THE AXIAL AND FLEXURAL LOAD BEHAVIOR OF CONCRETE-FILLED STEEL THIN-WALLED TUBES WITH STIFFENED SQUARE SECTIONS

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Abstract

A scheme called "tie-bar stiffening" was proposed for improving the performance of square concrete-filled steel tubes (CFTs) with thin-walled tubes. Axial load test and combined axial-and-flexural load test have both been conducted to circular, unstiffened and tie-bar-stiffened square CFT beam-columns. It is observed that the axial load strength and ductility of square CFT columns can be enhanced by the proposed stiffening scheme, and the spacing instead of diameter of the tie bars is the dominant factor to the scheme's effectiveness Stiffened square CFT beam-columns have a better flexural behavior, in terms of moment capacity and curvature ductility, than unstiffened ones. Such improvement in flexural behavior is more significant as the beam-column is subject to higher axial load.

INTRODUCTION

Many studies have shown that the performance of a square concrete-filled steel tube (CFT) is not as good as its circular counterpart. This is due to the fact that a square steel tube could only provide less confining pressure to the concrete core, and that its local buckling is more likely to occur. This fact has now been widely reflected in modern design codes such as *Manual of Steel Construction: Load and Resistance Factor Design (LRFD)* (AISC 1994) and *Seismic Provisions for Structural Steel Buildings* (AISC 1997), *Design of Composite Steel and Concrete Structures, Eurocode 4, ENV 1994-1-1* (BSI 1994), and *Recommendations for Design and Construction of Concrete-Filled Steel Tubular Structures* (AIJ 1997), in which the allowable width-to-thickness ratio for the steel tube with square cross-section is more restricted than that for circular one. Accordingly, an adequate stiffening measure for square CFTs with thin-walled tubes is highly desirable. Such stiffening measure will make square CFTs an economical construction material, too, and consequently the barrier to promote construction using square CFTs could be overcome.

Two stiffening measures have been reported for enhancing the behaviors of rectangular CFTs. One is to weld longitudinal steel strips on the internal surface of a steel tube, while the other one is to weld shear studs. Ge and Usami (1992) and Kwon and Song (1998) experimentally studied the effectiveness of the former measure on the behavior of square CFTs. It was found capable of increasing the axial load strength because the longitudinal strip stiffeners share to take some load. However, it also causes severe loss of stiffness in post-buckling. Lin *et al*. (1993) found that the second measure does not affect the strength but could improve the ductility of square CFTs.

Recently, a scheme has been proposed by the author as an alternative for improving the performance of square CFTs with thin-walled tubes. This scheme, called the "tie-bar stiffening scheme", is carried out by welding sets of stiffeners, each of which consists of four tie bars, at certain cross-sections with equal spacing along the tube axis. In such case, square tubes have to be assembled by using two U-shape parts cold-formed from steel plates, and the employed tie bars need to be welded at the two inner corners of a U-shape part before tube assembly. After the assembly, the welds at the same cross-section should divide the tube width B into three equal segments.

In order to investigate the effectiveness of this stiffening scheme, two phases of laboratory testing have been carried out, respectively. In the first phase of testing (axial load test), three variables were considered: the tube width-to-thickness ratio, the axial spacing of stiffening tie bars, and the diameter of these tie bars. The purpose of this phase was to identify the major factor that influences the effectiveness of this scheme most. While in the second phase of testing (combined axial-and-flexural load test), the effects of axial load upon the flexural behaviors of CFTs, among which some of the square ones were adequately tie-bar stiffened according to the findings in the first phase, were further investigated. Further information about these two phases of testing will be outlined as below, while detailed descriptions can be found in Huang *et al*. (2002), Liu *et al*. (2000, 2003) and Yeh *et al*. (2001).

