Australian Earthquake Engineering Society 2011 Conference, Nov 18-20, Barossa Valley, South Australia

# Improved behaviour of concrete-filled-Steel-tube columns with external confinement

**JOHNNY CHING MING HO[1]**


## ABSTRACT

In high-strength concrete columns, because of the heavy demand of confining steel to restore the column ductility, it is more efficient to provide the confinement in the form of steel tube to form concrete-filled-steel-tube (CFST) column. Comparing with the transverse steel, CFST columns provide a stronger and more uniform confining pressure to the concrete core, and reduce the steel congestion problem for better concrete placing quality. However, a major shortcoming of CFST columns is the imperfect steel-concrete interface bonding at the elastic stage as steel dilates more than concrete in compression. This adversely affects the confinement of the steel tube and decrease the elastic modulus. To resolve the problem, it is proposed in this study to use external steel confinement in the forms of rings and ties to restrict the dilation of steel tube. For verification, a series of uni-axial compression test was performed on some CFST columns to study the effectiveness of external confinement. From the results, it was found that: (1) Both rings and ties improved the stiffness of the CFST columns; (2) The rings improve significantly the axial strength of the CFST columns while the ties did not improve the axial strength; (3) All externally confined CFST columns can reach a strain of at least 20% before failure occurs.


Keywords: concrete-filled-steel-tube; external confinement; normal-strength concrete; rings; ties

## 1. Introduction

It is well know that the flexural strength and ductility performance of reinforced concrete (RC) columns can be significantly improved by installing more confining steel (Watson and Park 1996; Ho 2011) within the potential plastic hinge or critical regions or by steel-concrete composite columns (Young and Ellobody 2006; Valente and Cruz 2010). Nevertheless, the effectiveness of confinement decreases as the concrete strength increases (Pam and Ho 2001). Therefore, high-strength concrete (HSC) columns need larger amount of confinement if the same level of strength and ductility need to be provided (Lam et al. 2009). Consequently, it causes problematic steel congestion problem within the plastic hinge region of columns, which adversely affects the quality of concrete placing at these locations.

To resolve the problems and maintain sufficient confinement for ductility provision, composite concrete-filled-steel-tube (CFST) columns are advocated. It was found from previous research that CFST columns had superior performance to RC columns under uni-axial load (Furlong 1967, Usami and Fukumoto 1984), under flexure (Han et al. 2006) and under torsion (Hsu et al. 2009). From safety point of view, they are characterised by higher strength, ductility, buckling

[1]Assistant Professor, Department of Civil Engineering, The University of Hong Kong, Hong Kong

resistance and energy absorption before failure. From cost effectiveness point of view, the tubes act as both the longitudinal reinforcement and formwork that save the time and cost for construction. From environmental point of view, the size of CFST columns could be much smaller than that of ordinary RC columns due to steel and concrete composite action. Hence, they have less embodied energy and carbon. All of these help produce a more sustainable construction environment. Lastly, the floor area saved is always beneficial.

Notwithstanding the numerous benefits, one of the major shortcomings of the CFST columns is that the steel tube is not fully effective in confining the core concrete during initial elastic stage when the strain in concrete is still small (Kitada 1998). This is because steel tube dilates more than concrete and causes imperfect steel-concrete interface bonding (Uy 2001; Sakino et al. 2004). The imperfect bonding in turns adversely affect the confining pressure provide to the concrete core, stiffness and axial deformation of the CFST columns (Nezamen et al. 2006). Moreover, due to the imperfect interface bonding, the confining pressure provided by the steel tube is not uniform at the level of confinement even for column of circular cross-section, the confining pressure provided to the concrete core is then reduced.

To improve the confining effectiveness of the steel tube, it is proposed in this study to use external steel confinement to restrict the dilation of the steel tube. The proposed external confinement is divided into two types, which are in the form of steel rings welded around the outer perimeter of the CFST columns, and steel ties installed in the plane of column cross-section tightened by nuts against the external face of steel tube. It should be noted that both ends of the nuts are installed just tight, which means there is no initial pre-stressing force applied to the steel ties. Previously, instead of external confinement, internal steel ties (Hu et al. 2005), shear studs (Nakanishi et al. 1999) or welded steel stiffeners (Wright 1995) were adopted. Compared with the proposed form of external confinement, the internal shear studs and stiffeners are more difficult to be installed in columns of building structures. In order to verify the effectiveness of the proposed external confinement in restricting the lateral dilation of CFST columns, the authors have in this study carried out a series of uni-axial compression test for CFST columns confined by external steel rings and ties. The obtained load-displacement curves, Poisson's ratio, axial strength and stiffness for these columns were then compared with those of CFST columns without external confinement.

