# Bolted End-Plate Splice Method for Composite Column (BB Splice for PSRC Column)

**Jong–Jin Lim[1*], Dae-Kyung Kim[2], Seung-Hwan Lee[3] and Tae-Sung Eom[4*]**

[1] Senvex Co. Ltd., Seoul, Korea. *jjim@senkuzo.com.*
[2] Dep. of Architecture and Architectural Engineering, Seoul National Univ., Seoul, Korea. *wc2005@snu.ac.kr*
[1] Senvex Co. Ltd., Seoul, Korea. *shlee@senkuzo.com*
[3]Dep. of Architectural Engineering, Dankook Univ., Gyeonggi-do, Korea. *tseom@dankook.ac.kr (corresponding author)*

## Abstract

A bolted end-plate splice (BB splice) of L-shaped steel angles for encased composite column (PSRC column) is investigated. End plates are welded to the end of the spliced angles at a shop and are butted to each other with bolt tightening. Due to the bearing surface of end-plate, it is easy to connect column splice and the number of bolts can be reduced with a consideration of tensile resistance of bolts. The deformation and prying action need to be considered for a bolted end-plate splice, because the centroids of the angle and bolt sections do not coincide. Thus, the minimum thickness of end plate is proposed based on the yield line theory, and the tensile strength of the connection decreased by the prying force is estimated. The direct tension tests of bare angle splice and flexural tests of the encased composite column are performed to investigate the strength and failure mode of the connection. In addition, the stress distribution and force transfer mechanism are investigated through the finite element analysis. The proposed design method of bolted end-plate splice agrees well with the experimental and analytical results.

**Keywords:** Column splice, Bolted connection, End plate connection, Encased composite column, FE analysis

## 1. Introduction

In recent years, many prefabrication schemes using composite column, beam, and slabs have been developed to increase structural and economical efficiency. As a kind of prefabrication members, prefabricated steel-reinforced concrete (PSRC) column was developed as shown in Figure 1. In the PSRC column, the L-shaped angles are arranged around the column section. Thus, the tensile forces of angles can be significant when bending moment is applied.

The conventional slip-critical connection is relatively difficult to install at a construction site and the number of bolt rows tends to be increased. In addition, each angle located around the column section must be well aligned without tolerances to install lap plates and bolts. To overcome such problems of slip critical connection, the bolted connection method for PSRC columns using end-plates have been developed in this study (refer to Figure 2).


(a) Prefabrication in a shop (b) Erection in a construction site

Figure 1. Erection of prefabricated composite column

## 2 Design procedure

### 2.1. Minimum thickness of end plate

Since the lines of action of the angle and bolt tensions do not coincidence, deformation of end plate is inevitable. Thus, to reduce the excessive deformation of end plate and resulting prying action, limitations on end-plate thickness and bolt arrangement are required. Figure 2 shows the deformation and yield lines of the end plate occurring in the one-bolt connection at ultimate limit state.

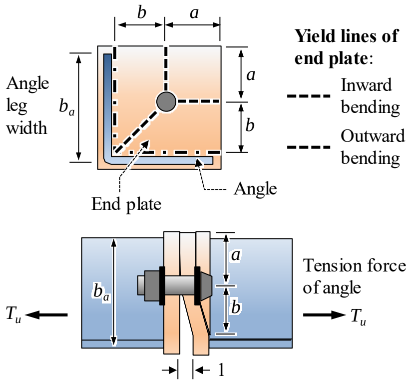


Figure 2. Yield line pattern of end-plate in tension

According to plastic theory, when a unit virtual displacement occurs in a left angle due to the applied tension Tu, the external work done by the angle tension should be the same as the internal strain energy stored in the end plate along the yield lines. Thus,

$$T_u \cdot 1 = m_p\left(2b+4a\right)\frac{1}{b} + m_p\sqrt{2}b\frac{\sqrt{2}}{b} = 4m_p\left(1+\frac{a}{b}\right) \qquad (1)$$

where $a$ and $b$ are the length parameters representing the yield lines of the end plate, and $m_p$ is the plastic moment strength of the end plate per unit length (= $F_y t_p^2/4$). Finally, the minimum thickness of the end plate, $t_{p,min}$, is as follows:

$$t_{p,\min} = 1.1\sqrt{\frac{T_u}{F_y\left(1+a/b\right)}} \tag{2}$$

A safety factor 1.1 is additionally included in Eq (2) according to AISC 358-16, because the yield lines shown in are ideal ones and thus the resistance of the end plate cannot be fully attained. If the thickness of end plate is not less than $t_{p,min}$, the deformation of end plate decreases and thus prying force at the connection is reduced. Note that the distance between bolt and angle $b$ should be same or smaller than $0.5b_a$ to reduce the eccentricity between angle and bolt.

