

Development and preliminary experimental characterization of a novel friction-based structural connection with predetermined discrete variable friction forces for high-performance earthquake-resistant buildings

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Abstract

This paper disseminates the development of a simple and practical structural connection able to develop predetermined discrete variable friction forces at target design displacement levels. The connection is termed Modified Friction Device (Modified FD). The Modified FD limits the forces transferred between the floor diaphragms and the core wall piers in buildings with a core wall seismic force-resisting system, while the predetermined discrete variable friction forces provide an equivalent post-elastic stiffness to prevent excessive connection deformations. The schematics of the physical embodiment, the components, and the assembly of the Modified FD are presented. The kinematics of the Modified FD are explained. The design parameters of the Modified FD are discussed. Two finite element modeling approaches, i.e., solid finite element modeling for assessing the expected kinematics and the expected force-displacement response of the Modified FD, and truss finite element modeling for simulating macroscopically the force-displacement response of the Modified FD in numerical earthquake simulations, are presented. The analytical formulation of the force-displacement response of the Modified FD is presented. Extensive material testing was conducted on the composite friction materials used in the Modified FD, focusing on the characterization of mechanical and tribological properties of the materials. The conclusions of the material characterization testing are discussed. The experimental testing plan for a reduced-scale Modified FD is presented.

Keywords: Friction devices, Structural connections, Earthquake-resistant buildings, Composite materials, Experimental testing, Earthquake structural engineering

Introduction

Practical force-limiting connections have been developed for earthquake-resistant buildings with planar seismic force-resisting systems (e.g., reinforced concrete planar shear walls or self-centering concentrically-braced steel frames) (Tsampras, 2016; Tsampras et al., 2016, 2017, 2018; Tsampras & Sause, 2022; D. Zhang et al., 2014; Z. Zhang et al., 2018). Figure 1 (a) shows a

schematic example of a building with reinforced concrete planar shear walls and force-limiting connections between the floor diaphragms and the walls. The use of force-limiting connections allows the relative movement between floor diaphragms and reinforced concrete planar shear walls and moreover, with force-limiting connections, seismic-induced horizontal forces are transferred from floor diaphragms to reinforced concrete planar shear walls in a controlled and limited manner. The force-limiting connections consist of friction devices and low-damping rubber bearings. Figure 1 (b) shows a slotted-bolted friction device designed and experimentally characterized by Tsampras et al. (2018). In the force-limiting connection in Figure 1 (a), low-damping rubber bearings provide out-of-plane stability to the reinforced concrete planar shear walls and post-elastic stiffness to the force-limiting connection to prevent excessive connection deformations.

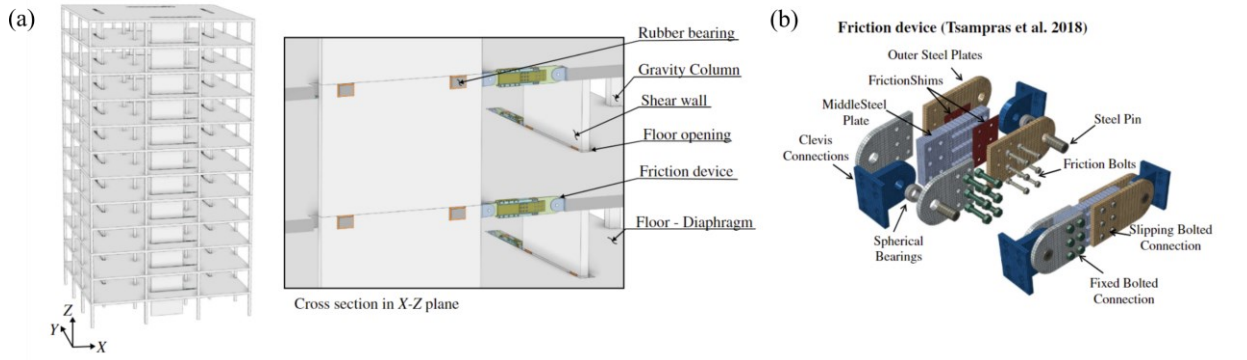


Figure 1 (a) Schematic example of a building with reinforced concrete planar shear walls and force-limiting connections consisting of friction devices and rubber bearings. (b) Sketch of the friction device developed by Tsampras et al. (2018).

