The Asymmetric Friction Connection Sliding Behaviour

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ABSTRACT

The Sliding Hinge Joint (SHJ) is a low-damage beam-column connection employed in steel moment-resisting frames. It facilitates large beam-column rotations with minimal damage by allowing sliding to occur within the asymmetric friction connections (AFCs) positioned at the web bottom bolt and bottom flange levels. The AFC serves as the primary friction-sliding seismic energy-dissipating component of the SHJ.

Extensive experimental and analytical research programmes on the AFCs have led to proposed modifications aimed at improving their performance, particularly by mitigating the loss of strength and stiffness following seismic events. A notable advancement includes the integration of partially deflected Belleville Springs (BeS), which have been specifically designed and manufactured for this purpose, along with installing the AFC bolts in the elastic range.

This paper explains the sliding behavior of the Asymmetric Friction Connection (AFC), offering a deeper insight into its structural performance.

1 INTRODUCTION

1.1 Background

In the event of a major earthquake, the building experiences a substantial amount of energy imposed on it due to its dynamic response to the ground excitation. The way this energy is dissipated within the structure plays a pivotal role in determining the extent of structural damage incurred. While it is generally impractical to design structures that are completely damage-resistant against all conceivable earthquakes, it is feasible to enhance traditional design and construction methods with the aim of reducing the likelihood and severity of structural and non-structural damage during major earthquakes and to elevate the structural damage threshold as much as possible[1].

Recognizing the high cost of designing and constructing structures to remain in the elastic range of structural materials under severe earthquakes, building codes acknowledge the need for an approach to allow controlled damage to occur in severe events, e.g. through ductile design. Moreover, stiffer structures, designed to remain elastic, with lower natural period, are likely to respond to specific ground excitations with high floor accelerations, leading to increased non-structural and contents damage. Current building codes emphasize the paramount importance of satisfying the life safety mandate. However, this implies that in events more severe than the design level, structural damage is anticipated in even well-designed and detailed buildings, necessitating repairs or, in some cases, demolition. This scenario imposes substantial costs and disruptions on affected communities and carries a significant environmental burden. To address this critical issue, there has been ongoing development in low-damage design and construction methodologies[1, 2].

1.2 The low-damage design philosophy

In the seismic design of structures, the ductile design concept allows structural designers to undertake a cost-effective design by incorporating post-elastic capacity of the structure. This means the energy is allowed to be dissipated through inelastic deformations of the structural members. However, this is associated with permanent damage. The repair of the damage may be significantly costly and/or not practical [1]. To avoid these undesirable economic effects of earthquakes, following recent several damaging events, the global tendency has been moving towards the development and implementation of low damage seismic resisting systems.

Two of the initial key motivations for the low damage design philosophy developments were the similar experiences in the 1994 Northridge [3] and the 1995 Kobe [4] earthquakes, in which significant unexpected damage to the welded connections of multi-story, moment-resisting steel-framed buildings were observed [5].

The low damage design philosophy aims, in addition to satisfying the well-accepted "life safety" mandate, to minimize the economic losses due to post-earthquake damage repair as well as downtime. The importance of this has again been illustrated in further major earthquakes such as the 2010/2011 Canterbury earthquake series, the 2010 Maule earthquake, and the 2016 Kaikoura earthquake [6]. These recent earthquakes have clearly demonstrated that conventional construction, even in technologically advanced countries with well-designed and detailed structures, is not immune to significant earthquake damage [2, 6].

1.3 The sliding Hinge Joint

An example of a low-damage system developed for seismic moment-resisting steel frames (MRSFs), one of the most commonly used lateral force resisting systems, is the Sliding Hinge Joint connection (SHJ) with Asymmetric Friction Connections (AFCs), as shown in Figure 1. The AFCs are energy dissipating components of the SHJ.

The SHJ, proposed by Clifton [7] and shown in figure 1, adopted the concept of pinning the beam to the column at the top flange, utilizing the AFC at the bottom flange and bottom web level.

