# Performance evaluation of a rocking steel column base equipped with asymmetrical resistance friction damper

Yu-Lin Chung<sup>\*1</sup>, Li-Jyun Du<sup>2</sup> and Huang-Hsing Pan<sup>2</sup>

<sup>1</sup>Department of Architecture, National Cheng Kung University, 701 No.1, University Road, Tainan City, Taiwan <sup>2</sup>Department of Civil Engineering, National Kaohsiung University of Science and Technology, 80778 No. 415, Jiangong Rd., Kaohsiung City, Taiwan

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**Abstract.** A novel asymmetrical resistance friction damper (ARFD) was proposed in this study to be applied on a rocking column base. The damper comprises multiple steel plates and was fastened using high-strength bolts. The sliding surfaces can be switched into one another and can cause strength to be higher in the loading direction than in the unloading direction. By combining the asymmetrical resistance with the restoring resistance that is generated due to an axial load on the column, the rocking column base can develop a self-centering behavior and achieve high connection strength. Cyclic tests on the ARFD proved that the damper performs a stable asymmetrical hysteretic loop. The desired hysteretic behavior was achieved by tuning the bolt pretension force and the diameter of the round bolt hole. In this study, full-scale, flexural tests were conducted to evaluate the performance of the column base and to verify the analytical model. The results indicated that the column base exhibits a stable self-centering behavior up to a drift angle of 4%. The decompression moment and maximum strength reached 42% and 88% of the full plastic moment of the section, respectively, under a column axial force ratio of approximately 0.2. The strengths and self-centering capacity can be obtained by determining the bolt pretension force. The analytical model results revealed good agreement with the experimental results.

Keywords: asymmetrical resistance; friction damper; self-centering; column base

#### 1. Introduction

In the design of the steel moment resisting frames (SMRFs), connections are expected to retain plastic deformation to dissipate energy when a major earthquake occurs. Performance of the post-Northridge connections (for instance, the reduced beam section connection (RBS)) have been evaluated in many experimental studies (FEMA350 2000, FEMA 355D 2000, Chen et al. 1996, Nakashima et al. 2000, Chou et al. 2010). Inelastic behaviors can be observed in the expected beam section and can lead to high ductility. The inelastic behaviors and local buckling of the connection or the residual deformation of the frame requires repairing cost and time to recover the structural performance or functionalities of the buildings. Connections with self-centering (SC) characteristics have been proposed to control damage and to reduce the repairing jobs. Mostly, post-tension (PT) members have been combined with dampers in a connection to provide recentering and energy dissipation abilities (Ricles et al. 2002, Christopoulos et al. 2002, Garlock et al. 2005, Tsai et al. 2008, Chou et al. 2008, Vasdravellis et al. 2013, Alfredo et al. 2016). Most related existing studies have focused on beam-column connections, and relatively few studies have focused on column bases.

A column is a critical component that should sustain a vertical load; it is difficult to repair a column when it is damaged. Ikenaga (2006) evaluated the effect of SC column bases on the mitigation of residual drifts by conducting a series of nonlinear time history analyses on low-rise SMRFs. The results indicated that an SC column base can ensure the most effective reduction in the residual drift when compared with a fixed-type column base. Developing column bases with SC characteristics seems to be an efficient alternative to reduce the repair tasks required after a major earthquake. Takamatsu (2005) developed a novel SC mechanism on an exposed-type column base. A counter wedge that was applied on the anchor bolts of the base plate was pushed into the gap between the base plate and the nuts by using a spring when the anchor bolts were stretched under a load. This arrangement reduces slip behavior and leads to an SC behavior in combination with a restoring force that is obtained from the column axial force. Ikenaga (2006) proposed a steel column base with PT bars and steel plate dampers to provide a recentering moment and to dissipate energy, respectively. Bi-directional bending tests indicated that such a connection provides a stable SC behavior and energy dissipation ability. Chou (2011) conducted a full-scale test on an SC frame that uses PT beam-to-column connections and PT box columns to eliminate residual deformations, especially for the first floor of the frame. Chi (2012) investigated the cyclic response of a PT column base connection. Additional shear resistance and energy dissipation can be provided by bolt keeper plates and buckling restrained steel plates, respectively.

<sup>\*</sup>Corresponding author, Assistance Professor E-mail: ylchung@mail.ncku.edu.tw



Fig. 1 Concept and mechanism of the proposed ARFD

Borzouie (2015) developed a new column base whose weak axis was aligned along an asymmetric friction connection that can generate asymmetrical resistance by inducing slides at various surfaces. The strong axis, weak axis, and bi-axial flexural behaviors were tested. Freddi (2017) tested the performance of a rocking damage-free steel column base that uses PT high-strength steel bars to control the rocking behavior and uses friction devices to dissipate seismic energy. Kamperidis (2015) used the finite element method on an SC column base that used four high-strength tendons to determine its SC behavior. Hourglass-shaped steel yielding devices were adopted to dissipate energy. The PT system has also been adopted in most of these proposed SC connections. However, pretension loss in the long-term use or after a major earthquake needs to be noted, and the building requires regular maintenance. In addition, the local additional enhancement in the design due to the axial load from the PTs should be considered.

Friction dampers mostly use high-tension bolts to provide a normal force on the sliding surface between plates. Experimental studies have proven that a damper can perform a stable and symmetrical hysteretic behavior under numerous loading cycles (Tsai et al. 2008, Chanchi et al. 2012, Loo et al. 2014, Lee et al. 2015). As an energy dissipation device is used in a free standing, pretension-free column base, friction resistance is the key to determine the connection strength and SC capacity. The high friction resistance is combined with the restoring force of the column to enable to the joint to reach the desired strength (e.g., vield or full plastic moment of column section). However, the SC capacity can be affected due to the symmetrical high friction resistance in the unloading direction. To achieve both performance targets, this paper proposed an asymmetrical resistance friction damper (ARFD) that has higher resistance in loading direction than in the unloading direction. In combination with the restoring force of the rocking column, the high loading resistance can increase the connection strength, and the unloading resistance can be tuned to be sufficiently small to develop the SC behavior. The mechanism and performance of ARFD were tested to evaluate the influence of the parameters such as pretension strength of the bolts and load histories. A full-scale specimen comprises a rocking column connected with the ARFDs that is designed and cyclically

tested to evaluate its performance. The analytical model of the connection was proposed. The analytical model results were compared with the experimental results to determine their practical use.