## 2. Test Programme

In this study, a total of 9 CFST column specimens have been fabricated and tested in a uni-axial compression machine of capacity 5,000 kN. The CFST column specimens are divided into 3 groups: (1) 4 CFST columns with external steel rings at different spacing (5t, 10t, 15t and 20t, where $t$ is the thickness of the steel tube) cast with normal-concrete strength (NSC); (2) 4 CFST columns with external steel ties at different spacing ($5t$, $10t$, $15t$ and $20t$) cast with NSC; (3) One CFST columns without external confinement cast with NSC for comparison purpose. The normal-strength concrete had concrete cylinder strength of about 30 MPa on testing day. The grade of steel is S355 produced as per BS EN 10210-2:2006. The thickness of the steel tube $t$ is 5 mm for all CFST specimens. The diameter of the CFST columns measured to the outer face of steel tube is 168 mm. The height of the CFST columns is 330 mm, which gives an aspect ratio of about 2. Fig

1(a) shows the photo of the CFST column specimens with various spacing of steel rings as external confinement. Fig 1(b) shows the photo of CFST column specimens with various spacing of steel ties as external confinement. Fig 1(c) shows the photo of the CFST column specimen without external confinement.

(a) Ring-confined columns (b) Tie-confined columns (c) Unconfined column

Fig 1 Photos of tested columns

All the external confinement was provided at spacing of 5*t*, 10*t*, 15*t* and 20*t*, which are 25, 50, 75 and 100 mm respectively. For the external steel rings, the diameters of all ring adopted are 8 mm and the nominal yield strength is 250 MPa. The steel rings were welded to the steel tube at 8 locations in each level of confinement, which were separated from each other by an angle of 45° at the centre of cross section. At the end of the steel rings, there was an overlapping length of 10 times the steel diameter, which is 80 mm. Fig 2 shows the details of the steel rings (welding locations and overlapping length) and the respective CFST specimens. For the steel ties, the diameter is 8 mm and with nominal yield strength of 250 MPa. The ties adopted in this test were all threaded. Nuts were installed at both of its ends to tighten the ties against the external face of the steel tube. At each level, a pair of steel ties (with a level difference of a steel diameter) was installed perpendicular to each other. The pair of ties was then rotated by 45° at the next level and the arrangement continued for the subsequent layers of ties. The details of the steel tie arrangement and the respective specimens are shown in Fig 3.

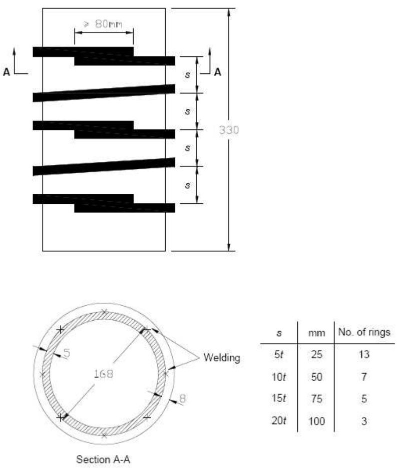



Fig 2 Steel rings arrangement

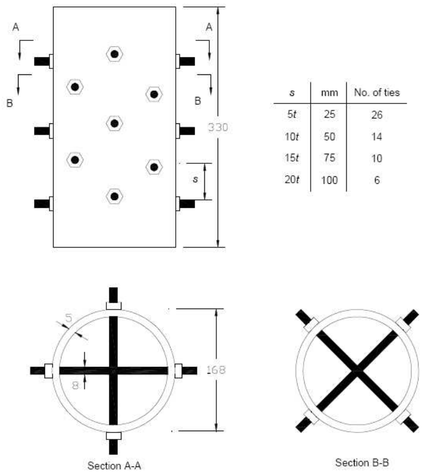



Fig 3 Steel ties arrangement

Each of the CFST column specimens was given a unique code. For example, 30-5-5R represents a CFST column specimen with concrete cylinder strength of about 30 MPa (indicated by the first number), thickness of steel tube $t$ equal to 5 mm (indicated by the second number), spacing of external confinement equal to $5t$ (indicated by the last number) and the suffix R stands for rings as external confinement, where T stands for ties as external confinement. The CFST column without external confinement is represented by 30-5-00X, where X stands for no confinement. Table 1 summarises the properties and details of external confinement for each of the CFST specimens. All the tests were carried out using a uni-axial compression testing machine of safe working capacity of 5,000 kN as shown in Fig 4.

