18th World Conference on Earthquake Engineering
(WCEE2024)

Structural Connection with Predetermined Discrete Variable Friction Forces

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Tsampras Research Group

Acknowledgment

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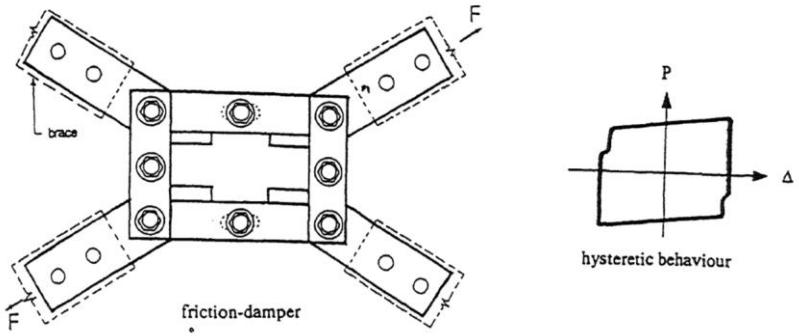
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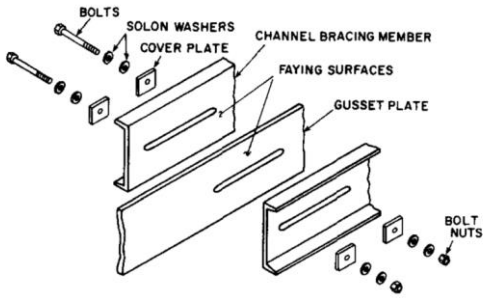
Background: friction devices

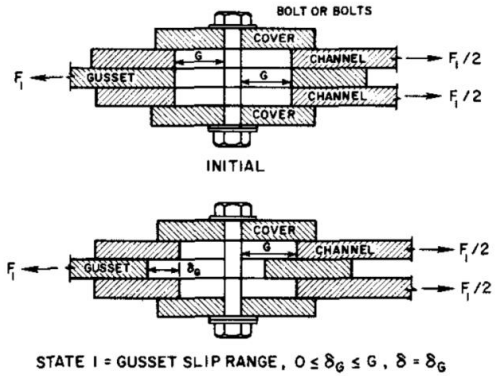
- Friction-based structural connections and dampers have received extensive research interest since the 1980s. Various types of friction devices have been developed.



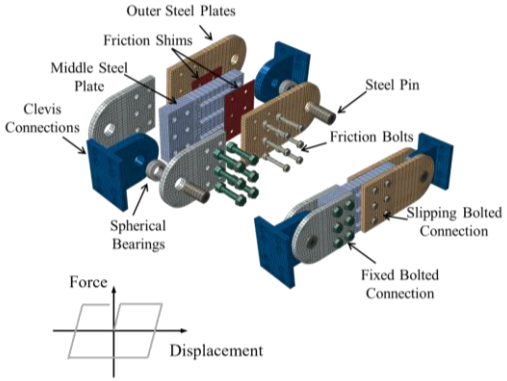
Vezina et al. (1992)

Pall friction damper



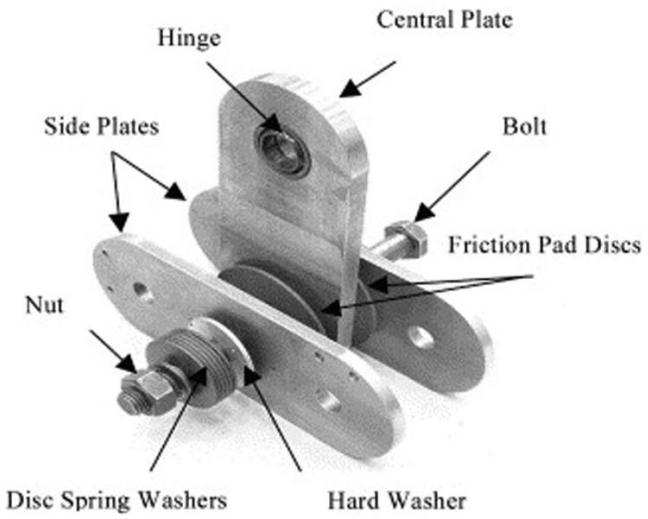


Fitzgerald et al. (1989)



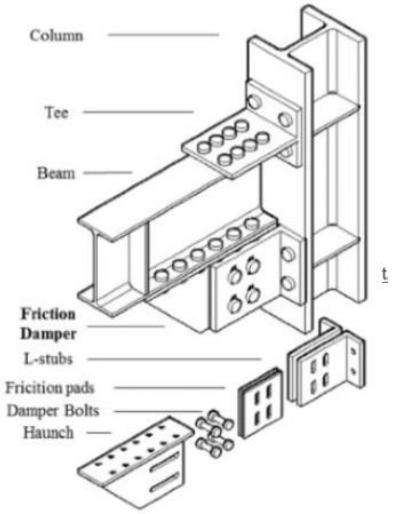
Tsampras et al. (2018)

Slotted-bolted friction connections



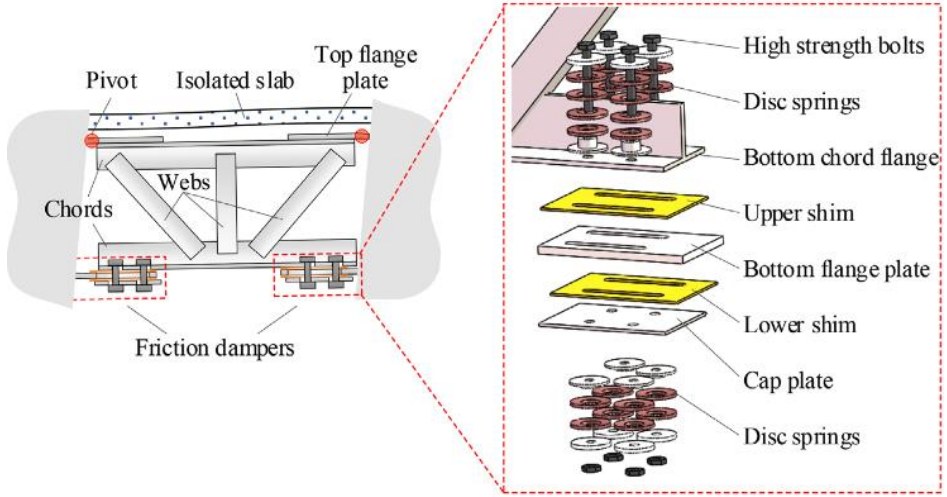
Mualla and Belev (2002)

Rotational friction damper



"FREEDAM" connection
(Di Benedetto et al., 2021)

Friction-based beam-column connection



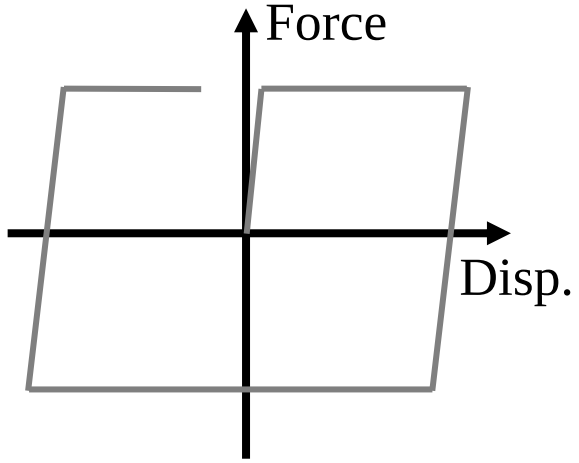
Cui et al. (2022)

Friction-based coupling beam

Some characteristics of friction devices

- Compared with yielding devices (like buckling-restrained braces), friction devices have the following advantages:
  - The **strength and stiffness** of the friction device are **decoupled**.
  - There are no issues related to strain hardening.
- The force transferred by friction devices can be well characterized.
  - One commonly adopted formula is the Coulomb friction equation: **f = μN**.
  - By characterizing the friction interface through experiments, the coefficient of friction μ can be determined.
  - The normal force N can be provided through bolt pre-tensioning.
- If well-designed, the friction device can remain **essentially damage-free** after earthquakes.

