(2015) including diaphragm, extended tee, T-stiffener, and bolted connections. The configurations detailed the development of the connections in order to achieve rigid behavior. The diaphragm connections are widely used in box column system because they do not provide much difficulty for installation and construction. More importantly, the diaphragms are able to enhance the performance of the connection significantly in terms of strength, stiffness, and ductility. The application of using diaphragm connections was observed in Japan (Park *et al*., 2005), which the connections were categorized respectively to external, through-, and internal diaphragms. In this study, the internal diaphragm connections to box column has been focused. The internal diaphragm can be used for both rolled-shaped and built-up box column as preferred for tall buildings (Morino *et al.*, 2001, Morino, 2002, Chen *et al.*, 2004)*.* As the beam transferred the loads to the column through the beam flange, the investigation of the connection between plate and box column with internal diaphragm, as shown in Fig. 1, is carried out in this paper. More importantly, several issues have been raised as concerned with the design and performance of the internal diaphragm. The parametric effects on the performance of the connection between plates and box column were indicated by Lu (1997). The study discovered the effect of plate width and concrete on the strength of the connection. The strength of the connection which was formulated using yield mechanism associated with the connection, was then modified. In AIJ specification (AIJ, 2008), the design of diaphragm connection to box column has been observed. However, the effect of the above parameters is not considered for the calculation of the strength of the connection. Recently, Doung and Sasaki (2019) also revealed the effect of plate width, column thickness, and diaphragm thickness and hole on the strength of the plate-to-box column connection with internal diaphragm. However, the investigation did not include those effects on the strength of the connection when column is filled by concrete.

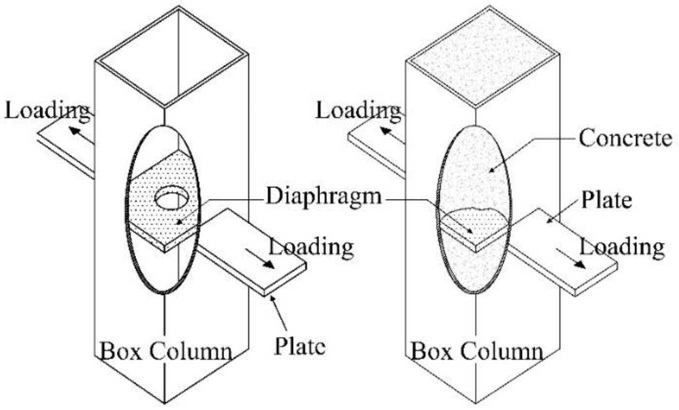


Fig. 1 Plate-to-box column connection with diaphragm

The objectives of this study are to provide the theoretical and numerical investigations on the performance evaluation of the plate-to-box column connections with internal diaphragms. The theoretical investigation was carried out to predict the strength of the connection using the assumed yield mechanism occurred in the active components of the connection. Hence, the design of the internal diaphragm can be proceeded. Further numerical investigation of the performance of the connection using finite element method (FEM) was assessed in terms of load-deformation characteristics considering the mentioned parametric effects. Since the strength of the connection got affected by the plate width, column thickness, and concrete, modification of strength formulation given by theoretical study was also provided.

2. LOAD-DEFORMATION RELATIONS

The load-deformation relations of the plate-to-box column connection can provide a precise information to explain the performance of the connection. However, prediction of load-deformation relations requires theoretical formulation to define the limit states associated with the components of the connection. Therefore, connection mechanism must be identified. For such that identification, the assumption is made regarding to the active components which participate into connection’s strength. A previous study by Doung and Sasaki (2019) suggested that the load-deformation relations of the plate-to-box column connection can be modelled as a tri-linear load-deformation curve corresponding to first yielding, full yielding, and ultimate states. The modelling was well compared with the numerical results for the plate-to-box column connection without concrete filling. However, it was observed that for the design aspect, there is not necessary to use the first yield strength. In this study, a tri-linear load-deformation curve as shown in Fig. 2 was proposed for both the plate-to-box column connections with and without concrete filling. The procedure required the calculation of strength and deformation at first yielding, full yielding, and ultimate states. The yield mechanism of the connection was assumed to be depended on the column flange and internal diaphragm. The column side walls were assumed to be rigid, which contributed no strength to the connection. Concrete effect was empirically considered as a constant for all strength levels.