The SHJ (with AFCs) has been used in New Zealand multi-story steel framed buildings. Being subjected to an event larger than the ULS event, the SHJ may undergo large beam-column relative rotation through sliding in two AFCs which are located at the beam web bottom bolt and bottom flange levels, as shown in Fig. 1. No lateral movement occurs between the beam and column at top flange level through an axially stiff, rotationally flexible detail. For the events smaller than the ULS, the SHJ is intended to remain rigid. At the end of an earthquake which is larger than the ULS earthquake, the SHJ is ideally intended to come back to its as-built condition. This necessitates the SHJ to dynamically self-center and to retain its as built AFCs' sliding strength through retaining the AFCs' clamping force provided by the initially fully tensioned high strength friction grip (HSFG) bolts[8].

The clamping force of a bolt refers to the compressive force that a bolt exerts on the materials or components it is fastening. This force is generated when the bolt is tightened, causing the bolt to stretch (tensile force in the bolt) and the connected parts to be compressed together. The clamping force is critical in maintaining the integrity of bolted joints under various loading conditions.

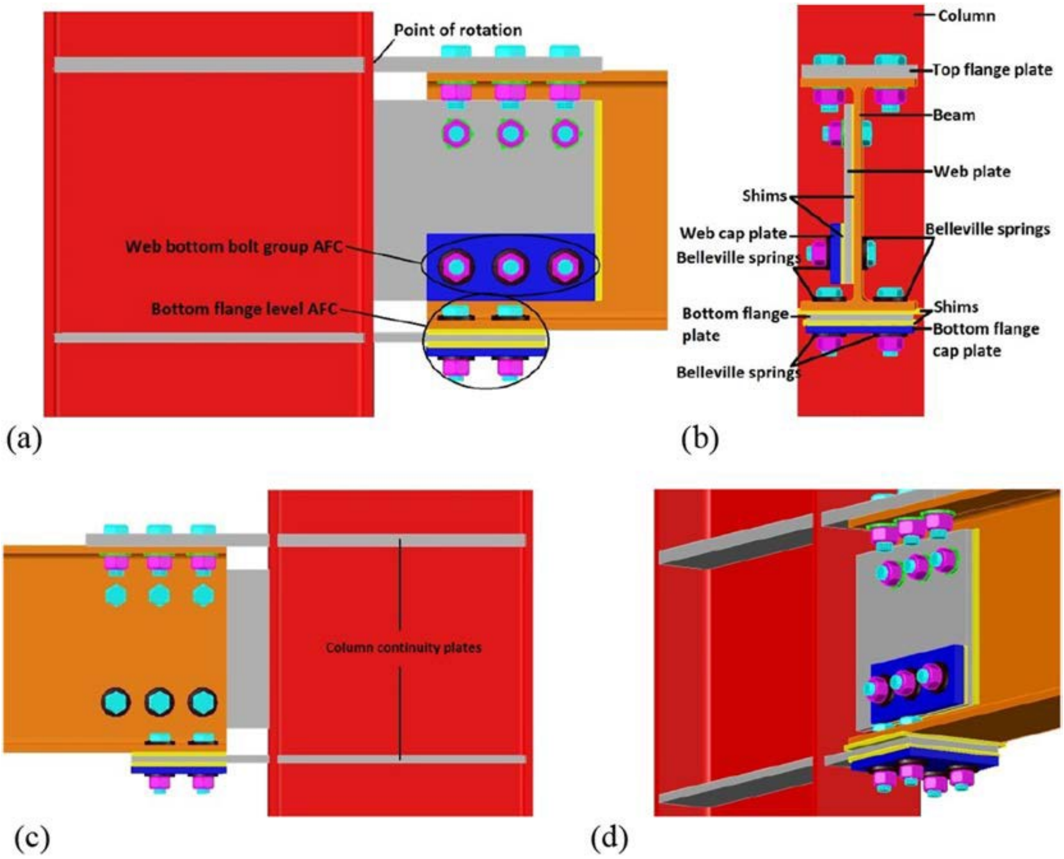

Figure 1: The sliding hinge joint (SHJ) views (a) front (b) beam cross-sectional, (c) back, and (d) 3D [2]

2 THE AFC BEHAVIOUR

This section discusses the behavior of the Asymmetric Friction Connection (AFC). Initially, it is essential to define certain terms to provide clarity and context.

