18th World Conference on Earthquake Engineering
Technical Session IDD-4

# Seismic Response of Core Wall Building with Force-limiting Connections

Kyoungyeon Lee, Graduate Student Researcher, UC San Diego

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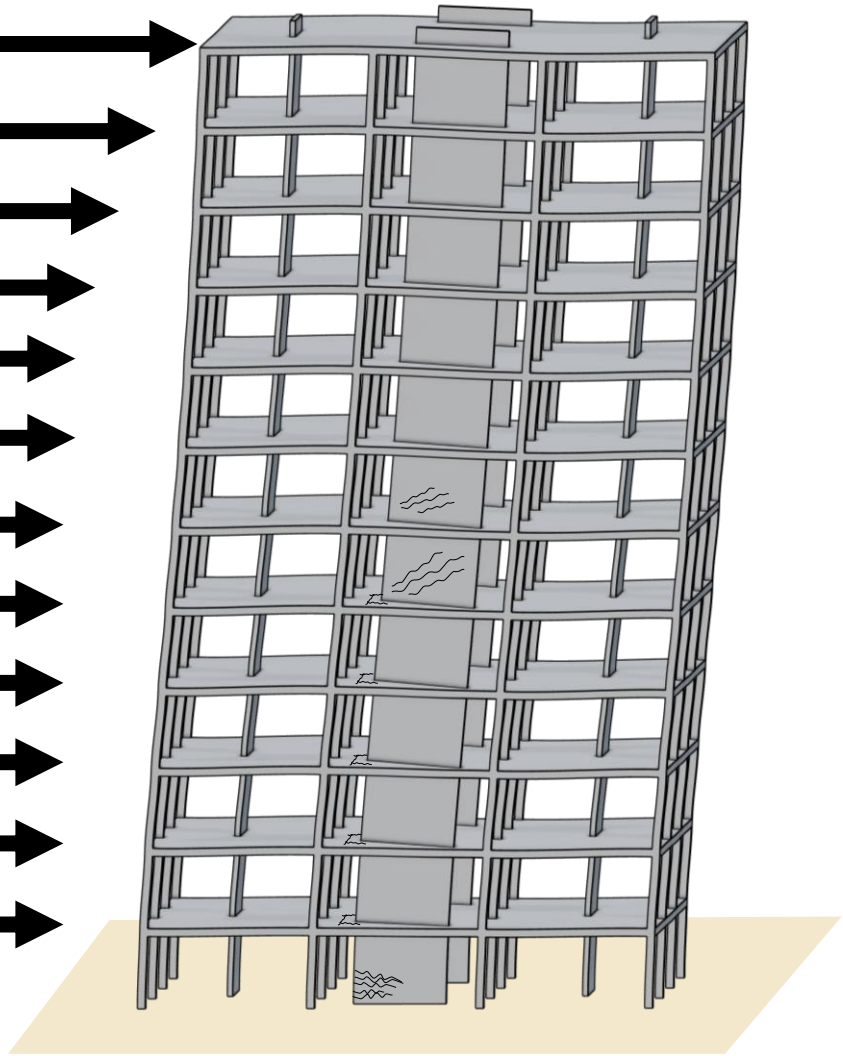
Kyoungyeon Lee; Georgios Tsampras;
C. Franco Mayorga (Forthcoming),
ASCE *Journal of Structural Engineering*,
DOI: 10.1061/JSENDH/STENG-13609

July 5, 2024
Milan, Italy

http://tsampras.ucsd.edu

# Buildings with flexural yielding base mechanism

Seismic induced horizontal forces

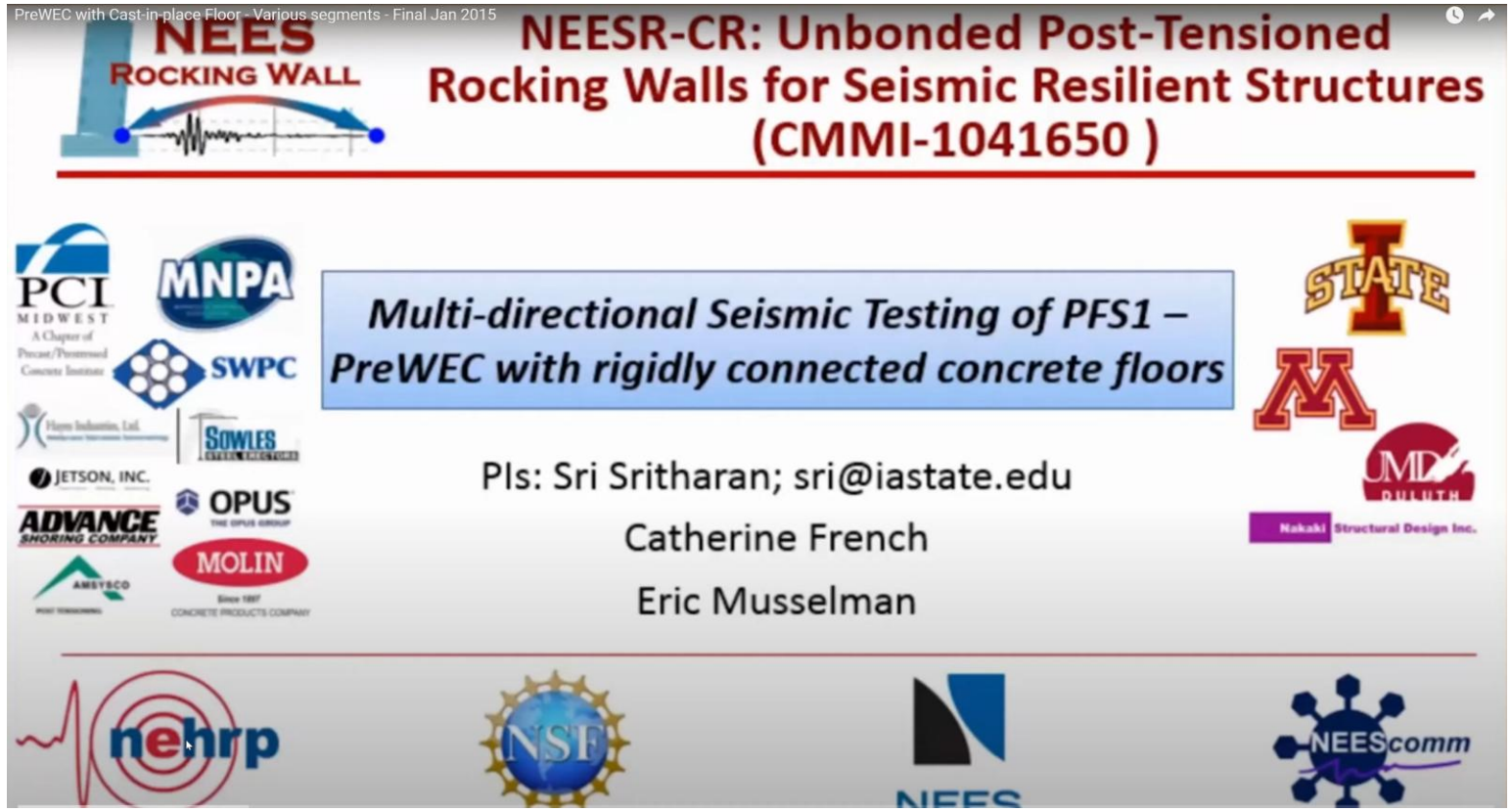


Flexural yielding base mechanism

Core wall building construction at UC San Diego



# Damage in floor diaphragms due to kinematics



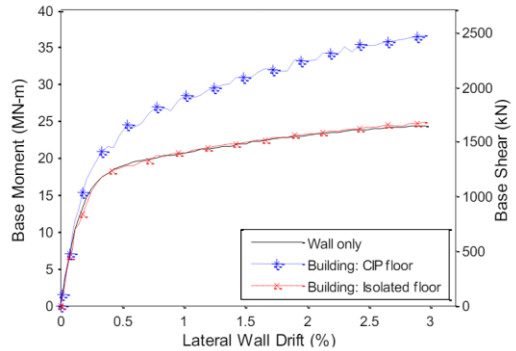




Figure 6 – Calculated response of the prototype building FEM with both cast-in-place and isolated floors

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.*

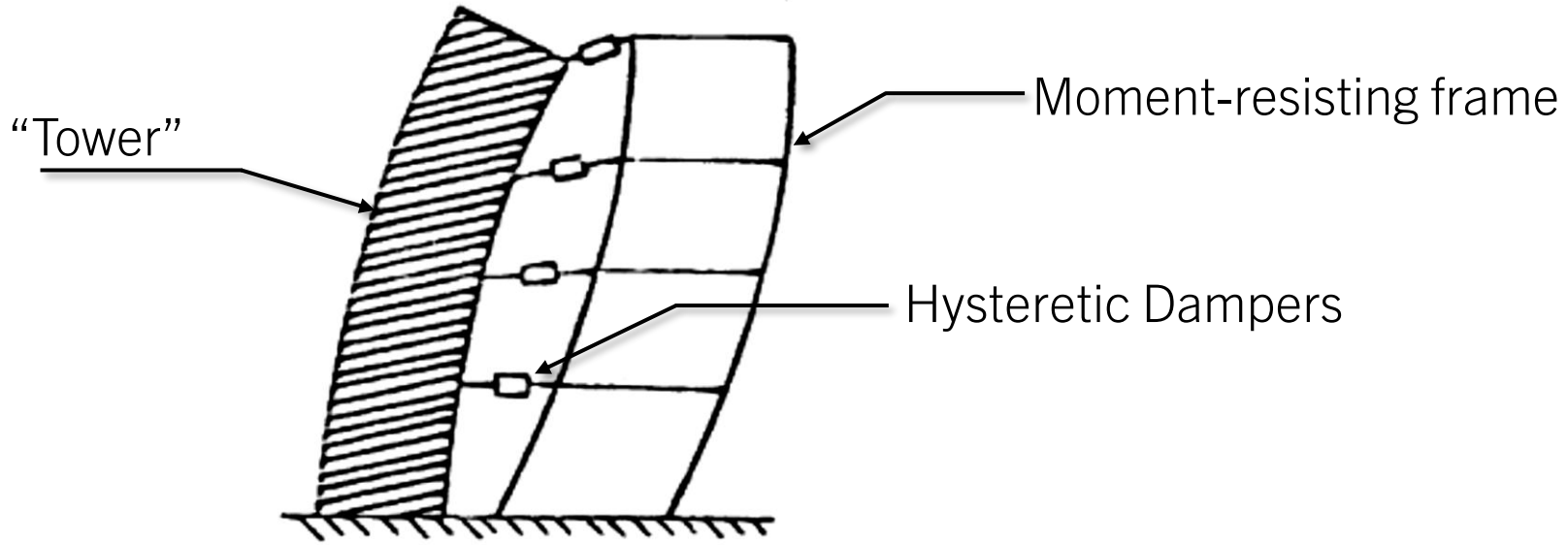
2012 NZSEE Conference

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

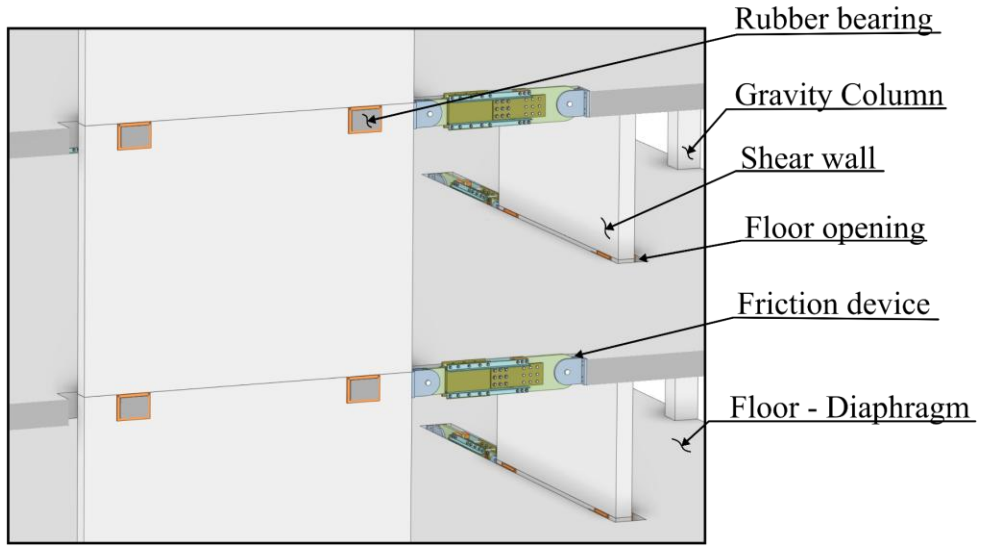
Openings in the Floor Systems
Force-limiting connections between Floor – LFRS with two types of components:

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

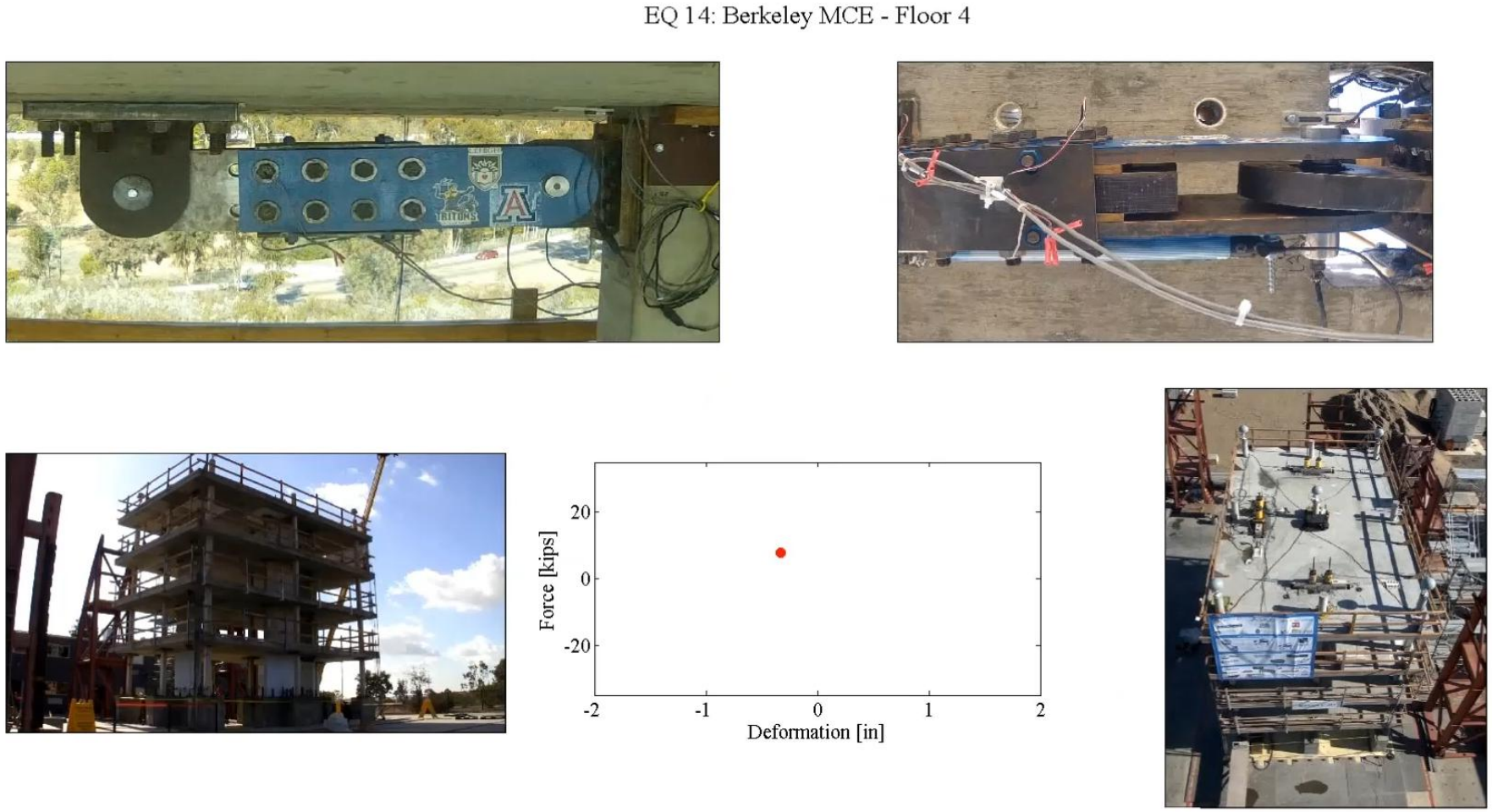



Cross section in *X*-*Z* plane


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

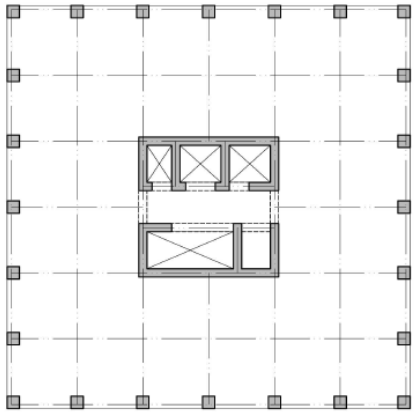
# Example Installation at NEES @ UCSD

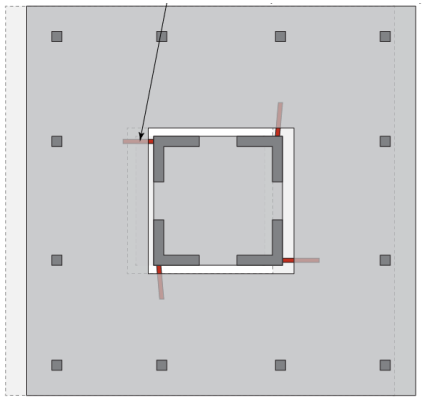


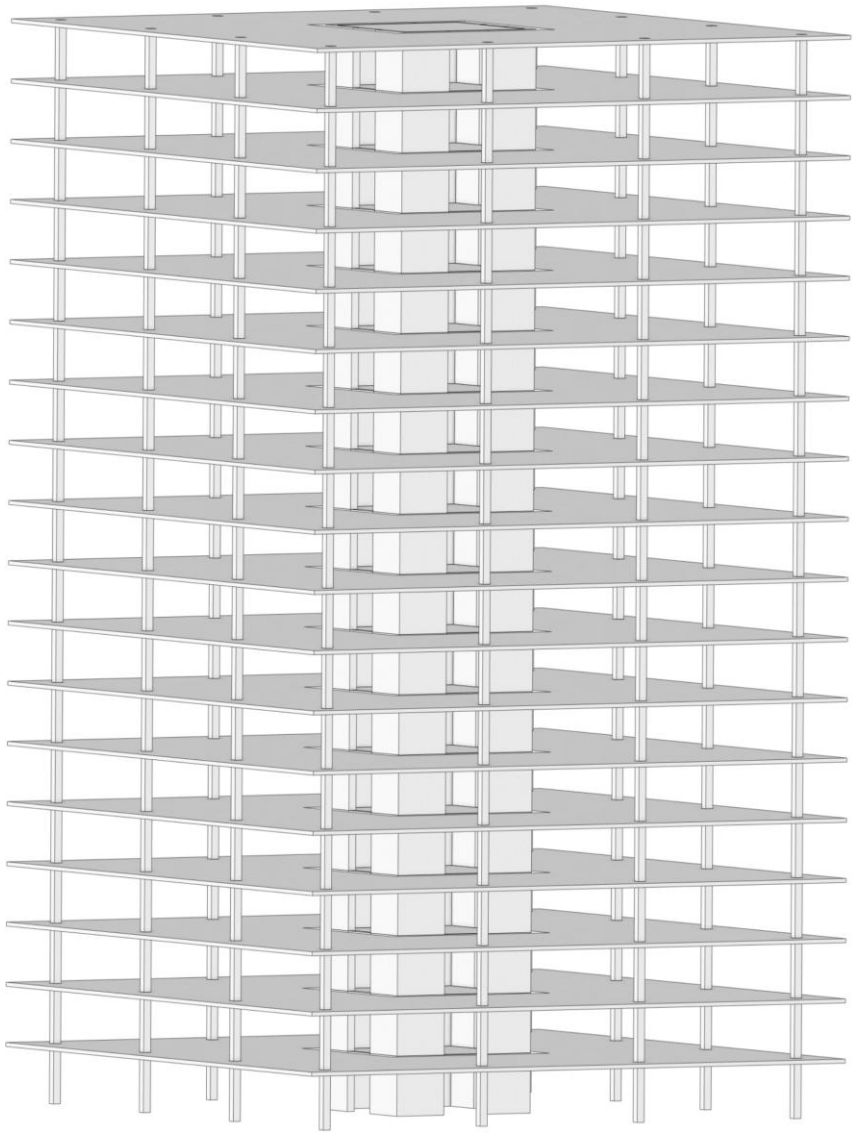

Zhi Zhang, Robert B. Fleischman, José I. Restrepo, Gabrielle Guerrini, Arpit Nema, Dichuan Zhang, Ulina Shakya, Georgios Tsampras, Richard Sause (2018), Shake table test performance of an inertial force-limiting floor anchorage system, Earthquake Engineering & Structural Dynamics, 47 (10), 1987-2011,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

# Can we use force limiting connections developed for planar seismic force resisting systems in core wall buildings?

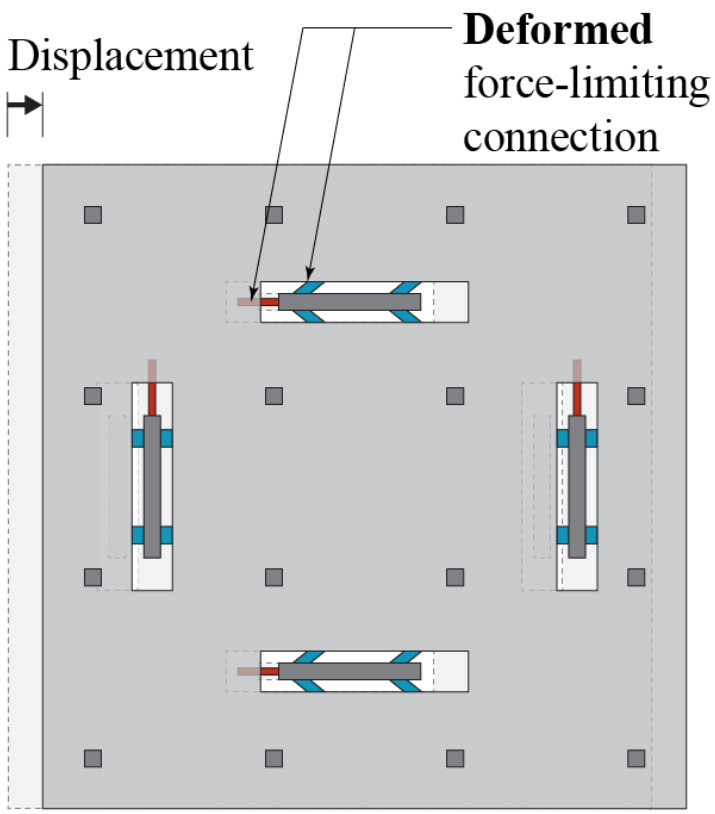




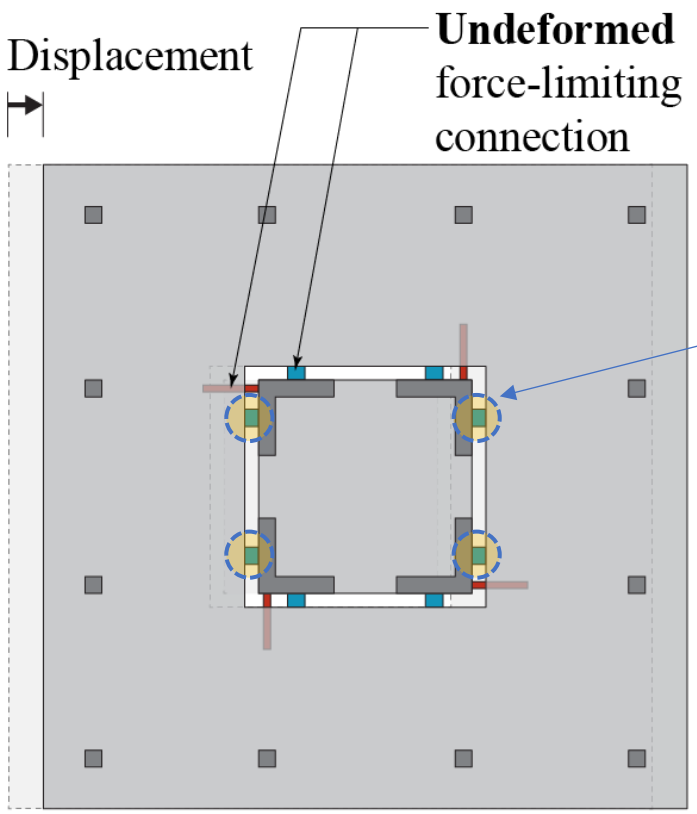


Kyoungyeon Lee; Georgios Tsampras; C. Franco Mayorga (Forthcoming), "Reinforced Concrete Core Wall Buildings with Modified Friction-Based Force-Limiting Connections: Connection Design Considerations and Three-Dimensional Response to Bidirectional Ground Motions " *Journal of Structural Engineering*, DOI: 10.1061/JSENDH/STENG-13609