2.2. Tensile strength of connection

For the one-bolt connection, the tensile strength of the connection due to bolt rupture, $T_n$, can be calculated as follows:

$$T_n = \lambda F_{nt} A_b \tag{3}$$

where $F_{nt}$ is the net tensile strength of the bolt considering the reduction in the threaded portion, which is taken as $0.75\ F_u$, $F_u$ is the ultimate strength of the bolt, and $A_b$ is the area of the bolt. A reduction factor $\lambda$ is used to consider an increase in bolt tension due to prying action. In fact, prying action is affected by various parameters, such as the thickness and dimension of the end plate, and the number, diameter, and location of the bolts. Thus, the $\lambda$ should be determined through experimental and analytical results. In this experimental study, the $\lambda$ is takes as 0.9.

## 3. Direct tension test of angle splices

Direct tension tests of the bolted end-plate connection for angle splice were performed. The size of angles was L-100x100x10. The end plates used for the connection were 120 mm x 120 mm in size, and their thickness was $t_p$ = 25 mm. Different diameters of high-strength M24 and M30 bolts were used for EPS1 and EPS2, respectively. As shown in Table 1, the thickness of end plate in EPS1 satisfies the $t_{p,min}$ (= 22.3 mm). However, in EPS2, the thickness of end plate was smaller than the required thickness of end plate $t_{p,min}$ (= 27.8 mm).

Table 1. Experimental results of angle splice

| Specimen | EPS1 | EPS2 |
|---|---|---|
| Failure mode | Bolt fracture in threaded portion | Slip failure of bolt threads |
| $T_u$ | 344 | 402 |
| $T_n = \lambda F_{nt} A_b$ | 336 | 523 |
| $t_{p,min}$ 1) | 22.3 | 27.8 |

1) The required thickness of end plate, $t_{p,min}$, was computed by substituting Tn for $T_u$ in Eq. (2)

Figure 3 shows the UTM (universal testing machine) load-displacement relationships of EPS1 and EPS2. Overall, both EPS1 and EPS2 showed ductile behaviors, although the threaded slip and rupture of the bolts occurred ultimately. Particularly, for the end-plate connection of angles tested in this study, the threaded slip occurred due to the bending action of the bolt shank caused by the prying action and deformation of the end plates, and thus the thread failure and subsequent rupture of the bolts occurred gradually along with considerable inelastic deformations.

As shown in Table 1, the maximum tension loads of the angle pulled directly were $T_u$ = 344 and 402 kN for EPS1 and EPS2, respectively. Such $T_u$ values were slightly less or more than a half of the yield strength of the spliced angle (i.e. $0.5F_yA_a$ = 388 kN). The predicted connection strengths, $T_n$ = 336 and 523 kN, were computed from Equation (2) by substituting $T_n$ for $T_u$.

For EPS1, the provided thickness of the end plate was greater than required $t_{p,min}$, and thus the deformation of end plate resulting prying force at the connection were relatively limited. Consequently, the connection strength by test, $T_u$ = 344 kN, was almost the same as the predicted strength, $T_n$ = 336 kN. The failure mode of EPS1 was bolt rupture in the threaded portion. In contrast, for EPS2 with M30 bolt, the provided thickness of the end plate, $t_p$ = 25 mm, was less than the required $t_{p,min}$ (= 27.8 mm). Furthermore, due to the increased deformation of the end plates, the separation between the top and bottom end plates was greater than 25 mm. Consequently, the connection strength by test, $T_u$ = 402 kN, was significantly less than the predicted strength, $T_n$ = 523 kN. The failure mode of EPS2 was slip in the threaded portion of the bolt.