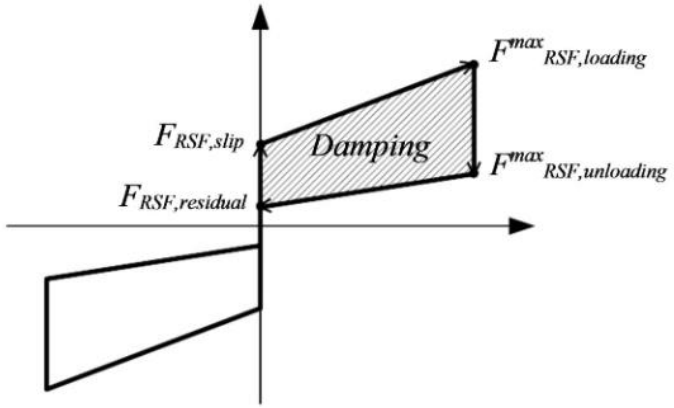
- Due to the characteristics of the friction mechanism, if not specially engineered, the friction devices generally have a very low (near zero) post-elastic stiffness. This could result in **increased connection deformation**.
  - This could become a concern when designing friction devices as force-limiting connections between structural systems



Friction devices with increased post-elastic stiffness

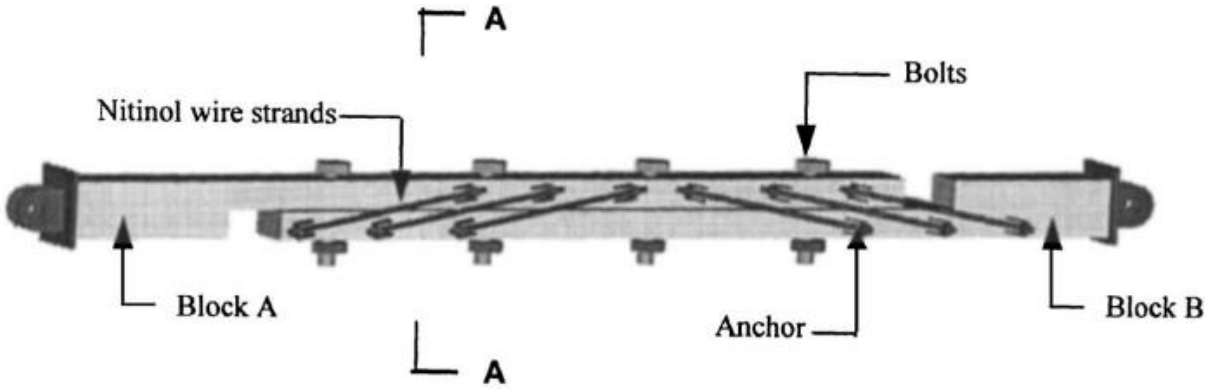
- The post-elastic stiffness can be provided by
  - The geometry of the device (for example, Hashemi et al. (2018))

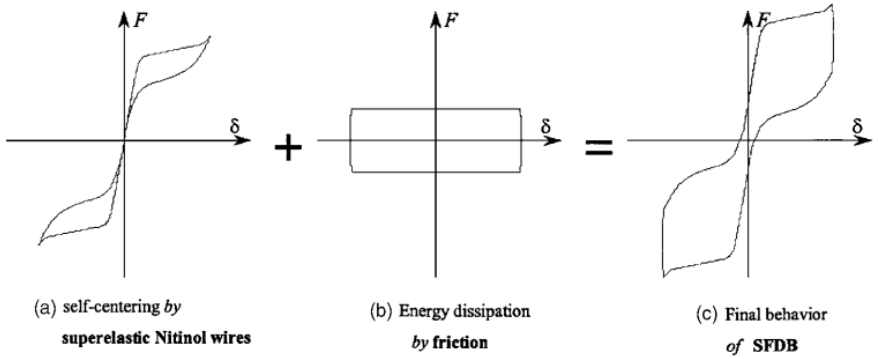




Post-elastic stiffness is provided by the inclined friction surface

  - Supplemental metallic yielding devices (for example, Zhu and Zhang (2008))



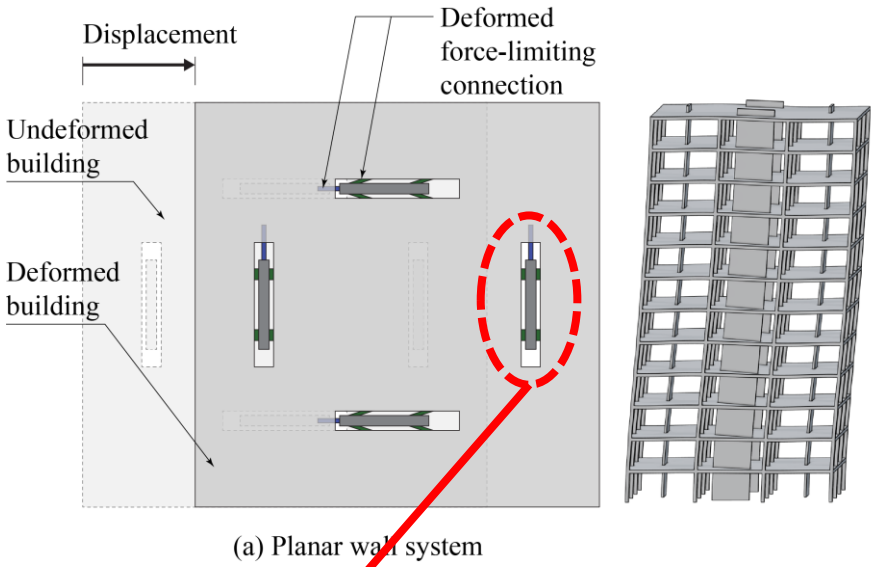


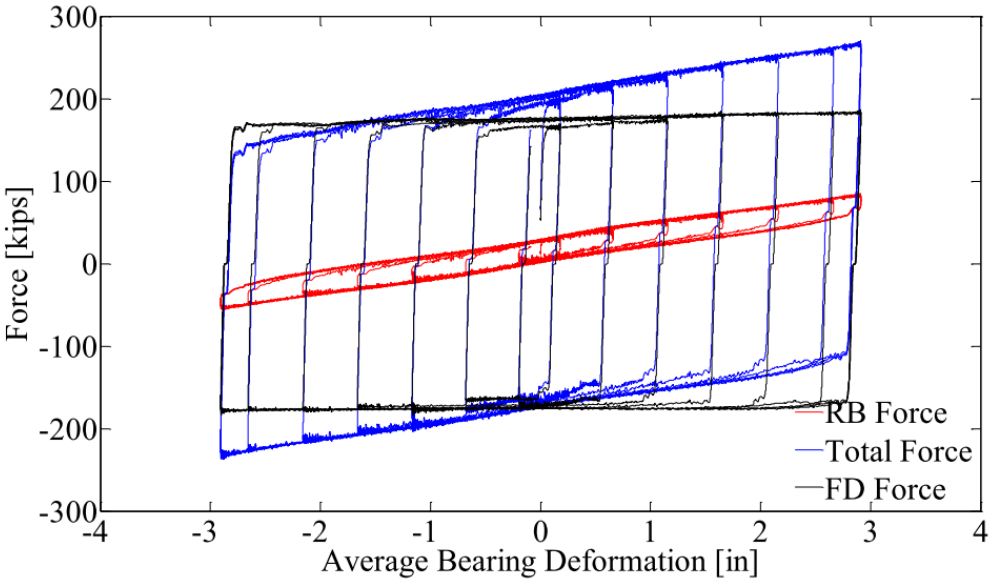
Shape memory alloy (SMA) wires provide self-centering capability and post-elastic stiffness to the device.

Friction devices with increased post-elastic stiffness

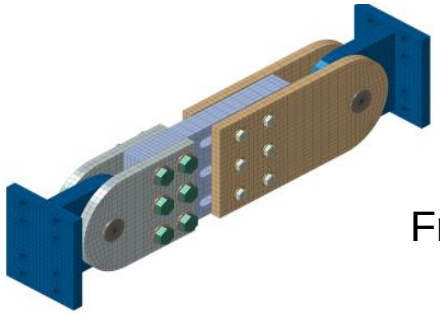
- The post-elastic stiffness can be provided by low-damping rubber bearings

This idea was proposed and has been experimentally characterized in the context of using friction devices as force-limiting connections between GLRS and SFRS.

