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DESIGN AND PHYSICAL TESTING OF BIAXIAL MINIMAL-DISTURBANCE ARM DAMPER FOR SEISMIC REHABILITAION

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Abstract

The hollow structural section (HSS) columns are commonly used to sustain the seismic loading from any direction in Japanese steel frames due to its uniform geometry along each principle axis of cross section. However, during the earthquake, the bottom flanges of beam ends are usually the vulnerable parts. Thus, to retrofit the all beam ends of beam-column connection is more practical. This paper introduces a seismic rehabilitation technique, named MDAD (Minimal-disturbance Arm Damper), which is a tension-only bracing system to improve the seismic performance of steel moment resisting frame by restraining the local deformation at the bottom flange of beam ends and utilizing the reserve capacity of frame. It not only aims at minimizing the obstruction of the visual and physical space for building users but is expected to provide a stable hysteretic behavior to the steel frames under the seismic loading. In this study, the MDAD is developed to be biaxial configuration which can accommodate the bidirectional loading. With this new configuration, the design equations were developed. Furthermore, under bidirectional loading, the MDAD will experience the in-plane and out-of-plane deformation. To verify the performance of MDAD, the quasi-static testes under both unidirectional and bidirectional loading are constructed.

Keywords: Steel moment-resisting frame; Seismic rehabilitation; Minimal disturbance; Bidirectional loading; Out-of-plane stability

1. Introduction

Historically, earthquake-induced building collapses have caused enormous societal losses, such as the casualties and property damage after the Northridge earthquake in US 1994 [1] and Kobe earthquake in Japan 1995 [2]. Presently, there are still a large number of existing buildings in earthquake-prone regions that suffer seismic risk since they do not satisfy the proper performance level of the current seismic code. In order to improve the seismic performance of existing buildings, seismic rehabilitation (or seismic retrofitting) started in the U.S. [3] and expanded to the other parts of the world due to its effectiveness. For existing steel moment-resisting frames, seismic retrofit has typically aimed to minimize seismic vulnerability by adding strength and stiffness, thus requires significant modification to the lateral resistance systems. Such efforts not only interrupt to building usage but are also inefficient in some cases as they do not fully utilize the residual capacity of lateral resistance system. In particular, for the composite steel-concrete beams, the bottom flanges of the beam ends are vulnerable to fracture and limit the deformation capacity of the frame [4-6] while beams or columns may have a reserved seismic capacity.

To solve the problems mentioned above, an existing research work, a tension-only rehabilitation technique within the design scheme of minimal disturbance, named MDAD (minimal disturbance arm damper), has recently been proposed to restrain the local deformation at the bottom flange of beam ends [7]. The MDAD is a light-weight bracing system, which can save the space of steel building and avoid the use of heavy construction equipment and welding during rehabilitation. Moreover, in the study of numerical analysis, MDADs successfully improved the seismic performance of steel frame and utilized the reserve capacity of the beams or columns.by redistributing the seismic resisting force in the beams and columns.

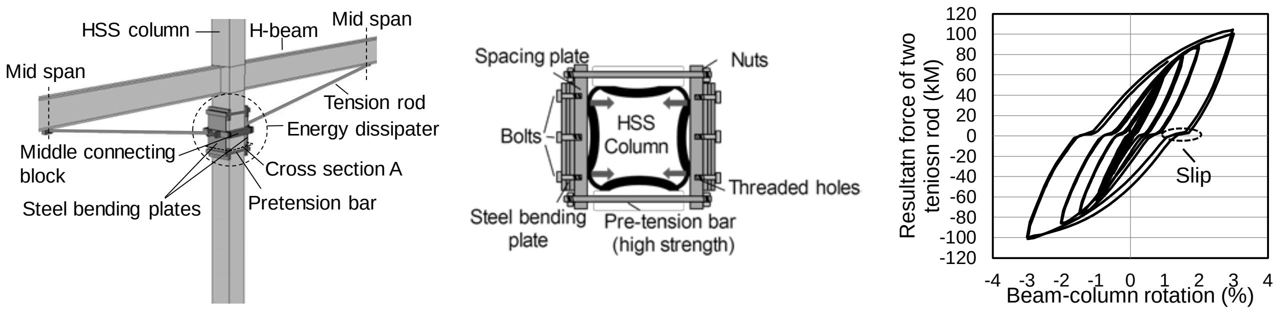
However, the original configuration of MDAD was applied to protect the beam-column connection only in one direction and did not consider the effects of the two directional loading on the behavior. In Japan, the hollow structural section (HSS) columns are commonly used to sustain the bidirectional loading. Since the four beams are connected to the HSS column as a beam-column connection, it is necessary to restrain the local deformation at the bottom flange of all beam ends under bidirectional loading. Thus, a new configuration of MDAD is proposed to accommodate the bidirectional requirement. Furthermore, under the bidirectional loading, the instability under compression was often aggravated by out-of-plane deformation within retrofitting techniques and particularly in seismic bracing systems [8]. The influence of out-of-plane deformation on performance of advanced MDAD should be taken into consideration carefully.

