13th International Congress on Mechanics
Hellenic Society of Theoretical and Applied Mechanics

FRICTION-BASED FORCE-LIMITING CONNECTIONS FOR EARTHQUAKE-RESISTANT BUILDINGS

Georgios Tsampras[1], Kaixin Chen[2], Kyoungyeon Lee[2]

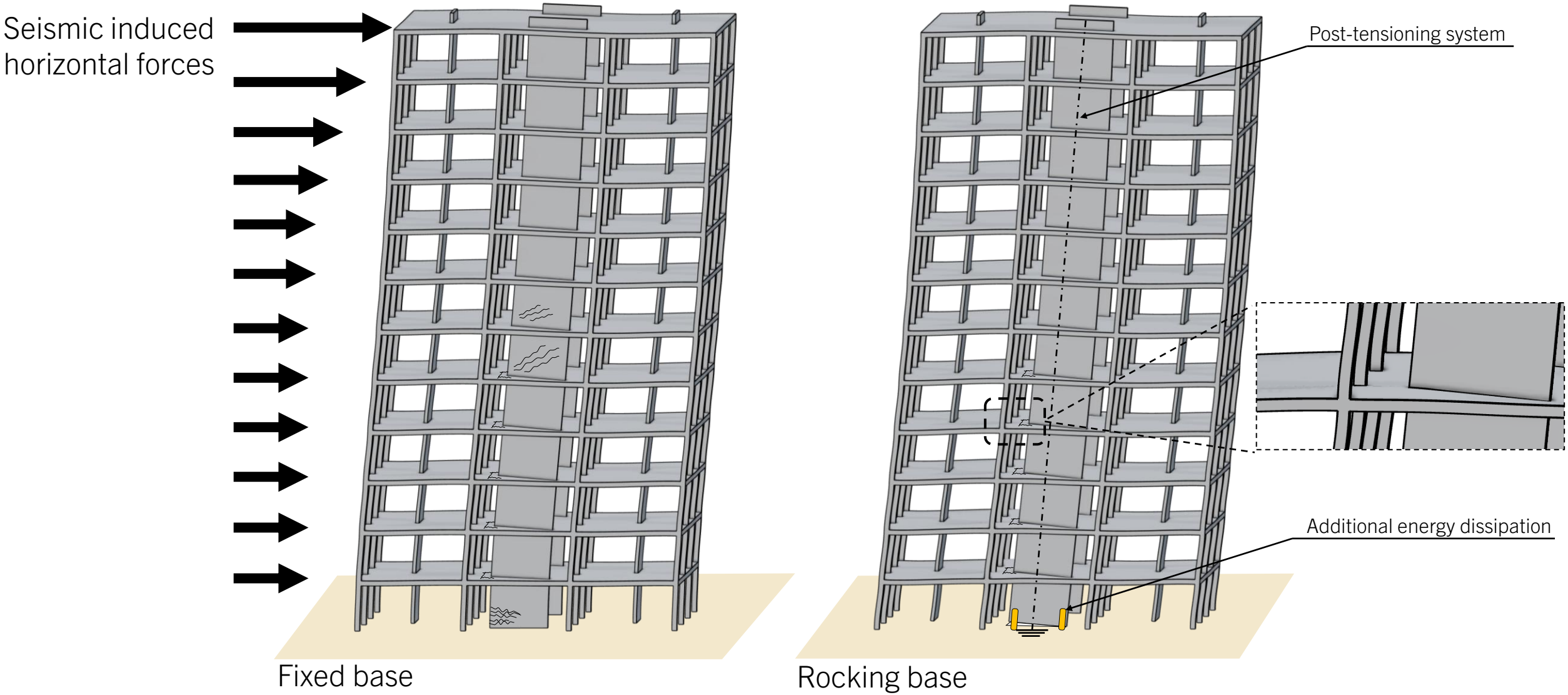
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http://tsampras.ucsd.edu

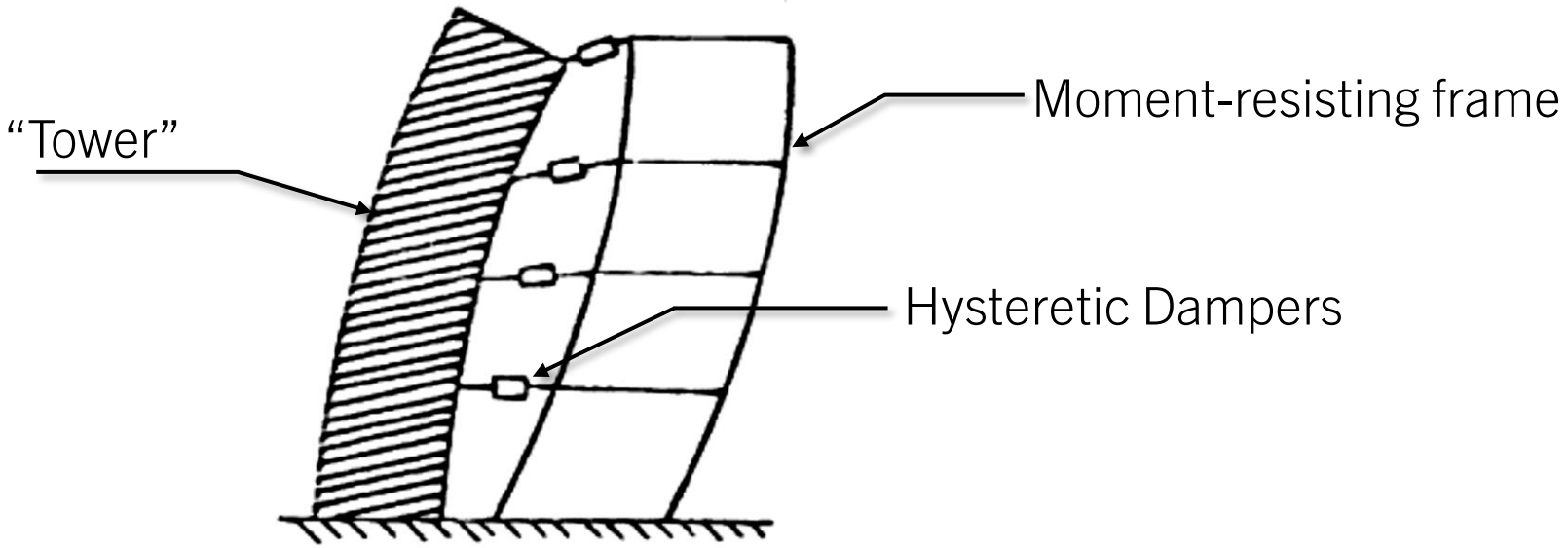
Buildings with monolithic floor-to-wall connections



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

Alternative system

S. T. Crane, "Influence of energy dissipation connections between floors and the lateral force resisting system," M.Sc. Thesis, University of California, San Diego, San Diego, CA, 2004.

Small-scale building model



Reduced floor acceleration and base moment at the wall

Connection between wall and floors

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

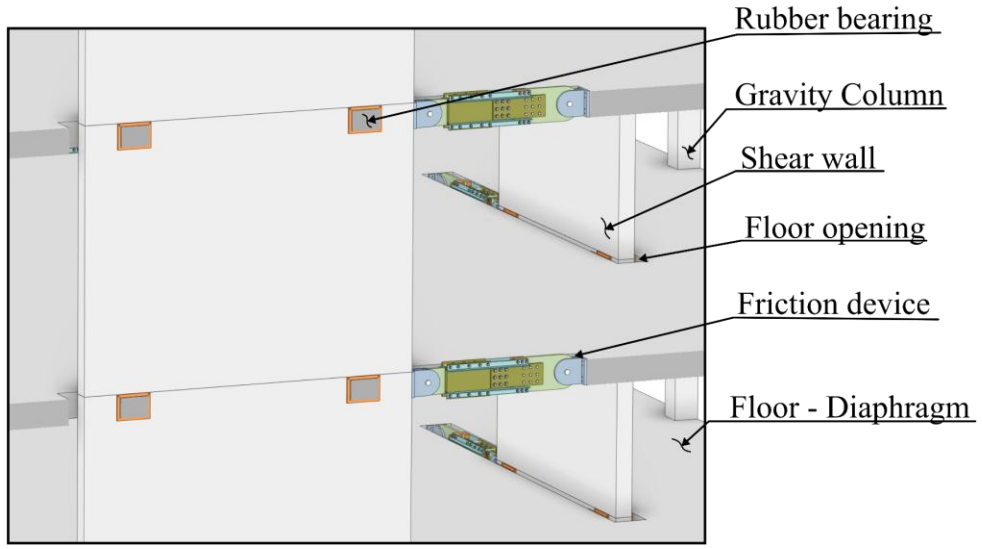
Openings in the Floor Systems
Force-limiting connections between Floor – LFRS with two types of components:

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



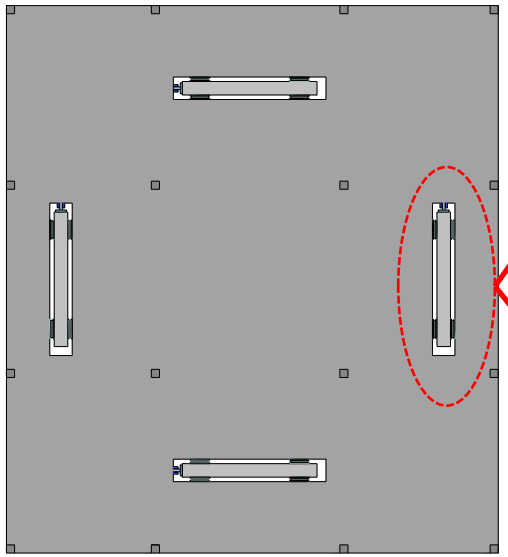


Cross section in *X*-*Z* plane

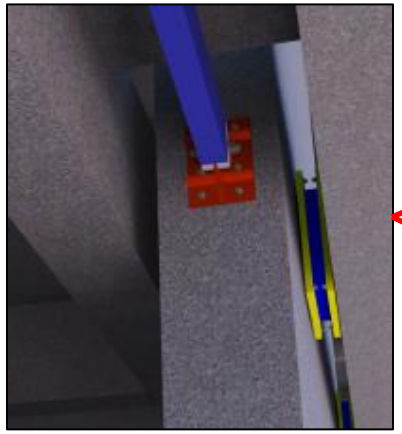
1. Zhang, D, R Fleischman, J Restrepo, R Sause, J Maffei, D Mar, and G Monti. "Development of a Floor Inertial Force Limiting Anchorage System Building Seismic Response." In 10th U.S. National Conference on Earthquake Engineering, 11. 10th U.S. National Conference on Earthquake Engineering, 2014.
2. 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