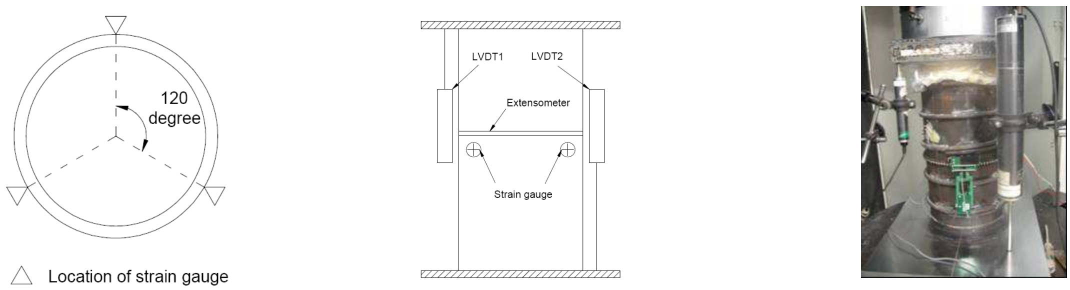
Fig 4 Test setup

Table 1 Cross-section properties and details of external confinement

| External confinement | Specimen code | Sectional dimensions | | | Concrete strength | Spacing | Confinement | |
|---|---|---|---|---|---|---|---|---|
| | | $D$ (mm) | $t$ (mm) | $H$ (mm) | $f_c'$ (MPa) | $s$ (mm) | $D_c$ (mm) | $f_y$ (MPa) |
| | 30-5-5R | | | | | 25 | | |
| Ring | 30-5-10R | 168 | 5 | 330 | 30 | 50 | 8 | 250 |
| | 30-5-15R | | | | | 75 | | |
| | 30-5-20R | | | | | 100 | | |
| | 30-5-5T | | | | | 25 | | |
| Tie | 30-5-10T | 168 | 5 | 330 | 30 | 50 | 8 | 250 |
| | 30-5-15T | | | | | 75 | | |
| | 30-5-20T | | | | | 100 | | |
| None | 30-5-00X | 168 | 5 | 330 | 30 | 0 | 0 | 0 |

## 3. Instrumentation

(1) Strain gauges - Two directional strain gauges to measure the longitudinal and transverse strains were installed on the steel tube of each of the CFST columns. Three strain gauges of this type were installed in every specimen, which were equally spaced with an angle of 120° at the centre of cross section. The arrangement of strain gauges is shown in Figs 5(a) and (b).
(2) Linear variable differential transducer (LVDT) - Two LVDTs were used to measure the axial deformation of the specimens. Two LVDTs were installed to measure the movement of the top and bottom platens as shown in Figs 5(b) and (c). The actual axial shortening of the test specimens can be obtained by the difference of the readings measured by both LVDTs.
(3) Circumferential extensometers - A circumferential extensometer was installed around the centre of each of the specimens to measure the dilation of the column at the initial stage of the loading process. The arrangement of the extensometer is also shown in Figures 5(b) and 5(c).




(a) Arrangement of strain gauges (b) Arrangement of LVDTs and extensometer (c) Photo of instrumentation

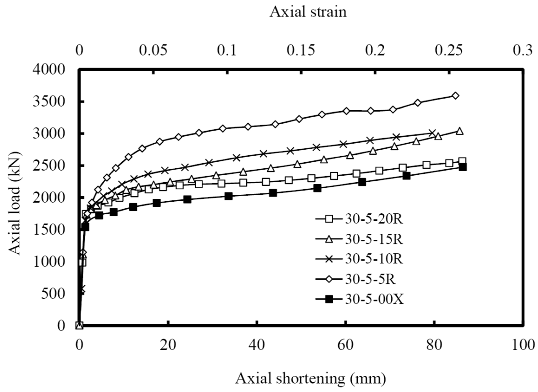
Fig 5 Instrumentation

All the loading tests were displacement-controlled. The loading rate is 0.3 mm/min. This rate would be increased incrementally by 0.2 mm/min for every 10 mm increase in axial displacement after the specimens had reached the yielding stage. The loading test will be stopped when the axial displacement had reached about 80 mm (25% axial strain).