# Force-limiting connections in core wall buildings




Planar Wall

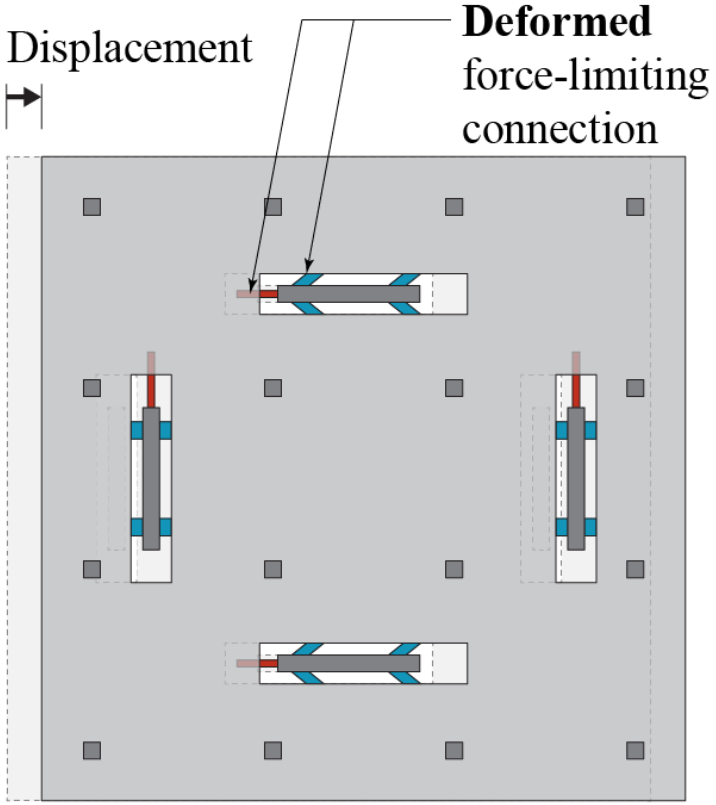



Core Wall

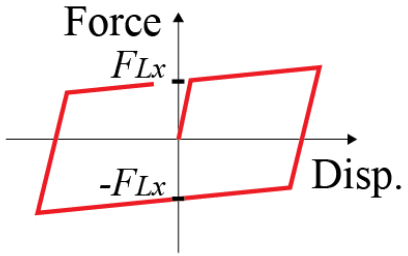
Rubber bearings constrain the relative movement between the wall and the floors.

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 " *Journal of Structural Engineering*, DOI: 10.1061/JSENDH/STENG-13609

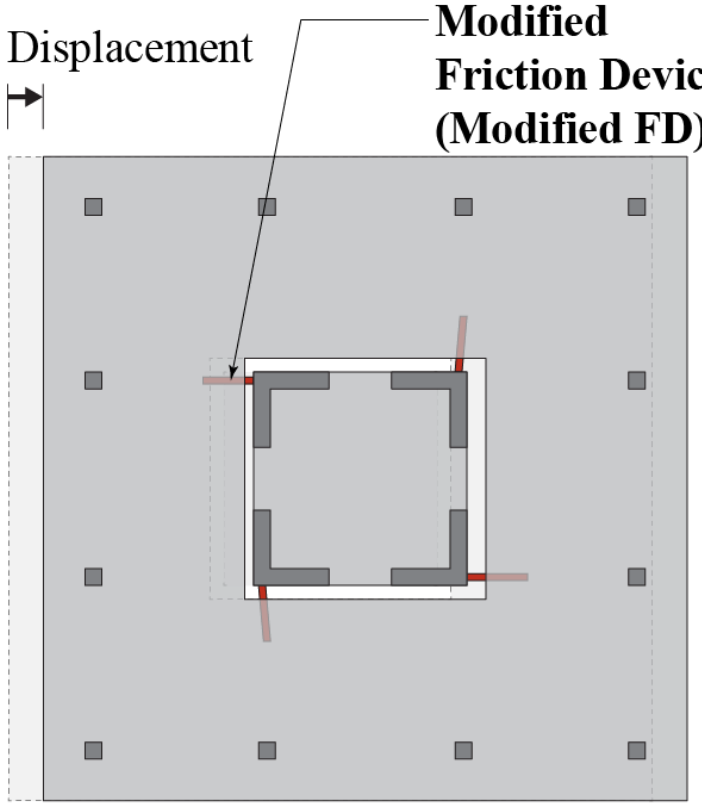
# Force-limiting connections in core wall buildings



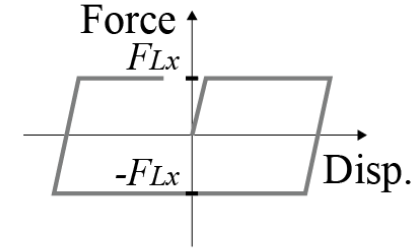

Planar Wall



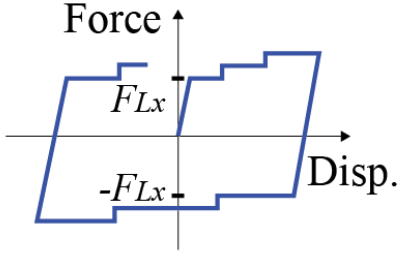

**FD+RB**
(Friction device
+ Rubber bearing)




Core Wall




**FD**
(Friction Device)




**Modified FD**
Discrete variable
limiting force

With Rubber bearing:
- Stabilize out-of-plane motion
- Provide post-elastic stiffness

Without Rubber bearing:
- Core wall can stabilize itself
- **Need post-elastic stiffness**

# Friction-based components 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 (Reinforced concrete and timber)
- Friction dampers
- Self-centering friction-based braces

Literature review available in:
Tsampras et al. (2018), Chen et al. (2023)

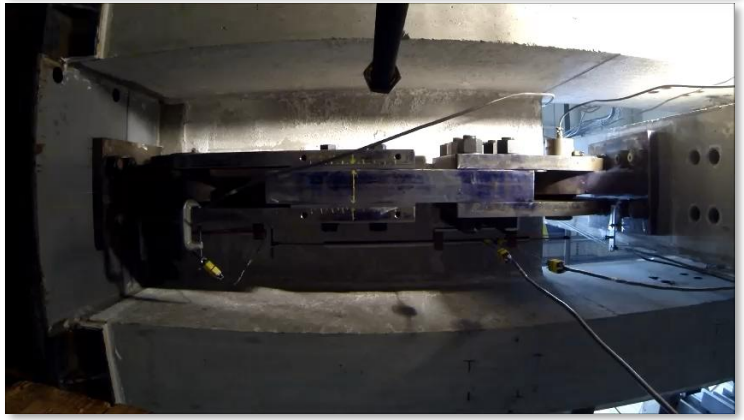
*Some examples from our past and ongoing research projects:*









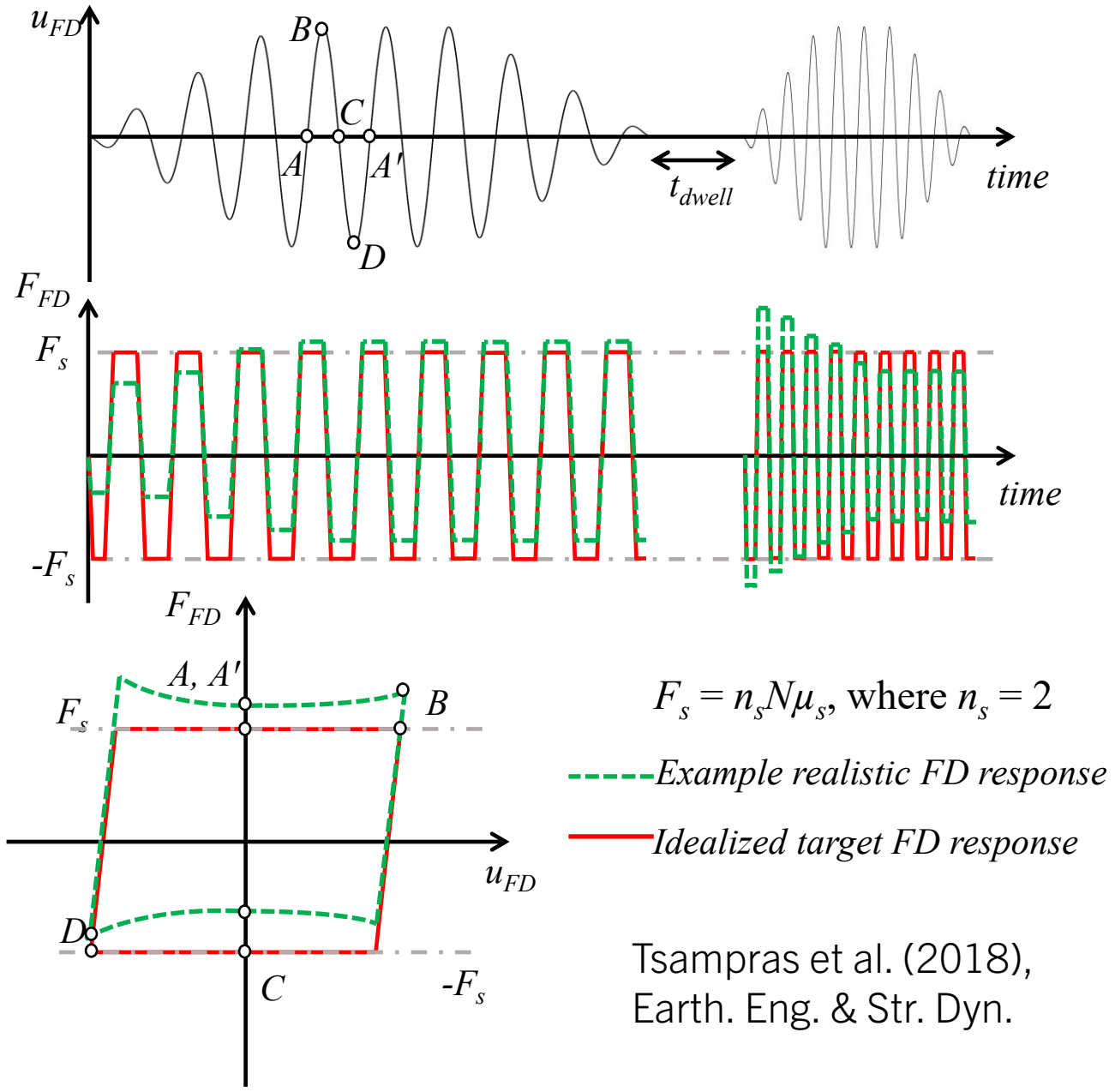



# Challenges with friction-based structural connections

Friction-sliding behavior of a bi-material interfaces is affected by:

- Sliding velocity
- Dwell time
- Galvanic corrosion in friction interface
- Creep of composite materials
- Break-in and cumulative sliding effects
- Geometric tolerances

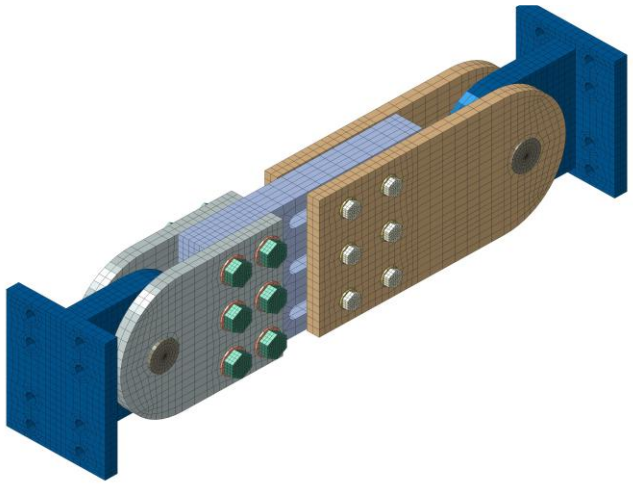
Limited large scale experimental data on mechanical and tribological properties of composite materials for friction-based structural connections

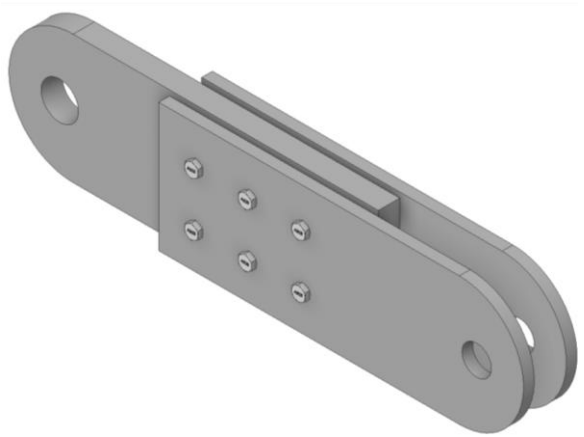


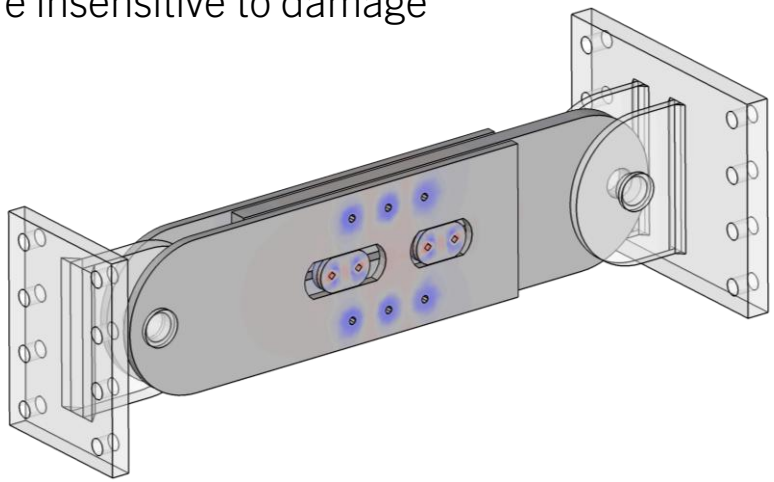

Tsampras et al. (2018), Earth. Eng. & Str. Dyn.

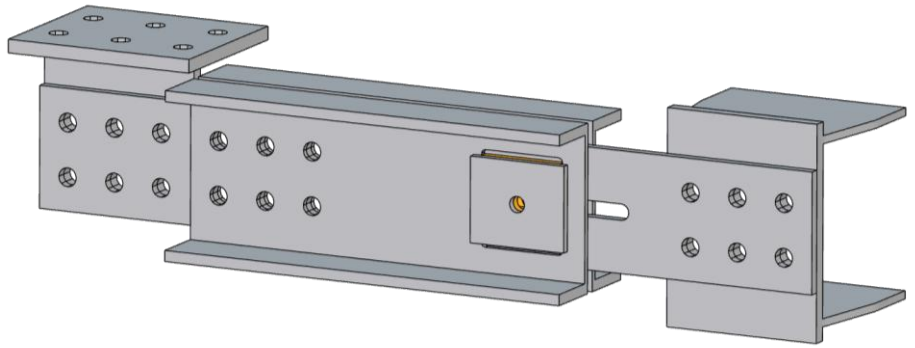
# Why friction-based force-limiting connections?

- Structural engineers have freedom in detailing
- Easy adjustments to achieve target force levels
- Decoupled stiffness and sliding friction force
- Possible designs with easy manufacturing and assembly
- Increase of displacement capacity by including longer slots in the design – no strain limitations
- Designs that allow low-damage and easy reparability
- Some designs are insensitive to damage







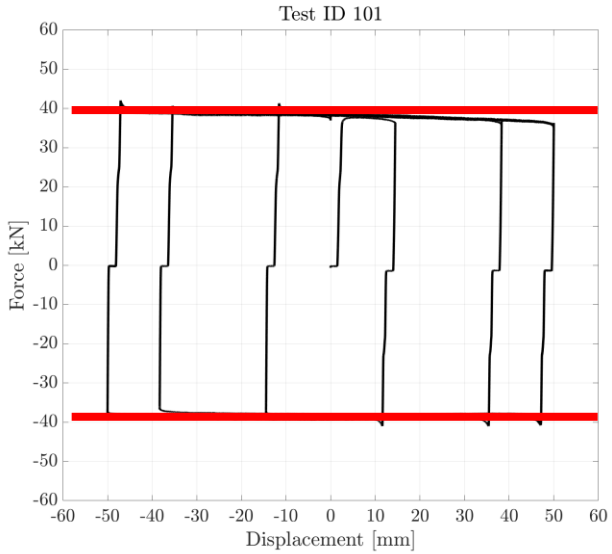


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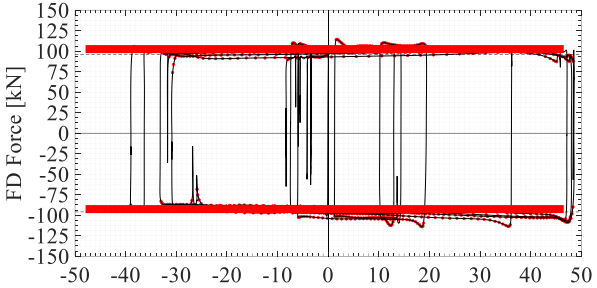
~40 kN





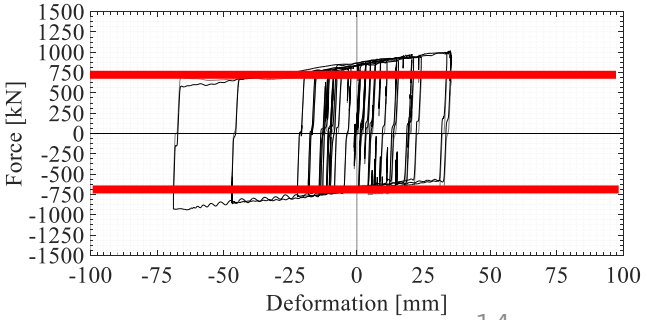

~100 kN



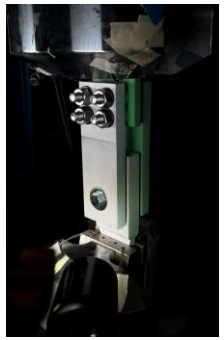


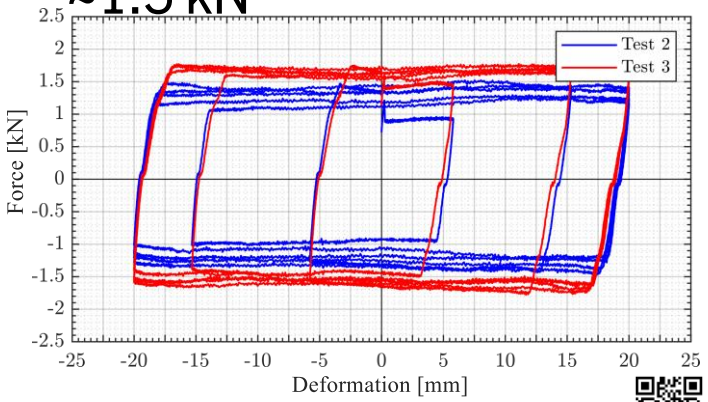

~750 kN






~1.5 kN

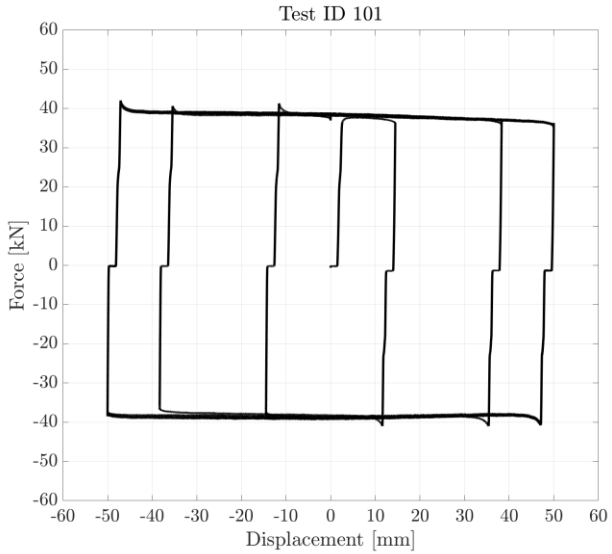




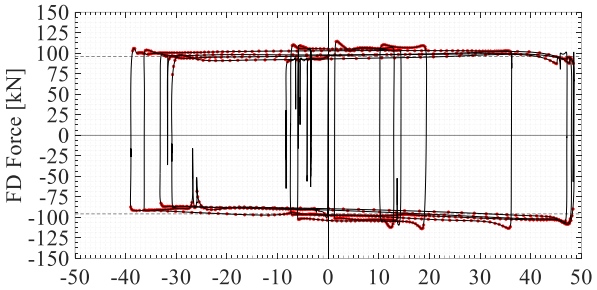
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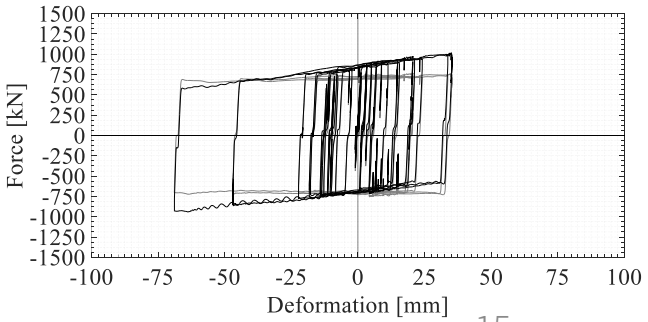








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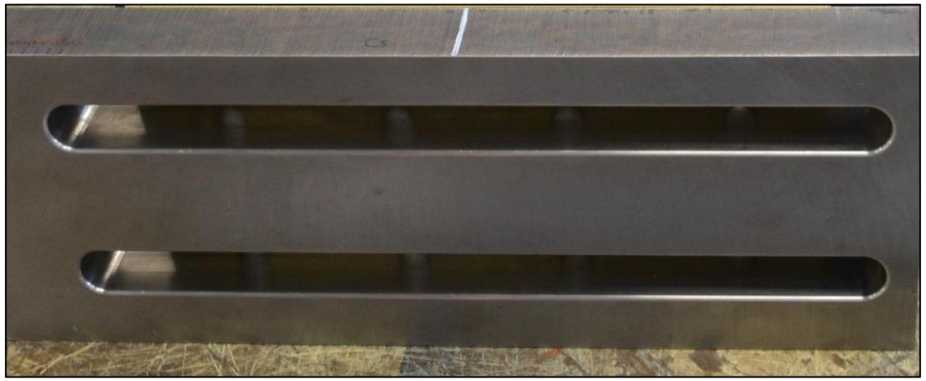