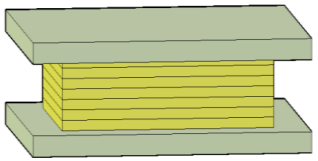








Friction Device (FD)

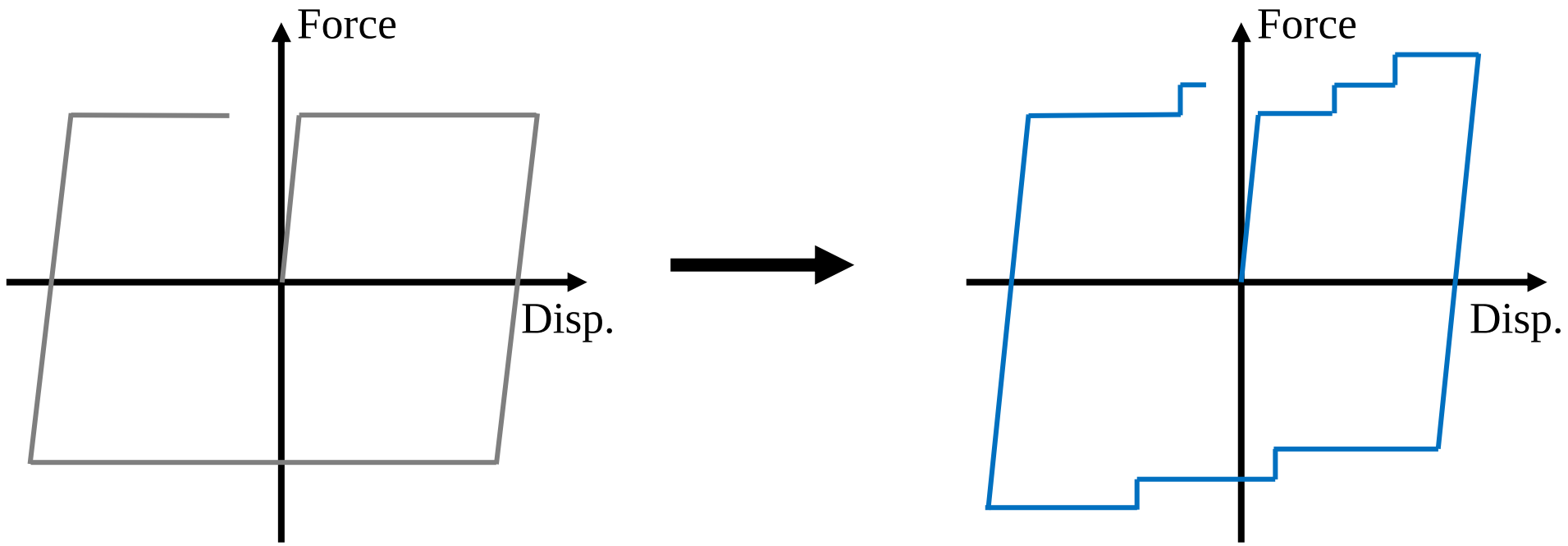


Low Damping
Rubber Bearings (RB)

Tsampras et al. (2018)

Friction devices with predetermined discrete variable friction forces at target displacement levels

- In this presentation, the development of an **innovative friction-based structural connection with predetermined discrete variable friction forces at target displacement levels** will be disseminated.
  - The increase of force resistance at certain displacement levels provides an **equivalent post-elastic stiffness** and hence, prevents excessive connection deformation.
  - It's possible to associate different levels of forces with **different levels of input excitations**.
  - The effectiveness of this device in reducing connection deformations (compared with friction devices with zero post-elastic stiffness) has been proved numerically (Lee et al., 2024).

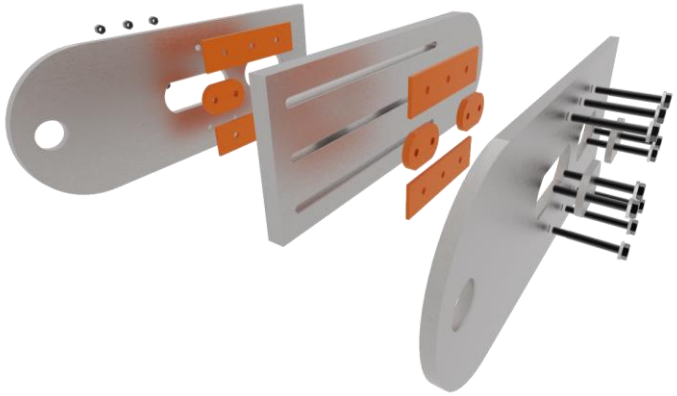


Modified Friction Device (Modified FD): Components and assembly

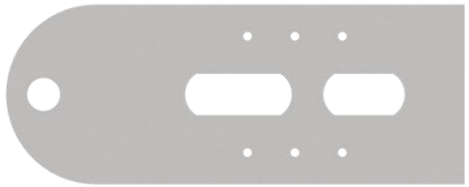


Modified FD





Exploded view



External plate x2



Internal plate x1



Bearing plate x4



Friction shim for external plates x4



Friction shim for bearing plates x4



Bolt x10



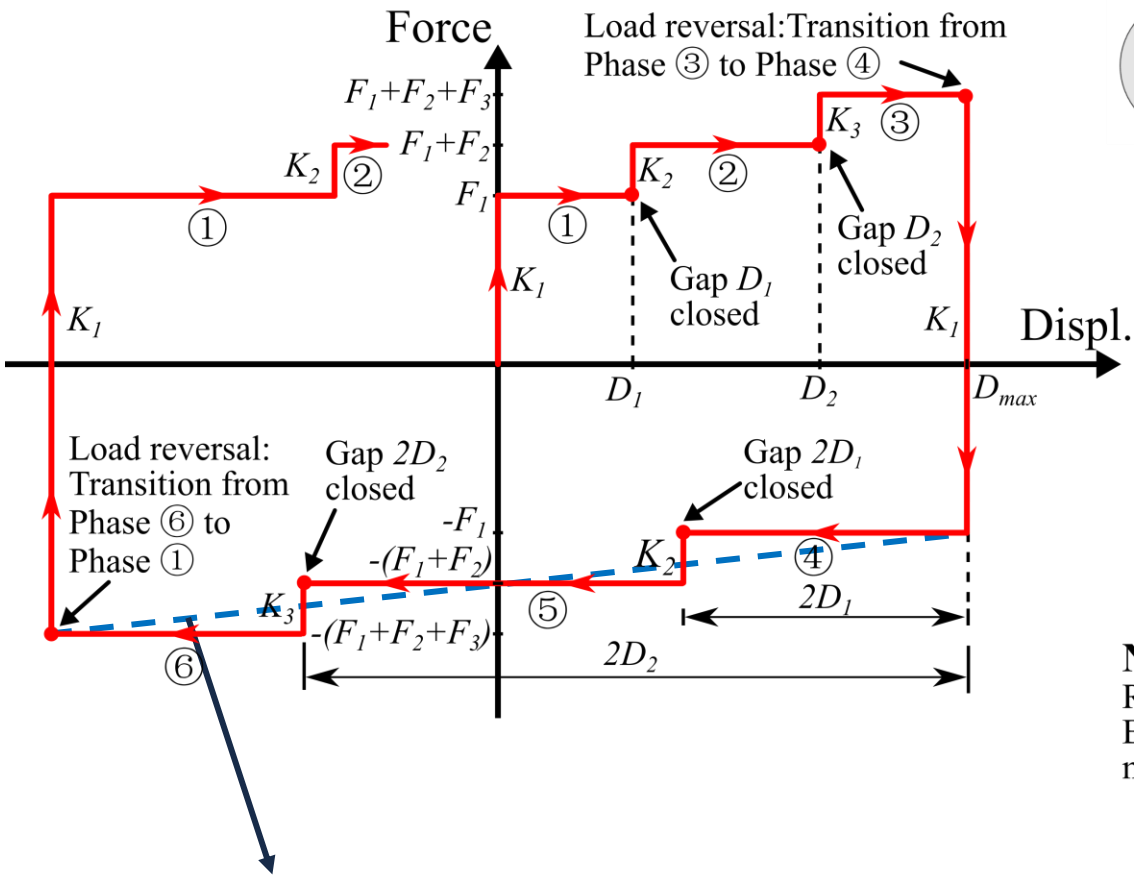
Spherical bearing x1

Components

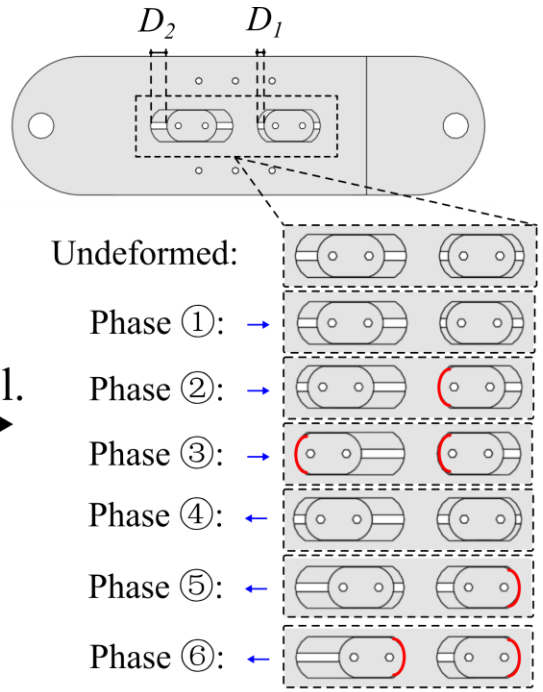
- The connection is termed **Modified FD**.
- The connection is **simple to manufacture, assemble, and install**. It is intended to be subjected to seismic events without damage, and thus, can be **immediately reusable after an earthquake**.
- Materials of the Modified FD:
  - External plates, the internal plate, bearing plates: structural steel (e.g., A572 Gr50 Steel)
  - Friction shims: fiber-reinforced **non-metallic** composite friction materials
  - Bolts: ASTM A325 structural bolts