AXIAL LOAD TEST AND RESULTS

Five, nine, and four CFT specimens with the B/t value (i.e. the tube width-to-thickness ratio) equal to 40, 70, and 150, respectively, were fabricated for axial load test. The specification of each specimen is summarized in Tab. 1. For the sake of comparison, circular CFT specimens were included in the test, too. Each specimen is numbered with letters followed by numbers. The first and second letters denote the shape of the tube's cross-section (S for square, C for circular) and the condition of stiffening (U for unstiffened, S for the tie-bar stiffened), respectively. The following two or three-digit number denotes B/t value of the specimen. For the tie-bar stiffened specimens, the axial spacing along the tube S (in terms of a fraction of the tube width) and the size number of the employed tie bars (the corresponding diameter is termed as φ_{tie}) are further denoted in the parentheses. Particularly, tie bars of three axial spacing (i.e. $B/3$, $B/2$ and $2B/3$) and three size numbers (i.e. #2, #3, and #4) were adopted to specimens with B/t equal to 70 such that their effectiveness could be evaluated parametrically.

Fig. 1 and Fig. 2 depict the cross-sectional and side views of the specimens, respectively. Fig. 3 depicts the schematic diagram of Specimen SS-70 (B/3, #3) and Pho. 1 illustrates the details of tie bars welded to Specimen SS-70 (B/5, #3) before tube assembly. All specimens with B/t = 40 and no specimen with B/t = 150 meet the AIJ, Eurocode 4, and AISC-LRFD requirements. But for those with B/t = 70, only CU-70 meets these requirements.

Tab. 1 Specifications and test results of CFT specimens in axial load test

Specimen	B mm	t mm	B/t	S mm	φ_{tie} mm	f_y MPa	$f_{c'}$ MPa	$f_{y,tie}$ MPa	P_{max} kN	P_{max} / P_n
SU-40	200	5	40	-	-	265.8	27.15	-	2312	1.15
SS-40 (B/4, #3)	200	5	40	B/4	9.52	265.8	27.15	410.9	2728*	1.35*
SS-40 (B/4, #4)	200	5	40	B/4	12.7	265.8	27.15	386.0	2903*	1.44*
SS-40 (B/2, #4)	200	5	40	B/2	12.7	265.8	27.15	386.0	2463	1.22
CU-40	200	5	40	-	-	265.8	27.15	-	2013*	1.27*
SU-70	280	4	40	-	-	272.6	31.15	-	3401	0.97
SS-70 (B/3, #2)	280	4	70	B/3	7	272.6	30.49	588.6	3744	1.08
SS-70 (B/3, #3)	280	4	70	B/3	9.52	272.6	30.49	615.3	3855	1.11
SS-70 (B/3, #4)	280	4	70	B/3	12.7	272.6	31.15	511.1	3807	1.13
SS-70 (B/2, #3)	280	4	70	B/2	9.52	272.6	29.84	615.3	3610	1.06
SS-70 (B/3, #4)	280	4	70	B/2	12.7	272.6	31.15	511.1	3579	1.08
SS-70 (2B/3, #3)	280	4	70	2B/3	9.52	272.6	29.18	615.3	3457	1.03
SS-70 (2B/3, #4)	280	4	70	2B/3	12.7	272.6	31.15	511.1	3507	1.03
CU-70	280	4	70	-	-	272.6	31.15	-	3025	1.23
SU-150	300	2	150	-	-	341.7	27.20	-	3062	0.96
SS-150 (B/6, #2)	300	2	150	B/6	7	341.7	24.00	735.8	3184	1.14
SS-150 (B/3, #2)	300	2	150	B/3	7	341.7	25.21	735.8	3105	0.97
CU-150	300	2	150	-	-	341.7	27.23	-	2608	1.04

*: No apparent softening is observed in the corresponding axial load-deformation curve within the axial strain of 2.5%.

