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Shear strength formula of CFST column-beam pinned connections

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Abstract. Recently, as the height of building is getting higher, the applications of CFST column for high-rise buildings have been increased. In structural system of high-rise building, The RC core and exterior concrete-filled tubular (CFST) column-beam pinned connection is one of the structural systems that support lateral load. If this structural system is used, due to the minimal CFST column thickness compared to that of the CFST column width, the local moment occurred by the eccentric distance between the column flange surface from shear bolts joints degrades the shear strength of the CFST column-beam pinned connections. This study performed a finite element analysis to investigate the shear strength under eccentric moment of the CFST column-beam pinned connections. The column's width and thickness were used as variables for the analysis. To guarantee the reliability of the finite element analysis, an actual-size specimens were fabricated and tested. The yield line theory was used to formulate an shear strength formula for the CFT column–beam pinned connection. the shear strength formula was suggested through comparison on the results of FEM analysis, test and yield lime theory, the shear strength formula was suggested.

Keywords: shear strength; concrete filled tubular column; pinned connections; width-thickness ratio; yield line method; fem analysis.

1. Introduction

In concrete filled steel tubular (CFST) column-beam rigid connections, diaphragms are applied to the inside or the outside of the columns to support and transfer the stress generated at the beams (Shin 2008, Cheng 2003, Kim 2005, Choi 2008). It deteriorates economical efficiency due to the complexity in producing the steel tubes. Column-beam pinned connections have been suggested in order to achieve convenience and economical efficiency in construction. In structural system of high-rise building, The RC core and exterior concrete-filled steel tubular (CFST) column-beam pinned connection as shown in Figs. 1, 2 is one of the structural systems that support lateral load. Theoretically, the application of this structural system does not generate moment to joints of columns-beam. However, due to the eccentric distance between the column flange surface and shear bolt joints, an eccentric moment by shear load is generated at flange surface of CFST column.

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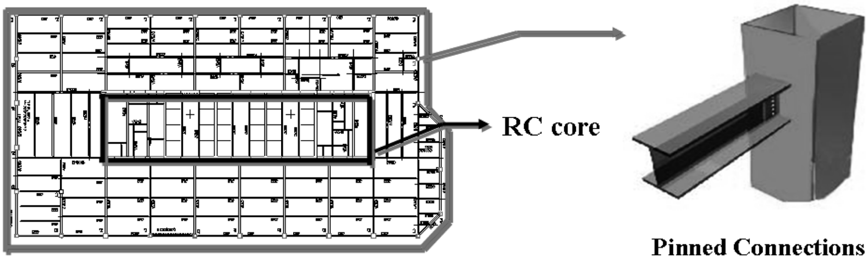


Fig. 1 RC core and pinned connections structural system

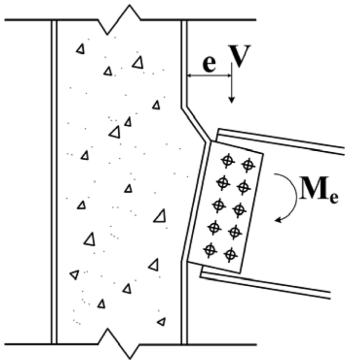


Fig. 2 CFST column-beam pinned connections

And, the eccentric moment deteriorates the shear strength of CFST column due to out-of-plane deformation at column surface. Shakir-Khalil (1994) conducted a study on the rotational rigidity and tensile strength of CFST column-beam connections using column width & thickness and eccentric distance as parameters. Malaska (2000) suggested strength formula for preventing out-of-plane deformation of CFST column using yield line theory. In Korea, Kim (2000) carried out a research on rotational rigidity and tensile strength of CFST column-beam connections using width-thickness ratio, internal reinforcement and slab as variables. AISC (1997), Hollow Structural Section Connections Manual, covers various elements associated with square tubular column pinned connections such as bolt, connection material, welding and punching shear at column surface, but AISC (1997) does not take into consideration strength decrease of columns caused by an eccentric moment. AISC (1997) says that the column surface of pinned connections does not reach in yield state because the bottom flange of beam contacts with column surface by the rotation of beam when the shear force of connections increase. Generally, though the clearance between steel tube surface and beam flange is varying depend on welding thickness, it is at least 1.27 mm (0.5 inch). Considering the fact that IIW (1989) defines the yield state of steel tube as displacement equivalent to 1% of column width, it is feasible that column surface can be a yield state prior to the column surface contacts with beam flange if the width of steel tubular column or the depth of beam is enough small. In this study, to investigate the structural characteristics of CFST column-beam pinned connections under eccentric moment by shear load, the finite element method was used. Width and thickness of CFST column were used as parameters. Tests on three specimens with the parameters of width-thickness ratio were conducted to guarantee the reliability of the results of the finite element analysis. Finally, yield line theory was applied to suggest shear strength formula for CFT column-beam pinned connections.

