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(WCEE2024)

Experimental Characterization of Composite Materials for Friction-based Connections

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Tsampras Research Group

Acknowledgment

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Kyoungyeon Lee (UCSD)
C. Franco Mayorga (UCSD)

Industry collaborator:
ScanPac Manufacturing, Inc.

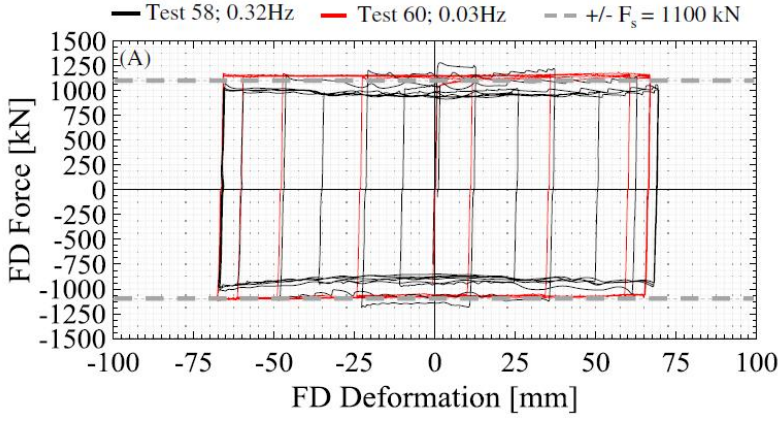
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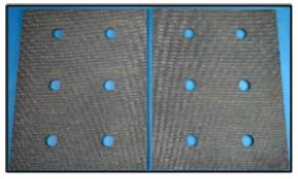
DP Jenny Fellowship from Precast/Prestressed Concrete Institute

Background: composite friction materials in structural applications

- **Composite friction materials** have been used in friction-based structural connections
  - Compared with bi-metallic friction interfaces, **composite-metallic friction interfaces** are **less vulnerable to galvanic corrosion**
- Past research about using composite friction materials in structural applications mainly focused on characterizing the **frictional behavior**
- Limitations of past research about using composite friction materials in friction-based connections
  - **Potential failure modes** of composite friction materials are seldom mentioned or assessed
  - How **constituents of composite friction materials** influence the property of the material hasn't been investigated extensively
  - The **manufacturing process** of composite friction materials and **how the manufacturing process would affect the property** of the materials haven't received much attention

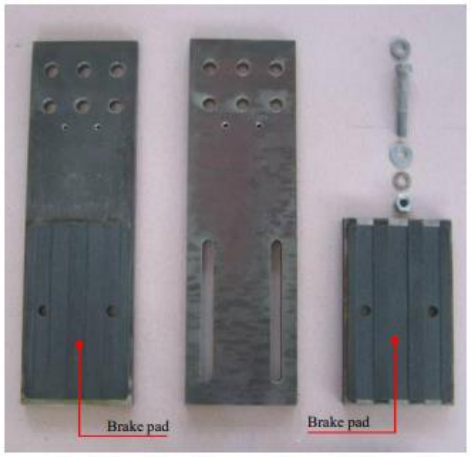
Steel-NAO (Gatke398)



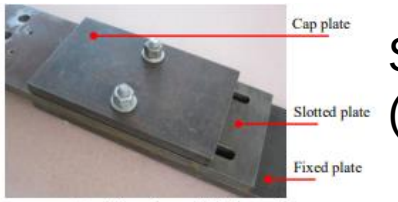

(B) Initial Conditions


(C) End Conditions

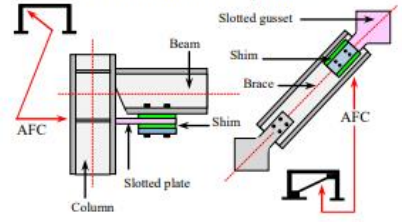
Application: friction-based force-limiting connections
Tsampras et al. (2018)



a. Fixed plate, slotted plate, cap plate, and bolt assembly



b. Plan view of AFC specimen



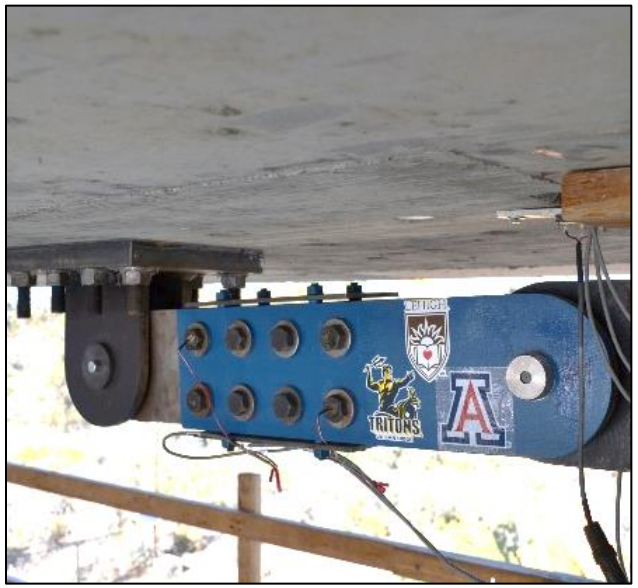
c. AFC configurations in steel framing systems

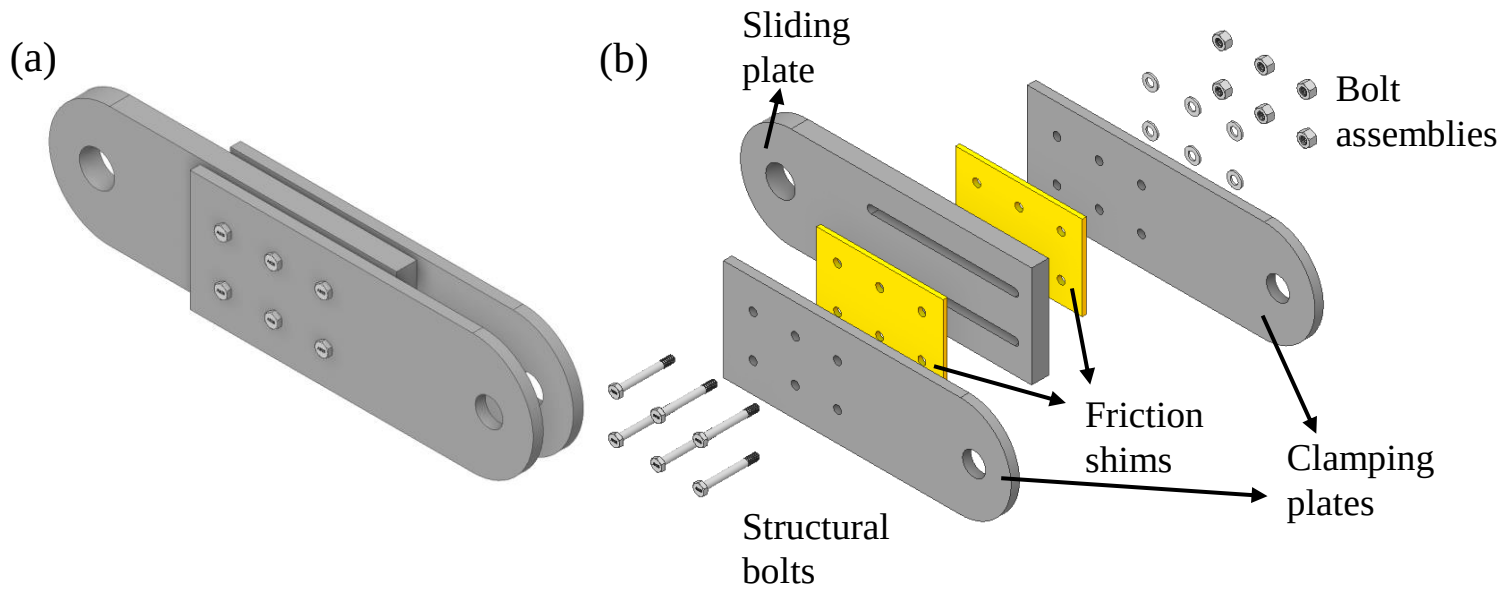
Steel-NAO
(Ferotec D3923)

Application: asymmetric friction connections
Golondrino et al. (2013)

Slotted-bolted friction-based connection







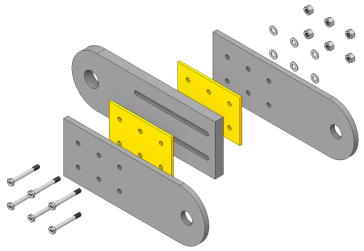
Composite friction material

Structural steel

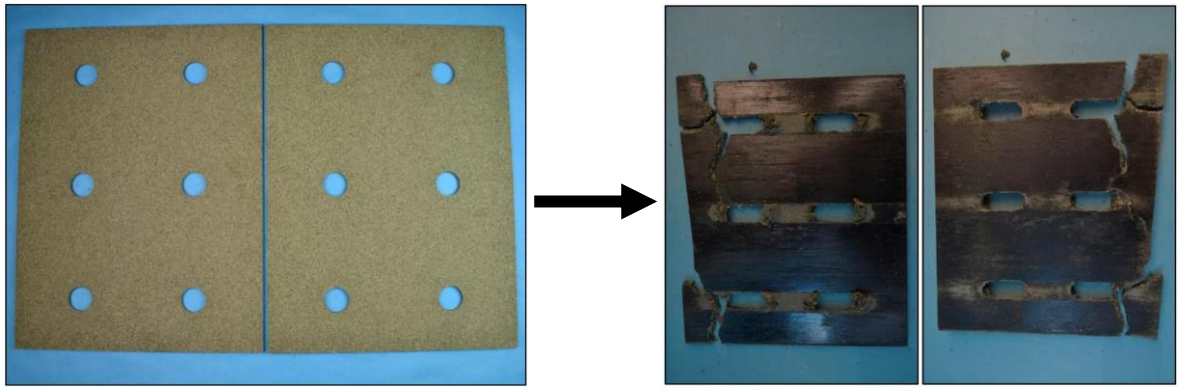
Slotted-bolted friction-based connection working as **force-limiting connection** between structural wall and floor diaphragm

Photos courtesy of Professor Tsampras

Failure modes of friction shims in slotted-bolted friction-based connection



Bearing action induced failure modes



Photos are from Tsampras and Sause (2015)

Elongated bolt holes + Section tensile failure

Failure mode related mechanical property

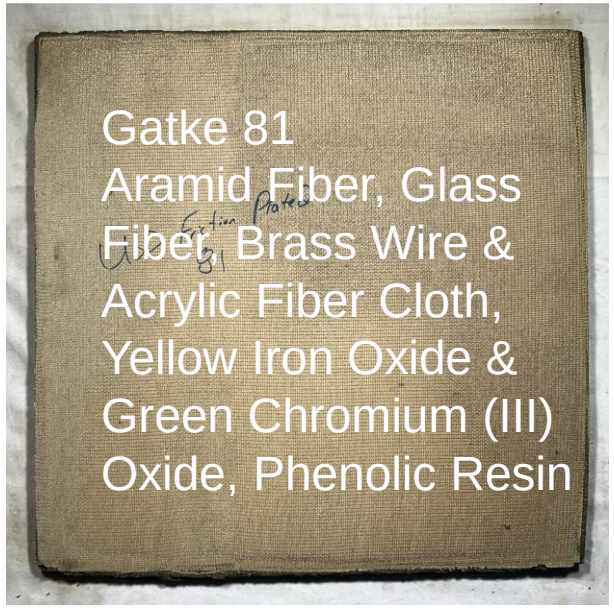
- Tensile strength
- Bearing strength

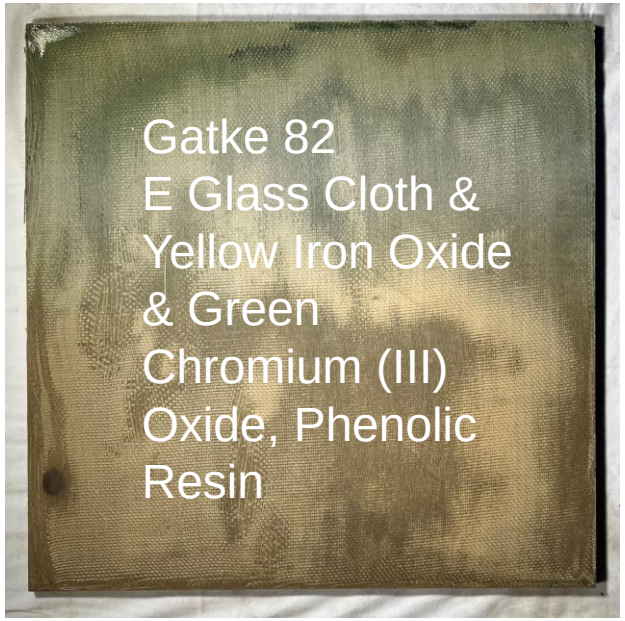
Contribution of this research

- In this research, we are trying to establish a **database**, in which we hope the **mechanical and tribological properties of commercially available composite friction materials** could be readily available **for structural engineers** for design purposes
  - To achieve this goal, we partner with composite friction material manufacturers and conduct **experimental characterization of mechanical and tribological properties** of composite friction materials
- We looked into the **constituents** of composite friction materials and revealed what type of constituent would be helpful in enhancing the mechanical and frictional properties of composite friction materials
  - We hope this could provide insights for future development of **high-performance composite friction materials for structural applications**

- We revealed how **material defects from the compression molding process** would affect the property of composite friction materials

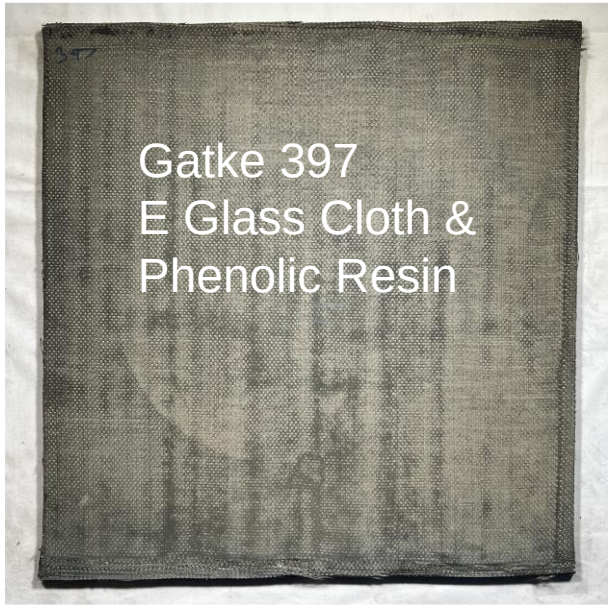
Materials overview

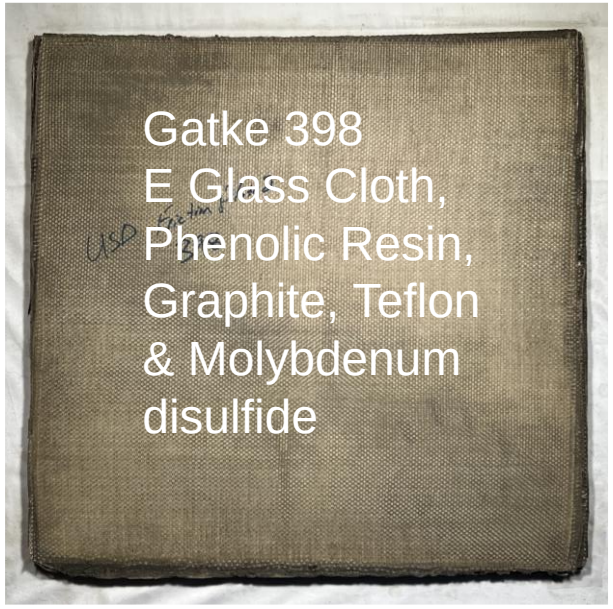








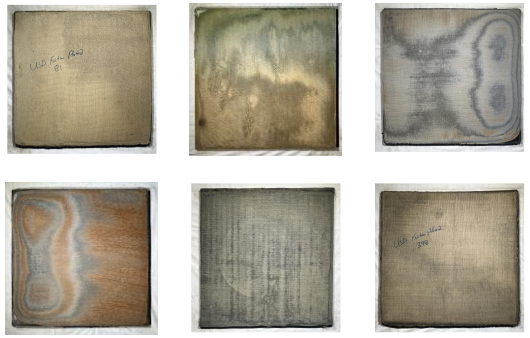




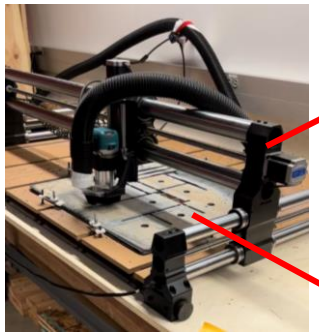
- Six types of composite friction materials from Scan-Pac Inc. were tested
- All the materials are commercially available and **phenolic-resin-based**
- All the materials are made through saturation and **flash compression molding** at 149 °C (300 °F) followed by grinding to the required thickness.