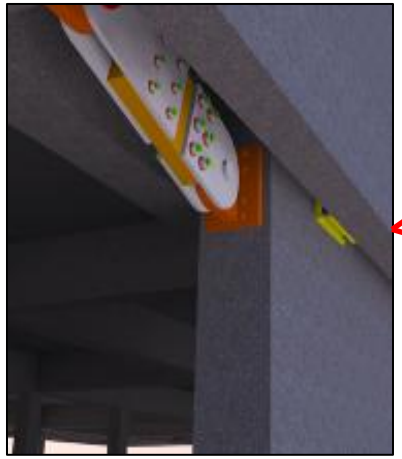
Components of force-limiting deformable connection

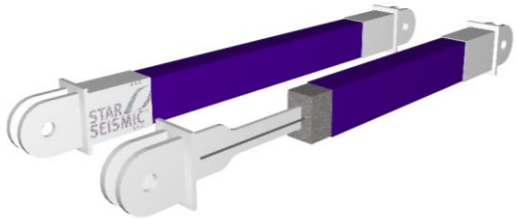
BRB+RB
Deformable Connection



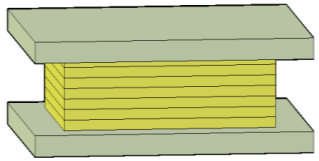
FD+RB
Deformable Connection



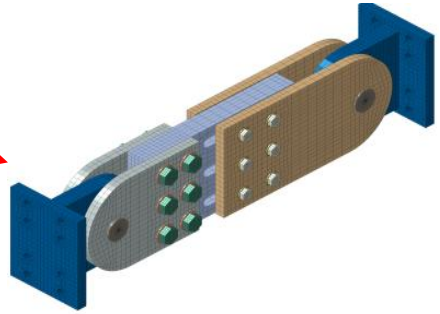




Buckling Restrained
Brace (BRB)



Low Damping
Rubber Bearings (RB)

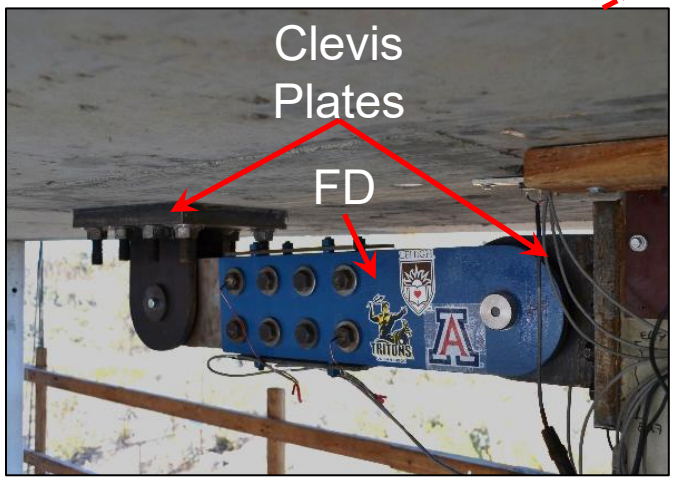


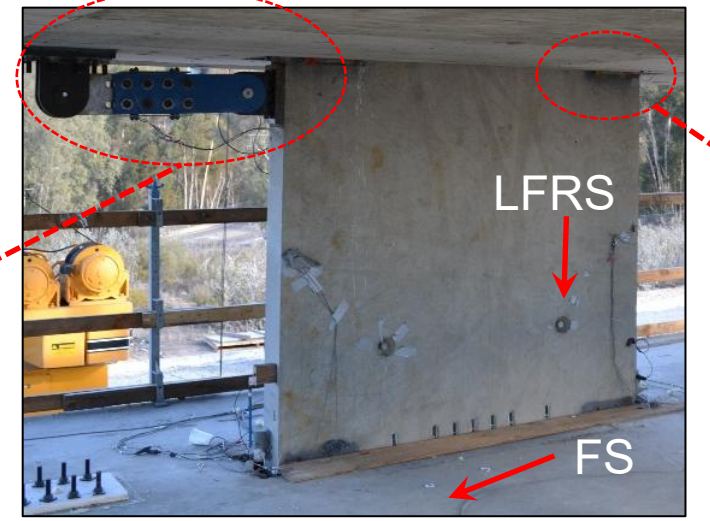
Friction Device (FD)

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.

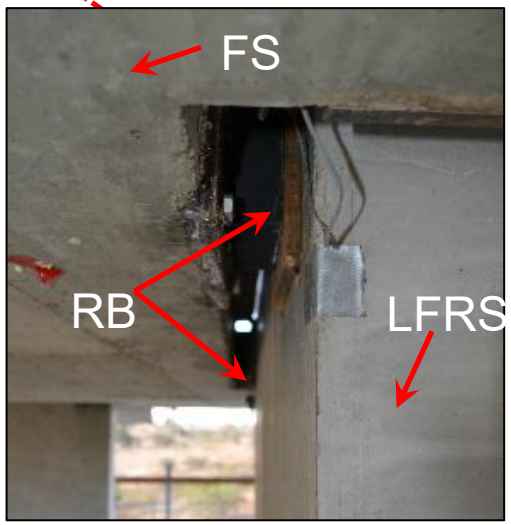
Example Installation of Force-Limiting Connection

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



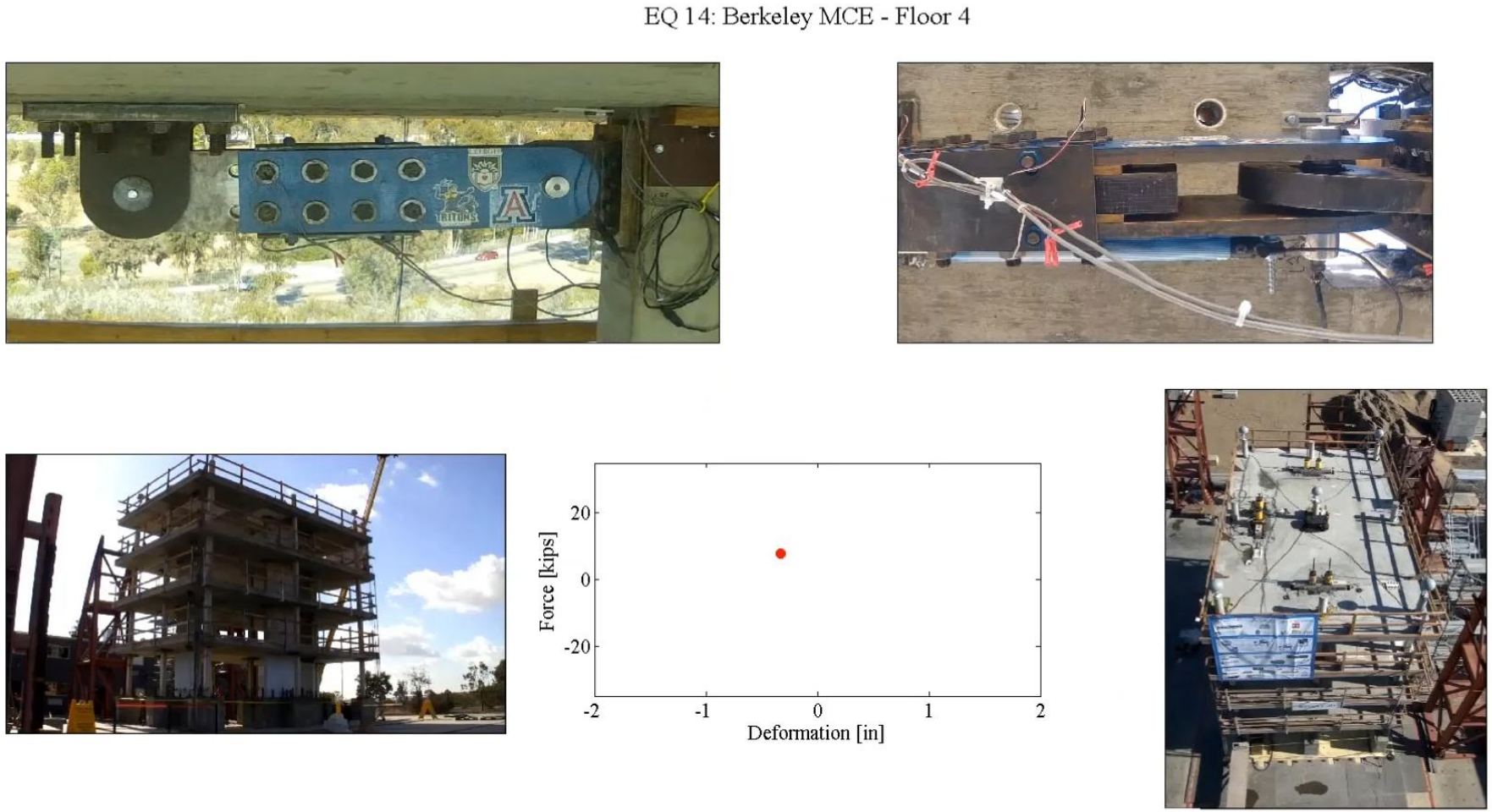






Zhi Zhang, Robert B. Fleischman, José I. Restrepo, Gabrielle Guerrini, Arpit Nema, Dichuan Zhang, Ulina Shakya, Georgios Tsampras, Richard Sause (2018), Shake table test performance of an inertial force-limiting floor anchorage system, Earthquake Engineering & Structural Dynamics, 47 (10), 1987-2011,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