Modified Friction Device (Modified FD): Expected kinematics and force-displacement response

The connection is fully characterized by **five parameters**: D_1, D_2, F_1, F_2, and F_3 (assuming $K_1 = K_2 = K_3 \cong \infty$)



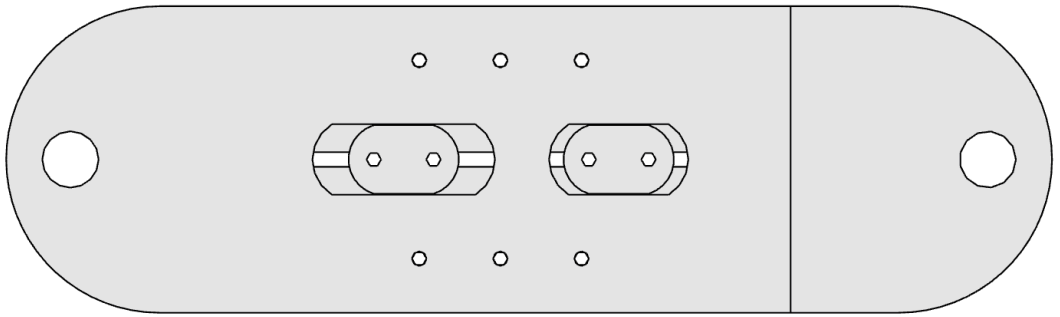
An **equivalent post-elastic stiffness** is developed



Note
Red arcs indicate established contact. Blue arrows indicate the direction of motion of external plates.

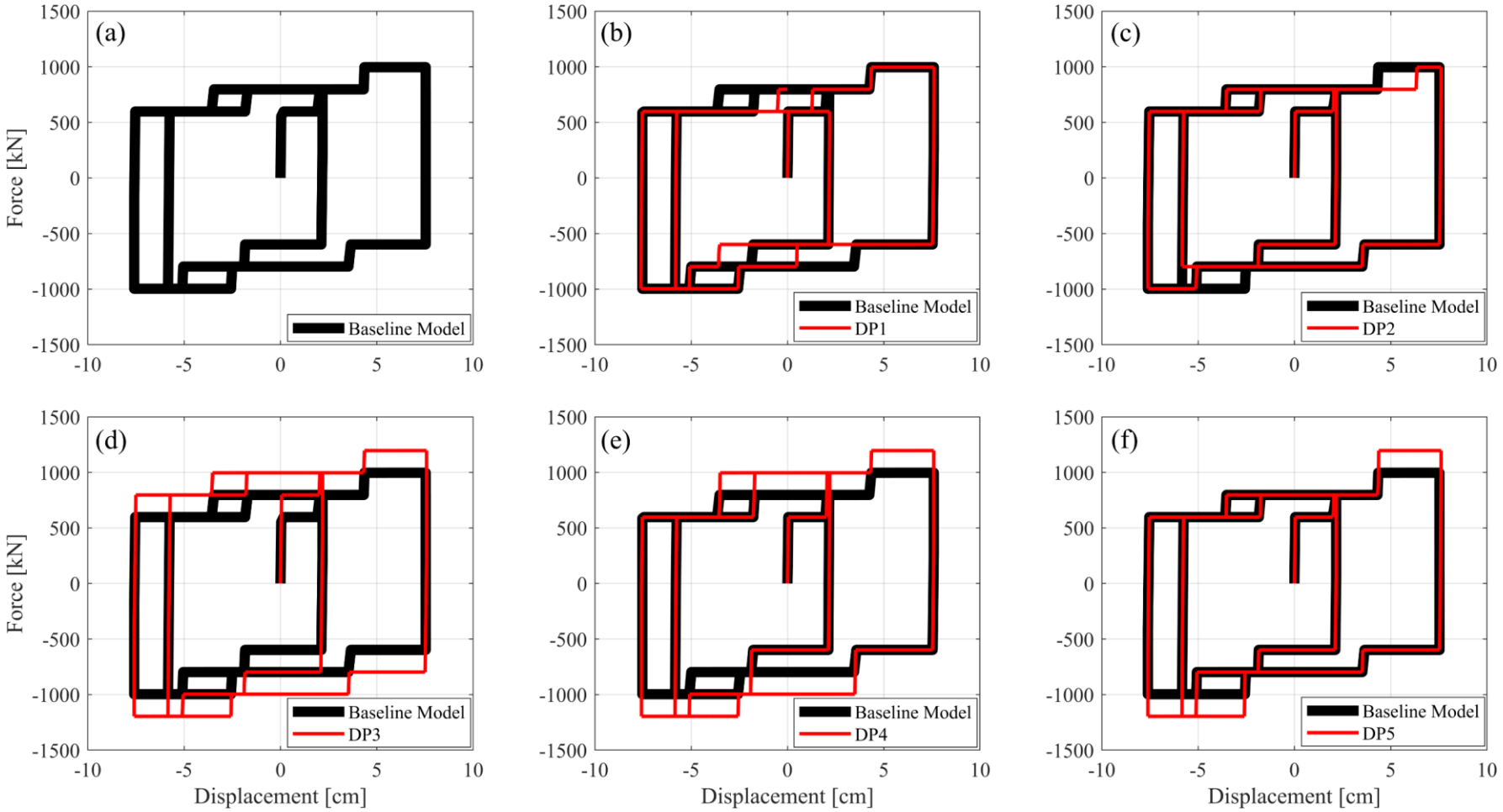
- When the gap is closed, **contact** is established between the external plate and the bearing plates, **activating the corresponding friction interface** and **causing an increase in the force of the connection**.
- It's worth noting that if needed, **more "steps"** can be incorporated into the force-displacement behavior, and the device can be **easily detailed** accordingly by creating additional slots on external plates and adding additional bearing plates.