The **installed bolt tension** refers to the initial preload applied to a bolt during installation to ensure a firm connection between components. This tension is critical for maintaining the integrity of the connection and ensuring that the connection can withstand applied loads without loosening or failure. The magnitude of installed bolt tension directly influences the connection's frictional resistance and ability to perform under cyclic or dynamic loading conditions.

The term **straight bolt** describes the condition where a bolt remains aligned along its longitudinal axis after installation. Such alignment ensures that the bolt experiences uniform stress distribution under load, minimizing the presence of stress concentrations, or bending.

Short and long term bolt tension loss refers to the reduction in bolt preload over time or after specific events, such as sliding or load cycles, in connections. This phenomenon is often due to relaxation, creep, or localized deformation at the contact surfaces. Understanding this loss is essential for designing connections that maintain adequate clamping force throughout their service life.

Double curvature describes a deformation pattern where a structural element bends in opposite directions along its length, forming an "S" shape. This behavior typically occurs in bolts under complex loading scenarios, such as combined bending and axial forces. Double curvature is a critical consideration in analyzing connection behaviour, as it influences stress distribution.

Stable sliding is the condition where a connection exhibits consistent and predictable sliding behavior under applied loads. It indicates that the frictional resistance between the connected surfaces remains uniform, without sudden changes or stick-slip behavior. Stable sliding is a desirable characteristic in connections like the Asymmetric Friction Connection (AFC), as it ensures reliable energy dissipation and performance under seismic or cyclic loading.

Pinched hysteretic behavior refers to a specific characteristic of the load-displacement or force-deformation response in cyclic loading, where the hysteresis loops exhibit a noticeable "pinching" effect. This phenomenon typically results in a reduction of energy required to bring a structural system to its original position, hence improving the self-centering tendency..

2.1 Sliding Mechanics and Hysteretic Behavior of the AFC

The AFC in the SHJ as shown in figure 2 (a), consists of five plies, including the beam bottom flange, bottom flange plate (cleat), cap plate, and two shims at both sides of the cleat, all clamped by the pre-tensioned high strength friction grip (HSFG) structural bolts. The AFC has two main sliding surfaces on both sides of the cleat. The force-displacement behaviour of the AFC is shown in Figs. 2(b). Concerning Fig. 2 (b), when the applied force overcomes the frictional resistance of the first sliding surface, i.e. the cleat and the upper shim interface, this surface starts to slide (i.e. cleat moves relative to the beam bottom flange), while the cap plate remains fixed relative to the cleat and moves relative to the beam bottom flange (shown as B).

After a short time or distance of movement along the first sliding surface, the cap plate starts to become fixed in position relative to the beam bottom flange. From this point onwards for that direction of displacement, the cleat slides between two sliding surfaces (i.e. upper and lower shims), which almost doubles the sliding shear resistance (called the stable sliding shear resistance) developed by the AFC (shown as C). At this stage, the bolts are pushed into the double curvature state. Following load removal and then load reversal, the sliding occurs on the first interface (shown as D) followed by the second interface (shown as E) pushing the bolts again into double curvature in the opposite direction. This provides the AFC with a "pinched" hysteretic behaviour, requiring less work to be done (or energy to be spent) to recover all of the travelled displacement.

