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SELF-CENTERING AND ENERGY DISSIPATION OF A POST-TENSIONED STEEL COLUMN BASE

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ABSTRACT

Seismic behaviour of a post-tensioned steel column base with friction dampers was studied to investigate the effects of initial post-tensioned force of strands and energy dissipation dampers on the cyclic behaviour of the column base connections. High-strength strands were used to join the column and foundation, and the friction type energy dissipation dampers were adopted to provide hysteretic behaviour. Therefore, the subassembly has the characteristics of self-centering and no residual deformation. Analytical and experimental evaluation was carried out on the cyclic behaviour of the subassembly. The results demonstrated that increasing post-tensioned force of the bolts used for friction dampers could effectively increase the area of the energy dissipation. Furthermore, the friction dampers installed at the column flange rather than the column web can lead to better energy dissipation behaviour. The column base connection with friction dampers includes the features of self-centering, gap opening and closing at the column-to-foundation interface, energy dissipation characteristics, and no residual deformation of the column. Moreover, analytical predictions and the experimental results are well correlated.

INTRODUCTION

In high seismic regions, special moment frames are generally used to resist forces exerted by earthquake. Structural members will undergo inelastic behaviour during a major earthquake. Plastic hinges formed on beams will be expected to dissipate energy. As a result, residual deformation of the frames will occur, causing problems such as the functions of the structures and retrofitting of the damaged frames. Therefore, post-tensioned frames have been developed to achieve no residual drifts of the frame after the earthquake (Sause et al. 2006; Garlock et al. 2007). Post-tensioned force is employed to connect the beam and column members as well as the column and foundation. The self-centering beam-to-column connections have been intensively studied (Ricles et al. 2001 and 2002; Christopoulos et al. 2002; Chou and Lai 2009). Chi and Liu (2012) recently studied the post-tensioned column base connection using buckling restrained steel plates as energy dissipator. The post-tensioned forces applied through strands will provide restoring forces and accomplish the self-centering nature of the frames. Friction dampers are one of the effective means to dissipate energy, and therefore friction devices are used in either braces or beam-to-column connections (Rojas et al. 2005; Zhu and Zhang 2008; Kim and Christopoulos 2008; Wolski et al. 2009).

In this paper, post-tensioned column base connections are evaluated analytically and experimentally. After determining the friction coefficient by bolted friction tests, friction dampers were incorporated at the column base to dissipate earthquake induced energy. A steel column was

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post-tensioned to the reinforced concrete foundation using high-strength strands. Hysteretic behaviour of the column base connections was analytically established, and large-scale test was conducted to elucidate the cyclic behaviour.

HYSTERETIC BEHAVIOUR

An one-story column subassembly isolated from a post-tensioned frame was studied. The subassembly includes a column and a foundation. Furthermore, the column is post-tensioned and joined to the foundation by the strands. Fig. 1 shows the free body diagram of the steel column. The lateral force applied to the column tip results in a moment at the base of the column, termed "column base moment" hereafter. When the column base moment is equal to the moment resisted by the strands and friction, a decompression moment, M_d, reaches and it is defined as

$$M_d = F_{pt,i}\frac{d_c}{2} + F_f r \tag{1}$$

where $F_{pt,i}$ is the initial strand post-tensioned force; d_c is the depth of the column; F_f is the friction; and r is the distance between the friction and rotational center.

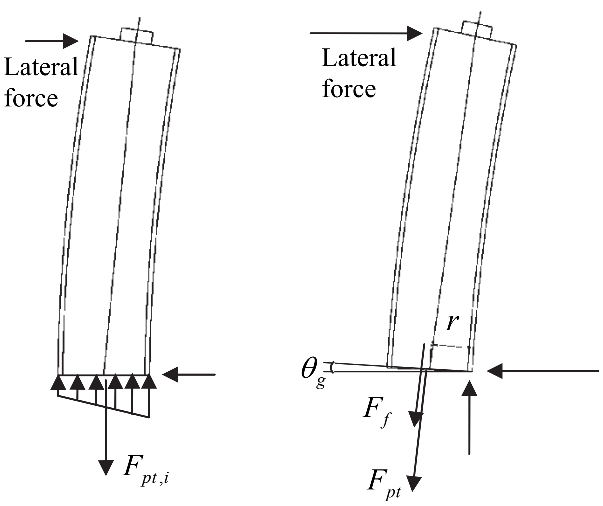


Figure 1. Free body diagrams of steel column

Fig. 2 shows the relationships between the column base moment and story drift angle. Once the column base moment is greater than the resisting moment, a gap between the column and foundation opens. The gap opening leads to an increase of the strand force and a shortening of the column. The increase of the strand force can be calculated as follows.