Expected kinematics



Modified Friction Device (Modified FD): Design parameters

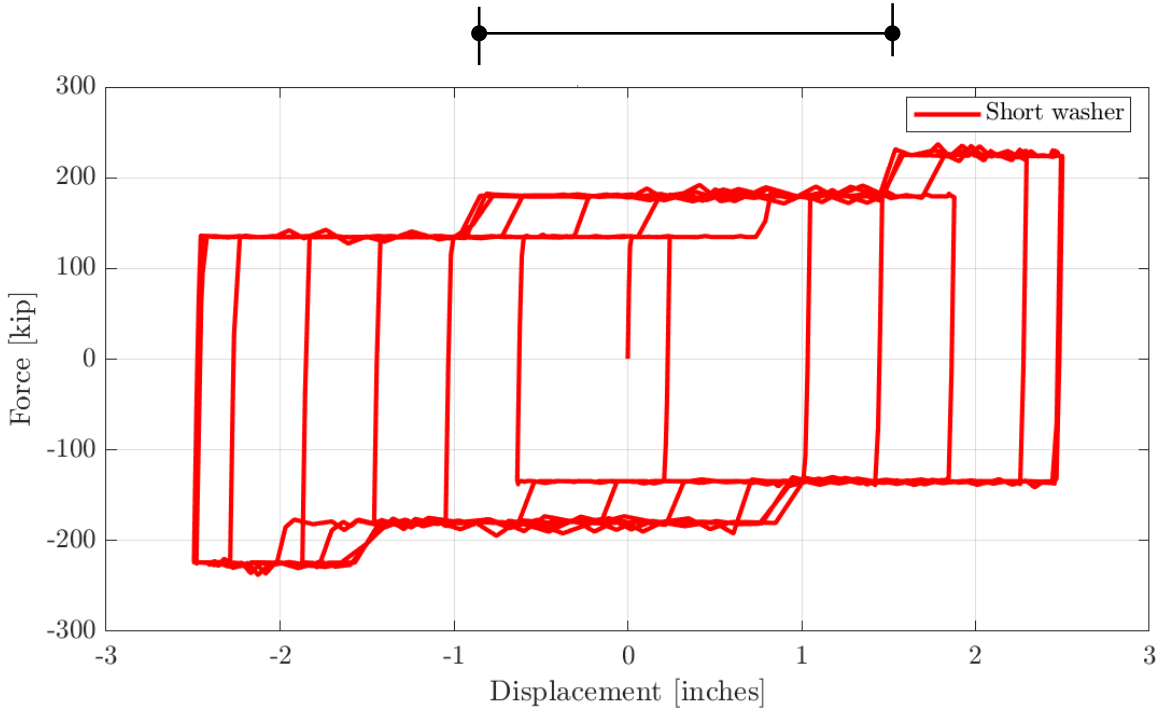
- Five parameters: D_1, D_2, F_1, F_2, and F_3 (assuming $K_1 = K_2 = K_3 \cong \infty$)
- The **design parameters are can be easily adjusted**, making the connection highly **customizable** and **versatile**.
  - F_1, F_2, and F_3 can be adjusted by changing: the number of bolts; the size of bolts; the level of bolt pretension; or the friction material used at the friction interface
  - D_1 and D_2 can be adjusted by changing the geometry of the plates

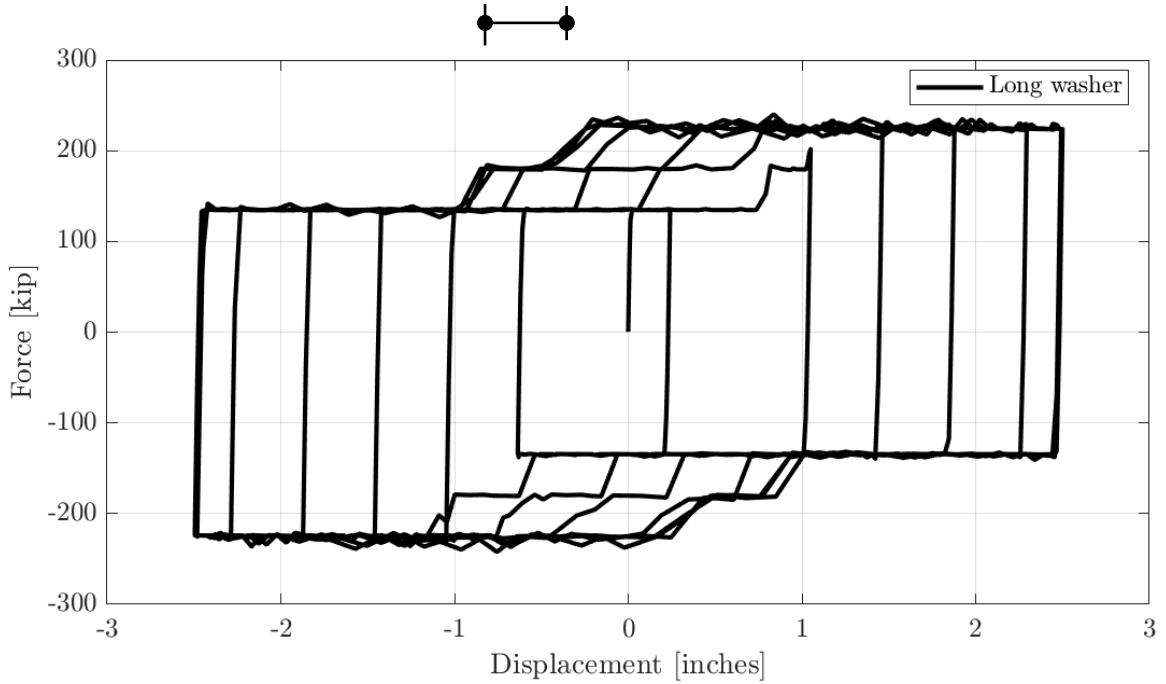


Cases of Design Parameters [-]	D_1 [cm]	D_2 [cm]	F_1 [kN]	F_2 [kN]	F_3 [kN]
Baseline Model	2.00	5.00	600	200	200
DP1	3.56	5.00	600	200	200
DP2	2.00	6.35	600	200	200
DP3	2.00	5.00	800	200	200
DP4	2.00	5.00	600	400	200
DP5	2.00	5.00	600	200	400

Modified Friction Device (Modified FD): Design parameters (Cont'd)





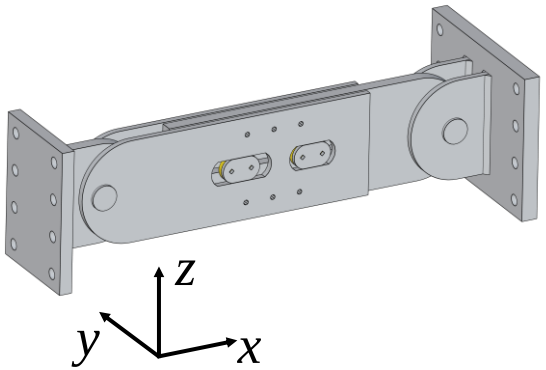


Numerical force-displacement response: Solid model

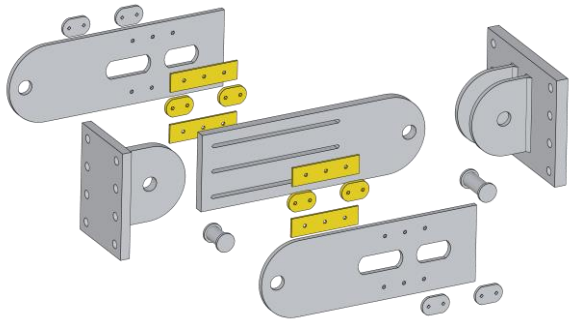
Numerical simulations with two types of finite element models are conducted to assess numerically the expected force-displacement response of the connection.

- Solid finite elements (termed as **Solid Model**)
  - Explicitly models the internal plate, the external plates, the bearing plates, the friction shims, and end clevises
  - Explicitly simulates the contact interfaces between the modeled components
  - Developed also for **rapid digital prototyping** purposes