The force-limiting connection in Figure 1 (a), which consists of friction devices and rubber bearings, is not applicable in earthquake-resistant buildings with core-wall seismic force-resisting systems because the relative high compressive stiffness of low-damping rubber bearing effectively restrains the relative movement between floor diaphragms and core wall piers (Lee et al., 2022, 2025). Therefore, rubber bearings cannot be used in force-limiting connections for earthquake-resistant buildings with core-wall seismic force-resisting systems. Recalling that in force-limiting connections for earthquake-resistant buildings with planar seismic force-resisting systems, the functions of low-damping rubber bearings are to provide out-of-plane stability to the planar seismic force-resisting system and to provide post-elastic stiffness to the force-limiting connection. For core-wall piers, they are self-stabilized in both in-plane and out-of-plane directions. However, alternative ways to prevent excessive connection deformations should be considered. Through numerical earthquake simulations, Lee et al. (2022, 2025) showed that in earthquake-resistant buildings with core-wall seismic force-resisting systems and without using rubber bearings, friction devices with discrete variable friction forces at target displacement levels can work as force-limiting connections between floor diaphragms and core-wall piers and they can effectively mitigate higher-mode effects and in the meantime, the increase of force resistance of the connection at target displacement levels can effectively reduce the connection deformation.

Modified Friction Device (Modified FD)

2.1 Components and Assembly

The development of the friction device used in Lee et al. (2022, 2025), which is able to develop predetermined discrete variable friction forces at target design displacement levels, has been discussed in detail in Chen et al. (2023). The friction device is termed the Modified Friction Device, or the Modified FD. Figure 2 shows the schematic representation of the Modified FD, including its components, the exploded view, the assembly, and the front view of the Modified FD showing two initial gap dimensions D_1 and D_2. The Modified FD consists of an internal plate, two external plates, four bearing plates, four friction shims between the external plates and the internal plate (termed friction shims for external plates), four friction shims between the bearing plates and the internal plate (termed friction shims for bearing plates), ten structural bolts with flat washers and nuts, and a spherical bearing. The external, internal, and bearing plates are expected to be made of structural steel such as ASTM A572 Grade 50 or A36 steel. The friction shims are expected to be made of non-metallic composite materials. The bolts are expected to be structural bolts such ASTM A325 bolts.

