

BEHAVIOR OF EXTERNAL DIAPHRAGM CONNECTIONS FOR SQUARE CFST COLUMNS UNDER BIDIRECTIONAL LOADINGS

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Abstract. *External diaphragm connections are suitable for two-way frames with concrete-filled steel tubular (CFST) columns. The connections have efficient force transfer mechanisms and require simple construction methods. However, studies on the behavior of such connections under bidirectional loading are still very limited. This paper presents a numerical study on external diaphragm connections under one-way and two-way loading. Initial yielding and residual deformation of steel tubes are considered as the design limit states for external diaphragm capacity. It is shown the perpendicular loading does not significantly affect the capacity demand. A simple design method is proposed based on the basic characteristics from numerical analysis results.*

1 INTRODUCTION

Concrete-filled steel tubular (CFST) columns are widely used in structures because they have good axial and flexural performances, which are mainly resulted from the mutual interaction between concrete core and steel tube in CFST columns. Local buckling of the steel tube is delayed due to the existence of the concrete core [1]. On the other hand, the concrete compressive strength is increased by the confining effect provided from the steel tube. The steel tube also can reach its plastic capacity since it is located on the outer part of the column section. CFST columns can also improve the construction efficiency by minimizing formwork and steel reinforcement as well as shorten construction time and reduce labour demands. The superiority of CFST columns as structural members is also proven in other studies [2][3].

Commonly, CFST columns have circular and square or rectangular cross sections. The circular CFSTs are stronger under axial loading. Meanwhile the square or rectangular CFSTs are easier for making connections due to their flat surfaces. Square CFSTs are also suitable for two-way frame structures because they have equal strength and stiffness in orthogonal directions. CFST beam-columns have similar performance, regardless of the loading direction. This benefit makes them suitable for two-way frames [4].

As members of frame structures, CFST columns need to be properly connected to steel beams. Series of analytical and experimental tests on various circular CFST column connections were conducted [5] [6]. It was concluded that continuous beam connections have the most rigid behavior. However, these connections require on-site welding and are not applicable for two-way frame connections. Other CFST column connections are diaphragm-type connections which can be internal or through diaphragms and external diaphragms. These connections can avoid direct welding of steel beams to CFST column tubes

which is not recommended for structures in seismic regions. Furthermore, the elastic and inelastic behavior of the connections can be improved by providing gap between beam ends and CFST column tubes. Moving away the beam failure locations further from the columns is proven to be an effective way to improve the behavior [7]. Those reasons make the external diaphragm connections become promising. In external diaphragm connections, diaphragm plates are placed and welded outside the steel tube as shown in Figure 1. This can also avoid difficulties in welding and concrete compaction work.

Even though the external diaphragms are promising for CFST column connections, there is still a lack of understanding of their performance, especially under bidirectional loading. A numerical study using finite element analyses is conducted to answer the following questions: (1) What is the behavior of external diaphragm connections under bidirectional loading? (2) How should they be designed based on their likely behavior?

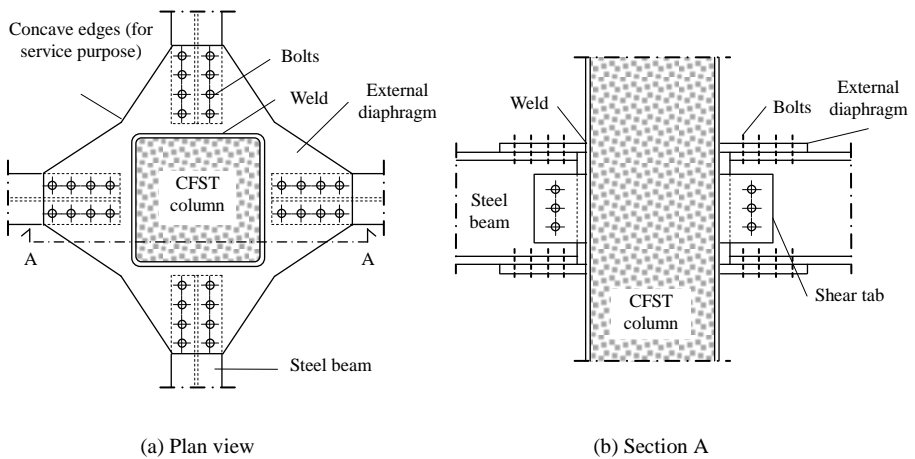


Figure 1. A square CFST column with an external diaphragm connection.

