2025 PEER Annual Meeting

Friction-based Force-limiting Connections

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Jacobs School of Engineering
UC San Diego

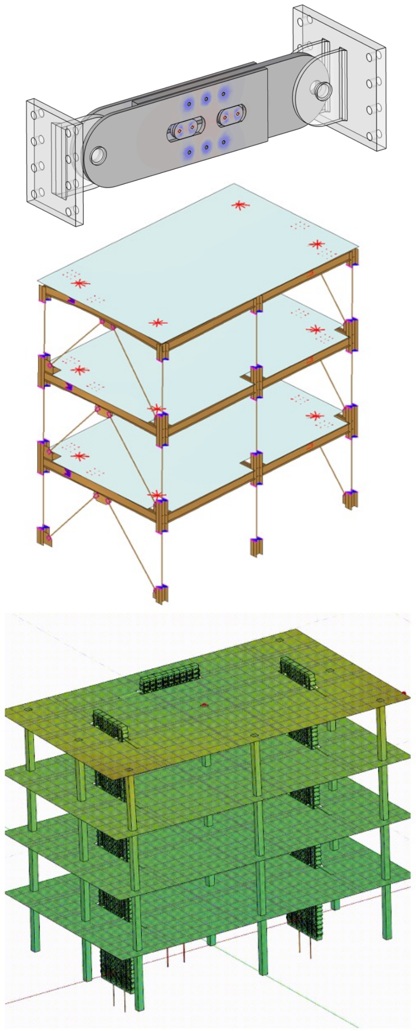
March 26, 2025
UC Berkeley, CA

http://tsampras.ucsd.edu

Overall, our research group at UC San Diego aims to contribute to the improvement of safety and resilience of our built environment and education of structural engineering students

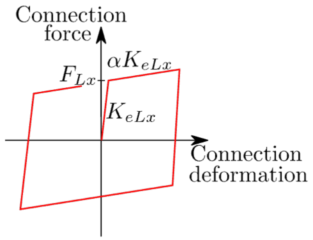
Experimental

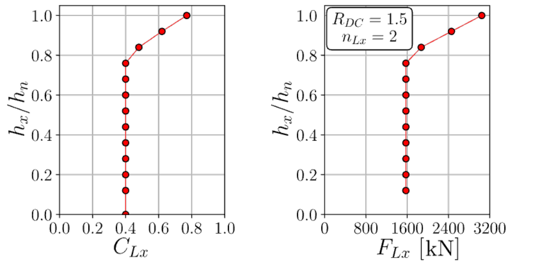
Computational

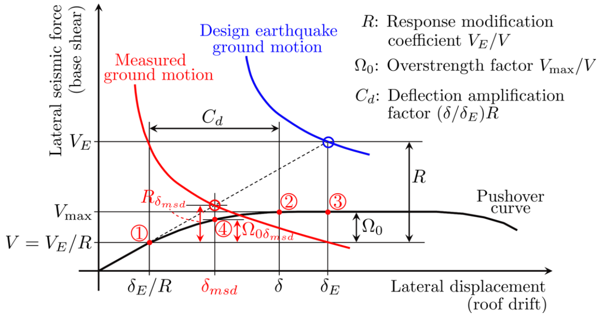


Design

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

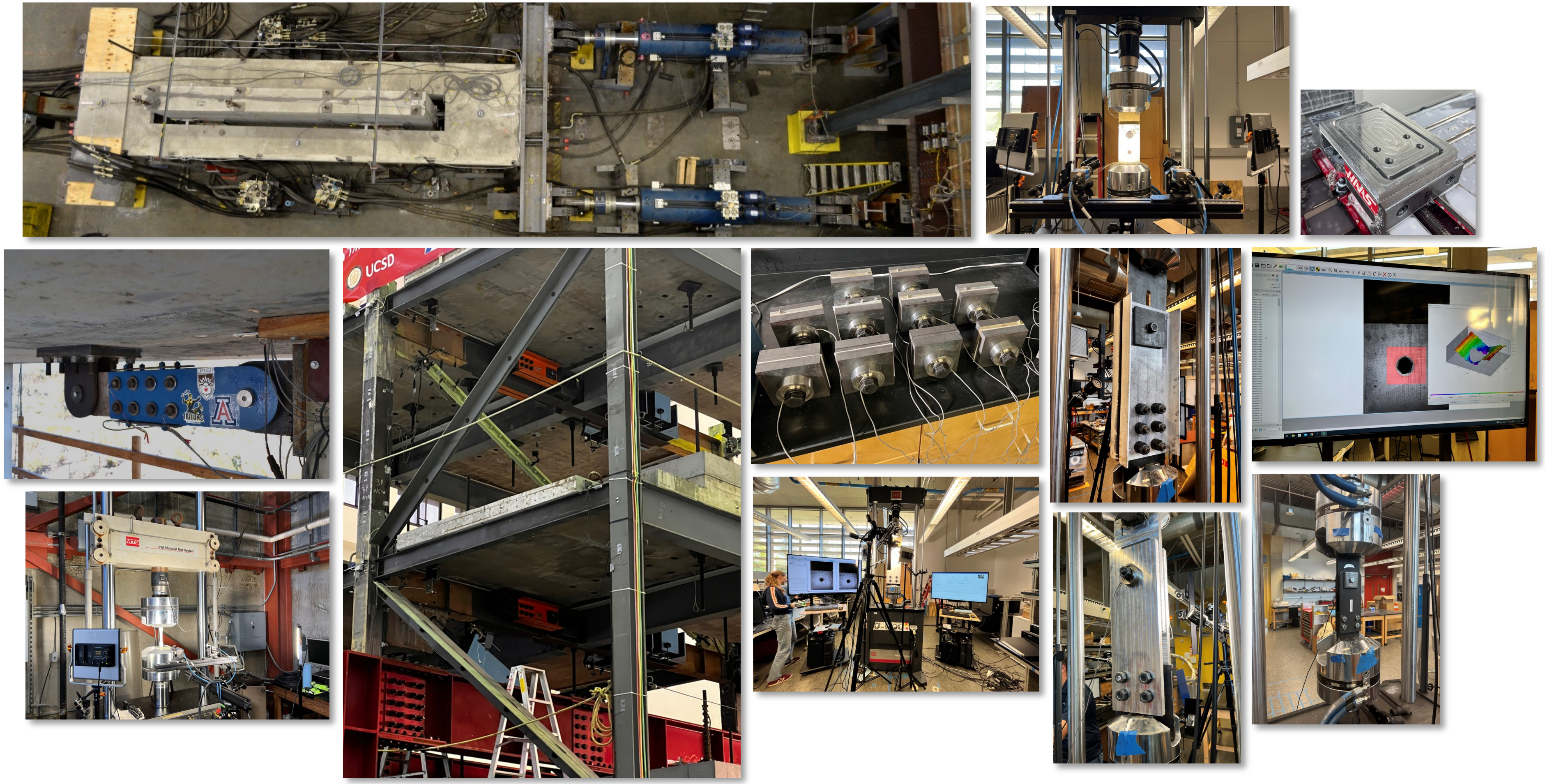






Hybrid Manufacturing

My **Goal** is to share findings from friction related experimental research at the material-, component-, and system-level that we conducted since 2011.



Scope

- Benefits of friction-based structural components
- Experimentally observed challenges
- Research to address the challenges

Acknowledgments – Work related to Friction

Inertial Force-limiting Floor Anchorage Systems For Seismic Resistant Building Structures (2011-2016): Robert Fleischman, Jose Restrepo, Richard Sause, Joe Maffei, David Mar, Dichuan Zhang, Zhi Zhang, Ulina Shakya, Arpit Nema, Gabriele Guerrini

Alternative designs of friction-based connections (2020-Present):

Kaixin Chen, Franco Mayorga, Yeon Li, Dominic Tran, Anne-Sophie Roobol, Anthony Li

Steel buildings with sliding floors and elastic frames (2022-2025): Chung-Che Chou, Shih-Ho Chao, Chia-Ming Uang, Li-Yu Huang, Chi-Jeng Wu, Alvaro Cordova, Huang-Zuo Lin, Shu-Hsien Chao, Nicholas Tedjasukmana, Ming-Yen Xie, Wei-Xuan Chen, Hao Wei Jian

Design related ongoing research

Disaster Resilience Research Grant

Project	Group/Board	Organization	Member
Resilience-based design of buildings with accelerated post-earthquake functional recovery	Research Group	UC San Diego	PI, Georgios Tsampras
			GSR, Franco Mayorga
		Lehigh University	Co-PI, Paolo Bocchini
			GSR, Sena Mursel
	Educational Outreach Group	Walgrove Elementary School	Coordinator, Andrea Kittelson
			STEAM Teachers
	Academic Advisory Board	Colorado State University	Advisor, Bruce R. Ellingwood
	Practicing Engineering Advisory Board	Maffei Structural Engineering	Advisor, Lawrence Burkett
		Magnusson Klemencic Associates	Advisor, John D. Hooper
		Mar Structural Design	Advisor, David Mar
		Skidmore, Owings & Merrill (SOM)	Advisor, Mark Sarkisian
	Industry Advisory Board	Gripple Inc.	Advisor, Prasad Naik











Video Presentation

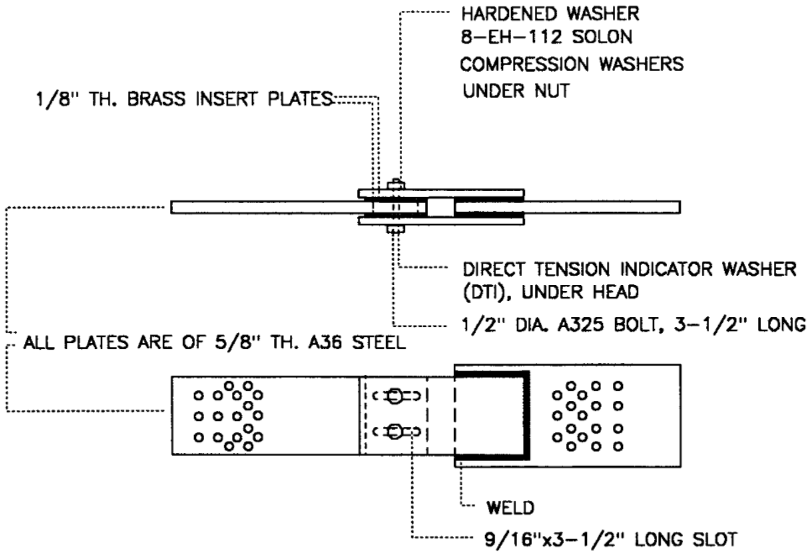
Friction-based components in structural engineering

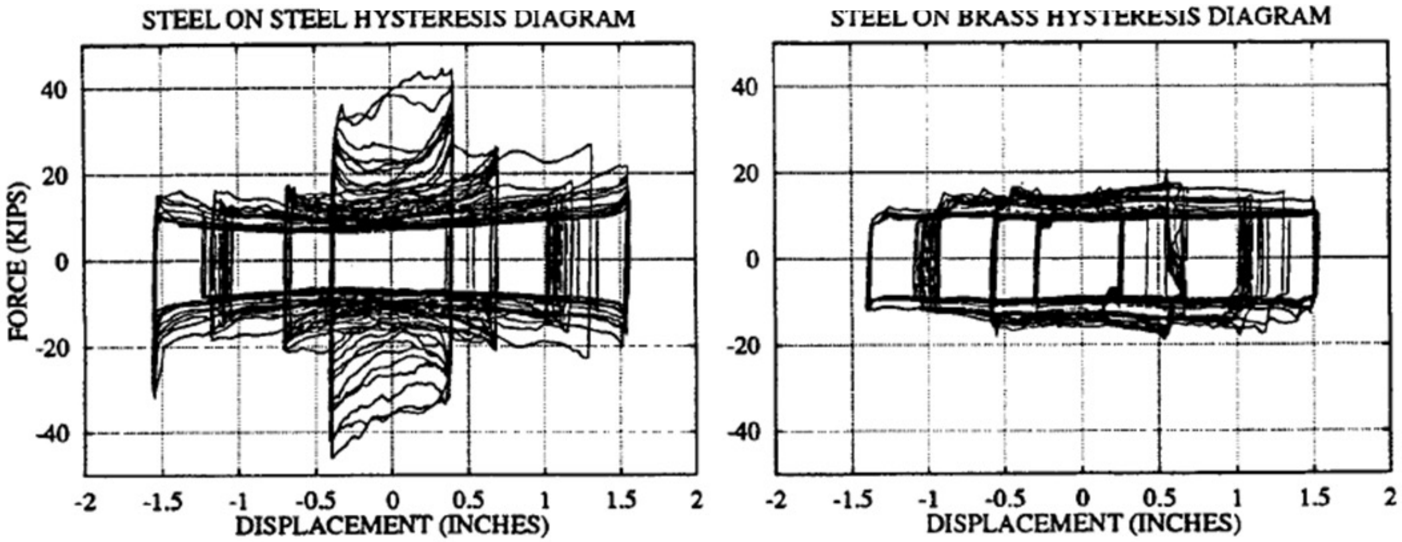
Early work by

- Clark et al. 1973 – Limit forces in foundations
- Pall 1979, Pall and Mash 1982
- Filiatrault and Cherry 1987
- Aiken, Kelly, Pall 1988
- Anagnostides 1988
- Giacchetti, Whittaker, Bertero, Aktan 1989
- FitzGerald, Anagnos, Goodson, and Zsutty 1989
- Tremblay 1993
- Grigorian, Yang and Popov 1993

