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Flexural Behavior of Exposed Column-Base Plate Weak-Axis Connections

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Abstract*—Most of existing small-size steel structures have been constructed without appropriate considerations for seismic design so that those structures have a potential of severe damage during an earthquake. In particular, the exposed column-base plate weak-axis connections that are the key element for small-size steel construction have the seismic vulnerability. In this study, cyclic loading tests were carried out for evaluating the flexural performance of the exposed column-base plate weak-axis connections with L-shaped threaded anchor bolts. The test specimens were designed in accordance with structural design criteria for one and two story small buildings (KSCE, 2012) and AISC design guidelines. Test parameters are the thickness of the base plate, the number of anchor bolts, the depth of the embedment length, and the presence of rib plates. Test results showed that bond performance of anchor bolts and the thickness of base plate had an influence on the structural performance and energy dissipation capacity and the L-shaped thread anchor bolts are applicable to use in the exposed column-base plate weak-axis connections of small-size steel structures. Finally, the comparison of the stiffness revealed that the column-base plate weak-axis connections that the L-shaped threaded bars were used as the anchor bolts could be the partially restrained connections

***Index Terms*—Cyclic behavior, Exposed column-base plate, Weak-axis connections, Small-size steel structures, Stiffness**

I. INTRODUCTION

Numerous existing structures have been constructed without consideration of appropriate seismic design in the world. In particular, small-size structures which is defined as a building with less than three floors and with smaller gross area than 500 m^2 occupy about 85% of the overall building structures in South Korea [Korean Structural Engineers Association (KSEA, 2012)]. According to National Emergency Management (NEM, 2011) in Korea, these structures do not need to be designed to resist earthquake. Thus, the small-size structures may have a possibility of severe damage during the earthquake.

This study focuses on the exposed column-base plate connections of small-size steel structures. Seismic performance of the exposed column-base plate connection was evaluated using both the connections with details obtained in existing steel structures and the connections with details improved the seismic performance under axial and cyclic loads.

II. TEST PROGRAM

A. Characteristics of the test specimens

Cyclic loading tests were carried out to investigate the flexural behavior of exposed steel column-base plate weak-axis connections. Fig. 1(a) shows the specimen details. The test specimens were designed by AISC design guidelines (AISC, 2003; AISC, 2005; and AISC, 2006) and Structural Design Criteria and Commentary for One and Two Story Small Buildings (KSEA, 2012). The test variables are the thickness of the base plate, the number of anchor bolts, the depth of embedment length, and the presence of rib plates (see Table 1 and Fig. 1). The size of the steel column with H-section (SS400, F_y = 235 MPa) is H-300 × 300 × 10 × 15 mm and its height is 1,000 mm. Here, F_y is the design yield strength. Test specimen had the number of four and six anchor bolts. In four specimens, the round bars were used as the anchor bolts and the threaded bars were used in two specimens. The diameter of the anchor bolt is 22 mm and SM45C steel (F_u = 700 MPa) was used, where F_u is the tensile strength of the material. The thread anchor bolts are manufactured in the factory to produce threads with a depth of 1 mm in steel rods having a diameter of 24 mm and have the same cross-sectional area as that of steel rods without threads. The concrete foundation had a dimension of 800 x 800 mm and the height is 775 mm. The design compressive strength of the concrete used for the foundation is 24 MPa. Mortar grouting was not performed between the base plate and the base concrete.

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Fig. 2 shows the detailed cross-section of the test specimens. For the WDf1 and WDf2 specimens, the size of the base plate is 400 x 400 mm and the thickness is 20 mm. A total of four anchor bolts with a depth of 500 mm are used. The length of the anchor bolt hook is 264 mm, and in WDf2, two rib plates were additionally installed at the center of the web. For WA series specimens, the base plate thickness is 450 x 450 mm, the embedment length of anchor bolt is 650 mm, and the anchor bolt hook length is 264 mm.

For the WA1, WA2 and WA3 specimens, the thickness of the base plate is 25 mm and the thickness of the base plate of the WA4 specimen is 30 mm. In the WA1, WA2, and WA4 specimen, the rib plates were not installed on the specimen, and two rib plates were installed on the WA3 specimen. Four anchor bolts were used for the WA2 specimen, and six anchor bolts were installed for the WA1, WA3, and WA4 specimens. The round steel bars were used for the anchor bolts of all the specimens except WA3 and WA4 specimens. On the other hand, L type hooked anchor bolts with threads were used for WA3 and WA4 specimens.