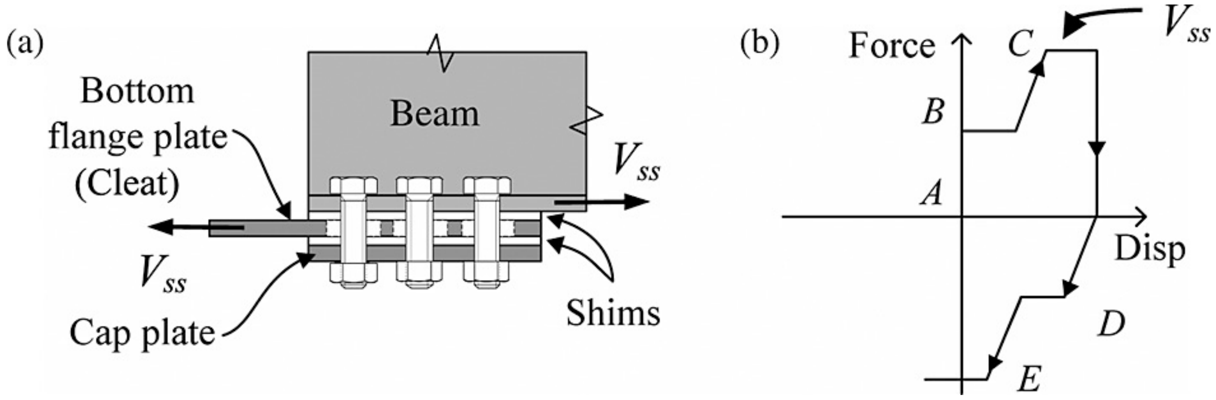

Figure 2: (a) The AFC at the bottom flange level and (b) AFC idealized force-displacement behaviour[9]

The AFC is subject to a post-sliding clamping force reduction because of the following reasons:

1. The MVP interaction in the bolt body during stable sliding state [10, 11] may yield the bolt material causing the post-sliding bolt tension to drop. It is worth noting that the bolts are currently tensioned into the post-yield condition at installation in practice making this reduction inevitable.

2. Wearing of the sliding surfaces will reduce the total thickness of the AFC plies per bolt, resulting in bolt tension reduction.

3. AFC bolts may rub against the sides of the cleat elongated holes, reducing their integrity and causing a drop in bolt tension.

4. Vibration-induced self-loosening, joint creep, and bolt relaxation are among the common bolt tension loss reasons that may be considered for any bolted connection amongst which the AFC may not be an exception.

2.2 Analysis of Wear-Induced Behavior and Bolt Tension Loss in AFC

The objective is to analyze the behavior of the Asymmetric Friction Connection (AFC) following various forms of wear, including galling and settling effects. The "settling," refers to, in this document, the initial adjustments among all components as the AFC begins to slide. This sliding causes a realignment of the components, which can lead to phenomena such as bolt tension loss. Given the bolt's critical role in the connection, the analysis begins by focusing on its behavior. Bolt tension is a key factor in evaluating friction-sliding connection performance, so interpreting the variations in bolt tension as a foundational aspect of the study is presented.

The tension in a bolt decreases over time due to various factors such as material deformation, relaxation, and external influences like temperature changes or dynamic loading. This phenomenon is known as bolt tension loss and typically occurs in two phases:

In the Absence of Sliding:

Initial Phase of Tension Loss: This phase occurs immediately after the bolt is tightened and is primarily due to the settling of the bolt threads and the clamped surfaces. Contributing factors include the flattening of surface roughness, thread deformation, and slight shifts in the clamped components. Tension loss in this phase is typically rapid.

Second Phase of Tension Loss: Following the initial phase, the rate of tension loss decreases, reflecting the long-term behavior of the bolt under static or dynamic conditions. This phase is influenced by factors such as material creep (gradual deformation under stress), environmental effects, and sustained external loading.

During Sliding:

Sliding occurs within a short duration, typically a few seconds or minutes, and significantly impacts bolt tension.

Immediate Bolt Tension Drop: At the onset of sliding, a sudden and sharp reduction in bolt tension occurs due to the rapid redistribution of forces within the joint.

Gradual Tension Loss Due to Galling: As sliding progresses, galling (adhesive wear between contacting surfaces) leads to a continuous yet slower reduction in bolt tension.

Tension Variations Due to Direction Changes: Changes in sliding direction cause fluctuations in bolt tension, influencing the overall stability of the connection.

Stable Sliding Bolt Tension: Once a steady sliding condition is established, the bolt tension reaches a relatively stable level, depending on factors such as friction, surface interactions, and material properties.

To better understand how these long-term factors affect the performance of the bolt and its connection, it is important to isolate and focus specifically on the second phase of tension loss. By doing so, we can analyze the bolt's behavior independent of the rapid changes that occur in the initial phase. This allows us to evaluate the bolt's intrinsic properties, such as its material response to sustained loads, the effectiveness of the clamping force, and its ability to maintain a secure joint over time.