Experimental tests conducted at UCSD

Material Plates (as Received)



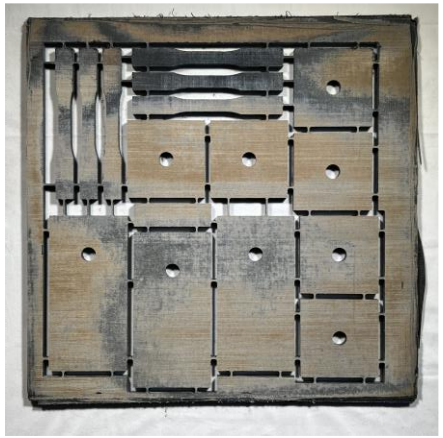
CNC Subtractive Machining



Onefinity CNC router

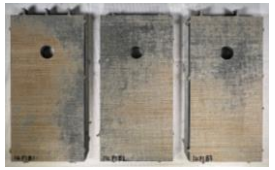
Material Plate

Material Plate (Machined)





Tensile coupons



Bearing plates

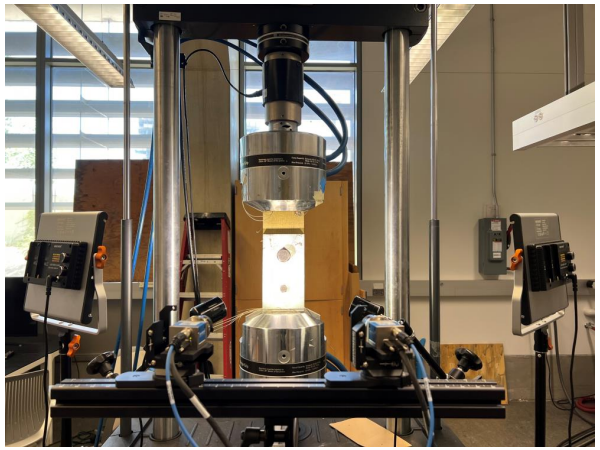


Square-shaped plates

Coupon Tensile Test



Plate Bearing Test



Bolt Relaxation Test

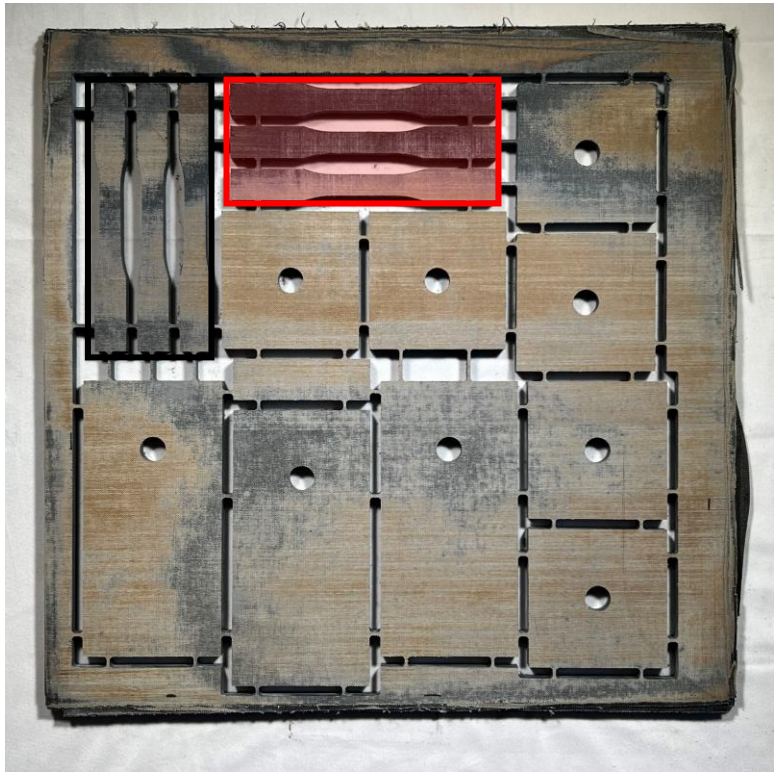


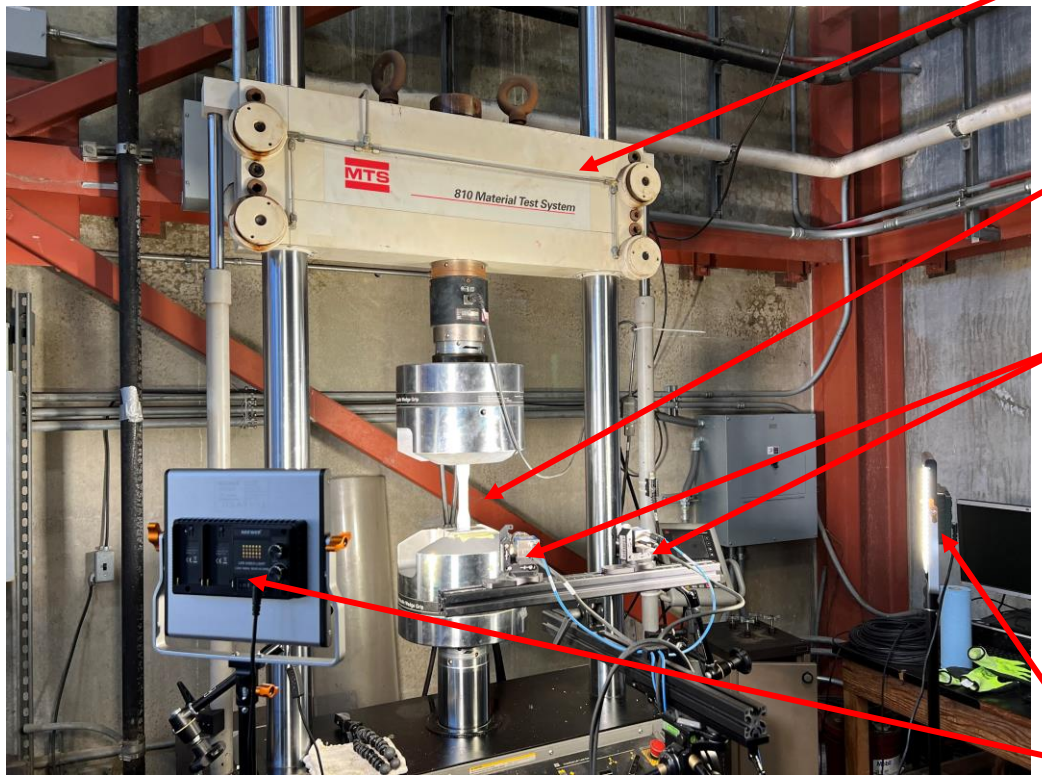
Friction Test



Coupon tensile test

- Standard
  - The tensile test follows ASTM D638 (Standard Test Method for Tensile Properties of Plastics)
- Testing Specimen
  - For each material, **six specimens** were tested.
    - Specimens are sampled in **two orthogonal directions (0° and 90°)**
- Digital Image Correlation (DIC) system was used to facilitate data collection





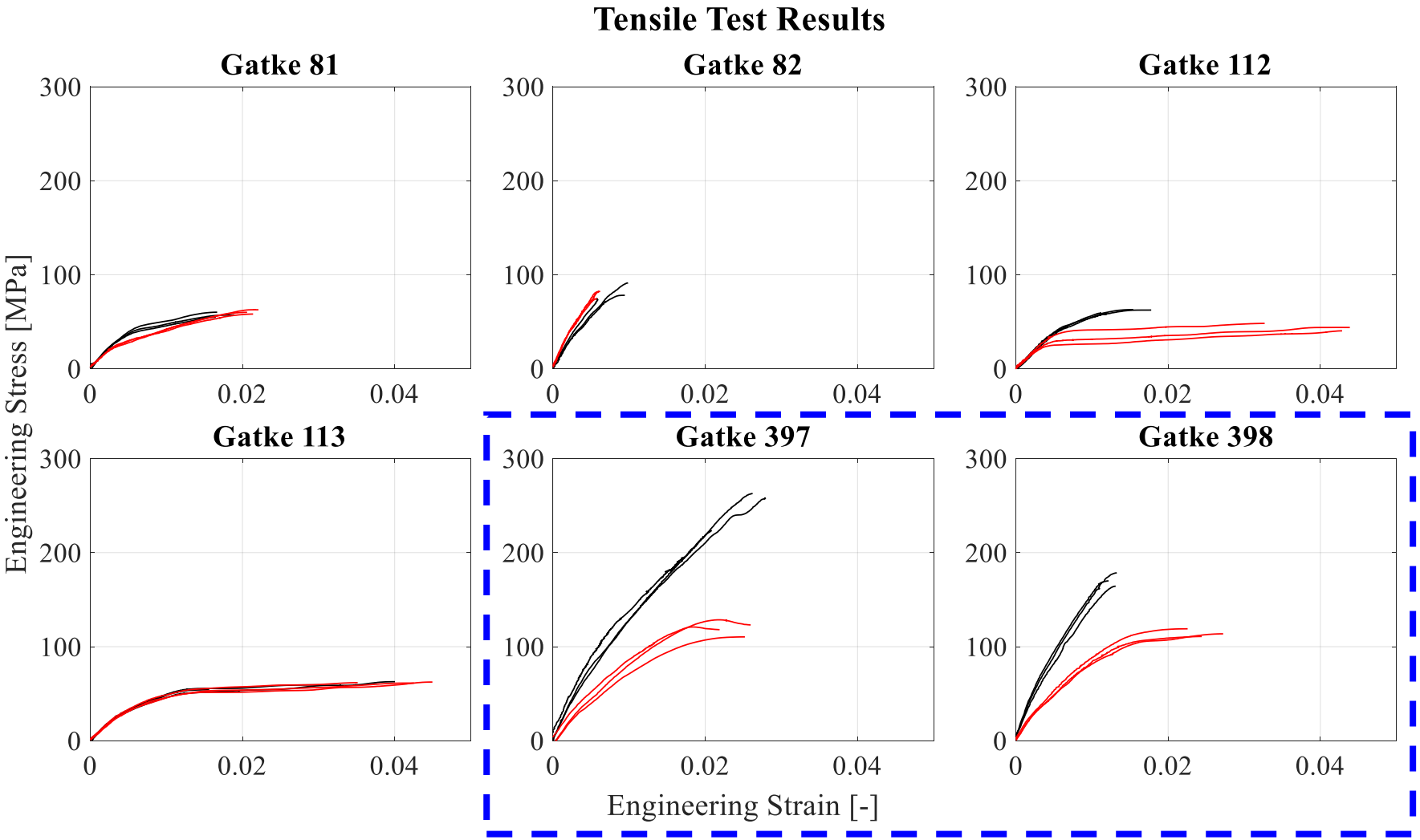
MTS 810 System

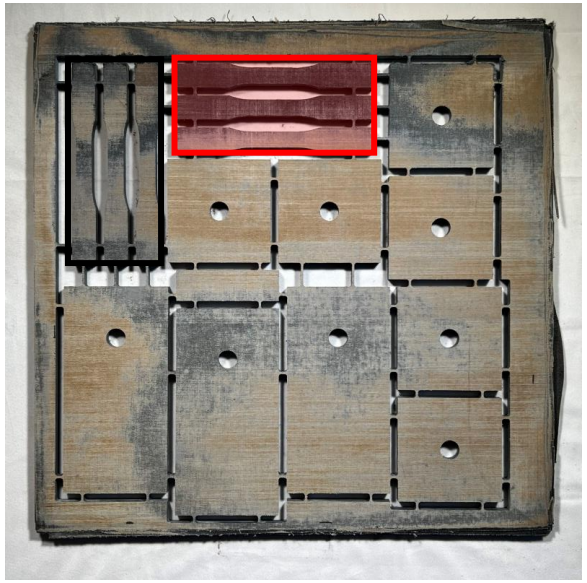
Testing Specimen

Cameras for DIC

LED Lights for DIC

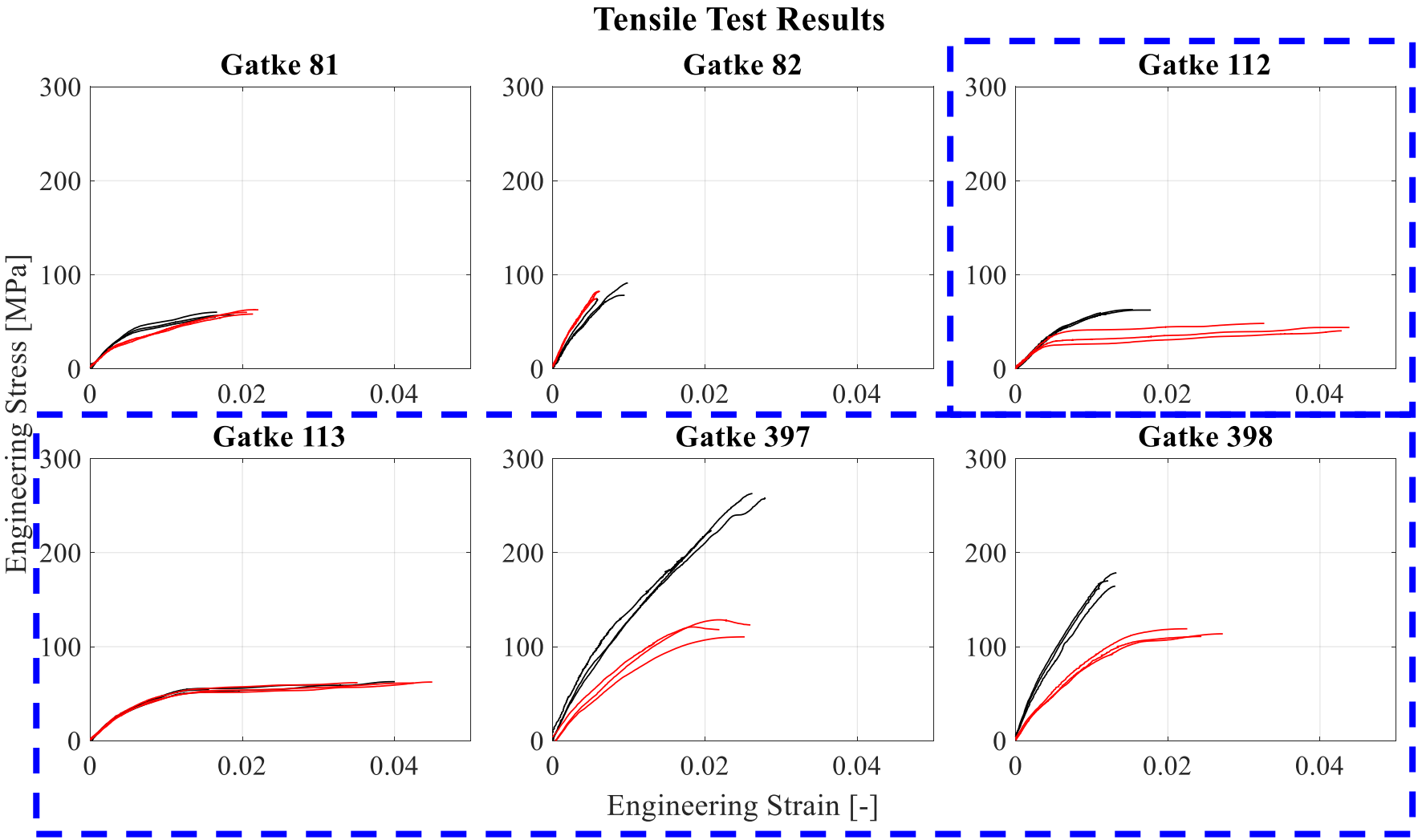
Coupon tensile test: results

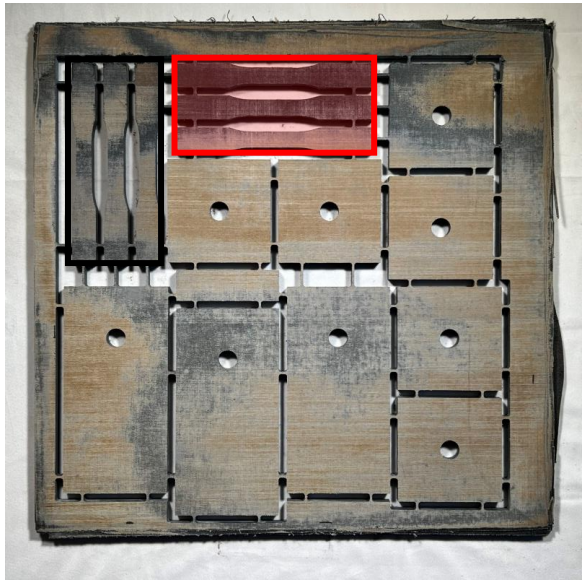




Observation 1: Laminated materials exhibited **directionality** with respect to **strength**.