Example Installation at NEES @ UCSD



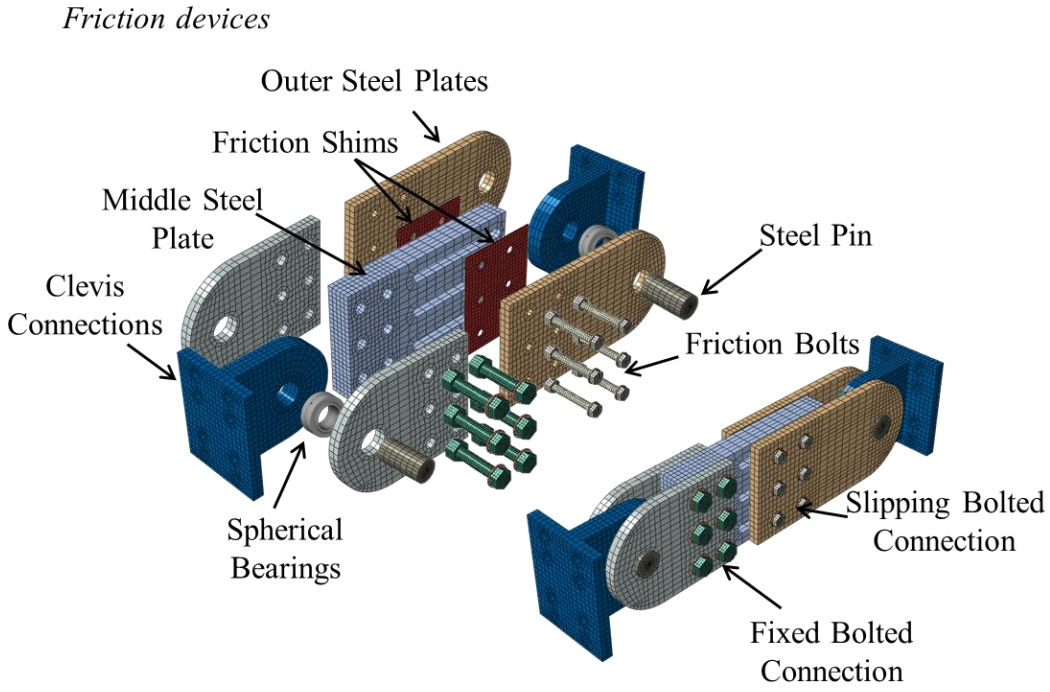
THE UNIVERSITY OF ARIZONA UC San Diego LEHIGH UNIVERSITY

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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

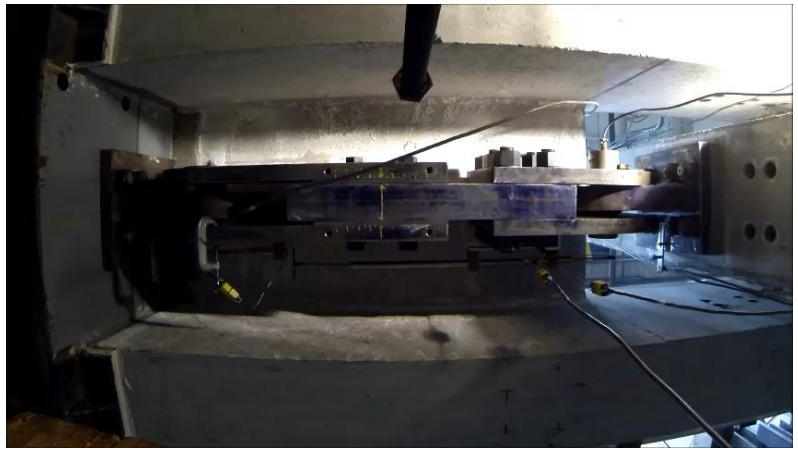
Friction in structural engineering

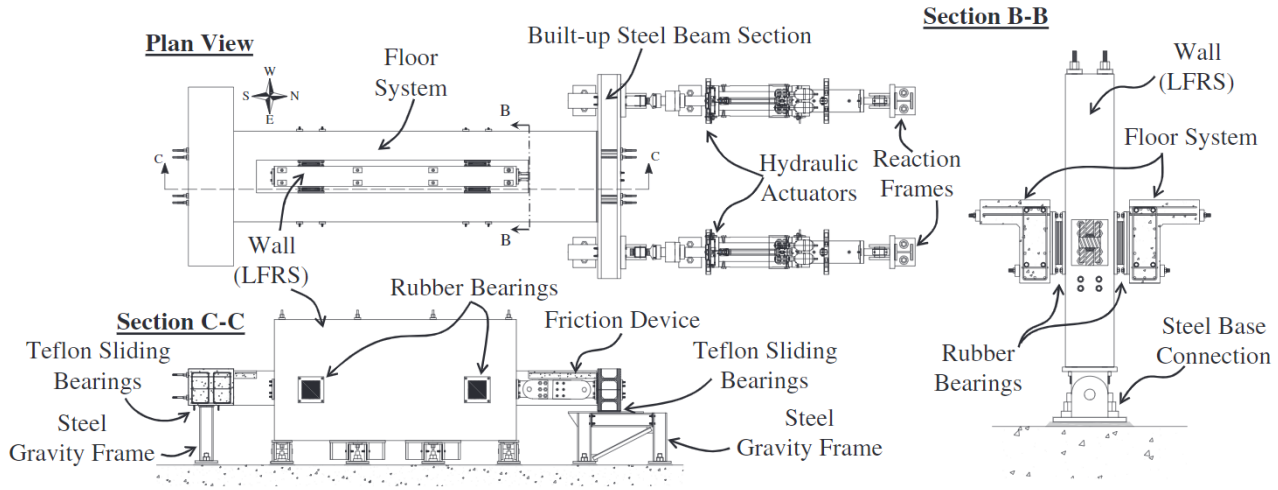
- Clark et al. 1973 – Limit forces due to differential settlement in foundations
- Bridge structures
- Precast concrete structures
- Steel braced frames
- Moment resisting frames
- Self-Centering Moment Resisting Frames
- Rocking Walls
- Friction dampers
- Self-centering friction-based braces



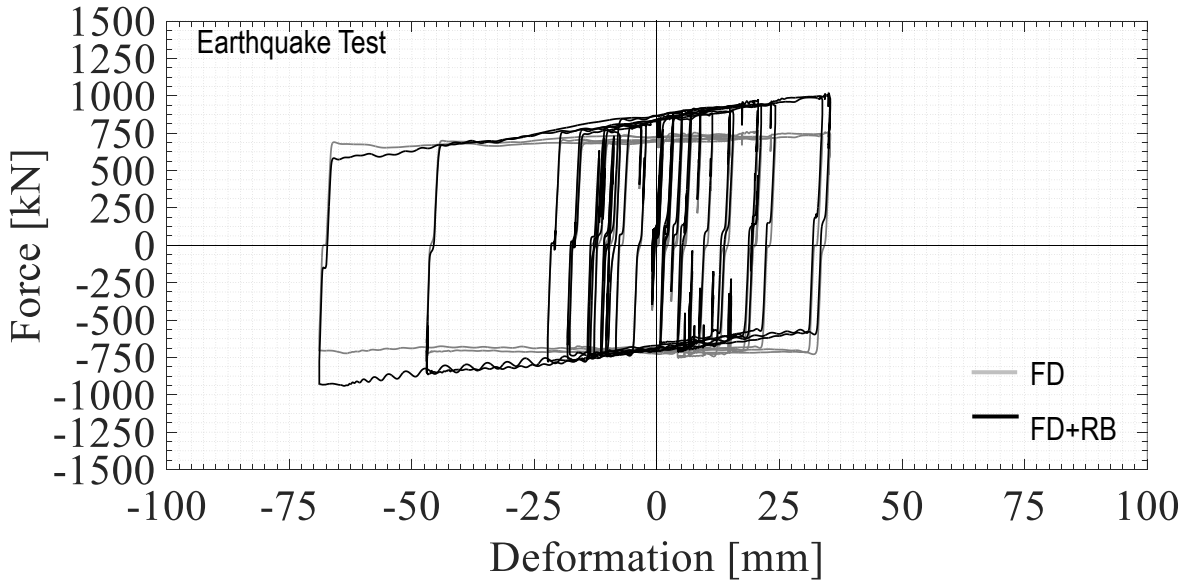
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Friction-based Force-Limiting Connections (Cont'd)