This paper presents the continuous efforts on the development of the MDAD. First, the concept and mechanism of MDAD are reviewed. Then, a new configuration is introduced to protect the beam-column connection in two directions. Second, the details of attachment are improved to effectively attach the MDAD on the column. Then, the design equations for stiffness and strength of MDAD are developed. Finally, the new configuration with the modified attachment was examined through two quasi-static tests of half-scaled specimens. Through the comparisons of results in unidirectional loading test and bidirectional loading test, the seismic performance of the MDAD with new configuration is discussed.

2. Mechanism and Development of Minimal-Disturbance Arm Damper

2.1 Original configuration of MDAD

Figures 1(a) and (b) show the original configuration of MDAD designed for uniaxial rehabilitation of beam-column connections. MDAD consists of two tension rods and an energy dissipater shown in Figure 1(a). The tension rods connect the mid-span of beam and the each side of the energy dissipater located at the three quarter of story height. The two steel bending plates, middle connecting blacks and other minor parts comprise the energy dissipater and this energy dissipater is attached to the two facing surfaces of the column using pretension bars. The middle connecting blocks are to maintain the reciprocating deformation of two steel bending plates under the cyclic loading and guarantee a stable hysteretic behavior. Figures 1(b) shows the detailed plate-column attachment at cross section A. Due to uneven surface of cold-formed HSS column, there are only few touch points between the spacing plates and the column. The two steel bending plates and the spacing plates are attached on the column by tightening a pair of pretension-bars to generate a large friction between spacing plates and column. Although a large pretension force of 35 kN was applied in the pretension-bars, the hysteretic behavior of MDAD under cyclic loading still exhibited a slip behavior caused by the slippage of the energy dissipater against the column surface [see Figure 1(c)]. Thus, an improved plate-column attachment is desired.

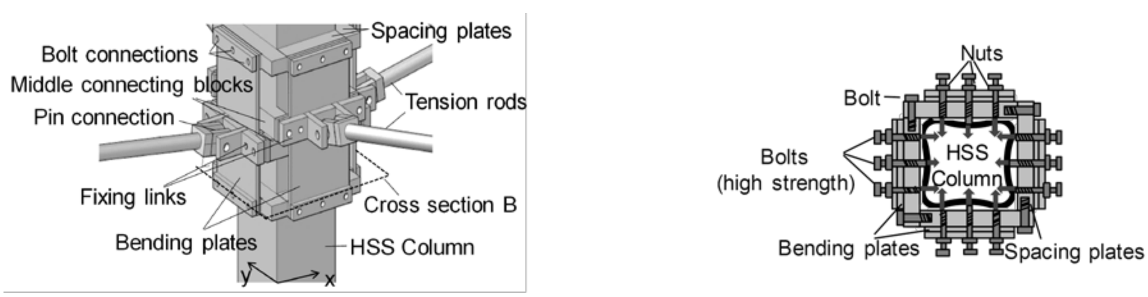


(a) (b) (c)

Fig. 1 – Minimal disturbance arm damper: (a) rehabilitated beam-column connection; (b) plate-column attachment at cross section A; (c) hysteretic behavior of MDAD [7].