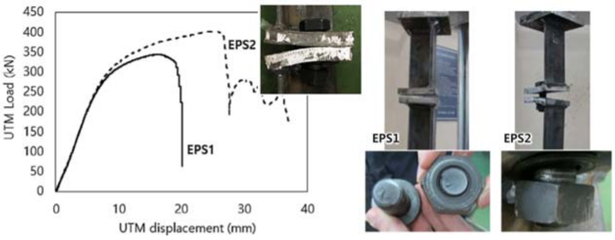


Figure 3. Yield line pattern of end plate in tension

The results direct tension tests indicate important issues regarding the design of bolted end-plate connection of angle, as follows:

1) In the one-bolt connection, the ultimate limit state is bolt rupture, rather than yielding of spliced angle.
2) The connection strength is significantly affected by the thickness of end plate. To prevent excessive deformation of end-plate and the resulting prying force, end plates of sufficient thicknesses greater than the minimum thickness $t_{p,min}$.

## 4. Flexural test of PSRC column splices

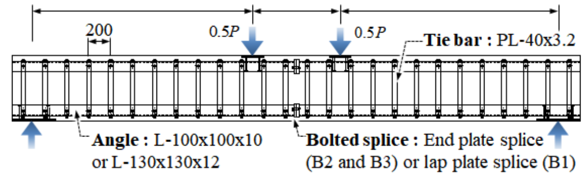
4.1 Test plan

Flexural tests of the PSRC column using the bolted end-plate splice of angle were performed. Figure 4 shows details three PSRC column specimens B1-B3. Gross-sectional dimensions of the columns were 600 mm x 600 mm, and their overall length was 5200 mm. Four L-100x100x10 and L-130x130x12 angles were used in B1 to B2 and B3, respectively. In each column, the bolted end plate splices of angle were placed at mid-span.

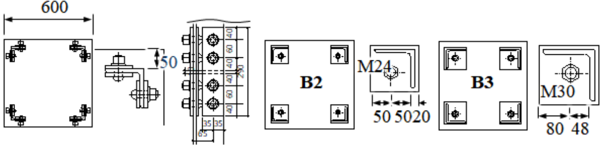
For B1, as shown in Figure 4(b), twelve M24 bolts per angle (L-100x100x10) were used for the friction-type splice. Lap plates of 9 mm thickness were used. The thickness of concrete cover was 50 mm. For B2, one M24 bolt per angle (L-100x100x10) was used at the bolted end-plate connection. The overall dimensions of the end plate were 120 mm x 120 mm, and its thickness was $t_p$ = 25 mm. The length parameters of the end plate were $a = b$ = 50 mm. For B3, the sized of angle and bolt were increased to L-130x120x12 and M30, respectively, and the thickness of the end plate was also increased to 30 mm.

The coupon tests were performed to investigate the material strengths. The yield strengths of L-10T and L-12T angles were 349 MPa and 348 MPa, respectively. The yield strengths of end plates with the thickness of 25 mm and 30 mm were 403 MPa and 368 MPa, respectively. In addition, the ultimate strengths of high-strength bolts of M24 and M30 were 1025 MPa and 1060 MPa, respectively.

As shown in Figure 4(a), simple beam test of two-point loading was applied to the PSRC column specimens. Thus, the columns were horizontally placed on the roller supports at both ends. To produce a uniform bending moment region in mid-span where the angle splices were located, the loading was symmetrically applied at two points. The UTM loads were unloaded to zero at 60~75% of the nominal strengths, and then reloaded until failure of the columns.



(a) Configuration of angles, tie bars, and end plate splice



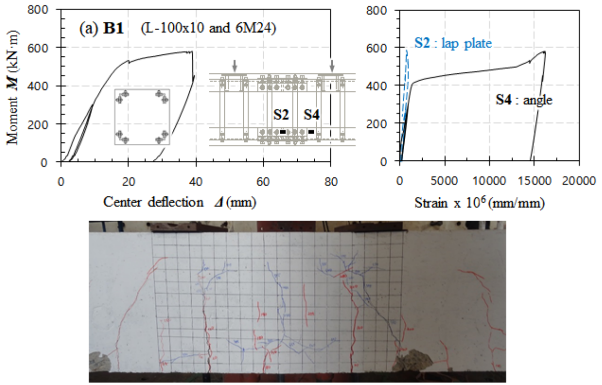
(b) Lap plate splice detail of **B1** (c) End plate splice details of **B2 and B3**