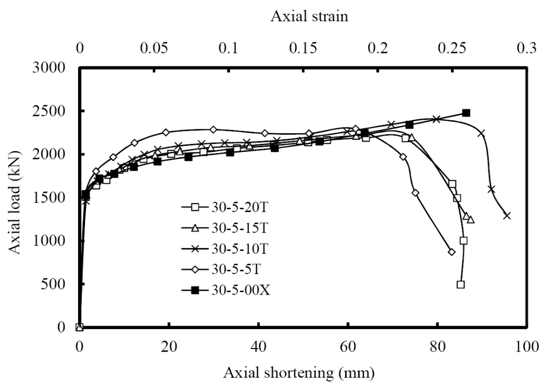
## 4. Experimental results

### 4.1 Axial load – shortening curves

Fig 6 shows the axial load against axial shortening curves of CFST column specimens with spacing of external confinement (rings and ties) and specimens without external confinement. The *y*-value represents the total axial load applied to the specimens, whereas the *x*-value represents the axial shortening of the specimens under axial load. From the figure, it can be observed that the CFST specimens with external confinement performed better in terms of strength and stiffness than that without confinement. The reasons are that the external confinement, i.e. steel rings and ties, effectively restricted the lateral dilation of the steel tube under uni-axial compression. Therefore, larger confining pressure was provided to confine the steel tube as well as the concrete core.




(a) Ring-confined columns




(b) Tie-confined columns

Fig 6 Axial load – shortening curves

(a) Ring-confined columns

(b) Tie-confined columns

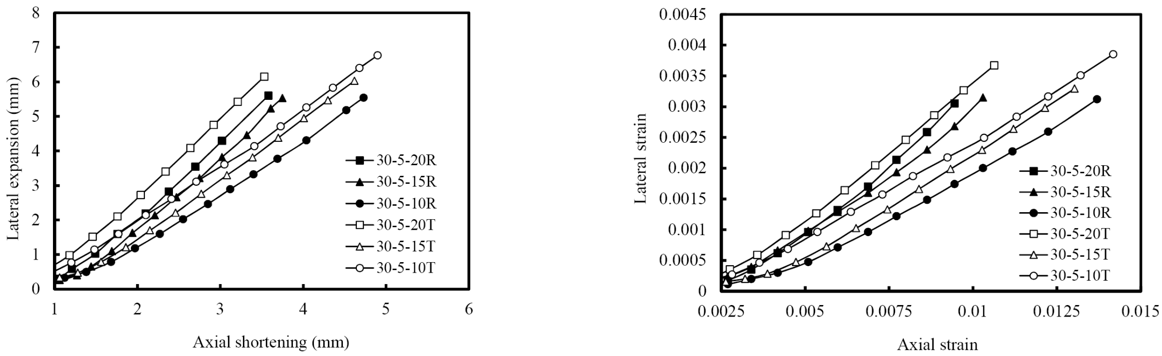
(c) Unconfined column

Fig 7 Failure modes of tested columns

On the other hand, between the two types of external confinement, the steel rings performed better than the steel ties provided at the same spacing in terms of strength and stiffness. This is because the steel rings were able to provide a more uniform and continuous confining pressure to both the steel tube and the concrete core. Compared with the steel rings, the steel ties could only provide the discrete confining pressure at the locations where the ties were tightened against the steel tube. Between these locations in the planes of both horizontal and vertical directions, the confining pressure decreases. Furthermore, the openings (holes) for steel ties form the weak points in the steel tube under uni-axial load because of the reduced moment of inertia. At large longitudinal axial strains, horizontal splitting stress would be concentrated at the openings and caused longitudinal crack to form along the steel tube, which started at the openings at roughly the mid-height of the steel tube and between the steel ties (i.e. furthest away from the points of effective lateral restraint). Fig 7 shows the failure modes.