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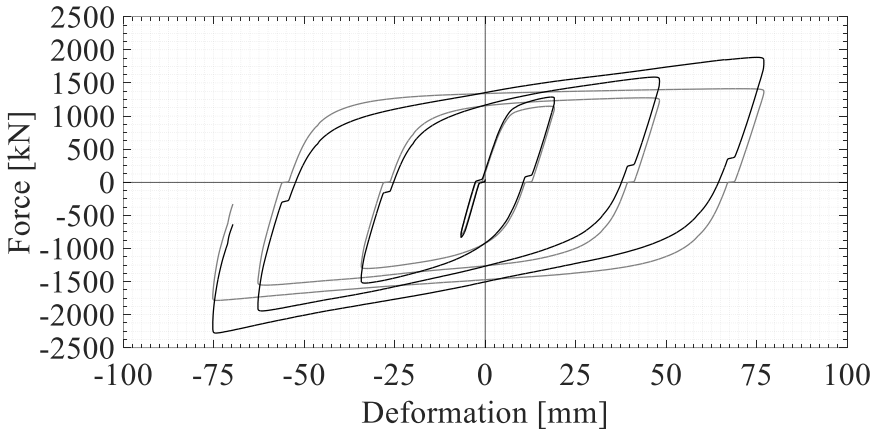
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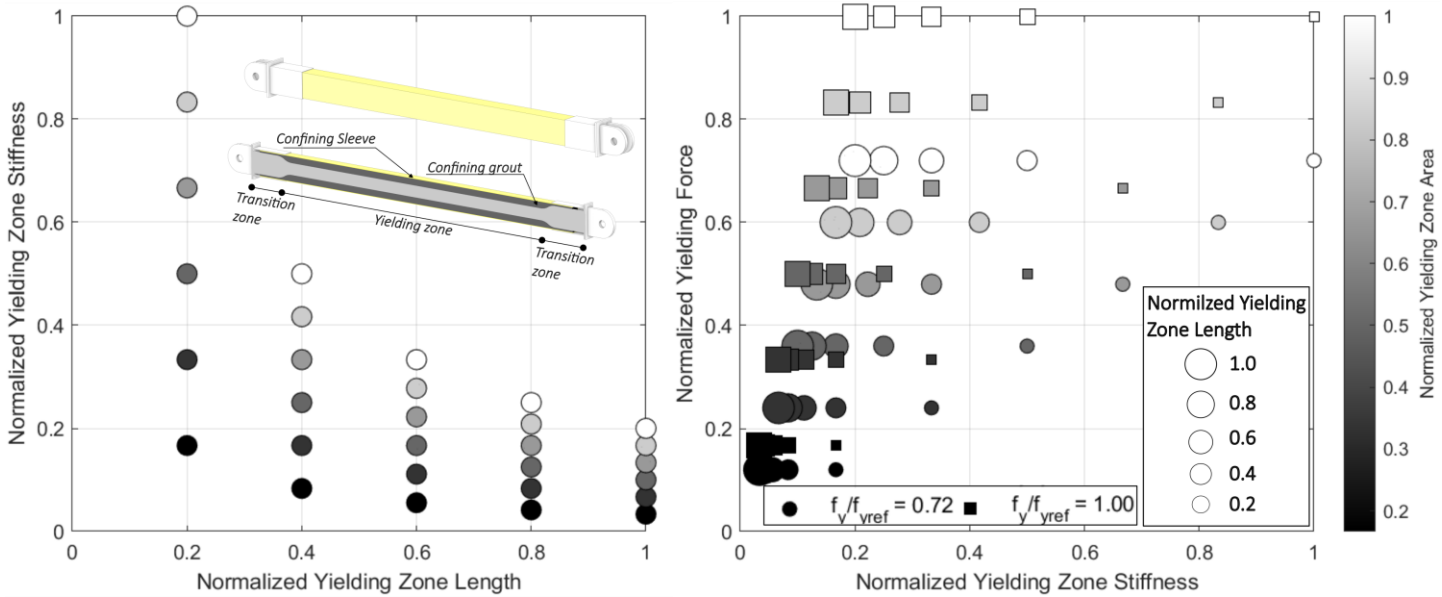




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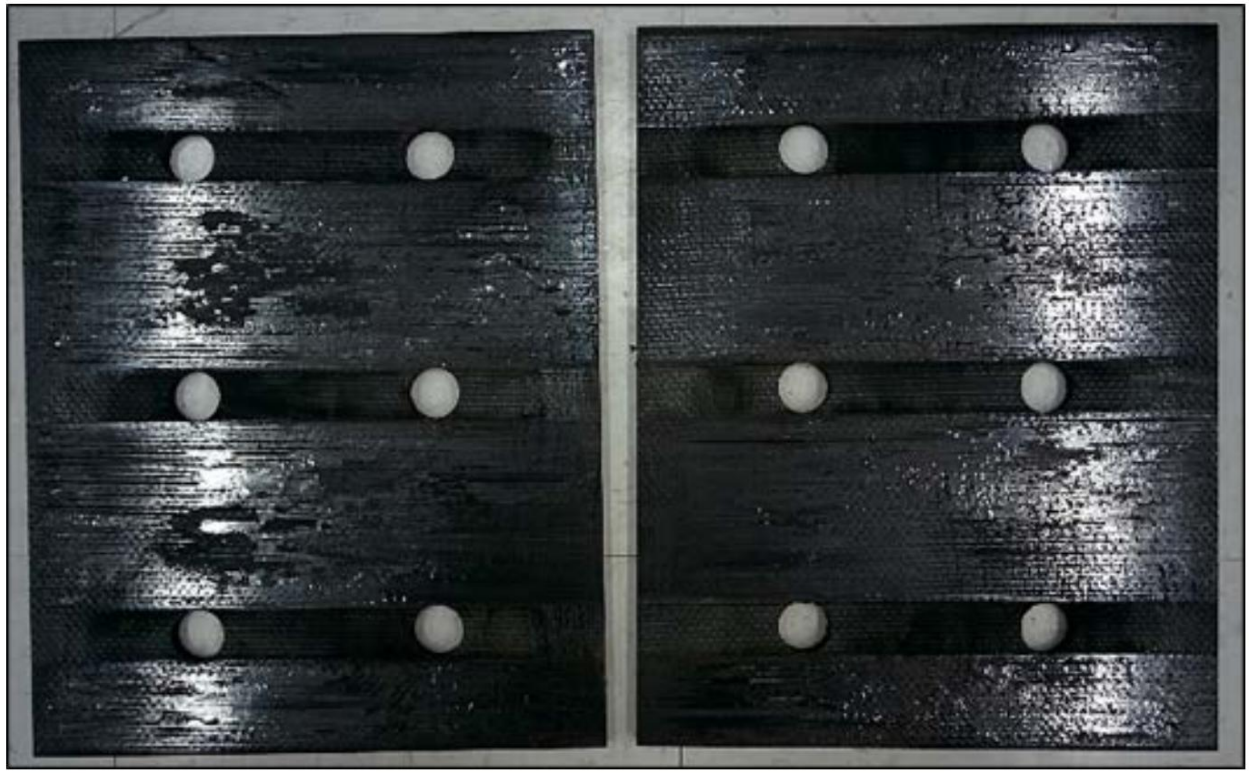
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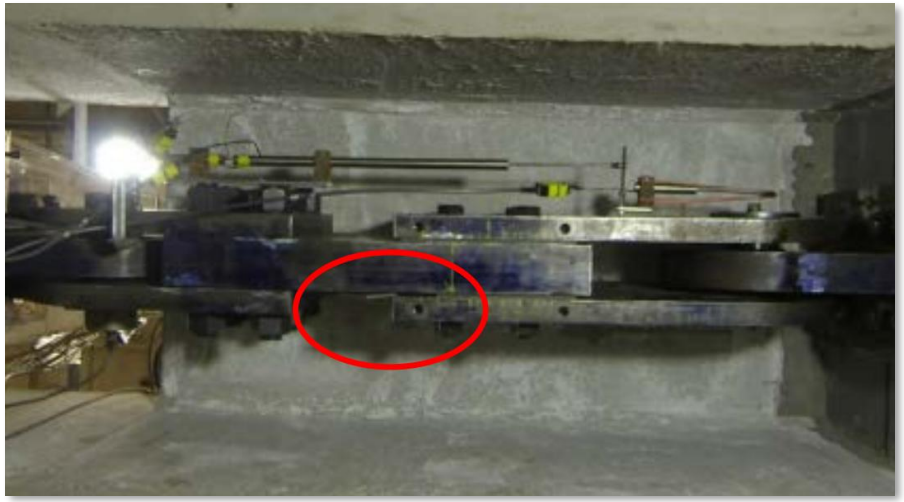
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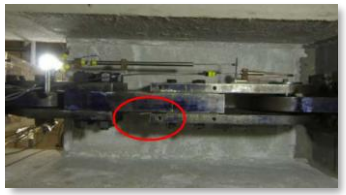