Example applications

- 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

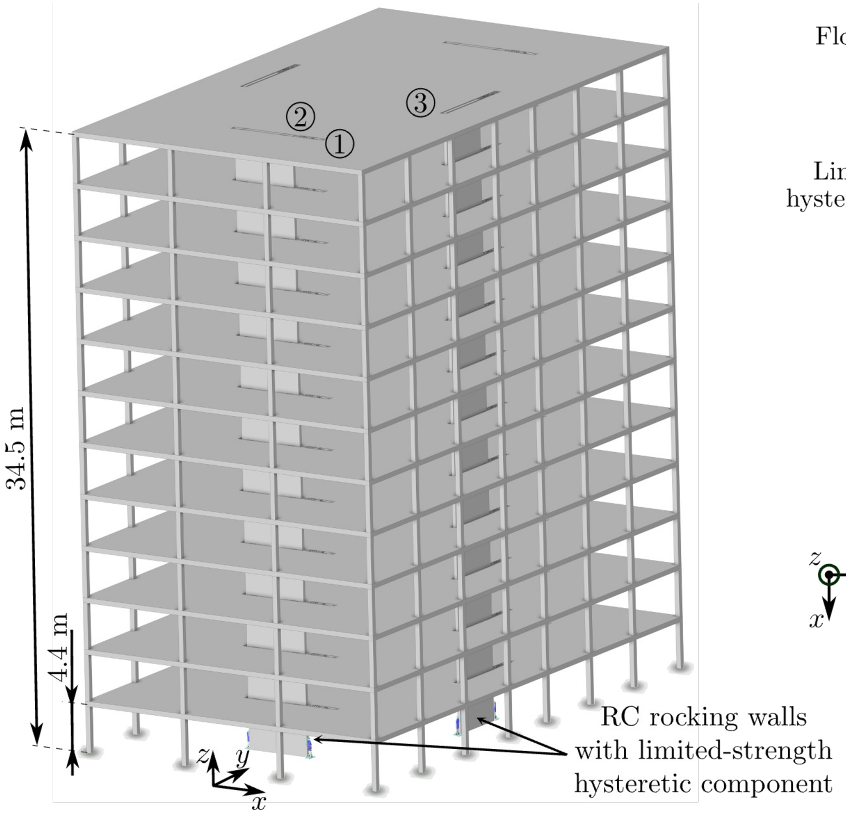


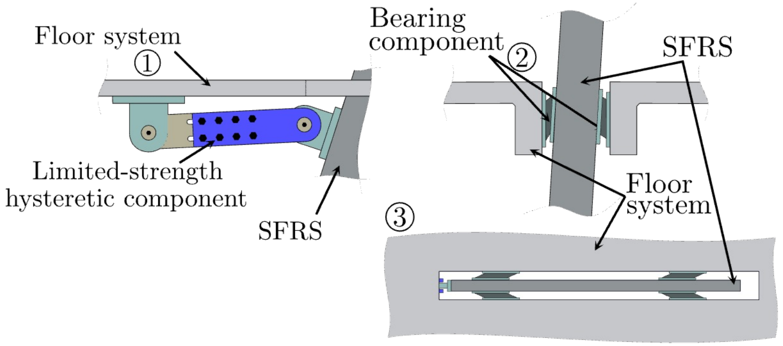


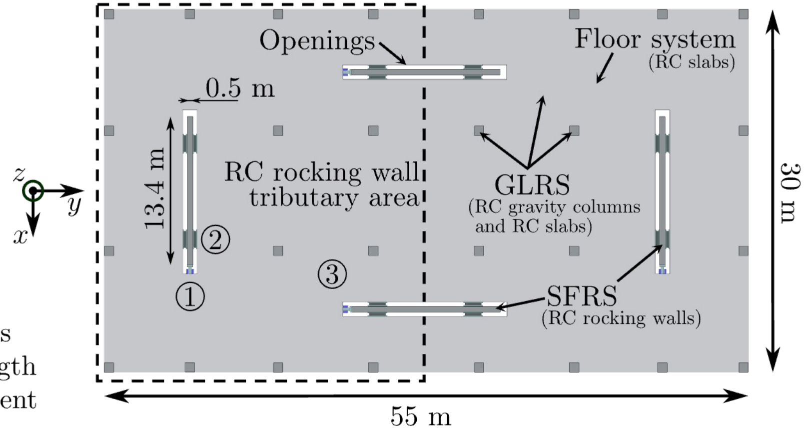
Grigorian, Yang and Popov 1993

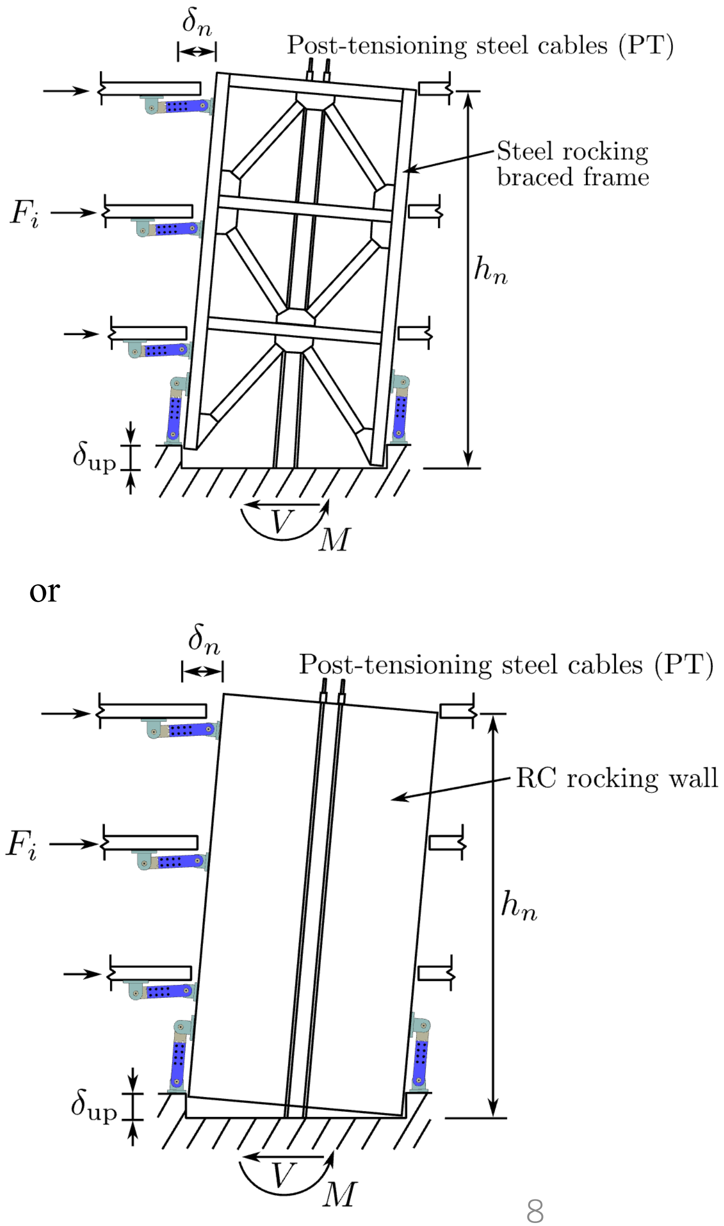
Literature review available in:
Tsampras et al. (2018), Chen et al. (2023)

Example use of friction-based force-limiting connections



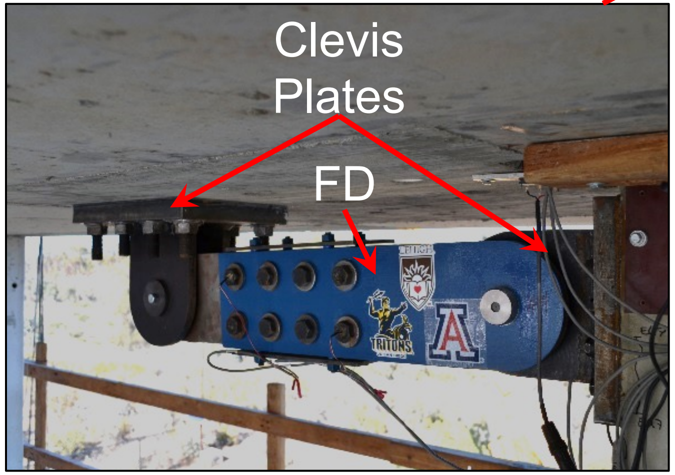


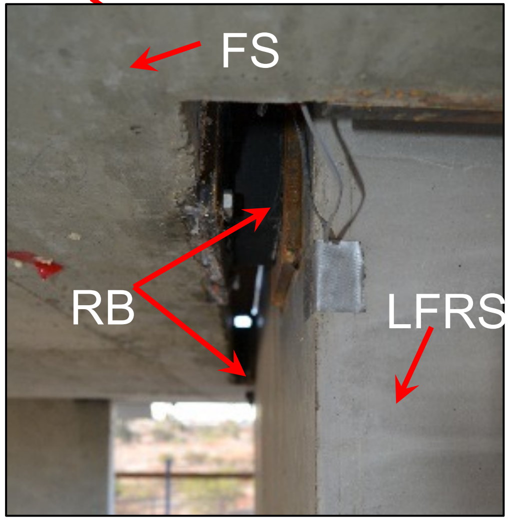




Example Installation of Force-Limiting Connection

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

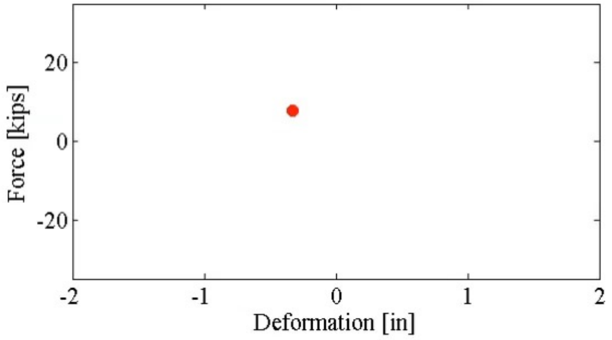


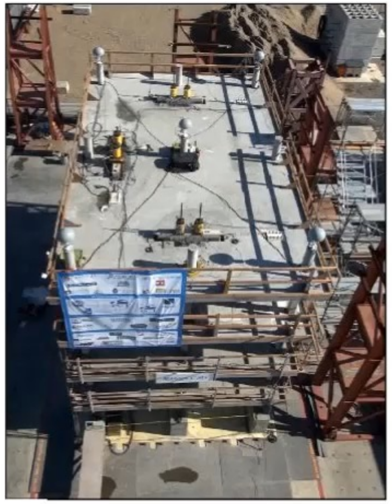


Zhi Zhang, Robert B. Fleischman, José I. Restrepo, Gabrielle Guerrini, Arpit Nema, Dichuan Zhang, Ulina Shakya, Georgios Tsampras, Richard Sause (2018), Shake table test performance of an inertial force-limiting floor anchorage system, Earthquake Engineering & Structural Dynamics, 47 (10), 1987-2011,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

Example Installation at NEES @ UCSD

EQ 14: Berkeley MCE - Floor 4





THE UNIVERSITY OF ARIZONA UCSanDiego LEHIGH UNIVERSITY

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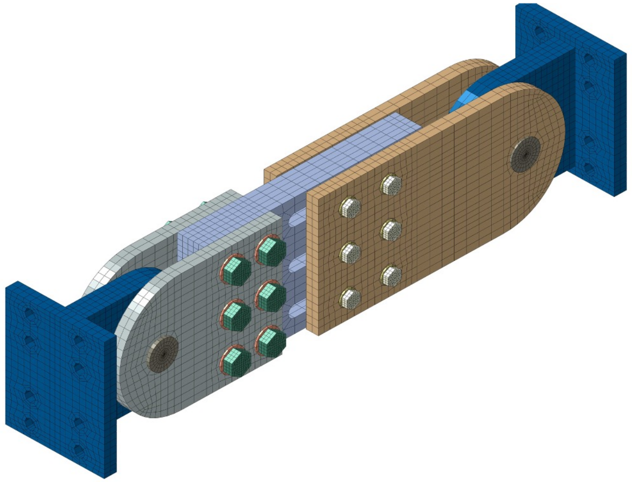
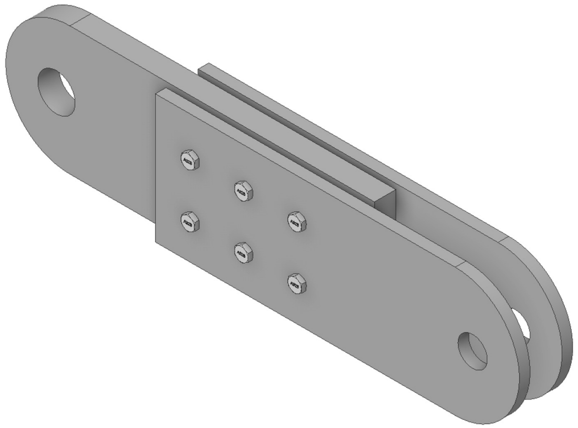
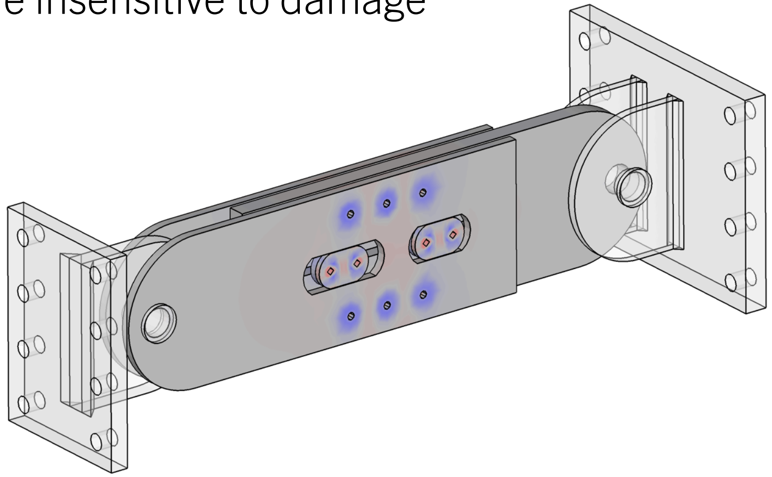
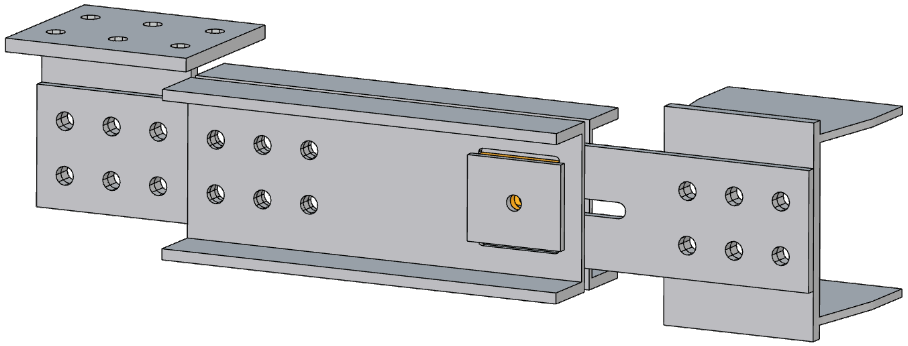
Why friction-based force-limiting connections?

- 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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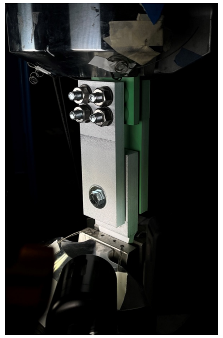
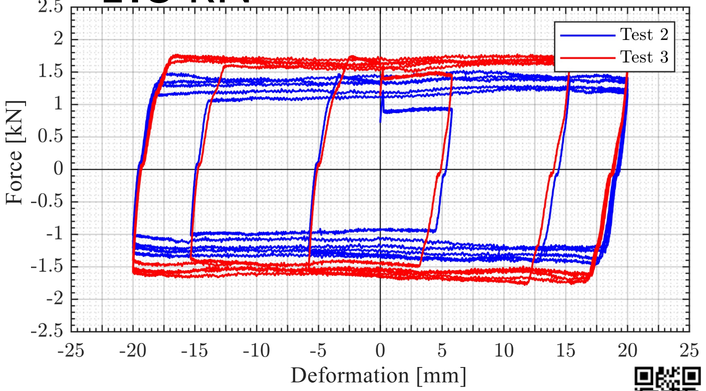
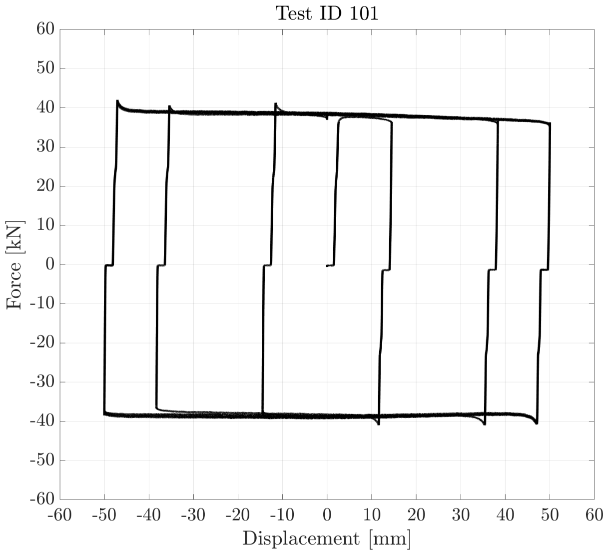
~1.5 kN

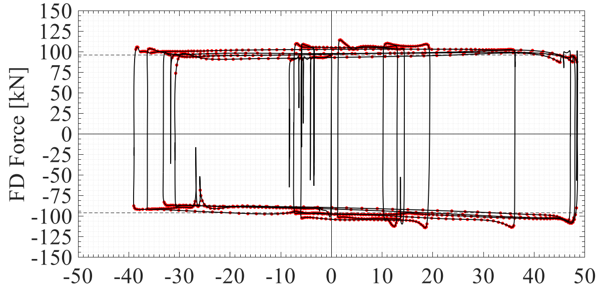




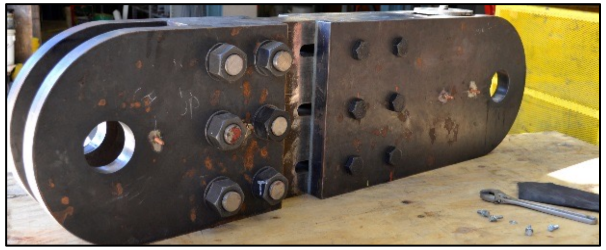
~40 kN

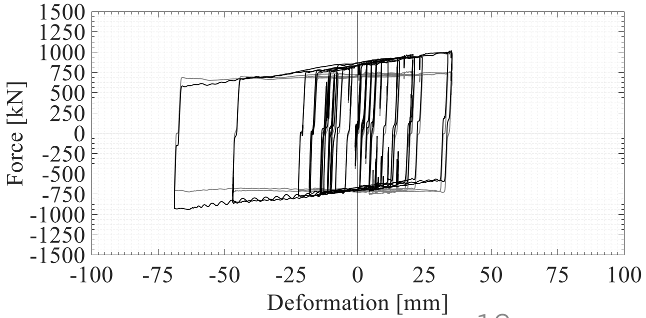


~100 kN



~750 kN





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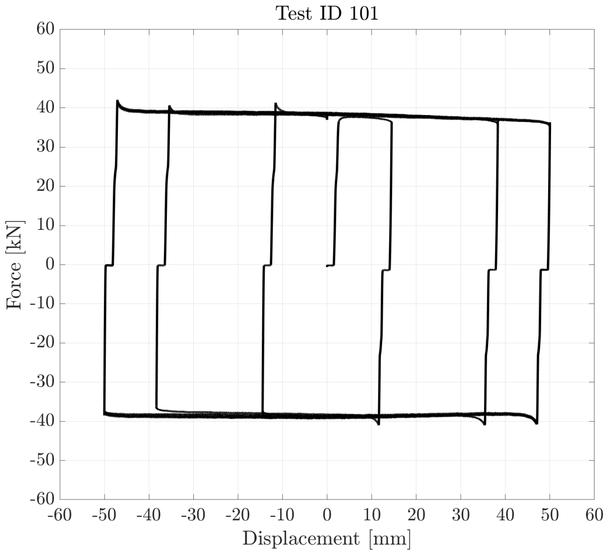