Coupon tensile test: results

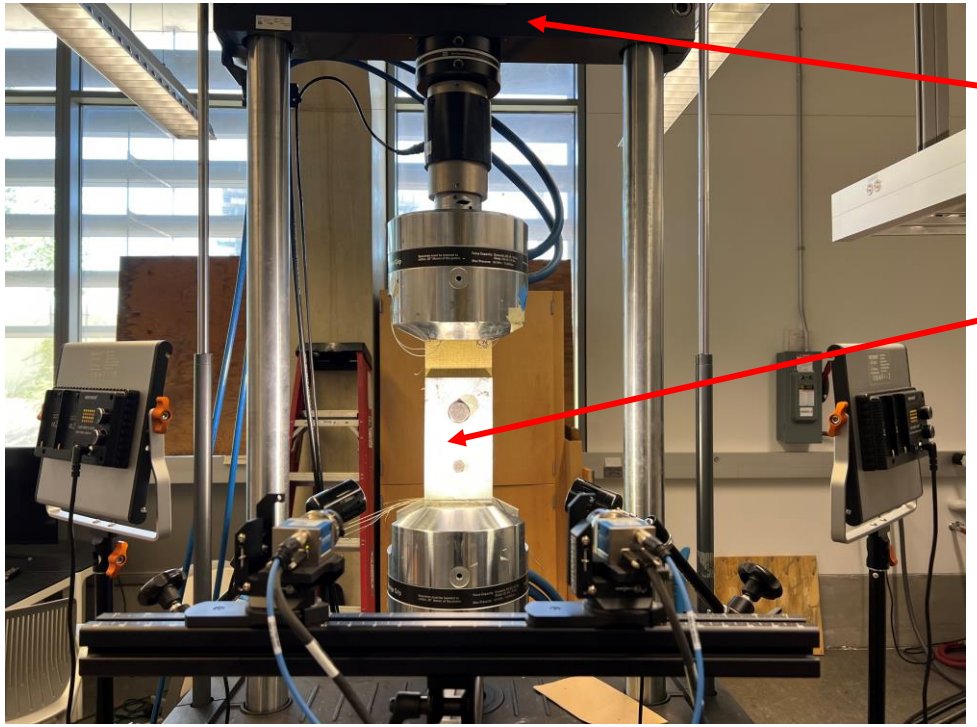




Observation 1: Laminated materials exhibited **directionality** with respect to **strength**.

Observation 2: **E-glass cloth** gives **higher strength** to the material than cotton cloth.

Plate bearing test

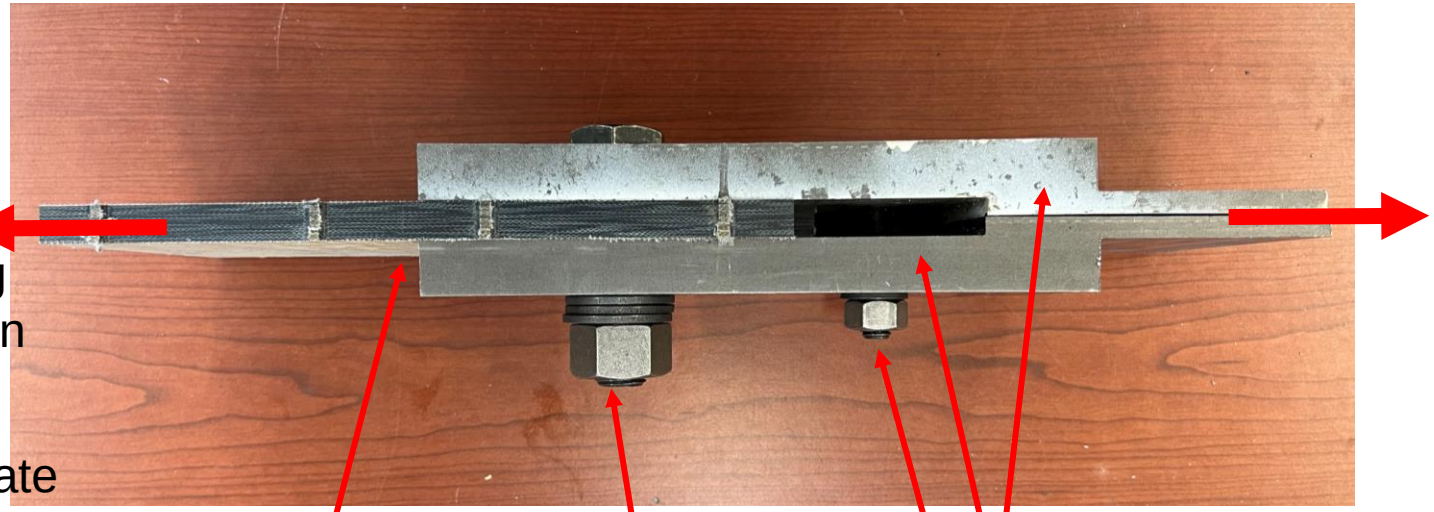


MTS Machine

Testing Specimen and Fixture







Loading Direction

Bearing Plate Specimen

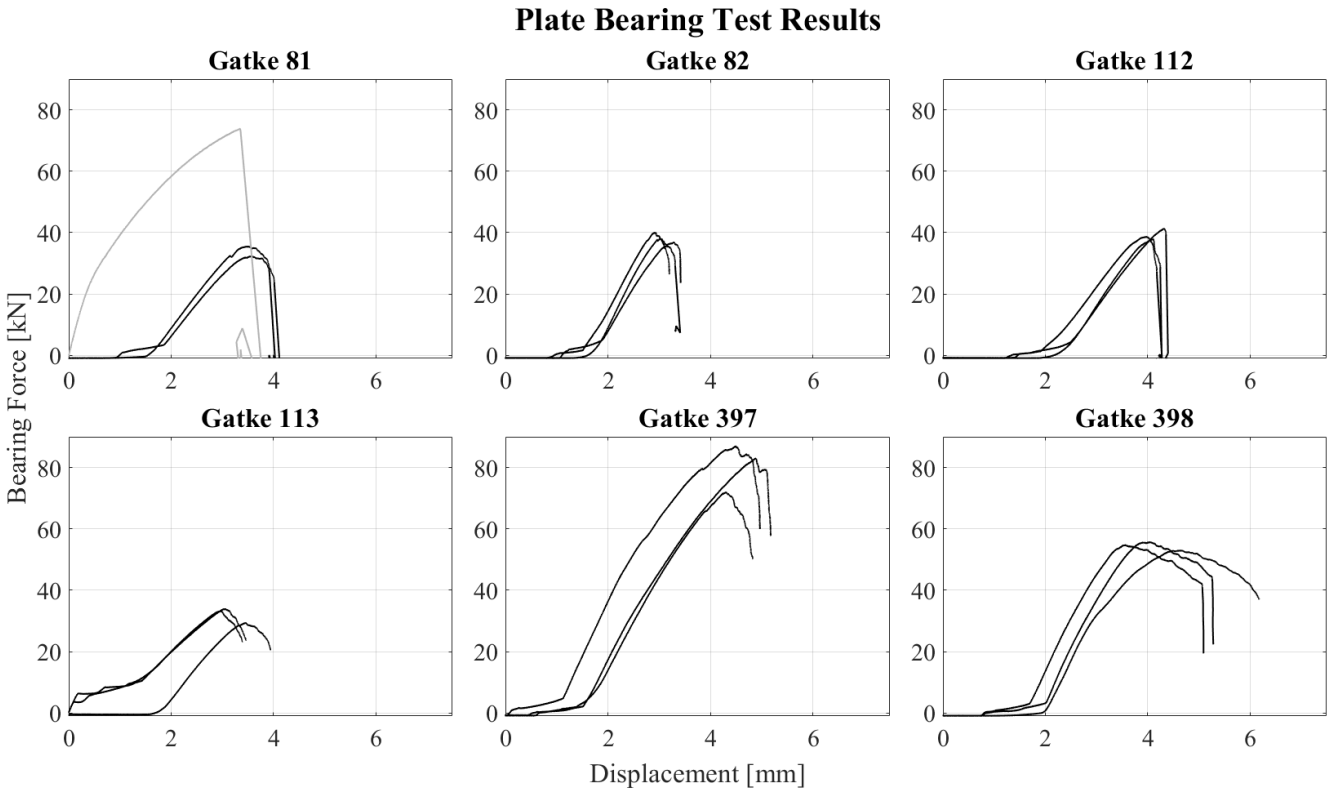
Bearing Fastener

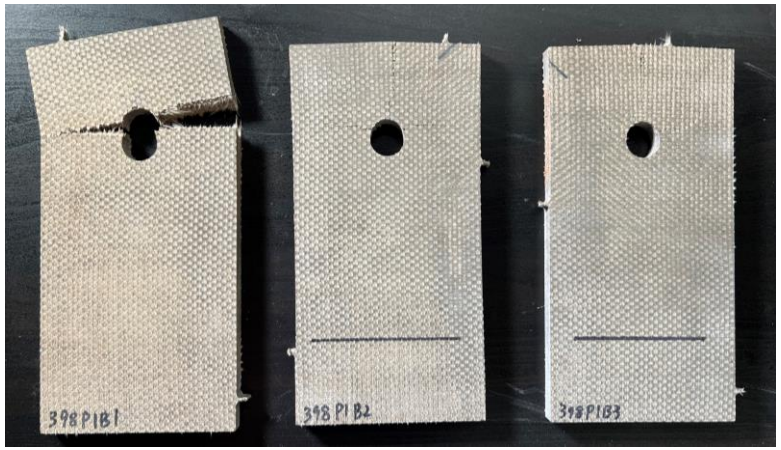
Steel Fixtures

Supplemental Fastener

A minimum clamping load was provided just enough to stabilize the test set-up
→ deemed to be conservative

Plate bearing test: results



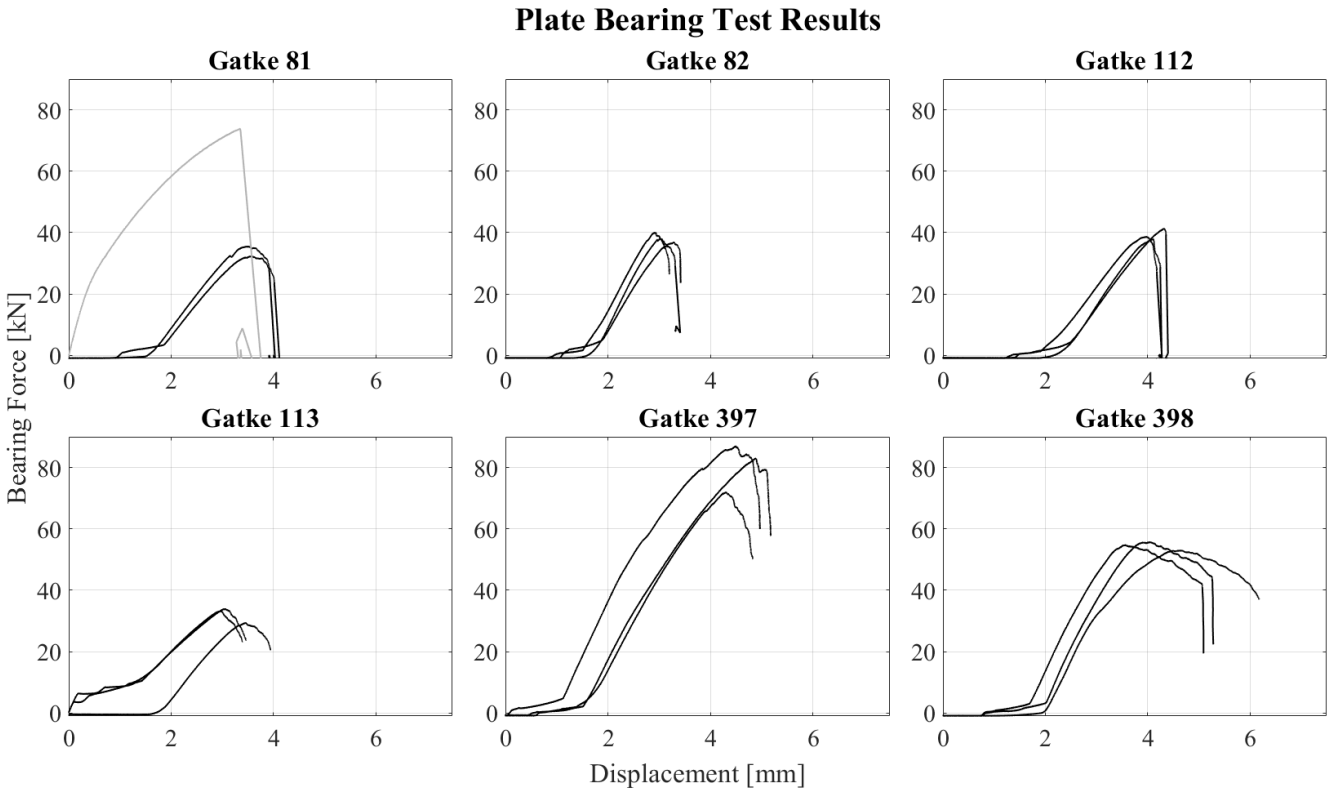


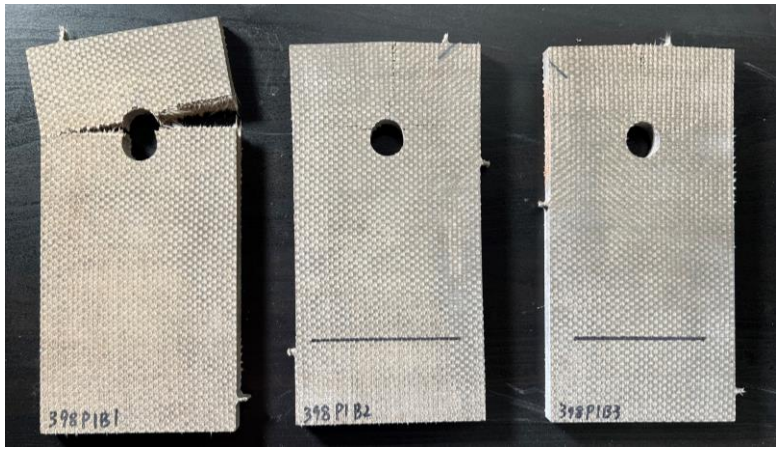
Example of Damaged Specimens (Gatke 398)

Materials	Ultimate Bearing Strength F^{bru} [MPa]	Failure Mode
Gatke 81	112.03	All specimens failed due to net tension
Gatke 82	126.58	All specimens failed due to cleavage
Gatke 112	129.72	All specimens failed due to net tension
Gatke 113	106.36	All specimens failed due to net tension
Gatke 397	266.53	All specimens failed due to cleavage
Gatle 398	180.06	One specimen failed due to net tension; two specimens failed due to cleavage

- Observation 1: **Pure bearing failure** (characterized by elongated bolt holes) **is not observed** in this test.
- Observation 2: Gatke 397 and 398 have higher bearing strength than Gatke 112 and 113; **E-glass cloth gives higher strength to the material than cotton cloth**