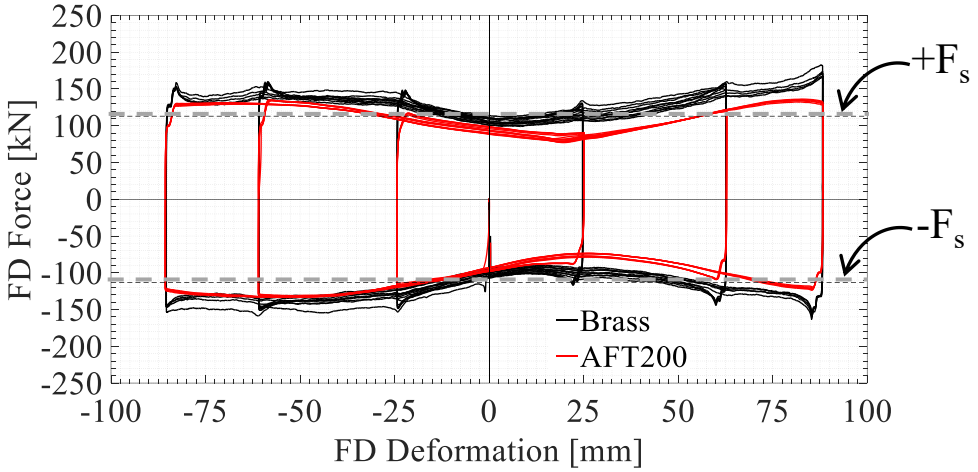


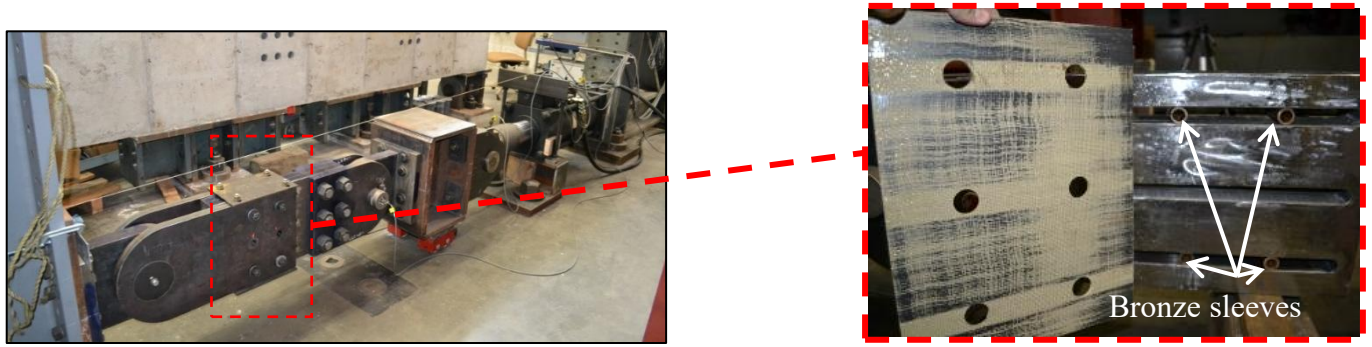
Geometric tolerances
Materials in frictional interface
Break-in effects
Sliding velocity
Dwell time



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 Engng Struct Dyn*. 2018;47:1032–1053. https://doi.org/10.1002/eqe.3004

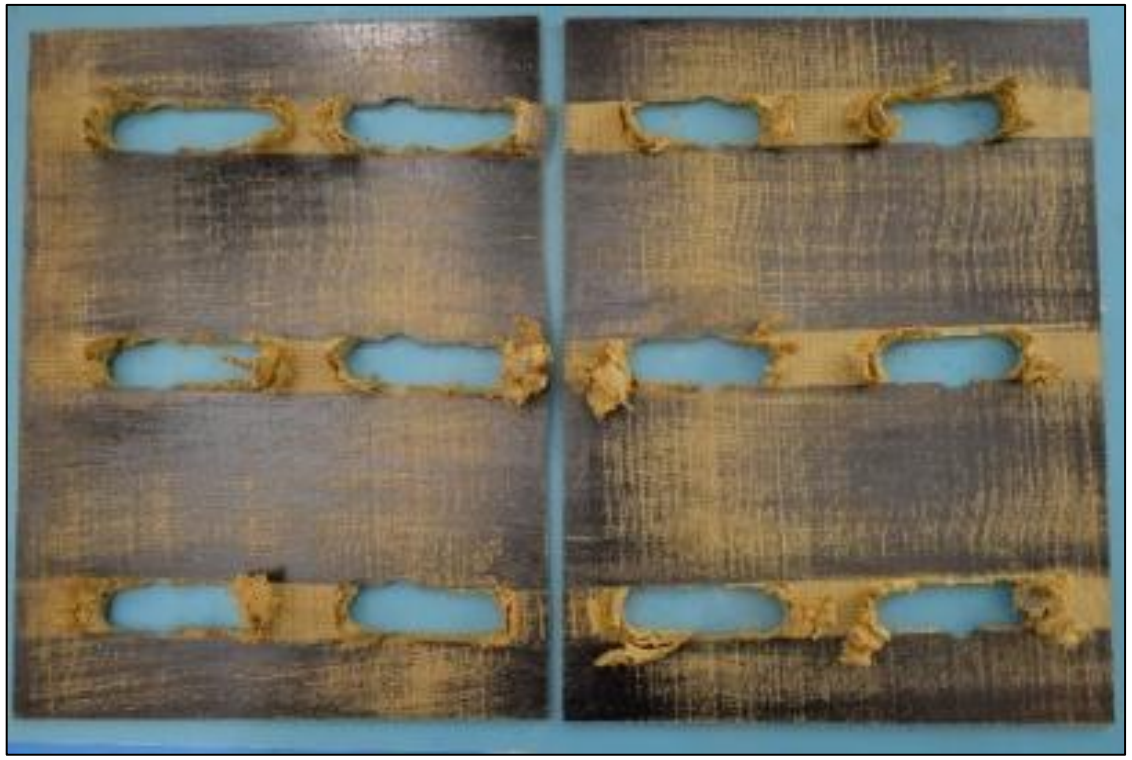
Machining of steel plates

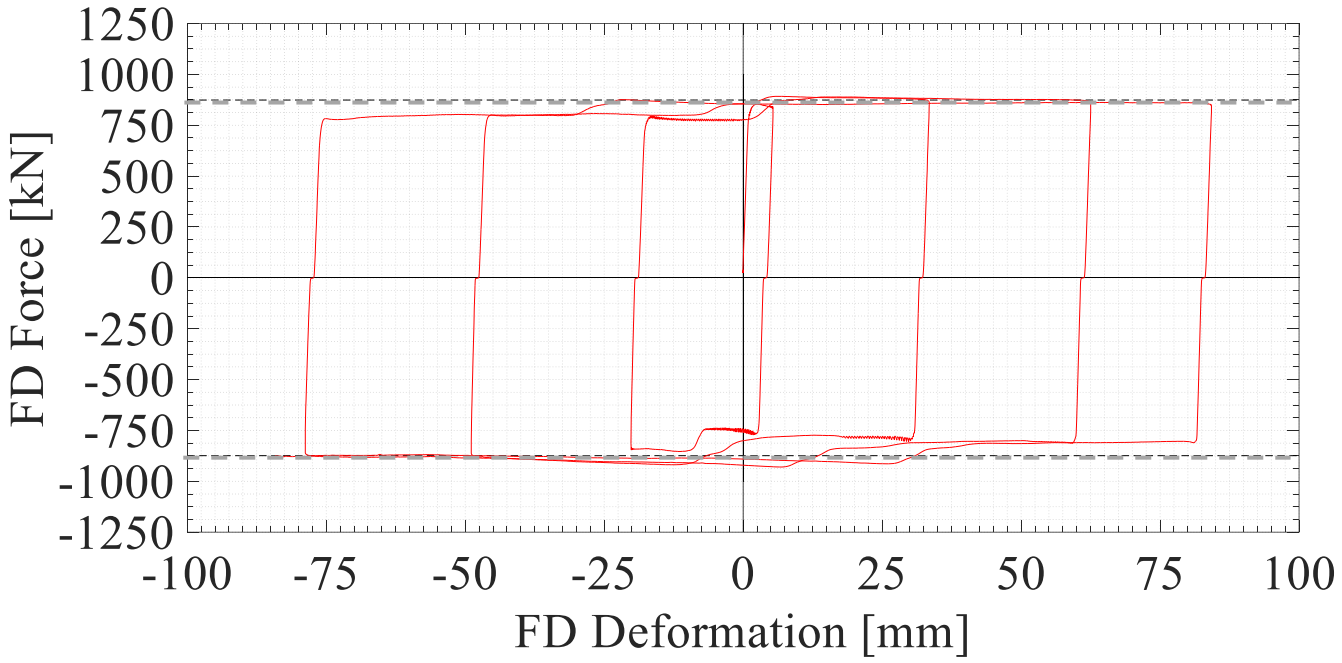




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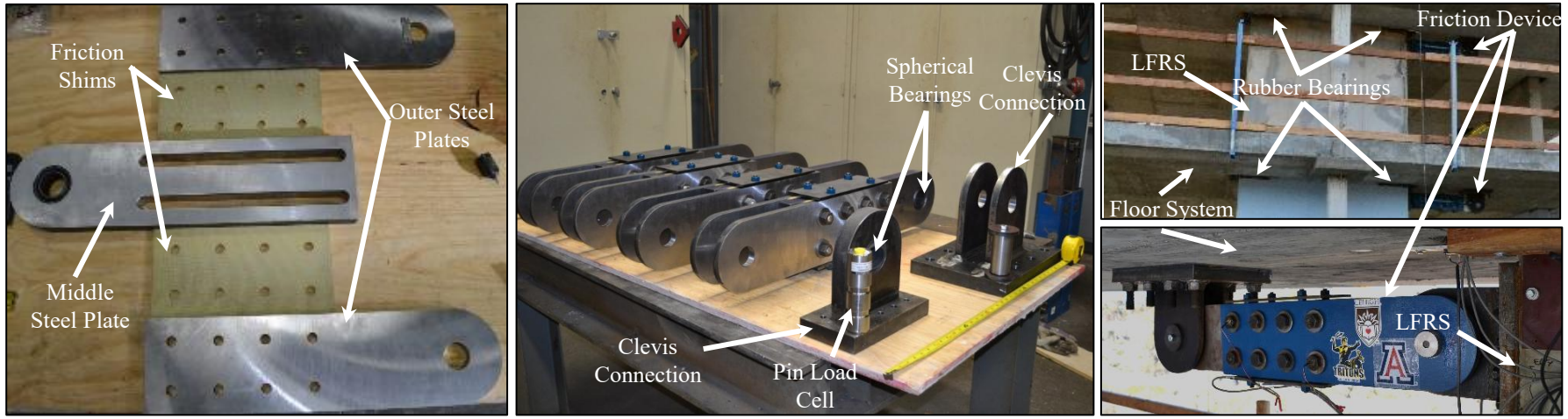
Damage of friction shims