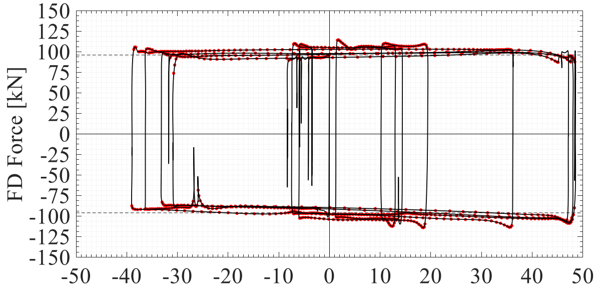

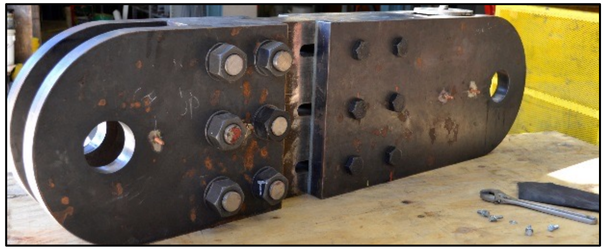

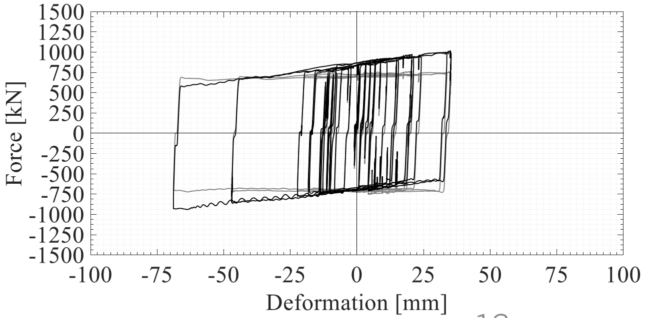

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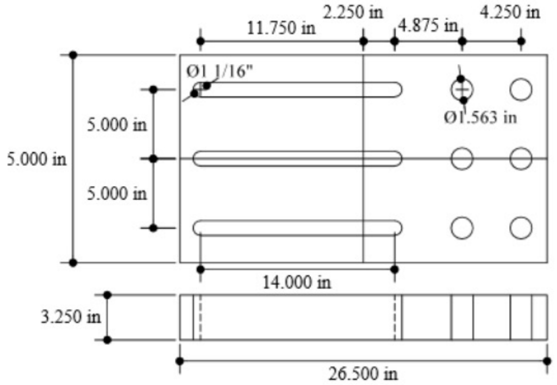
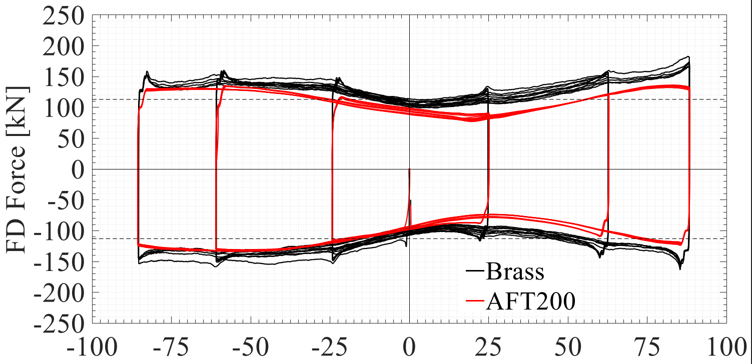
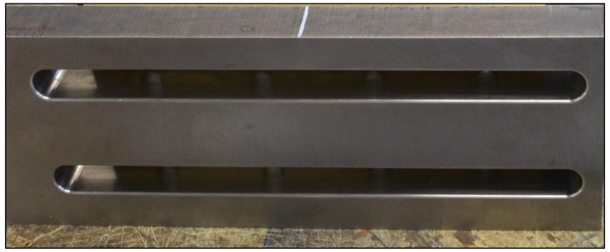
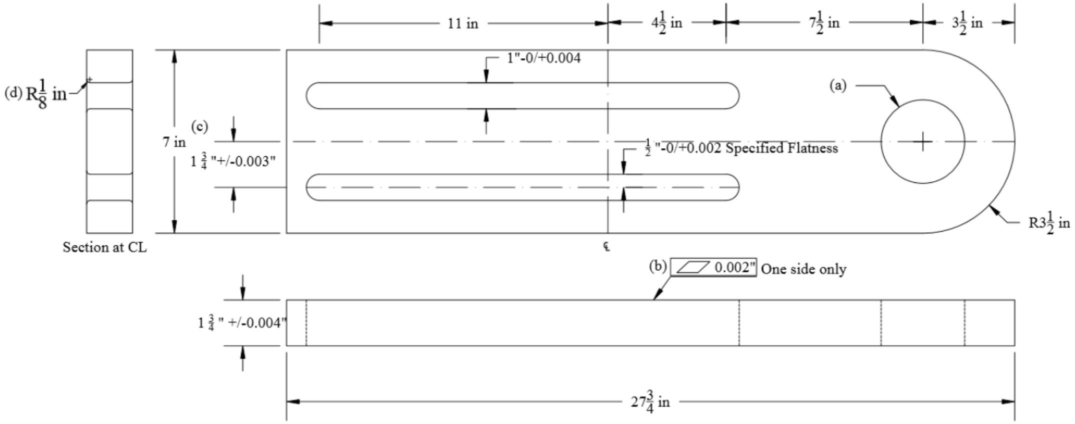
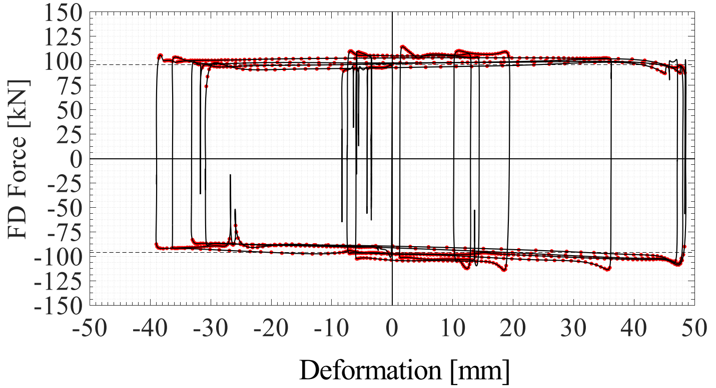
*Manufacturing requirements depend on the design











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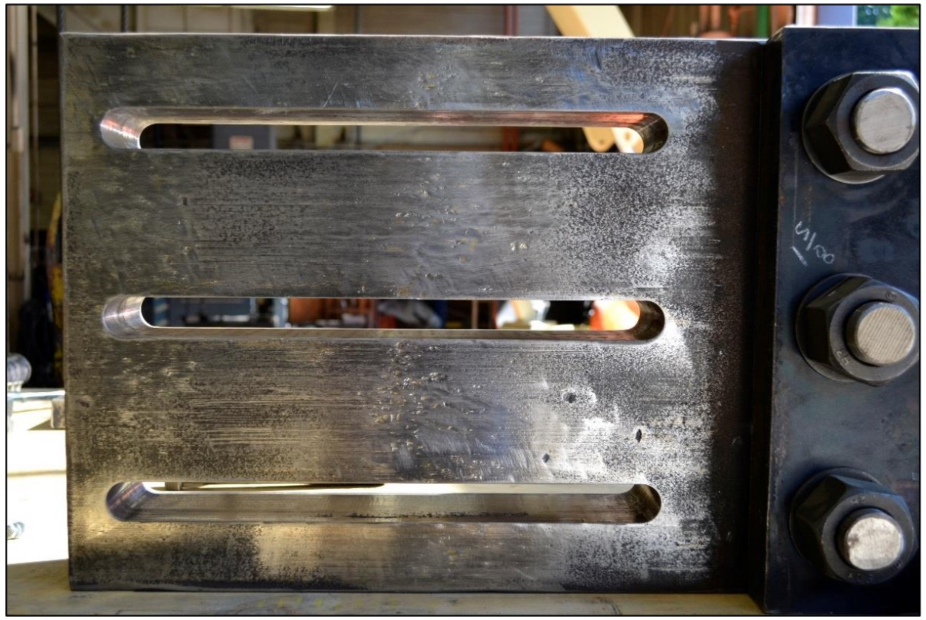

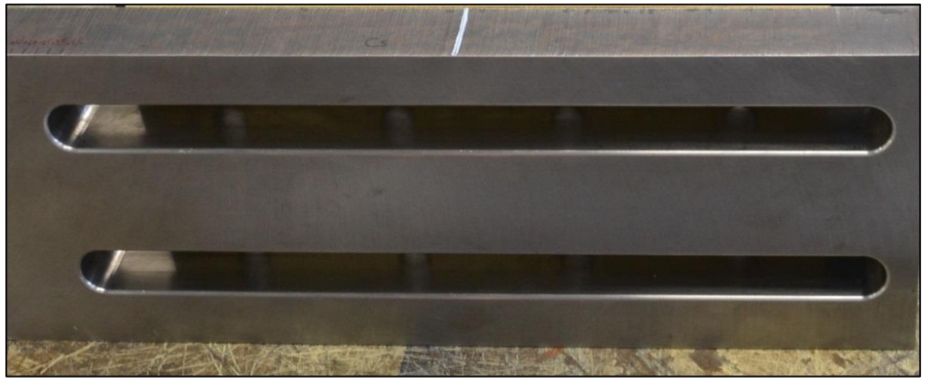

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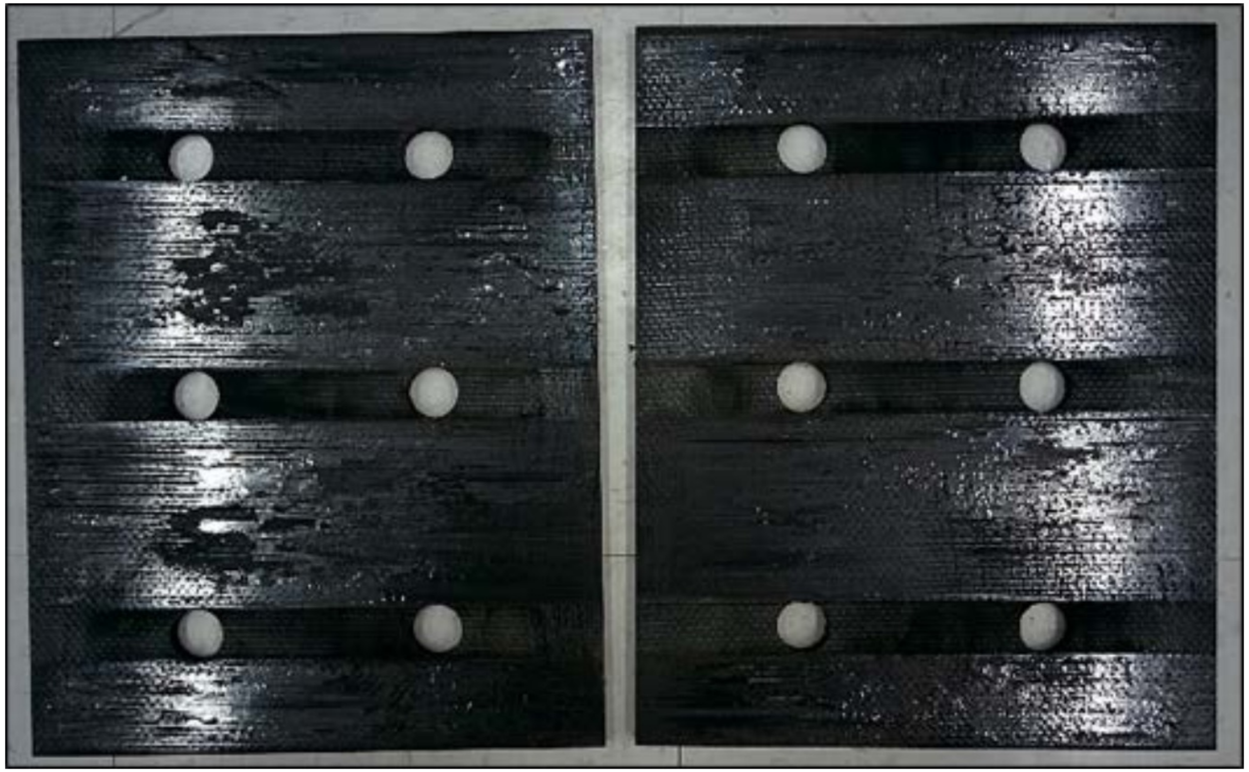

*Depends on design

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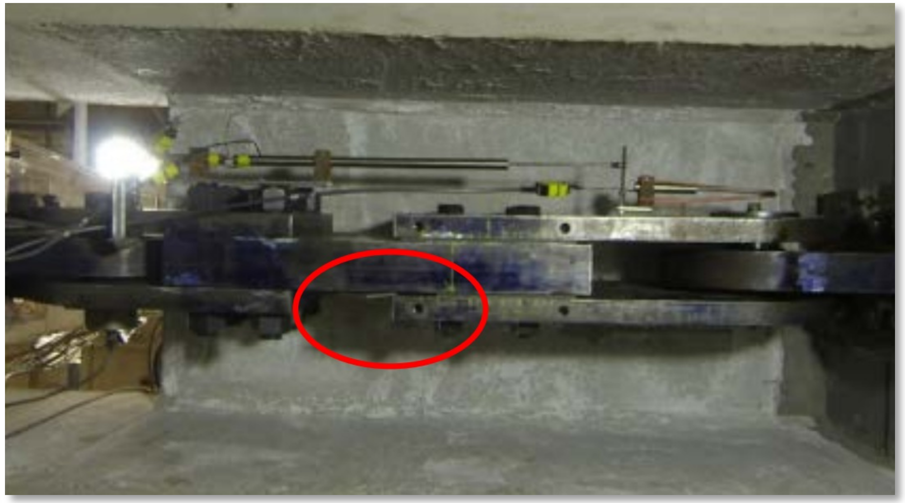

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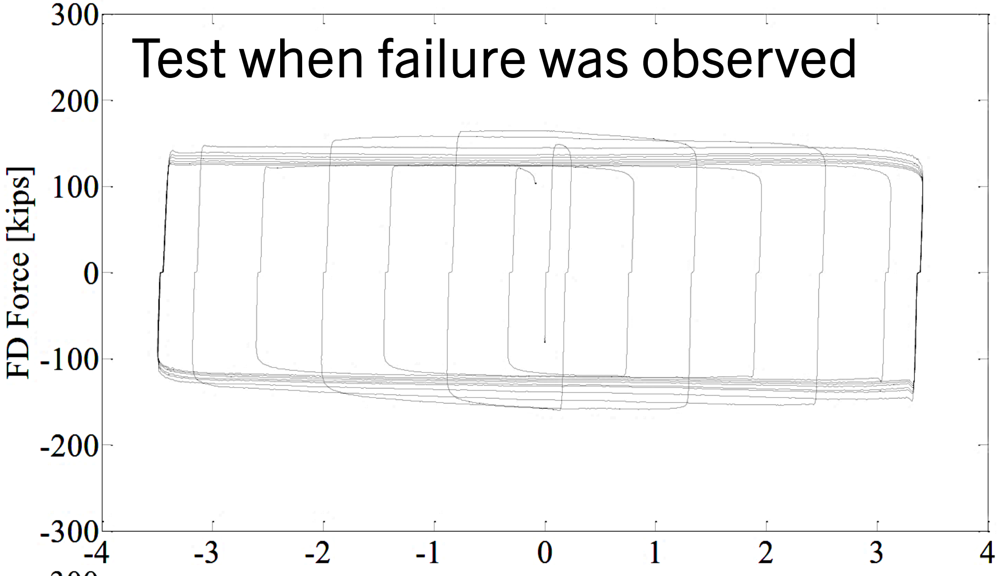
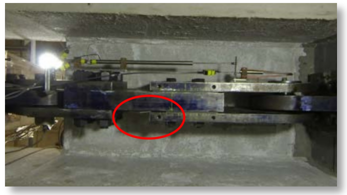
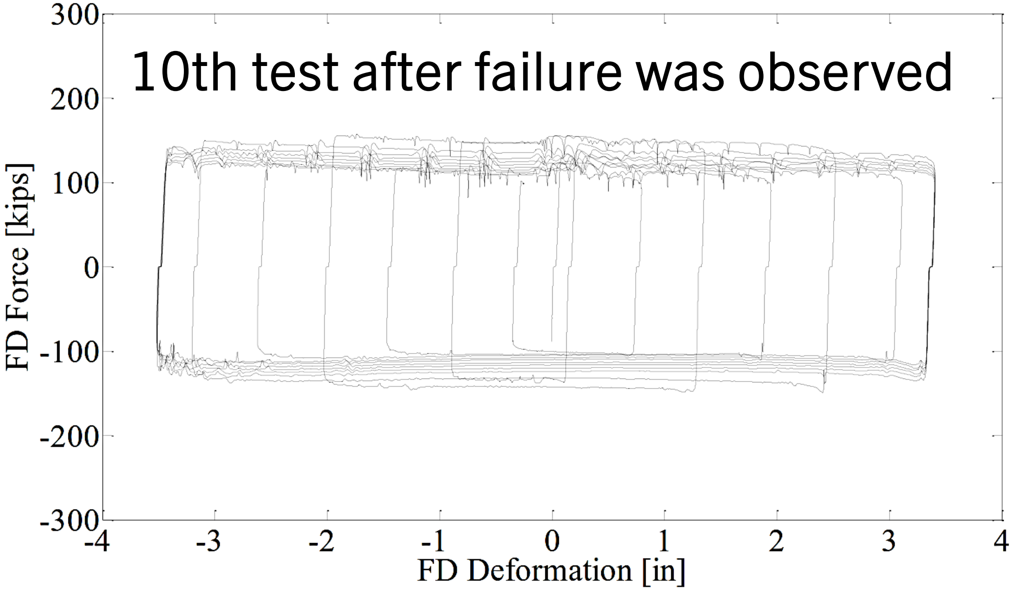