Plate bearing test: results





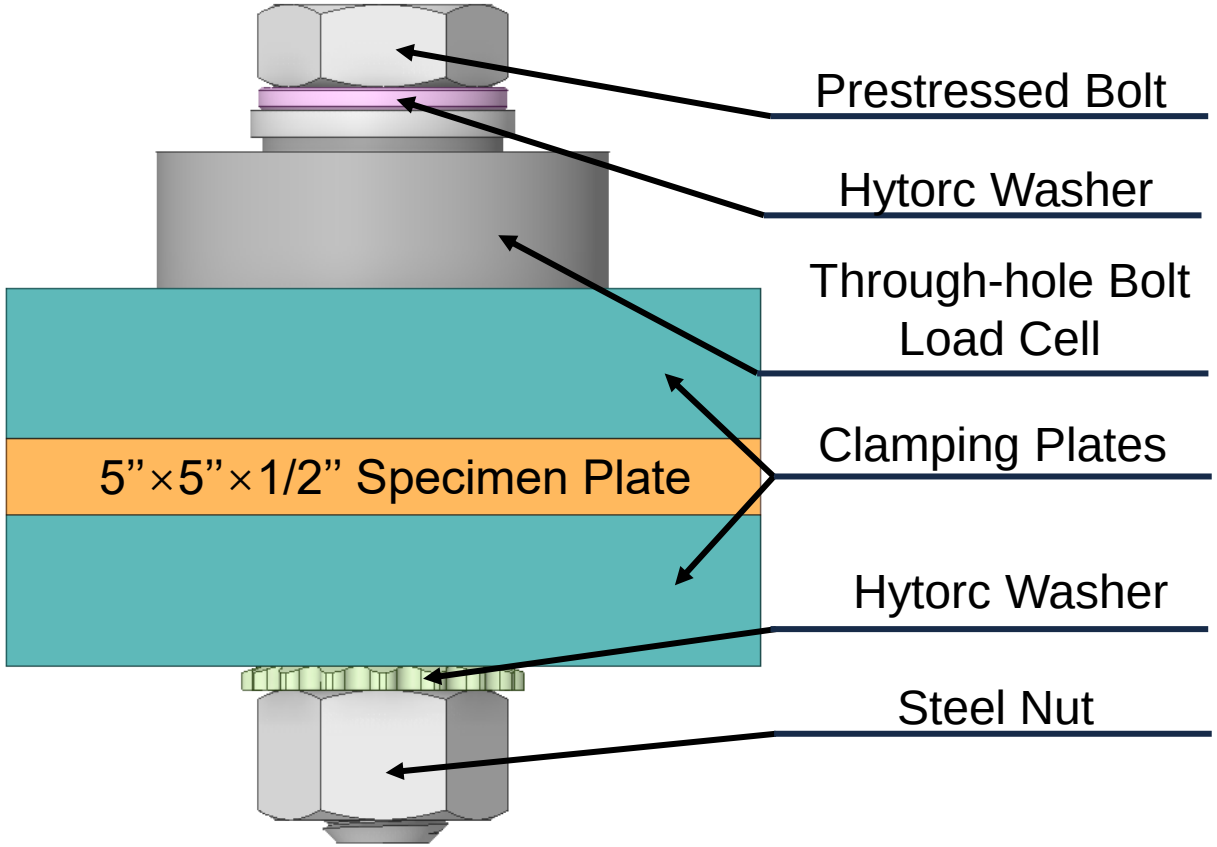
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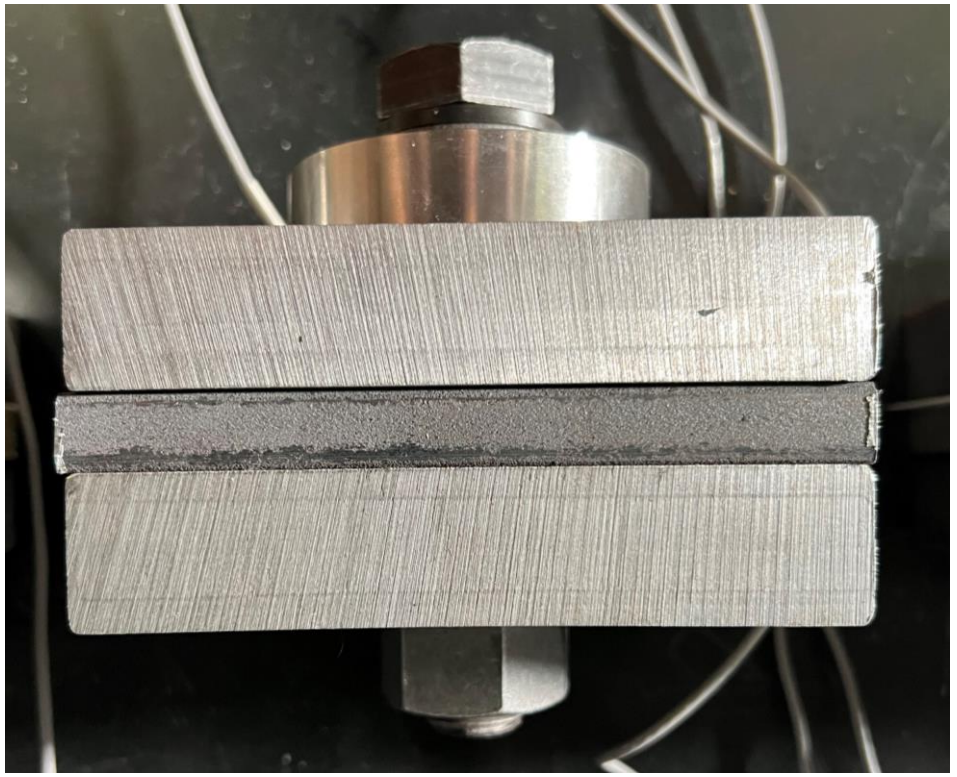
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- Observation 1: **Pure bearing failure** (characterized by elongated bolt holes) **is not observed** in this test.
- Observation 2: Gatke 397 and 398 have higher bearing strength than Gatke 112 and 113; **E-glass cloth gives higher strength to the material than cotton cloth**
- Observation 3: Gatke 112 has higher strength than Gatke 113; Gatke 397 has higher strength than Gatke 398; **friction modifiers Graphite, Teflon and Molybdenum disulfide potentially reduces the material strength**

Bolt relaxation test

- Test set-up



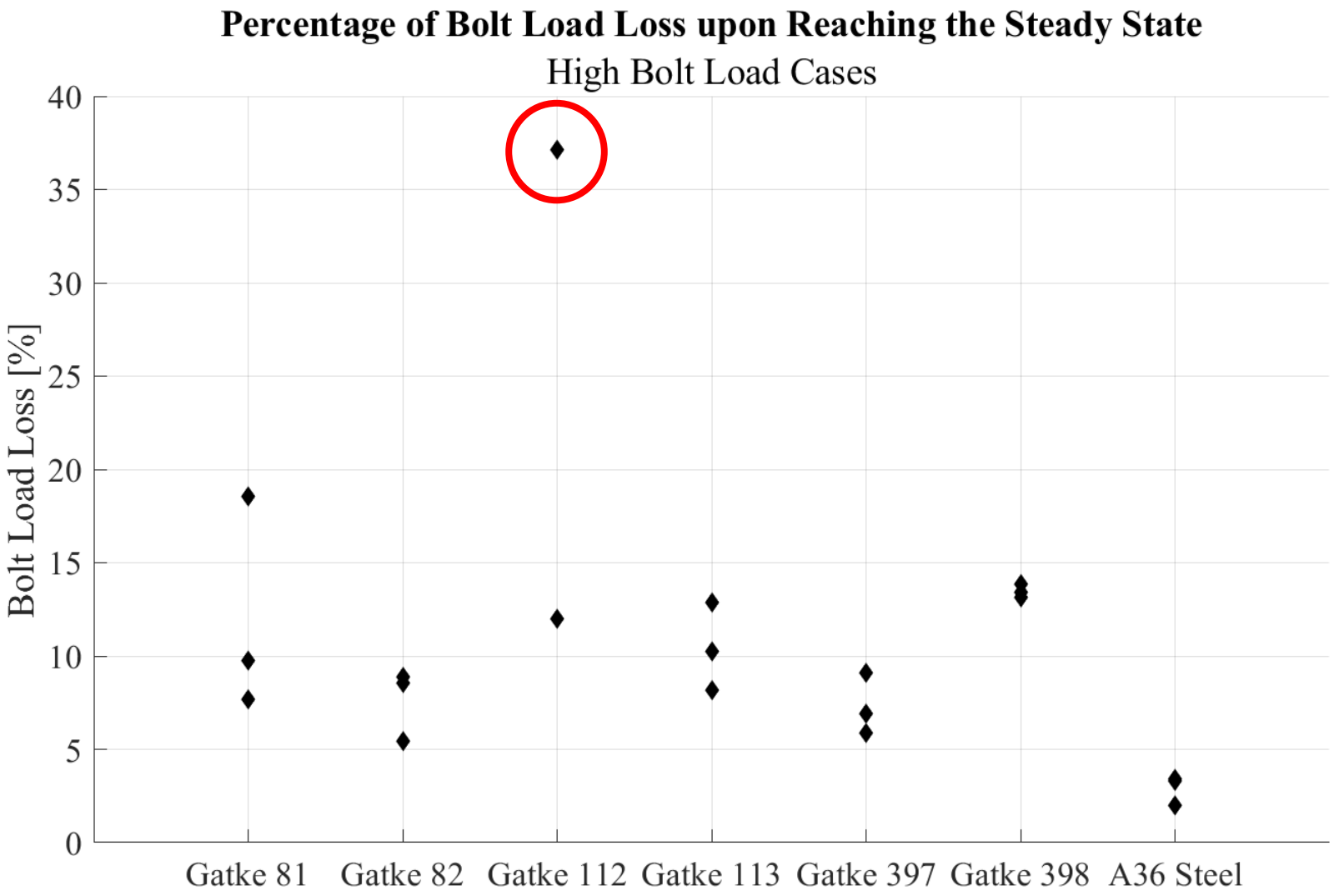


When a steady state of bolt load (defined as when the bolt load loss rate drops to -1e-10 N/min) is observed, data recording is stopped.

Bolt relaxation test

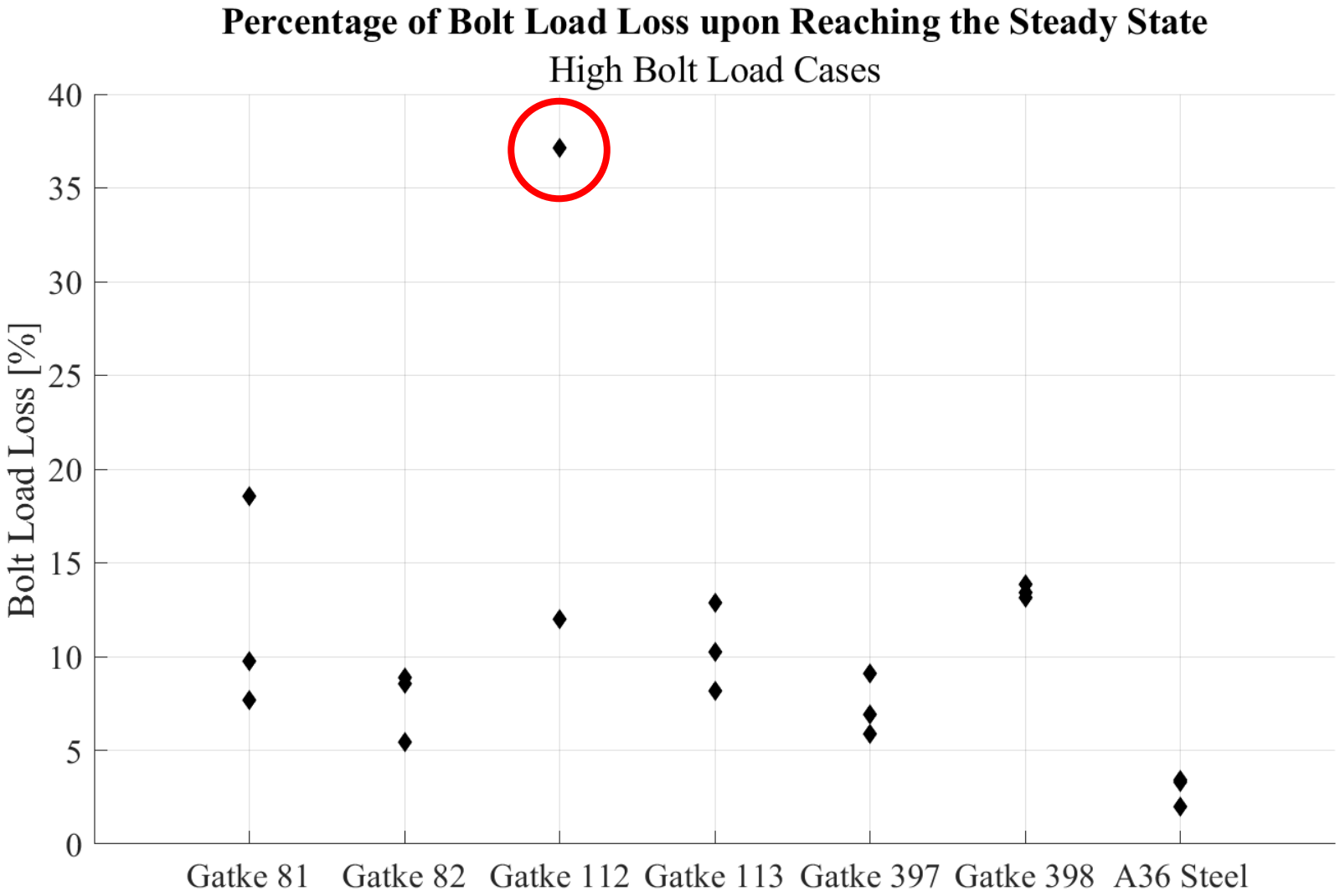
- **Two target bolt load levels** were considered
  - High bolt load (173.5 kN = 39 kips): minimum pretension of 7/8” ASTM A325 structural bolt
    - Nominal normal pressure = 11 MPa
  - Low bolt load (57.8 kN = 13 kips): 1/3 of high bolt load
    - Nominal normal pressure = 3.7 Mpa
- For each material under each load level, **three samples** were tested
- 3 samples of A36 steel plates were tested, as a reference group
- In this presentation, only the results from the high bolt load cases will be presented

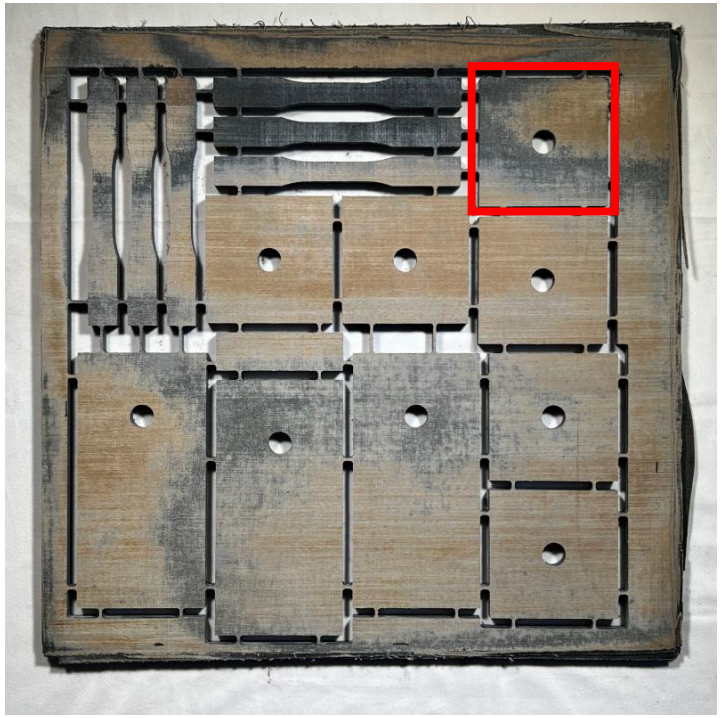
Bolt relaxation test: selected results



- Composite friction materials showed **similar performance in bolt load loss**; the **average bolt load loss** upon reaching the steady state is **about 10~15%**
- One of the Gatke 112 specimens shows **undesired bolt load loss**