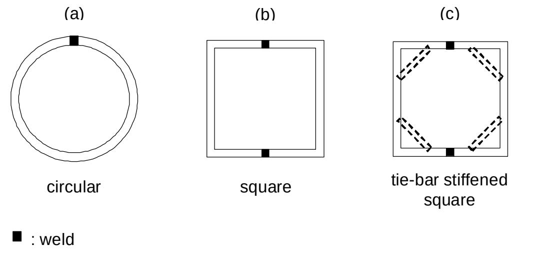

Fig. 1: Cross-sectional views of CFT column specimens

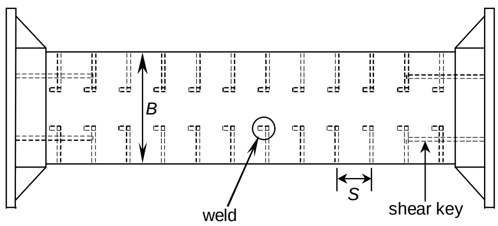

Fig. 3: The schematic diagram of Specimen SS-70 (B/3, #3)

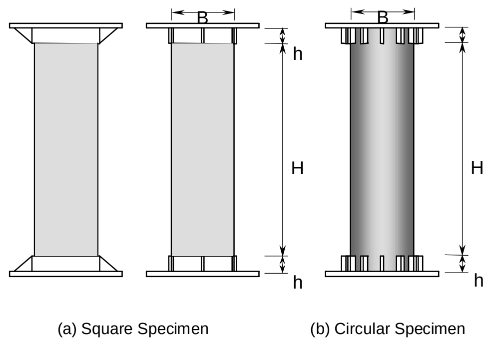

Fig. 2: Side views of CFT column specimens

Pho. 1: Details of tie bars in Specimen SS-70 (B/5, #3) before tube assembly

Fig. 4 to Fig. 7 depict the axial load-deformation curves for specimens with a B/t value of 40, 70 (for #3 tie bars), 70 (for spacing of $B/3$ and for #4 tie bars), and 150, respectively. The axial load in each curve was normalized with respect to the nominal strength P_n of the corresponding specimen given by direct strength superposition, i.e.:

$$P_n = A_s \cdot f_y + A_c \cdot f_c' \tag{1}$$

where A_s and A_c are the cross-sectional areas of the steel and concrete section, and f_y and f_c' are the yield strength of steel and the compression strength of concrete, respectively. For the case square tubes, the above equation is identical to that of Eurocode 4, and differs from that of AIJ Code in that the later additionally adopt a reduction factor (i.e. 0.85) for the compression strength of concrete. The ratio of experimental to nominal axial load strength of each specimen, i.e. P_{max}/P_n, is summarized in the last column of Tab. 1. It is observed that the axial load strength of a square CFT with B/t = 40 could be significantly enhanced by stiffening. The Eurocode 4 predicts the axial load strength well for those with a B/t value equal to 70 and 150, and this also imply that the adoption of a reduction factor for concrete in the AIJ Code might not be necessary.

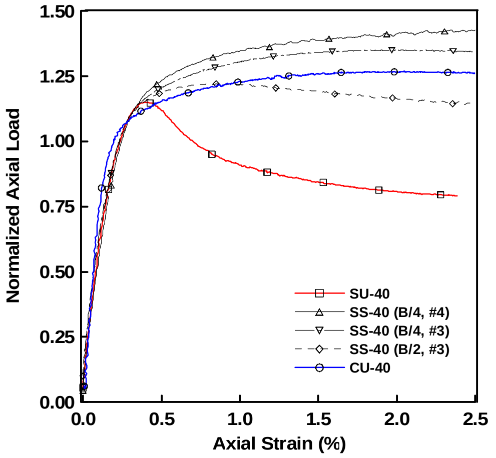

Fig. 4: Axial load-deformation curves for specimens with B/t = 40

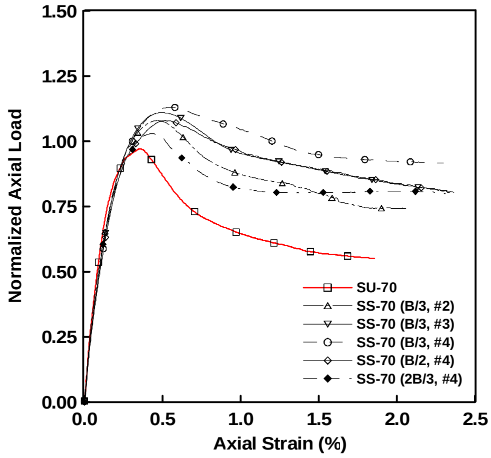

Fig. 6: Axial load-deformation curves for specimens with B/t = 70 (Part II)