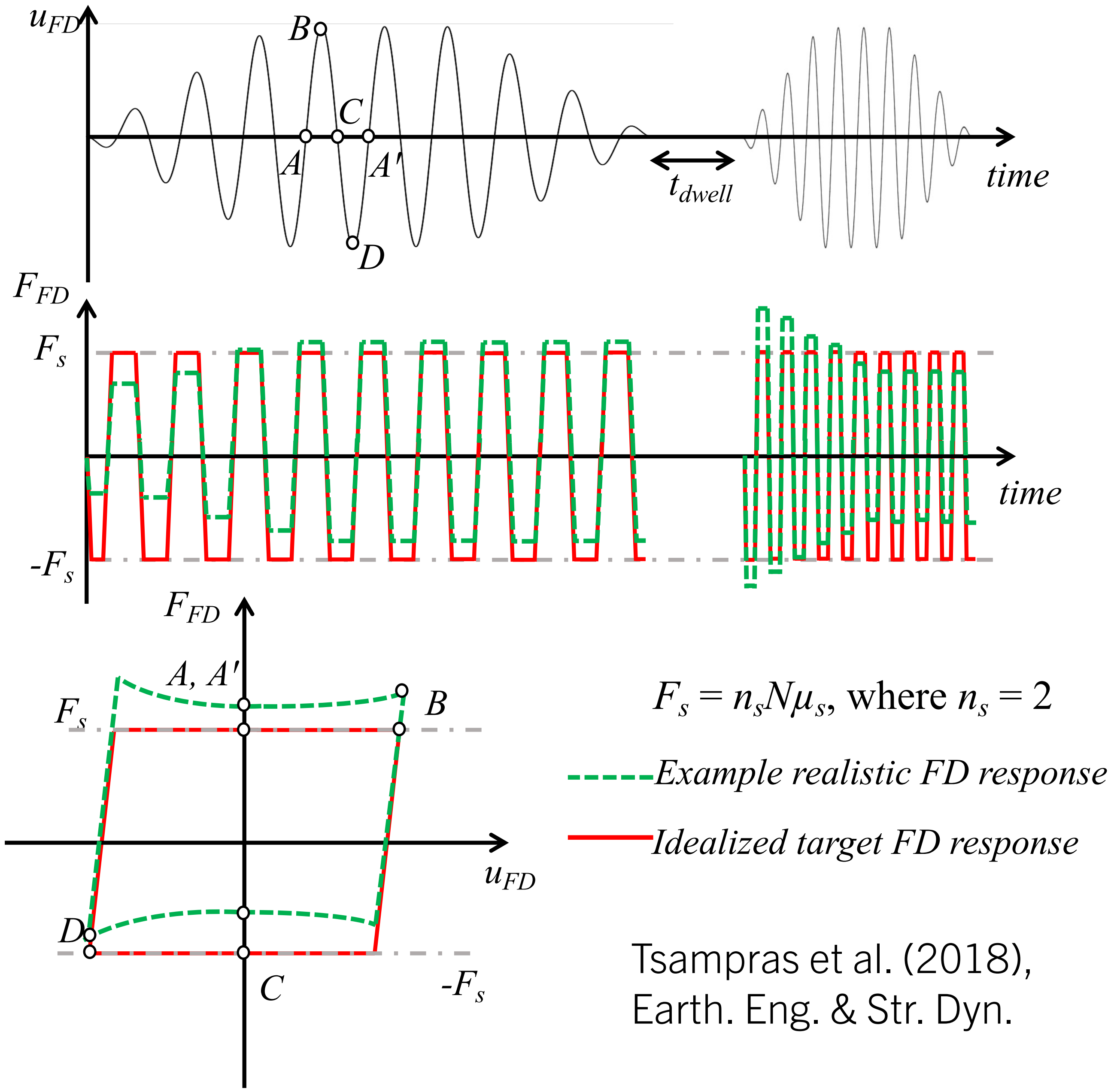


Challenges

Challenges with friction-based structural connections

Friction-sliding behavior is affected by:

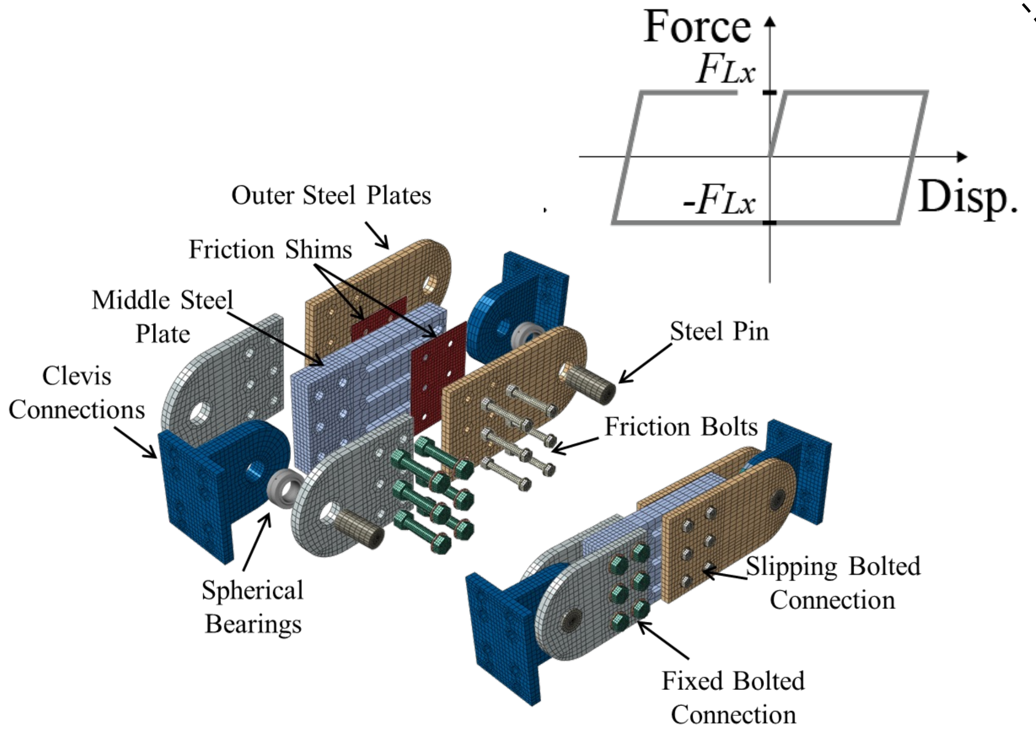
- Sliding velocity
- Dwell time
- Galvanic corrosion in bimetallic friction interface
- Creep of composite materials
- Break-in and cumulative sliding effects
- Effect of machining and geometric tolerances
- The effectively zero post-elastic stiffness can be both an advantage and disadvantage



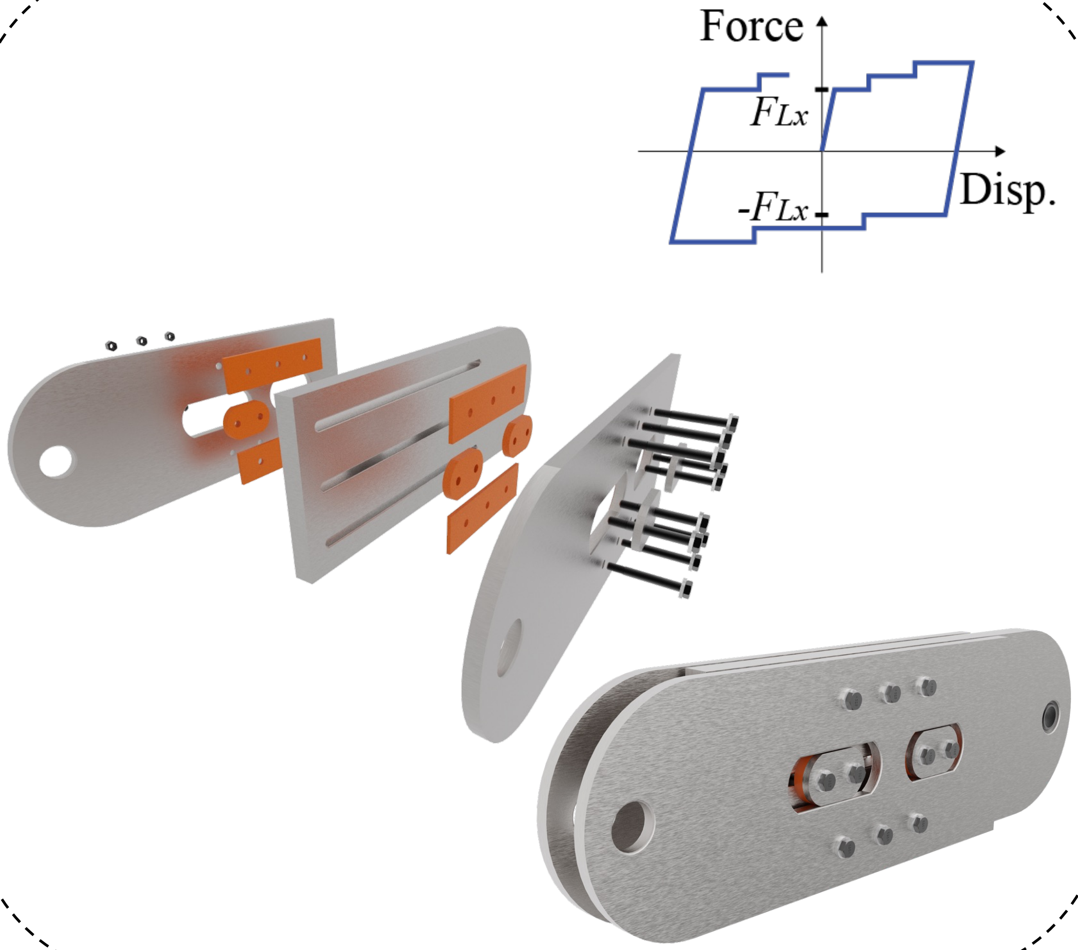
Tsampras et al. (2018), Earth. Eng. & Str. Dyn.