Bolt relaxation test: selected results



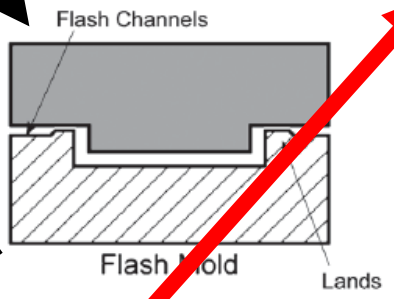


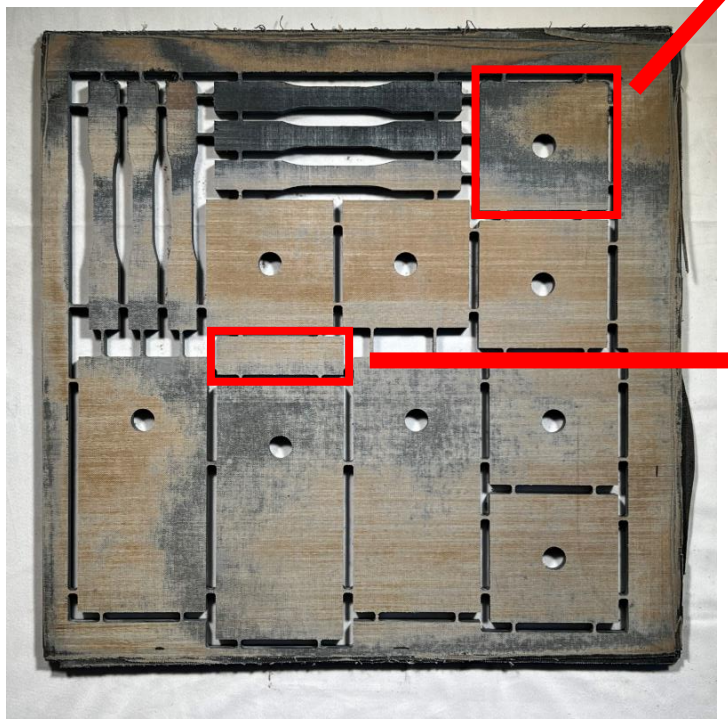
Specimen with excessive bolt load loss

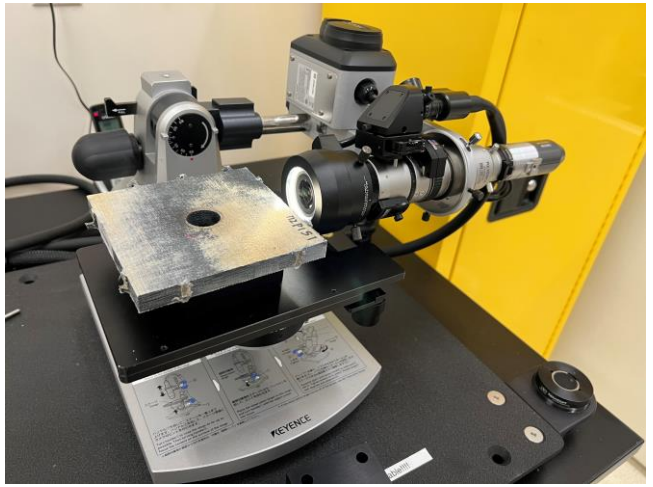
Bolt relaxation test: selected results -- influence of manufacturing

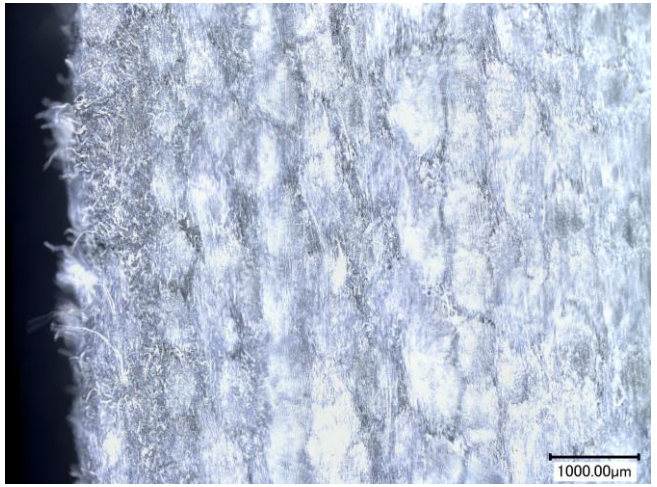
Raw Constituent

During flash molding, overflow of overcharged resin causes some regions in the composite friction materials to have **less resin**

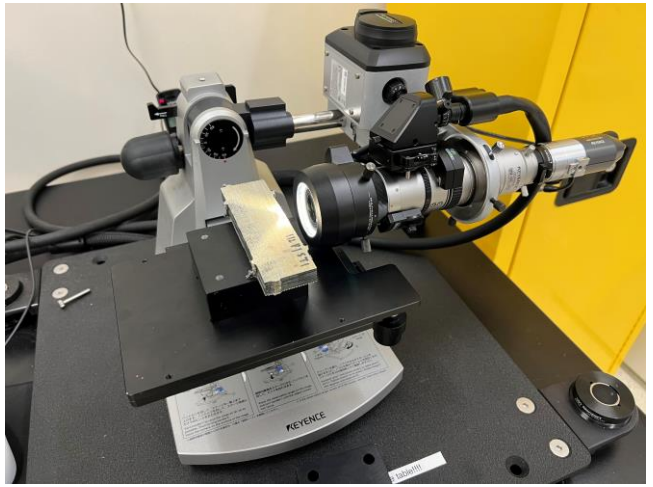








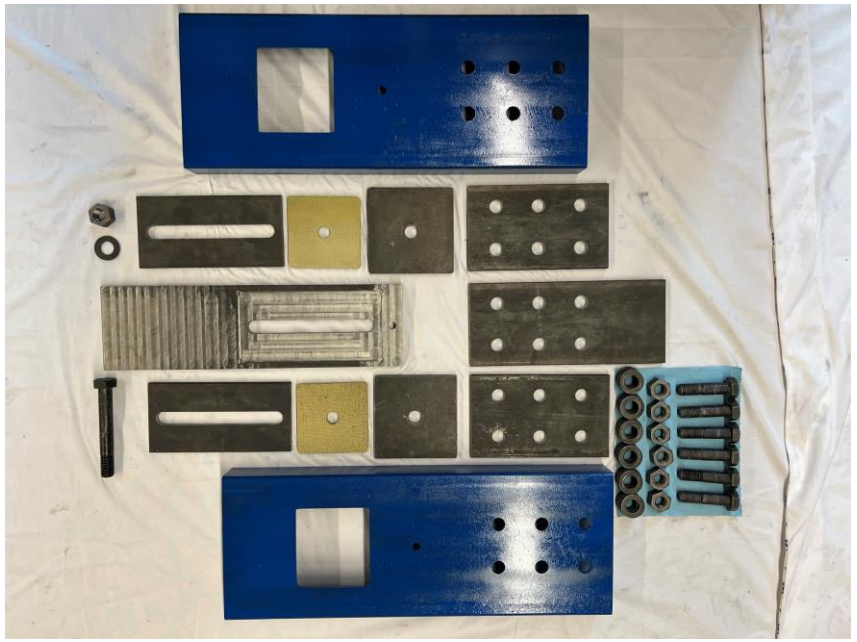
Structural integrity is affected, causing **undesired bolt relaxation performance**





Clear and well-defined laminated structure

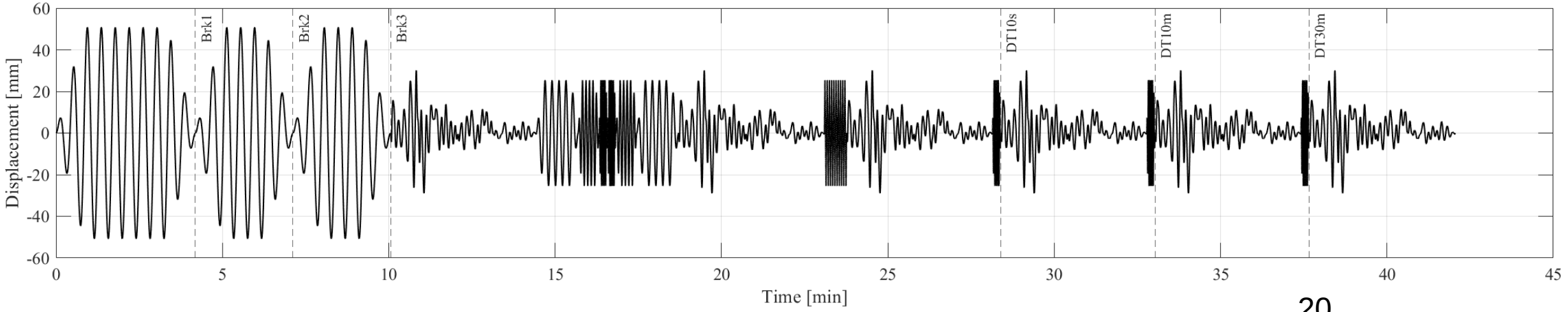
Friction test





- A slotted-bolted friction-based connection was designed
- The friction interface was established between **composite friction materials** and **A36 steel**
- Two normal load levels were considered, i.e., 39 kips and 13 kips

Loading protocol:



Effect of constituents

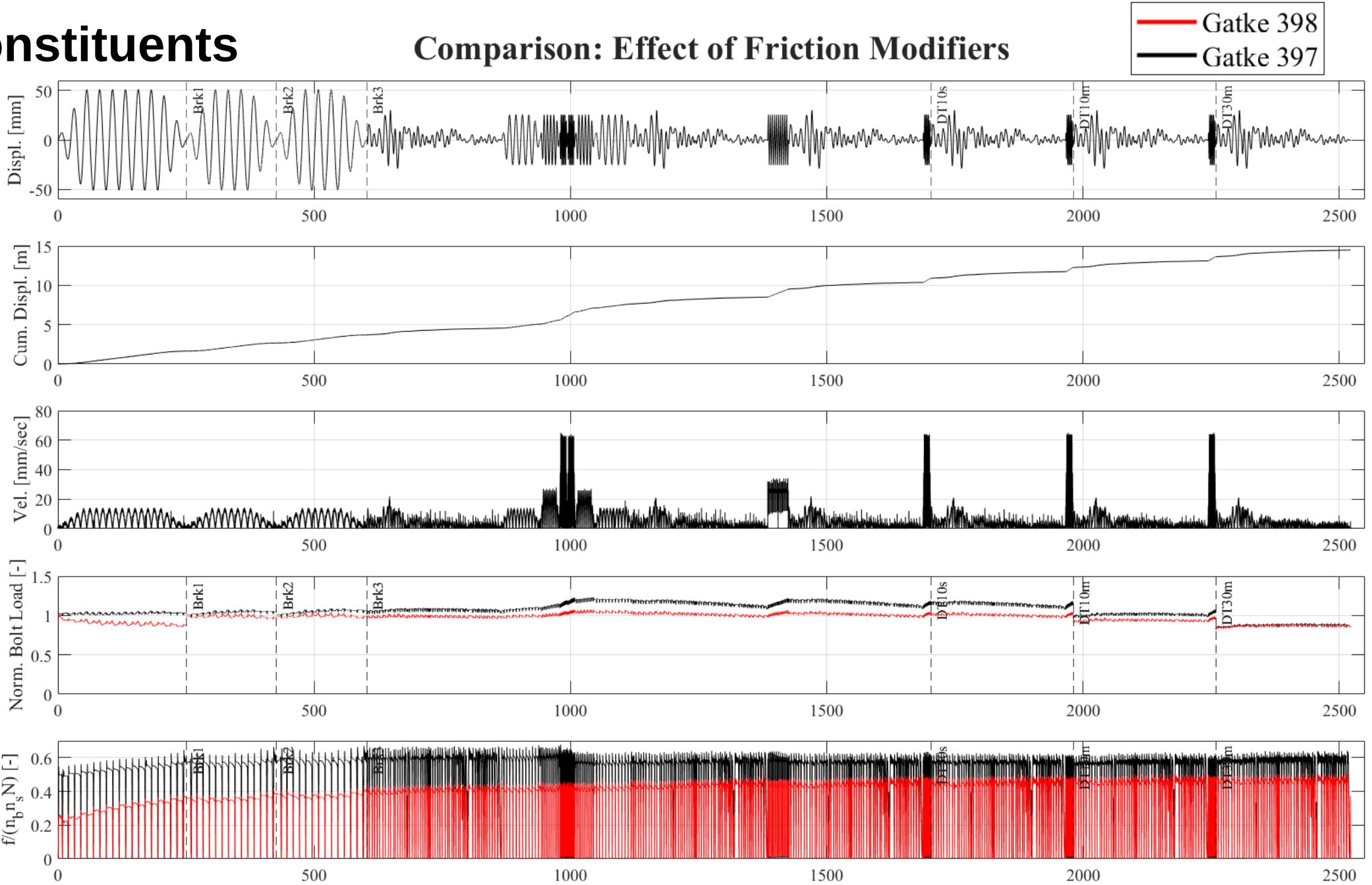
Recorded displacement history

Cumulative displacement history

Recorded absolute velocity history

Normalized bolt load history (bolt load normalized by the initial value)

Quantity: $f/(n_b n_s N)$ -- representative of coefficient of friction



After breaking-in, both cases exhibit stable frictional behavior

Adding friction modifiers (Graphite, Teflon & Molybdenum disulfide) reduces the coefficient of friction

Effect of constituents

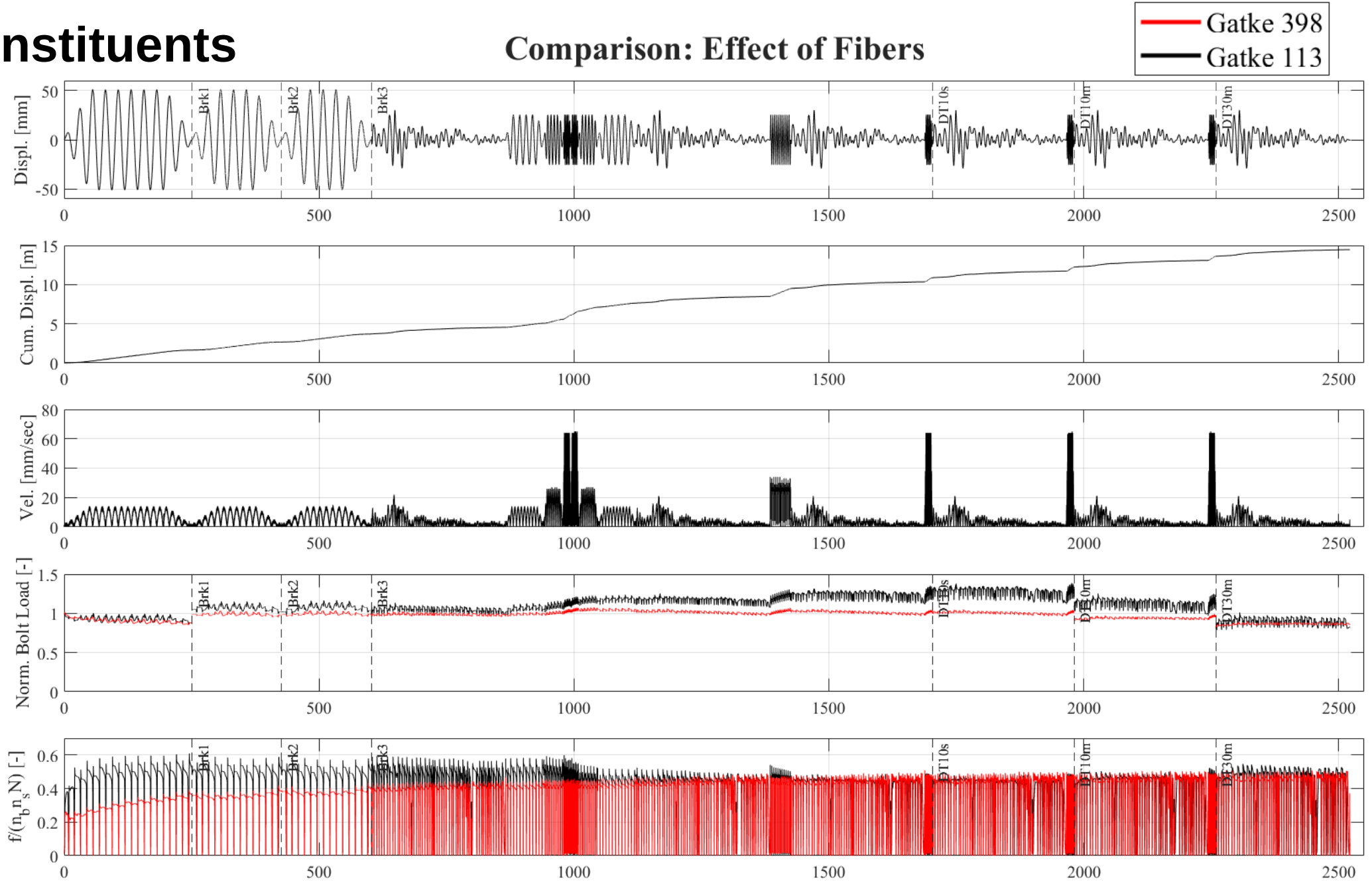
Recorded displacement history

Cumulative displacement history

Recorded absolute velocity history

Normalized bolt load history (bolt load normalized by the initial value)

Quantity: $f/(n_b n_s N)$ -- representative of coefficient of friction



Gatke 113 (with cotton fibers) shows faster break-in than Gatke 398 (with glass fibers)

Glass 398 has more stable frictional behavior than Gatke 113

Conclusions

- This presentation shows our efforts in characterizing **mechanical and tribological properties** of composite friction materials for structural applications; the goal is to establish a **database** for structural engineers for design purposes
- Six materials consisting of various constituents were characterized; the following preliminary conclusions regarding material constituents were made:
  - Glass fibers
    - Provide **higher mechanical strength** than cotton fibers
    - Give **more stable frictional behavior** compared with cotton fibers
  - Friction modifiers (Graphite, Teflon & Molybdenum disulfide)
    - **Reduce the material strength** by a certain amount
    - **Reduce coefficient of friction**
- **Flash molding process** results in regions with less resin; composite friction materials sampled from those regions potentially induce **increased bolt load loss over time** because **structural integrity** is weaker
- Collected data indicated that mechanical and tribological properties of composite friction materials with **phenolic resin as binder** and **with glass fibers** are **more applicable to structural applications**

Selected references

- Cox, R. (2011). Engineered tribological composites: the art of friction material development. SAE international.