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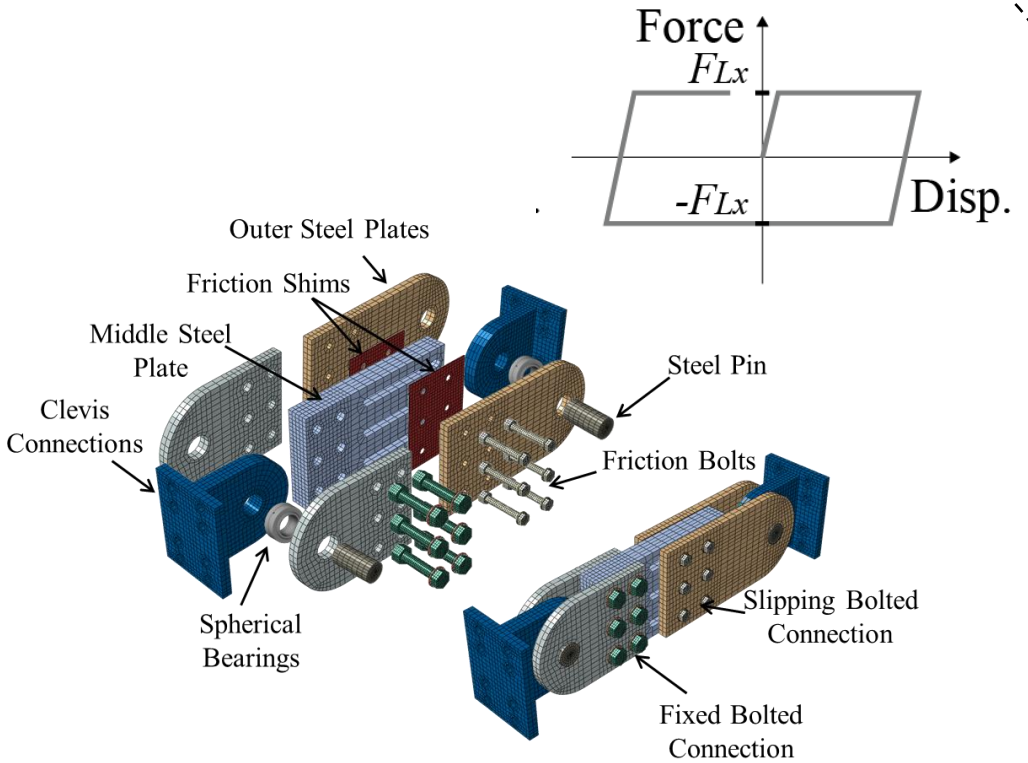
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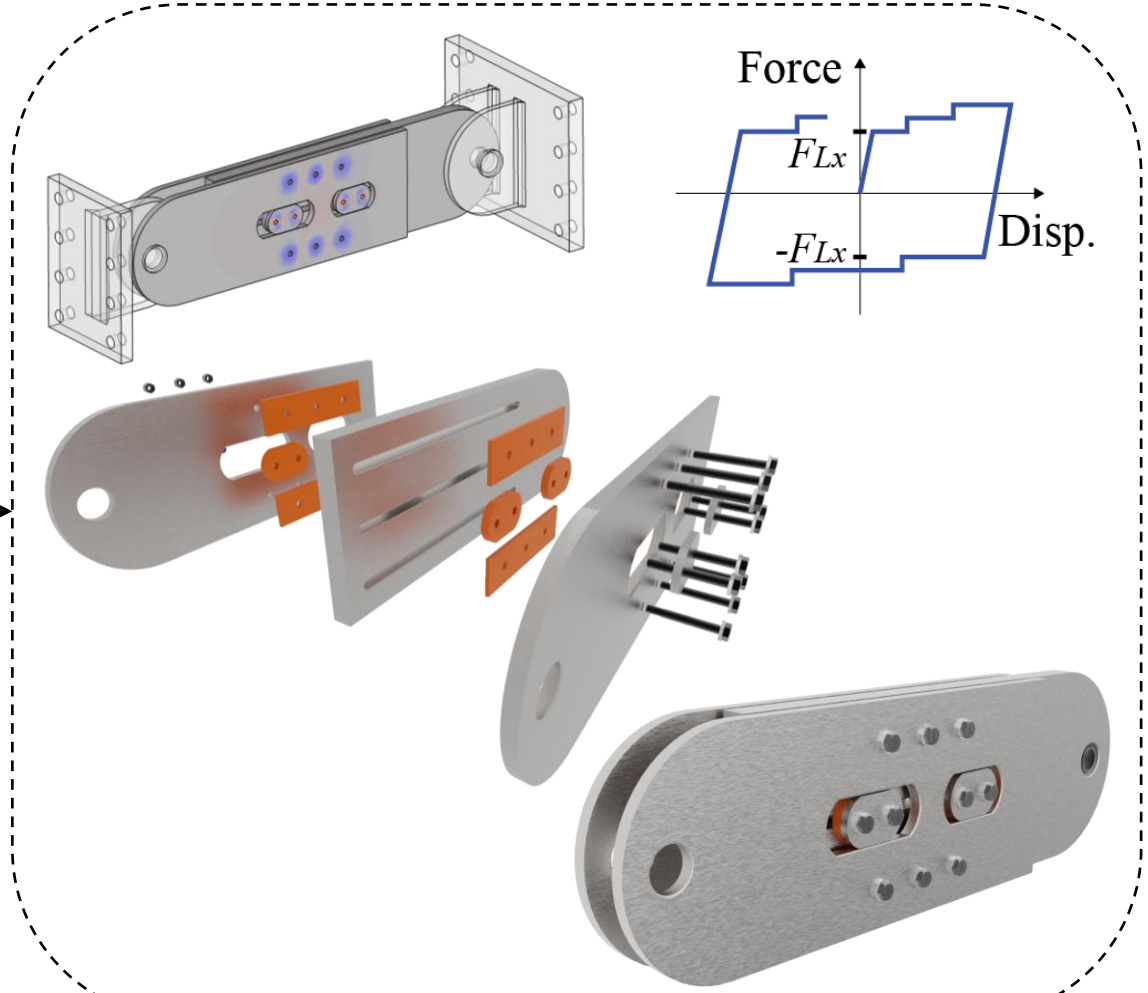


# Modified Friction Device



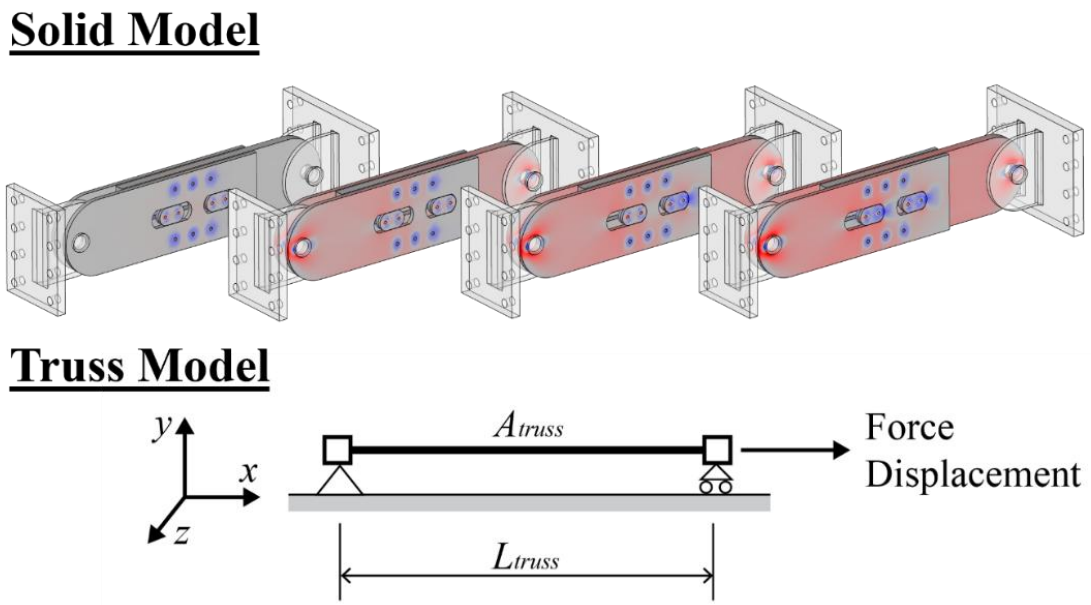

Tsampras et al. 2018 Earth. Eng. Str. Dyn.

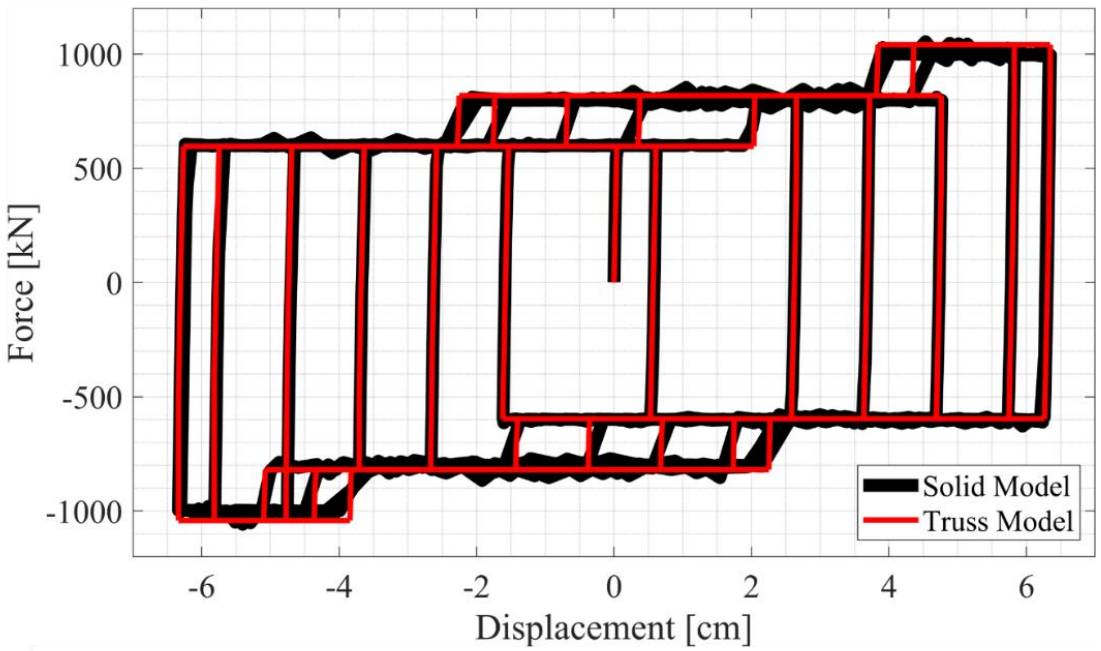
Modified friction device




Chen et al. 2023. Resilient Cities and Structures, https://doi.org/10.1016/j.rcns.2023.02.006.

# Numerical force-displacement response

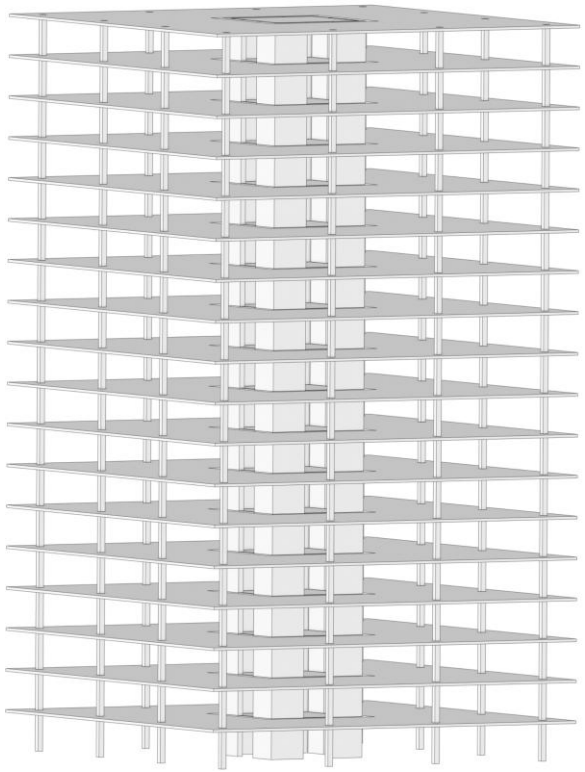


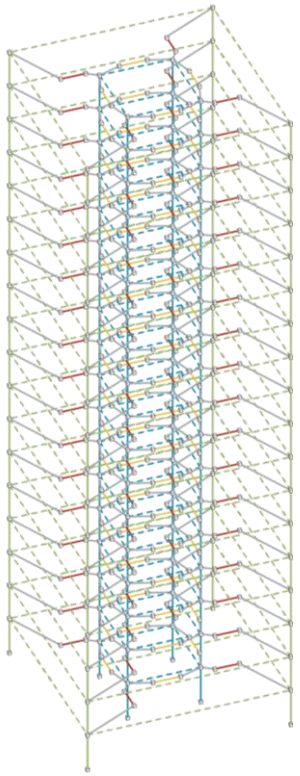

Chen, K., G. Tsampras, and K. Lee. 2023. "Structural connection with predetermined discrete variable friction forces." Resilient Cities and Structures, Resilience of Structures to Earthquakes, 2 (1): 1–17. https://doi.org/10.1016/j.rcns.2023.02.006.