2 NUMERICAL MODEL

For a simple approach, an external diaphragm connection can be designed to resist tension and compression forces from beam end moments as shown in Figure 2. Since the steel tube can be easily pulled away from the concrete, the tension force is more critical for the diaphragm connection. Meanwhile, the compression force is less critical because the concrete core can directly bear such forces. Vertical force from beam shear force is assumed to be not significant to the diaphragm.

Based on above assumption, a numerical model is developed using ABAQUS v6.11. A diaphragm plate is connected to a CFST column at its half-length. Homogenous shell elements are used to model the diaphragm plate and steel tube. A bilinear stress-strain relationship is used to model the steel material with yield strength, $f_y = 300$ MPa. The concrete core is modelled as a rigid solid element, assuming its deformation is negligible to the entire structural response. The interaction between the concrete core and the steel tube internal surfaces is defined as a normal “hard” contact behavior. This feature allows separation between those surfaces under tension and results in contact pressure under compression. Friction between the two surfaces is ignored. The welded connections between the diaphragm and tube are assumed to develop full strength.

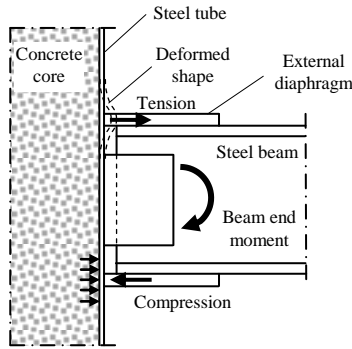


Figure 2. Force transfer mechanism of an external diaphragm connection.

A profile of the modelled connection detail is given in Figure 3. For parametric evaluations, parameters t_c , h_d , t_d , and $f_{d,y}$, are varied as described in Table 1. The other parameters are fixed. The outer corner radius, r_c , is taken as three times as the column tube thickness, t_c , as specified for standard cold-formed square hollow sections with thickness equal to 3 mm or larger. Fixed restraints are applied at the top and bottom ends of the column as shown in Figure 4. The diaphragm forces are applied as nodal shear forces at the bolt centres on each side of the diaphragm and gradually increased. Diaphragm forces at the tension and compression sides of the column are applied simultaneously both for the one-direction (x-axis direction only) and the two-direction (x-axis and y-axis) loading cases.

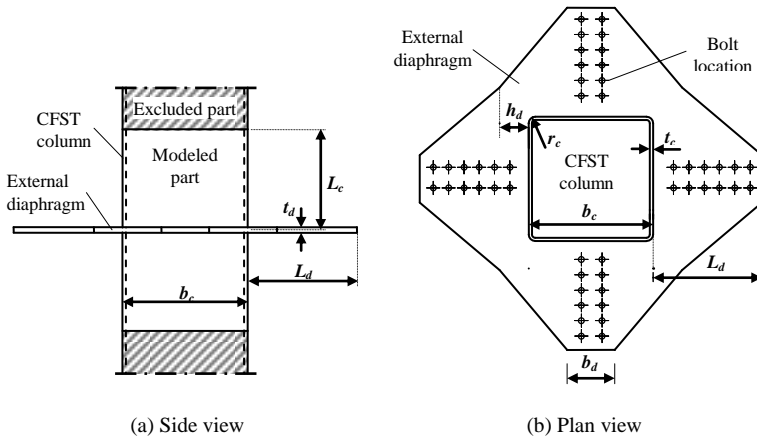


Figure 3. Modelled profile.

Table 1. Numerical model parameters.

Fixed parameters					Varied parameters				
b_c (mm)	L_d (mm)	b_d (mm)	L_c (mm)	$f_{c,y}$ (MPa)	t_c (mm)	h_d (mm)	t_d (mm)	$f_{d,y}$ (MPa)	
600	525	230	1200	300	12, 16 & 20	20, 80 & 140	15, 20, & 25	250, 300, & 350	

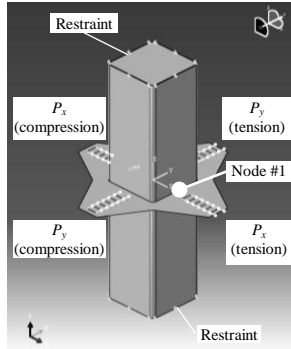


Figure 4. An external diaphragm connection numerical model (isometric view).