2.2 Development of MDAD for bidirectional loading

To protect the beam-column connection against seismic loading in any direction, the new configuration of MDAD was introduced as shown in Figure 2. In Figure 2(a), the energy dissipater of the modified MDAD is comprised of four steel bending plates and four tension rods. Each tension rod connects a steel bending plate and the mid span of beam by pin connections. For the *x* or *y* direction, a pair of steel bending plates is connected by a pair of middle connecting blocks. As a result, under the seismic loading, the two tension rods of each direction can alternatively pull the pair of steel bending plates. Additionally, in order to avoid the collision of middle connecting blocks arranged in two directions, the location of connections between middle connecting block and tension are adjusted, lower in the *x* direction and higher in the *y* direction. To improve the performance of MDAD and eliminate the slip behavior in the hysteretic behavior, the energy dissipater is attached on the column by bolts instead of the pretension bars. Figure 2(b) displays the detailed design of modified plate-column attachment at the cross section B. The four spacing plates are connected by bolts and form a rigid rectangular frame. The bending plates are connected to the spacing plate through high-strength bolts at each side of column and they are fixed on the column by applying the axial compression to each bolt. In this configuration, the surface unevenness of the column is accommodated by the bolt connection. Thus, the new configuration of MDAD not only inherits the merits of the original configuration but also implement the extension for bidirectional loading.

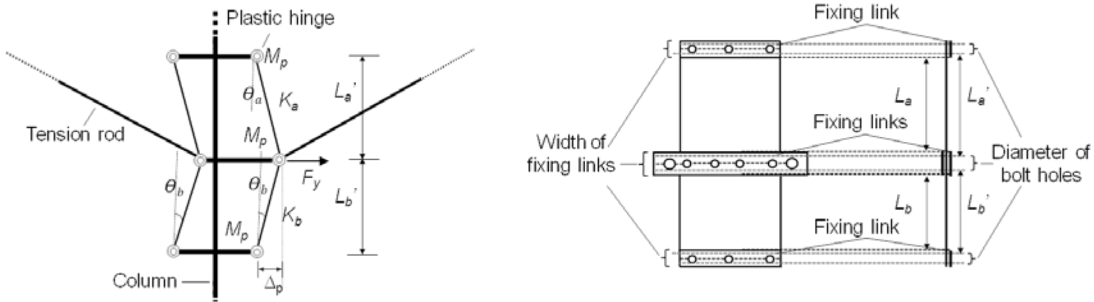


(a) (b)

Fig. 2 – Biaxial minimal disturbance arm damper: (a) modified configuration of energy dissipater; (b) modified plate-column attachment at cross section B.

2.3 Design equations of biaxial MDAD

Considering the variation of configuration of MDAD, the new design equations are developed. Figure 3(a) describes the idealized model of energy dissipating system in MDAD. As same as the force-resisting mechanism in the original MDAD, it is assumed that the plastic deformation of steel bending plates concentrate on the top, middle and bottom part when the MDAD reaches its maximum strength.



(a) (b)

Fig. 3 – Moment distribution of beam and column with MDAD: (a) idealized model of energy dissipating system; (b) effective length of steel bending plate.

Based on the plastic moment at the cross section of bending plates (M_p, as shown in Figure 3(a)), the strength F_y of MDAD is computed by the following equation:

$$F_{yMDAD} = b^p \left(t^p\right)^2 \sigma_y^p \times \left(\frac{1}{L_a'} + \frac{1}{L_b'}\right) \tag{1}$$

b^p, t^p and σ_y^p are the width of the plates, thickness of the plates and yielding stress of the plates; L_a' and L_b' are the effective length which consider the flexibility of the boundaries for the two parts of the bending plates [see Figure 3(b)]. Accordingly, the suggested effective length is made up of: the actual length plus the 0.5 times fixing links minus the 0.5 times the diameter of the bolt holes. The ultimate strength of the MDAD Q_u is approximately $1.5F_y$.

As the MDAD consists of steel bending plate and tension rod, its initial stiffness is expressed by

$$k_{MDAD} = \frac{k_p k_t}{k_p + k_t} \tag{2}$$

Where $k_p = 2Eb^p (t^p)^3 \times \left(\frac{1}{(L_a')^3} + \frac{1}{(L_b')^3}\right)$ and $k_t = \frac{EA^t}{l^t}$. A^t and l^t are the sectional area and length of tension rods, respectively. E is the elastic modulus of steel.