# 2. Mechanism and hysteretic properties of the rocking column using ARFDs

The rocking column base designed for a low-rise building is placed on a steel base plate that is anchored to the foundation. The ARFDs are connected with the column and base plate so that they can slide when a gap is formed between the column and the base plate.

# 2.1 Concept and mechanism of ARFD

The ARFD comprises five plates that are fastened to each other by using PT high-strength bolts for providing normal compression forces. As presented in Fig. 1(a), the five plates-including two cap plates, two floating plates, and a central plate—were assembled symmetrically.  $S_L$  bolts were used to fasten five plates, and  $S_H$  bolts were used to fasten three plates. Sliding was triggered at different surfaces by controlling the diameters of the round holes on the plates. The hole diameters on the floating plates and the central plate were large; they were designed to provide clearance for sliding. The interface between the cap plates and floating plates (denoted as a CF surface in Fig. 1(a)) sustained normal compression forces of the  $S_L$  bolts. The interface between the floating plates and the center plate (denoted as an FC surface) sustained normal compression from both  $S_L$  and  $S_H$  bolts. Thus, the sliding first occurred at the CF surfaces when the load exceeded the static friction resistance. The sliding was forced to stop due to the contact between the S<sub>L</sub> bolt shank and the floating plates at the edge of the holes. Sliding was switched to the FC surface when the load exceeded the resistance on the surface. This switch generated a sudden increase in the resistance response in the hysteretic loop. To accommodate the slides, the diameters of the round holes on the central plate,  $d_{c1}$  and  $d_{c2}$ , should be designed to be larger than the diameter of the  $S_L$  bolt hole on the floating plates,  $d_{\rm f}$ . The sliding clearance for the low resistance,  $d_{\rm B}$ , is the summation of the net clearance



Fig. 2 Rocking column base with ARFDs

between the  $S_L$  bolt and the aligned round hole on the cap and floating plates, as presented in Eq. (1). Here,  $d_b$  and  $d_{bs}$ are the diameters of the bolt and the aligned round hole, respectively. The mechanism under various moving conditions and the corresponding strength are presented in Fig. 1(b). Sliding at the CF surface exhibited a low friction resistance,  $F_L$ , whereas sliding at the FC surface exhibited a high resistance,  $F_H$ . When the load direction was revised, the sliding was switched back to the CF surface again due to its lower resistance. When the sliding surfaces were switched, an asymmetrical resistance was generated in the loading and unloading directions. The resistances in the two stages can be determined by the pretension forces of the  $S_L$ and  $S_H$  bolts.

$$d_{\rm B} = (d_{\rm bs} - 2d_{\rm b} + d_{\rm f})/2 \tag{1}$$

$$F_{\rm L} = 2 \times N_{\rm bL} \times \mu \times f_{\rm L} \tag{2}$$

$$F_{\rm H} = F_{\rm L} + (2 \times N_{\rm bH} \times \mu \times f_{\rm H}) \tag{3}$$

where  $N_{bL}$  is the number of  $S_L$  bolts;  $N_{bH}$  is the number of  $S_H$  bolts;  $f_L$  and  $f_H$  are the pretension forces of the  $S_L$  and  $S_H$  bolts, respectively. Here,  $\mu$  is the friction coefficient and is assumed as constant over the friction surface. Sliding clearance for low resistance,  $d_B$ , can be tuned by tuning the bolt hole diameter,  $d_f$ , on the floating plate, as presented in the aforementioned equations. The maximum allowable sliding distance,  $d_{limit}$ , that is measured from the initial position of the bolt to the position when the bolt contacts the central plate at the edge of the holes should be determined as below.

$$d_{\text{limit}} = d_{\text{B}} + (d_{\text{c1}} - d_{\text{f}} + d_{\text{bs}} - d_{\text{b}})/2 = d_{\text{B}} + (d_{\text{c2}} - 2d_{\text{b}} + d_{\text{bs}})/2$$
 (4)

As the sliding clearance on both sides of the bolts is symmetrical, the asymmetrical resistance on the positive position can be obtained if the sliding distance,  $d_{\rm C}$ , is smaller than  $2d_{\rm B}$ . The C point is presented in Fig. 1(b). The objective hysteretic friction behavior can be determined by determining the bolt pretension forces and diameters of the round holes.

#### 2.2 Hysteretic properties of the rocking column base

A rocking column base with the proposed ARFDs is presented in Fig. 2. The ARFDs were attached on both sides of the column flanges. Cap plates were fabricated with



Fig. 3 Mechanism of the rocking column

holes at angles; the cap plates are bolted to the column flanges. The central plates were prewelded to the steel base plate. Two floating plates were placed in between the central and cap plates. When the column sustained a lateral load, the interface between the column and base plate opened. The relative movement between the cap and central plates caused friction resistance. Fig. 3 presents a threestory steel moment frame equipped with the rocking column bases to illustrate the system. The column axial load would cause compression force at the interface between column and base plate and induce resistance for column base rotation. The restoring moment,  $M_{\rm N}$ , was the product of column axial force and half width of the column. The resultant moment of the column base was contributed by the frictional moment,  $M_{\rm f}$ , that was generated from the ARFDs and the restoring moment,  $M_{\rm N}$ , that was generated from the axial load of the column.  $M_N$ , would reduce with the increase of horizontal deformation of the frame. Considering the ductility demand for a qualified connection (i.e., 4% drift angle deformation requirement in the seismic provisions of American Institute of Steel Construction, AISC), the restoring moment could remain existing under the deformation level when the dimensions of the column and the frame were carefully designed. A combination of the restoring moment and the appropriately designed ARFDs can enhance the connection strength and develop desirable recentering and sufficient energy dissipation capabilities.