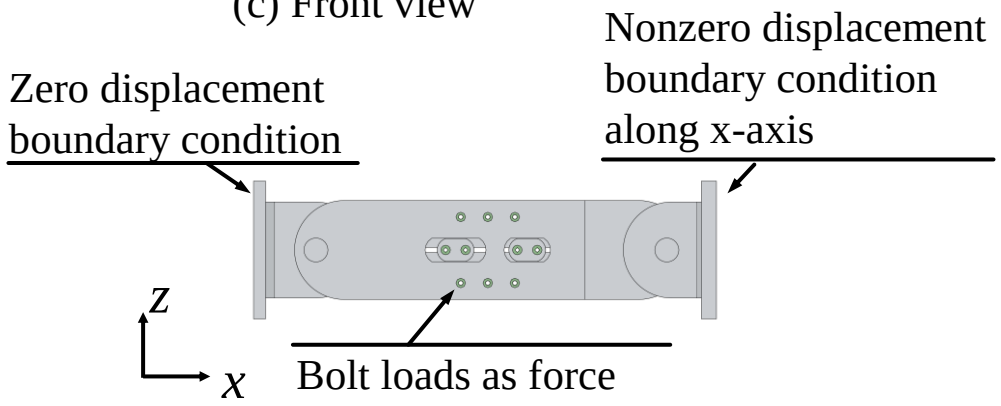
(a) Isometric view



(b) Exploded view

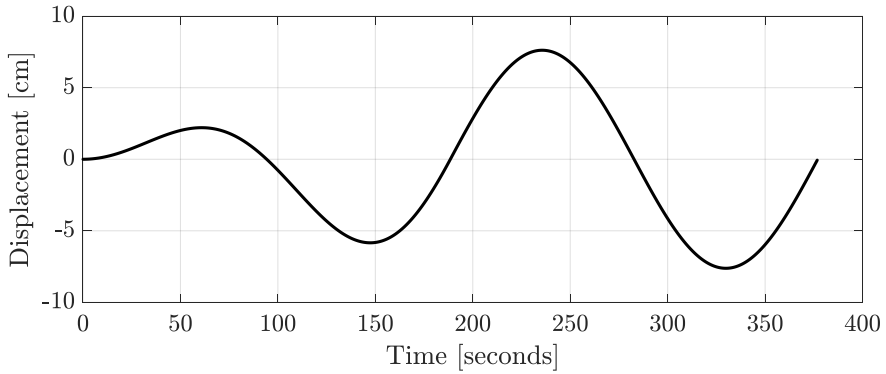


(c) Front view

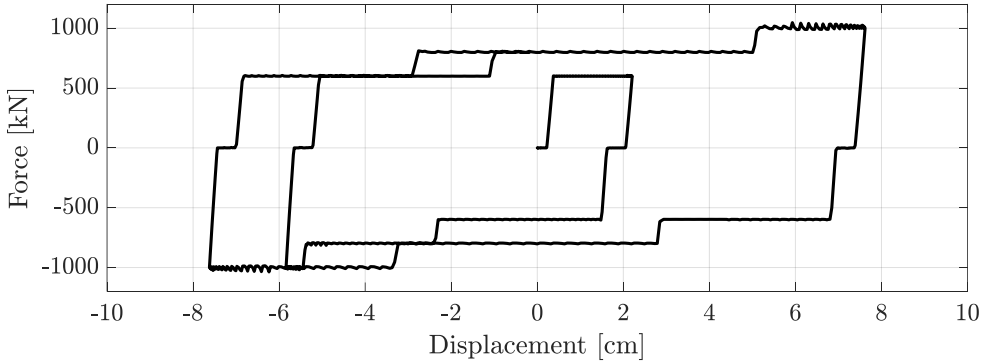


Design parameters for this model:

D_1 = 2 cm, D_2 = 5 cm, F_1 = 600 kN, F_2 = 200 kN, F_3 = 200 kN



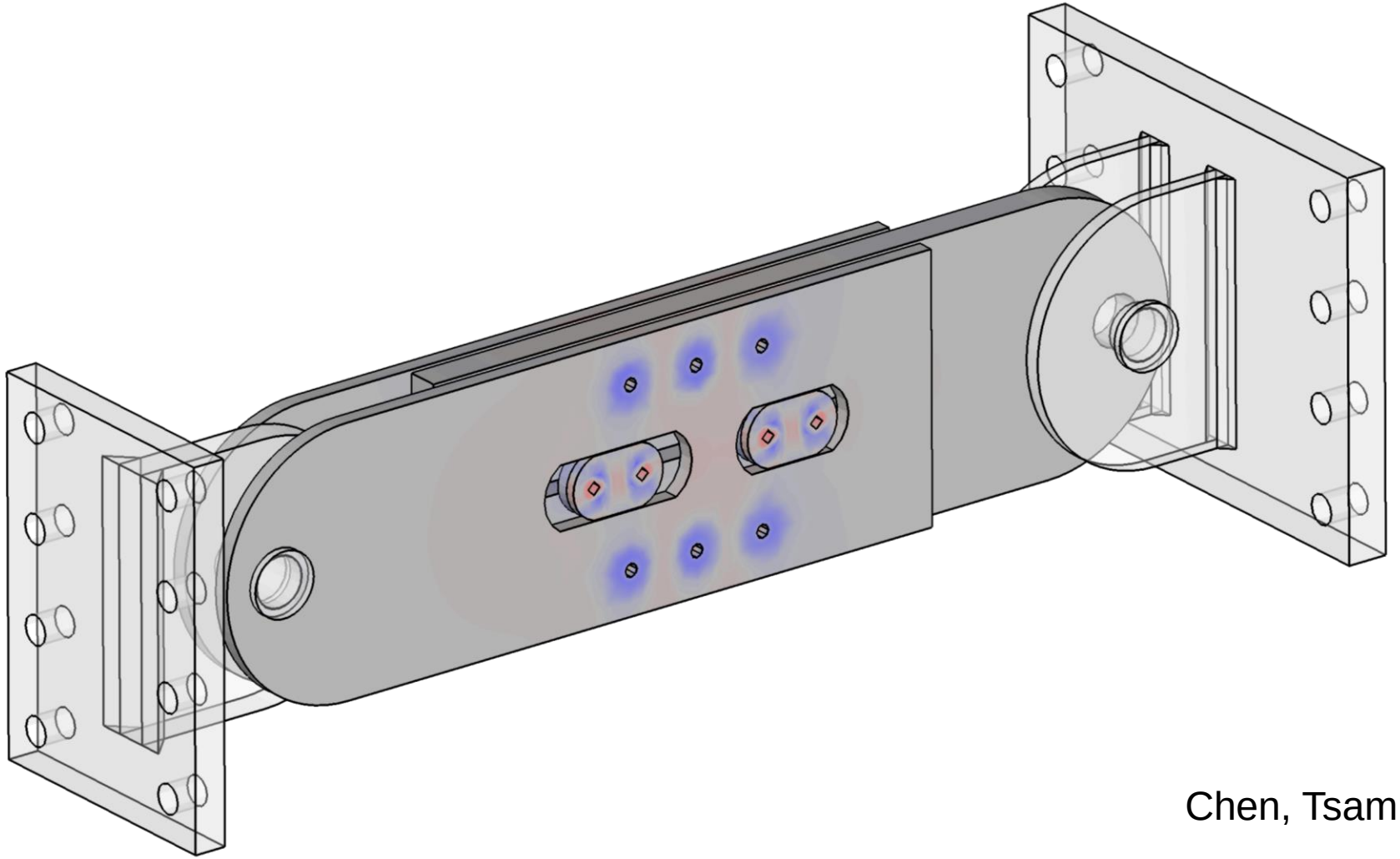
Imposed displacement history



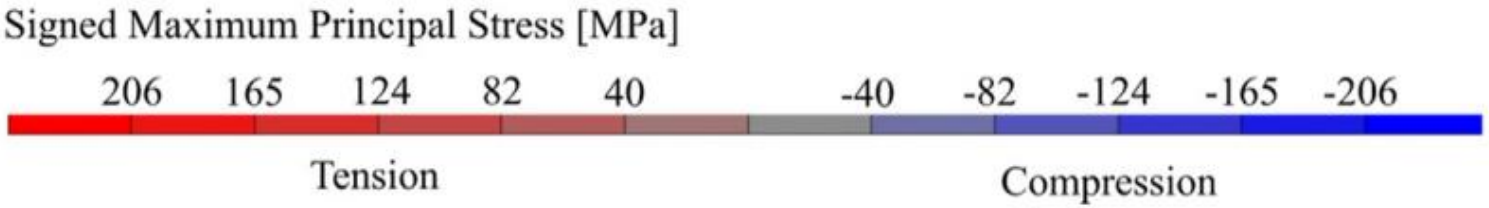
Force-displacement response

- Zero force pinching deformation is due to the modeling of standard oversized pin-holes
- In manufacturing, it can be reduced by **tighter quality control**

Numerical force-displacement response: Solid model (CONT'D)