# Numerical earthquake simulations: Three-dimensional model

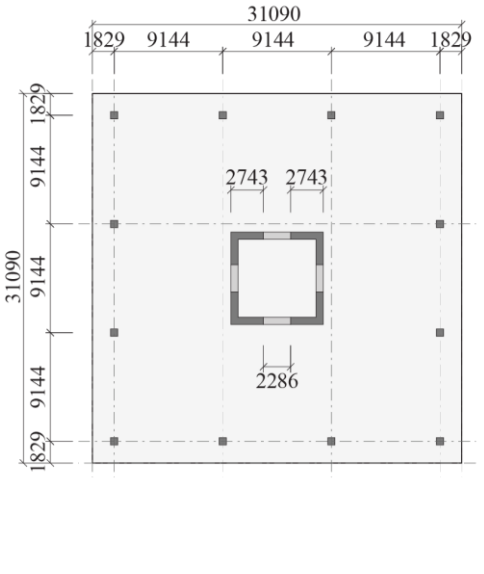
Building sketch

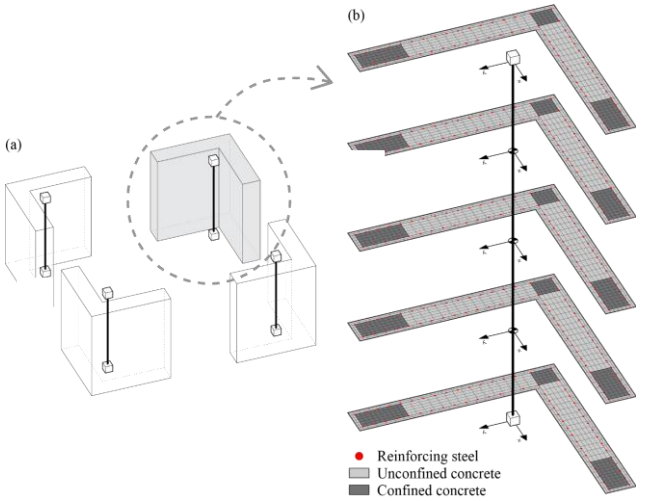


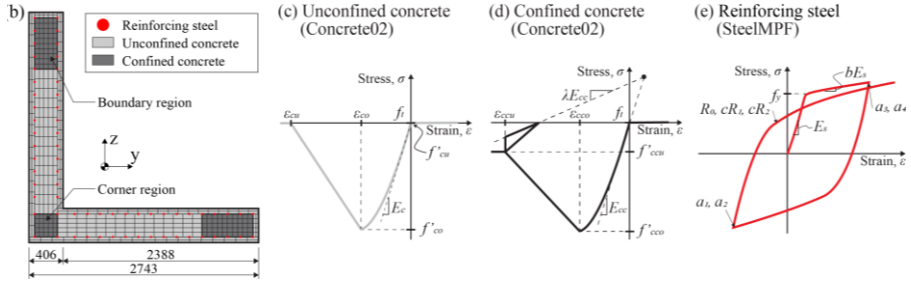
OpenSees model

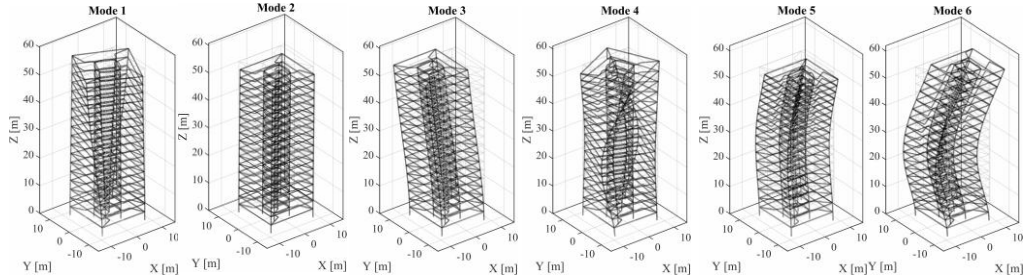


Typical floor sketch



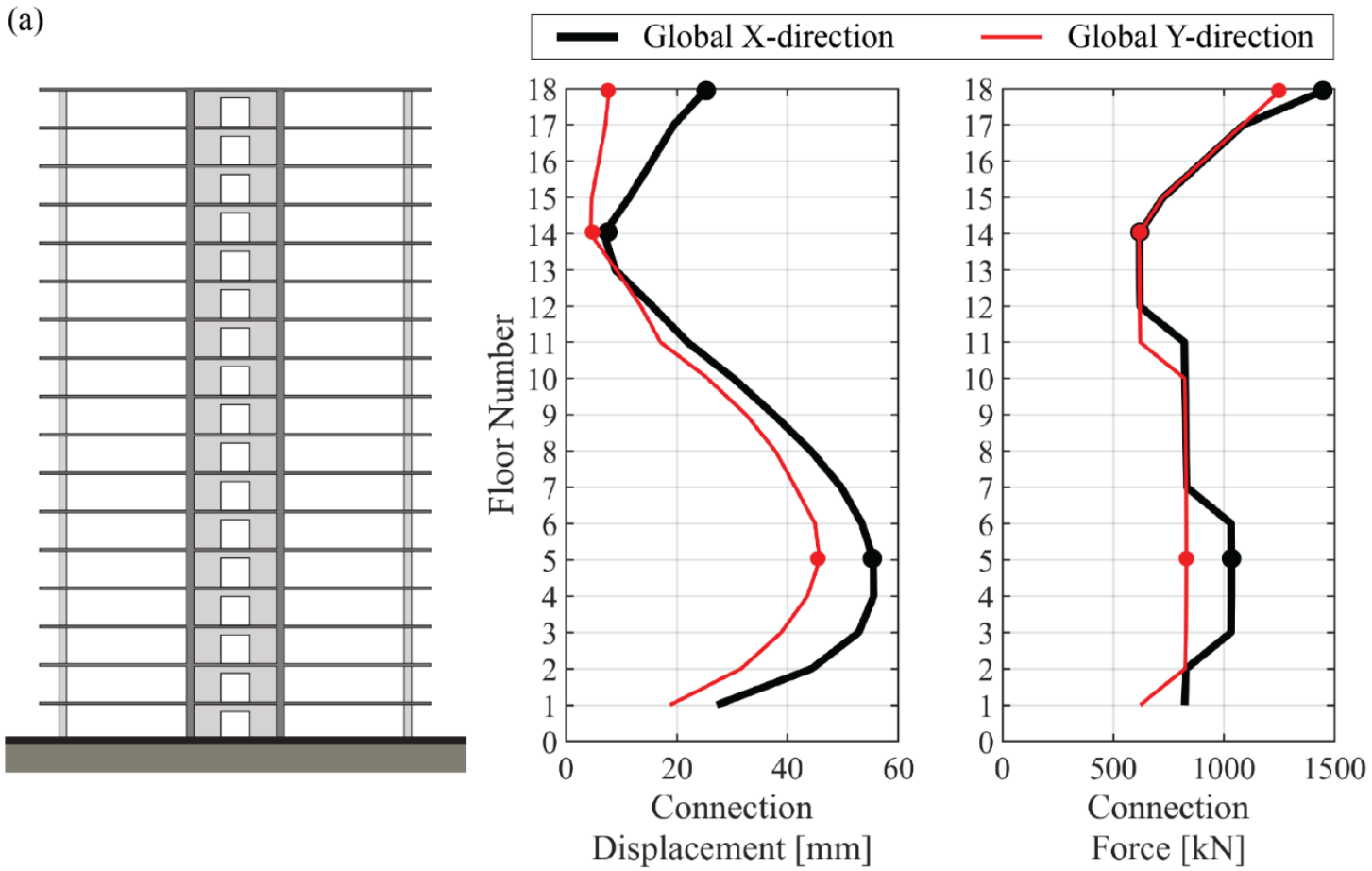



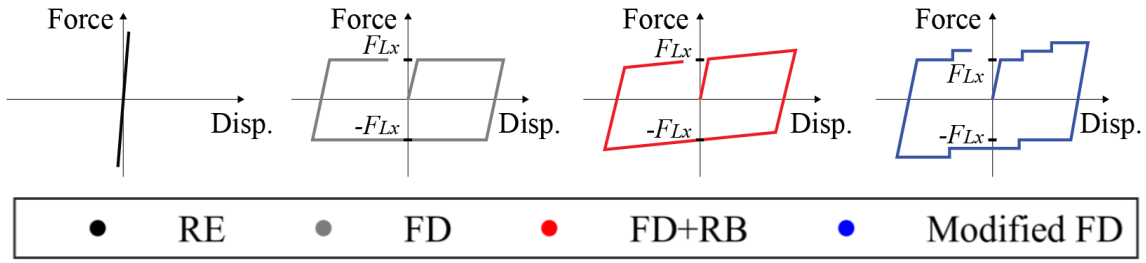

| | | | | | | |
|---|---|---|---|---|---|---|
| Period (sec) | 3.18 | 2.06 | 2.06 | 0.95 | 0.54 | 0.54 |

# Numerical Earthquake Simulation Results

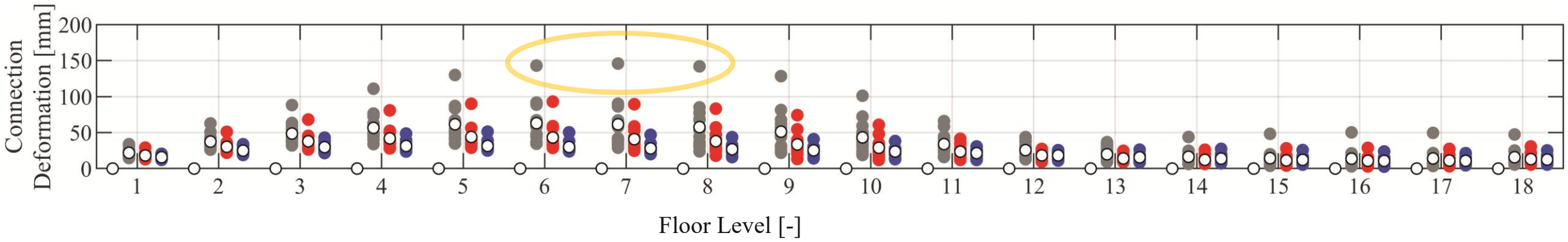


# Numerical Earthquake Simulation Results: Connection Deformation

1) Connection deformation is largest without post elastic stiffness. (FD analysis case)
2) The Modified FD type has similar result to FD+RB analysis case, which means the Modified FD has a reasonable connection deformation.




1. RE: Rigid Elastic
2. FD: Friction Device
3. FD+RB: Friction Device + Rubber Bearing
4. Modified FD: Modified Friction Device





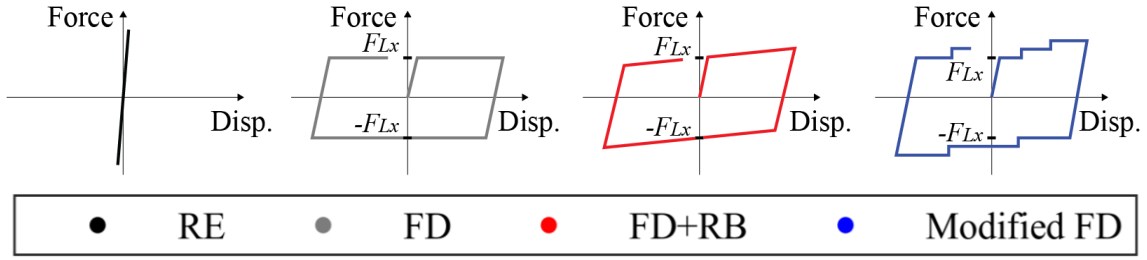


Kyoungyeon Lee; Georgios Tsampras; C. Franco Mayorga (Forthcoming), "Reinforced Concrete Core Wall Buildings with Modified Friction-Based Force-Limiting Connections: Connection Design Considerations and Three-Dimensional Response to Bidirectional Ground Motions " *Journal of Structural Engineering*, DOI: 10.1061/JSENDH/STENG-13609

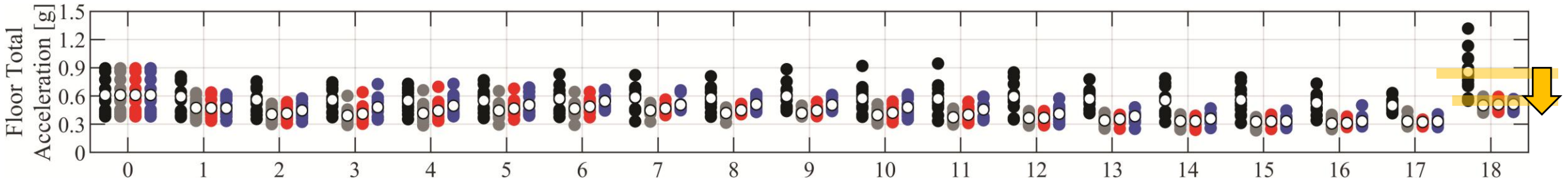
# Numerical Earthquake Simulation Results (Cont'd): Floor Total Acceleration

Each marker represents the peak (absolute maximum) values from the time history response.

1) The use of Modified FD reduces the maximum peak floor total acceleration in magnitude and variability.
2) The floor total acceleration response from the Modified FD analysis case is similar to the FD+RB analysis case.