By concentrating on the second phase, the parameters that play a critical role in long-term joint performance—such as material characteristics, joint design, and the effects of external influences—can be identified and quantified. This approach ensures that the findings are not overshadowed by the transient effects of the initial phase and provides a clearer understanding of the bolt's behavior under realistic, long-term conditions.

To simplify the behavior analysis, we define two primary sections. The first one occurs when the cleat has been changing direction. Displacement is applied to the cleat's edge, resulting in a cyclic motion where the cleat travels back and forth (moving in both the negative and positive directions) over multiple cycles.

The following images, derived from finite element models, depict the asymmetric friction connection (AFC) in a configuration that is the inverse of the mode shown in Figure 2a. The distribution of stress is illustrated in these figures. As observed in Figures 3-5, as the loading direction changes, the stress in the bolts increases when they come into contact with the plates. Just before the change in direction occurs, a loss of bolt tension is observed. The tension loss is notably greater during compression (when the cleat and the beam bottom flange move towards each other) due to the higher degree of distortion that occurs compared to tension (from the positive to the negative direction).

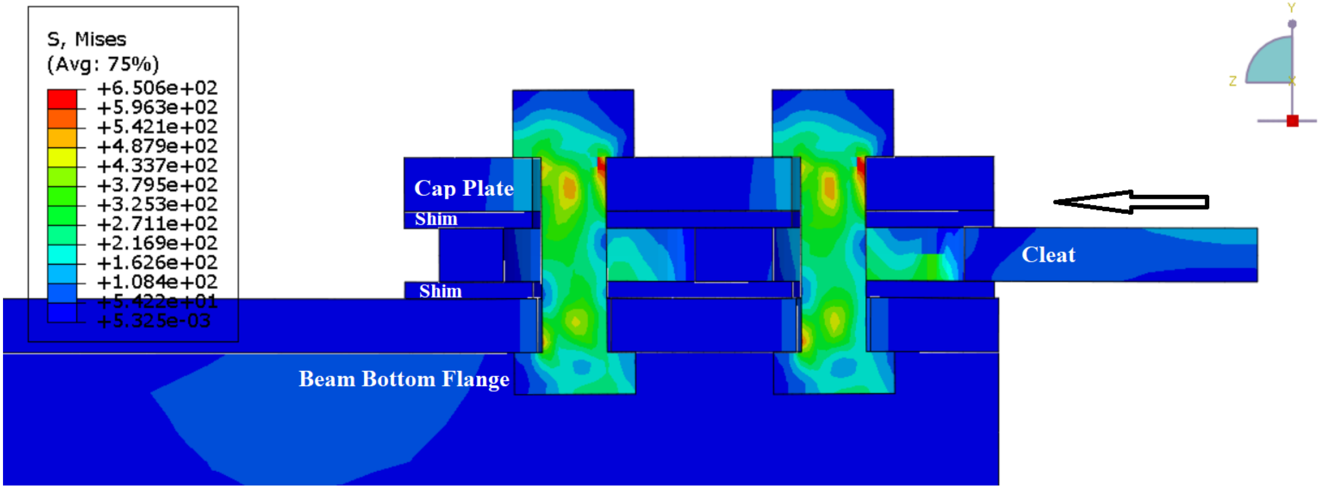

Figure 3: Compression Beginning (the cleat and the beam bottom flange move towards each other)