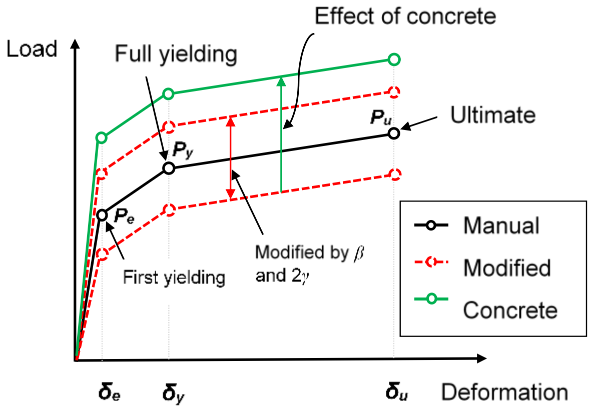


Fig. 2 Tri-linear load-deformation characteristics

The yield mechanism of the connection maintained the yield lines occurred in each active component. The yield line method is used to determine the yield strength of the bended panel according to designated failure modes. The yield line method was provided by Johasen (1962), and it was associated with bending of panels, particularly for slab members. More importantly, this method was widely used to predict the flexural strength of box column flanges (Lu, 1997, Cao *et al.*, 1998). The yield lines of the internal diaphragm were assumed to lay from the edge of the plate to the center of the internal diaphragm. Thereafter, the full yield strength could be established according to axial yield sections of the internal diaphragm. The full yield strength of the internal diaphragm can be expressed as:

$$P_{yd} = F_{yd}A_d \tag{1}$$

where F_{yd} and A_d represent the yield stress and section of the diaphragm, respectively. Similarly, the ultimate strength can be calculated using the tensile stress (F_{ud}). For the box column, using the 12 yield lines patterned in the column flange and applying the work principle corresponding to the failure modes, the yield strength of the column flange can be given by

$$P_{yc} = \frac{4M_xD}{l_y} + \frac{4M_y(2l_y+t_d)}{l_x} \tag{2}$$

where M_x and M_y represents the yield moments along x and y directions, and l_x, l_y, and t_d are the geometric dimensions, as shown in Fig. 3. δ_{cy} denotes the maximum yield deflection of the column flange. The vertical yield length is defined by l_y and can be calculated using Eq. (3) below.

$$l_y = \sqrt{\frac{M_xDl_x}{2M_y}} \tag{3}$$

The first yield and ultimate strength of the column flange can be calculated using the first yield and ultimate moment of the column flange. The strength of the plate-to-box connection can be obtained using the superposition of strengths of the diaphragm and column flange at each state. The corresponding deformations are necessary in order to construct the load-deformation curve. The full yield deformation (δ_y) of the connection was given by Fukumoto *et al.* (2000, 2002, 2015), which related to the initial yield deformation (δ_e), as controlled by the column flange.