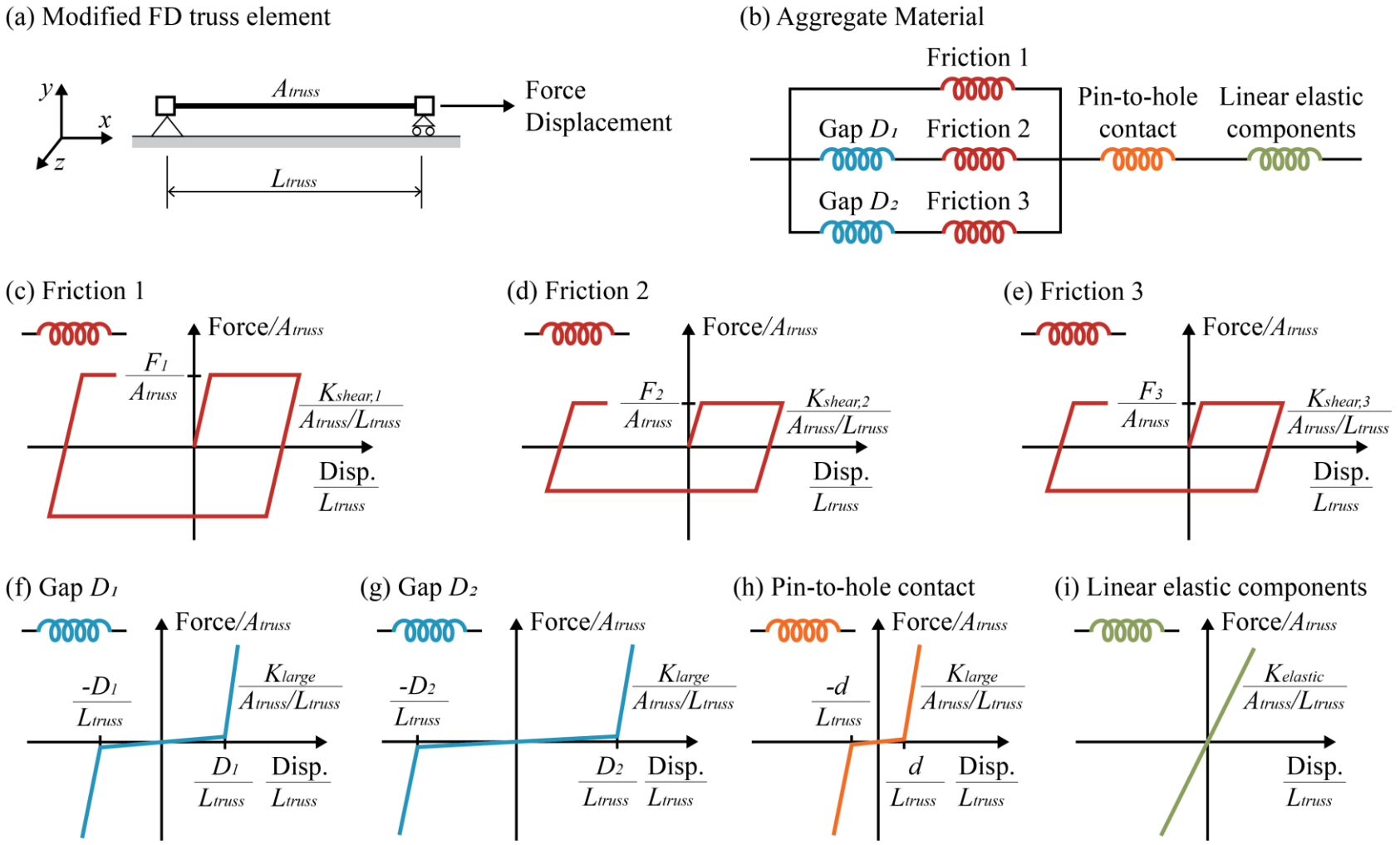
Chen, Tsampras, and Lee (2023)



Numerical force-displacement response: Truss model

Numerical simulations with two types of finite element models are conducted to assess numerically the expected force-displacement response of the connection.

- Truss elements (termed as **Truss Model**)
  - Simulates the expected force-displacement response of the connection at a macroscopic level
  - Developed for facilitating **numerical earthquake simulations**



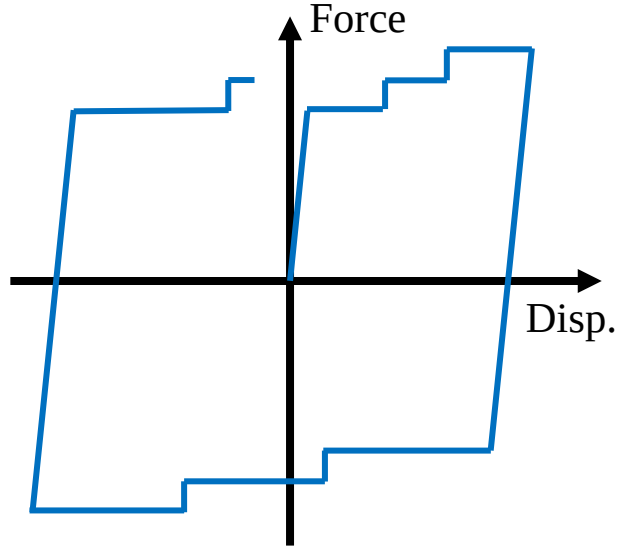
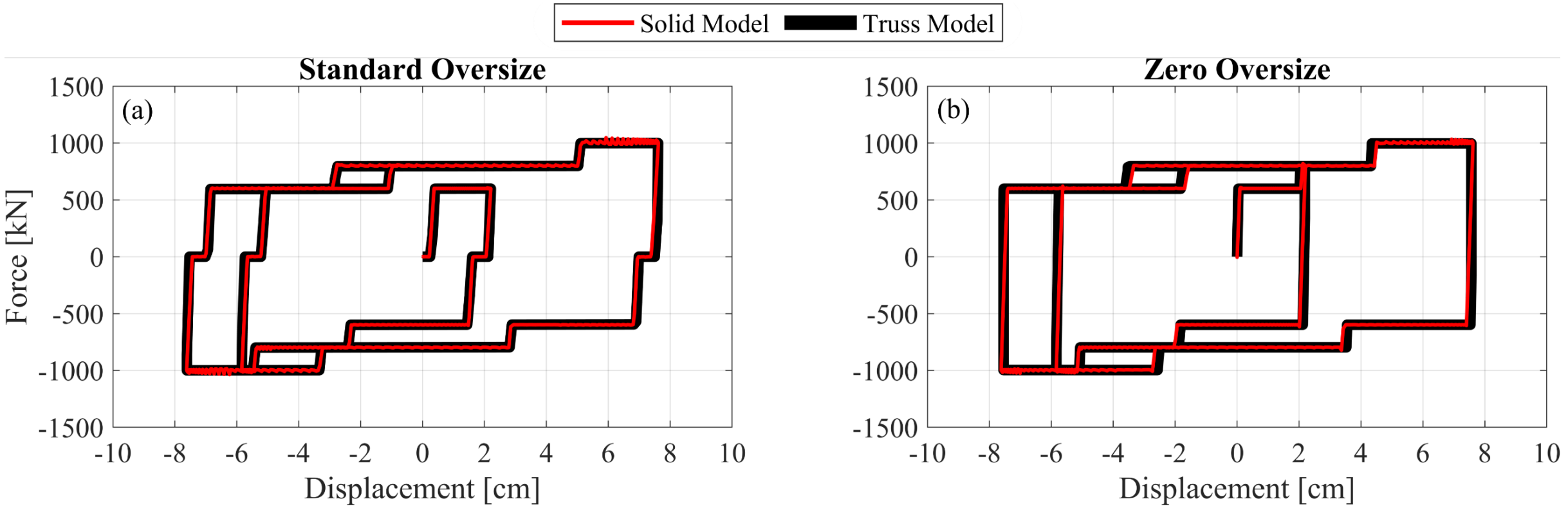


Figure courtesy of Kyoungyeon Lee

Numerical force-displacement response: Comparison



Results from two models have good agreement.

Conclusions

- In this study, a **novel type of friction device (Modified FD) with predetermined discrete variable friction force at target displacement levels** is developed.

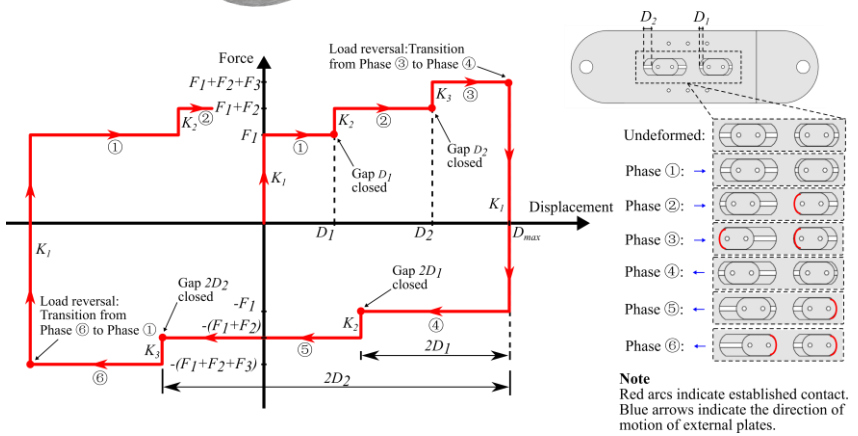
- The connection is **simple to manufacture, assemble, and install**. It is intended to be **damage-free**, and thus, can be **immediately reusable after an earthquake**. The design parameters of the Modified FD can be easily adjusted, making the connection **highly versatile**.