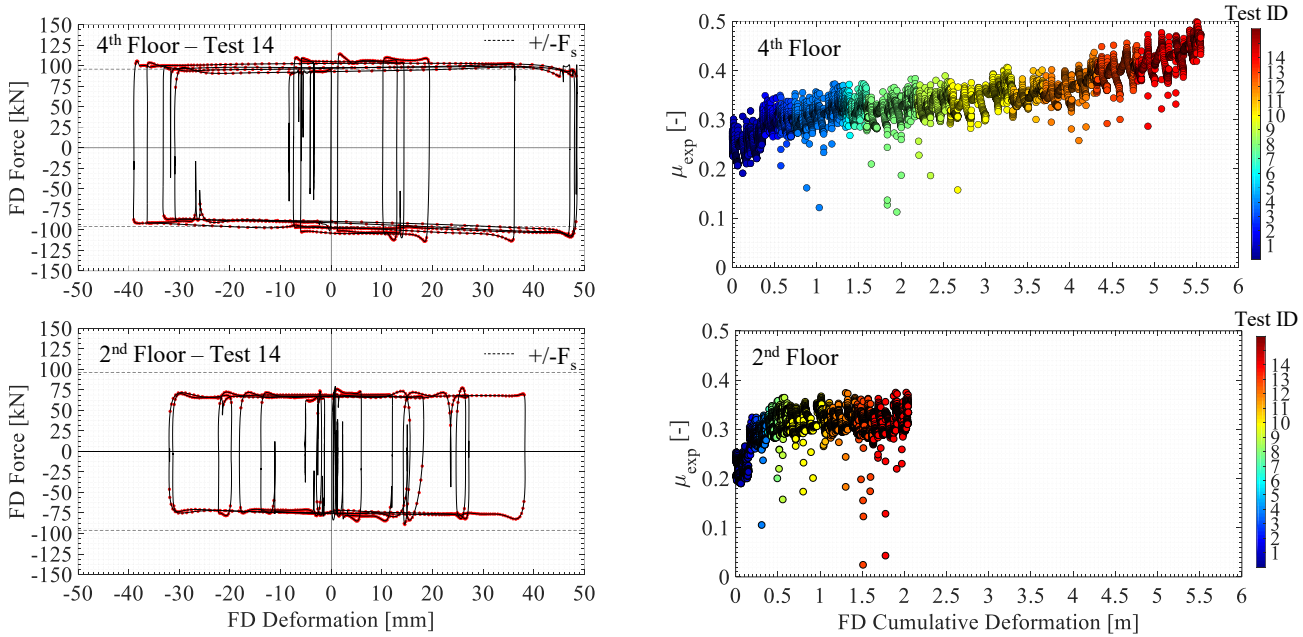




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Sliding History: Break-in effect

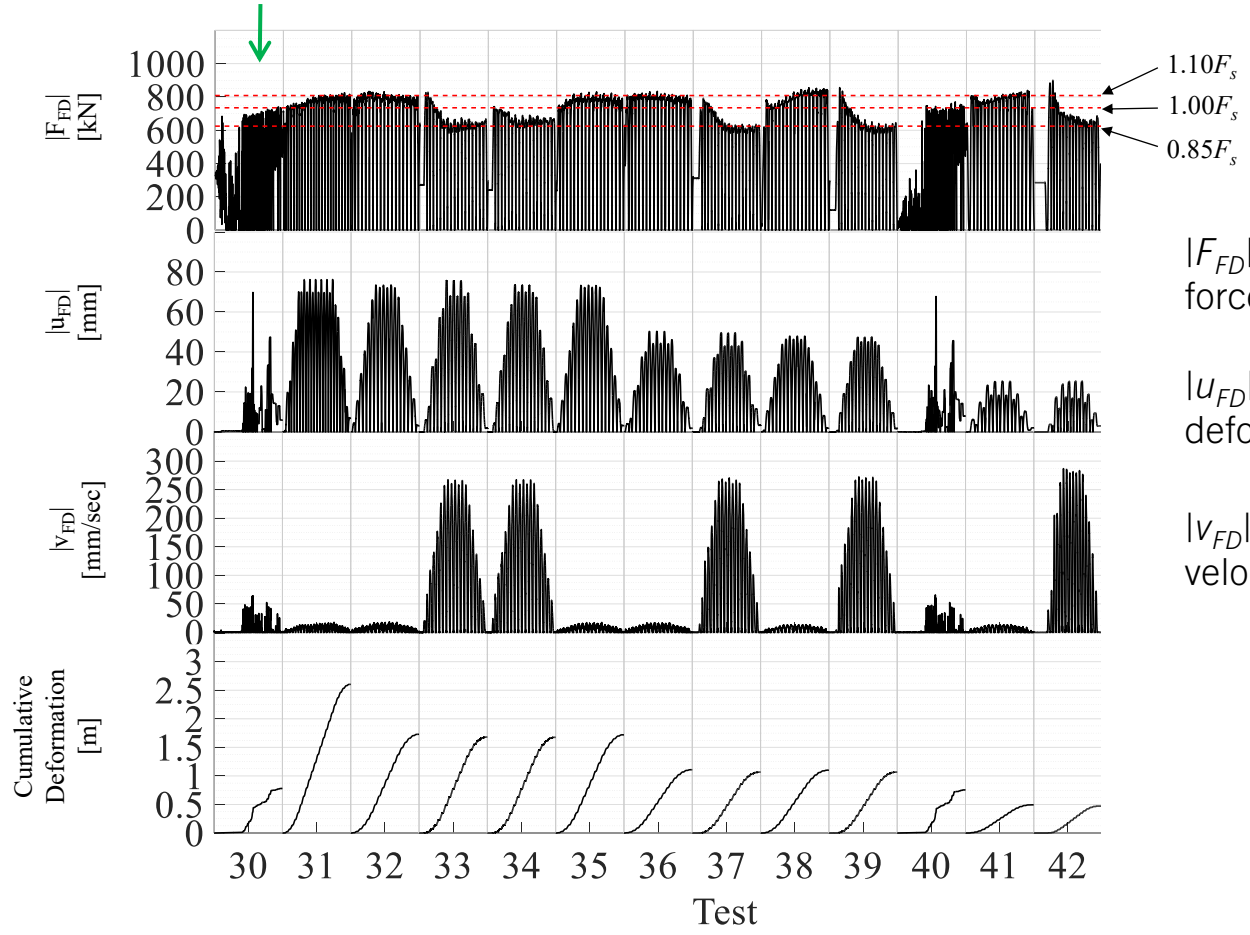




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Sliding History: Break-in effect (Cont'd)

$|F_{FDs}|$ increases from approximately $0.92F_s$ to approximately $1.00F_s$ due to the "break-in" effect



$|F_{FD}|$ is the absolute FD force

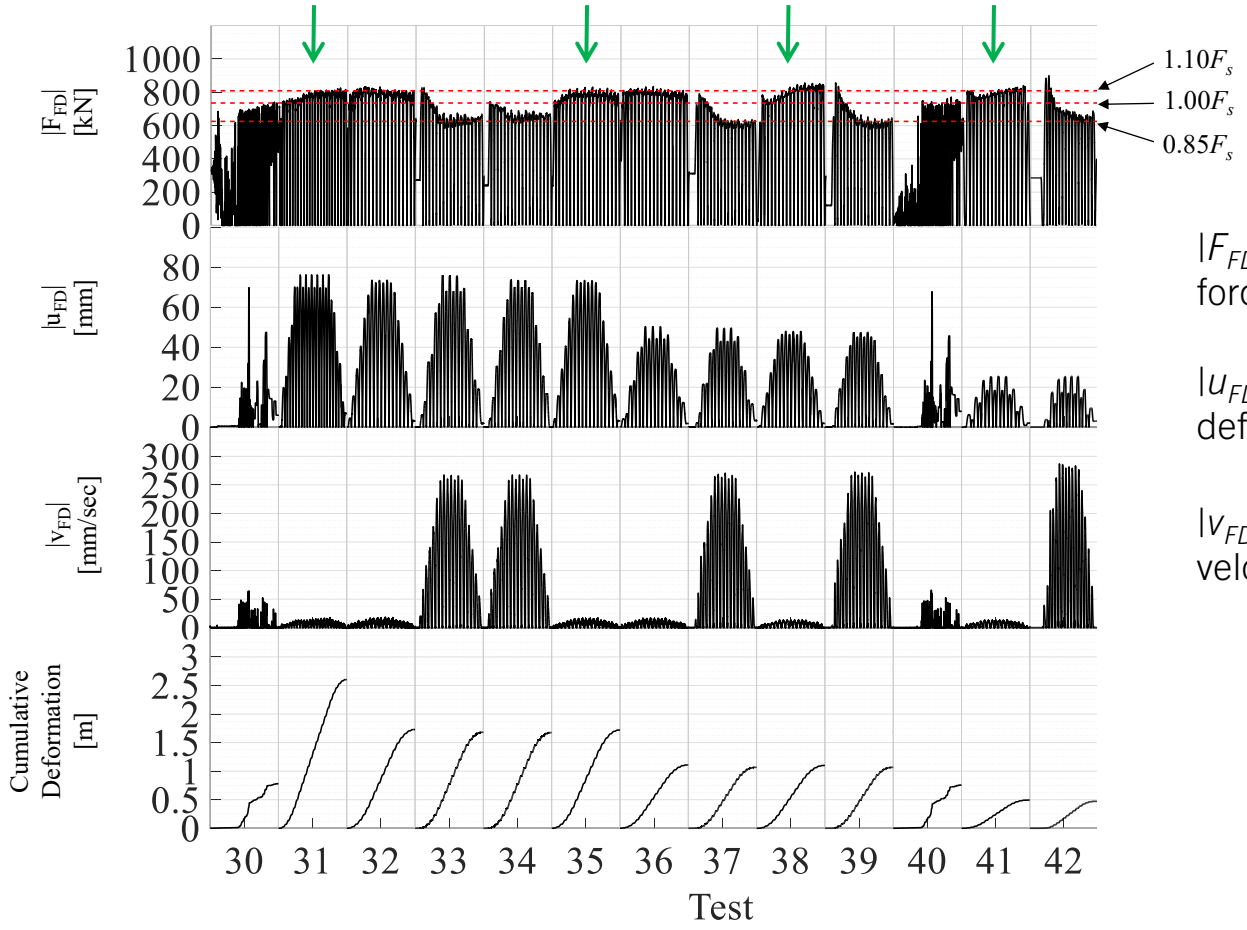
$|u_{FD}|$ is the absolute FD deformation