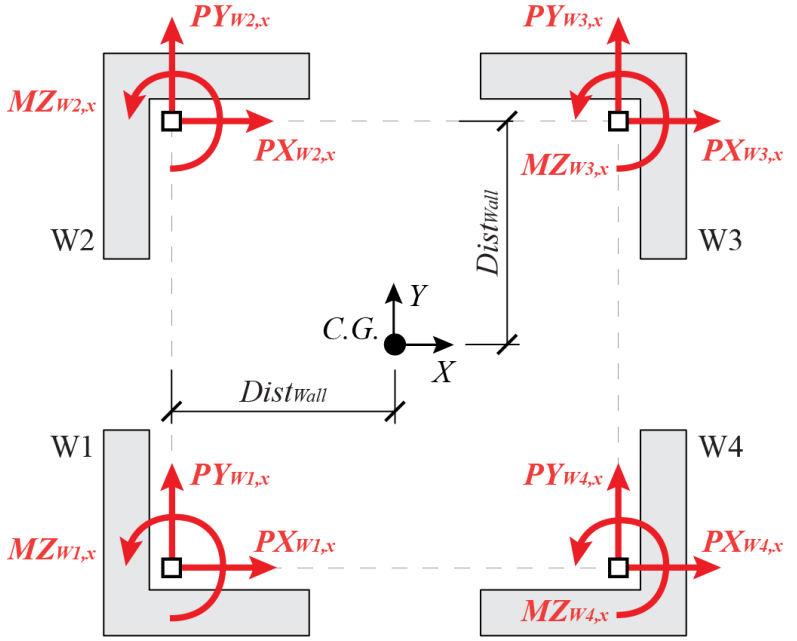

1. RE: Rigid Elastic
2. FD: Friction Device
3. FD+RB: Friction Device + Rubber Bearing
4. Modified FD: Modified Friction Device

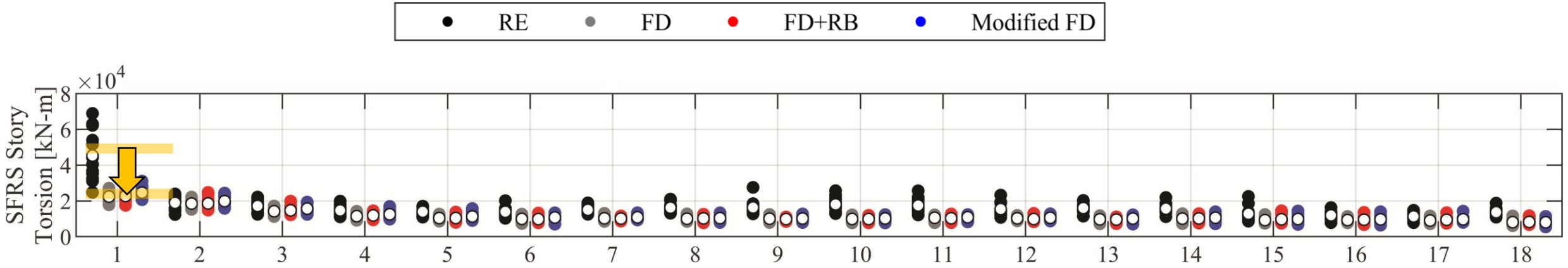


# Numerical Earthquake Simulation Results (Cont'd): SFRS Story Torsion

$$SFRS\ story\ torsion\ at\ story\ level\ x$$
$$= MZ_{W1,x} + MX_{W2,x} + MZ_{W3,x} + MZ_{W4,x}$$
$$+ Dist_{Wall}\left(+PX_{W1,x} - PX_{W2,x} - PX_{W3,x} + PX_{W4,x}\right)$$
$$+ Dist_{Wall}\left(-PY_{W1,x} - PY_{W2,x} + PY_{W3,x} + PY_{W4,x}\right)$$

1) The use of Modified FD reduces the peak SFRS story torsion in magnitude and variability.
2) The SFRS story torsion response from the Modified FD analysis case is similar to the FD+RB analysis case.



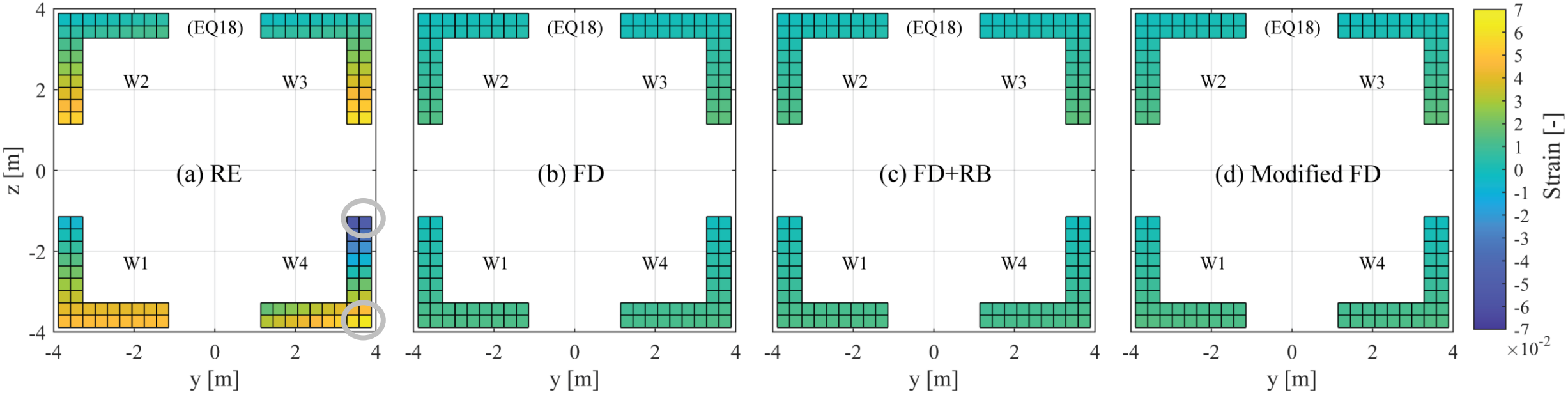




Kyoungyeon Lee; Georgios Tsampras; C. Franco Mayorga (Forthcoming), "Reinforced Concrete Core Wall Buildings with Modified Friction-Based Force-Limiting Connections: Connection Design Considerations and Three-Dimensional Response to Bidirectional Ground Motions " *Journal of Structural Engineering*, DOI: 10.1061/JSENDH/STENG-13609

# Numerical Earthquake Simulation Results (Cont'd): Strain at Core Wall Base

The use of the force-limiting connection with variable friction force reduced the absolute values of the maximum and minimum strain in the core wall base section, compared to the use of monolithic connections.



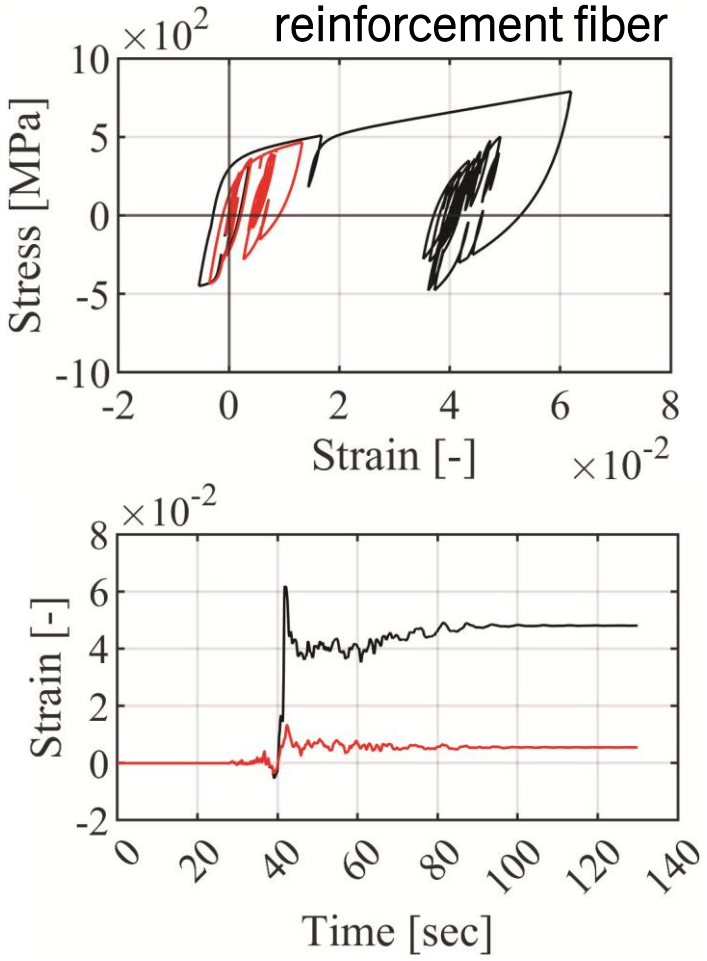

Kyoungyeon Lee; Georgios Tsampras; C. Franco Mayorga (Forthcoming), "Reinforced Concrete Core Wall Buildings with Modified Friction-Based Force-Limiting Connections: Connection Design Considerations and Three-Dimensional Response to Bidirectional Ground Motions " *Journal of Structural Engineering*, DOI: 10.1061/JSENDH/STENG-13609

# Numerical Earthquake Simulation Results (Cont'd): Strain at Core Wall Base

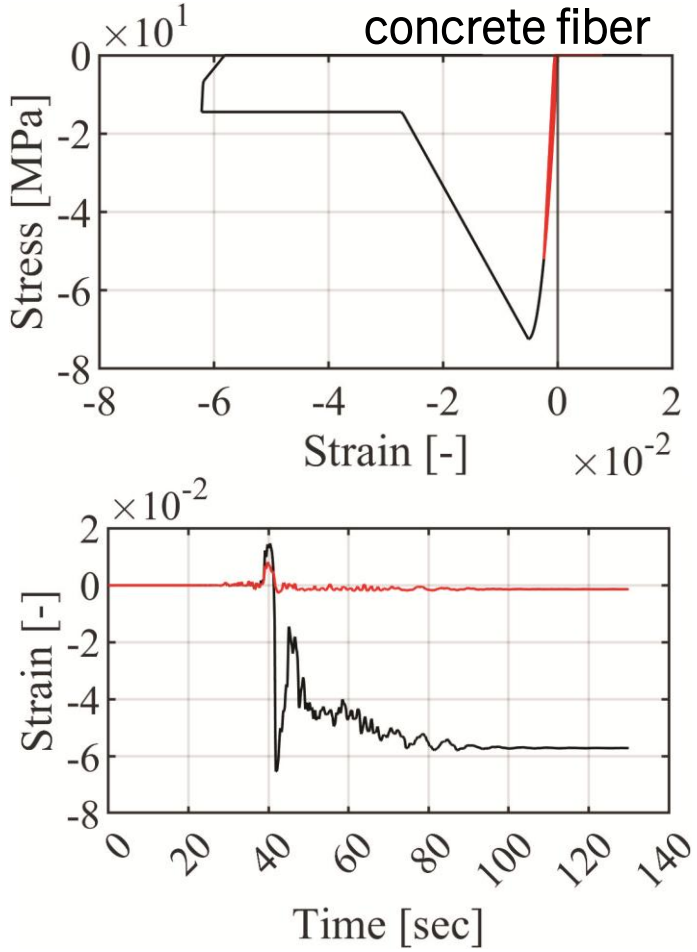
RE

Modified FD

Strain in extreme steel reinforcement fiber




Strain in extreme concrete fiber




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 " *Journal of Structural Engineering*, DOI: 10.1061/JSENDH/STENG-13609

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, Georgios, 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.

3. 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

4. Tsampras G., Sause R., Fleischman R. B., Restrepo J. I., Nema A., Zhang Z., Practical force-limiting deformable connections in buildings with rocking base mechanism and limited higher-mode responses. Proceedings of the 12th National Conference in Earthquake Engineering, Earthquake Engineering Research Institute, Salt Lake City, UT. 2022.

5. 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.

6. 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.

7. 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.

8. C. Franco Mayorga, Georgios Tsampras. "Reinforced concrete wall buildings with force-limiting connections: Modeling effects and uncertainty propagation". Earthquake Engng Struct Dyn. 2024; 1-27. https://doi.org/10.1002/eqe.4073

9. 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

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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 |