2. Finite element analysis

The finite element analysis was conducted to investigate the shear strength under eccentric moment of the CFST column-beam pinned connections.

2.1 Analysis model

ANSYS 8.0 Version was used for non-linear analysis. Solid 65 was used as analysis element for steel and concrete. Solid 65 have 8 nodes and 3 degree of freedom. For the boundary surface between steel and concrete, TARGET 170, a 3-D target segment and CONTA 174, a 3-D 8-Node surface-to-surface contact element, were used. The friction coefficient between steel and concrete applied 0 (zero) to resist compressive force only as shown in Fig. 3. Considering the configuration of connection and conditions of load, 1/4 symmetry model was made as shown in Fig. 4 instead of full model. And, shear load was applied to bolt holes of shear tap in order to generate eccentric moment at column surface. The parameter of analysis used width and thickness of CFST steel tube. Table 3 shows specimens of FEM analysis, where Group 1 is specimens to evaluate the strength of column flange associated with thickness of steel tube, Group 2 is specimens to evaluate the strength of column flange associated with width of CFST column and Group 3 is specimens to evaluate the strength of column flange associated with the eccentric moment of CFST column under the limit width-thickness ratio ($\sqrt{3E/F_y}$) that regulated in AIK (2004). The bi-linear isotropic element was used for the stress-strain characteristics of steel. Table 2 shows the material properties used in FEM analysis, where E_s = 210 GPa, F_y = 330 MPa (SM490), second modulus of elasticity was 2.1 GPa and cylinder strength (f_{ck}) of Concrete used 49 MPa.

2.2 Analysis result

As shown in Fig. 5, a eccentric moment caused by shear force is translated into tensile force. And, the horizontal displacement at tensile side was attained from FEM analysis. In Fig. 6, Finite element analysis results of Group 1 and Group 2 showed that the tensile strength variation associated with

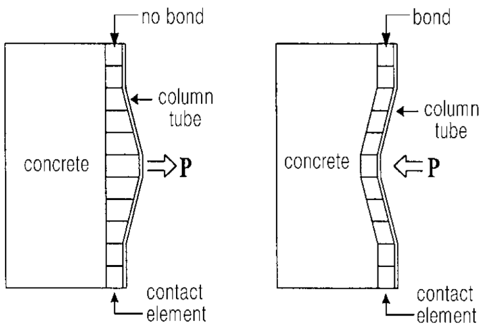


Fig. 3 Contact element (Target170, Conta174)

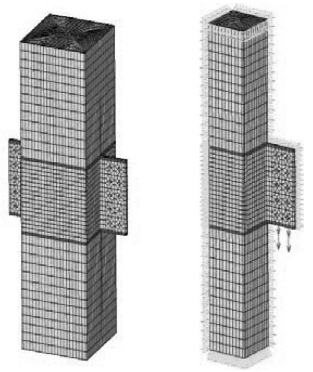


Fig. 4 Analysis model (Full, 1/4)

Table 1. Specimens for FEM analysis

Specimens	width-thickness ratio	Dimension (mm)
Group 1	20-50	–400×400×8 –400×400×10 –400×400×12 –400×400×14 –400×400×16 –400×400×18 –400×400×20
Group 2	15-40	–300×300×20 –400×400×20 –500×500×20 –600×600×20 –700×700×20 –800×800×20
Group 3	43.69	–400×400×9.16 –500×500×11.45 –600×600×13.74 –700×700×16.03 –800×800×18.32 –900×900×20.6 –1000×1000×22.84 –1100×1100×25.18 –1200×1200×27.47
Shear tap		320×160×20