$$\Delta F_{pt} = \frac{E_{pt}A_{pt}d_c}{2L_{pt}\left(1+\dfrac{E_{pt}A_{pt}L_c}{E_s A_c L_{pt}}\right)}\theta_g \tag{2}$$

where E_{pt} is the modulus of the strand; A_{pt} is the cross-sectional area of the strand; L_{pt} is the strand length; L_c is the column length; E_s is the modulus of the steel; and A_c is the cross-sectional area of the steel column. Then, the column base moment becomes

$$M = M_d + \Delta F_{pt}\frac{d_c}{2} \tag{3}$$

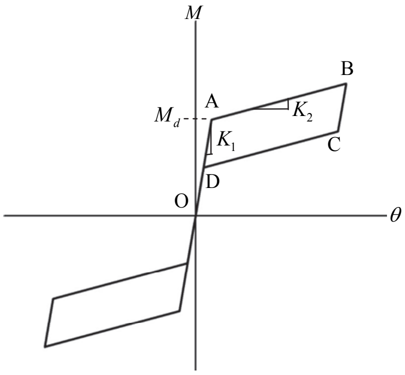


Figure 2. Column base moment versus story drift angle relationships

As shown in Fig. 3, the rotational stiffness of the subassembly, K, can be calculated as follows.

$$K = \frac{1}{\dfrac{1}{K_c} + \dfrac{1}{K_{pt} + K_f}} \tag{4}$$

where K_c is the flexural rotational stiffness of the column; K_{pt} is the rotational stiffness due to the strand; and K_f is the rotational stiffness due to the friction. When the gap is not opened, the column deflects with its flexural stiffness as

$$K_c = \frac{3E_s I_c}{L_c} \tag{5}$$

Once the gap opens, the rotational stiffness due to the strands is

$$K_{pt} = \frac{E_{pt} A_{pt} d_c^2}{4L_{pt}\left(1 + \dfrac{E_{pt} A_{pt} L_c}{E_s A_c L_{pt}}\right)} \tag{6}$$

Considering the nature of the friction, K_f is infinite when the gap is closed, and K_f is zero after the gap opens. The rotational stiffness of the subassembly is

$$K_1 = K_c \tag{7}$$

$$K_2 = \frac{1}{\dfrac{1}{K_c} + \dfrac{1}{K_{pt}}} \tag{8}$$

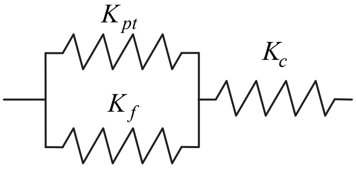


Figure 3. Rotational stiffness of subassembly

EXPERIMENTAL PROGRAM

The specimens represent a subassembly of a post-tensioned frame, including a steel column, reinforced concrete foundation, and friction dampers. Table 1 lists the test matrix and specimen design parameters. The steel columns are rolled H-shaped steel H400×400×13×21, confirming to A572 Gr. 50 steel. Due to the concentrated compressive force occured at the tip of the column base when the gap opened, the steel column was reinforced with a trapezoid steel plate on both sides of the column flange.

As shown in Fig. 4, friction dampers were installed on either the column web or the flange to investigate the effects of the location of friction damper on the behaviour. Aluminum alloy plates were used for the friction damper. Bolt gauges were used to measure the pre-tensioned force on the bolts. The magnitude of the column base moment contributed from the friction dampers, M_f, is also one of the parameters. Initial post-tensioned force, $M_{pt,i}$, varies as a ratio of the flexural yield strength, M_y, of the steel column. Design considerations includes the requirements to keep the steel column within elastic, strand force less than the design capacity when the gap opening reaching maximum value, and maximum column base moment contributed from friction dampers to attain self-centering.

Table 1. Specimen matrix

Specimen	Location of friction damper	$M_{pt,i}/M_y$	M_f/M_y
F0	None	0.40	0
WF1	Web	0.40	0.10
WF2	Web	0.40	0.25
WF3	Web	0.45	0.25
FF1	Flange	0.40	0.10
FF2	Flange	0.40	0.25

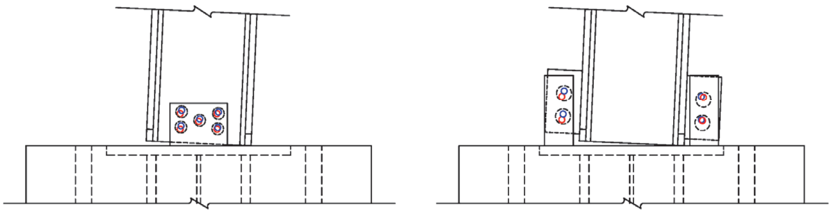


Figure 4. Location of friction dampers

TEST SETUP AND LOADING HISTORY

Fig. 5 shows the schematic and photo of the test setup. The reinforced concrete foundation was anchored on the strong floor by four high tensile rods. A hydraulic actuator applied horizontal lateral force to the column tip. Four load cells were set up on the top of the column to measure the strand force. Lateral braces were installed to prevent out-of-plane deformation of the subassembly.