3 BEHAVIOR

3.1 Stress and force transfer mechanism

Compression and tension forces are applied simultaneously, both in one-way (x-direction only) and two-way loading. The forces result in-plane stresses in the diaphragm plate. As the forces are increasing, the maximum stress is also increasing and reaching the yield strength of the diaphragm material. Von Mises stresses at initial yielding are plotted in Figure 5. The stresses are not distributed equally on the compression and the tension side of the diaphragms. Maximum stresses occur on the tension sides near CFST column corners. Meanwhile, minimum stresses occur in areas which are not affected by the forces, e.g. the tips of diaphragm plate. Stresses near the middle part of the column on tension side are relatively small compared to the corners.

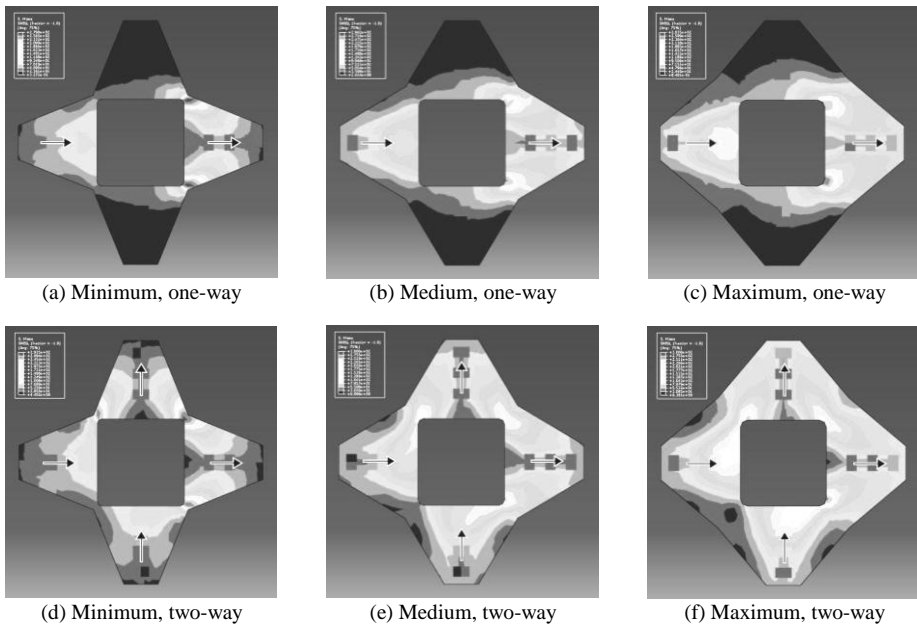


Figure 5. External diaphragm von Mises stress at initial yielding.

3.2 Stress and force transfer mechanism

Since there is no tensile resistance between concrete core and steel tube surfaces, the tension forces pull out the diaphragm and the tube, and make them disconnected from the concrete core as shown in Figure 6. Maximum displacements occur in the middle part of the CFST column. Diaphragm forces in x -direction, P_x , versus displacement in x -direction, δ_x , at Node #1 are plotted in Figure 7. In all configurations, the application of perpendicular force, P_y , does not affect significantly on the force-deformation of the diaphragms. It is also obvious that the connections can resist much higher force after initial yielding is reached.

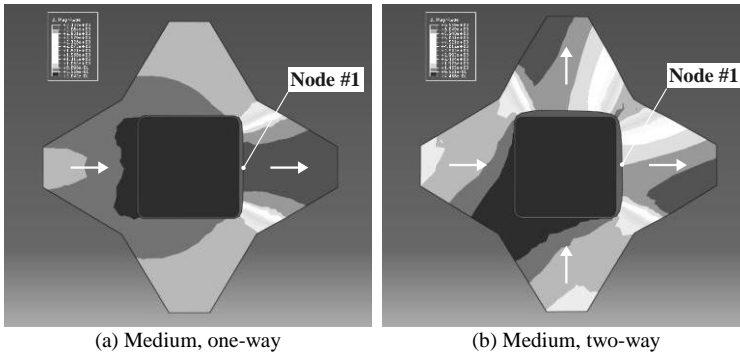


Figure 6. Displacement contour at 200% initial yielding force.