A simplified analysis of the behavior of the column base can be explained using the free-body diagram presented in Fig. 4(a). When the external moment exceeded the decompression moment, a gap was formed and activated the ARFDs to induce energy dissipation. Fig. 4(b) presents the ideal hysteretic loop of the ARFDs. The horizontal axis is the column base rotation angle, and the vertical axis is the frictional moment. A low frictional moment was contributed by the friction forces of the  $S_L$  bolts and is denoted as  $f_{Lfi}$ and  $f_{\text{Lni}}$  in the figure. The subscripts f and n denote whether the bolts have to be far or near to the center of rotation, respectively. The horizontal and vertical components of the bolt friction force acting on the floating plate cause various movements, as presented in Fig. 4(a). The horizontal components,  $f_{Lfi_h}$  and  $f_{Lni_h}$ , cause the plates to rotate at the center of the S<sub>H</sub> bolts. The contribution to the connection resistance was small and is not considered in the analysis. The vertical components,  $f_{Lfi_v}$  and  $f_{Lni_v}$ , caused the translation of the plates. The two stages of the frictional



Fig. 4 Analytical model of the rocking column base: (a) Mechanism of strong axis bending, (b) hysteretic behavior of ARFDs, and (c) hysteretic behavior of the column base

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moments are presented below.

$$M_{\rm fL} = 2 \times \left(\sum f_{\rm Lfi\_v} \times D_{\rm f} + \sum f_{\rm Lni\_v} \times D_{\rm n}\right) \times \mu \qquad (5)$$

$$M_{\rm fH} = 2 \times \left(\sum f_{\rm Hfi\_v} \times D_{\rm f} + \sum f_{\rm Hni\_v} \times D_{\rm n}\right) \times \mu + M_{\rm fL} \quad (6)$$

D is the lever arm of the vertical component of the friction force. Fig. 4(c) presents a flag-shaped hysteretic loop of the column base, illustrated as the moment and drift angle relationship. The decompression moment,  $M_A$ , at point A is the summation of the restoring moment,  $M_N$ , and the frictional moment,  $M_{\rm fL}$ . Decreasing of strength and stiffness due to the horizontal displacement of the frame is considered in the following equations.  $M_{\rm N}$  and  $M_{\rm A}$  can be expressed as presented in Eqs. (7) and (8), where N is the axial load of the column,  $L_c$  is the column length,  $\theta$  is the drift angle, and  $d_c$  is the column section depth. By assuming a rigid body rotation of the column about the compression toe, the stiffness of various stages can be expressed as presented in Eq. (9) with considering the contributions of column and ARFDs.  $K_{\rm f}$  is the stiffness of ARFDs. The flexural stiffness,  $K_1$ , can be obtained by the column elastic flexural stiffness,  $K_c$ , which can be represented as  $6EI_c/L_c$ . The corresponding drift angle,  $\theta_{a}$ , can be determined by solving the Eqs. (8) and (9). The result is shown in Eq. (10). After the gap is formed, deformation concentrated on the connection and stiffness of ARFDs,  $K_{\rm f}$ , becomes zero. Thus  $K_2$  is simplified to be  $K_{PD}$ .

$$M_{\rm N} = N \frac{d_{\rm c}}{2} - N L_{\rm c} \theta, \text{ let } K_{\rm PD} = -N L_{\rm c}$$
(7)

$$M_{\rm A} = M_{\rm N} + M_{\rm fL} \tag{8}$$

$$K_{\rm i} = \frac{1}{\frac{1}{K_{\rm c}} + \frac{1}{K_{\rm f}}} + K_{\rm PD}$$
(9)

$$\theta_{\rm a} = \frac{N\frac{d_{\rm c}}{2} + M_{\rm fL}}{K_{\rm c}} \tag{10}$$

When the gap keeps increasing up to the point where the  $S_L$  bolt contacts the floating plate at the edge of holes,  $M_{\rm fH}$  is induced. The corresponding drift angle,  $\Theta_{\rm b}$ , can be obtained using Eq. (11). Here,  $\Theta_{\rm j}$  is the gap angle of the point at which the resistance of the ARFDs increases, as presented in Fig. 4(b).

$$\theta_{\rm j} = d_{\rm B}/R_{\rm fmax}, \ \theta_{\rm b} = \theta_{\rm a} + \theta_{\rm j}$$
 (11)

$$M_{\rm B} = M_{\rm A} + K_2(\theta_{\rm b} - \theta_{\rm a}) = M_{\rm A} + K_2\theta_{\rm j}$$
(12)

where  $R_{\text{fmax}}$  is the maximum distance between the  $S_L$  bolts and the center of rotation.  $M_{\rm B}$  can be obtained from Eq. (12). All the  $S_L$  bolts are placed at different distances from the center of rotation, which implies that the bolts touch the floating plates under various levels of rotation. This causes the friction resistance to increase relatively gently instead of causing a sudden jump in the resistance. Thus, the equivalent stiffness,  $K_{feq}$ , was induced to describe the resistance and displacement relationship from the point at which the first  $S_L$  bolt contacts the plate to the point at which all  $S_L$  bolts contact the plate.  $K_{\text{feq}}$  is expressed in Eq. (13).  $R_{f_{max}}$ ,  $R_{n_{min}}$  represent the maximum distance between the far side  $\bar{S}_L$  bolt to the center of rotation, and the minimum distance between the near side  $S_L$  bolt to the center of rotation, respectively. The flexural stiffness,  $K_3$ , can be obtained by considering  $K_{\text{feq}}$  as the friction stiffness that is presented in Eq. (9). Point C represents that the ARFDs have reached the high resistance  $M_{\rm fH}$  and can be represented as expressed in Eq. (14). The corresponding rotation,  $\theta_c$ , can be obtained from Eq. (15).