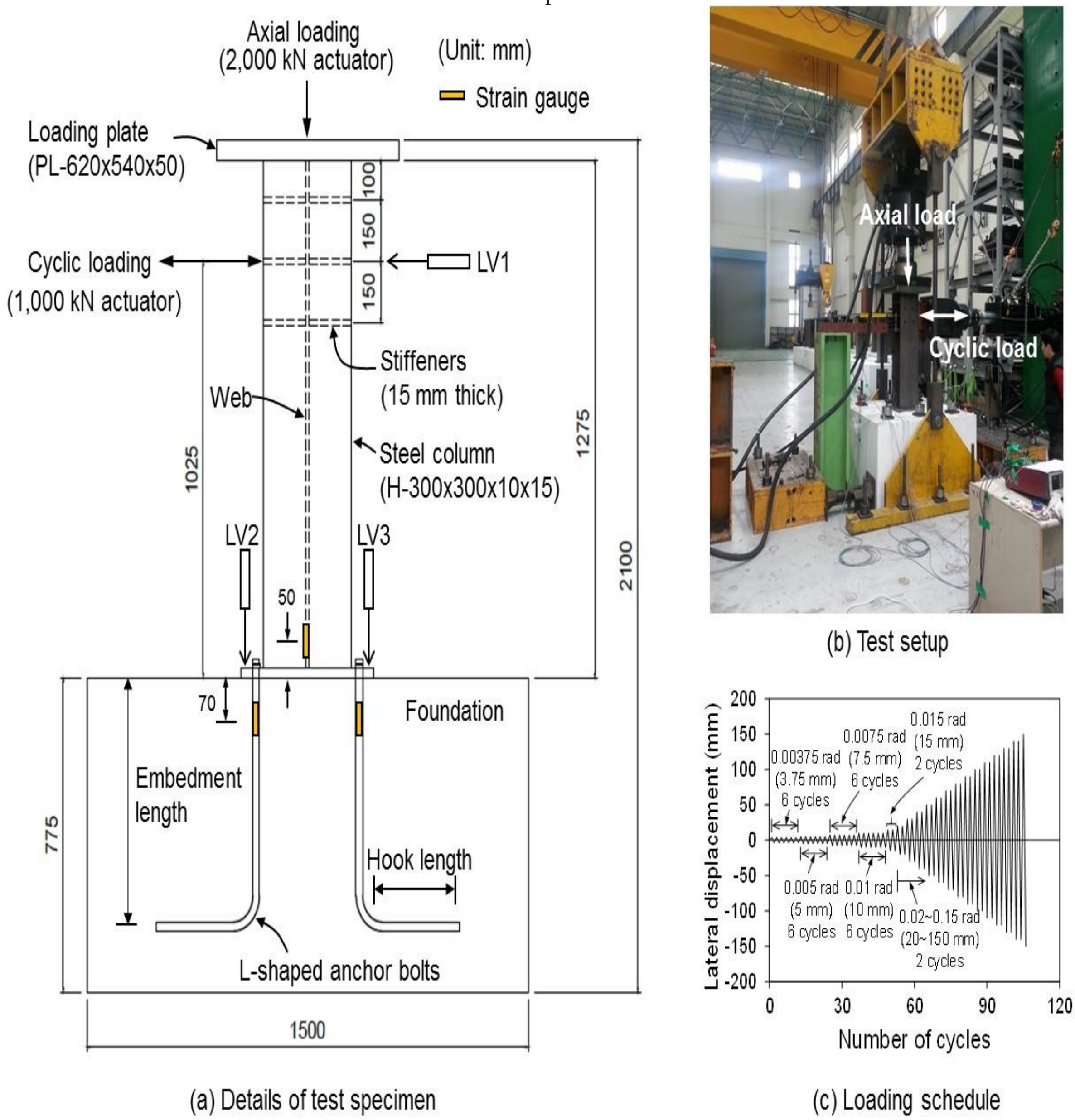

Fig. 1: Configuration of the test specimens and test setup

Table 1: Characteristics of test specimens

Specimens	Base plate		L-shaped anchor bolt					No. of rib plates
	Dimension (mm)	Thickness (mm)	No. (EA)	Diameter (mm)	Embedment length (mm)	Hook length (mm)	Type	
WDf1	400×400	20	4	22	500	264	Round bars	-
WDf2	400×400	20	4	22	500	264	Round bars	2
WA1	450×450	25	6	22	650	264	Round bars	-
WA2	450×450	25	4	22	650	264	Round bars	-
WA3	450×450	25	6	22*	650	264	Thread bars	2
WA4	450×450	30	6	22*	650	264	Thread bars	-