Table 2. Material properties

Classification		Steel type	F_y (MPa)	Modulus of elasticity (GPa)	Modulus of tangent llne (GPa)	Poisson's ratio
Steel	Steel tube Shear tap	SM490	330	210	2.1	0.3
Concrete		f_{ck}: 49MPa				

Table 3. Specimens for Test

Specimens	Width-Thickness ratio (W_c/T_c)	Concrete-filling	Dimension (mm)
P1	40	Yes	400×400×10
P2	33.3	Yes	400×400×16
P3	20	Yes	400×400×20

column thickness on CFST column-beam pinned connections was greater than that of column width. Fig. 7 shows the result of the analysis conducted with varying column width at fixed width-thickness

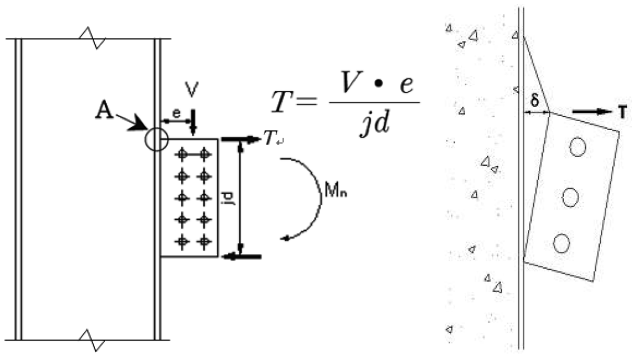
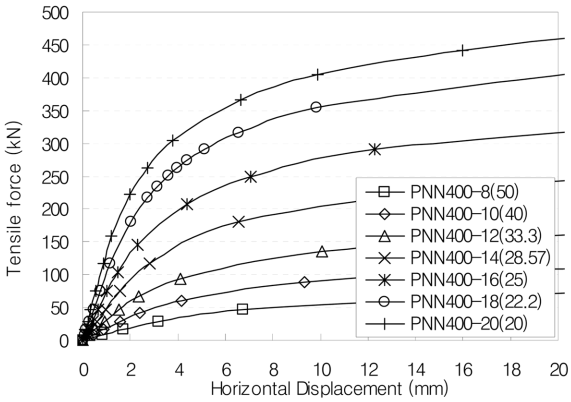
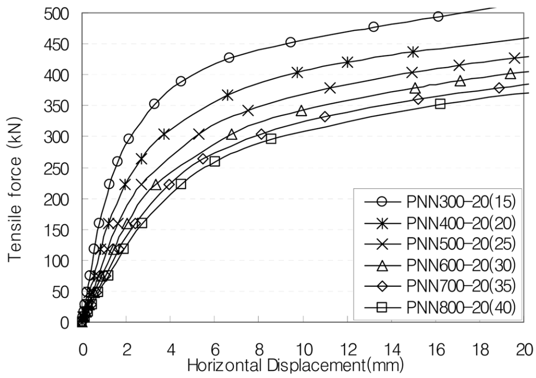


Fig. 5 Eccentric moment and tensile force at CFT column surface



(a) Tensile force-Displacement relations according to column thickness (Group 1)



(b) Tensile force-displacement relations according to column width (Group 2)

Fig. 6 Tensile force-displacement relations according to column width and thickness

ratio of 43.69, which is the limit width-thickness ratio in AIK (2004) on CFST column with yield strength of 330 MPa. And, the results shows that the strength of CFST column-beam pinned connections

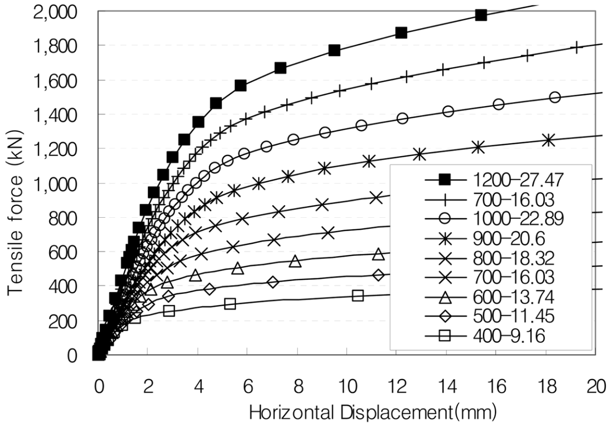


Fig. 7 Tensile force-Displacement relations according to varying column size at limit width-thickness ratio (43.69)

increased as column width was increased, though the width-thickness ratio remained same in all column.