Modified Friction Device

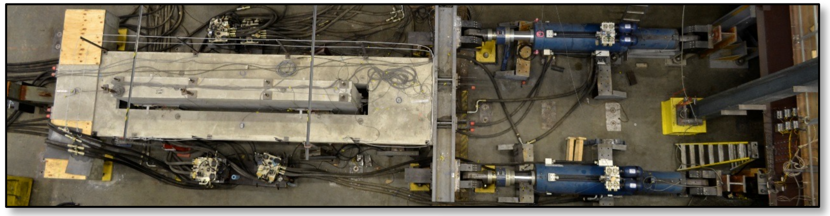
Tsampras et al. 2014, 2018



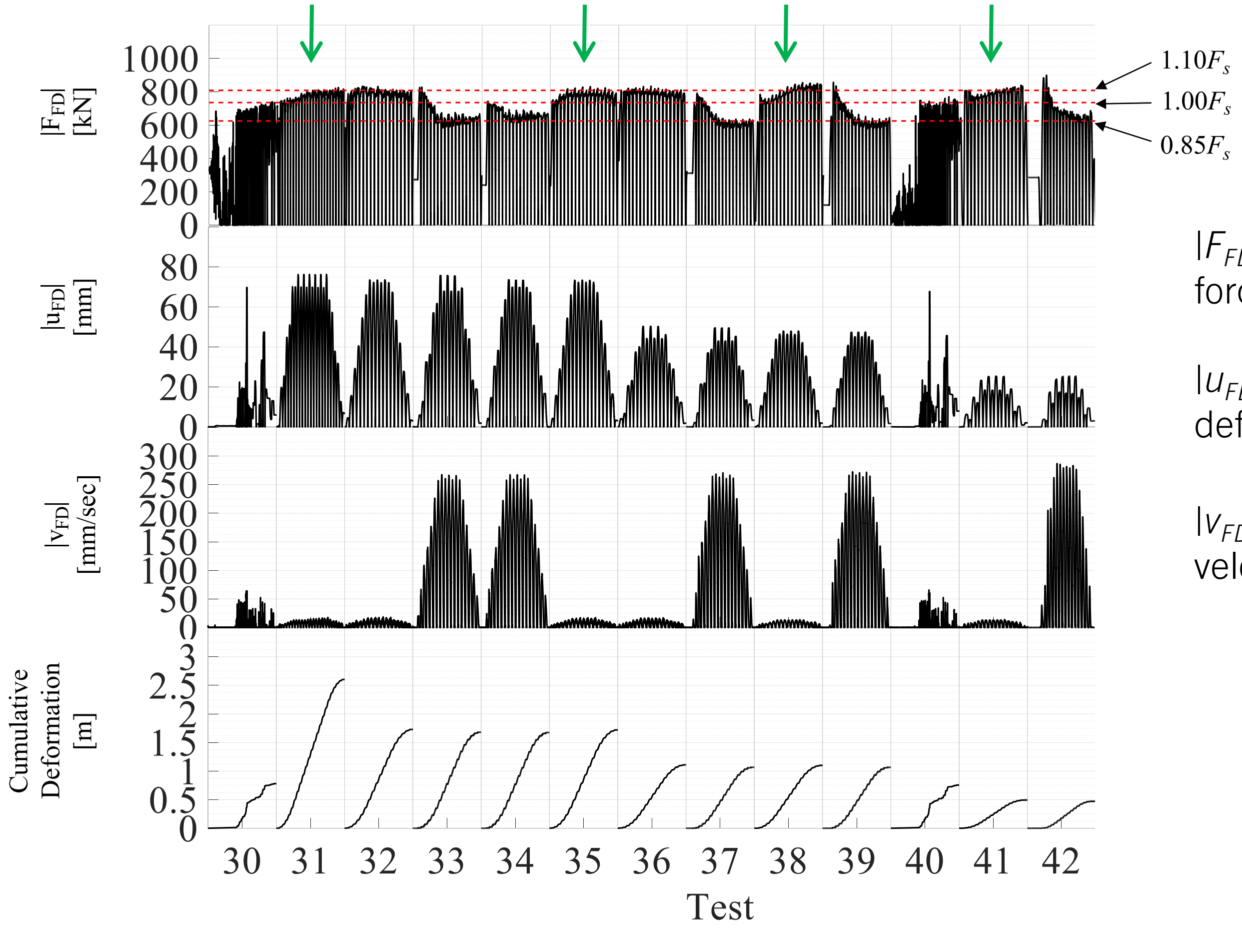
Modified friction device



Sliding History: Low velocity effect



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



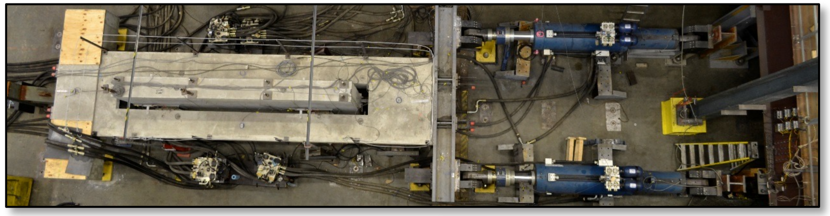
$|F_{FD}|$ is the absolute FD force

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

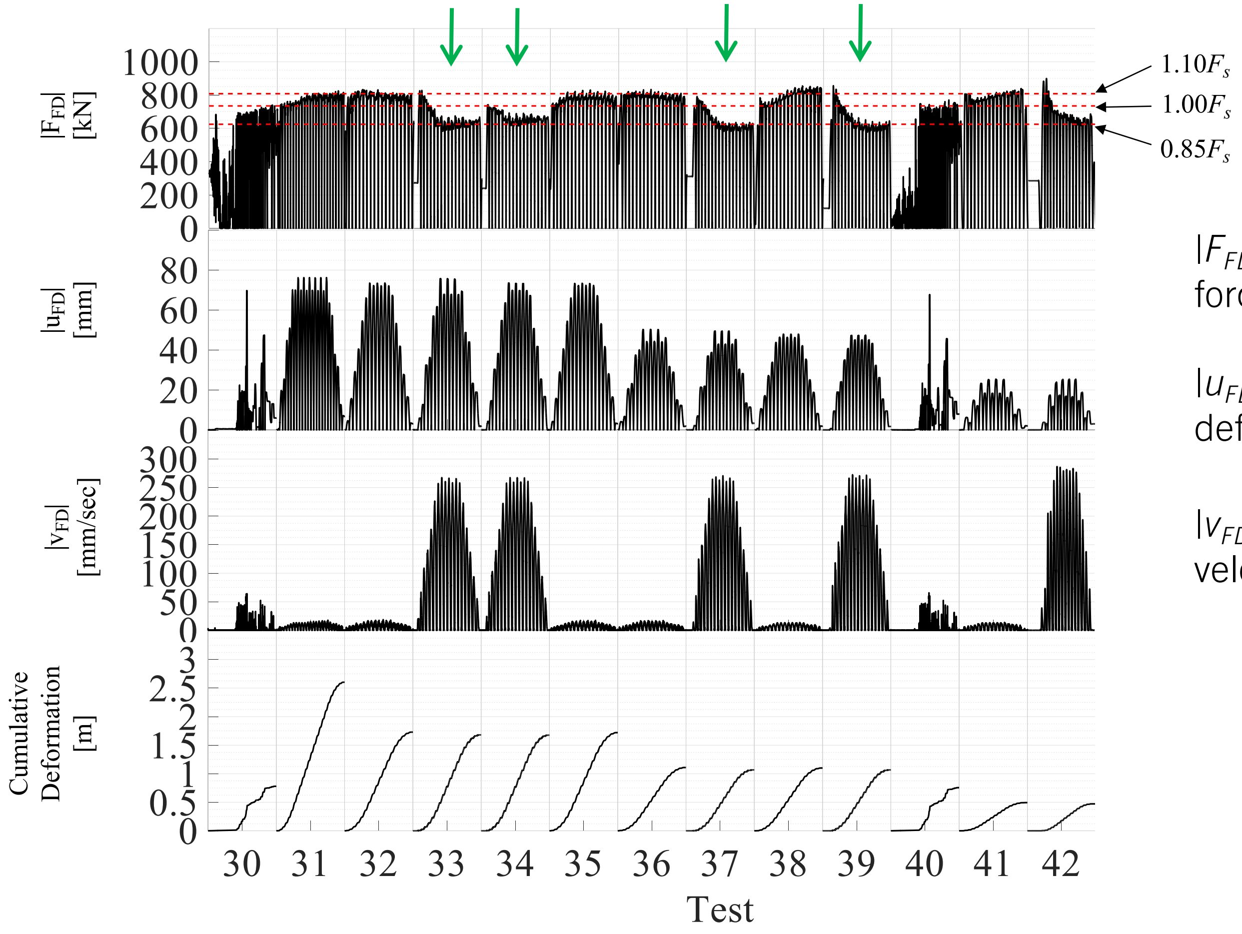
$|v_{FD}|$ is the absolute FD velocity

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 $0.85F_s$



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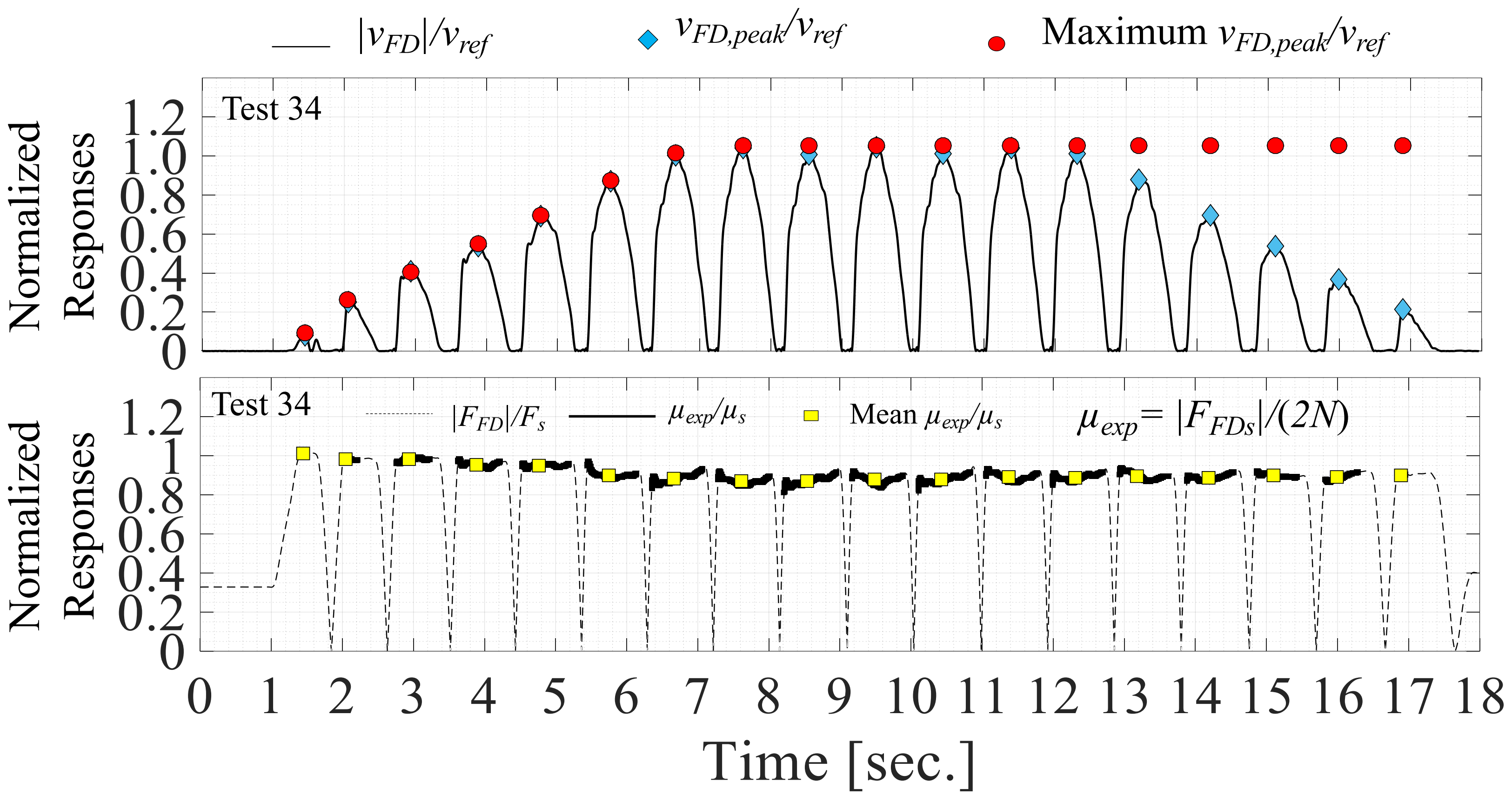
Sliding History: High velocity effect (Cont'd)

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

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



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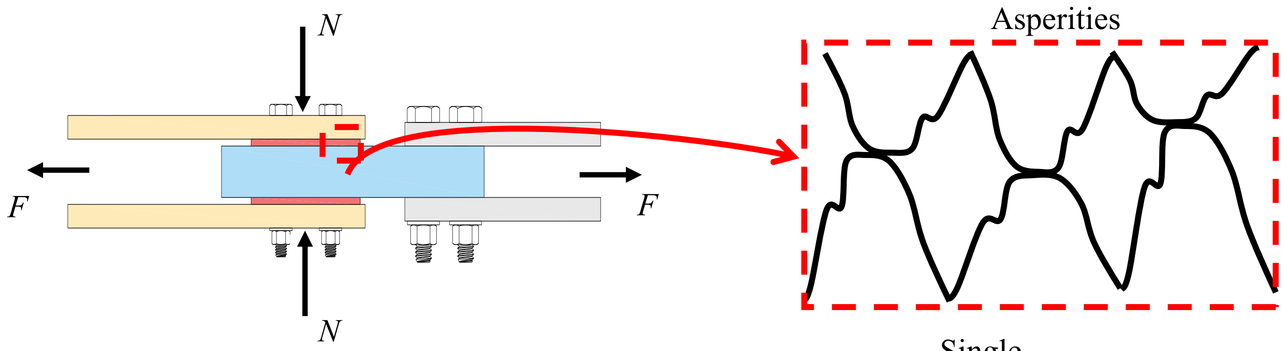
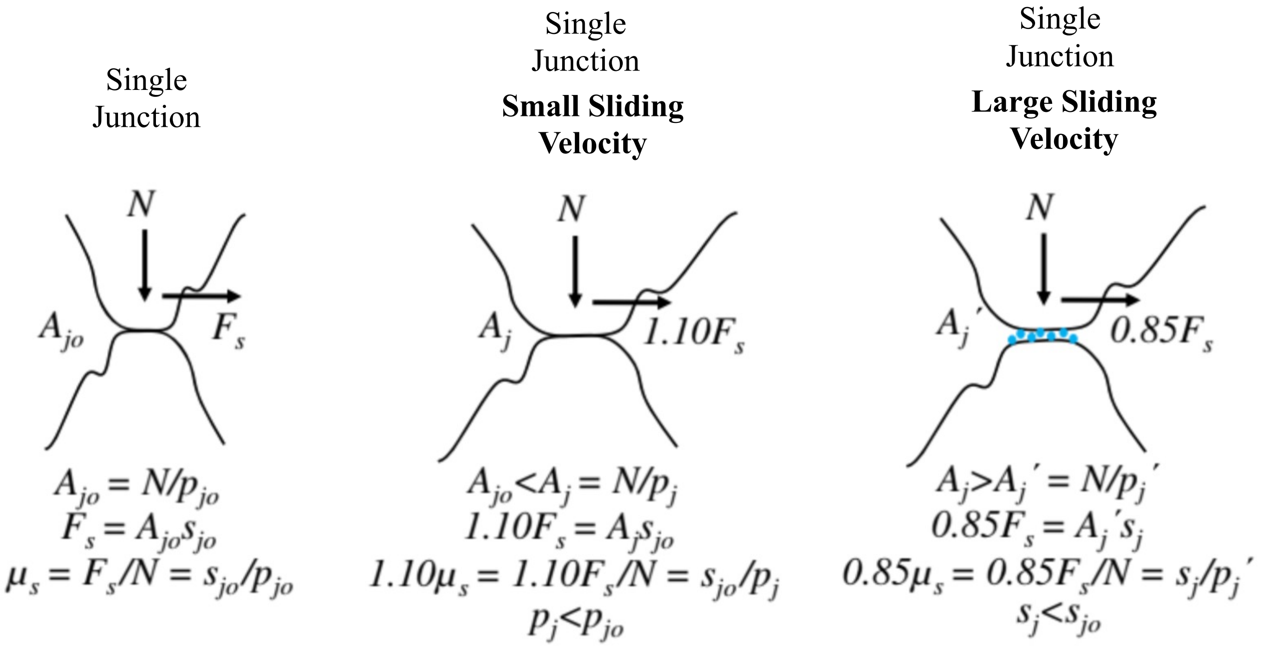
Evolution of friction interface with respect to sliding velocity





A_j : true contact area

N : total normal force at friction interface

p_j : normal pressure

s_j : interface shear stress (strength)

μ_s : friction coefficient

- D. Tabor, "Friction - The present state of our understanding," Journal of Lubrication Technology, vol. 103, pp. 169-179, 1981
- 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

Research to address material-level challenges

Challenges with friction-based structural connections

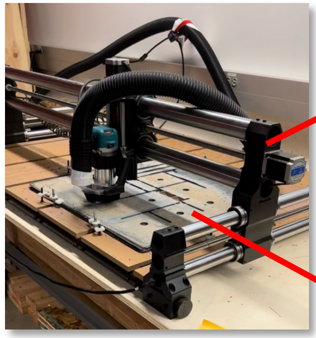
Friction-sliding behavior is affected by:

- Sliding velocity
- Dwell time
- Galvanic corrosion in bimetallic friction interface
- Creep of composite materials
- Break-in and cumulative sliding effects
- Effect of machining and geometric tolerances
- The effectively zero post-elastic stiffness can be both an advantage and disadvantage

Experimental characterization of composite materials in friction interfaces for structural applications

Material Plates

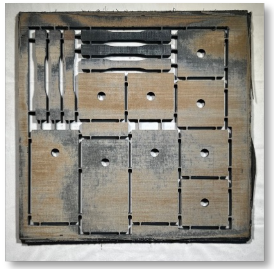
CNC Subtractive Machining

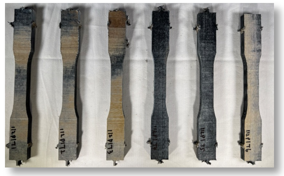


Onefinity CNC router

Material Plate

Material Plate (Machined)





Tensile coupons

Bearing plates

Square-shaped plates

Coupon Tensile Test

Plate Bearing Test

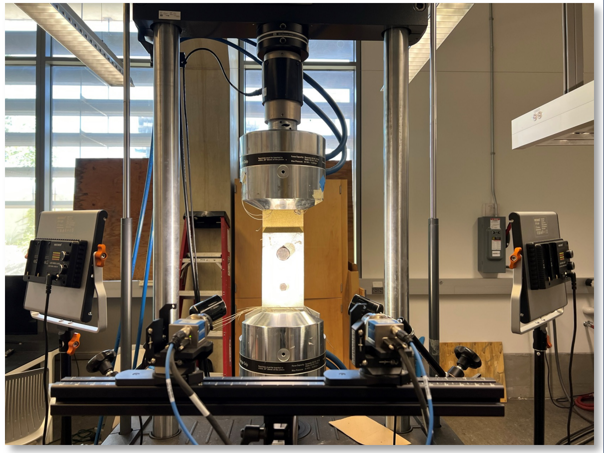
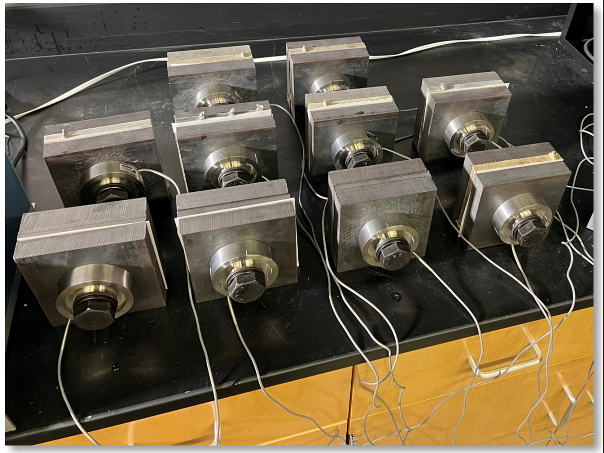


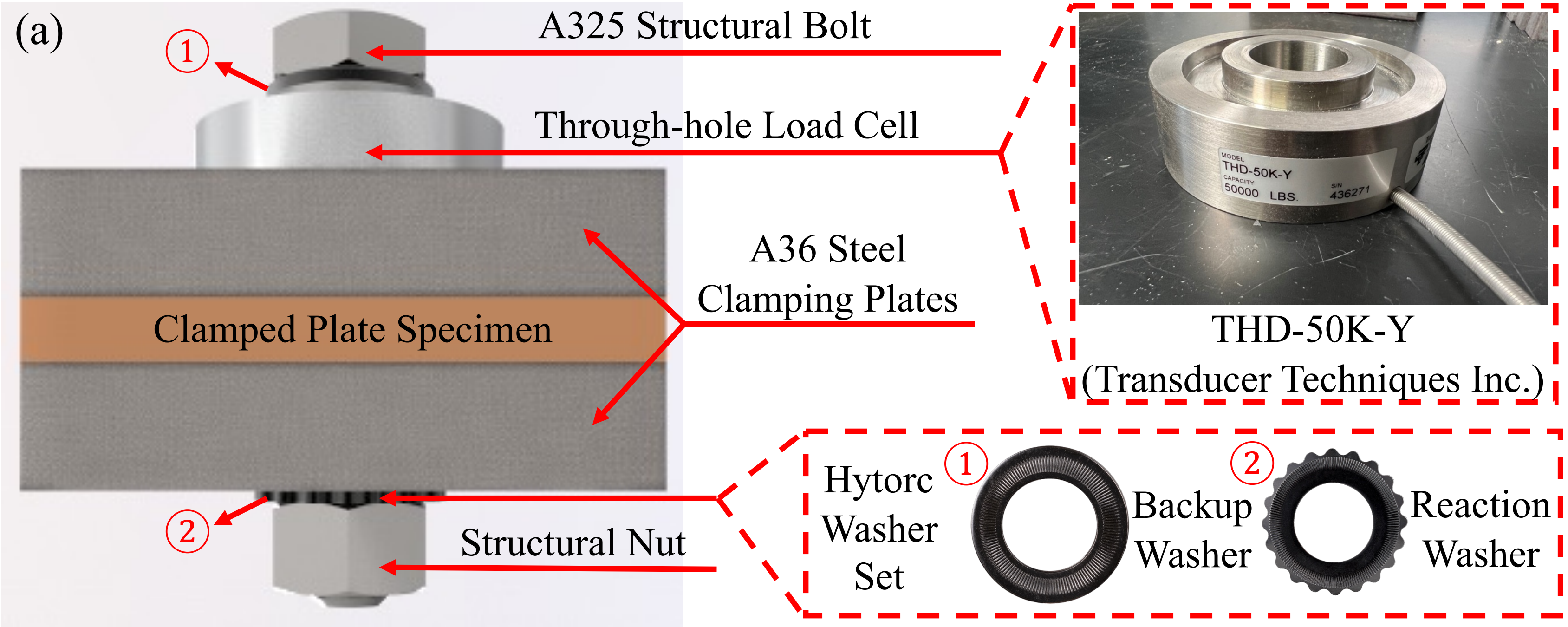
Plate Creep Test

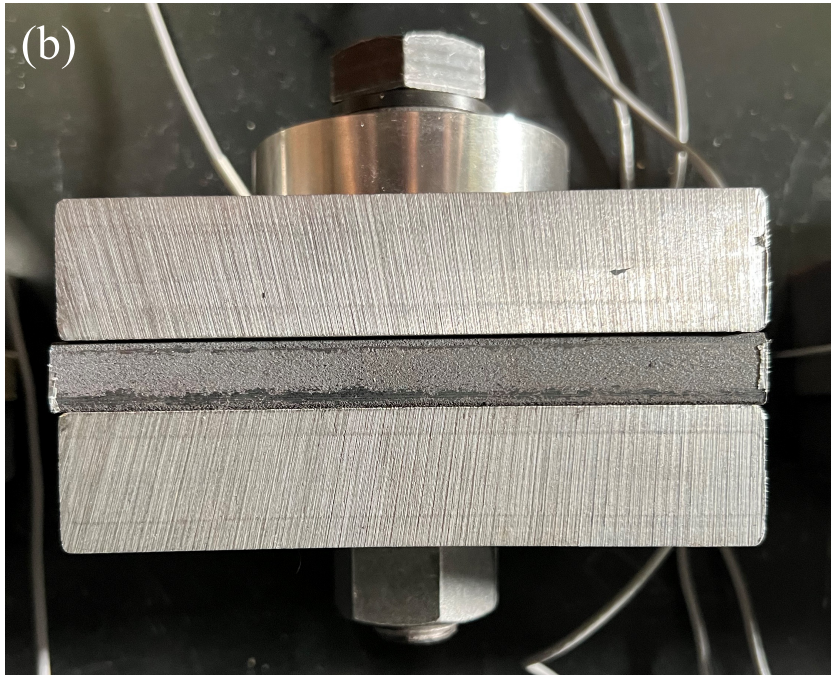


Friction Test

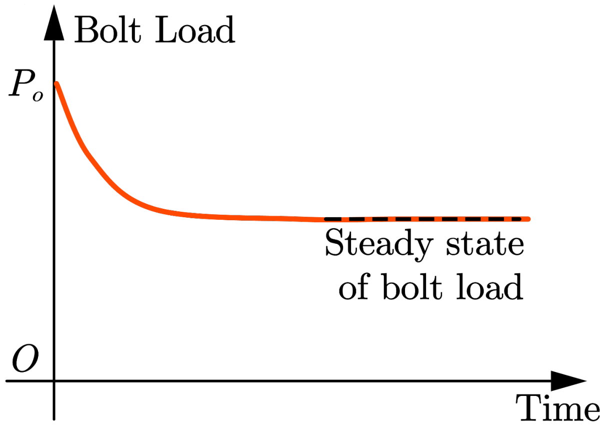
Kaixin Chen, Georgios Tsampras, Shivaglal Cheruvalathb, Mary Thundathilb and Craig Armstrong, Experimental Characterization of Mechanical Properties of Composite Friction Materials for Slotted-Bolted-type Friction-based Structural Connections, Composites Part B, (Under Review, R1)