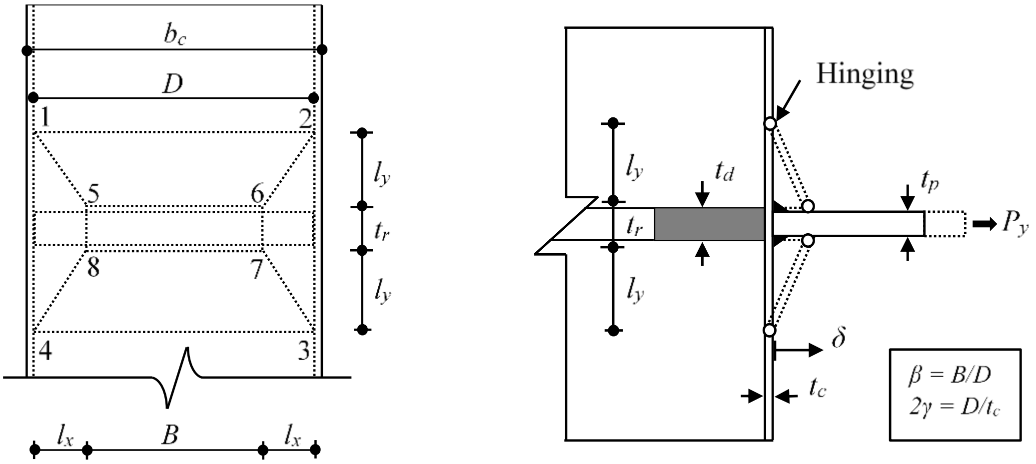
$$\delta_y = \frac{95}{18}\delta_e \tag{4}$$

where δ_e is the first yield deformation of the connection due to the initial yield stress distribution of the column flange. The first yield deformation can be calculated based on the yielded panels of the column flange in both horizontal and vertical directions. The calculation procedure for δ_e can be found in Fukumoto et al. (2000, 2002, 2015) and elsewhere in AIJ specification (AIJ, 2008). The maximum deformation (δ_u) of the column flange was recently revealed by Jones and Wang (2010) that various ranges of column width-to-thickness ratios (2γ) lead to generating different maximum deformations. The maximum deformations (δ_u) of the column flange are listed below.

$$0.06b_c - 0.07b_c \qquad \text{for } 0 < t_c/b_c \leq 0.05 \tag{5a}$$

$$\left[\left(-140 \times \frac{t_c}{b_c}\right) + 13\right]\frac{b_c}{100} \qquad \text{for } 0.05 < t_c/b_c \leq 0.075 \tag{5b}$$

$$0.025b_c - 0.03b_c \qquad \text{for } t_c/b_c \geq 0.075 \tag{5c}$$



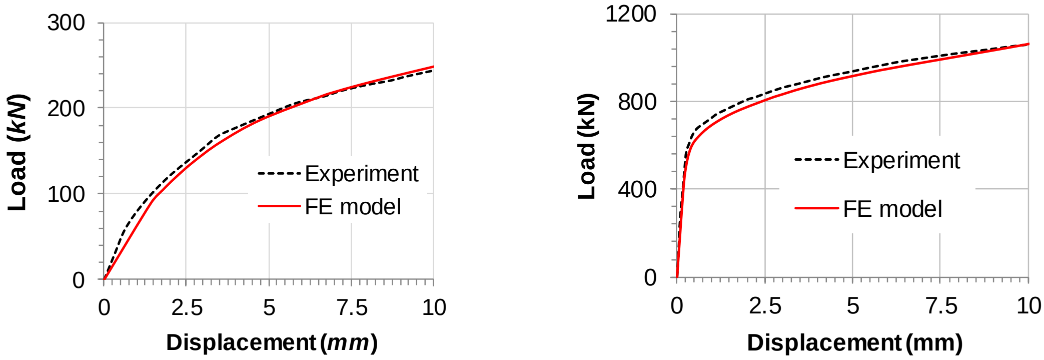
(a) Column flange yield line (b) Yield mechanism