3. Test Plan

3.1 Test setup

The performance of a biaxial MDAD was examined through the quasi-static tests under unidirectional and bidirectional loading. In particular, the influence of out-of-plane deformation on in-plane behavior was carefully investigated. Figure 4(a) shows the component-level test setup, which consists of a rigid frame, an elastic center column with a biaxial MDAD and two orthogonal jacks, was constructed on the shaking table at DPRI, Kyoto University. The rigid frame includes four H-300×300×10×15 exterior columns and a cruciform beam of H-300×200×8×12. As shown in Figure 4(a), in the *x* direction, the frame has the long span and the *y* direction is defined as the out-of-plane direction relative to the *x* direction; on the contrary, the *x* direction is the out-of-plane direction for the frame with very short span. The overall dimensions of the rigid frame were approximately 5,000 mm × 3,000 mm × 2,500 mm (in the *x*, *y*, and *z* directions). Two cases of frame are formed to study the effect of out-of-plane deformation on MDAD.

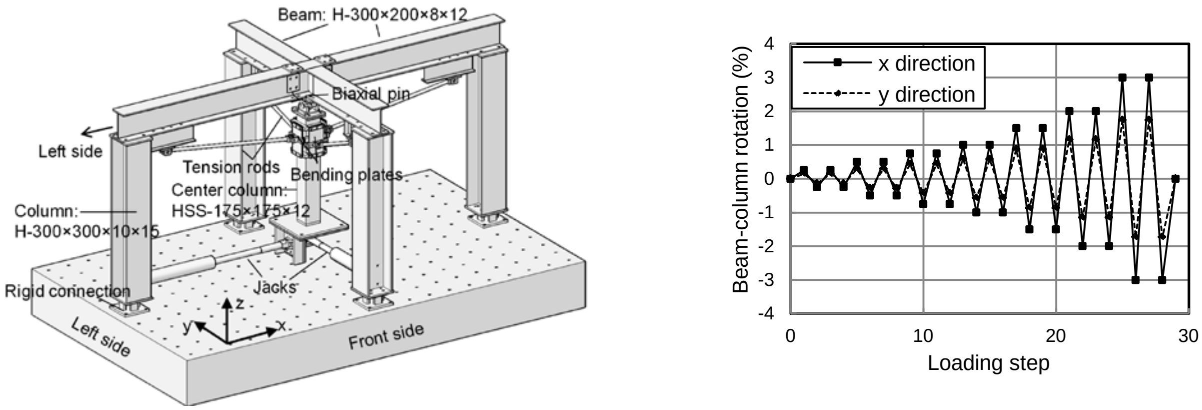
The MDAD was originally designed for retrofitting a steel moment-resisting frame with H-400×200×9×16 beams of 7,200 mm and HSS-350×350×19 columns of 3,600 mm. The design yielding strength of MDAD was tentatively set at around 10% of the column shear resistance. In the test, the MDAD were scaled down to a half size and the dimensions were selected as: 1) steel bending plates for all directions: 270 mm × 140 mm × 9 mm; and 2) tension rods: M30 × 1650 mm for the *x* direction, M32 × 700 mm for the *y* direction. To examine the performance of MDAD at the component level, a half-scaled HSS-175×175×12 column with MDAD is connected to the rigid frame by a biaxial pin. The MDAD was located at a distance of 400 mm away from the biaxial pin which is corresponding to the three-quarter of the story height. Two orthogonal jacks in the *x* and *y* directions are pin-connected to the column bottom of the rigid frame and apply the displacements at the bottom of center column.

The rigid frame has the long span in the *x* direction and the short span in the *y* direction. Accordingly, the tension rods are inclined with a small angle in the *x* direction, 0.16 rad, and with a large angle in the *y* direction, 0.37 rad. This is to examine the influence of the out-of-plane deformation on the in-plane behavior of the MDAD. The larger the angle of the tension rod, more out-of-plane deformation exhibits in the tension rods.

Table 1 shows the test list. Test 1 was to verify the in-plane behavior of MDAD with modified configuration. The effect of out-of-plane deformation on the in-plane behavior was examined in the Test 2.

Table 1 Test list of MDAD

Test	Loading condition	Loading direction		Loading type	Loading angle (degree)
		x	*y*		
1	quasi-static	o	-	cyclic loading	0
2	quasi-static	o	o	cyclic loading	30



(a) (b)

Fig. 4 – Quasi-static test: (a) test setup; (b) loading protocol.