$|v_{FD}|$ is the absolute FD velocity

Tsampras G., Sause R., Fleischman R. B., Restrepo J. I., Experimental study of deformable connection consisting of friction device and rubber bearings to connect floor system to lateral force resisting system. Earthquake Engng Struct Dyn. 2018;47:1032-1053. https://doi.org/10.1002/eqe.3004

Sliding History: Low velocity effect

$|F_{FDs}|$ in quasi-static tests that follow dynamic tests or earthquake tests increases to approximately $1.10F_s$



$|F_{FD}|$ is the absolute FD force

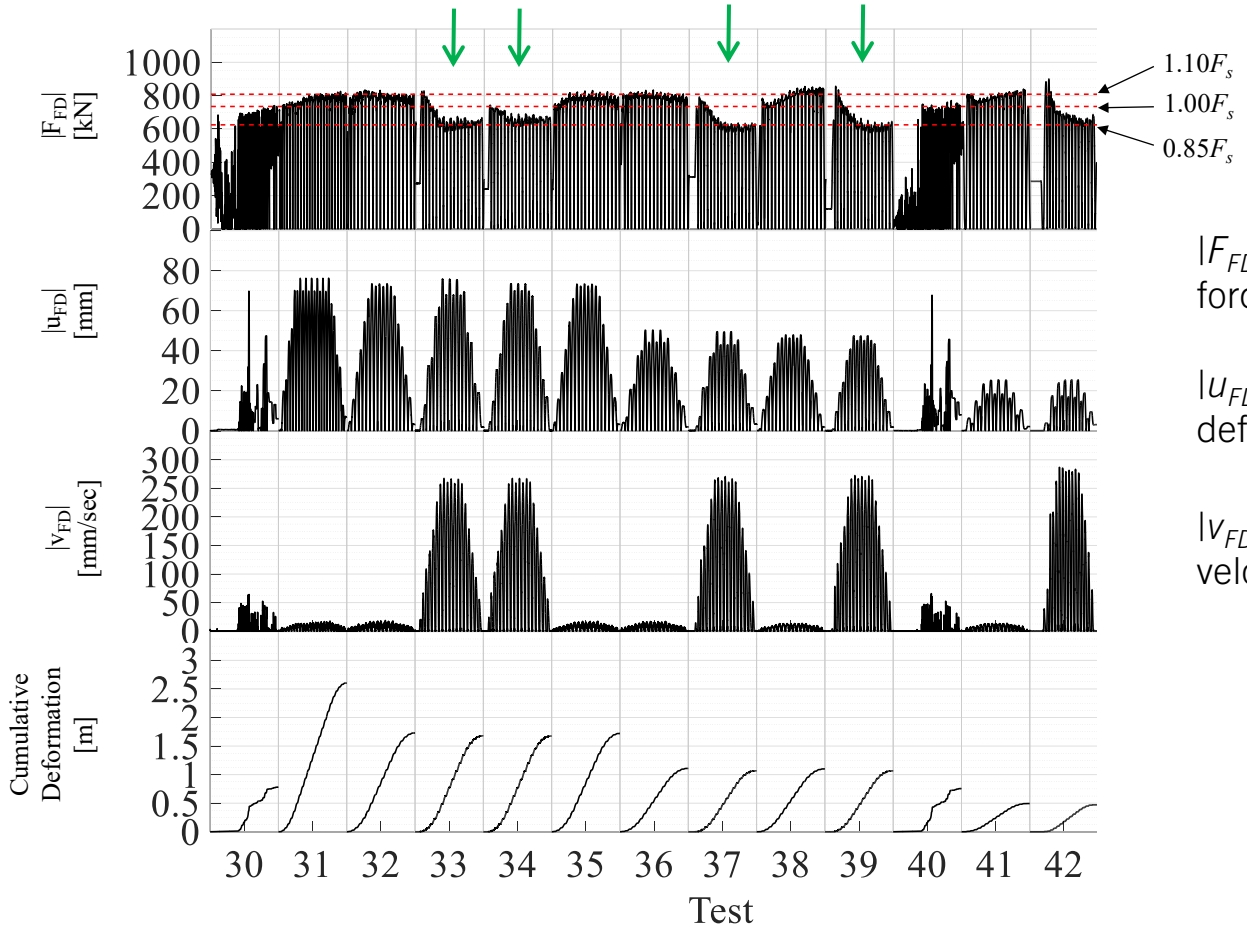
$|u_{FD}|$ is the absolute FD deformation

$|v_{FD}|$ is the absolute FD velocity

Tsampras G., Sause R., Fleischman R. B., Restrepo J. I., Experimental study of deformable connection consisting of friction device and rubber bearings to connect floor system to lateral force resisting system. Earthquake Engng Struct Dyn. 2018;47:1032-1053. https://doi.org/10.1002/eqe.3004

Sliding History: High velocity effect

$|F_{FDs}|$ in dynamic tests decreases to approximately $0.85F_s$



$|F_{FD}|$ is the absolute FD force

$|u_{FD}|$ is the absolute FD deformation

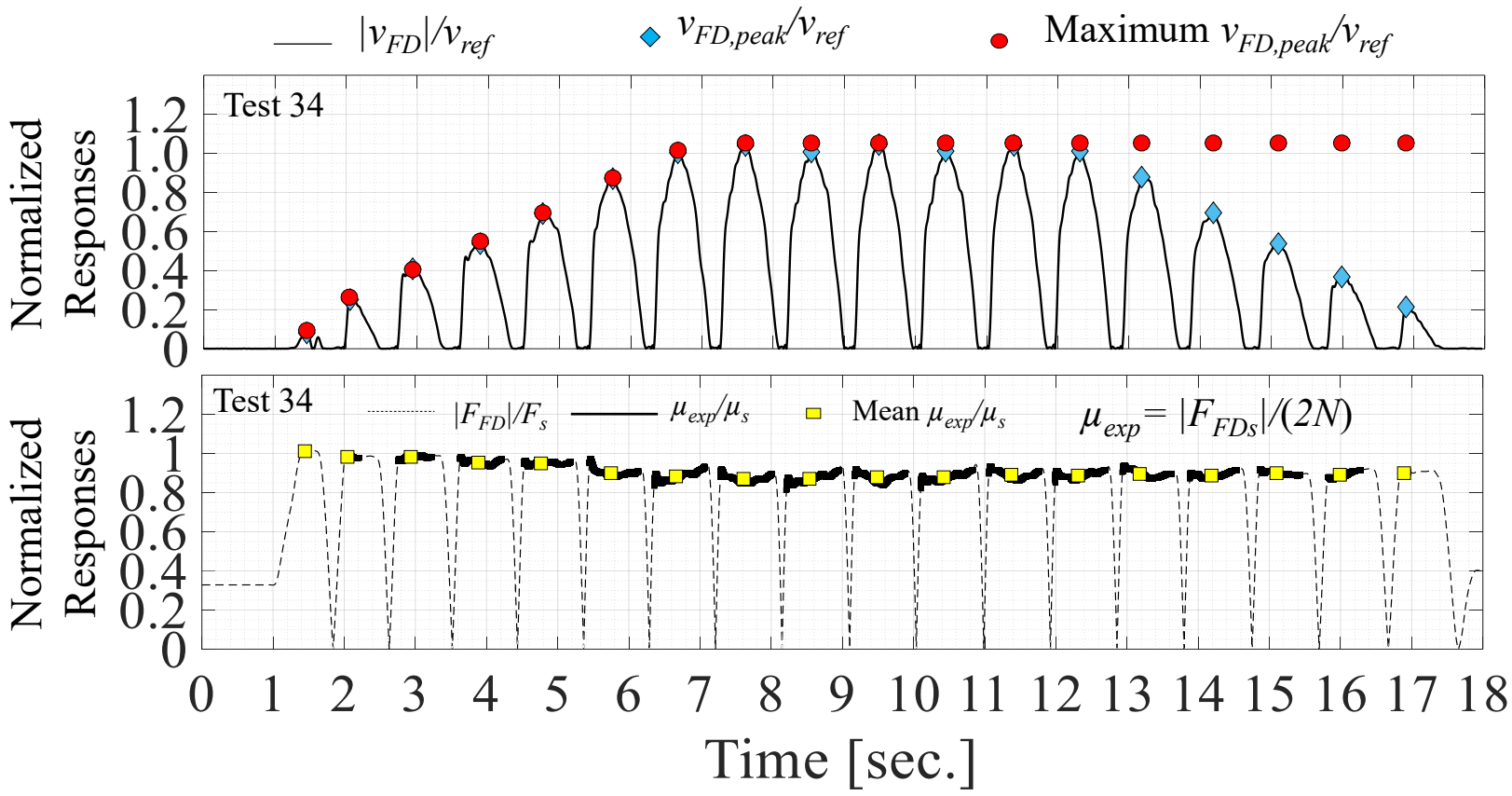
$|v_{FD}|$ is the absolute FD velocity

Tsampras G., Sause R., Fleischman R. B., Restrepo J. I., Experimental study of deformable connection consisting of friction device and rubber bearings to connect floor system to lateral force resisting system. Earthquake Engng Struct Dyn. 2018;47:1032-1053. https://doi.org/10.1002/eqe.3004

Sliding History: High velocity effect (Cont'd)