$$K_{\rm feq} = \frac{M_{\rm fH} - M_{\rm fL}}{\frac{d_{\rm B}}{R_{\rm f} \max} + \frac{d_{\rm B}}{R_{\rm n} \min}}$$
(13)

$$M_{\rm C} = M_{\rm B} + (M_{\rm fH} - M_{\rm fL})$$
 (14)

$$\theta_{\rm c} = \theta_{\rm b} + (M_{\rm fH} - M_{\rm fL})/K_3 \tag{15}$$

$$M_{\rm E} = M_{\rm D} - M_{\rm fH} - M_{\rm fL} \tag{16}$$



Fig. 6 Experimental results

where  $\theta_d$  and  $M_D$  represent the maximum considered rotation and strength in the design, respectively. The stiffness  $K_4$  and the unloading stiffness  $K_6$  are assumed to be equal to  $K_2$ .  $K_5$  is equal to the initial stiffness  $K_1$ .  $M_E$  can be obtained using Eq. (16). The entire behavior can be estimated using the aforementioned relationships.

# 3. Performance evaluation of ARFDs

#### 3.1 Friction coefficient test

Aluminum or brass shims have been mostly used in friction dampers (Chanchi et al. 2012, Rojas et al. 2005) to provide stable and high friction coefficients. These tests indicate that the two friction materials exhibit friction coefficients in the range of 0.34-0.4. To specify the friction behavior of the shims used in AFRDs, a friction test was conducted. As presented in Fig. 5, the specimen comprised three plates and two bolts. SS400 steel plates with a thickness of 10 mm were used. The round hole diameter for the center plate was 40 mm. 5050 series aluminum shims with a thickness of 3 mm were inserted between the plates. The specimen was installed in the MTS machine and cyclically loaded using displacement control. The initial amplitude value was 2 mm, and this value was increased by 2 mm for each level. The maximum amplitude reached 10mm. Five cycles were conducted for each amplitude value. Two specimens were prepared by using two bolt pretension forces-30 and 50 kN. The pretension forces were controlled and monitored using bolt gauges. Fig. 6 presents the experimental results. The friction coefficient was obtained by dividing the friction force by the bolt tensile force. The friction coefficient became stable and





Fig. 8 Test setup

constant after several cycles. The average of the stable values under the two tests were both approximately 0.44.

#### 3.2 Cyclic tests on ARFD

# 3.2.1 Specimen design and test program

The specimen was designed using two bolts for each sliding stage, as presented in Fig. 7. The cap, floating, and central plates were fabricated using SS400 steel with a thicknesses of 14, 14, and 18 mm, respectively. M20 highstrength bolts and an aligned round hole diameter of 21 mm were used. The hole diameter for the  $S_{I}$  bolt (denoted as  $d_{f}$ in Fig. 1(a)) on the floating plate was 30 mm, which provides a clearance of 5.5 mm ( $d_{\rm B}$ ) for a low resistance sliding. The bolt holes on the central plate for the  $S_{\rm L}$  and  $S_{\rm H}$ bolt (denoted as  $d_{c1}$  and  $d_{c2}$  in Fig. 1(a), respectively) were 42 and 32 mm, respectively. The maximum sliding distance,  $d_{\text{limit}}$ , was 12 mm, as calculated from Eq. (4). Both sides of the specimen were fixed using the MTS machine, as presented in Fig. 8, and loaded with increasing amplitude values from  $\pm 4$  to  $\pm 14$  mm. The amplitude increases by 2 mm for each level, and five cycles were conducted at each amplitude. An asymmetrical protocol, which was produced by rearranging the previous protocol, was also developed to evaluate the sliding behavior while the device was subjected to a random amplitude history (as presented in Fig. 9). LVDTs were installed to measure the relative displacement between the cap and central plates. Bolt gauges were applied to monitor and control the tensile force. Specimens were loaded with a constant speed of 0.1 mm/s.

Four specimens were prepared to evaluate the behaviors

Table 1 Test program

Specimen	Bolt Preter	_ Londing Protocol	
specifien	$f_{\rm L}$	$f_{\rm H}$	
F30_30S	30	30	Symmetric
F30_50S	30	50	Symmetric
F50_30S	50	30	Symmetric
F30_30A	30	30	Asymmetric
- 20 (mm) - 0 Disblacement D - 20 - 20 - 20 - 20 - 20 - 20 - 20 - 20			15 20

Fig. 9 Asymmetrical loading protocol

under various bolt pretension forces and loading protocols. As summarized in Table 1, 30 and 50 kN pretension forces were used for  $S_L$  or  $S_H$  bolts. The F30\_30A specimen is the counterpart of the F30\_30 specimen; however, the F30\_30A specimen was tested by an asymmetrical protocol.