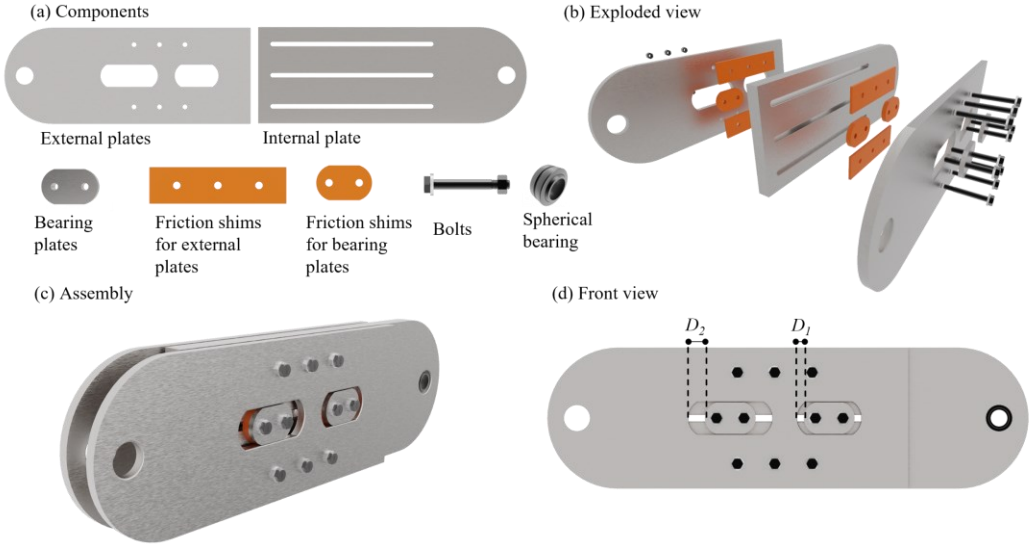


Figure 2 Schematic representation of the Modified FD (a) components, (b) exploded view, (c) assembly, and (d) front view with initial gap dimensions D_1 and D_2 between the bearing plates and the slots in the external plates.

In the assembly of the Modified FD, bolts are pretensioned to clamp the external plates, the bearing plates, the friction shims, and the internal plate. Friction interfaces are established at the contact surfaces between the internal plate and the friction shims. The pretension of bolts provides normal load acting on the friction interface. The slots in the internal plate allow the longitudinal movement of the bolts and thus the longitudinal motion of the friction shims, the external plates, and the bearing plates relative to the internal plate. The bearing plates and the associated friction shims are positioned within openings in the external plates, and they are not expected to move relative to the internal plate until the bearing plates are in contact with the external plates. The first gap distance between the bearing plates and the opening in the external plates is termed D_1, and the second gap

distance between the bearing plates and the opening in the external plates is termed D_2, as shown in Figure 2 (d) (by default, it is assumed that $D_1 \leq D_2$). With spherical bearings at the end, the Modified FD is expected to develop axial load along its longitudinal direction and zero moments at the ends.

2.2 Expected Kinematics and Force-displacement Response

The expected kinematics and the force-displacement response of the Modified FD have been discussed in Chen et al. (2023). Figure 3 shows the expected kinematics and the force-displacement response of the Modified FD. Assuming the elastic stiffness K_1, K_2, K_3 to be infinity, the kinematics and the force-displacement response are defined by five design parameters: the first gap between the bearing plates and the opening in each external plate: D_1; the second gap between the bearing plates and the opening in each external plate: D_2; the friction force generated by the friction interface between the internal plate and the friction shims for the external plates: F_1; the friction force generated by the friction interface between the internal plate and the friction shims for the bearing plates in the slots associated with D_1: F_2; the friction force generated by the friction interface between the internal plate and the friction shims for the bearing plates in the slots associated with D_2: F_3. When there is relative displacement between the external plates and the internal plate, the friction interfaces between the internal plate and the friction shims for the external plates first get activated. As the relative displacement increases, the friction interfaces between the internal plate and the friction shims for the bearing plates in the slots associated with D_1 and D_2 get activated progressively. The Modified FD thus generates a unique step-type force-displacement response, as shown in Figure 3. The design parameters D_1 and D_2 can be adjusted by modifying the geometry of the plates; 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. Easily adjusted design parameters make the application of the Modified FD customizable and versatile.