Figure 4. Dimensions and connection details

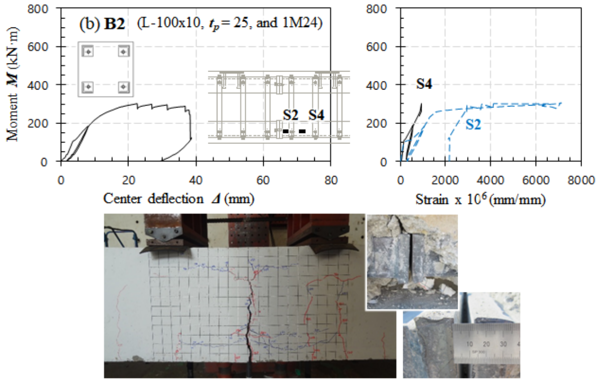
### 4.2 Test results

Figure 5 shows the midspan moment-deflection ($M - \Delta$) relationships, failure modes, and strain measurements (i.e. $M - \varepsilon$ relationships) of columns. The midspan column moment $M$ was computed by multiplying a half of the UTM load (=0.5$P$) by shear span (= 2000 mm).

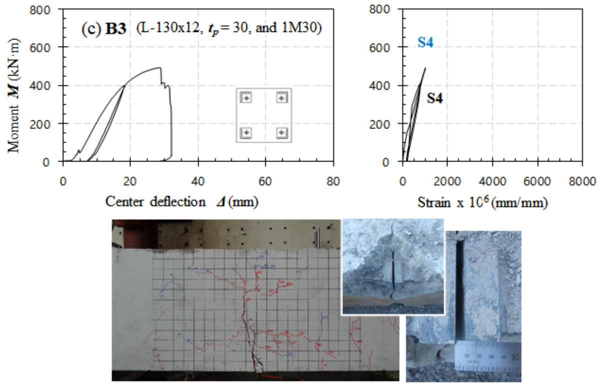
In B1 with friction-type angle splice (see Figure 5(a)), vertical cracks occurred in midspan with relatively uniform intervals. Such vertical cracks were not concentrated at the column splice, but distributed over the uniform bending moment region. The crack width was greater at the distance of 300 mm from the center of the span to both sides, which indicates that slip deformation of the angle was effectively restrained. In the $M - \Delta$ relationship, a post-yield ductile behavior occurred, and the maximum load was $M_u$ = 581 kN-m. Finally, net section fracture of the spliced angle occurred in the splice region. The test strength $M_u$ = 581 kN-m was slightly less than the calculated strength $M_n$ = 594 kN-m based on the tensile strength of the net section. As shown in $M - \varepsilon$ relationships, strain of lap plate at the connection (S2) remained in the elastic range, while the angle strain outside the splice region was significantly greater than the yield strain.



Concrete cracking in midspan



Concrete cracking and end plate deformation



Concrete cracking in midspan

Figure 5. Load-deflection relationships, strains, and failure modes

In B2, with the bolted end-plate splice of L-100x100x10 angles ($t_p$ = 25 mm and M24 bolt), the stiffness and maximum load ($M_u$ = 303 kN-m) were less than those of B1. During the post-yield ductile behavior after $\Delta$ = 15 mm, the width of the vertical crack occurring near column splice increased significantly. The failure modes were excessive deformation of the end plates and slip in the threaded portion of the bolts. Such failure modes indicate that the prying action at the connection was significant. As shown in the $M - \varepsilon$ relationships, the angle strains (S2) measured at the location of the net section with holes for connecting flat tie bars exceeded the yield strain (0.00175 mm/mm). In contrast, the angle strain (S4) measured at the gross section remained in the elastic range.

For B3 using L-130x130x12 angles, end plates of $t_p$ = 30 mm, and M30 bolts, the maximum loads were increased to $M_u$ = 495 kN-m. The width of vertical cracks occurring at the location of the angle splice in midspan increased significantly. The principal failure mode was bolt rupture occurring in the threaded portion. As shown in the $M - \varepsilon$ relationships, the angle strains remained in the elastic range.