#### 3.2.2 Experimental results

Fig. 10 presents the friction force and displacement behavior of the four specimens. Displacement responses were obtained from LVDTs. Each specimen exhibited a stable, asymmetrical resistance response. The strength of the specimens started to increase to the high resistance level at the displacement range of approximately 5-6 mm, which is line with the estimation results. The low resistance,  $F_{\rm L}$ , and high resistance, F<sub>H</sub>, of F30\_30S (Fig. 10(a)) were 54 and 111 kN, respectively, which are in line with the corresponding estimations of 52.8 and 105.6 kN obtained using Eq. (1). When the pretension force of the  $S_H$  bolt was increased to 50 kN (Fig. 10(b)),  $F_{\rm L}$  remained approximately 50 kN, and  $F_{\rm H}$  was increased to approximately 130 kN. For the F50\_30S specimen (Fig. 10(c)), the pretension force  $f_L$ of the  $S_L$  bolt was increased to 50 kN, and  $f_H$  remained 30 kN. The measured strength of  $F_{\rm L}$  and  $F_{\rm H}$  increased by approximately 30 kN and reached 88 and 136 kN, respectively. The low resistance,  $F_{\rm L}$ , was determined using the pretension of the  $S_L$  bolt. For the high resistance,  $F_{\rm H}$  is

Table 2 Experiment and estimation

Specimen	$F_{L\_cal}$ (kN)	$F_{L\_test}$ (kN)	$F_{L_{test}}/$ $F_{L_{cal}}(\%)$	$F_{H\_cal}$ (kN)	$F_{H\_test}$ (kN)	$F_{H_{test}}$
F30 30S	52.8	54	102.3	105.6	111	105.1
150_505	52.0	54	102.5	105.0	111	105.1
F30_50S	52.8	50	94.7	140.0	130	92.9
F50_30S	88.0	86	97.7	140.0	136	97.1
F30_30A	52.8	48	90.9	105.6	103	97.5

the summation of  $F_{\rm L}$  and the friction resistance induced by the  $S_H$  bolts. The enhanced resistance can be independently determined using the pretension of the S<sub>H</sub> bolt, as presented by the F30\_50S specimen (Fig. 10(b)).

For an asymmetrically loaded specimen (Fig. 10(d)),  $F_L$ and  $F_H$  can be clearly recognized as 48 and 103 kN, respectively, which are similar to those of the F30\_30S specimen. The hysteretic loop presents some oblique and disordered tracks near the origin point area. This might because when the amplitude is asymmetrical in the positive and negative directions or when large amplitudes randomly appear in the loading history, the S<sub>L</sub> bolt might come in contact with the floating plate at small amplitude levels and cause the slash to appear at the origin point area. However, the hysteretic loop presents a similar strength, skeleton curve, and behavior as the counterpart specimen. The effect of asymmetrical loading is minor.

The measured  $F_{\rm L}$  and  $F_{\rm H}$  values are summarized in Table 2 together with the estimates obtained from Eqs. (2) and (3). The maximum difference between the experimental and calculated strength was less than 10%. The estimated values were in agreement with the experimental results. The strength and hysteretic behavior of the ARFD can be tuned by determining the bolt pretension forces and diameters of the bolt holes.

#### Cyclic test of rocking column base with the ARFD

#### 4.1 Design of specimens

Fig. 11 presents the details of the test specimen. The column was SS400,  $H300 \times 300 \times 10 \times 15$  steel. This column was placed on a 20-mm-thick base plate that was bolted to a foundational beam with dimensions of  $H500 \times 200 \times 10 \times 16$ . Two ARFDs were arranged on both sides of the column flanges to provide resistance when the column sustains strong axis bending. The two central plates were welded to





Fig. 11 Rocking column base specimen



Fig. 12 Test system and specimen.

the base plate. The cap plate was fabricated as an angle and bolted to the column flange. Aluminum shims measuring 3 mm in thickness, which were tested in the previous section, were inserted between the plates. The net horizontal clearance between the two central plates was set to be 300 mm so that the column could be accommodated. Moreover, the value was selected to operate as a shear key to prevent the column from sliding. The width of the central plate was gradually decreased to allow column rotations of up to 5% without touching the central plate. The axial load ratio of the column was 0.2, which is 550 kN. The contributed restoring moment,  $M_N$ , was 82.5 kN·m, which is approximately 22.5% of the column nominal full plastic moment,  $M_{\rm p}$ . Due to the limitations of the loading system, a pair of PT bars were used for applying axial loads to the column. M20, F10T bolts were used. Pretention forces of the  $S_L$  and  $S_H$  bolts were set to 60 and 120 kN, respectively, so that  $M_{\rm fL}$  and  $M_{\rm fH}$  were 36.3 and 125.3 kN·m, which were 9.9% and 34.1% of  $M_{\rm p}$ , respectively. Thus, the decompression moment was 31.9% of  $M_{\rm p}$ . If  $M_{\rm fL}$  is smaller than  $M_{\rm N}$ , an SC characteristic is achieved in the design.

The thicknesses of the cap, floating, and central plates were determined by considering the bearing force at the edge of the holes. The diameters of the round holes of  $d_{\rm bs}$ ,  $d_{\rm f}$ ,  $d_{\rm c1}$ , and  $d_{\rm c2}$  were 21, 29, 44, and 39 mm, respectively. Thus, the flexural resistance increased at a gap angle,  $\Theta_{\rm j}$ , of 0.01 rad, as presented in Eq. (11). The diameter on the central plate allowed the gap angle to grow to 5% without touching the bolt.

#### 4.2 Test program

#### 4.2.1 Test system

The test setup and the specimen are displayed in Fig. 12. The foundational beam was fixed to the test frame. Two PT bars with a diameter of 30 mm were adopted to apply the axial load to the column. The load cell was placed on the top of the column to measure the force of the PT bars. The PT bars were passed through the foundational beam, column, and load cell and were connected to the cap beam that was placed on the load cell. A 100-ton jack pin was connected to the column at a height of 1620 mm from the column base. The jack applied cyclic lateral force by using displacement control. Bolt gauges were inserted in every bolt of the ARFDs to control the pretention forces. After applying the strong axis loads, the specimen was rotated by





(b) weak axis loading (a) Strong axis loading Fig. 13 Loading conditions

90° to test the weak axis flexure performance. Fig. 13 presents the specimen under strong and weak axis loads.