- Golondrino, J. C., MacRae, G. A., Chase, J. G., Rodgers, G. W., & Clifton, G. C. (2013). Application of brake pads on asymmetrical friction connection (AFC). New Zealand Society for Earthquake Engineering.

- Tsampras, G. & Sause, R. (2015). Development and Experimental Validation of Deformable Connection for Earthquake-resistant Building Systems with Reduced Floor Accelerations

- Tsampras, G., Sause, R., Fleischman, R. B., & Restrepo, J. I. (2018). 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.

UC San Diego

18th World Conference on Earthquake Engineering
(WCEE2024)



Thank you for your attention!

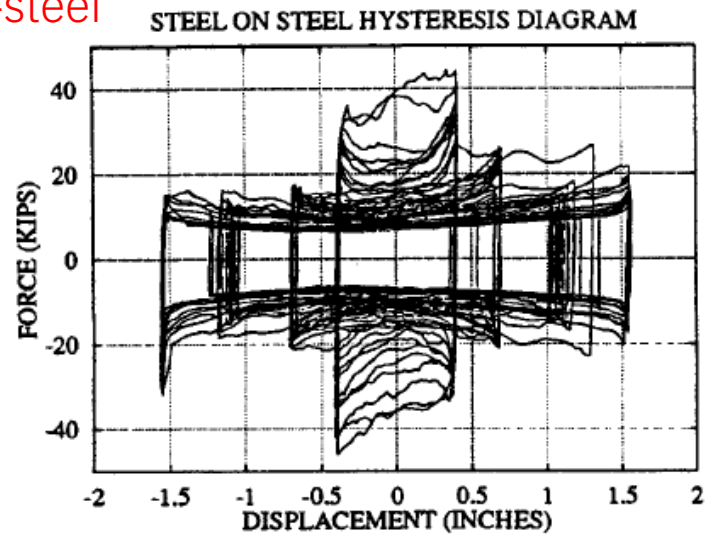
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kac011@ucsd.edu
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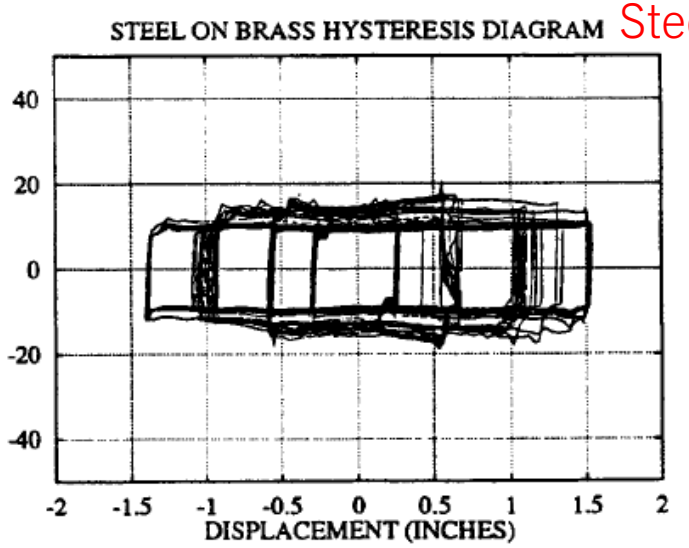
Tsampras Research Group

Background: friction interface

- Tremendous research efforts have been put into characterizing friction interfaces for friction-based connections

Steel-steel

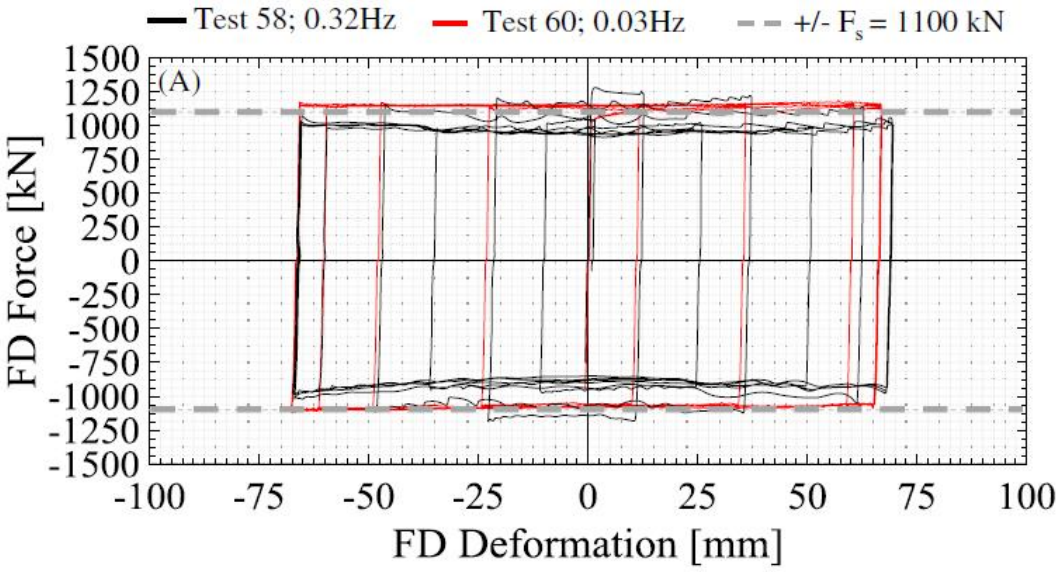


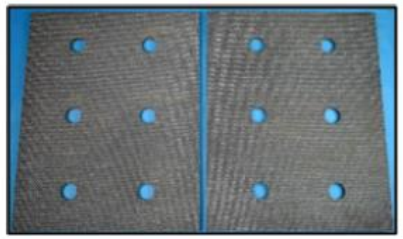


Steel-brass

Grigorian, Yang, and Popov (1993)

Steel-NAO (Gatke398)





(B) Initial Conditions



(C) End Conditions

Tsampras et al. (2018)

Background: friction interface (CONT'D)

- Bi-metallic friction interfaces could induce galvanic corrosion, which changes the property of a friction interface and could result in undesired frictional behavior



Chan and Tang (2022)

Table 1
Summary of individual SBC tests.

Specimen	Surface condition	$+F_s$	$-F_s$	$F_{f,max}$ (kN)	$F_{f,min}$ (kN)	E (kJ)	μ(see Note 1)
SBC-1	Rust & dry	20.0	−21.0	37.1	−38.6	6.026	0.35
SBC-2	Rust & greased	9.5	−12.0	34.1	−28.9	3.799	0.16
SBC-3	Polished & dry	30.0	−30.0	63.3	−57.5	8.707	0.70
SBC-4	Polished & greased	22.0	−3.0	36.5	−23.4	3.946	0.30

When rust is generated at the friction interface, the coefficient of friction is reduced by 50%

- Galvanic corrosion problem associated with bi-metallic friction interfaces motivates the use of non-metallic composite friction materials in friction-based connections as an alternative

Background: composite friction materials -- constituents

- Though composite friction materials have been widely used in the automotive industry, they are fairly new for structural applications
- Constituents of composite friction materials
  - Binder
    - As the matrix of the composite friction material, binder helps to hold the constituents of the composite materials together
    - Commonly used binder for composite friction materials: phenolic resin or modified phenolic resin
  - Fiber
    - Work as structural reinforcement
    - Can be organic (e.g., cotton fibers), inorganic (e.g., glass fibers), or metallic (e.g., brass fibers)
  - Friction modifier
    - Adjust the coefficient of friction and wear rates
    - Two sub-categories
      - Abrasives: hard materials (e.g., metal oxides) to increase the coefficient of friction
      - Lubricants: soft materials (e.g., graphite) to reduce the coefficient of friction and adjust the wear rate
  - Filler
    - Occupy the space, modify certain properties, and reduce the cost
- The ratios of each constituent are manufacturer-specified and are usually confidential



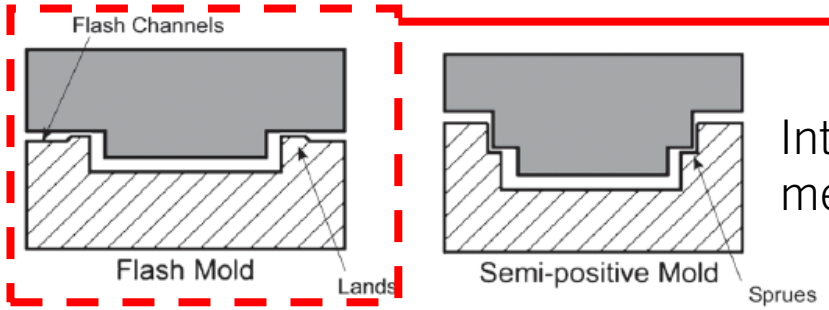
Gatke 398 used in Tsampras et al. (2018)

- Binder: phenolic resin
- Fiber: glass fiber
- Friction modifier: graphite, Teflon, and molybdenum disulfide (as lubricants)
- Filler: unknown

Composite friction materials -- manufacturing (compression molding)

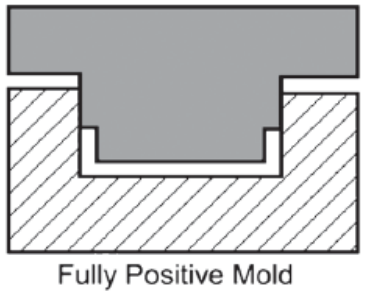
- Compression molding method typically involves three steps
  - Mixing of raw constituents of the composite friction material
  - Compression molding of the mix of constituents in a mold fixture

Cheapest; worst density control



Intermediate method

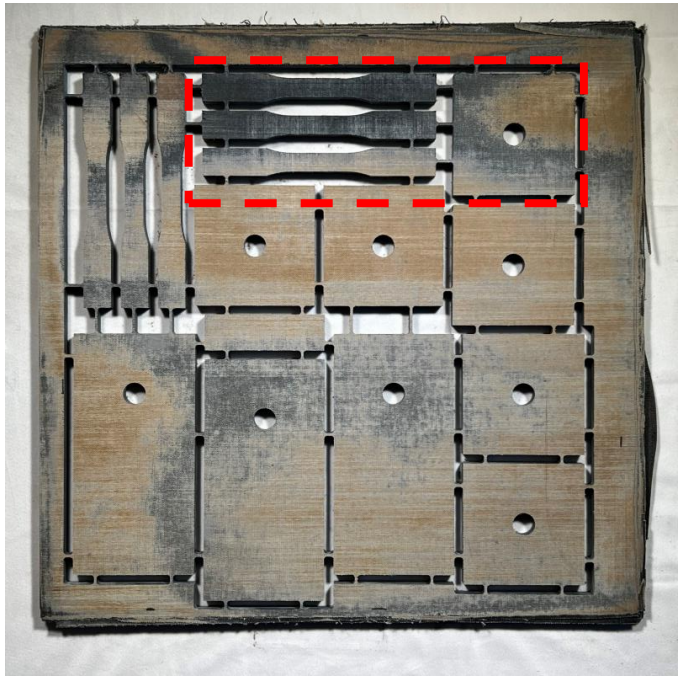
Most expensive; best density control



Cox (2012)

Fig. 5.8 Compression molding techniques from Carswell.

Resin is overcharged when loading the materials; during compression, overflow of overcharged resin causes some regions in the composite friction materials to have less resin



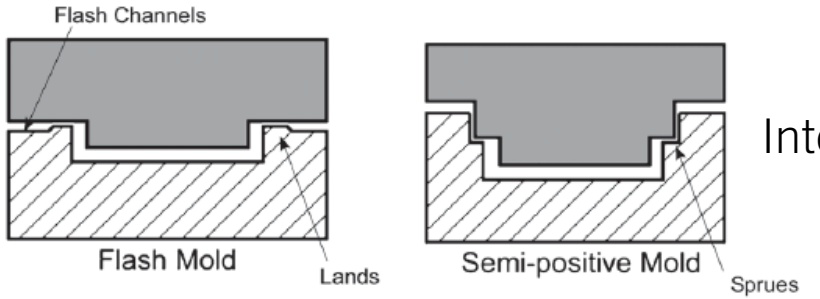
Gatke 112 machined plate

- Post curing of the molded material in a pre-heated oven

Background: composite friction materials -- manufacturing

- Compression molding method is introduced here since molded materials share the largest majority of the modern composite friction material market.
- Compression molding method typically involves three steps
  - Mixing of raw constituents of the composite friction material
  - Compression molding of the mix of constituents in a mold fixture

Cheapest; worst density control



Intermediate

Cox (2012)

Most expensive; best density control

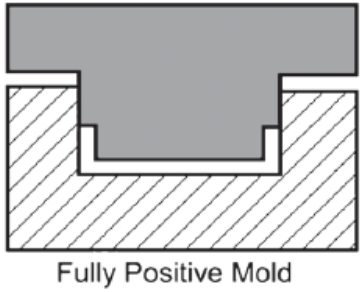


Fig. 5.8 Compression molding techniques from Carswell.

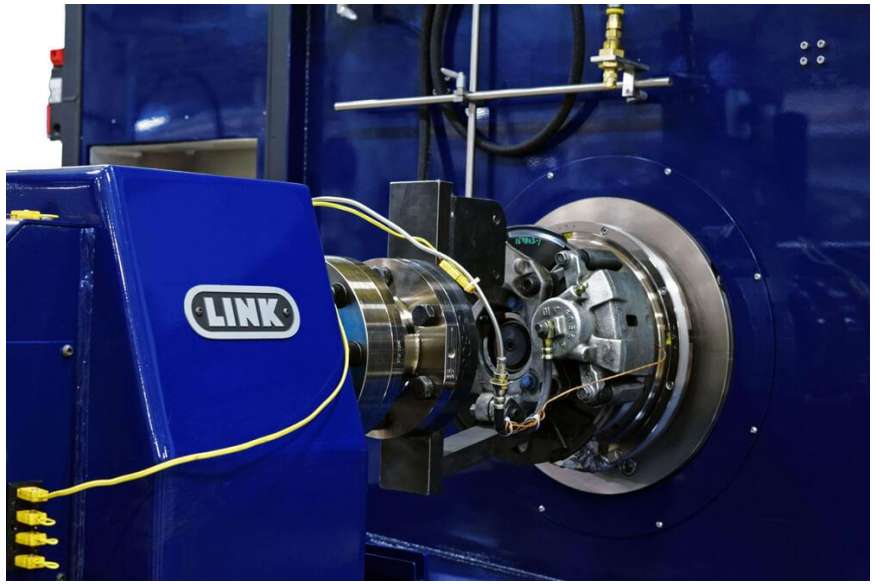
- Post curing of the molded material in a pre-heated oven

Background: composite friction materials -- testing

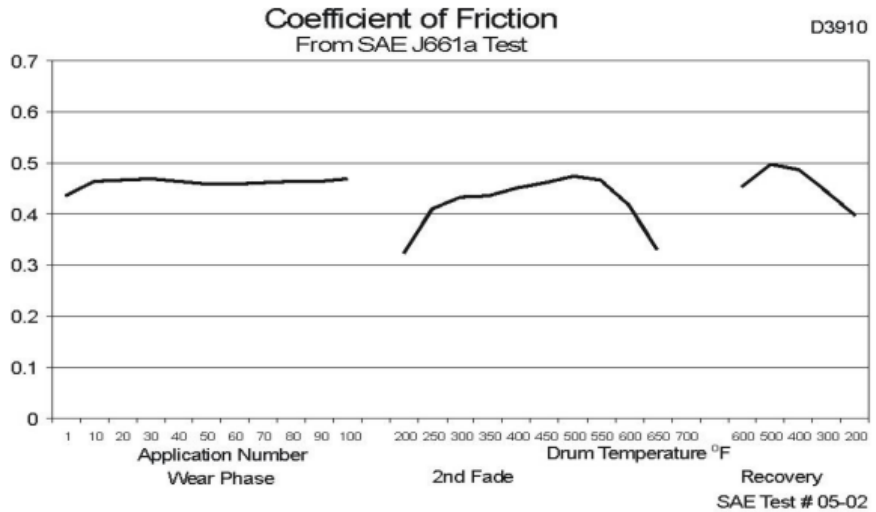
- For the automotive industry, testing methods for composite friction materials working in the braking system have been well-established
  - Physical property tests: for example, specific gravity and hardness
  - Mechanical property tests: for example, compressibility
  - Chemical property tests: for example, working PH range
  - Friction tests