(1) μ_{exp} does not depend on the instantaneous v_{FD}

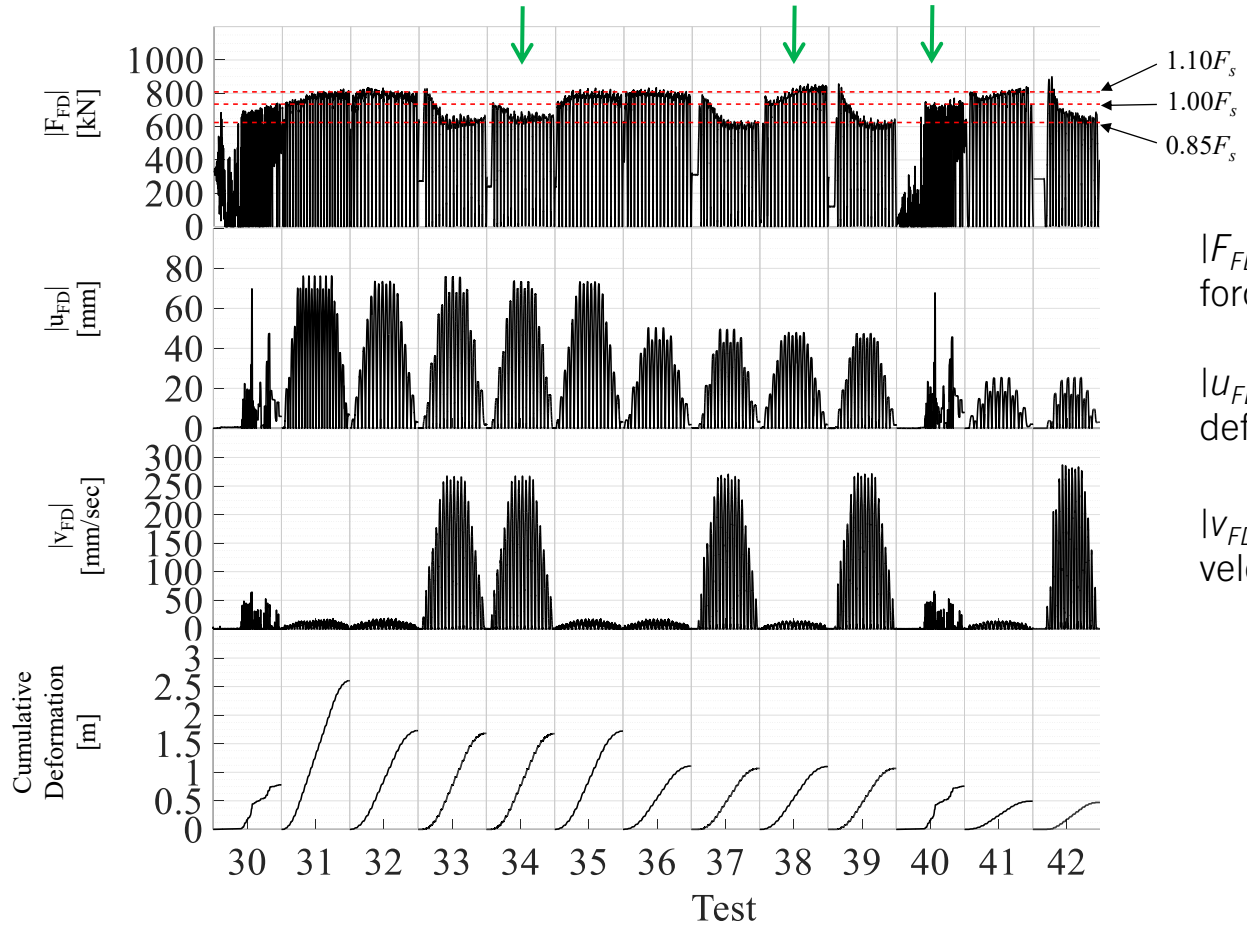
(2) μ_{exp} decreases as the maximum $v_{FD,peak}$ increases



Tsampras G., Sause R., Fleischman R. B., Restrepo J. I., Experimental study of deformable connection consisting of friction device and rubber bearings to connect floor system to lateral force resisting system. Earthquake Engng Struct Dyn. 2018;47:1032-1053. https://doi.org/10.1002/eqe.3004

Sliding History: Dwell time effect

$|F_{FDs}|$ increases to approximately $1.00F_s$ after dynamic tests during t_{dwell}



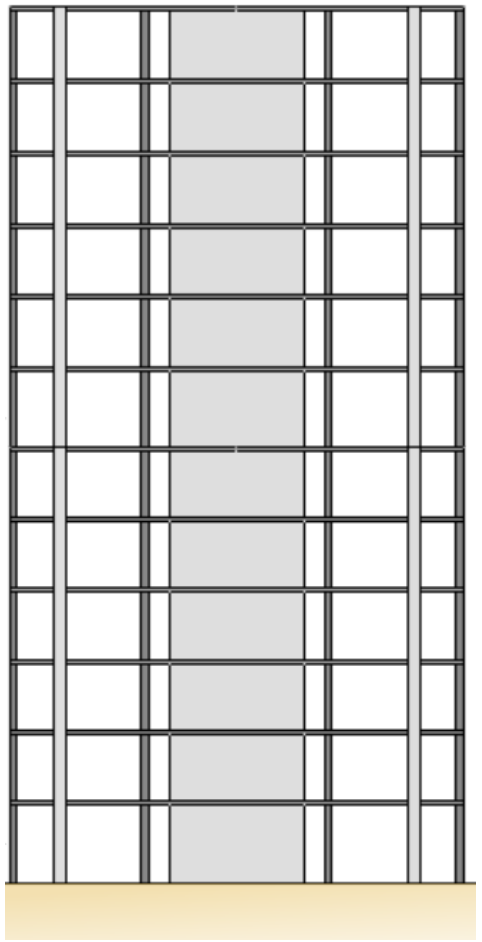
$|F_{FD}|$ is the absolute FD force

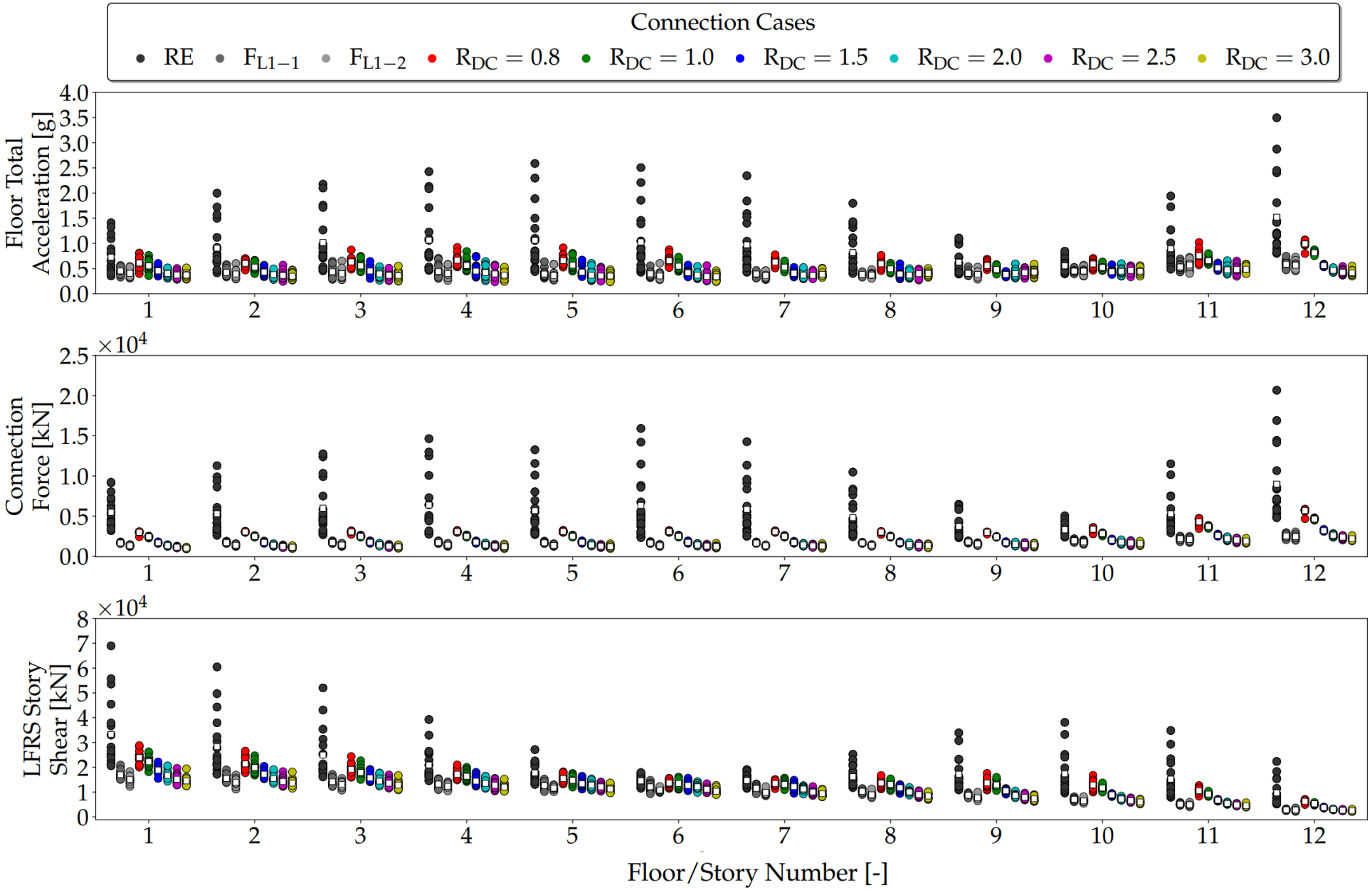
$|u_{FD}|$ is the absolute FD deformation