Material-level Study: Bolt Relaxation Test





- Two target bolt load levels were considered
  - High bolt load (173.5 kN = 39 kips): minimum pretension of 7/8'' ASTM A325 structural bolt
    - Nominal normal pressure = 11 MPa
  - Low bolt load (57.8 kN = 13 kips): 1/3 of high bolt load
    - Nominal normal pressure = 3.7 Mpa
- For each material under each load level, three specimens were tested
- Three specimens of A36 steel plates were tested, as a baseline test case
- Bolt load was recorded until a steady state of bolt load was observed
  - In this test, defined as when the bolt load loss rate was lower than or equal to -5×10^{-6} kN/sec



Schematic representation of the bolt load time history

Material-level Study: Bolt Relaxation Test Results

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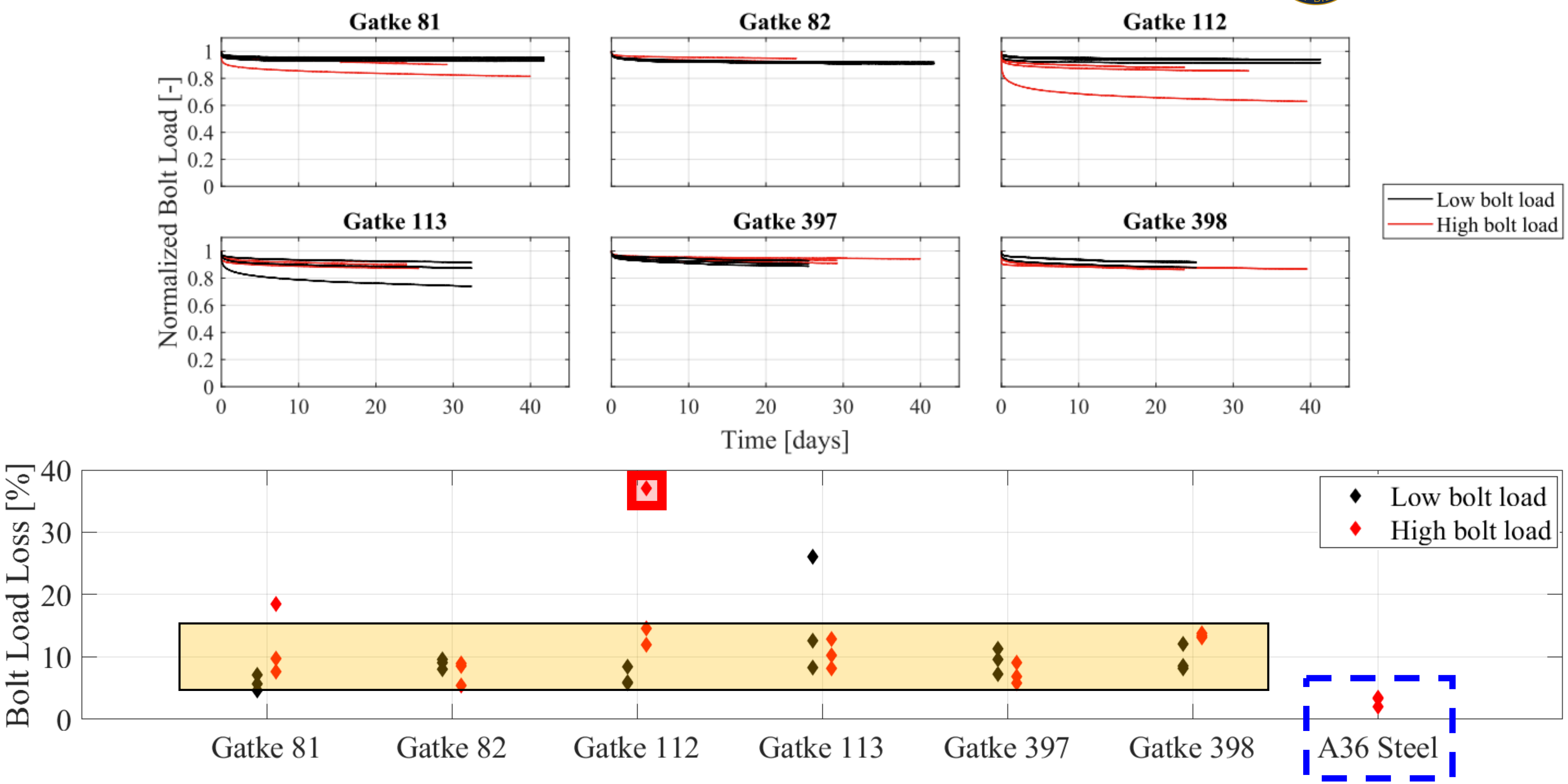
Structural Engineering
Tsampras Research Group

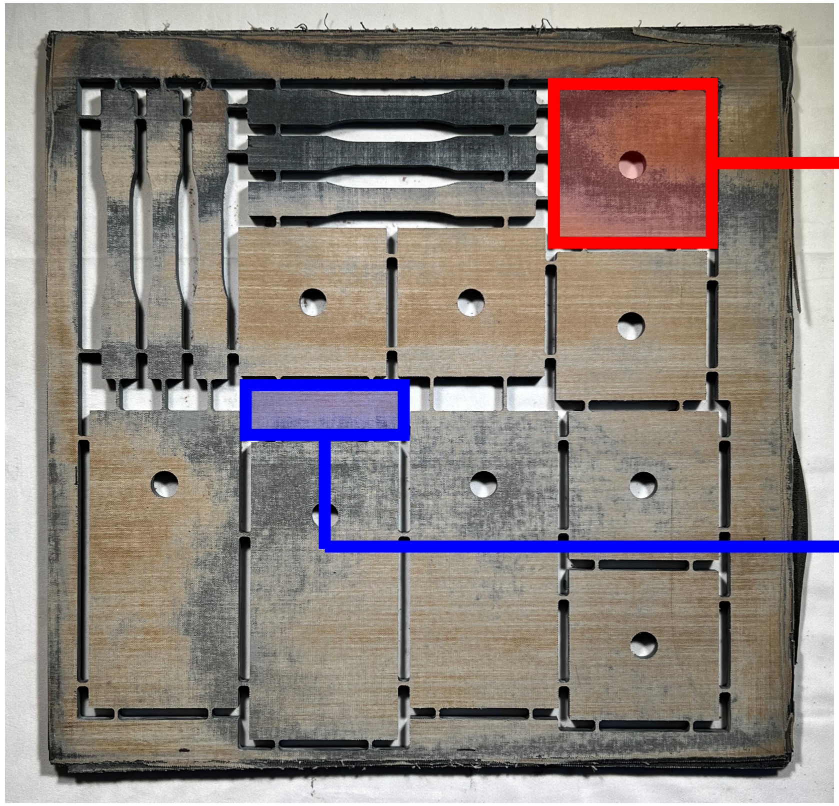


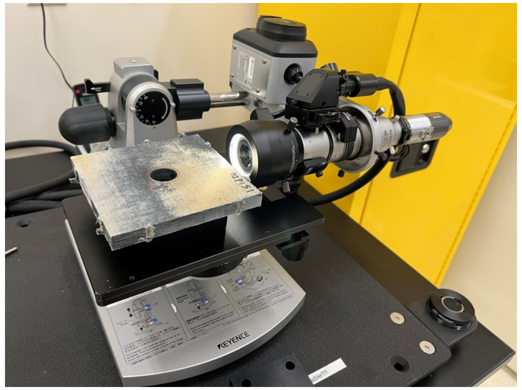
- Observation 1: As expected, the reference test group with A36 steel exhibited least percentage of bolt load loss
- Observation 2: For all the composite materials, the percentage of bolt load loss ranged approximately from 5 to 15%
- Observation 3: The correlation between material constituents and the percentage of bolt load loss was insignificant
- Observation 4: One specimen of Gatke 112 exhibited a 37.12% bolt load loss
  - Deemed to be excessive and required further investigation

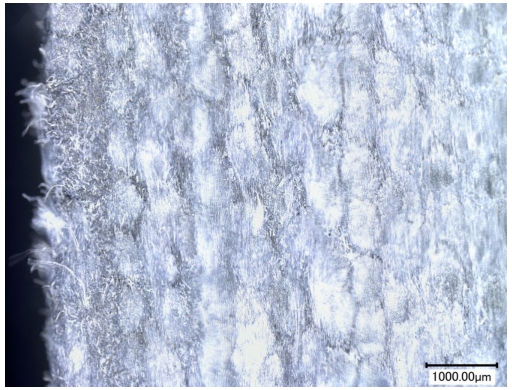
Material-level Study: Bolt Relaxation Test Results

UC San Diego JACOBS SCHOOL OF ENGINEERING Structural Engineering
Tsampras Research Group

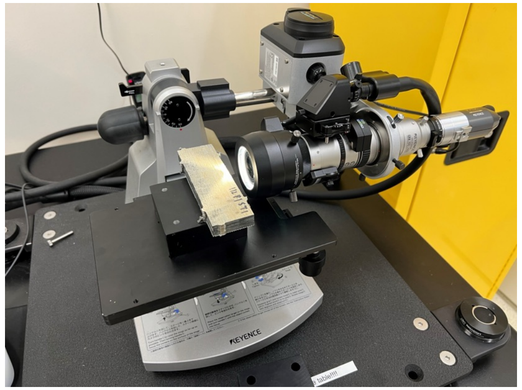
- Microscopy study of the Gatke 112 specimen with a 37.12% bolt load loss

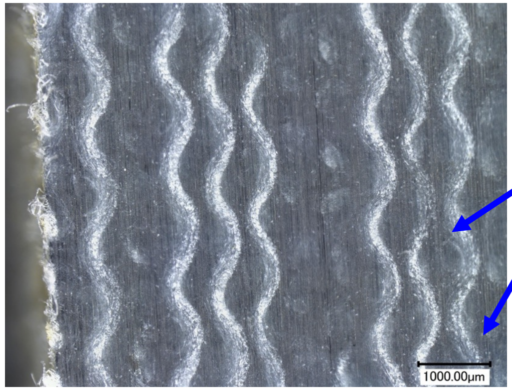






The cross section exhibited a relatively **low volumetric ratio** of phenolic resin





Fiber Cloth

Phenolic Resin

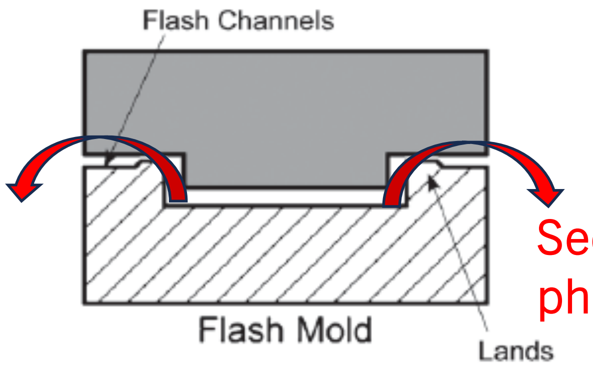
- Gatke 112 plate inducing a 37.12% bolt load loss exhibited a relatively low volumetric ratio of phenolic resin

Material-level Study: Bolt Relaxation Test Results

UC San Diego JACOBS SCHOOL OF ENGINEERING Structural Engineering

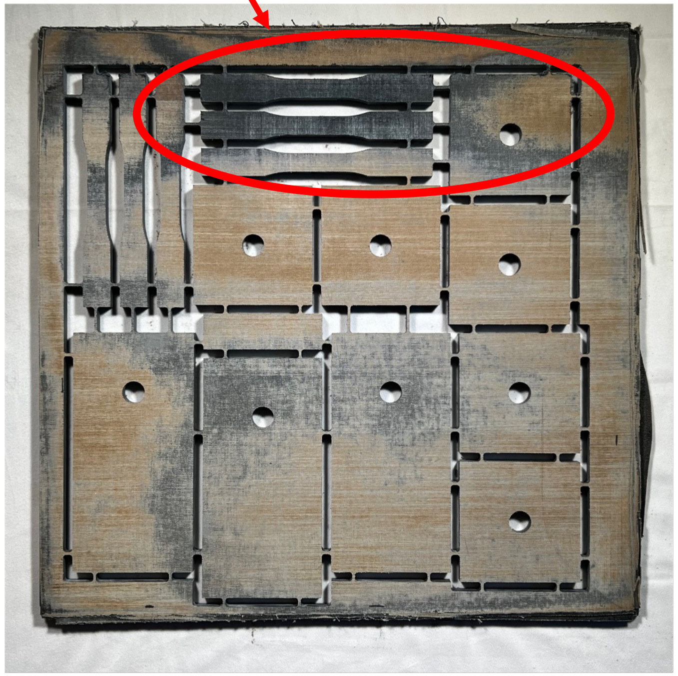
Tsampras Research Group

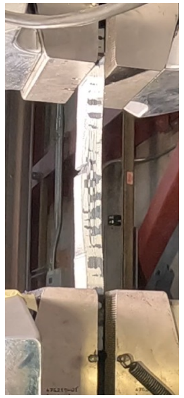
- The relatively low volumetric ratio of phenolic resin was attributed to the **flash compression molding manufacturing process**

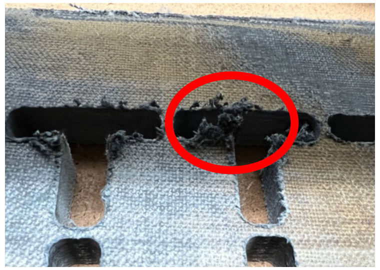


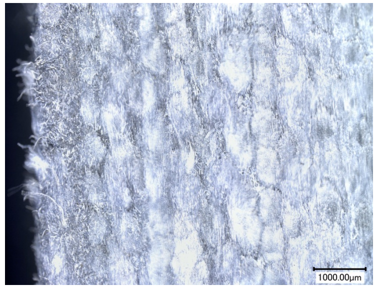
Seepage of phenolic resin

Resin-poor region

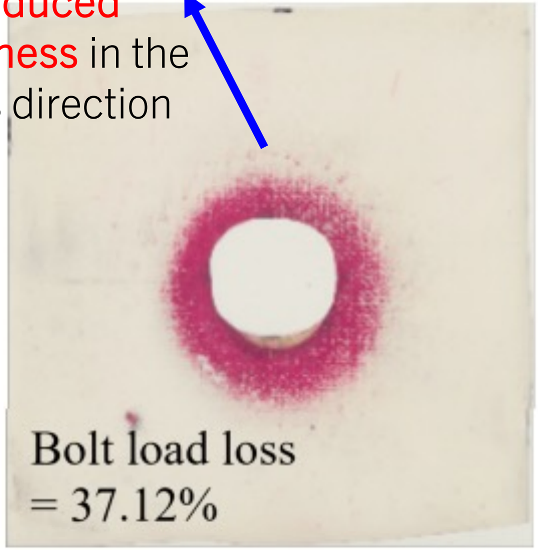








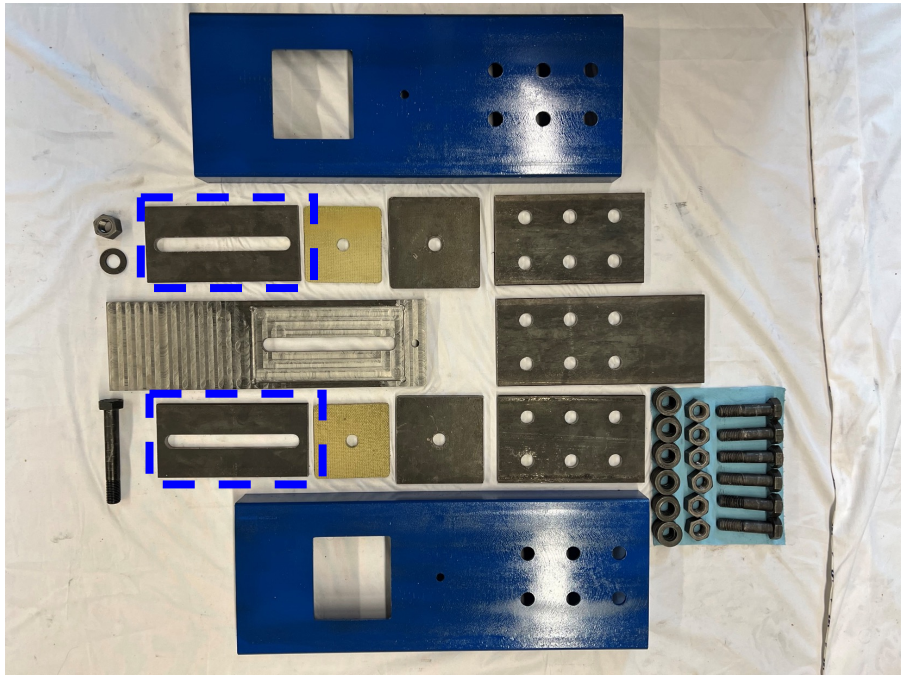
Concentrated normal pressure due to **reduced compressive stiffness** in the through-thickness direction

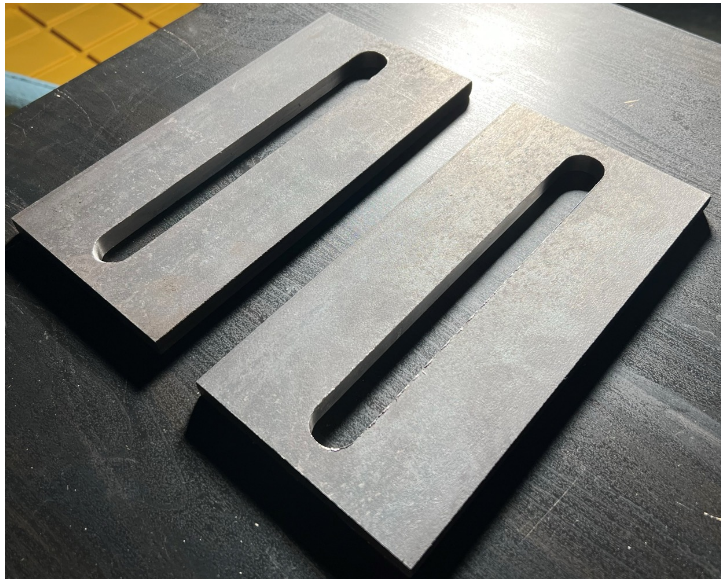


Selected pressure recording film results of Gatke 112 specimens

The results of the bolt relaxation test highlighted the **importance of quality control in the manufacturing process** of composite friction materials for friction-based structural components.