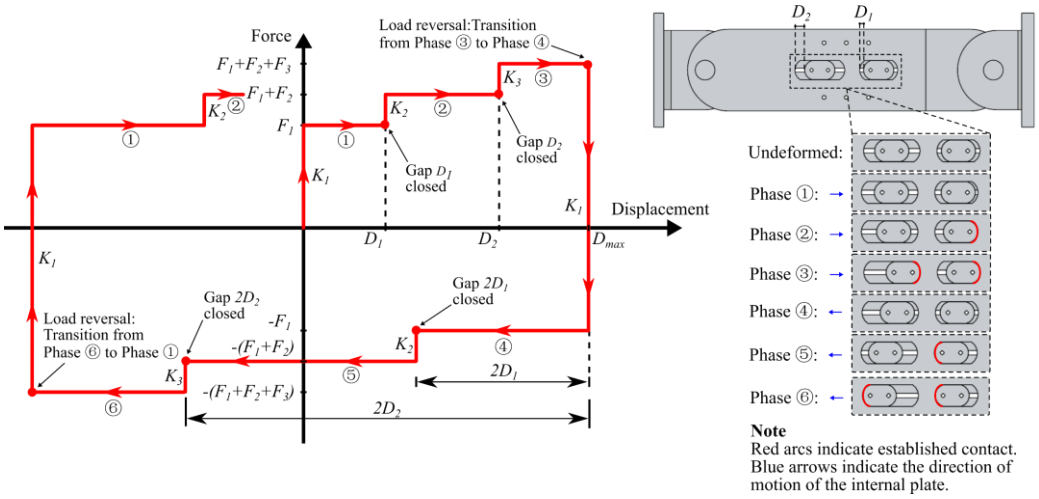
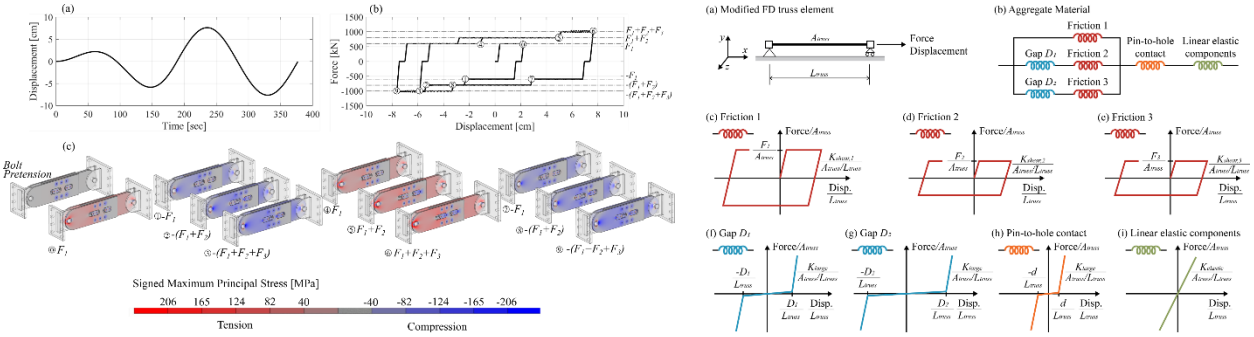


Figure 3 Expected kinematics and force-displacement response of the Modified FD

2.3 Modeling

Chen et al. (2023) introduced two modeling approaches of the Modified FD, as shown in Figure 4. The Solid Model explicitly simulates the components of the Modified FD and was developed to assess the expected kinematics and the expected force-displacement response of the Modified FD and also for rapid digital prototyping purposes. The Truss Model simulates the expected force-displacement response of the Modified FD at a macroscopic level and was developed to facilitate numerical earthquake simulations of structural systems equipped with the Modified FD. Details of these two modeling approaches can be found in Chen et al. (2023).



(a) Solid Model (b) Truss Model

Figure 4 Modeling approaches of the Modified FD presented in Chen et al. (2023): (a) Solid Model (b) Truss Model

This section introduces a new modeling approach of the Modified FD, which is to formulate the force-displacement response of the Modified FD analytically in a numeric computing environment. The proposed analytical formulation offers an alternative way to model macroscopically the force-displacement response of the Modified FD as pseudo material properties in numerical simulations, without using springs in parallel or springs in series compared to the Truss Model.