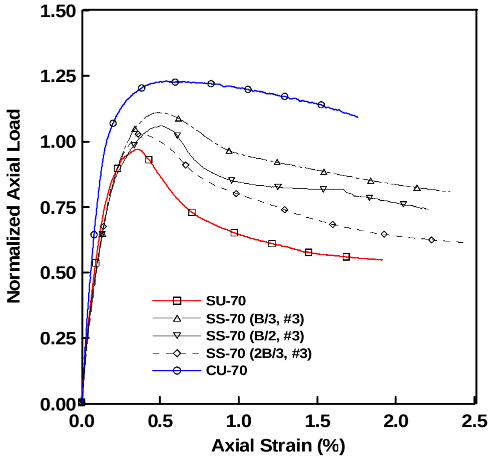

Fig. 5: Axial load-deformation curves for specimens with B/t = 70 (Part I)

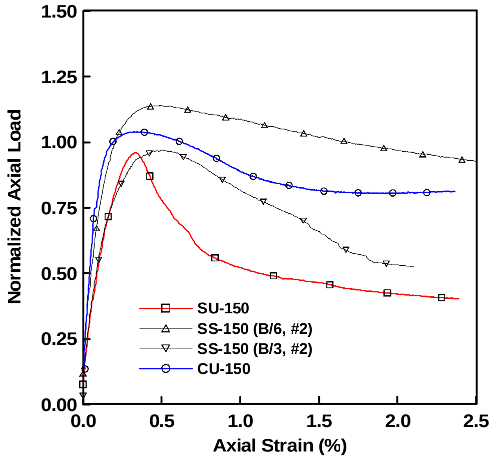

Fig. 7: Axial load-deformation curves for specimens with B/t = 150

Fig. 4 to Fig. 7 demonstrate that circular CFTs always have a better ductility than unstiffened square ones, and CFTs of high *B*/*t* value always have a worse ductility than those of low *B*/*t* value. Regarding the unstiffened and tie-bar-stiffened square CFTs, experimental results indicate that the axial load behaviors could be easily improved by stiffening at a customary *B*/*t* value (40). While for a high *B*/*t* value (70), the stiffening scheme is effective, too. A comparison between Fig. 5 and Fig. 6 shows that for all three considered axial spacing (i.e. *B*/3, *B*/2 and 2*B*/3), the employment of thicker tie bars (size #4) can uplift the axial load performance very few; an axial spacing of *B*/3 always yields a satisfactory axial load performance, regardless of using Size #3 or #4 tie bars. Particularly, it seems from Fig. 6 that the change in axial spacing results in a more significant variation in axial load behaviors than the change in tie bar diameter. Thus, the axial spacing is the more dominant factor to the effectiveness of tie-bar stiffening scheme. Finally for extremely high *B*/*t* value (150), the axial load behaviors would be very poor unless they are really densely stiffened.

In summary, the axial load test results indicate that the axial load strength and ductility of square CFTs could be enhanced by the proposed tie-bar stiffening scheme. In addition, the spacing instead of diameter of the tie bars is the dominant factor to the enhancement.

COMBINED AXIAL-AND-FLEXURAL LOAD TEST AND RESULTS

Knowing that the proposed tie-bar stiffening scheme is effective for square CFTs at high (but not extremely high) width-to-thickness ratio subject to axial load, in the following phase of testing we will focus upon CFT specimen with *B*/*t* = 70, and the major concern here is to further identify the effectiveness of this scheme to the enhancement of flexural behaviors of square CFT beam-columns under various levels of axial load. Since the spacing instead of diameter of the tie bars is more dominant to the effectiveness, a unique size of tie bars (#3, diameter 9.52mm) would be employed here and, for the sake of comparison, two values of spacing, i.e. *B*/3 and *B*/5, were considered.