$|v_{FD}|$ is the absolute FD velocity

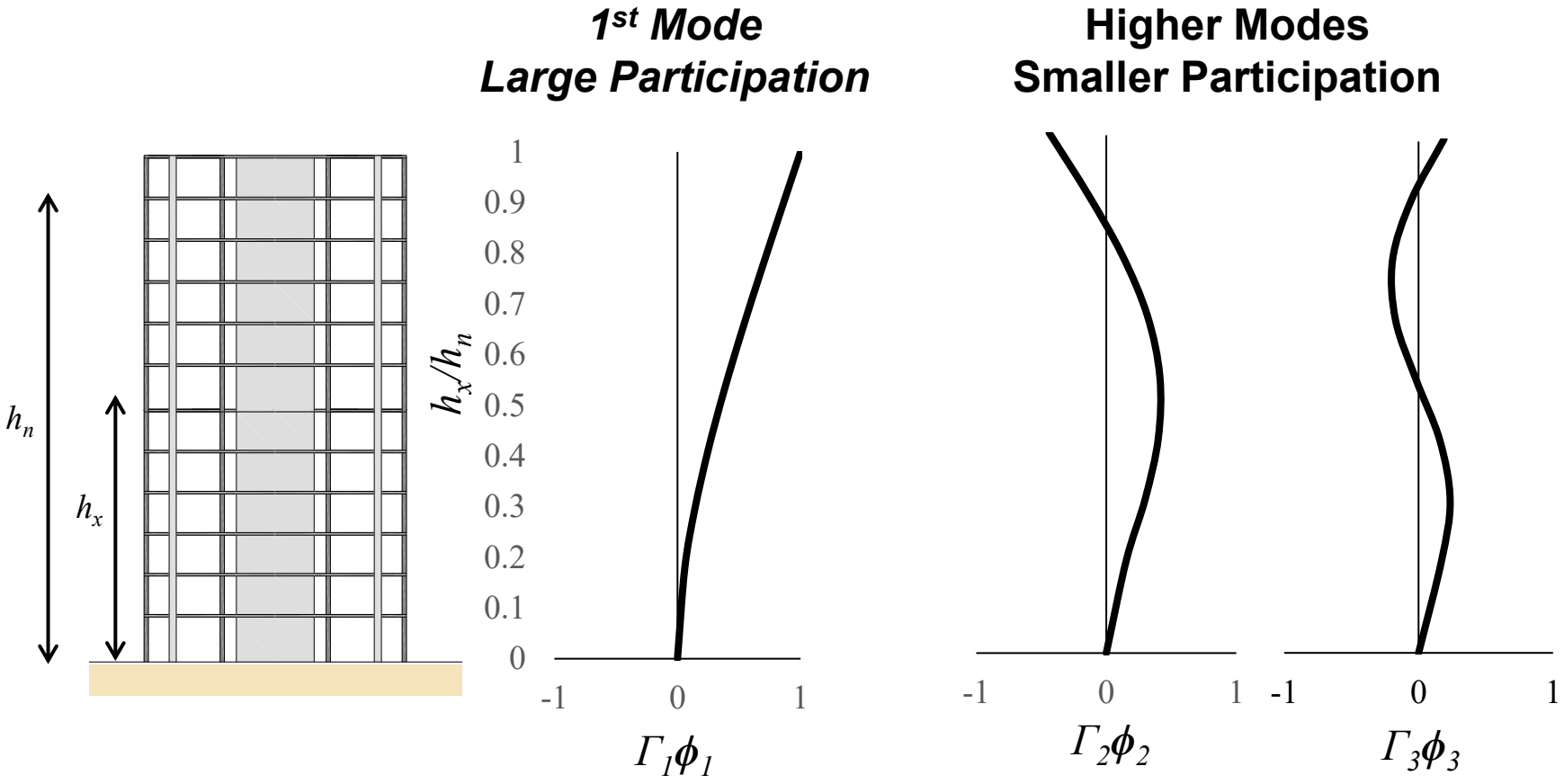
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Limited acceleration and force responses



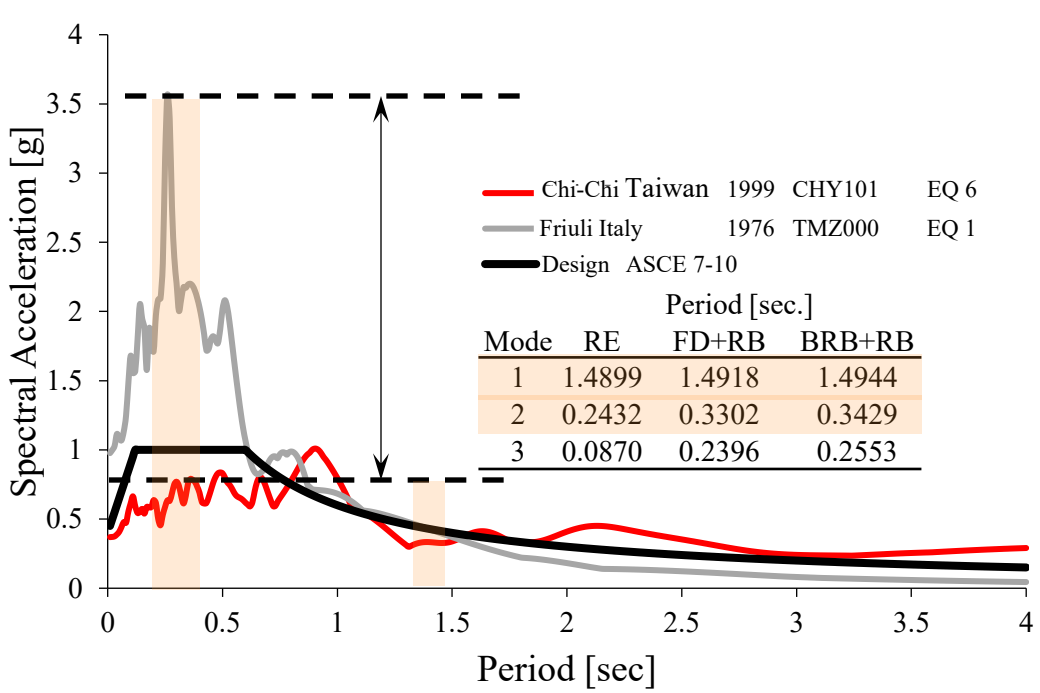


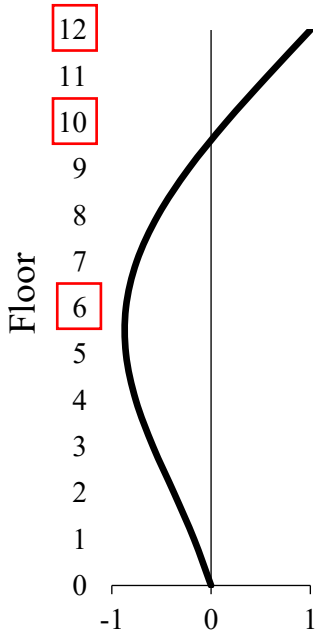
Higher Mode Responses



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.

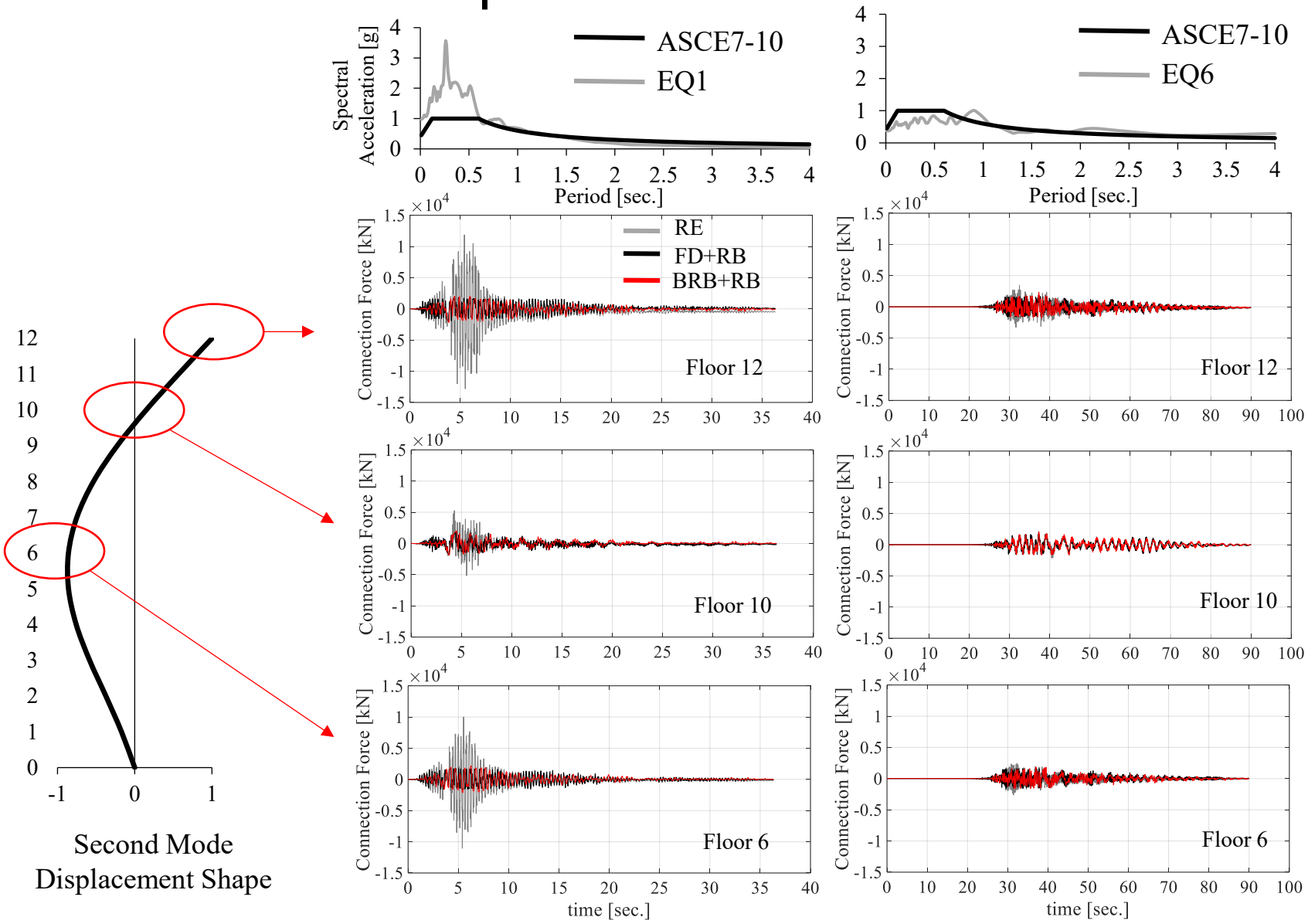
Higher Mode Responses





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Higher Mode Responses



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