#### 4.2.2 Loading protocol and test schedule

Two types of loading protocols were adopted. The symmetrical protocol followed the AISC standard (2010), as presented in Fig. 14(a). The amplitude started from 0.375% and increased to 4%. To evaluate the performance of the column base when subjected to a real seismic load, the amplitudes presented in the Fig. 14(a) were rearranged randomly and asymmetrically. Large amplitudes (4% and 3%) and medium amplitudes (2% and 1%) were interlaced and followed by many small amplitudes. Various amplitudes were arranged in the positive and negative directions along the series to evaluated the sliding behaviors, strengths and residual deformation of the damper, as presented in Fig. 14(b).

Experimental parameters such as bolt pretension, bolt hole diameter, and loading situation were tested to evaluate the influence of these parameters on the global column base behaviors. The parameters are listed in Table 3 with the design strengths. The strength and stiffness estimations were modified due to the presence of PT bars. The decompression moment,  $M_A$ , is the sum of the moments generated due to the PT bars and ARFDs, as expressed in Eq. (17). The initial flexural stiffness,  $K_1$ , uses the column elastic flexural stiffness,  $K_c$ , which can be represented as  $3EI_c/L_c$ .  $L_c$  is the length of column specimen. After the gap is formed, the stiffness should be modified as presented in Eq. (18). The PT bars will be elongated and the ARFDs will be activated only when the gap is opened. The two devices would behave like two springs connected in parallel.

<sup>⊗</sup>2 angle ili-2 -4 0 15 20 25 30 5 10 Cycle number (a) Symmetrical % angle Ü 30 0 5 15 20 25 Cycle number (b) Asymmetrical Fig. 14 Loading protocol

$$M_{\rm A} = F_{\rm pt} \frac{d_{\rm c}}{2} + M_{\rm fL} - F_{\rm pt} L_{\rm c} \theta, K_{\rm PD} = -F_{\rm pt} L_{\rm c}$$
 (17)

$$K_{\rm i} = \frac{1}{\frac{1}{K_{\rm c}} + \frac{1}{K_{\rm f} + K_{\rm pt}}} + K_{\rm PD}$$
(18)

Here,  $F_{pt}$  and  $K_{pt}$  are the force and stiffness that are generated due to the PT bars. The equation can be expressed as follows

$$K_{\rm pt} = \frac{E_{\rm pt}A_{\rm pt}d_{\rm c}^2}{4L_{\rm pt}} \tag{19}$$

Where the  $E_{pt}$ ,  $A_{pt}$  and  $L_{pt}$  are the Young's modulus, section area, and length of the PT bars. When the bolt begins to come in contact with the floating plates,  $K_{\rm f}$  should be considered as  $K_{\text{feq}}$ , and the equation can be expressed as presented in (20).

$$K_{3} = \frac{1}{\frac{1}{K_{c}} + \frac{1}{K_{pt} + K_{feq}}}$$
(20)

Resistances contributed by various components were calculated using the previously discussed equations to

Table 3 Specimens and parameters

Specimen -	Bolt Pretension (kN)		- d (mm)	ρ	A	Drotocol	M /M	M /M	M/M	M /M	M /M
	$f_{\rm L}$	$f_{ m H}$	$- u_{\rm f}(\rm mm)$	$O_{j}$	$O_{\rm b}$	FIOLOCOI	1 <b>v1</b> <sub>N</sub> /1 <b>v1</b> <sub>p</sub>	m <sub>fL</sub> /m <sub>p</sub>	<i>w</i> A/ <i>w</i> p	IVI fH/IVI p	1 <b>v1</b> 0.04/1 <b>v1</b> p
SPC	60	120	29	0.010	0.012	Sym.	22.5	9.9	31.9	34.1	68.3
SPCB	120	120	29	0.010	0.012	Sym.	22.5	19.9	42.1	44.6	78.4
SPCH	60	120	34	0.015	0.017	Sym.	22.5	9.9	31.9	34.1	68.3
SPCA	60	120	29	0.010	0.012	Asym.	22.5	9.9	31.9	34.1	68.3
WPC	60	120	29	-	-	Sym.	49.2	-	47.8	-	86.5

\*Note:  $M_{\rm ps} = 367.5 \text{ kN} \cdot \text{m}, M_{\rm pw} = 167.5 \text{ kN} \cdot \text{m}$ 



Fig. 15 Experimental and analytical results of SPC

estimate the participation levels. The SPC specimen that sustained strong axial bending when 60 and 120 kN bolt pretensions were used was the standard specimen. The SPCB specimen had an identical design but enhanced the pretension of the S<sub>L</sub> bolts up to 120 kN. The estimated  $M_{\rm fL}$ was about 88% of the restoring moment,  $M_{pt,i}$ . The decompression moments of the specimen using  $S_L$  bolt pretensions of 60 and 120 kN were 31.9% and 42.1% of  $M_{\rm p}$ . The moment at a drift angle of 4% was 75.3% and 89.2% of  $M_{\rm p}$ , respectively. The SPCH specimen enlarged the diameter of the round hole,  $d_{\rm f}$ , up to 34 mm from 29 mm. The SPCA specimen was identical to the SPC specimen but was loaded by an asymmetrical protocol (Fig. 14(b)). The WPC specimen sustained weak axis loading. Due to the location of the ARFDs, the device would not be activated and the contribution was not considered in the analysis.

#### 5. Analysis of experimental results

## 5.1 Hysteretic behavior and strength

#### 5.1.1 SPC specimen

Fig. 15 presents the experimental responses of the SPC specimen with the responses obtained using the analytical model. The vertical axis presents the product of the jack load and column length, and the horizontal axis is the drift angle that is obtained by dividing the jack displacement by the column length. The specimen exhibited a stable SC behavior up to a drift angle of 0.04 rad. The column base detached the base plate at an angle of approximately 0.00375 rad, and the corresponding decompression moment was approximately 115 kN·m. A sudden increase in the strength can be observed at the angle of approximately 0.012 rad. This increase may have happened because the  $S_{L}$ bolt began to contact the floating plate. The analytical results obtained from the previous equations agree well with the experimental results. However, the initial stiffness was approximately 34% lower than the estimated value. Fig. 16 displays the damage on the aluminum shims. Most abrasion surrounded the bolt holes. Some bearing failures were also observed at the edges of the holes due to the contact between the bolt shank and the aluminum shim.