2.3 Analysis & interpretation

IIW (1989) defines yield load and ultimate load as displacement corresponding to 1% and 3% of the width of steel tubular column, respectively. Fig. 8 shows yield load against column width obtained from the results shown in Fig. 7 using the definition of yield load provided by IIW (1989). It is shown that strength increased as column width increased for CFST column employing limit width-thickness ratio of AIK (2004). Accordingly, if the yield tensile strength (T of point A in Fig. 5) of column surface for varying column width is obtained, it can be used for design of CFST column-beam pinned connections.

3. Test

CFT column-beam pinned connections were tested to verify the reliability of the finite element analysis.

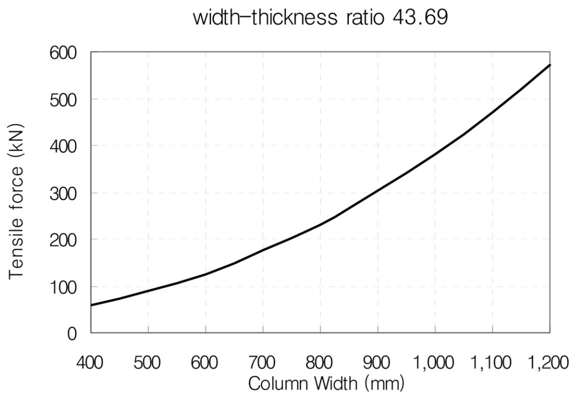


Fig. 8 Yield Tensile force-column width relations according to varying column width at limit width-thickness ratio of 43.69

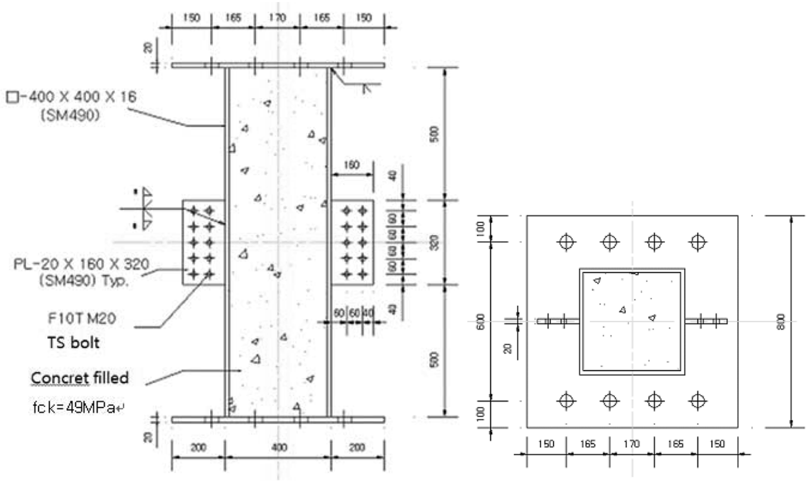


Fig. 9 Detail of specimen

3.1 Specimens

Three Specimens were fabricated as shown in Table 4 in order to investigate the decrease in strength caused by the eccentric moment at CFT columns. Mild steel of SM490 was used in specimens. Table 4 and Fig. 9 show the dimensions and details of the specimens, respectively. And, Table 5 shows the material properties used in specimens. In specimens, the nominal shear tab strength of V_u = 392 kN was designed.