Fig. 3 Connection mechanism

3. NUMERICAL PARAMETRIC INVESTIGATION

3.1. Finite element modeling and validation

This numerical investigation was assisted by a finite element (FE) software Abaqus (Abaqus/CAE, 2017). To ensure the reliability, it requires comprehensive modeling including geometry, material, element type, meshing, and contact, etc. This study used a 3D solid 8-node element (C3D8-R) in associating with the one-eighth geometric model of the actual connection. The steel material was modeled as a multi-linear curve with yield plateau corresponding to JSCE specification (JSCE, 2007a). A confined concrete was considered for modeling the concrete material (Ellobody and Young, 2006, Hu and Schnobrich, 1989, Giakoumelis and Lam, 2004, Hu *et al.*, 2003, and JSCE, 2007b). The contact between concrete and steel tube was characterized by a friction coefficient of 0.25. The penetration between concrete and steel tube is not allowed. A mesh size of one-half and one time of the element thickness was applied to the thickness and the interested portions of the connection's components. Two test samples of the plate-to-box column connections with and without diaphragm and concrete were selected for FE modeling validation. A push plate test sample without diaphragm and concrete (1R3) given by Lu (1997) consists of a 300x300x10mm box column with the length of 1.8 m and a pate with the width and thickness of 170 mm and 11.5 mm, respectively. A S355 steel grade was used for the steel material. Another concrete-filled plate-to-box column connection with internal diaphragm (Fukumoto and Taki, 2002) subjected to tension, was also included for validation purpose. The sample contained a 200x200x6mm box column with the length of 400 mm, a 12mm-thick diaphragm with the hole diameter of 100mm, and a 16mm-thick plate with 150mm-wide. SM490 steel grade was used for the box column and internal diaphragm while the pull plate is made of SA440 steel grade. The FE results were compared with the test in terms of the load-deformation relations. As observed in Fig. 4, the FE models fairly agreed with the load-deformation characteristics given by the experiment. Therefore, FE modeling method above was validated to assess numerical investigation of the plate-to-box column connections.



(a) Lu (1997) (b) Fukumoto and Taki (2002)

Fig. 4 Load-deformation relations comparison

3.2. Connection with variation of plate width and column thickness

The consideration of parametric effects was carried out including the plate-to-column width ratio (β) and column width-to-thickness ratio (2γ). Previous studies by Lu (1997) on the connection between plates and box columns without diaphragms admitted that the connection strength is associated with the plate-to-column width (β) and the column width-to-thickness (2γ) ratio. These mentioned parameters may affect the strength by manual calculation. In this study, parameter β and 2γ varied from 0.315 to 0.855 and 18.83 to 39.667, respectively. The variation of β and 2γ corresponds to plate widths of 75, 100, 125, 150, 175, and 200 mm and column thicknesses of 6, 8, and 12 mm. The thickness and hole diameter of diaphragm were 12 mm and 125 mm, respectively. Steel grade SM490 with the minimum specified yield strength of 325 MPa was used for steel material. Table 1 below shows the geometric and material properties of the connection components.

Table 1 Geometric and material properties of the plate-to-box column connections

Model	Column				Plate				Diaphragm			
	b_c	t_c	Steel Grade	L_c	B	t_p	Steel Grade	L_p	D	D_d	t_d	Steel Grade
IP-t_c6	250	6	SM490	800	75-200	16	SM490	150	238	125	12	SM490
IP-t_c8	250	8			75-200				234			
IP-t_c12	250	12			75-175				226			

Note: dimension in mm, stress in MPa

Commonly, the strength of the connections increased when the wider plate and thick column are used. However, the strength difference between FEM and manual calculation was observed associated with the parameters β and 2γ. The difference indicated in terms of yield strength ratio which can be seen in Table 2 below. This circumstance revealed the effect of β and 2γ to the theoretical formulation on strength of the connection, suggesting that modification of strength equation is a must. The inelastic performance of a connection was also presented in terms of von Mises stress distribution including yield lines associated with diaphragm, as seen in Fig. 5. The stresses concentrated at the edge of the plate region and headed to the center of the diaphragm. This circumstance admitted that the yield lines of the diaphragm can be traced from the edge of the plate to the center of the diaphragm.