#### 5.1.2 SPCB specimen

The hysteretic loop is presented in Fig. 17. By



Fig. 16 Damages on the aluminum shims



Fig. 17 Experimental and analytical results of SPCB

comparing the response of the SPCB specimen with that of the SPC specimen, it can be found that the decompression strength and maximum strength of SPCB increased to 155 and 325 kN·m from 115 and 274 kN·m, respectively. When the pretension of the  $S_L$  bolts was doubled,  $M_A$  and  $M_{4\%}$ increased to values in the range of 40-50 kN·m. The increased resistance was slightly larger than  $M_{\rm fL}$  of the SPC specimen. This behavior can be observed in the response of the F50\_30S specimen in the previous ARFD test.  $M_{\rm fL}$  is designed such that it is near to  $M_N$  (Table 3). The response shows that the column recentered to the original position with a very slight residual rotation, and the SC capacity was retained. Moreover, the energy dissipation ability of the SPCB specimen should be increased because the hysteretic loop of the SPCB specimen has a higher width compared with that of the SPC specimen. A sudden strength increase can also be observed from approximately 0.013 rad. The analytical model results also agree well with the experimental results, especially for maximum strength.

#### 5.1.3 SPCH specimen

Fig. 18 presents the response of the SPCH specimen. The diameter of the round hole  $(d_f)$  was enlarged to 34 mm, and this led to a delay in strength increase. The rotation at the strength increase point,  $\Theta_b$ , was approximately 0.019 rad, which is slight larger than the estimation result of 0.017 rad. This might involve off-centering of the bolt position in assembling. The strength increasing response is delayed, the maximum strength of the SPCH specimen remains similar to that of the SPC specimen. The analytical responses agree well with the experimental responses.

#### 5.1.4 SPCA specimen

SPCA specimen was loaded by the asymmetrical



Fig. 18 Experimental and analytical results of SPCH



Fig. 19 Experimental and analytical results of SPCA

protocol. As presented in Fig. 19, the test specimen exhibited a hysteretic loop that was similar to that of the SPC specimen in terms of the decompression strength, maximum strength, and the sudden increase in the drift angle of the strength. The response reveals a clear SC behavior but a more complex movement around the origin position. Several amplitudes that exceed 0.02 rad do not exhibit a strength increase in  $M_{\rm fH}$  and thus lead to a low strength. This might be due to the movement of the floating plates. The bolt at the farthest location from the center of rotation first controls the movement of the floating plates, as presented in the Fig. 4(a). The center of rotation at the column base switches back and forth under the cyclic loads and causes the floating plates to translate and rotate in different directions. Due to the asymmetrical protocol, a large amplitude causes residual translation and rotation of the floating plates. For the subsequent smaller amplitudes, the center of rotation switches, and another bolt that might not be the farthest from the rotation center first touches the plate and forces the plate to move in another direction. Therefore, the oblique and disordered tracks can be observed at the origin point area. Moreover, the residual translation due to a big amplitude provides a larger clearance for the next sliding in the opposite direction and



Fig. 20 Experimental and analytical results of WSPC

leads to a delay in strength increase. These asymmetrical movements slightly increase the width of the hysteretic loop of the SPCA specimen than the width of the hysteretic loop of the SPC specimen. In general, the effect of asymmetrical loading is small.

# 5.1.5 WPC specimen

Fig. 20 presents the experimental response of the weak axis loading with the analytical response. The estimated initial stiffness is the elastic flexural stiffness of the weak axis of the column. The effects of the PT bars were considered in the calculation of secondary stiffness (Eq. (18) and (19)). The ARFDs are located at the center of the flange width. The central plate flexural behavior dominates the response. Only the flexural resistances obtained from column axial load and the central plates were considered in the simplified analysis. The estimated strength and secondary stiffness results are in agreement with the experimental results. However, the initial stiffness was approximately 36% lower than the estimated value. The stiffness deterioration can be observed in the cycles. Local inelastic deformation might occur under axial compression. for instance, a strain concentration might occur at the flange toes of the rotational center. This should be responsible for the stiffness deterioration.

#### 5.1.6 Strength

Table 4 summarizes the experimental strengths and analytical results. For the strong axis loading specimens, the difference between the experimental and analytical results is lower than 15% in terms of the decompression strengths and maximum strengths. The analytical equations provide reasonable and reliable predictions of the connection performance. The decompression moments of the SPC, SPCH, and SPCA specimens, which have identical bolt pretension forces but use different bolt hole diameters or are loaded by different protocol, were approximately in the

Table 4 Summary of the experimental and analytical strengths

Specimen	$M_{\rm A}({\rm kN-m})$	$M_{A\_Cal.}(kN-m)$	$M_{\rm A}/M_{\rm A\_Cal.}(\%)$	$M_{\rm A}/M_{\rm p}(\%)$	$M_{4\%}$ (kN-m)	$M_{4\%$ _Cal.(kN-m)	$M_{4\%}/M_{4\%}$ _Cal.(%)	$M_{4\%}/M_{\rm p}(\%)$
SPC	115	117.3	98.0	31.3	274	251.5	108.9	74.5
SPCB	155	154.4	100.4	42.2	325	287.5	113.0	88.4
SPCH	128	117.3	109.1	34.8	290	250.8	115.6	78.9
SPCA	129	117.3	110.0	35.1	292	251.5	106.1	79.4
WPC	70	80.1	87.5	41.9	146	144.5	101.0	87.4



Fig. 21 Flexural contribution from PT bars and ARFDs

range of 31% to 35% of  $M_{\rm p}$ . Moreover, the strengths of the specimens at 0.04 rad were approximately in the range of 75%-79% of  $M_{\rm p}$ . The exhibited strengths were similar. When the strength of the S<sub>L</sub> bolt were doubled to 120 kN, the decompression moment of the SPCB specimen reached 42.2% of  $M_{\rm p}$ , and the maximum strength reached 88.4% of  $M_{\rm p}$ . Therefore, the low and high resistances and the shape of the hysteretic loops can be determined by the bolt pretension forces and diameters of the bolt holes of the ARFDs. The SC capacity can be determined by controlling the low frictional resistance,  $M_{\rm fL}$ .