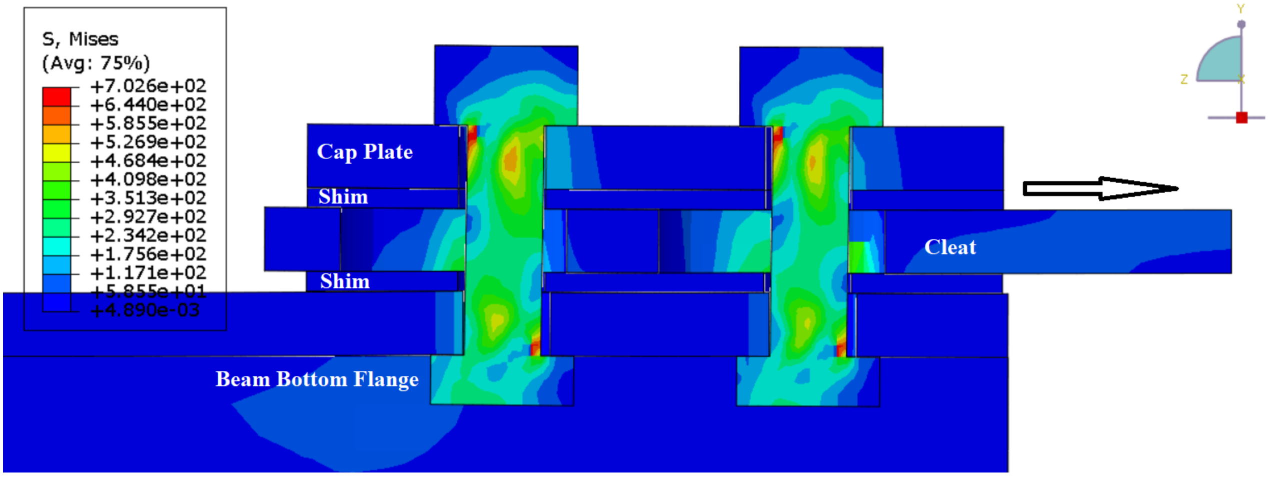

Figure 4: Tension Beginning (the cleat and the beam bottom flange move against each other)

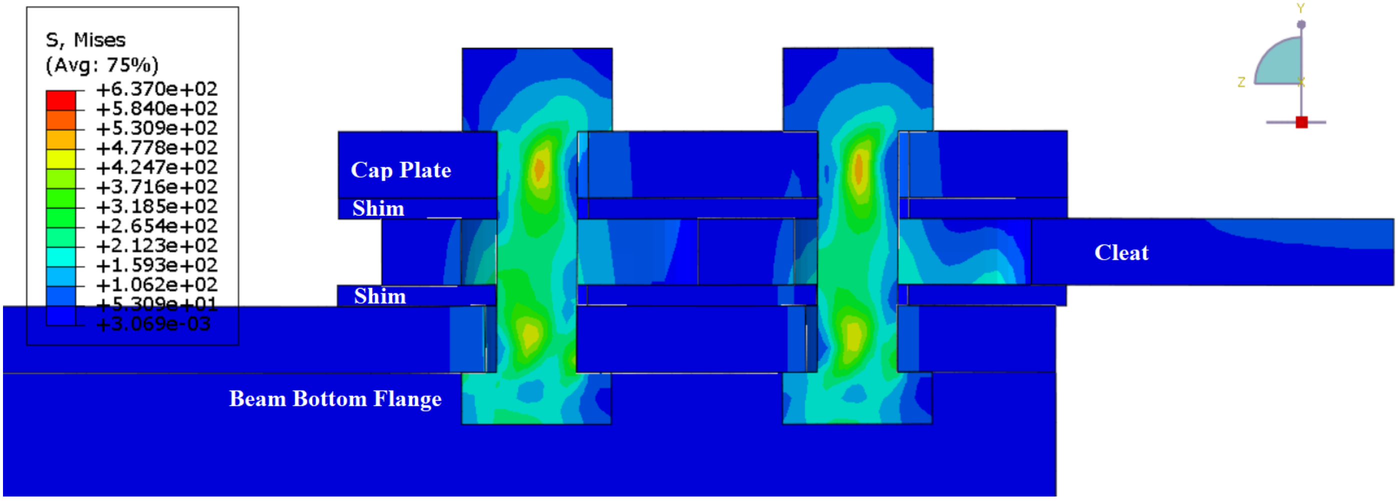

Figure 5: Straight Position of bolts

As part of illustrating the overall behavior and complementing the VM stress distribution images, the hysteresis loop is also presented in Figure 6[6, 12].