4.2 Lateral strain and Poisson's ratio

Because of the different Poisson's ratios of steel (~0.3) and concrete (~0.2), the steel tube is not fully effective to confine the concrete core during initial elastic stage. Therefore, it is proposed to use external confinement to restrict the dilation of the steel tube and hence improve the steel-concrete interface bonding and the confining pressure provided to the concrete core. At the same time, the external confinement also provides some confining pressure to the steel tube to improve the axial strength of the steel tube and hence the capacity of the CFST columns. The effectiveness of the external confinement could be studied by plotting the lateral expansion (dilation) against the axial shortening of the CFST specimens during the elastic stage.




(a) Lateral expansion against axial shortening for CFST columns

(b) Lateral strain against axial strain for CFST columns

Fig 8 Measured lateral expansion and strain

Fig 8(a) shows the lateral expansion against axial shortening for the CFST columns with and without external confinement. Fig 8(b) shows the respective graphs of lateral strain against axial strain for the CFST columns. The lateral strain is obtained by dividing the circumferential expansion by the circumference of the steel tube and further by $\pi$. The axial strain is obtained by dividing the axial shortening of the CFST columns by the overall height of the specimen. The Poisson's ratio of the CFST columns is calculated from the initial slope of the graph before reaching 1/3 of the maximum load. The results are summarised in Table 2. From the table, it can be seen that the Poisson's ratios of all ring-confined CFST columns and the tie-confined CFST columns with close spacing (i.e. 10*t* and 15*t*), are about or smaller than 0.2, which is regarded as the average Poisson's ratio of NSC. Hence, it indicates that both types of external confinement, when provided at small spacing, can effectively restrict the lateral dilation of steel tube and maintain an intact steel-concrete interface bonding.

On the other hand, for CFST columns confined by steel ties, the evaluated Poisson's ratio of column with tie spacing of 20*t* is slightly larger than 0.2, which indicates that the steel ties at such large spacing are not capable of effectively restricting the lateral dilation of the steel tube. Therefore, the confining pressure, axial strength and stiffness would be smaller than those of CFST columns confined by steel rings at the same spacing. Nonetheless, when compare with the Poisson's ratio of steel (~0.3), the value is still smaller. In other words, it can reasonably be deduced that the steel ties were still able to restrict partially the lateral dilation of the steel tube. For other set of tie-confined CFST columns with spacing of 10*t* and 15*t*, the Poisson's ratio are about 0.2, which indicates that for closely spaced tie-confined CFST columns, the confinement is able to effectively restrict the lateral expansion of the steel tube.

Table 2 Poisson's ratio of tested CFST specimens

| Specimen code | Poisson's ratio |
|---|---|
| 30-5-10R | 0.172 |
| 30-5-15R | 0.205 |
| 30-5-20R | 0.219 |
| 30-5-10T | 0.201 |
| 30-5-15T | 0.197 |
| 30-5-20T | 0.235 |

Table 3 Axial strength enhancement ratio and stiffness enhancement ratio

| Specimen code | Axial strength (kN) | Axial strength enhancement ratio $\omega_S$ | Stiffness (kN/mm) | Stiffness enhancement ratio $\omega_E$ |
|---|---|---|---|---|
| 30-5-5R | 3590 | 1.450 | 1341 | 1.354 |
| 30-5-10R | 3006 | 1.214 | 1321 | 1.334 |
| 30-5-15R | 3041 | 1.228 | 1295 | 1.308 |
| 30-5-20R | 2566 | 1.036 | 1265 | 1.277 |
| Average | | 1.232 | | 1.319 |
| 30-5-5T | 2329 | 0.941 | 1332 | 1.345 |
| 30-5-10T | 2408 | 0.973 | 1233 | 1.245 |
| 30-5-15T | 2228 | 0.900 | 1199 | 1.211 |
| 30-5-20T | 2199 | 0.888 | 1141 | 1.153 |
| Average | | 0.925 | | 1.238 |
| 30-5-00X | 2476 | 1.000 | 990 | 1.000 |

4.3 Improvement on axial strength and stiffness due to external confinement

Table 3 summarises the axial strength and stiffness of the CFST columns. The relative strength and stiffness increase due to the installation of external confinement is studied by the axial strength and stiffness enhancement ratio $\omega_S = P_c/P$ and $\omega_E = E_c/E$, where $P_c$ ($E_c$) and $P$ ($E$) are the experimentally measured axial strengths (stiffness) of CFST columns with and without external confinement respectively. The values of $\omega_S$ are listed in Table 3. From the table, it is evident that the average axial strength (stiffness) enhancement ratios are about 1.232 (1.319) and 0.925 (1.238), for CFST columns confined by steel rings and ties respectively.