* The diameter of L-shaped threaded anchor bolt for the WA3 and WA4 specimen means the effective diameter.

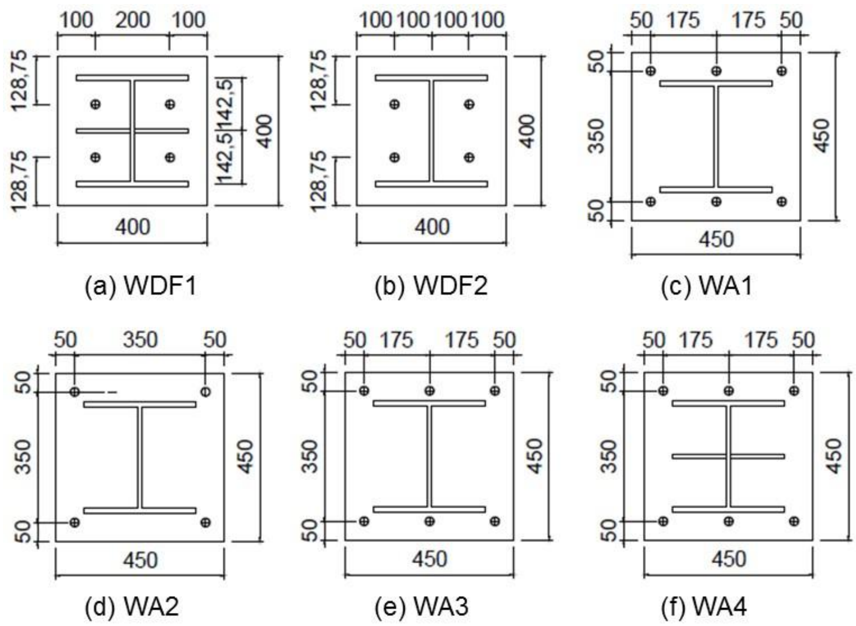

Fig. 2: Cross-section of the test specimens

B. Test Setup

The specimens were subjected to a lateral force at a distance of 1000 mm from the top of the foundation using an actuator with a capacity of 1000 kN and an axial force of $0.15F_yA_g$ (= 413 kN) was applied using a 2000 kN capacity dynamic actuator as shown in Fig. 1(b). Fig. 1(c) shows the load history curve. The first step (6 cycles) is 0.00375 rad (= 3.75 mm), the second step is 0.005 rad (5 mm), the third step is 0.0075 rad (7.5 mm), 0.01 rad (10 mm) for the fourth cycle, 0.015 rad (15 mm) for the second cycle, 0.02 rad (20 mm) for the second cycle, (2 cycles), it was repeatedly increased by 0.01 rad increments [ANSI/AISC 341-10, 2010]. Here, θ is the rotation angle, and is obtained by dividing the lateral displacement (mm) measured by the LVDT with the distance from the concrete base to the loading point.

The strain and displacement were measured by strain gage and Linear Variable Differential Transducers (LVDTs) respectively shown in Fig. 1(a). The lateral displacement of the column was measured by the LV1 at a distance of 1000 mm from the base plate. The LV2 and LV3 were installed on the base plate to measure the vertical deformation of the base plate.

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C. Material Properties

To investigate the material properties of the steel column, base plate, and anchor bolt, material tests were carried out in accordance with ASTM E8/E8M (2016) and ASTM A615/615M (2016). Table 2 shows the properties of the steel used for each specimen. SS400 grade steel was used for the steel column of all specimens and SM45C grade steel was used for anchor bolts, regardless of thread presence.