Table 2 Yield strength ratio of the connections corresponding to β and 2γ

Model	t_c = 6 mm (2γ=39.667)		t_c = 8 mm (2γ=29.25)		t_c = 12 mm (2γ=18.83)	
	β	$P_{y,FEA}/P_{y,theory}$	β	$P_{y,FEA}/P_{y,theory}$	β	$P_{y,FEA}/P_{y,theory}$
IP- t_cX	0.315	1.49	0.321	1.35	0.332	0.99
	0.420	1.25	0.427	1.18	0.442	0.88
	0.525	1.13	0.534	1.06	0.553	0.81
	0.630	1.02	0.641	0.99	0.664	0.73
	0.735	0.94	0.748	0.88	0.774	0.65
	0.840	0.86	0.855	0.79	-	-

Note: X represents the value of column thickness

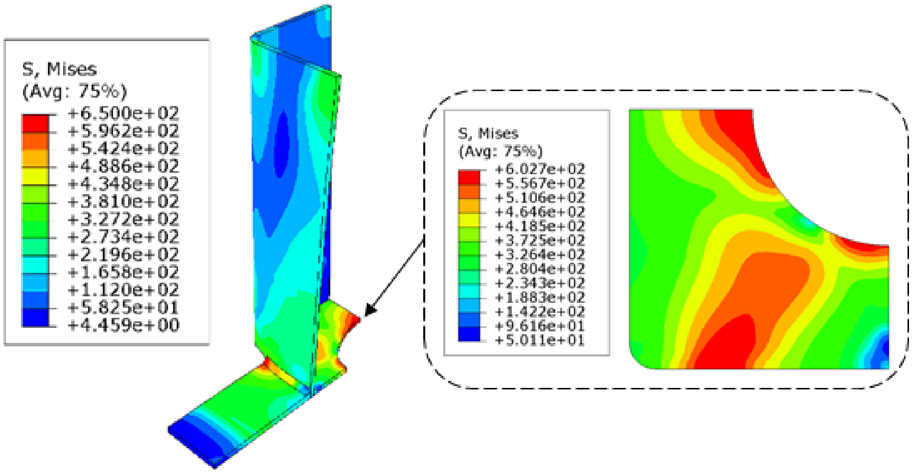


Fig. 5 von Mises stress distribution for connection IP-t_c6-β=0.63 at 20 mm pulling

3.3. Connection with concrete filling

The strength of concrete-filled plate-to-box column connection with internal diaphragm was numerically investigated following the aspect that the configuration of the connection changed regarding to the diaphragm parameters, plate width, and column thickness. The effect of concrete was empirically considered as the strength ratio between the connection with and without concretes. In this study, 27 numerical models corresponding to different configurations were performed in order to settle load-deformation relationship. Thereafter, the strength level at each designated deformation could be defined. The strength ratio at each level is summarized in Table 3. Concrete participated in strength by 13 to 44% at first yielding, 23 to 45% at full yielding, and 30 to 59% at maximum. The significant change in strength ratio was also observed when the plate width and column thickness changed. However, the effect of concrete can be simply considered as the average value as of 1.31, 1.37, and 1.42 at first yielding, full yielding, and ultimate respectively. To be more practical for the design, this factor can be simplified to 1.3 at yield states and 1.4 at ultimate state, as meant that there was 30% strength improvement when the column was filled by concrete.