Figure 5 shows the pseudocode of the analytical formulation. The proposed analytical formulation of the force-displacement response of the Modified FD takes the five design parameters (D_1, D_2, F_1, F_2, and F_3) of the Modified FD and the imposed displacement time history $u(t)$ as the input and returns the expected time history of the connection force response. The analytical formulation assumes the elastic stiffness K_1, K_2, K_3 to be infinity. The programming starts by initializing the vectors representing the gap distances between the bearing plates and the external plate on both sides in the longitudinal direction in the undeformed configuration. The two vectors are named $Gap1 = [D_1, D_1]$ and $Gap2 = [D_2, D_2]$. The total gap distances associated with $Gap1$ and $Gap2$, termed $gap1_{total}$ and $gap2_{total}$, can be computed as $gap1_{total} = D_1 + D_1 = 2D_1$ and $gap2_{total} = D_2 + D_2 = 2D_2$, respectively. The main part of the program is to loop through the length of the imposed displacement time history $u(t)$ from the timestep $i = 2$. Within each timestep, the connection force $F(i)$ is first initialized as F_1, as the friction interfaces associated with F_1 always get activated when there is relative displacement between external plates and the internal plate. Then the incremental displacement of this timestep du is computed as $du = u(i) - u(i-1)$. The new gap distances associated with $Gap1$ can be computed as follows. First, the gap distance on one side of the bearing

plate is termed $gap1_{left}$ and can be computed as $gap1_{left} = min(gap1_{total}, max(Gap1(1) – du,0))$. $Gap1(1)$ represents the first element of the vector $Gap1$. It will be later noted that $Gap1$ is updated within each timestep throughout the looping process. The $max()$ function is used to take into account that physically the gap distance $gap1_{left}$ cannot be a negative number. The $min()$ function is used because the gap distance $gap1_{left}$ cannot exceed the total gap distance $gap1_{total}$ associated with $Gap1$. Although the gap distance is named $gap1_{left}$, it will be later observed that left or right is used only for terminology and the result will not be affected even if they are interchanged. After determining $gap1_{left}$, the gap distance on the other side of the bearing plate, termed $gap1_{right}$, can be computed as $gap1_{right} = gap1_{total} – gap1_{left}$. The new gap distances associated with $Gap1$ can then be updated as $Gap1 = [gap1_{left}, gap1_{right}]$. After determining the new gap distances associated with $Gap1$, we can check if either $gap1_{left}$ or $gap1_{right}$ is equal to zero. If either one of gap distances is equal to zero, it means that there is no gap between the bearing plates associated with D_1 and the external plates and therefore, contact is established between the bearing plates associated with D_1 and the external plates. The connection force is thus updated as $F(i) = F(i) + F_2$. The same procedures can be adopted to check and update the gap distances associated with $Gap2$ and update the connection force if needed. The last step within this timestep is to update the sign of the connection force. In the analytical formulation, it is assumed that tensile force is positive, and that a positive incremental displacement generates tensile force in the connection. By this assumption, the connection force will have the same sign as the incremental displacement, and it can be updated as $F(i) = F(i) \times sgn(du)$. We then finish computing the connection force response $F(i)$ of the timestep of interest (i.e., timestep i). After looping through all the timesteps, the corresponding expected time history of the connection force response $F(t)$ associated with the imposed displacement time history $u(t)$ can be obtained.

Program starts
- **Input** design parameters of the Modified FD: D_1, D_2, F_1, F_2, F_3
- **Input** the imposed displacement time history: $u(t)$
- **Initialize** the vectors representing the gap distances between the bearing plates and the external plate:
  - $Gap1 = [D_1, D_1]$; $Gap2 = [D_2, D_2]$
- **Compute** the total gap distances associated with $Gap1$ and $Gap2$:
  - $gap1_{total} = D_1 + D_1 = 2D_1$; $gap2_{total} = D_2 + D_2 = 2D_2$
- **Loop** for i from 2 to the length of $u(t)$
  - **Initialize** the connection force of this timestep: $F(i) = F_1$
  - **Calculate** the incremental displacement: $du = u(i) – u(i – 1)$
  - **Compute** the new gap distances associated with $Gap1$:
    - $gap1_{left} = min(gap1_{total}, max(Gap1(1) – du,0))$; $gap1_{right} = gap1_{total} – gap1_{left}$
  - **Update** the gap distances associated with $Gap1$: $Gap1 = [gap1_{left}, gap1_{right}]$
  - **Update** the connection force:
    - If $gap1_{left} = 0$ or $gap1_{right} = 0 \rightarrow F(i) = F(i) + F_2$
  - **Compute** the new gap distances associated with $Gap2$:
    - $gap2_{left} = min(gap2_{total}, max(Gap2(1) – du,0))$; $gap2_{right} = gap2_{total} – gap2_{left}$
  - **Update** the gap distances associated with $Gap2$: $Gap2 = [gap2_{left}, gap2_{right}]$
  - **Update** the connection force:
    - If $gap2_{left} = 0$ or $gap2_{right} = 0 \rightarrow F(i) = F(i) + F_3$
  - **Determine** the sign of the connection force: $F(i) = F(i) \times sgn(du)$
- **End loop**