Table 2: Material properties

Specimens	Members		Yield Strength (MPa)	Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Elongation (%)
WDf1 WDf2 WA1 WA2	Base plate (SS400)		250.0	422.9	196.1	35.4
	Column (SS400)	Flange (15 mm)	329.0	476.4	203.8	32.0
		Web (10 mm)	332.2	498.2	206.2	30.2
	Anchor bolt (SM45C)		608.7	757.2	201.6	10.8
WA3 and WA4	Base plate (SS400)	25 mm	243.7	440.7	170.7	28.7
		30 mm	296.7	523.1	151.5	26.6
	Column (SS400)	Flange (15 mm)	299.3	458.1	202.8	41.1
		Web (10 mm)	324.8	179.2	199.6	37.3
	Anchor bolt (SM45C)		414.0	577.4	123.9	4.2

III. TEST RESULTS AND CONCLUSION

A. Failure Modes

Fig. 3 shows the typical failure mode of a typical column-base plate weak-axis connection. As shown in Fig. 3(a), the anchor bolt was pulled out, resulting in slip behavior. Especially, in case of WDf1 and WDf2 specimens, the yielding on the compression plane of the base plate occurred before yielding of anchor bolts. The fracture modes of the two specimens were very similar. The compressive yield of the base plate occurred at about 0.029 rad and the yield of the anchor bolt occurred after 0.03 rad. On the other hand, for WA1 specimens, the yielding of the anchor bolts preceded the yielding of the base plate. Fig. 3(b) shows the final fracture shape of the WA1 specimen. The anchor bolts yielded about 0.01 to 0.02 rad displacement, after which the base plate surrendered at about 0.03 rad. For the WA2 specimen, yielding of the base plate and yielding of the anchor bolt occur almost simultaneously. In case of WA3 and WA4 specimens using 6 anchor bolts with thread, the anchor bolt pulling phenomenon can be prevented somewhat due to the increase of the anchor bolt attachment. Fig. As shown in Fig. 3(c), local buckling occurred at the lower flange of the WA4 column at a rotation angle of 0.01 rad.

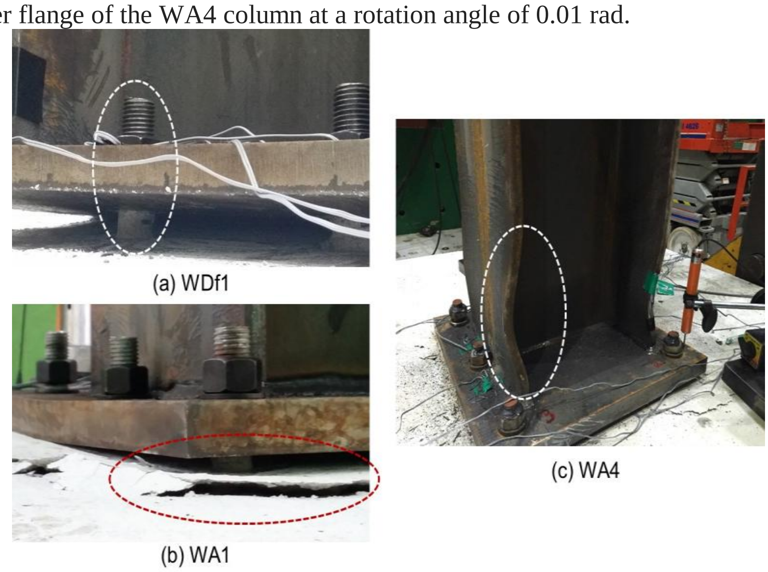

Fig. 3: Failure modes of test specimens

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B. Moment-rotation Angle Curves

Fig. 4 shows the moment-rotation relationship of each specimen. The plastic moment (M_p) of the steel column (= F_yZ_w) is 160.7 kN.m. Here, F_y is the design yield strength (= 235 MPa) of the steel column and Z_w is the section modulus (= 684 x 10^3 mm^3). The yield point is defined as the intersection point at which the line connecting the point corresponding to 75% of the peak load and the vertical line at the point where the horizontal line at the maximum load meets the moment-curvature curve of the test specimen. The lateral displacement (Δ) represents the value of the displacement measured at the point of load force and θ represents the rotation angle. Initial stiffness (k_y) is the slope of the straight line connecting the origin and yield point. The lateral displacement at failure was defined as the point at which 80% of the peak moment strength as shown in Fig. 5 (Lim et al., 2016).