3.2 Loading protocol

The loading protocol in the quasi-static test is plotted in Figure 4(b). The relative rotation between the beam and the column is defined as the beam-column rotation, which is used as measure of displacement control. In order to explore the effect of the out-of-plane deformation on the in-plane behaviors, the loading protocol of the *x* direction in bidirectional loading test was kept the same as that in the unidirectional loading test. In the *x* direction, the loading increased from 0.25% to 3.0% including two cycles for each amplitude. For the *y* direction, due to the small deformation capacity of the biaxial pin in the *y* direction, the loading was set as the 0.57 times of the loading in the *x* direction and this proportion maintained a loading angle of 30 degrees. Consequently, the maximum out-of-plane deformation of MDAD was 1.7% in terms of the beam-column rotation in long span frame and 3% in terms of the beam-column rotation in short span frame.

4. Test Results

4.1 Test 1: Results under the unidirectional loading

The basic behavior of biaxial MDAD was first tested under the unidirectional loading and the results of Test 1 are shown in Figure 5. Figure 5(a) illustrates the relationship between the resultant force of two tension rods and the beam-column rotation. The initial stiffness of MDAD was 65.8×10^2 kN/rad and the yielding strength was 44.1 kN. At the maximum beam-column rotation of 3%, the strength reached 63.9 kN. The calculated values of design equations were 69.3×10^2 kN/rad for initial stiffness, 44.1 kN for yielding strength and 66.2 kN for maximum strength. There was a small discrepancy less than 5% between the experimental values and the calculated values. Hence, the design equations provided the accurate and consistent results with the test results.

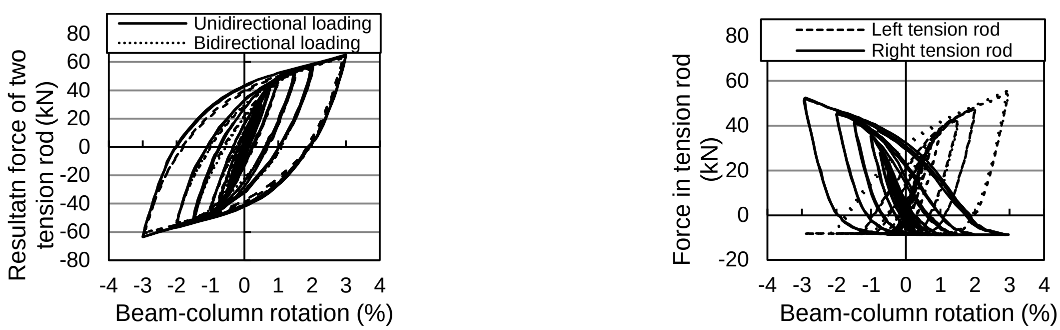
Compared with the results in Figure 1(c), Figure 5(a) shows stable hysteretic loops without slip behavior. In Figure 5(b), the vertical slippage of MDAD was plotted. With the original plate-column attachment, the slippage of MDAD became larger as the beam-column rotation increased. As a result, the tension rods in MDAD became slack and cannot provide the resisting force against beam-column opening effectively. The maximum slippage around 4.3 mm caused the obvious slip behavior in hysteretic loop [see Figure 1(c)]. In contrast, the slippage of MDAD with new plate-column attachment was almost zero until the maximum the beam-column rotation of 3%. This result proved that the modified plate-column attachment was effective to properly attach the energy dissipater of MDAD on the column.

(a) (b)

Fig. 5 – Test result under unidirectional loading: (a) force-deformation relationship; (b) slippage of MDAD.