Program ends

Figure 5 Pseudocode of the analytical formulation of the Modified FD force-displacement response in a numeric computing environment

Figure 6 shows the comparison of the force-displacement response computed using the Solid Model, the Truss Model, and the Analytical Formulation. All three models assumed the following design parameters: D_1 = 2 cm, D_2 = 5 cm, F_1 = 600 kN, $F_2 = F_3$ = 200 kN and they were subjected to the same imposed displacement time history. It can be observed that force-displacement responses computed using three models have reasonably good agreement. The corresponding computed cumulative dissipated hysteretic energy from the force-displacement response using three models is presented in Table 1 and the results also show reasonably good agreement.

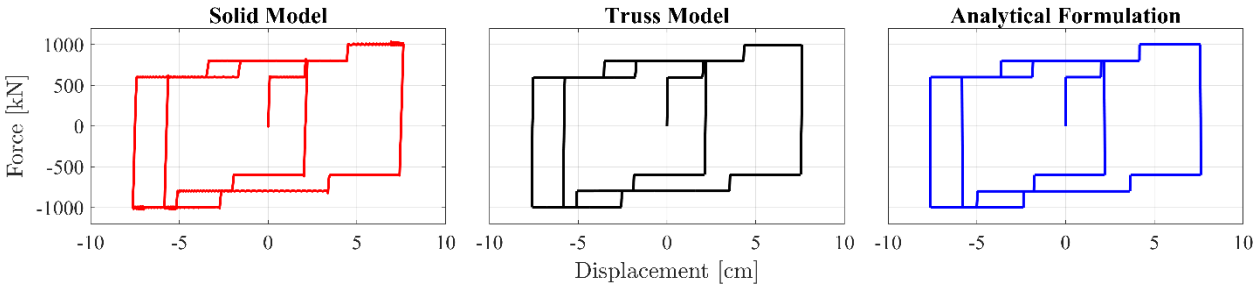


Figure 6 Comparison of force-displacement responses computed using the Solid Model, the Truss Model, and the Analytical Formulation

Table 1 Comparison of computed cumulative dissipated energy from three models

	Solid Model	Truss Model	Analytical Formulation
Cumulative dissipated energy [kN-m]	61.5	62.1	62.2

3 Experimental Testing Related to Modified FD

3.1 Composite Friction Material Testing

As mentioned in Section 2.1, the friction shims used in the Modified FD are expected to be made of non-metallic composite materials. Those materials are typically developed for heavy industrial or automotive applications and not typically for structural applications. Therefore, to use composite friction materials in the Modified FD, the material properties should be characterized considering loading conditions in earthquake structural engineering applications. The characterization of mechanical and tribological properties for composite friction materials for the Modified FD has been conducted in Chen et al. (2025). In Chen et al. (2025), six types of phenolic-resin-based fiber-reinforced composite materials were characterized following a systematic experimental testing program, including the coupon tensile test, the plate bearing test, the bolt relaxation test, and the friction test. The workflow for the composite friction material characterization study in Chen et al. (2025) is shown in Figure 7. Based on the experimental testing results, Chen et al. (2025) revealed that the flash compression molding process in the manufacturing of composite friction materials could produce materials have a lower concentration of phenolic resin than design. Those materials were more prone to delamination and exhibited exacerbated through-thickness creep behavior, which could in turn result in increased bolt load loss in long-term operation. Through the friction test, Chen et al. (2025) also