3.2 Test plan

In the test, 10,000 kN UTM was used. Vertical load caused shearing force to the shear taps at both

Table 4. Material properties

	Thickness (mm)	*E* (Gpa)	F_y (Mpa)	F_u (Mpa)	F_y/F_u	Elo (%)
P1 column	10	207GPa	361	507	0.71	26
P2 column	16	211GPa	358	502	0.71	25
P3 column shear tab	20	205GPa	392	531	0.73	26

Table 5. Tensile strength of FEM results and test results

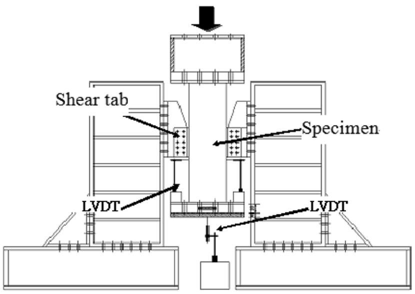
Specimens	Yield strength (kN)		Ratio [B/A]
	FEM [A]	Test [B]	
P1	73	122	1.67
P2	223	392	1.76
P3	382	620	1.62
	Mean		1.68

sides. For eccentric load, the eccentric distance from column flange surface was 90 mm. Fig. 10 shows the test plan and the photo of completed test setting. to consider the axial load of 2,000 kN, which is 0.15% of axial resistance for CFST columns, 8 high-strength steel bar were used as shown in Fig. 10(b). Each steel bar was tighten by tension of 250 kN using hydraulic pressure machine as shown in Fig. 11. 2 LVDT were installed at a distance of 20 mm below the location of shear tab at the tension side of shear tap for the purpose of measuring the horizontal displacement of column surface as shown in Fig. 10.

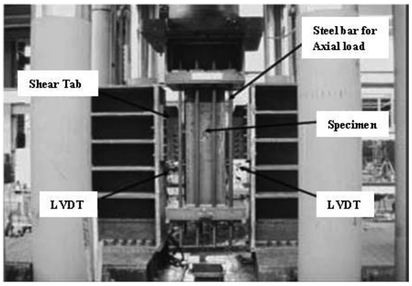
3.3 Test results & analysis

The calculated tensile force ($T = V{\cdot}e\,/\,jd$) from results of test and horizontal displacement relations of each specimen was drawn in Fig. 12.

For specimen P1, P2 and P3, Fig. 13(a)-(c) shows the failure state of specimens, there was no significant deformation on the compression side due to the influence of concrete inside the column, while out-of-plane deformation occurred in the end of shear tab on the tensile side due to eccentric moment. The final failure shape of P1 was the fracture of steel tube face and the final failure shape of P2, P3 were the failures of the shear tab occurred in the 1st row bolts. Fig. 14 shows the yield tensile strength comparison of the test results and the FEM analysis results. Applying the definition of yield strength proposed by IIW (1989), the strength obtained from the test was about 1.68 times lager than that from the finite element analysis as shown in Table 5. This is attributed to the fact that FEM analysis



(a) plan



(b) Completed photo

Fig. 10 Test setting

Fig. 11 Hydraulic pressure to generate axial load ratio of 0.15

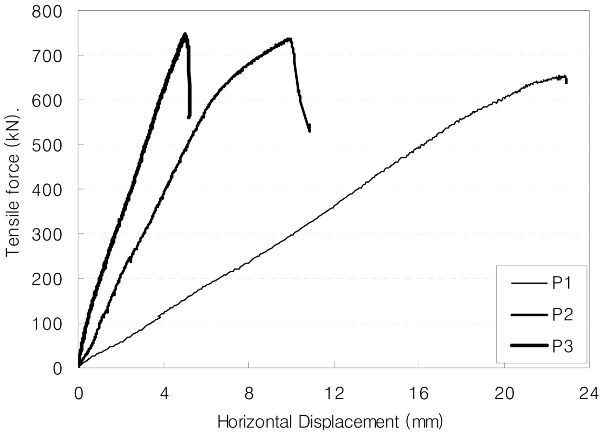


Fig. 12 Tension-displacement relations of specimens

(a) P1 (b) P2 (c) P3

Fig. 13 Failure observed at the specimens

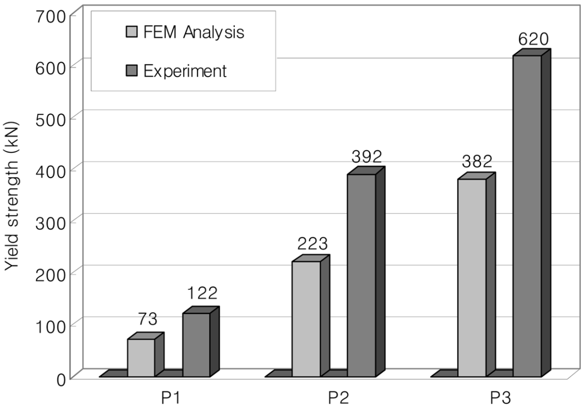


Fig. 14 Tensile strength comparison of FEM results and test results

used the nominal yield strength of materials. It was verified through the test that the result obtained from the finite element analysis was on the conservative side.