4.2 Test 2: Results under the bidirectional loading

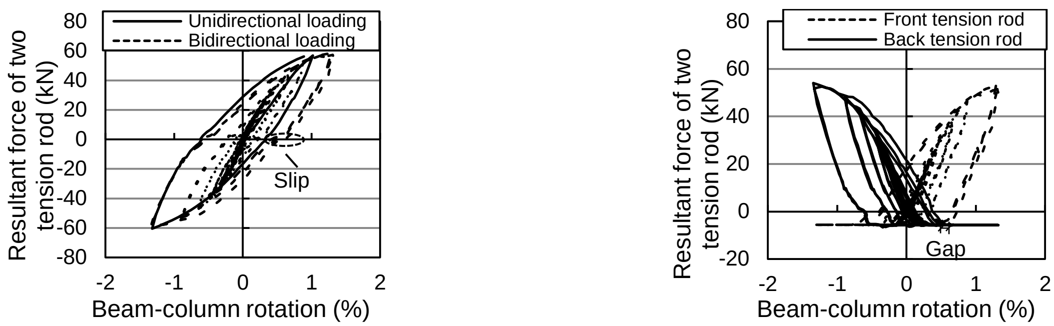
In Test 2, the loadings were applied in the both directions simultaneously. Figure 6 shows the test results of MDAD for the longer span frame. Under the bidirectional loading, the MDAD in the *x* direction not only resisted the in-plane deformation but also experienced the out-of-plane deformation. The comparison of hysteretic loops between the unidirectional loading test and the bidirectional loading test is described in Figure 6(a). The yielding strength of MDAD under the bidirectional loading was 45.4 kN at the beam-column rotation of 0.67% and the maximum strength was 62.7 kN at the beam-column rotation of 3.0%. There were the difference of 3.0% for initial stiffness and 2.0% for the maximum strength compared with the results under the unidirectional loading. Figure 6(b) plots the force history in tension rods. The two tension rods only sustained the tension force and resisted the deformation alternatively when the loading direction changed. The maximum force was 52.9 kN and much smaller than the yielding strength of the tension rods. As a result, the elastic tension rods without compression force contributed to a stable hysteretic behavior of MDAD. The test results demonstrated that the behaviors of MDAD in the *x* direction were independent of the deformation in the *y* direction and there was no effect of out-of-plane deformation on the in-plane behavior of MDAD in rehabilitating the frame with long span.



(a) (b)

Fig. 6 – Test result of MDAD in *x* direction: (b) comparison of hysteretic behaviors in unidirectional loading test and bidirectional loading test; (a) force of tension rod in the bidirectional loading test.

For the MDAD in the short span frame, the test results are shown in Figure 7. Figure 7(a) describes the hysteretic behaviors of MDAD in the *y* direction. Under the bidirectional loading, the initial stiffness of MDAD was 109.3×10^2 kN/rad and the yielding strength was 49.1 kN, which were consistent with the calculated stiffness of 113.4 kN/rad and the yielding strength of 50.8 kN from the design equations. When the in-plane deformation reached the beam-column rotation of 1.3%, the MDAD sustained the maximum out-of-plane deformation of 3.0% in terms of the beam-column rotation and a slip behavior became notable in the hysteresis loop. To verify the behavior of MDAD, one cycle of unidirectional loading was performed on MDAD and there was no slip behavior in the results. It suggested that the slip behavior of MDAD only occurred in the bidirectional loading test. In fact, the end of the tension rods close to the pin connection slid along the out-of-plane direction during the bidirectional loading and thus the tension rod became slightly slack. The force in the tension rods was shown in Figure 7(b), where the small gap suggested that tension rods became slightly slack when the tension rods alternatively resisted the deformation. However, there was no instability of tension rods and a stable behavior of MDAD was presented.



(a) (b)

Fig. 7 – Test result of MDAD in *y* direction: (a) comparison of hysteretic behaviors in unidirectional loading test and bidirectional loading test; (b) force of tension rod in the bidirectional loading test.

5. Conclusions

To sustain the seismic loading from any direction, the new configuration of MDAD was developed. Two main quasi-static experiments were executed to examine the performance of MDAD under bidirectional loading. The primary findings are as follows:

(1) The modified plate-column attachment was confirmed to provide sufficient friction by bolts and effectively prevented the slip of MDAD against the column in the unidirectional loading test.

(2) The design equations were developed for the stiffness and strength of MDAD and provided the consistent results with the test results.

(3) In the *x* direction of the bidirectional loading test, the MDAD in the long span frame exhibited a stable hysteretic behavior. The comparison of hysteretic behaviors in the unidirectional loading test and the bidirectional loading test indicated that there was nearly no effect of out-of-plane deformation on the in-plane behavior of MDAD designed for the long span frame.

(4) For the behavior of MDAD in the short span frame, the results of bidirectional loading test demonstrated that the sliding of the tension rods along the out-plane direction resulted in slightly slip behavior in hysteretic loops.

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