revealed the relationship between the velocity-dependent frictional behavior and the material constituents of the composite friction materials. Chen et al. (2025) suggested that the friction interface with the composite friction material Gatke 398 (containing glass reinforcing fibers, phenolic resin binder, and graphite, Teflon and molybdenum disulfide MoS_2 lubricants) in contact with low-carbon structural steel appeared to exhibit the most stable frictional behavior. Hence, the Gatke 398 to low-carbon structural steel friction interface was considered suitable for use in the Modified FD.

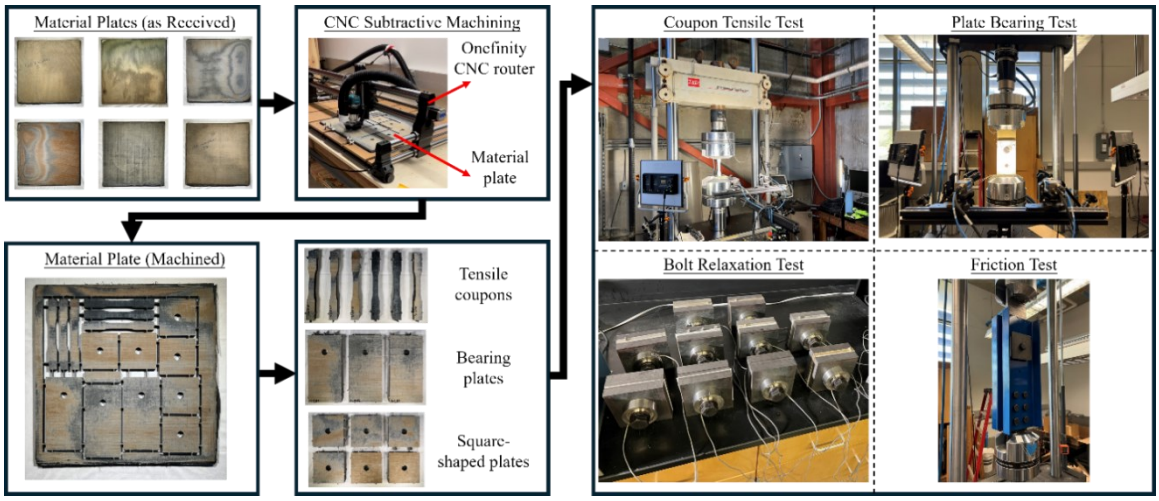


Figure 7 Workflow for composite friction material characterization in Chen et al. (2025)

3.2 Test Plan for the Modified FD

A reduced-scale Modified FD was designed to be tested for proof-of-concept purposes. The scale of this Modified FD is considered "reduced" because the force and displacement capacities of this Modified FD is smaller than the expected force and displacement capacities of Modified FDs working as floor-to-wall force-limiting connections in earthquake-resistant buildings. Figure 8 (a) shows the schematic assembly of the reduced-scale Modified FD. As the testing is to be completed using a universal testing machine (UTM), the end connection of the Modified FD was modified to adapt to the grips of the testing machine. Stacked end connection plates are used. The baseline design parameters of this Modified FD are: F_1 = 107 kN (provided by six ASTM A325 bolts of 12.7mm (0.5 inch) diameter and assuming a coefficient of friction equal to 0.5); $F_2 = F_3$ = 36 kN (each provided by two ASTM A325 bolts of 12.7mm (0.5 inch) diameter); D_1 = 12.7 mm; D_2 = 25.4 mm. Figure 8 (b) shows the components of the Modified FD to be tested, excluding the friction shims. The experimental program involves seven test phases. Test Phase 0 is to establish the break-in effect of the friction interfaces in the Modified FD, following the parameters suggested by Chen et al. (2025). Test Phase 1 aims to assess the response of the Modified FD when the bearing plates are not in contact with the external plates, i.e., when the maximum connection force resistance is F_1. Test Phase 2 aims to assess the response of the Modified FD when the bearing plates associated with D_1 are in contact with the external plates, i.e., when the maximum connection force resistance is $F_1 + F_2$. Test Phase 3 aims to assess the response of the Modified FD when the bearing plates associated with both D_1 and D_2 are in contact with the external plates,