4. Strength formula and verification

The yield line theory has been used for plastic analysis of general plates. The strength formula for the CFST column-beam pinned connections was proposed by applying the yield line theory, and the proposed strength formula was compared and evaluated with the result of the FEM analysis.

4.1 Strength formula

Yield line of tension side for specimens were supposed using the yield line of Sherman (2000) and Higgins' theory as shown in Fig. 15. It was assumed that the yield line 1 and 2 are $M_p = 0$ and the other yield lines are $M_p = F_y t^2 / 4$. The effect of strain hardening was ignored and the strain of compression side was assumed to be zero. The formula from yield line theory is shown in Eq. (1). In Fig. 16, the length of B is an unknown value. It was identified that the tensile fore was a minimum value when B converged to 0.49 times of column width in ascending order. It was also identified that B converged to 0.49 times of the column width with varying column thickness (t_c) and shear tab length (h_p). Eq. (2) was obtained by substituting $B = 0.49W_c$

$$T = \frac{f_{yc}t_c^2}{4}\left[\frac{8(B+h_p)}{W_c - t_p} + \frac{2W_c}{B} + \frac{2W_c - t_p}{h_p}\right] \tag{1}$$

$$T = \frac{f_{yc}t_c^2}{4}\left[4.1 + \frac{3.92W_c + 8h_p}{W_c - t_p} + \frac{2W_c - t_p}{h_p}\right] \tag{2}$$

4.2 Verification of suggested strength formula

For the verification of the suggested strength formula, Eq. (2) was compared with the results of finite element analysis. The same parameters with those used in the FEM analysis were used for the verification of suggested strength formula. The yield tensile strength depending on the column width is

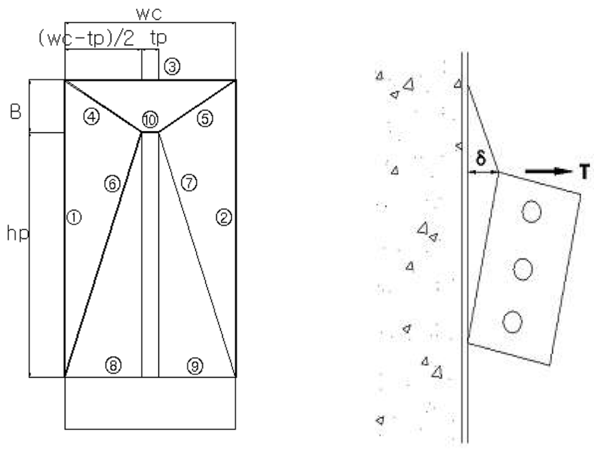
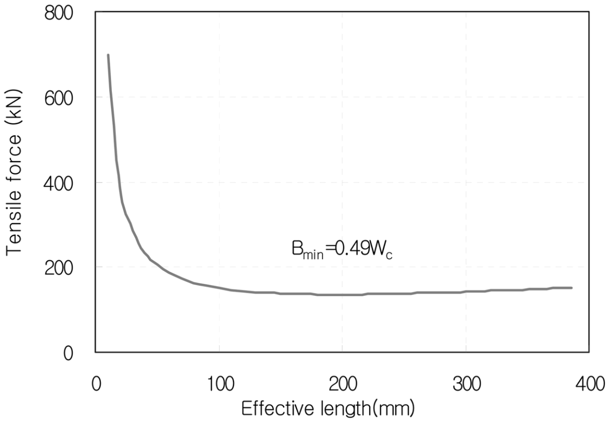
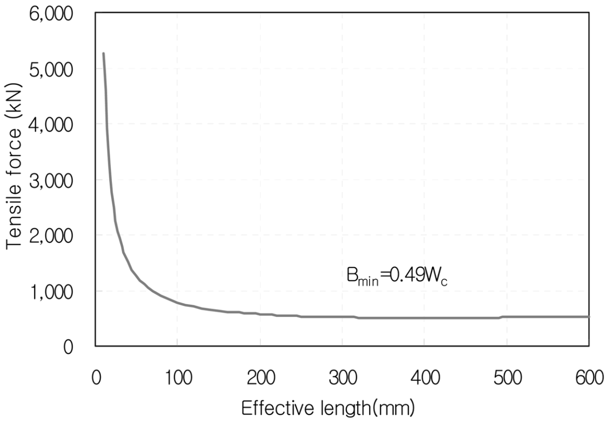