Table 3 Strength ratio between connection with and without concretes

Model	t_c	β	t_d	D_d	F_y/F_u	$C1/C0$		
						First yielding	Full yielding	Ultimate
1	6	0.315	12	125	325/490	1.30	1.42	1.50
2		0.420				1.31	1.45	1.59
3		0.525				1.25	1.39	1.55
4		0.630				1.21	1.35	1.47
5		0.735				1.16	1.31	1.43
6		0.840				1.13	1.23	1.42
7	8	0.321	12	125	325/490	1.44	1.42	1.40
8		0.427				1.37	1.40	1.41
9		0.534				1.36	1.40	1.41
10		0.641				1.31	1.35	1.40
11		0.748				1.27	1.31	1.36
12		0.855				1.24	1.24	1.32
13	12	0.332	12	125	325/490	1.39	1.38	1.48
14		0.442				1.42	1.43	1.84
15		0.553				1.41	1.39	1.34
16		0.664				1.35	1.39	1.35
17		0.774				1.32	1.34	1.31
18	8	0.641	8	125	325/490	1.35	1.39	1.35
19			10			1.31	1.38	1.37
20			16			1.25	1.35	1.34
21			20			1.23	1.34	1.35
22	8	0.641	12	100	325/490	1.20	1.31	1.30
23				150		1.61	1.54	1.46
24	8	0.641	12	125	235/400	1.31	1.40	1.37
25					245/400	1.35	1.40	1.37
26					365/490	1.30	1.36	1.36
27					445/610	1.31	1.35	1.37
					Mean	1.31	1.37	1.42
					SD	0.09483	0.06014	0.10791

Note: C0 = without concrete filling, C1 = with concrete filling, dimension in mm, stress in MPa

3.4. Modification of connection strength

The strength of the connection was affected by the plate-to-column width ratio (β), column width-to-thickness ratio (2γ), and concrete, as observed in the numerical studies. The strength equation at each state was modified by the functional factors represented the effect of β and 2γ. Using regression analysis, the functional factors $f(\beta)f(2\gamma)$ for β ranged from 0.315 to 0.855 and 2γ from 18.83 to 39.667 can be expressed as:

$$f(\beta)f(2\gamma)=\frac{0.0104(2\gamma)+0.414}{\sqrt{\beta}} \tag{6}$$

The modified yield strength of the plate-to-box column connection with internal diaphragm can be calculated using equation (7) below.

$$P_y=f(\beta)f(2\gamma)\left(P_{yd}+P_{yc}\right) \tag{7}$$

For the connection with concrete filling, Eq. (7) is adjusted by a factor of 1.3, which represents the effect of concrete. The yield strength of the connection with concrete filling is shows as follows.

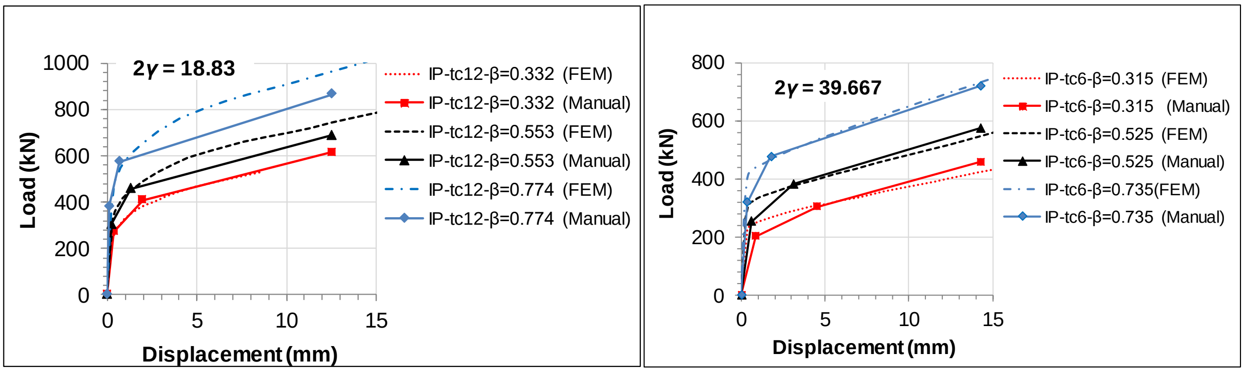
$$P_y=1.3\left[\frac{0.0104(2\gamma)+0.414}{\sqrt{\beta}}\right]\left(P_{yd}+P_{yc}\right) \tag{8}$$