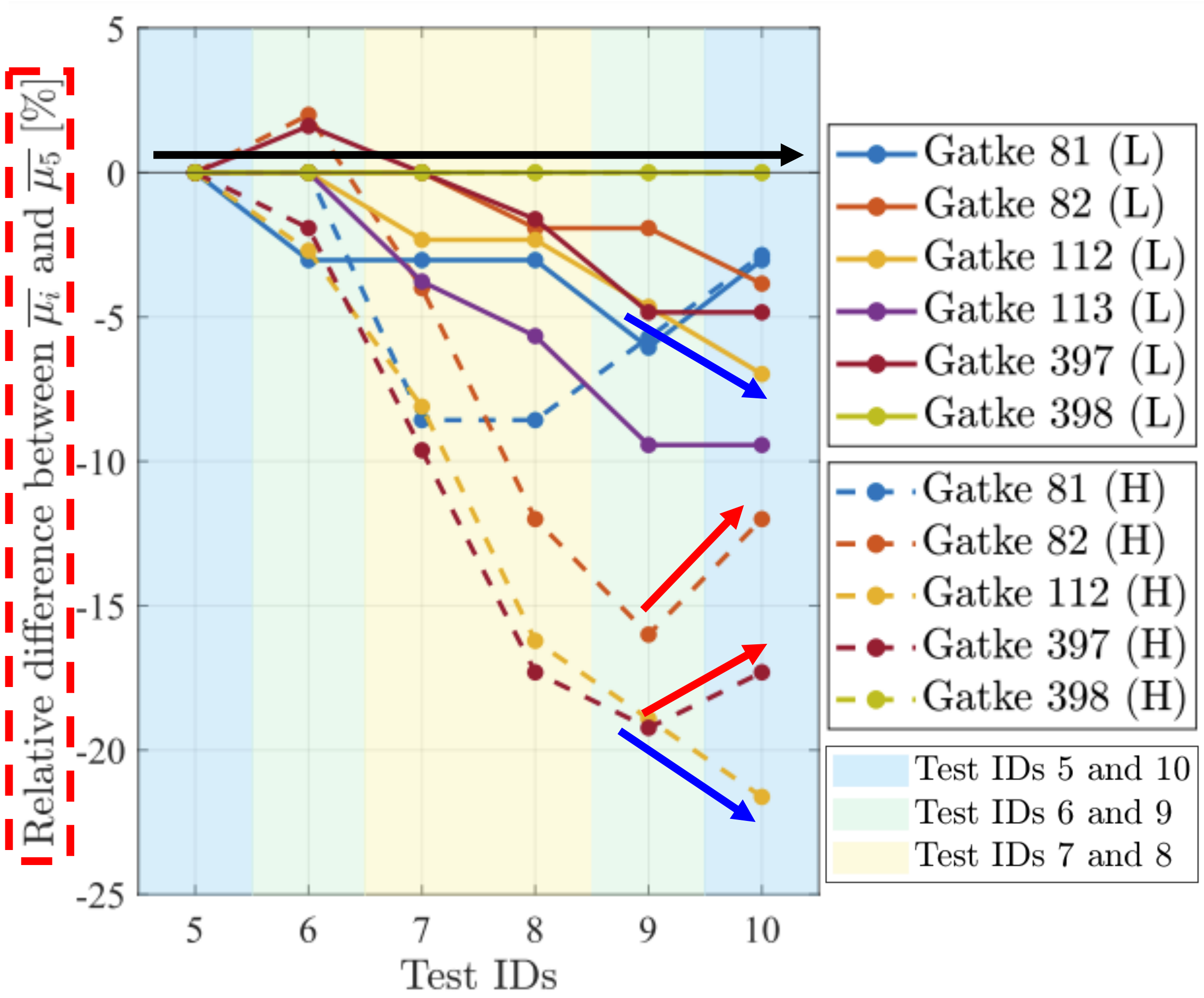
Material-level Study: Friction Test





- A slotted-bolted friction-based component was designed for the friction test
- The friction interface was established between composite friction materials and A36 steel (low-carbon structural steel)
  - The surface of the A36 steel sliding plates was not specially treated
- Two normal load levels were considered, i.e., 39 kips and 13 kips
  - Exception for Gatke 397 under higher normal load case: a reduced normal load of 31 kips was applied (to prevent the friction force from exceeding the testing machine's capacity)
- Data collection
  - Connection force
  - Connection displacement
  - Bolt load

Test IDs 5~10
Velocity effect
assessment



- Composite materials that consist of phenolic resin, glass fibers, graphite, Teflon and molybdenum disulfide MoS_2 are among the most suitable materials for use in friction-based structural components for earthquake structural engineering applications.

Challenges with friction-based structural connections

Friction-sliding behavior is affected by:

- Sliding velocity
- Dwell time
- Galvanic corrosion in bimetallic friction interface
- Creep of composite materials
- Break-in and cumulative sliding effects
- Effect of machining and geometric tolerances
- The effectively zero post-elastic stiffness can be both an advantage and disadvantage

NOTES:

(1) Draft drawings for the 40 kN friction connections used in the NCREE Shake Table test, December 2023

(2) Concept of "loose plates" was implemented to limit the effect of the bolted end connections shared with the buckling-restrained braces.

(3) Load cells allow for control of normal force. Composite friction pads allow for reduced axial compressive stiffness. Assume no use of Spring Washers.

$F_{slip} = \mu \times N \times n_b \times n_s$ = 0.4 x 50 kN x 1 x 2 = 40 kN

where

- μ is the friction coefficient in the interface between structural steel clean of mill scale (no special surface finish) and the composite friction pad
- N is the normal force due to the bolt preload
- n_b is the number of bolts in the friction interface
- n_s is the number of friction interfaces

For past research on the composite friction pads see:

- 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

- Georgios Tsampras, Richard Sause (2014), Full-scale, components test of Inertial Force-Limiting Floor Anchorage Systems for Seismic Resistant Building Structures using a Buckling Restrained Brace and Steel Reinforced Low Damping Rubber Bearings, DesignSafe-CI, 10.4231/D3N87311M https://www.designsafe-ci.org/data/browser/public/nees.public/NEES-2011-1083.groups/Experiment-2

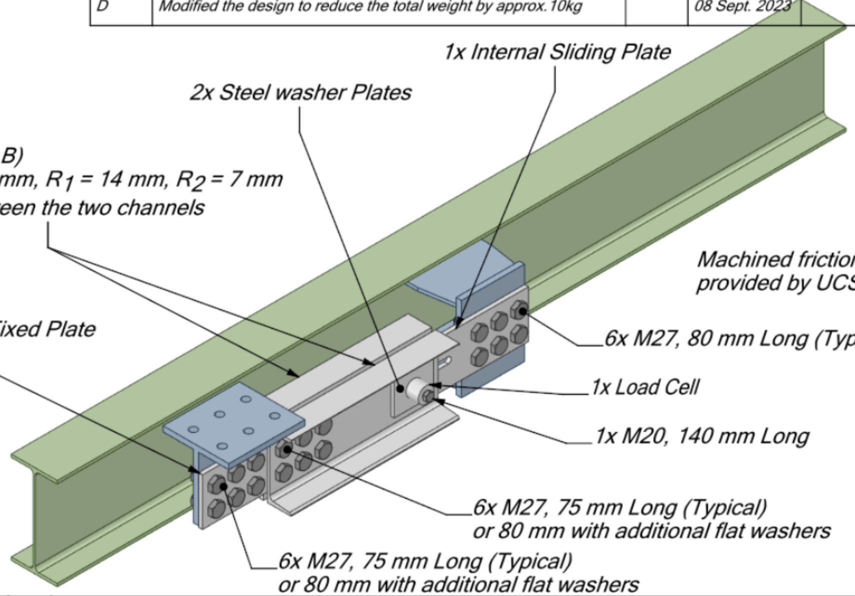
Approximate mass = 85 kg
Including bolts and load cell, excluding end connections and steel beam

Approximate eccentricity = 17.5 mm

Units: mm

REVISION HISTORY

REV	DESCRIPTION	INCORP BY	DATE	CHECKED
A	*Initial drawing*		*28 Aug. 2023*	*NCREE, UTA, UCSD*
B	*Single bolt in friction interface*		*06 Sept. 2023*	*N/A*
C	*Eccentric, one-sided end connection, similar to HBRB. Used channel steel section common in Taiwan. Added parts for end connections and framing beam. Added simple safety mechanism to prevent out of plane spread of channels (unlikely to happen due to small load & large channel section)*		*07 Sept. 2023*	*N/A*
D	*Modified the design to reduce the total weight by approx.10kg*		*08 Sept. 2023*	



-2	-1	ITEM NO.	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION
QTY REQD				

PARTS LIST

INIT	APPROVALS	DATE	INIT	APPROVALS	DATE

9/8/2023 10:26:23 AM
Georgios Tsampras

CONTRACT NO.