Chase friction test machine (SAE J661 test)



Friction test dynamometer



Example friction test data (https://www.ferotecfriction.com/Product%20pdfs/D3910.pdf)

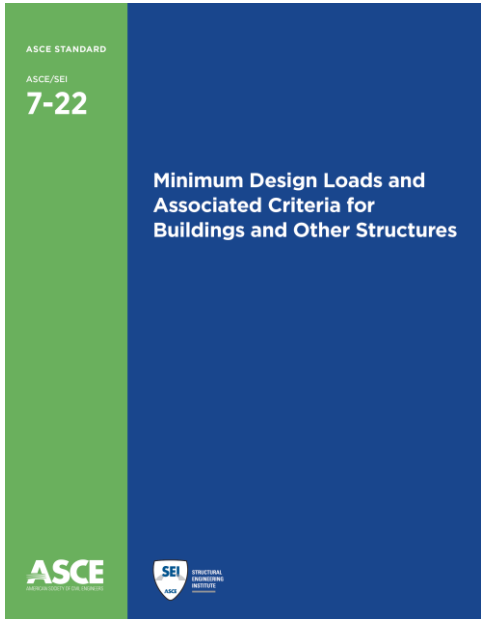
Testing methodology: the testing involves simulating braking conditions through controlled rotational motion and contact between the composite friction material sample and a back plate to measure the friction and wear characteristics of the material

ASCE/SEI 7-22 specified issues related to friction devices

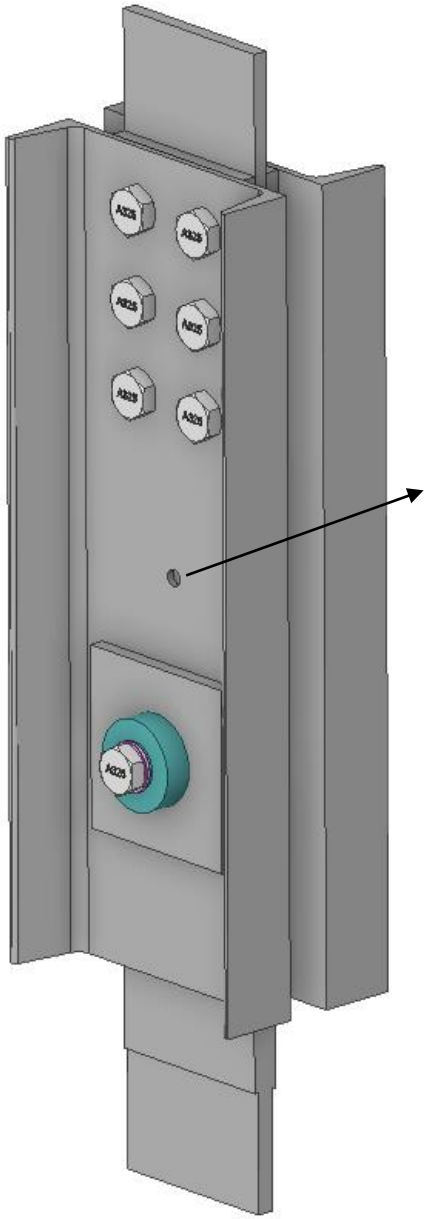
- In ASCE/SEI 7-22, the following issues are highlighted for the use of friction-based connections
  - Preload may reduce over time
    - For slotted-bolted friction-based connections, this refers to the loss of bolt load over time
    - Composite-metallic friction interfaces are more vulnerable to bolt load loss over time because of the viscoelastic characteristics of composite friction materials
  - The coefficient of friction could change substantially
- To address the issues, the following tests are required in the characterization and selection of composite friction materials for slotted-bolted friction-based connections
  - Bolt relaxation test
  - Friction test that reflects real working conditions of a friction-based connection

4. Friction devices. Friction devices operate on the principle of preloaded sliding interfaces. There are two issues with such devices:
   (a) The preload may reduce over time because of creep in sliding interface materials or the preloading arrangement, or wear in the sliding interface when there is substantial service-load related motion or after high-speed seismic motion. It is not possible to know what the preload may be within the lifetime of the structure, but the loss may be minimized when high-strength bolts are used and high-strength/low-wear materials are used for the sliding interface.
   (b) The friction coefficient at the sliding interface may substantially change over time. The engineer is directed to Constantinou et al. (2007) for a presentation on the nature of friction and the short-term and long-term behavior of some sliding interfaces. In general, reliable

Screenshots from ASCE/SEI 7-22

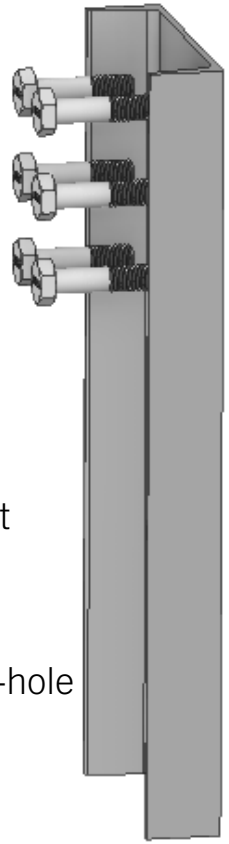


Friction test



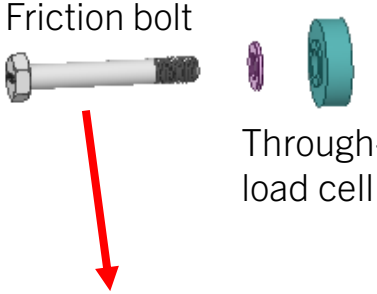
Assembly hole

Bolts for connection



Washer for friction bolt

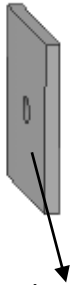
Friction bolt



Through-hole load cell

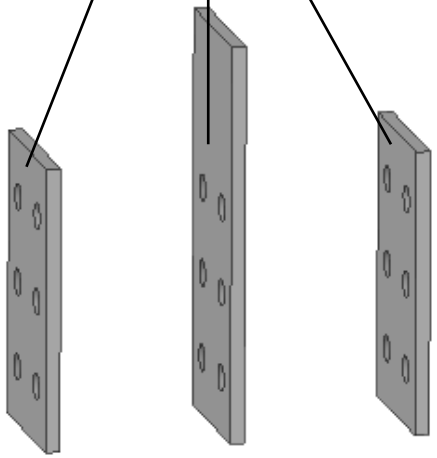
Two load levels were considered, i.e., 39 kips and 13 kips

Steel channel with an opening

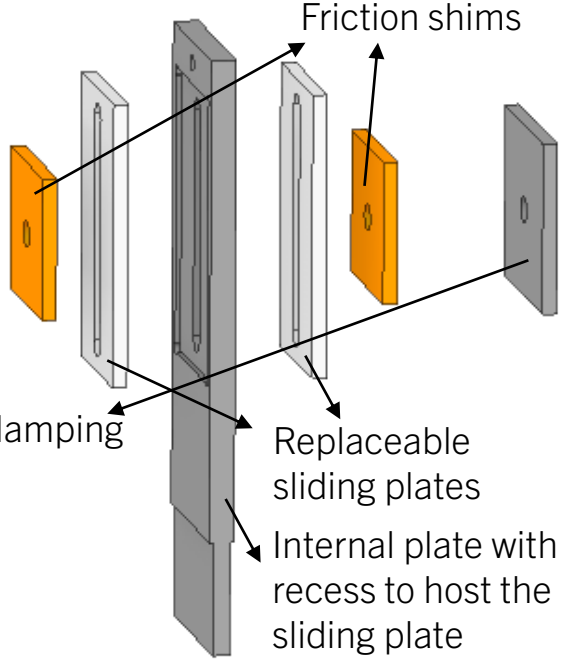


Loose clamping plates

Connection plates x 3 on the fixed end

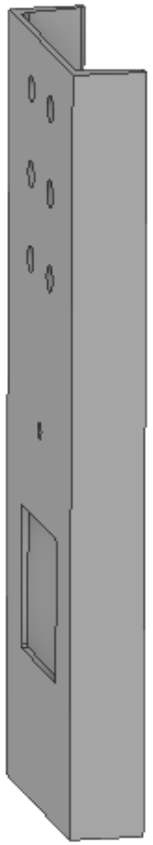


Friction shims



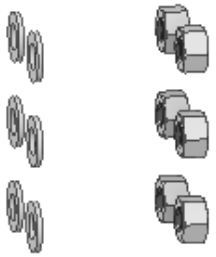
Replaceable sliding plates

Internal plate with a recess to host the sliding plate



Steel channel with an opening

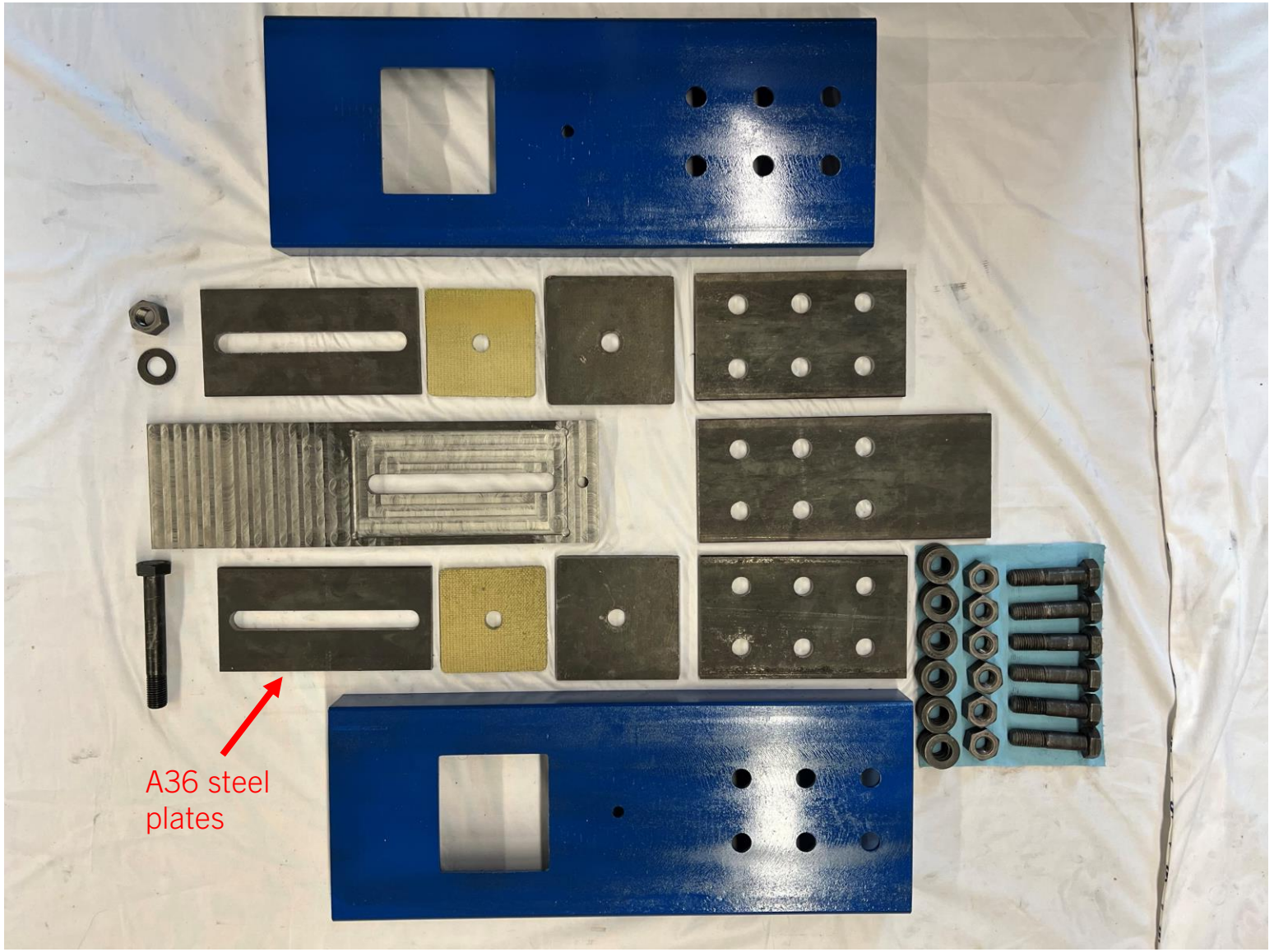
Washers and nuts for connection on the fixed end