Fig. 6 presents the loading history (AISC 2010). A predetermined cyclic displacement history was applied to the top of the column. The sequence included six successive cycles at the story drift angles of 0.375%, 0.5% and 0.75% rad, four cycles of 1.0% rad, and two cycles of 1.5% rad. Afterward, two cycles of 2.0% rad and over were followed until 5.0% rad.

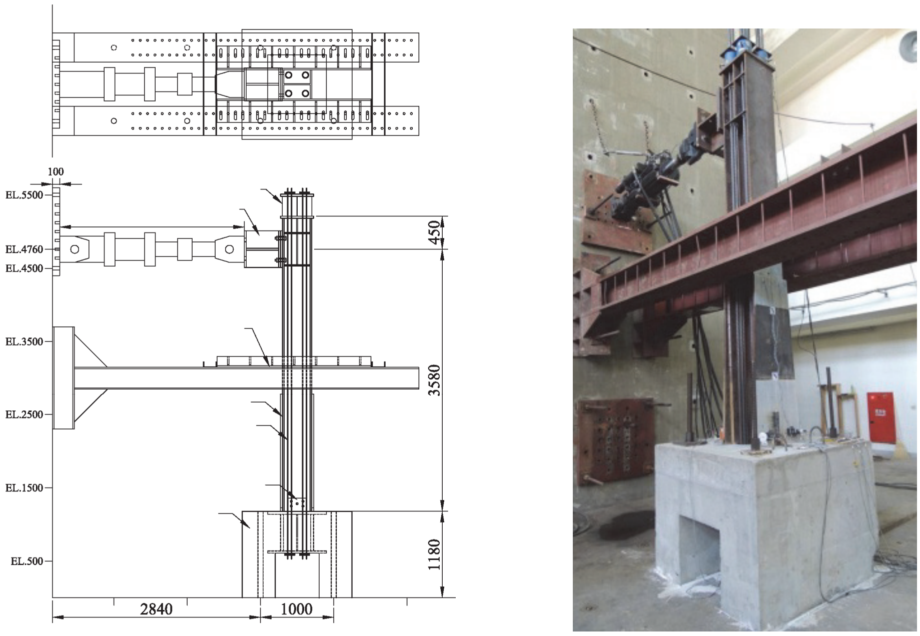


Figure 5. Schematic figure and photo of test setup

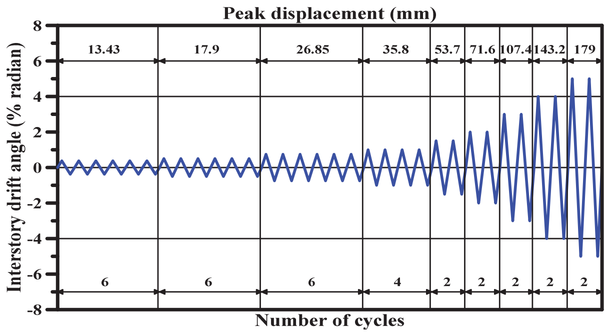
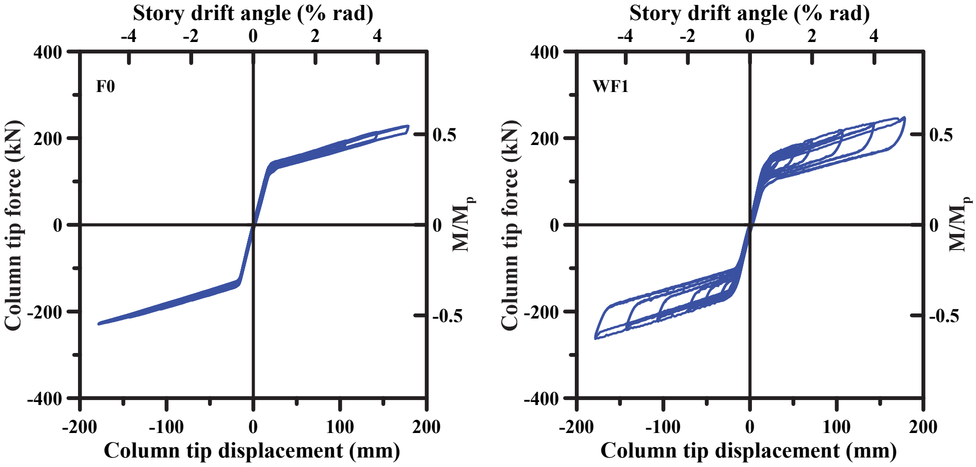