## Conclusions

The following conclusions are drawn from the test results:

(1)CFST columns with external confinement were effective in restricting the lateral dilation of the columns and maintain an intact steel-concrete interface bonding.

(2)The performance of ring-confined CSFT columns is better than the tie-confined CFST columns in terms of strength and stiffness. It is because the steel rings provide a more effective, uniform and continuous confining pressure to the concrete core.

(3)The external confinement, in the form of either rings or ties, can effectively increase the axial strain of CFST columns to more than 20% without failure.

(4)The external ring confinement can effectively improve the axial strength of CFST columns by an average value of 23.2%, whereas the tie confinement cannot improve the axial strength.

(5)The external ring and tie confinement can effectively improve the stiffness of CFST columns by an average value of 31.9% and 23.8% respectively.

## Acknowledgments

The work described in this paper has been substantially supported by a grant from the Research Grants Council of the Hong Kong, China (Project No. HKU 712310E).

## References

Furlong R.W. (1967), "Strength of steel-encased concrete beam columns", *Journal of Structural Division, ASCE*, **93**(ST5), 113-124.

Han L.H., Lu H., Yao G.H. and Liao F.Y. (2006), "Further study on the flexural behaviour of concrete-filled steel tube", *Journal of Constructional Steel Research*, **62**(6), 554-565.

Ho J.C.M. (2011), "Limited ductility design of reinforced concrete columns for tall buildings in low to moderate seismicity regions", *The Structural Design of Tall and Special Buildings*, **20**, 102-120.

Hsu H.L., Juang J.L. and Luo K.T. (2009), "Experimental evaluation on the seismic performance of high strength thin-walled composite members accounting for sectional aspect ratio effect", *Steel and Composite Structures*, **9**(4), 367-380.

Hu H.T., Huang C.S. and Chen Z.L. (2005), "Finite element analysis of CFT columns subjected to an axial compressive force and bending moment in combination", *Journal of Constructional Steel Research*, **61**, 1692-1712.

Kitada T. (1998), "Ultimate strength and ductility of state-of-the-art concrete-filled steel bridge piers in Japan", *Steel and Composite Structures*, **20**(4-6), 347-354.

Lam J.Y.K., Ho J.C.M. and Kwan A.K.H. (2009), "Maximum axial load level and minimum confinement for limited ductility design of concrete columns", *Computers and Concrete*, **6**(5), 357-376.

Nakanishi K. Kitada T. and Nakai H. (1999), "Experimental study on ultimate strength and ductility of concrete filled steel columns under strong earthquake", *Journal of Constructional Steel Research*, **51**(3), 297-310.

Nezamian A., Al-Mahaidi R. and Grundy P. (2006), "Bond strength of concrete plugs embedded in tubular steel piles under cyclic loading", *Canadian Journal of Civil Engineering*, **33**(2), 111-125.

Pam H.J. and Ho J.C.M. (2001), "Flexural strength enhancement of confined reinforced concrete columns", *Structures and Buildings*, **146**(4), 363-370.

Sakino K, Nakahara H., Morino S. and Nishiyama I. (2004), "Behavior of centrally loaded concrete-filled steel tube short columns", *Journal of Structural Engineering, ASCE*, **130**(2), 180-188.

Usami T. and Fukumoto Y. (1984), "Welded box compression members", *Journal of Structural Engineering, ASCE*, **110**(10), 2457-2470.

Uy B. (2001), "Strength of short concrete filled high strength steel box columns", *Journal of Construction Steel Research*, **57**, 113-134.

Valente I.B. and Cruz P.J.S. (2010), "Experimental analysis on steel and lightweight concrete composite beams", *Steel and Composite Structures*, **10**(2), 169-185.

Watson S., Zahn F.A. and Park R. (1994), "Confining reinforcement for concrete columns", *Journal of Structural Engineering*, *ASCE*, **120**(6), 1799-1824.

Wright H.D. (1995), "Local stability of filled and encased steel sections", *Journal of Structural Engineering*, *ASCE*, **121**(10), 1382-1388.

Young B. and Ellobody E. (2006), "Experimental investigation of concrete-filled cold formed high-strength stainless steel tube columns", *Journal of Constructional Steel Research,* **62**, 484-492.