For the WPC specimen, the decompression and maximum strengths reach approximately 42% and 87% of the  $M_{\rm p}$ . The decompression moment was approximately 85% of the analytical value, and the accuracy of the maximum strength reached approximately 98% of the analytical value. The contribution of ARFDs is small due to the flexural behavior of the central plates.

#### 5.2 Flexural contribution of PT bars and ARFDs

Fig. 21 presents the flexural contribution of the PT bars and ARFDs under various drift angle amplitudes. The contribution of the PT bars is obtained from the load cell reading that is placed on the top of the column (Fig. 11 and 12). The ARFDs response is the difference obtained by subtracting the PT contribution from the global behavior, as presented in Figs. 15 to 19. Deformation before the gap of the column base is formed is not considered in the figure due to the nonactivation of the ARFDs. The horizontal axis of the figure begins from 0.005 rad.

Flexural responses of the ARFDs are similar to the responses obtained after conducting cyclic ARFD tests in the previous section. The low and high frictional moments and the asymmetrical behaviors can be observed. The



Fig. 22 Energy dissipation under various amplitudes

gradual increase in the stiffness in the strength increase area and the high resistance area might be due to the rotation of the floating plates. The flexural contribution of the ARFDs can be reasonably predicted using the proposed analytical model. For each specimen, the contribution of the PT bar begins from 22% of  $M_p$  and reaches to approximately 39% of  $M_p$  under a drift angle of 4%, which agrees with the analytical values of 22.5% and 39.7% of  $M_p$ .

# 5.3 Energy dissipation capacity

The averaged hysteretic energy dissipations that are obtained by using the area of the hysteretic loops are summarized in Fig. 22. Four specimens dissipate similar energy under a small deformation region. The SPC and SPCH specimens present similar results under amplitudes of 3%. Due to delay in strength increase, the SPCH specimen dissipates approximately 10% less energy than that dissipated by the SPC specimen at an amplitude of 4%. The angle of the strength sudden increase  $(\theta_i)$  does not change the strength but affects the energy dissipation ability. The energy dissipation of SPCA is slightly larger than that of the SPC specimen at a drift angle more than 2%. Asymmetrical loading causes the width of the hysteretic loop of SPCA to be higher than the width of the hysteretic loops of the counterpart specimens and leads to an increase in energy dissipation ability. The SPCB specimen, whose low frictional resistance is enhanced, exhibits higher resistance and thus presents a higher energy dissipation capacity. The ability of the SPCB specimen increases by 25% than the ability of the SPC specimen at a drift angle of 4%.

#### 5. Conclusions

A novel ARFD was proposed and used on a rocking column base to develop a low-damage, SC connection. Cyclic component tests were conducted on the ARFD to evaluate the effects of the bolt pretention force, sliding clearance, and asymmetrical amplitude protocol. To evaluate the performance of the column base with ARFDs, full-scale, cyclic flexural loading tests were conducted. The results of the test were compared with that of the analytical model. The primary conclusions are as follows:

• The proposed ARFD comprises multiple friction

surfaces which are forcibly switched because the bolt comes in contact with the floating plate at the edge of the holes and causes sudden increase in resistance. The cyclic experimental results indicated that the low and high resistances can be determined using the pretensions of the bolts. The sliding clearance for the low resistance can be tuned by determining the diameter of the round holes in the floating plates. The asymmetrical amplitudes of loads did not affect the hysteretic behavior and strengths. The results of the presented equations used for the analysis were in agreement with the experimental results with less than 10% difference.

· A series of full-scale experimental results revealed that the column with an axial force ratio of 0.2 can exhibit a stable and SC behavior when ARFDs are used. All specimens reached a drift angle of 4% without strength deterioration. When the low flexural resistance of ARFDs was doubled to about 88% of the restoring moment, the SC capacity was retained; the decompression moment and maximum moment reached 42.2% and 88.4% of the full plastic moment of the column section, respectively; and a 25% increase was observed in the energy dissipation ability. The low and high flexural resistances of ARFDs can be determined using the pretension of the relative bolts and can be used to enhance the decompression moment and maximum strengths of a connection. The diameter of the round holes on the floating plates can be used to determine the point at which the low frictional resistance jumps to the high frictional resistance. By using these parameters, the shape of the hysteretic loop of the column base can be determined.

• The column base exhibits a similar behavior when it is under symmetrical and asymmetrical protocol loads. The performance of the column base including strength and SC capacity were almost unaffected. The asymmetrical loads slightly increase the width of the hysteretic loop and enhance the energy dissipation ability comparing with that of the counterpart specimen. The high frictional resistance of the ARFDs were delayed in several cycles due to the asymmetrical movements.

• For the weak axis loads, the flexural behavior of the central plates dominated the response of the ARFDs. Sliding of ARFDs were not activated. Deterioration was observed in the loading stiffness. The local inelastic behavior at the toe of the rotational center might be responsible for this deterioration. The consideration that the axial load of a column is the only contribution to the resistance is reasonable based on the comparison with the test result.

• The results of the proposed analytical models notably agree well with the experimental results, especially the decompression strength, maximum strength, and secondary stiffness results. The difference between the experiment and estimated results was less than 15%. However, the experimental initial stiffness values were approximately 35% lower than the estimated values. This difference might be because inelastic behaviors concentrate in a small region such as the toe of the column flanges.

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