Fig. 15 Yield line supposition



(a) Column width 400mm



(b) Column width 800mm

Fig. 16 Minimum length of B at strength formula

shown in Fig. 17, which shows the results of the strength formula before applying the safety factor. In Fig. 17, the tensile strength of strength formula was higher than that of finite element analysis, although was similar in its distribution. Applying the safety factor (α) of 0.5 for the strength formula, it was considered more conservative than the function in the finite element analysis, and applicable to the design. Eq. (3) is the completed strength formula using safety factor (α) of 0.5.

$$V_u = 0.5\frac{f_{yc}t_c^2 h_p}{e}\left[4.1 + \frac{3.92W_c + 8h_p}{W_c - t_p} + \frac{2W_c - t_p}{h_p}\right] \tag{3}$$

V_u : Shear force by factored load
T : Tensile force applied on the column surface
f_{yc} : Yield stress of column
W_c : Column width

t_c : Column thickness
h_p : Shear tab length
e : Eccentric distance

5. Conclusions

In this study, finite element analysis and test were carried out to analysis the shear strength of the CFST column-beam pinned connections by eccentric moment, which is occurred by the eccentric distance between the column flange surface and shear bolts joints. Yield line theory was used to determine the shear strength formula of the connections. Conclusions in this study are as follows.

It was identified that out-of-plane deformation occurred in the column flange surface because of a local moment by the eccentric distance between bolt row and column flange and that the yield strength of CFST column-beam pinned connections increased as column width increased, although the width-thickness ratio of column do not change. The formula (Eq. (2)) for column tensile strength associated with eccentric moment was obtained by substituting the known value of B with $0.49W_c$ in Eq. (1). The Shear strength formula (Eq. (3)) was derived from the application of safety factor 0.5 as below. It is considered that the suggested shear strength formula can be used for calculation of CFST column-beam pinned connections.

$$T = \frac{f_{yc}t_c^2}{4}\left[\frac{8(B+h_p)}{W_c-t_p}+\frac{2W_c}{B}+\frac{2W_c-t_p}{h_p}\right] \tag{1}$$

$$T = \frac{f_{yc}t_c^2}{4}\left[4.1+\frac{3.92W_c+8h_p}{W_c-t_p}+\frac{2W_c-t_p}{h_p}\right] \tag{2}$$

$$V_u = 0.5\frac{f_{yc}t_c^2h_p}{e}\left[4.1+\frac{3.92W_c+8h_p}{W_c-t_p}+\frac{2W_c-t_p}{h_p}\right] \tag{3}$$

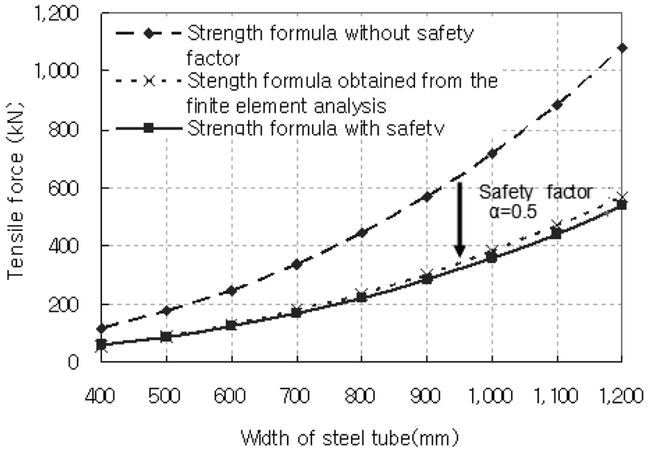


Fig. 17 Comparison between strength formula and FEM analysis

Acknowledgment

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