Washer and nut for friction bolt

Friction test

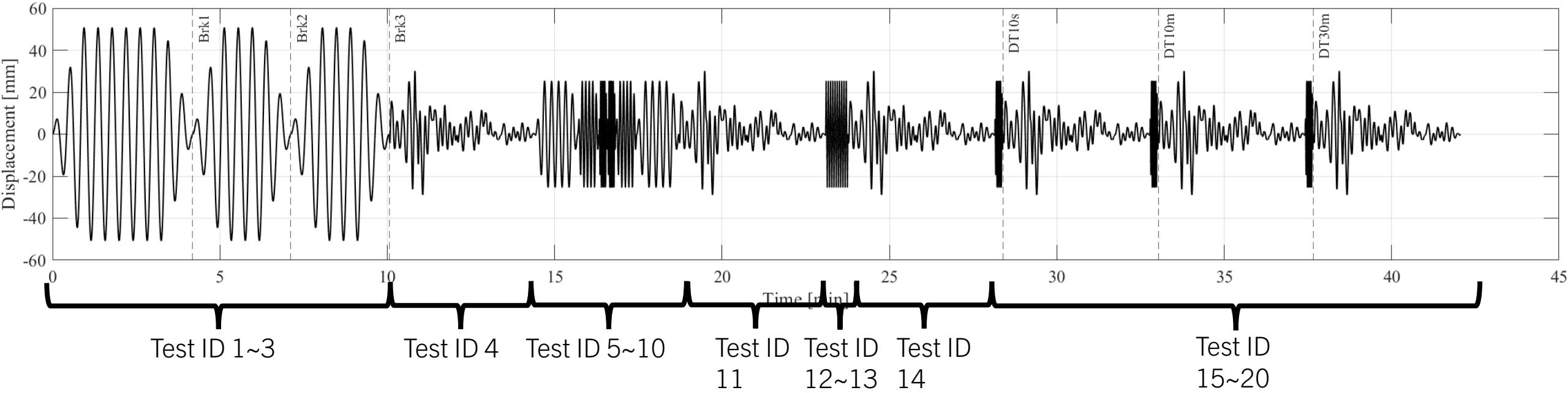




Two load levels were considered, i.e., 39 kips and 13 kips

Friction test: loading protocol

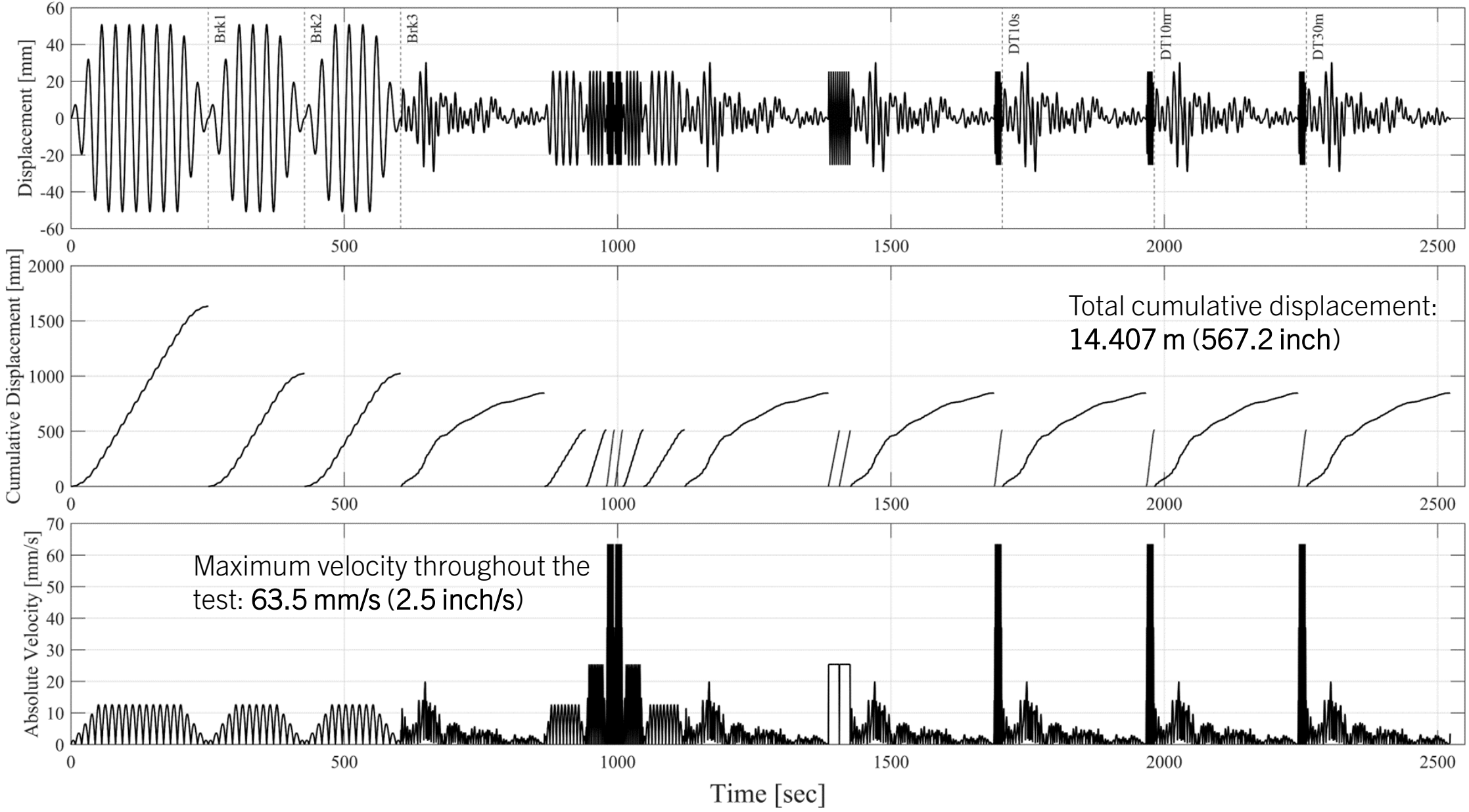
Brk(1,2,3) = End of Break-in cycles 1~3, during which bolt retightening is applied if needed
DT = dwell time (10 secs; 10 mins; 30 mins)



Test ID 1~3 | Test ID 4 | Test ID 5~10 | Test ID 11 | Test ID 12~13 | Test ID 14 | Test ID 15~20

- Test ID 1~3: Cycles for assessment of break-in effect
- Test ID 4,11,14: EQ response assessment
- Test ID 5~10: Ramped sinusoidal waves with various frequencies
- Test ID 12~13: Assess the performance of the friction interface under a linear ramp displacement input excitation
- Test ID 15~20: Assess the effect of dwell time
  - Running a fast ramped sinusoidal wave displacement input excitation to establish the effect of dynamic input excitation on the friction interface
  - Waiting for various dwell time (10 secs; 10 mins; 30 mins)
  - Running an EQ response input excitation to see how the coefficient of friction changes after a certain amount of dwell time

Friction Test Loading Protocol



Effect of normal load

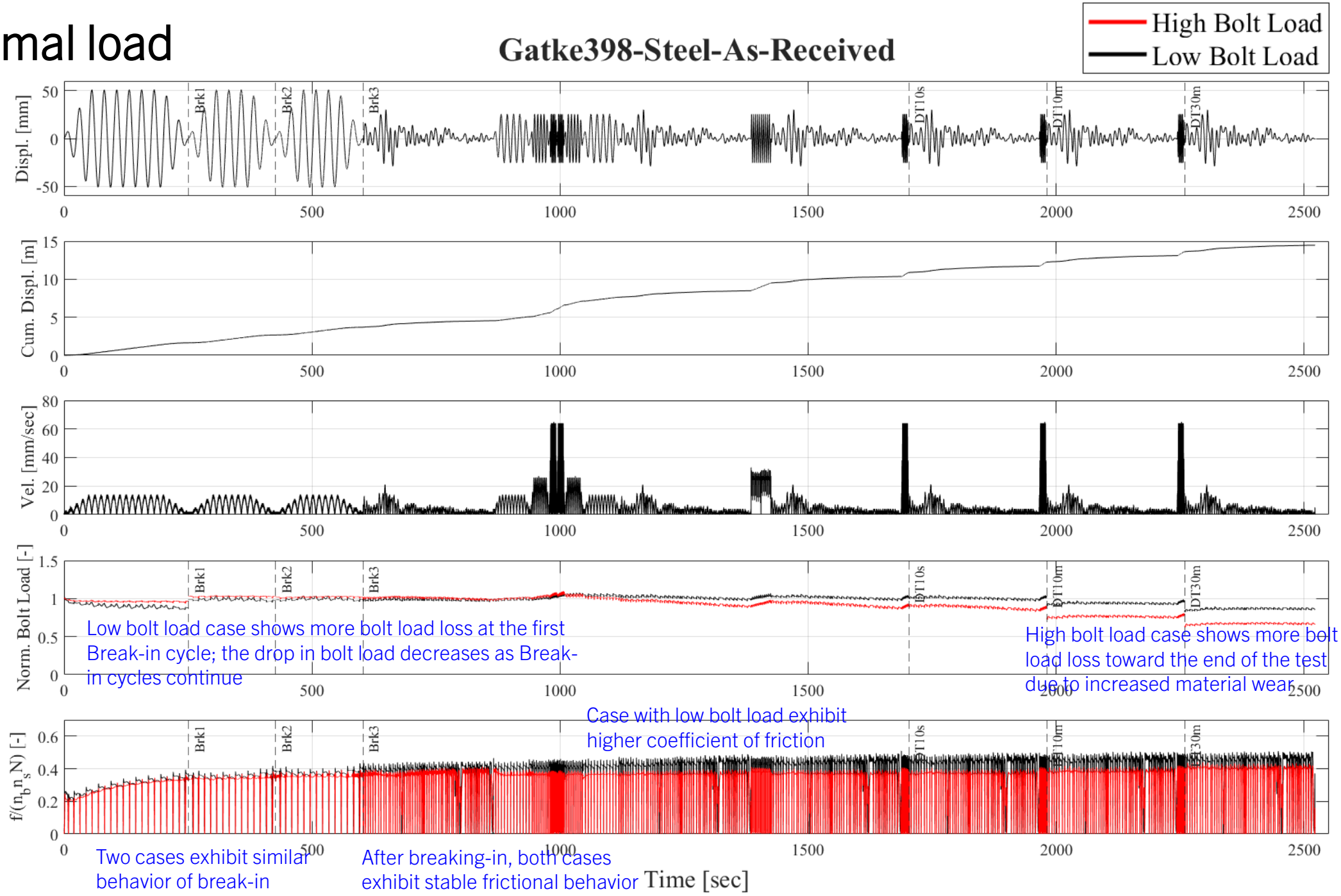
Recorded displacement history

Cumulative displacement history

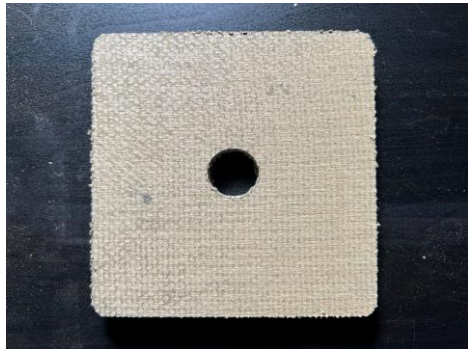
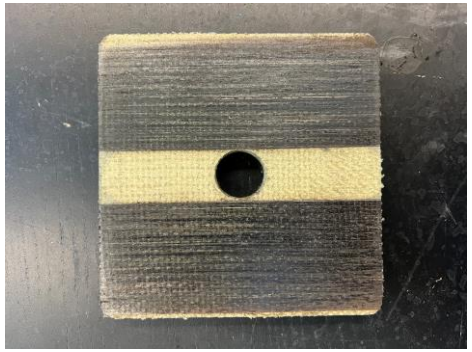
Recorded absolute velocity history

Normalized bolt load history (bolt load normalized by the initial value)

Quantity: $f/(n_b n_s N)$ -- representative of coefficient of friction



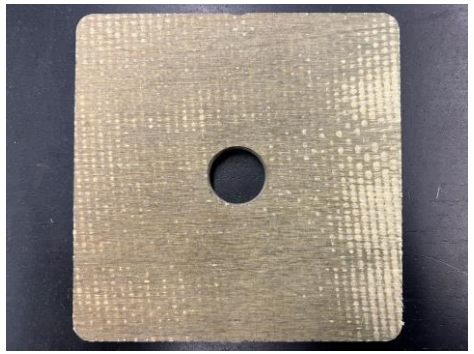
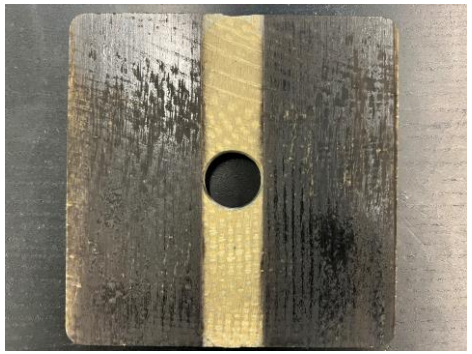
Effect of manufacturing

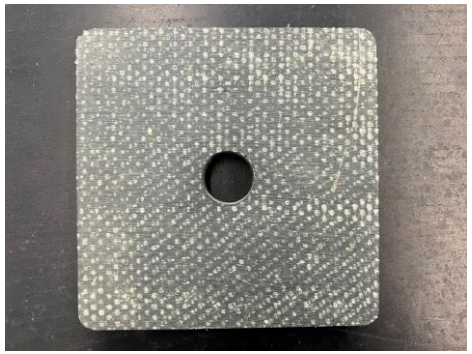
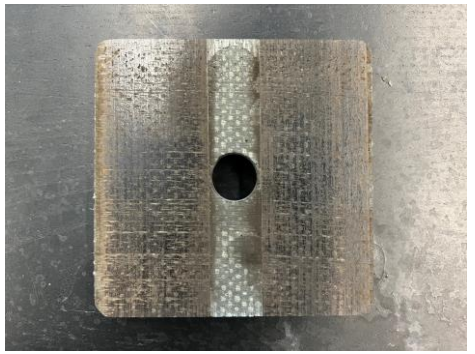
Gatke 81 before and after friction test



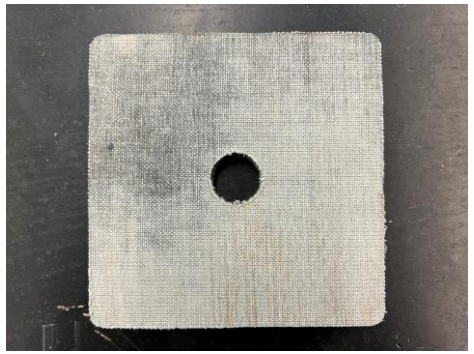
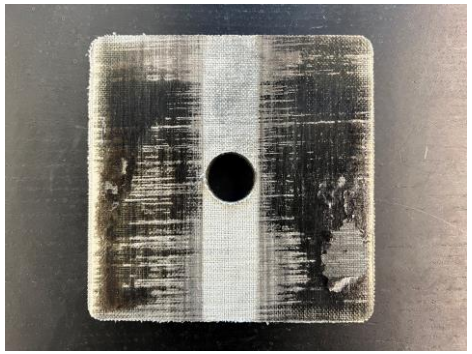

Gatke 113 before and after friction test

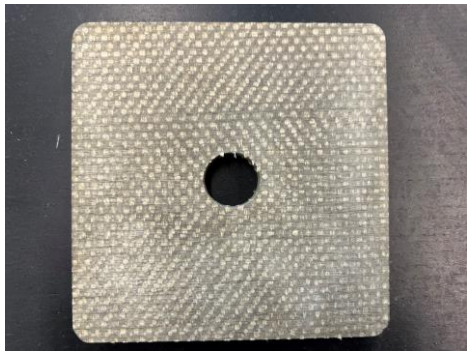
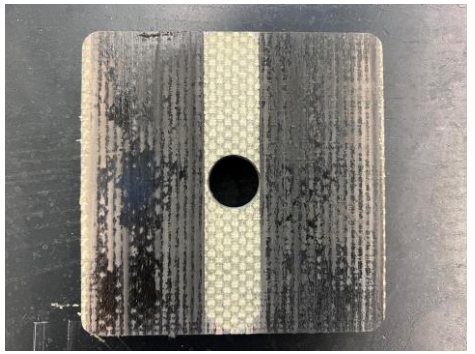
Gatke 82 before and after friction test

Gatke 397 before and after friction test

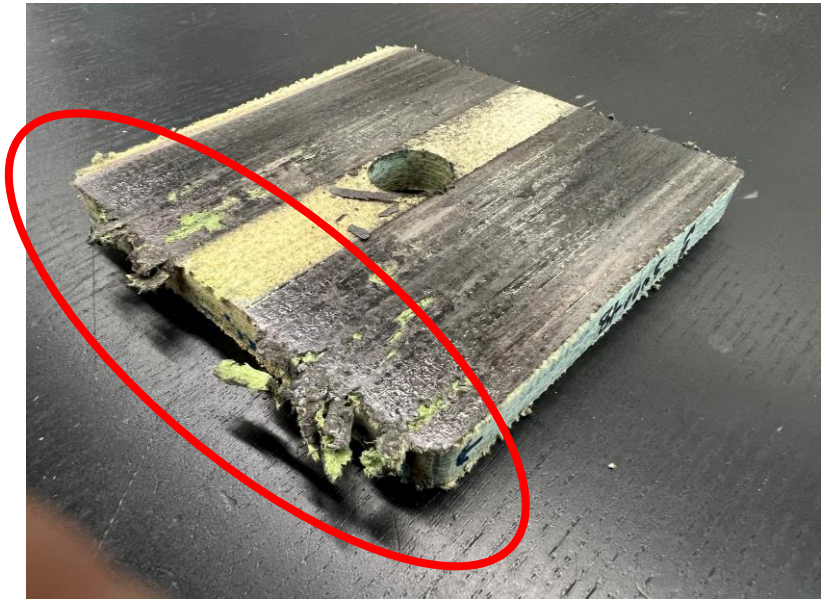



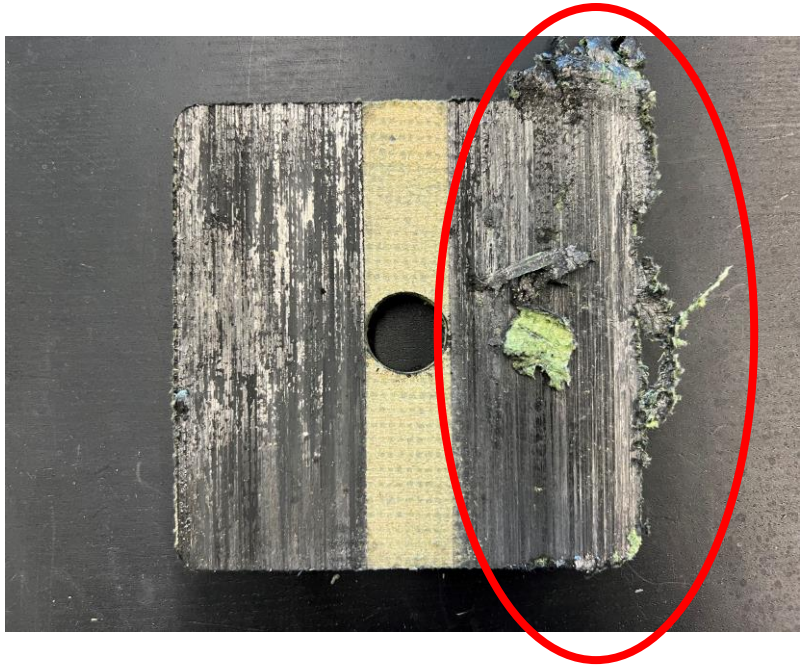
Gatke 112 before and after friction test

Gatke 398 before and after friction test

Effect of manufacturing





After the friction test, for specimens (example above: Gatke 81) from region with less resin, surface damage was observed