The load-deformation curve comparison between manual calculation and FEM were given and shown in Figs. 5 to 6. The comparison was assessed on the connections related to the parameters β, 2γ, and concrete filling. The comparisons showed that for the connection without concrete filling, the proposed tri-linear load-deformation curves were well comparable with FE results. Moreover, when column was filled by concrete, it was observed that unmatched load-deformation characteristics between manual calculation and FE results. This was due to an assumption that concrete effect was empirically simplified as a factor of 1.3, which was not additionally considered the effect of β and 2γ. However, this simplification was well used for the connection with greater column thickness. Therefore, the proposed load-deformation relations are alternative in using to predict the capacity of the plate-to-box column connections with internal diaphragms with the range of β between 0.315 and 0.855 and 2γ between 18.83 and 39.667.

4. CONCLUDING REMARKS

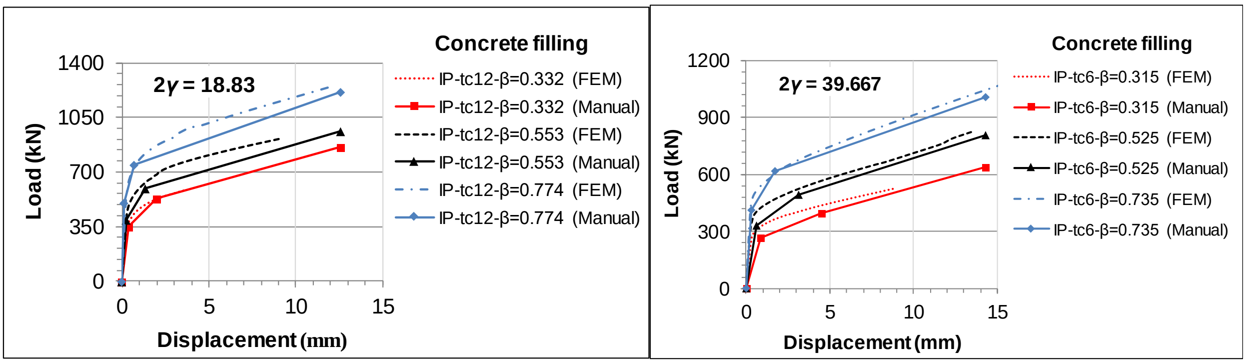
This study provided the numerically parametric investigation on the effect of plate-to-column width, column width-to-thickness, and concrete to the strength of the internal diaphragm connections between plates and box columns obtained from the manual calculation. The numerical assessment required to utilize FEM which assisted by a computer software Abaqus. The significant findings in this paper are summarized as follows.

- ○ For the internal diaphragm, as the proposed yield line was considered, this study provided the minimal strength to the connection because the diaphragm yield line leaded to rendering the smaller yield sections. Using the assumed yield mechanism associated with the column flange and diaphragm, the strength of the plate-to-box column connection with internal diaphragm was manually evaluated.
- ○ The effects of plate width and column thickness on the strength of the connection were observed. The strength equation at each level has to be modified by multiplying to two functional factors that represents the effects of plate-to-column width and column width-to-thickness ratios.
- ○ Concrete effect was numerically evaluated and simplified as 30% strength increase compared with the connection without concrete filling.
- ○ The proposed tri-linear load-deformation curve was alternative to predict strength of the connection, as it was well matched to the FEM results.



(a) $2\gamma = 18.83$ ($t_c = 12$ mm) (b) $2\gamma = 39.667$ ($t_c = 6$ mm)

Fig. 5 FEM and manual load-deformation curves comparison for connections without concrete filling



(a) $2\gamma = 18.83$ ($t_c = 12$ mm) (b) $2\gamma = 39.667$ ($t_c = 6$ mm)

Fig. 6 FEM and manual load-deformation curves comparison for connections with concrete filling

ACKNOWLEDGMENT

Many thanks are given to Japan International Cooperation Agency (JICA) for financial support under AUN/SEED-Net Program.