MATERIAL

FINISH

TREATMENT

SIMILAR TO

THIRD ANGLE PROJECTION

NEXT ASSY | USED ON

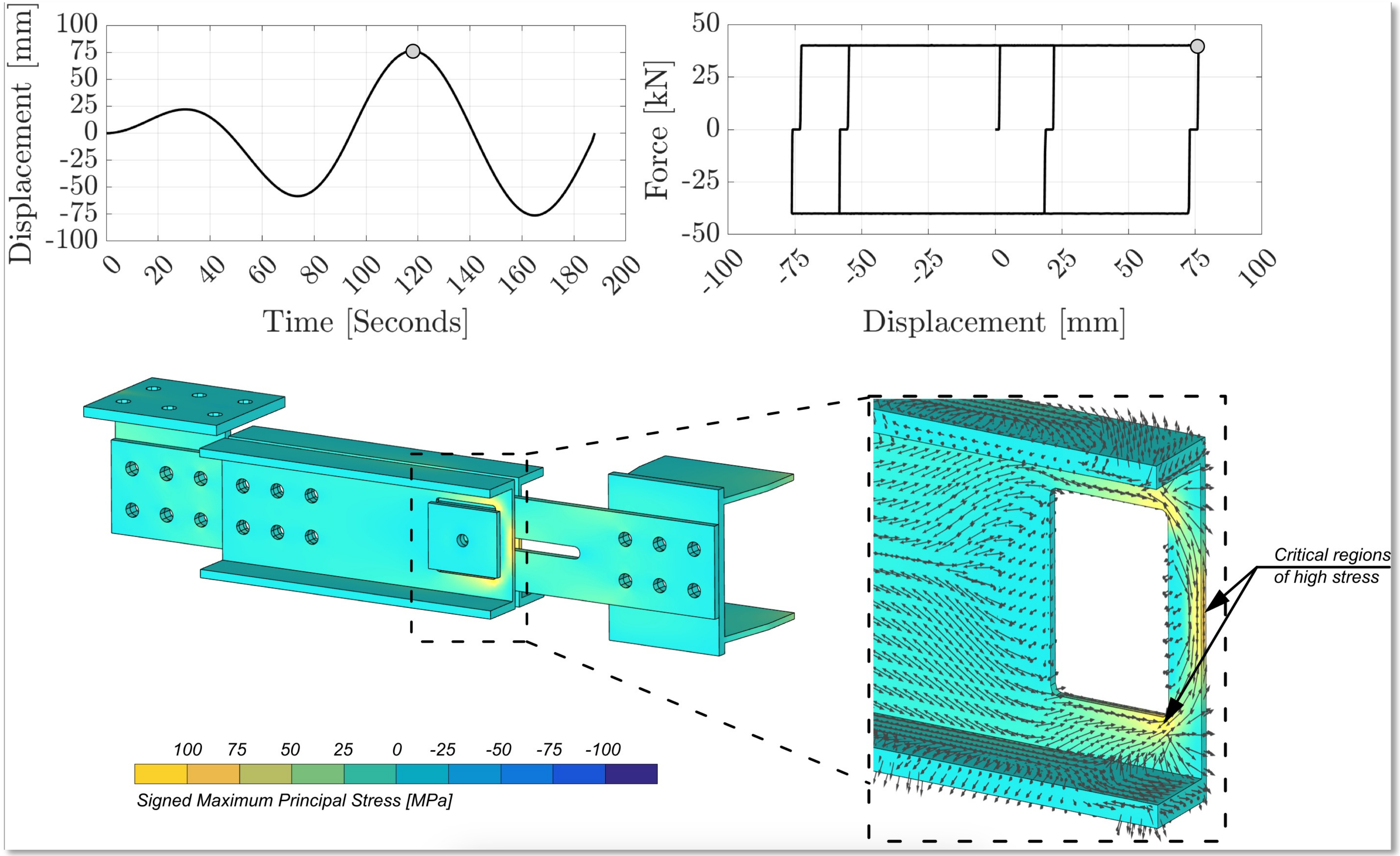
APPLICATION

TITLE
Friction Device 40 kN

SIZE: B | CAGE CODE | DWG NO. *UCSD001* | REV *D*

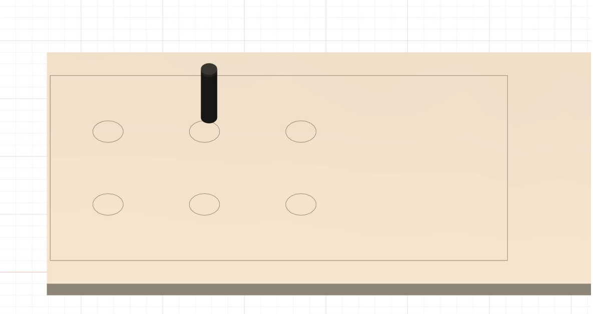
SCALE *1:12* | SHEET *1 of 7*

SIMULATIONS

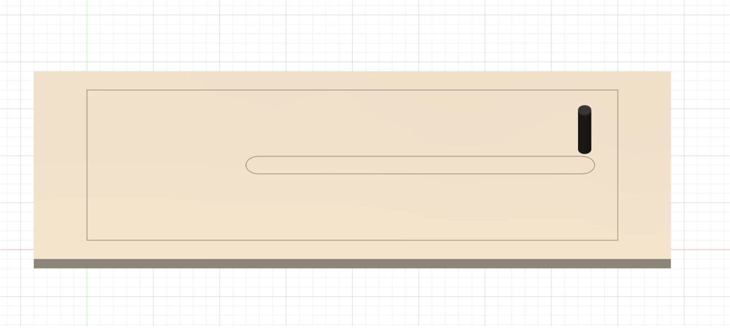


Manufacturing - Programming

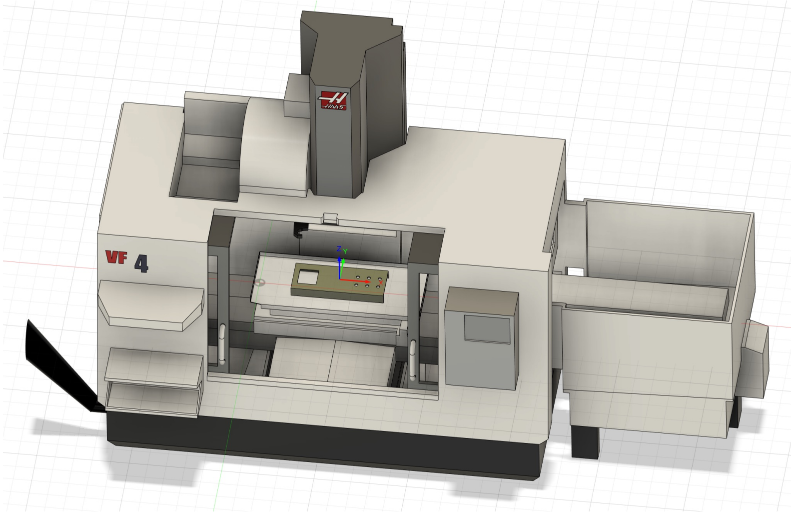
Internal fixed plate

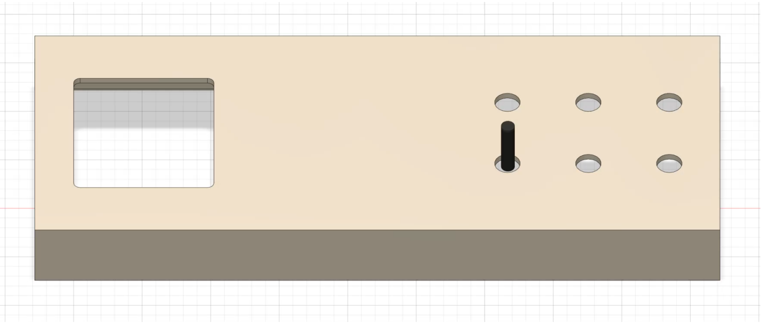


Internal sliding plate

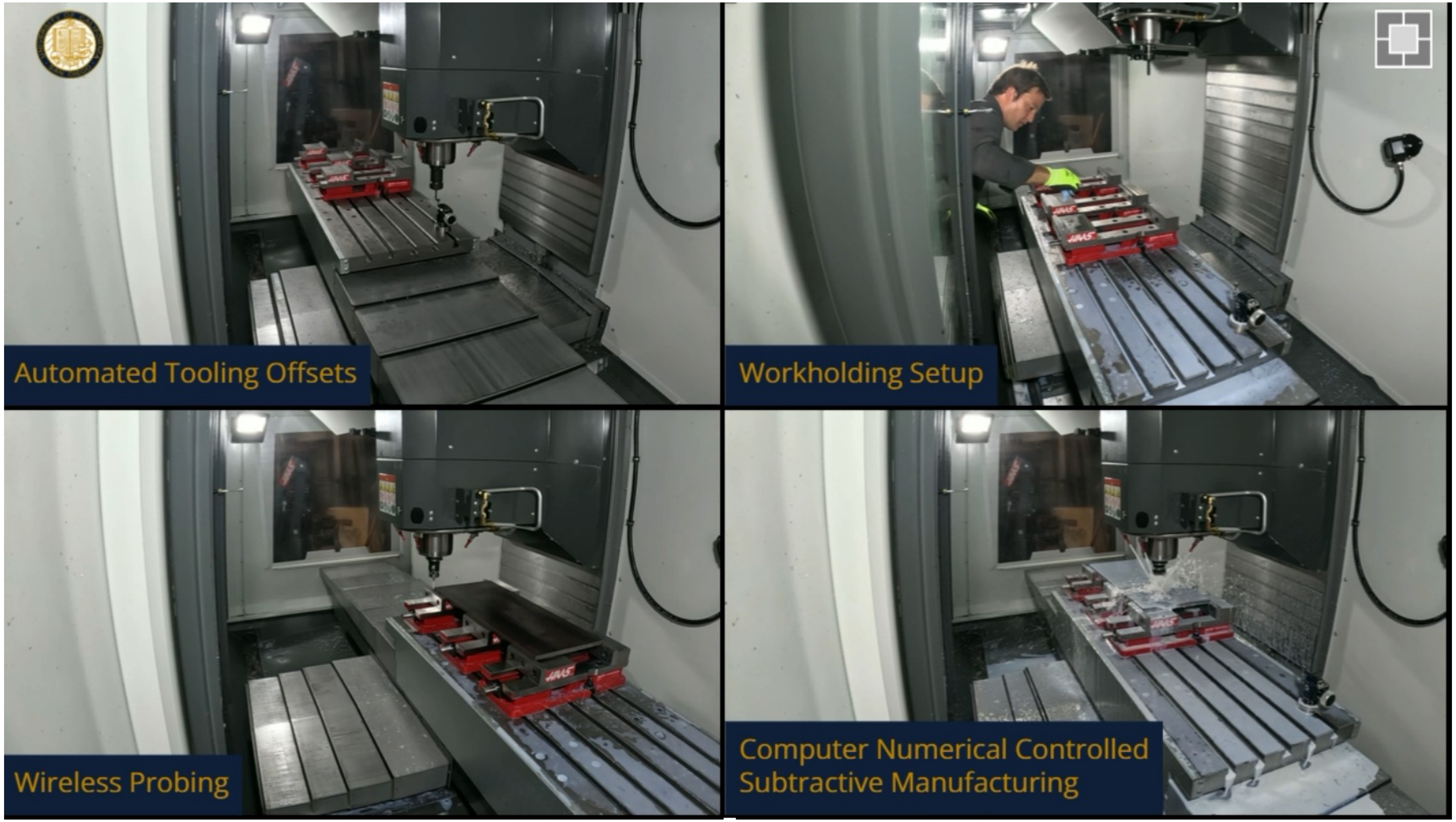


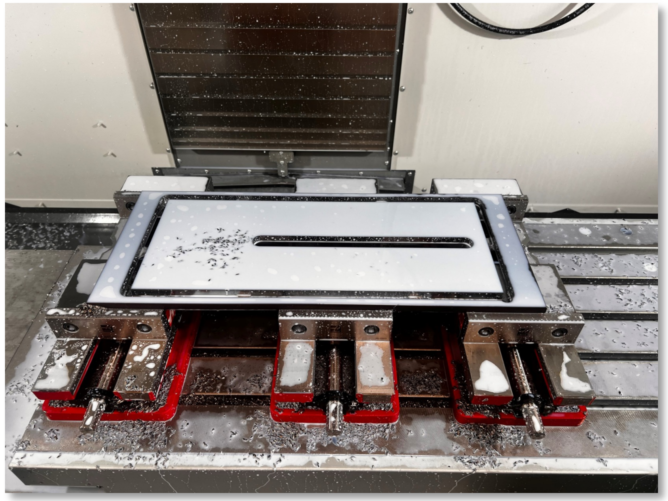
Channels



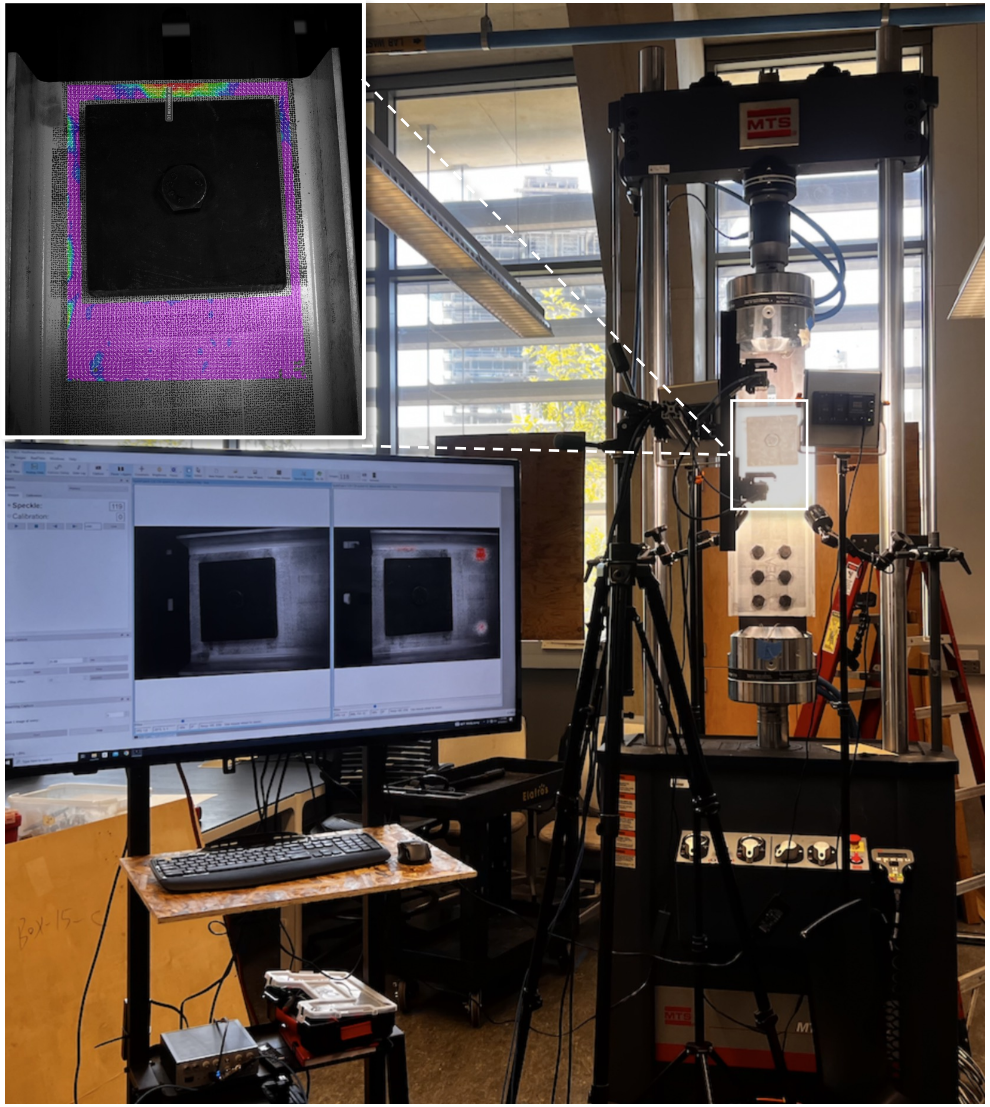


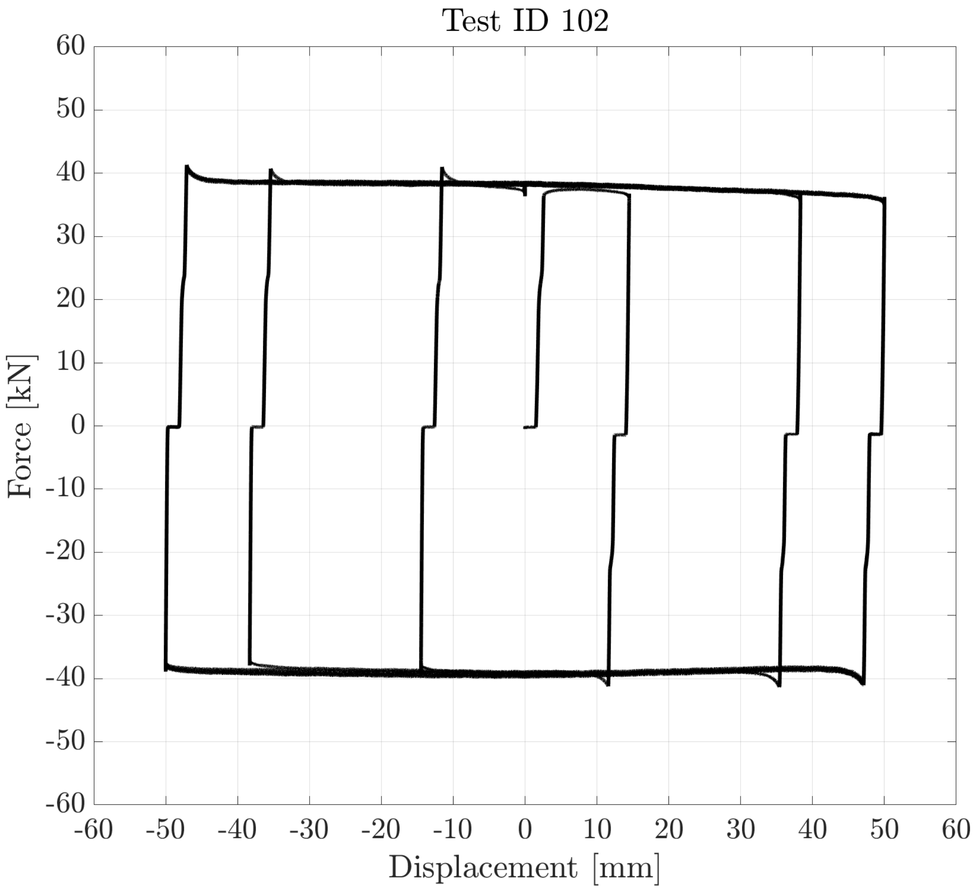
Automated Manufacturing



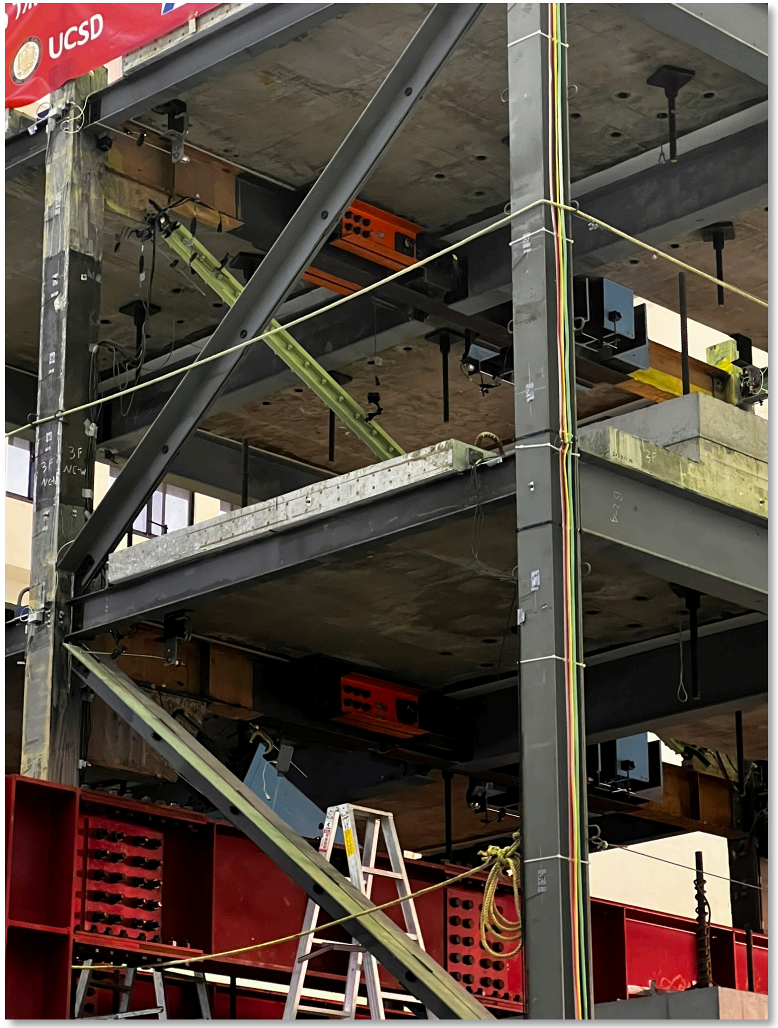


Component Level Testing





2023 NCREE Shake Table Testing



Demonstration of repairability – If needed

Relevant Publications, Open Data, and Patent

- Tsampras, Georgios; Sause, Richard, (2014), "Full-scale, components test of Inertial Force-Limiting Floor Anchorage Systems for Seismic Resistant Building Structures using a Friction Device and Carbon Fiber Reinforced Low Damping Rubber Bearings", DesignSafe-CI [publisher], doi: 10.4231/D3HH6C68B https://www.designsafe-ci.org/data/browser/public/nees.public/NEES-2011-1083.groups/Experiment-3
- Georgios Tsampras, Richard Sause, Dichuan Zhang, Robert B. Fleischman, José I. Restrepo, David Mar, Joseph Maffei (2016), Development of deformable connection for earthquake-resistant buildings to reduce floor accelerations and force responses, Earthquake Engineering & Structural Dynamics, 45 (9), 1473–1494, doi:10.1002/eqe.2718
- 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
- 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
- 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.
- 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
- Chung-Che Chou, Huang-Zuo Lin, Alvaro Córdova, Jian-Ming Chen, Daniel Yen-Hsun Chou, Shu-Hsien Chao, Shih-Ho Chao, Georgios Tsampras, Chia-Ming Uang, Hsin-Yang Chung, Chin-Hsiung Loh, Hsuan-Teh Hu, "Earthquake simulator testing of a three-story steel building for evaluating built-up box column performance and effect of sliding slab". Earthquake Engng Struct Dyn. 2024; 1-19. https://doi.org/10.1002/eqe.4130
- Georgios Tsampras, Kaixin Chen, Dominic Tran, Anne-Sophie Roobol (2024) Friction-based connections: materials, designs, manufacturing, simulations, and experiments, 18th World Conference on Earthquake Engineering, Milan, Italy
- Alvaro Córdova, Chung-Che Chou, Chi-Jeng Wu, Georgios Tsampras, Chia-Ming Uang, Shih-Ho Chao (2025), Modeling and Response of a Three-Story Steel Building with Sliding Slabs in Earthquake Motions, Earthquake Engng Struct Dyn., https://doi.org/10.1002/eqe.4300
- Chen, K., Tsampras, G., Cheruvalath, S., & Thundathil, M., Experimental Characterization of Mechanical and Tribological Properties of Composite Materials for Friction-based Force-limiting Structural Components. Composites Part B, Accepted.
- Tsampras, G., Chen, K., Chou, C., Lin, H., Wu, C., Córdova, A., Uang, C., & Chao, S., Development, design considerations, and experimental characterization of a low-cost friction-based force-limiting structural connection with reduced sensitivity to machining tolerances and accelerated repairability. In Preparation
- Tsampras, Georgios, and Chen Kaixin. "Friction devices for energy dissipation." U.S. Patent Application No. 18/508,087.