i.e., when the maximum connection force resistance is $F_1 + F_2 + F_3$. In Test Phases 1~3, sinusoidal waves will be used as the imposed displacement time history of the input excitation. In Test Phase 4, the Modified FD will be subjected to an earthquake-type input excitation, by using the representative response of a friction-based structural connection from numerical earthquake simulations as the imposed displacement time history. Test Phases 5 and 6 aim to assess the adjustability of the design parameters of the Modified FD. In Test Phase 5, longer bearing plates as shown in Figure 8 (c) will be used. By using longer bearing plates, either D_1 or D_2 can be adjusted to be smaller and thus this design phase can prove the adjustability of D_1 and D_2. In Test Phase 6, the pretension level of the bolts that provide normal load acting on the friction interface will be adjusted to prove the adjustability of F_1, F_2, and F_3. Through-hole bolt load cells, as shown in Figure 8 (a), will be used for precise applying and monitoring of the bolt load. The experimental testing is to be completed in the upcoming months. It should be noted that this test aims to examine experimentally the force-displacement response and kinematics between the components of the Modified FD. The investigation of the frictional behavior at the friction interface is beyond the scope of this test. A separate study has been conducted to investigate the friction interface behavior and the results can be found in Chen et al. (2025).

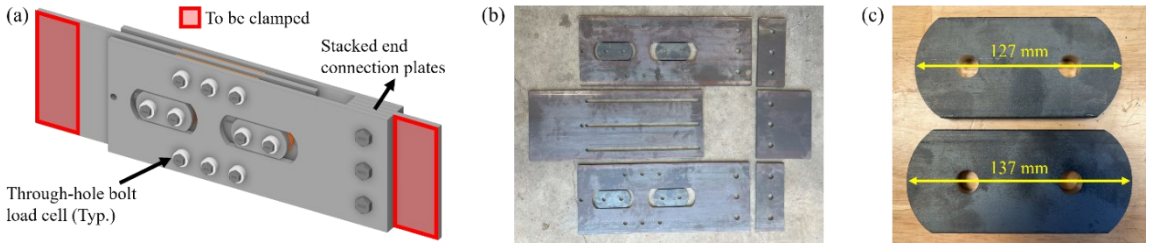


Figure 8 (a) Schematic assembly of the reduced-scale Modified FD; regions shaded in red showing the parts to be clamped by UTM grips (b) Components of the reduced-scale Modified FD (excluding friction shims) (c) Comparison of short and long bearing plates

4

Conclusions

This paper presents the development of Modified Friction Device (Modified FD), a novel yet practical structural connection capable of developing predetermined discrete variable friction forces at target design displacement levels. The design, kinematics, force-displacement responses, and modeling approaches of the Modified FD were presented. The analytical formulation of the force-displacement response of the Modified FD in a numeric computing environment was explained in detail. Composite friction materials were experimentally characterized, and Gatke 398 (composite friction material containing glass reinforcing fibers, phenolic resin binder, and graphite, Teflon and molybdenum disulfide MoS_2 lubricants) was identified as a suitable material for use in the Modified FD for its stable frictional behavior. A reduced-scale prototype of the Modified FD was developed, and a multi-phase experimental testing program was established to validate the force-displacement response of the Modified FD and the adjustability of its design parameters.

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