REFERENCES

Abaqus/CAE (2017), User’s Manual, Dassault Systemes; Vélizy-Villacoublay, France.

AIJ (2008), Recommendations for Design and Construction of Concrete Filled Steel Tubular Structures, Architectural Institute of Japan; Tokyo, Japan.

Cao, J.J., Packer, J.A., and Yang, G.J. (1998), “Yield line analysis of RHS connections with axial loads”, *J. Constr. Steel Res.*, **48**(1), 1–25.

Chen, C., Lin, C., and Tsai, C. (2004), “Evaluation of reinforced connections between steel beams and box columns”, *Eng. Struct.*, **26** (2004), 1889–1904.

Chen, Z., Qin, Y., and Wang, X. (2015), “Development of connections to concrete-filled rectangular tubular columns”, *Adv. Steel Constr.*, **11**(4), 408–426.

Doung, P. and Sasaki, E. (2019), “Load-deformation characteristics and performance of internal diaphragm connections to box columns”, *Thin-Walled Struct.*, **143**, 1–14.

Ellobody, E. and Young, B. (2004), “Nonlinear analysis of concrete-filled steel SHS and RHS columns”, *Thin-Walled Struct.*, **44**, 919-930.

Fukumoto, T (2015), “Local elasto-plastic behavior of steel beam to concrete-filled square steel tube column moment connections”, *J. Struct. Constr. Eng.*, **80**(714), 1337–1345.

Fukumoto, T. and Morita, K. (2000), “Connection between concrete-filled square steel tubular column and steel beam reinforced with internal diaphragm: elasto-plastic behavior of the local connection”, *J. Struct. Constr. Eng.*, **65**(528), 175–182.

Fukumoto, T. and Taki, M. (2002), “Local elasto plastic behavior of steel beam to concrere-filled square steel tubular column connections - internal diaphragm type of column to wide flange beam connections”, *J. Struct. Constr. Eng.*, **67**(560), 213–220.

Giakoumelis, G. and Lam, D. (2004), “Axial capacity of circular concrete-filled tube columns”, *J. Constr. Steel Res.*, **60**, 1049–1068.

Hu, H., Huang, C., Wu, M., and Wu, Y. (2003), “Nonlinear analysis of axially loaded concrete-filled tube columns with confinement effect”, *J. Struct. Eng.*, **129**(10), 1322-1329.

Hu, H. and Schnobrich, W. (1989), “Constitutive modeling of concrete by using nonassociated plasticity”, *J. Mater. Civ. Eng.*, **129**(10), 1322-1329.

Johansen, K.W. (1962), *Yield Line Theory*, Cement and Concrete Association, London.

Jones, M.H. and Wang, Y.C. (2010), “Tying behaviour of fin-plate connection to concrete-filled rectangular steel tubular column - Development of a simplified calculation method”, *J. Constr. Steel Res.*, **66**(1), 1–10.

JSCE (2007a), Standard Specifications for Steel and Composite Structures, Japan Society of Civil Engineers; Japan.

JSCE (2007b), Standard Specifications for Concrete Structures, Japan Society of Civil Engineers; Japan.

Lu, L.H. (1997), “The Static Strength of I-Beam to Rectangular Hollow Section Column Connections”, Ph.D. Dissertation; Technical University of Delft, Delft, Netherlands

Morino, S. (2002), “Concrete-filled steel tube column system: recent research and construction in Japan”, *Proc. 1st Fib Congr.*, Osaka, 2002.

Morino, S., Uchikoshi, M., and Yamaguchi, I. (2001), “Concrete-filled steel tube column system-its advantages”, *Int. J. Steel Struct.*, **1**(1) 33–44.

Park, J.W., Kang, S.M. and Yang, S.C. (2005), “Experimental studies of wide flange beam to square concrete-filled tube column joints with stiffening plates around the column”, *J. Struct. Eng.*, **131**(12), 1866–1876.