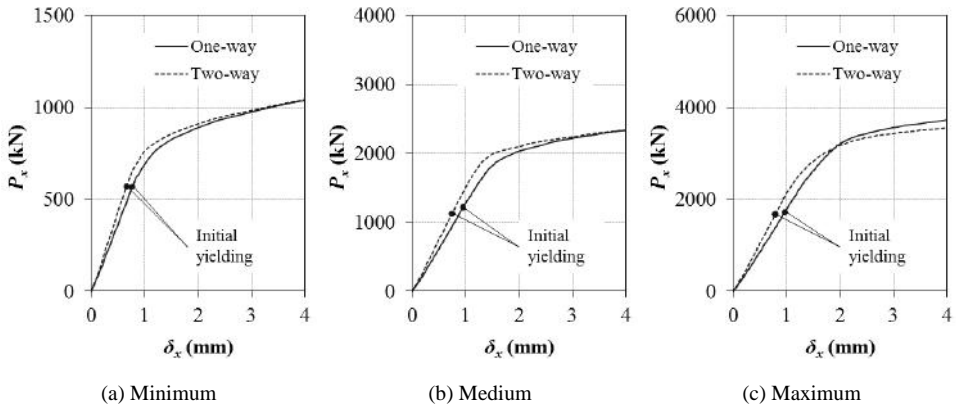


Figure 7. Diaphragm force versus displacement in x -direction at Node #1.

3.3 Perpendicular loading interaction

The effect of perpendicular loading on external diaphragm connections is also evaluated. Two parameters are used to indicate the external diaphragm capacity: the force magnitude at initial yielding, P_{yield} ; and force that cause a 0.5 mm residual displacement, or equal to 0.083% of the CFST column width, at Node #1. As described in Figure 8, $P_{0.5}$ is obtained by taking the intersection between the force-displacement curve and a 0.5 mm offset line parallel to the elastic part of the curve. The diaphragm capacity interaction curves are plotted in Figure 9. It is shown that the diaphragm capacity is not significantly affected by the perpendicular forces.

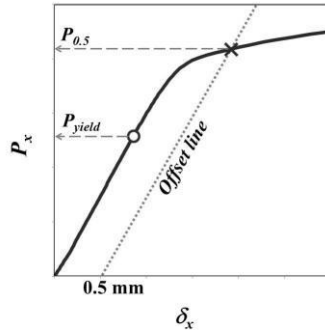
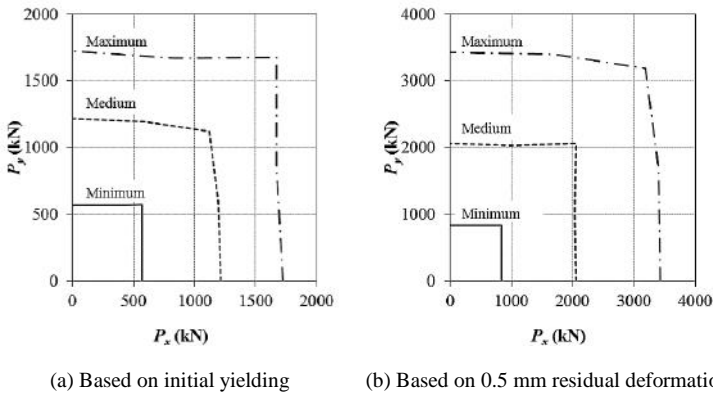


Figure 8. P_{yield} and $P_{0.5}$ definition.



(a) Based on initial yielding

(b) Based on 0.5 mm residual deformation

Figure 9. Perpendicular load interaction.

4 DESIGN RECOMMENDATION

As described in this paper, finite element analyses can be used for external diaphragm connection design. Alternatively, a simple calculation method can be developed by considering the most appropriate limit state and the behavior under bidirectional loading [8].

4.1 Design limit state

In order to develop a design method for external diaphragm connections, the design capacity should be defined based on a reasonable limit state. As shown in Figure 7, the connections can still resist significant load increases. A design method based on the initial yielding limit state will make non-economic external diaphragm connections. The other approach, i.e. a residual deformation of 0.5 mm, which is equal to 0.083% of the CFST column width, seems to be more reasonable.