Figure 6. Loading history

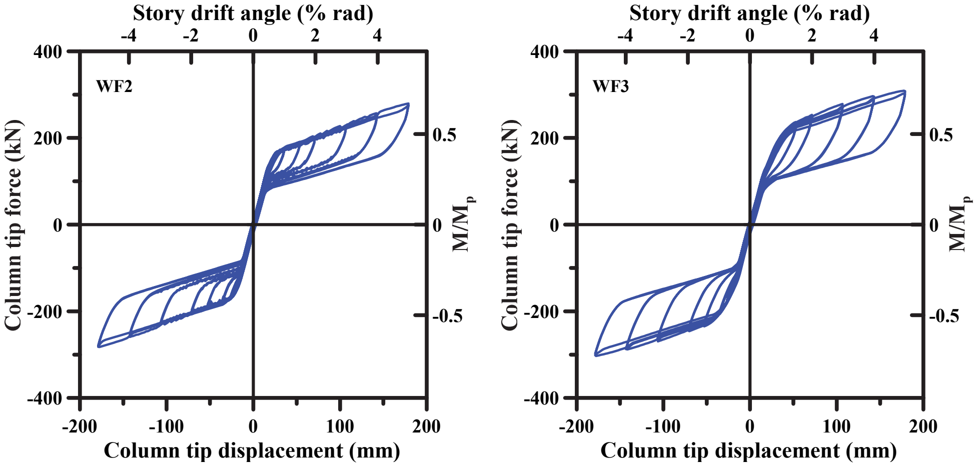
TEST RESULTS AND DISCUSSION

Test results are presented and discussed in the form of hysteretic response of the subassembly. The lateral force-displacement hysteretic curves of all the specimens are shown in Fig. 7. Specimen F0, without friction damper, demonstrated bi-linear behaviour. Before the gap was opened, linear elastic behaviour represented the flexural stiffness of the column only. After decompression, the rotational stiffness decreased attributed to the axial stiffness of the strands. Unexpected minor hysteresis loops caused by the friction between the column and lateral braces were noticed.

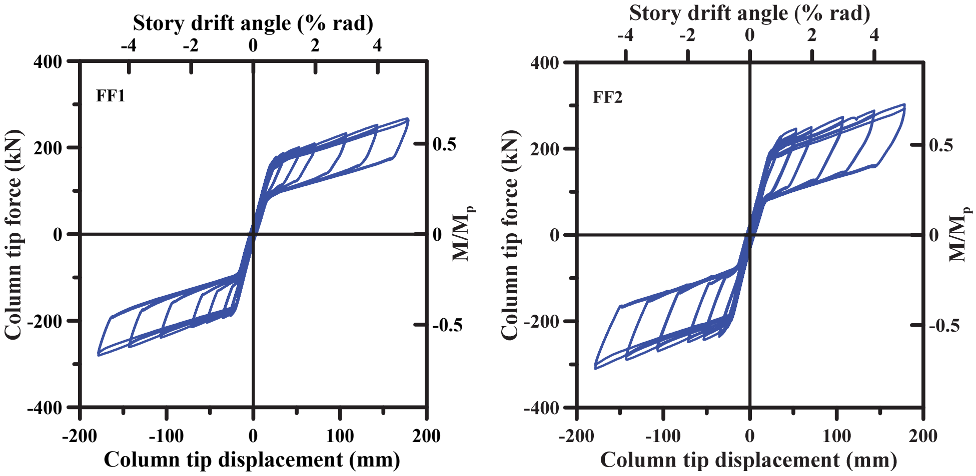
All the specimens equipped with friction dampers behaved similarly. Hysteresis loops were observed in the lateral force-displacement curves, which indicated that friction dampers provided stable energy dissipation. The post-tensioned column base connection characterized the behaviour of gap opening, gap closing, and self-centering. Fig. 8 shows the gap opening of specimen WF1 at a cycle of 5.0% rad story drift angle.