Test results showed that the peak moment of the WDf1 and WDf2 specimens were less than the plastic moment due to the pullout failure of the anchor bolts. For the WA series specimens with anchor bolts installed outside the steel columns, the peak moment of all specimens exceeded the plastic moment. As a result, the location and the number of the anchor bolts had a great influence on the flexural behavior of the connections. In case of the WA1 and WA2 specimens, the pinching phenomenon was somewhat alleviated in comparison with the WDf series. Especially, the flexural performance of the WA3 and WA4 specimens that have threaded anchor bolts was improved due to the fact that the bond strength of anchor bolt is enhanced compared with other test specimens.

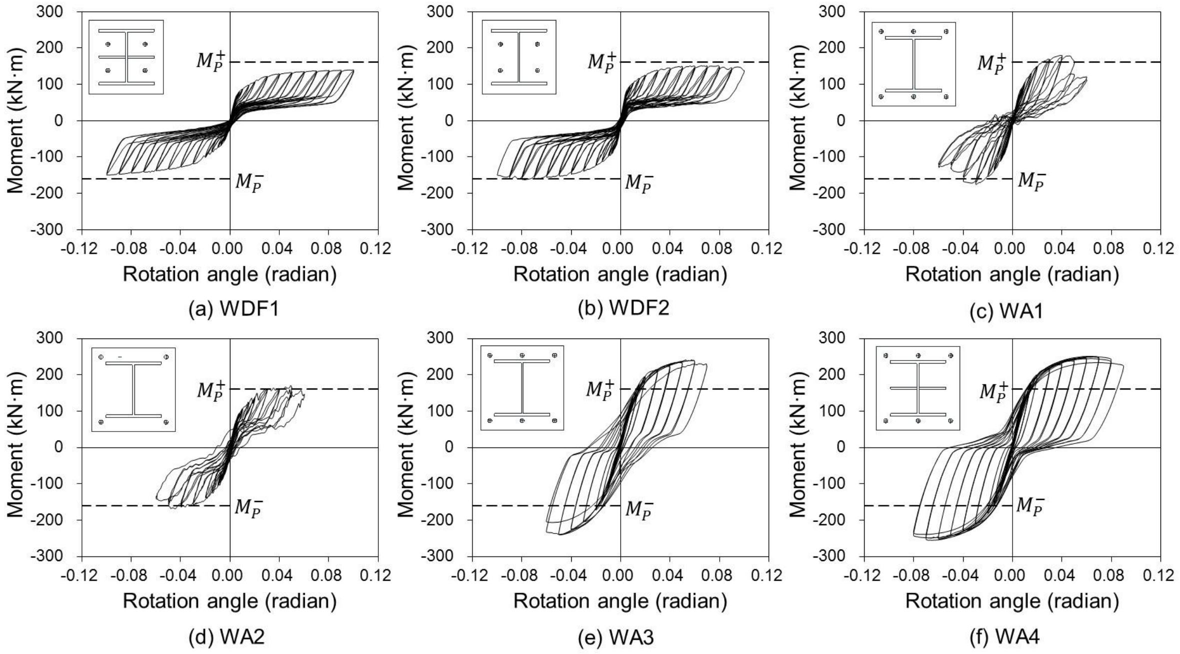

Fig. 4: Moment-rotation angle curves

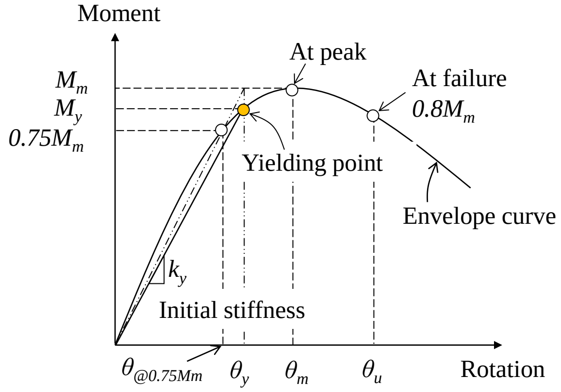

Fig. 5: Definition of yielding point and initial stiffness

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C. Energy Dissipation Capacity

Fig. 6 represents the cumulative energy dissipation capacity per target displacement. In this study, the cumulative energy dissipation capacity was obtained by summation of all the energy dissipation per target displacement (ACI T1.1-01, 2001).

