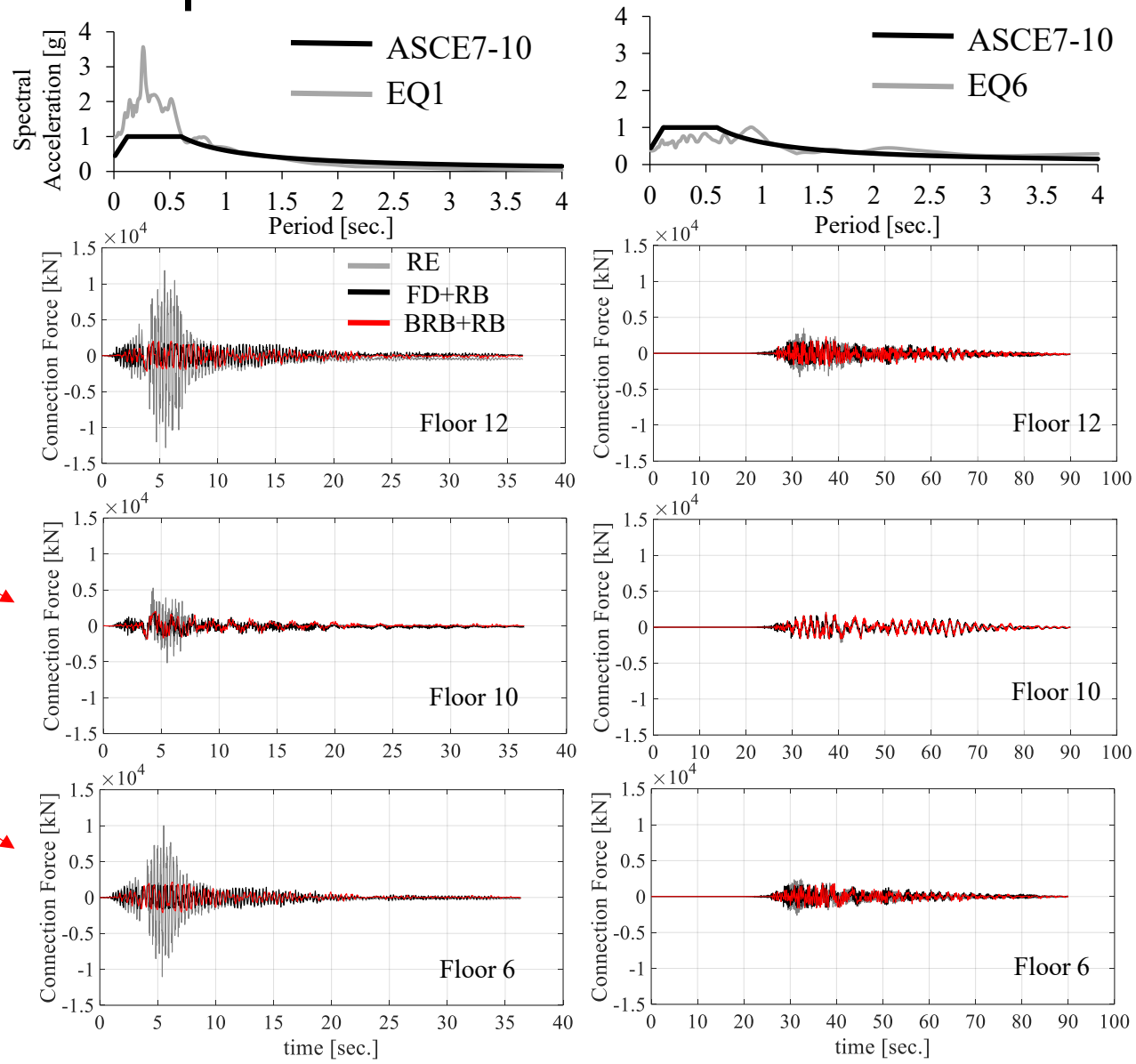


Tsampras, G., Sause, R., Zhang, D., Fleischman, R. B., Restrepo, J. I., Mar, D., and Maffei, J. (2016) Development of deformable connection for earthquake-resistant buildings to reduce floor accelerations and force responses. *Earthquake Engng Struct. Dyn.*, 45: 1473–1494. doi:10.1002/eqe.2718.

Higher Mode Responses



Second Mode
Displacement Shape



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.

UC San Diego

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18TH WORLD CONFERENCE ON EARTHQUAKE ENGINEERING WCEE2024 MILAN

Day	Room	Time	Session	Title
MONDAY	SPACE 3	11:36 - 11:45	IDD11	EFFECT OF UNCERTAINTY IN RC WALLS ON SEISMIC RESPONSES OF BUILDINGS WITH FORCE-LIMITING CONNECTIONS
WEDNESDAY	SUITE 6	09:35 - 09:45	SDM5	PRACTICAL DESIGN OF FORCE-LIMITING CONNECTIONS FOR BUILDINGS WITH REDUCED HIGHER-MODE RESPONSES
WEDNESDAY	SPACE 3	09:50 - 10:00	IDD7	FRICTION-BASED CONNECTIONS: MATERIALS, DESIGNS, MANUFACTURING, SIMULATIONS, AND EXPERIMENTS
THURSDAY	AMBER 7	15:09 - 15:21	IDD4	EXPERIMENTAL CHARACTERIZATION OF COMPOSITE MATERIALS IN FRICTION-BASED FORCE-LIMITING CONNECTIONS
FRIDAY	MONITOR 20	09:24 - 09:36	IDD4	STRUCTURAL CONNECTION WITH PREDETERMINED DISCRETE VARIABLE FRICTION FORCES
FRIDAY	SPACE 3	09:36 - 09:48	CMS2	SHAKE TABLE TESTS OF A FULL-SCALE THREE-STORY STEEL BRBF WITH SLIDING SLABS IN CHIHSHANG EARTHQUAKE
FRIDAY	SUITE 9	09:38 - 09:47	EVO9	ASSESSMENT OF ALTERNATIVE SEISMIC DESIGN PROVISIONS FOR DIAPHRAGMS PER ASCE/SEI 7-22
FRIDAY	SUITE 8	10:54 - 11:06	IDD4	SEISMIC RESPONSE OF CORE WALL BUILDING WITH FRICTION-BASED FORCE-LIMITING CONNECTIONS

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