(a) Specimen F0

(b) Specimen WF1


(c) Specimen WF2

(d) Specimen WF3


(e) Specimen FF1

(f) Specimen FF2

Figure 7. Lateral force-displacement hysteretic curves of specimens

Figure 8. Gap opening of specimen WF1 at 5.0% rad drift

The WF series of specimens were designed to provide friction damper on the column web. Since the moment arm between centroid of the bolt group and rotational centre of the column during the gap opening or closing was small, the total pre-tensioned force of the bolts should be large enough to attain appropriate energy dissipation. Hence, the total pre-tensioned forces of five friction bolts used on the column web were 530, 1145 and 1056 kN for specimen WF1, WF2 and WF3, respectively. As indicated in Fig. 7, the area of the energy dissipation increased with an increase of bolt pre-tensioned force. Increasing the initial post-tensioned force of the strands can move up the hysteretic loop and ensure self-centering of the column. Furthermore, the total pre-tensioned forces of two bolts used on each side of the column flange were 179 and 407 kN for specimen FF1 and FF2, respectively. With less bolt pre-tensioned force, friction dampers on the column flange attained comparable energy dissipation as those on the column web. Moreover, increasing the bolt pre-tensioned force resulted in the increase of the decompression moment, as compared specimen FF1 with FF2. Fig. 9 shows the scratched surface of the aluminium alloy friction plate installed on the column flange.

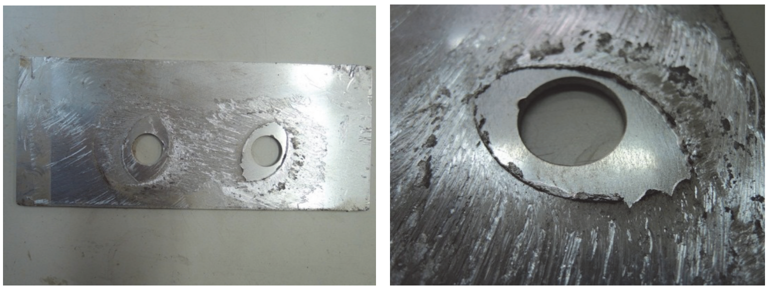
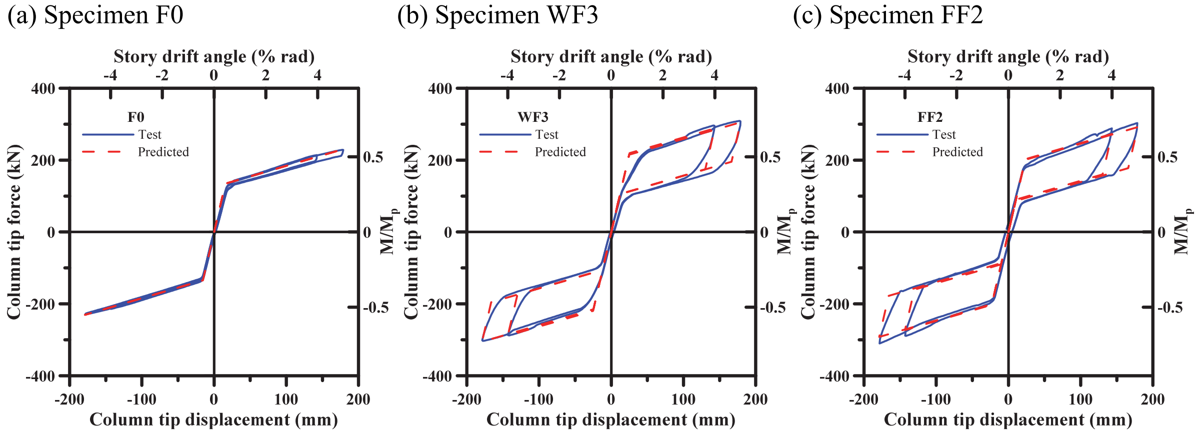


Figure 9. Scratched surface of aluminium alloy plate

Fig. 10 presents the predicted hysteretic curves calculated based on the analytical approach and experimental ones. Good correlations between predicted and experimental results had been attained. The behaviour of the post-tensioned column base connection can be well predicted by the analytical approach.



(a) Specimen F0

(b) Specimen WF3

(c) Specimen FF2

Figure 10. Comparison between experimental and predicted lateral force-displacement curves

CONCLUSIONS

On the basis of the analytical and experimental results of the post-tensioned column base connection, the following conclusions were drawn.

1. Post-tensioned column base connection is capable of achieving self-centering and no residual deformation when subjected to cyclic lateral force.
2. Friction damper can provide stable energy dissipation to enhance the earthquake resistance capability of the post-tensioned column base connection.
3. Higher bolt pre-tensioned force results in larger energy dissipation. The friction damper installed on the column flange is more effective than that on the column web.
4. The analytical approach can well predict the behaviour of the post-tensioned column base connection.

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