### 4.3 Comparison of the predicted and test strengths

To compare the predicted and test strengths, the tension force $T_u$ acting on the bottom angle was calculated by the cracked section analysis, as shown in Figure 6. For the cracked section analysis, the tensile stress of concrete was neglected, and under compression, a linear stress-strain relationship following the elastic modulus $E_c$ = 26400 MPa was assumed.

In B2 and B3, the nominal strengths $T_n$ computed from Equation (3) were 47% ~ 49% of the yield strength of angle (= $F_yA_a$, where $F_y$ and $A_a$ = yield strength and gross section area of the angle, respectively). The tension forces of angle $T_u$ calculated from cracked section analysis were larger than the nominal strength $T_n$ ($T_u/T_n$ = 1.05 and 1.10, respectively, in B2 and B3). In addition, B2 and B3 satisfied the minimum thickness of end plate computed from Equation (2) by substituting $T_n$ for $T_u$.

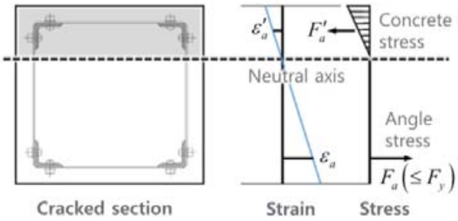


Figure 6. Cracked section analysis of PSRC column

## 5. Design procedure and recommendations

Based on the investigations discussed in the previous sections, the design procedure of the bolted end-plate connection of angle used for encased composite columns such as the PSRC column, is suggested as follows.

1) Required strength of angle, $T_u$: By performing a cracked section analysis on member forces (i.e. combined axial load $N_u$ and bending moment $M_u$) acting at the location of the column splice, the tension force of the angle, $T_u$, is calculated. Since $T_u$ cannot exceed the yield strength of the angle, $T_u$ is taken as $F_yA_a$ if the calculated tension force is greater than $F_yA_a$. In addition, if $T_u$ is less than $0.5F_yA_a$, $T_u$ is taken as $0.5F_yA_a$ for conservative design.
2) Bolt arrangement: The primary bolt, placed close to the centroid of the angle section, should be located at a distance b not greater than 0.5ba from the surface of the angle (i.e. $b \le 0.5b_a$).
3) Size and thickness of end plate: The size of the end plate is determined so that $a + b \le b_a$. In addition, the thickness of the end plate, which is not less than $t_{p,min}$ computed by Equation (2) based on the required strength of the angle, $T_u$, is assumed.
4) Connection strength by bolt rupture: By assuming the diameter and arrangement of bolts, the tensile strength of the connection, $T_n$, expressed in terms of angle tension, is computed by equation (3). The computed $T_n$ should satisfy $\phi T_n \ge T_u$ ($\phi$ = 0.75).

## 6. Conclusions

In this study, the bolted end-plate connection of angle that is sued to spliced encased composite columns was investigated. By performing both direct tension tests of bare angle splice and flexural tests of composite PSRC column splice, the strength and failure mode were investigated. The conclusion are as follows

1) For the bolted end-plate connection of angles in tension, the connection strength is less than the tensile strength of the bolt, due to prying action.
2) The minimum thickness of end plate is determined based on the yield line theory. The minimum thickness of end plate required at the connection increases with increasing angle tension, but decreases when the yield strength of the end plate is large.
3) The bolt needs to be placed as close to the centroid of the angle section as possible. According to the tests, the predicted connection strength based on bolt rupture agrees well with the test strength.
4) The connection strength is less than the yield strength of the spliced angle. Thus, when the bolted end-plate angle connection is used for encased composite columns, the splice zone should be located where bending moment is not large.

## 7. References (Times New Roman, 10 Point, Bold)

Eom, T. S., Hwang, H. J., Park, H. G., Lee, C. N., and Kim, H. S. (2013). “Flexural test for steel-concrete composite members using prefabricated steel angles.” *Journal of Structural Engineering*, 140(4).

Murray, T. M., and Sumner, E. A. (2003). Steel design guide 4 extended end plate moment connections seismic and wind applications. Chicago: AISC.

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