4.2 Design approach

From numerical analyses, there are two major findings about the basic characteristics of external diaphragm connections. The first is the location of maximum stresses and the stress path in diaphragm plates under one-way and two-way loadings. Maximum stresses occur near CFST column corners and relatively small stresses occur near the middle part of steel tube on the tension side. The second is the typical deformation of diaphragm plates, especially under tension forces.

A design approach is proposed based on those basic characteristics. By ignoring the compression forces, the diaphragm plate is considered to behave in a similar way as a tie is looped around the column and pulled out at one or two sides as shown in Figure 10. In this method, there is no interaction between two perpendicular diaphragm forces, P_x and P_y , so the diaphragm could be designed to resist either P_x or P_y independently. The diaphragm design capacity is defined as the diaphragm force that causes the tie element to reach its tension capacity of the critical section.

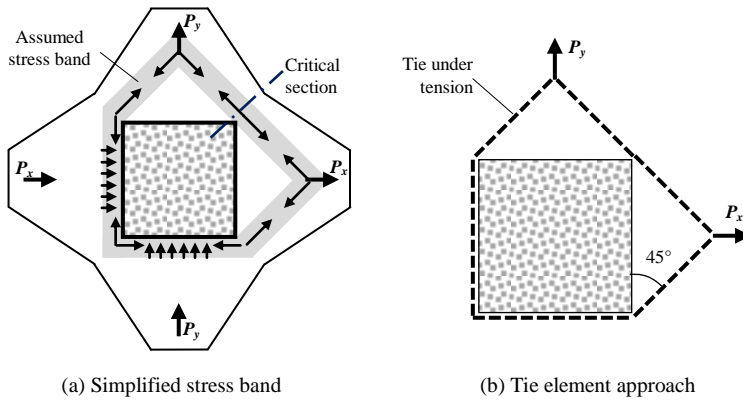


Figure 10 The tie method concept

5 CONCLUSIONS

Numerical analyses have been carried out to understand the behavior of external diaphragm connections for CFST columns. The application of perpendicular loads does not significantly affect the maximum stress and the nonlinear deformation of steel tubes. In all cases, maximum stresses occur on the tension sides near CFST column corners. A design limit state based on nonlinear deformation under tension on the middle part of CFST column is recommended. A simple design method is proposed to estimate the capacity of external diaphragm connections. The capacity is determined by the critical size of the external diaphragm without considering the effect of perpendicular loading.

REFERENCES

- [1] Morino S, Uchikoshi M, and Yamaguchi I, "Concrete-filled steel tube column system - its advantages", *Steel Structures*, vol. 1, pp. 33-44, 2001.
- [2] Guo L, Zhang S, Kim WJ, and Ranzi G, "Behavior of square hollow steel tubes and steel tubes filled with concrete", *Thin-Walled Structures*, vol. 45, pp. 961-973, 2007.
- [3] de Oliveira W, De Nardin S & de Cresce El Debs A, "Evaluation of passive confinement in CFT columns", *Journal of Constructional Steel Research* 66, pp. 487-495, 2010.

- [4] Inai E, Mukai A, Kai M, Tokinoya H, Fukumoto T, and Mori K., "Behavior of Concrete-Filled Steel Tube Beam Columns", *Journal of Structural Engineering*, vol. 130, pp. 189-202, 2004.
- [5] Alostaz Y, and Schneider S, "Analytical behavior of connections to concrete-filled steel tubes", *Journal of Constructional Steel Research*, vol. 40, no. 2, pp. 95-127, 1996.
- [6] Schneider S, and Alostaz Y, "Experimental behavior of connections to concrete-filled steel tubes", *Journal of Constructional Steel Research*, vol. 45, no. 3, pp. 321-352, 1998.
- [7] Chiew SP, Lie ST, and Dai CW, "Moment Resistance of Steel I-Beam to CFT Column Connections", *Journal of Structural Engineering*, vol. 127, pp. 1164-1172, 2001.
- [8] Tjahjanto HH, MacRae GA, Abu AK, Clifton GC, Beetham T, and Mago N, "Design capacity of external diaphragm connections for square CFST columns", *Steel and Composite Structures*, (submitted for publications).