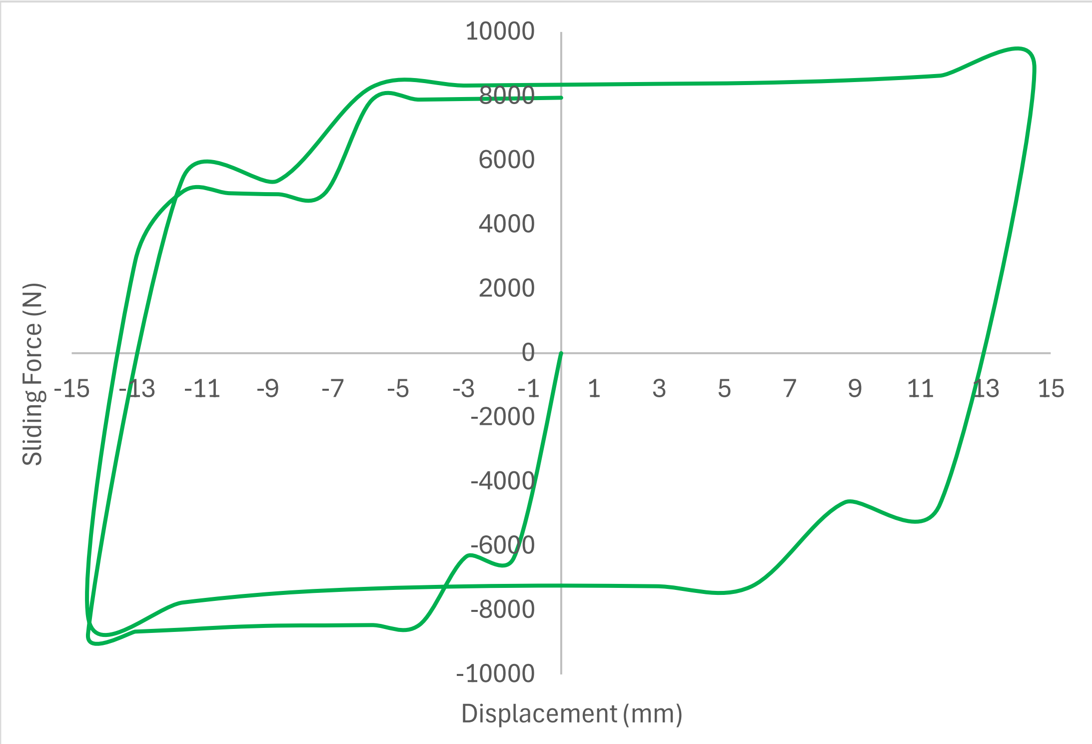

Figure 6: Forces vs displacements applied on the end of the cleat (i.e. hysteresis loop).

3 CONCLUSION

This paper explained the sliding behaviour of the AFC along with the reasons that the AFC without partially deflected Belleville Springs is subjected to a post-sliding elastic strength reduction due to bolt tension loss. This is because:

- I. When the AFC starts to slide, the bending moment induced tensile stress, the additional tensile stress in the bolt, and the shear stress combine with the high bolt installed tensile stress to further plasticize the bolt. As the fully tensioned bolt is expected to be yielded at installation, it undergoes further local plastic action under a small increase particularly in tensile stress over the part of its cross section, where the bending induced stress is tensile. In addition to the connections geometry, the coefficient of friction as well as the clamping force are the influential parameters on this MVP interaction according to the plastic theory based AFC bolt model [7].
- II. Due to the clamping force generated by the AFC bolts, localized bearing stresses can reduce the total thickness of the AFC plates and shims per bolt during the time of sliding and even over the time without sliding.
- III. AFC bolts can potentially rub against sides of the slotted holes resulting in a shear force imposed on the bolts and reducing their integrity. This may potentially occur, for example, for the SHJ's AFC at beam web bottom bolt level or for the AFCs with long slotted holes and potential long sliding travels not perfectly aligned with the slotted holes.
- IV. Similar to any other type of bolted connection, AFC bolts may be susceptible to the tension loss due to the factors such as short term and long term bolt relaxations, joint creep, and vibration induced bolt self-loosening.

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