The cumulative energy dissipation capacity of the WA3 and WA4 specimens with threaded anchor bolts at a rotation angle of 0.06 rad was 2.15 times greater than that of WDf1 and WDf2 specimens. These results are considered to be due to the fact that the anchor bolts with thread are excellent in the bond performance and the energy is sufficiently dissipated from the base plate and the column flange after the local buckling occurred in the column flange.

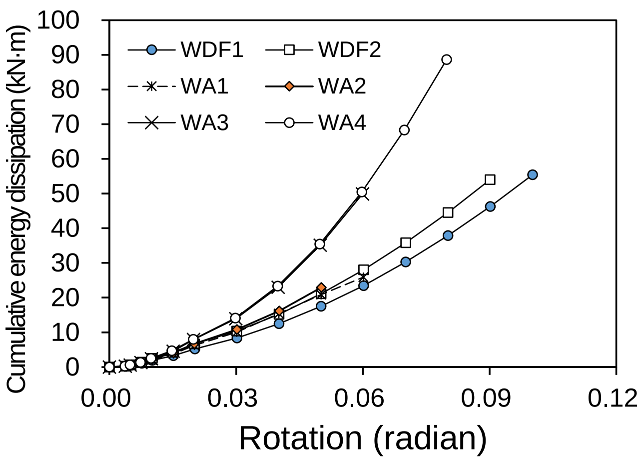

Fig. 6: Cumulative energy dissipation

D. Stiffness

The stiffness of the weak-axis connection was highly dependent on the test parameters such as the bond capacity of the anchor bolt, the thickness of the base plate, and the number of anchor bolts. Table 2 compares the initial stiffness of the weak-axis connection obtained from the experimental results and the value proposed in NZS 3404 (2009). As a result of comparison, all the specimens were smaller than the lower limit ($k_f = 1.67EI_c/L_c$) assuming fixed joint at NZS 3404 and larger than the upper limit ($k_p = 0.1EI_c/L_c$) assuming pinned connection. Here, E is the elastic modulus, I_c is the moment of inertia, and L_c is the length of the column. These results indicate that the proposed weak-axis connection can be assumed to be a semi-rigid connection.

Table 2: Comparison of initial stiffness between test data and NZS 3404 (2009) design codes

Specimens	Fixed end		Pinned end	
	k_y^+/k_f	k_y^-/k_f	k_y^+/k_p	k_y^-/k_p
WDf1	0.18	0.17	2.94	2.64
WDf2	0.17	0.14	2.77	2.27
WA1	0.35	0.35	5.53	5.66
WA2	0.32	0.32	5.11	5.12
WA3	0.38	0.35	6.09	5.53
WA4	0.40	0.35	6.45	5.66

Note: k_y^+ and k_y^- are the initial stiffness for positive and negative loading, respectively.

IV. CONCLUSION

In this study, the flexural performances of the exposed column-base plate weak-axis connections with various details are evaluated through cyclic loading tests. The experimental parameters are the thickness of the base plate, the number of the anchor bolts, the depth of the embedment length, and the presence of the rib plate. The findings of the experimental study are as follows.

(1) Test results showed that bond performance of anchor bolts and the thickness of base plate was attributed to the

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structural performance and energy dissipation capacity of the column-base plate weak-axis connections. Even if satisfied with the requirements for minimum thickness of the base plate that is provided in the current design provisions, which means that the base plate has been yielded prior to reaching the capacity of steel column to plastic moment, the structural performance of the connections could be decreased.

(2) The L-shaped thread bars are applicable to use as anchor bolts in the exposed column-base plate weak-axis connections of small-size steel structures. When the anchor bolts for column-base plate connections are designed according to current concrete design codes, if the bond strength of the bars is insufficient, the slip behavior may occur during the lateral cyclic loading. However, when the L-shaped threaded bars are used in the connections, the flexural moment strength, energy dissipation capacity, and stiffness were improved.

Finally, the comparison of the stiffness revealed that the connections with improved details could be the partially restrained connections. The stiffness of connections with thread anchor bolts placed beyond the cross-sectional area of the steel column was in the range between the lower limit for assuming fixed ends and upper limit for pinned ends which was obtained in accordance with current design guidelines (NZS 3404, 2009)

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