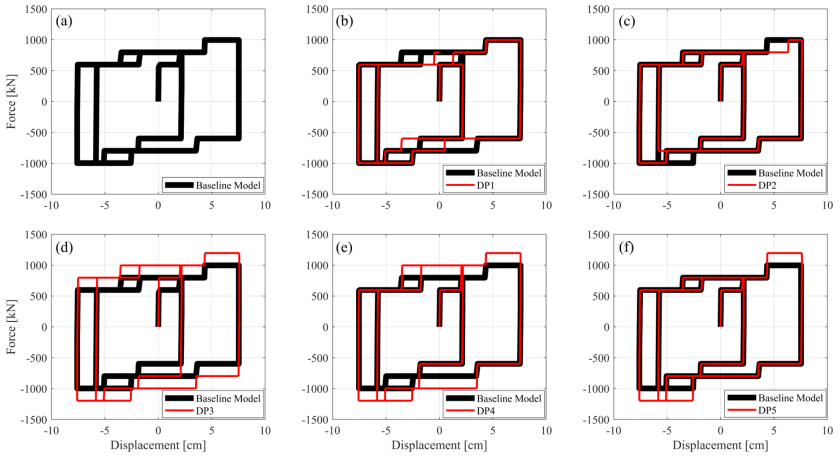
- The connection is able to develop an **equivalent post-elastic stiffness** by its unique force-displacement response and therefore, can **prevent excessive connection deformations**, compared with conventional friction devices that have zero post-elastic stiffness.

- **Numerical simulations** using solid finite elements and truss elements demonstrated the **feasibility and simplicity of modeling the connection** using different approaches to facilitate the design and research needs.

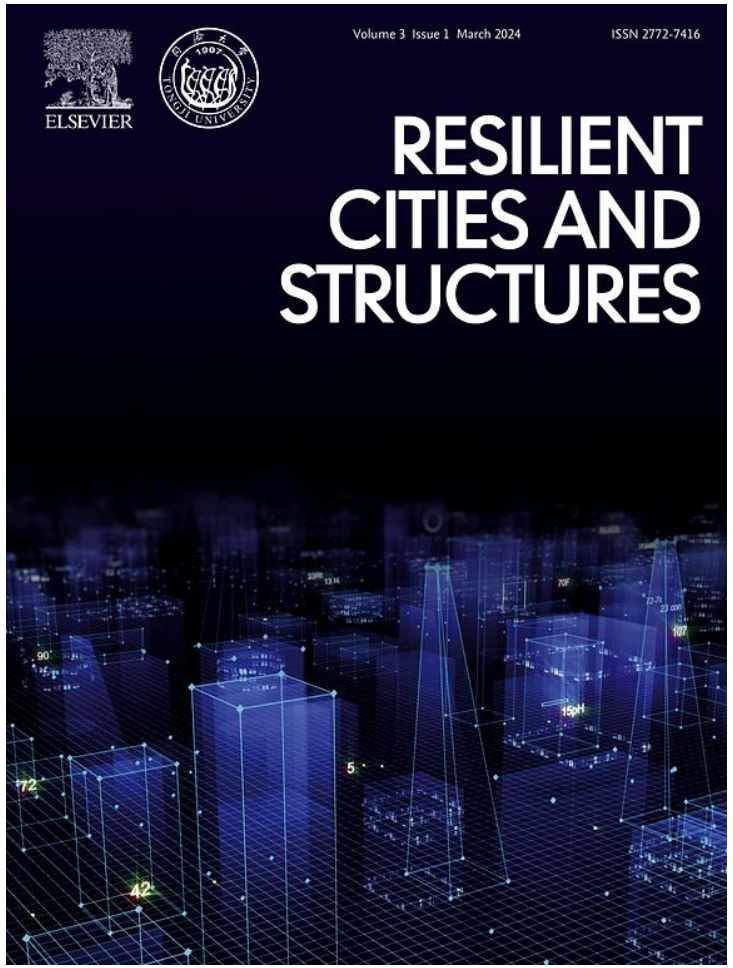
- For future work, **experimental characterization** of the Modified FD is required; **parametric study** is required to understand how each design parameter would affect the dynamic response of the structure.







Related Publication



Chen, K., Tsampras, G., & Lee, K. (2023). Structural connection with predetermined discrete variable friction forces. Resilient Cities and Structures, 2(1), 1-17.

Selected References

- **Chen, K., Tsampras, G., & Lee, K. (2023). Structural connection with predetermined discrete variable friction forces. Resilient Cities and Structures, 2(1), 1-17.**

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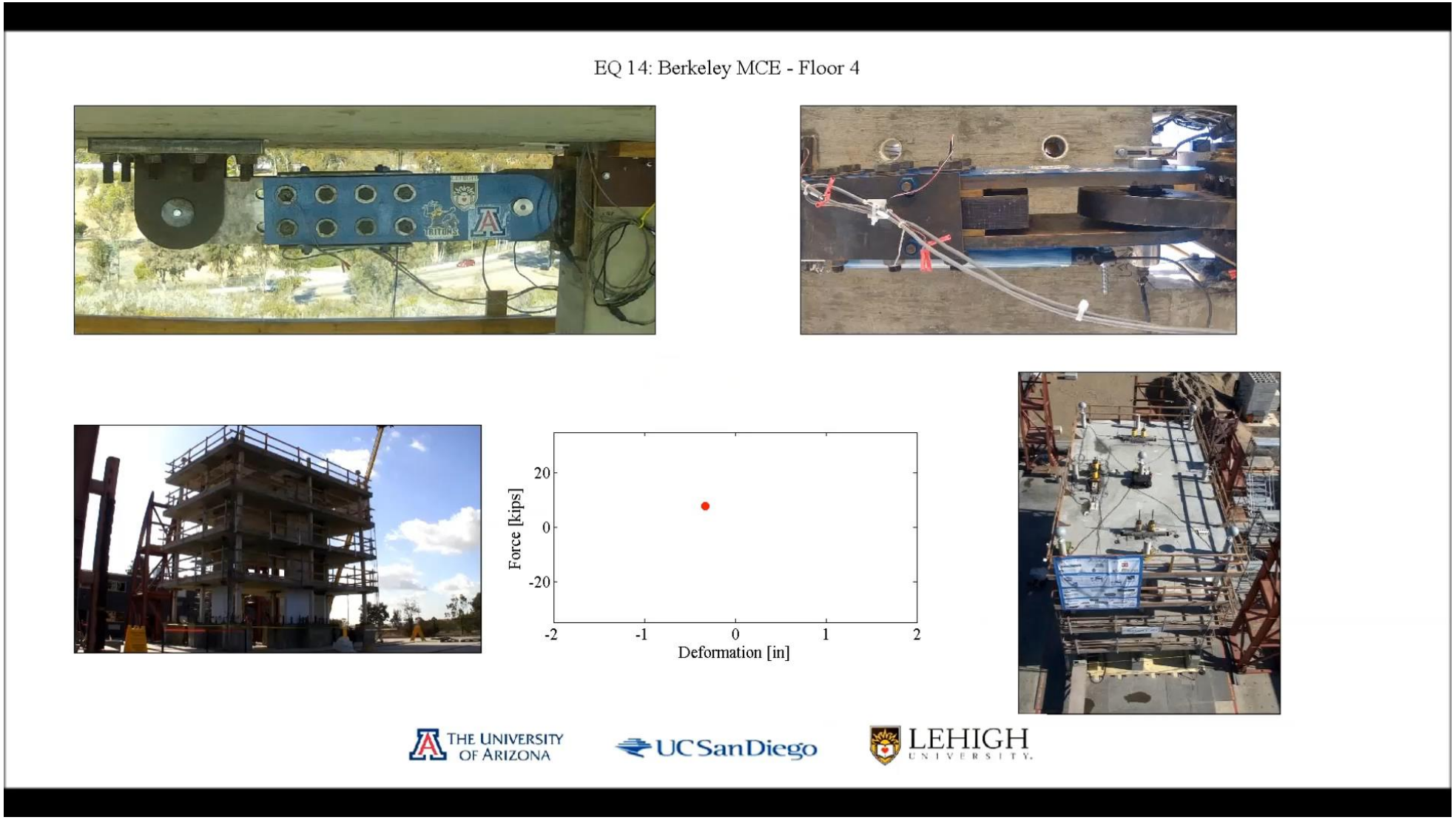


Thank you for your attention!

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Tsampras Research Group

Using friction devices as force-limiting connections between GLRS and SFRS



Video courtesy of Professor Georgios Tsampras
(Zhang et al.,2018)