The loading frame depicted in Fig. 8 and Pho. 2 was employed for the combined axial-and flexural load test, upon which a 2500kN actuator was axially positioned and kept under force control, and a 1000kN actuator was laterally positioned and kept under displacement control. It functioned as a four-point-bending apparatus, whose conceptual sketch is depicted in Fig. 9. The specimen could be installed as a part of the middle loaded segment which was hinge-and-roller supported at both its ends, and could be subject to constant axial load and monotonically increased flexural deformation, with the influence of shear force being eliminated theoretically.

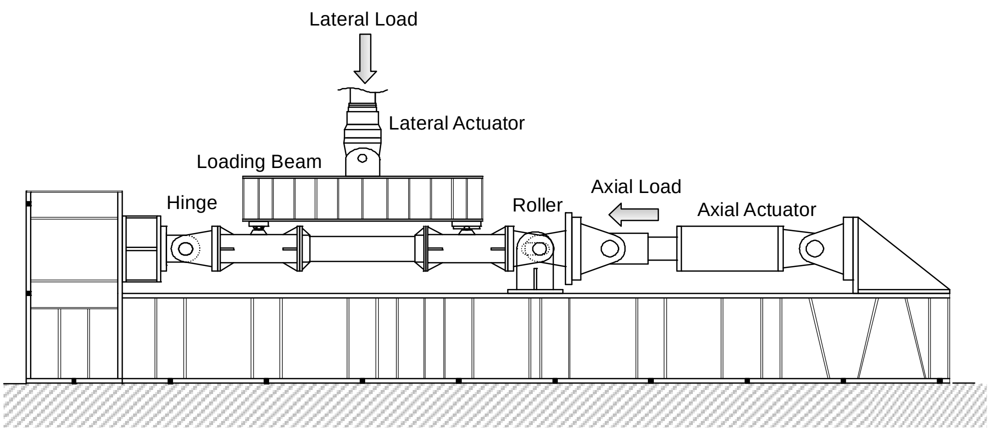

Fig. 8 Loading frame for applying combined axial-and-flexural load to a beam-column

A total of 20 CFT specimens with a common width *B* of 280mm and a *B*/*t* value of 70 were fabricated for the combined axial-and-flexural load test. They can be grouped into four series: the C Series (circular tubes), S Series (square tubes, unstiffened), B-3 Series (square tubes, tie-bar stiffened with the axial spacing equal to *B*/3) and B-5 Series (square tubes, tie-bar stiffened with the axial spacing equal to *B*/5). Again, among these specimens, those with square tubes met neither the Eurocode 4 nor the AIJ Code. The level of constant axial load applied to the five specimens in each Series was equal to the axial load ratio (i.e. times of its axial load strength N_0 suggested by the Eurocode 4) of 0.0, 0.2, 0.3, 0.4, 0.5, respectively. The specification of each specimen is summarized in Tab. 2.

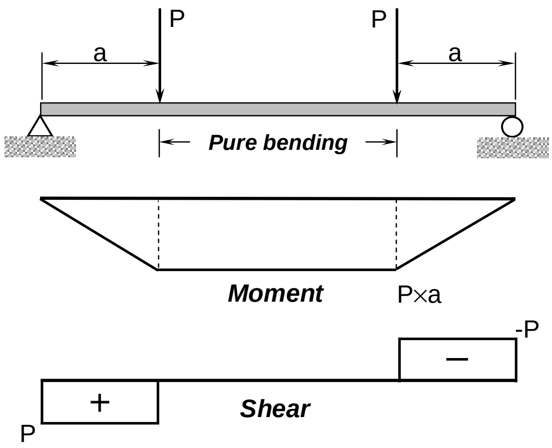

Fig. 9: Conceptual sketch for the loading condition of four-point-bending

Pho. 2: Loading frame for applying combined axial-and-flexural load to a beam-column

Tab. 2: Specifications and test results of CFT specimens in combined axial-and-flexural load test

Specimen	B mm	t mm	B/t	S mm	φ_{tie} mm	f_y MPa	$f_{c'}$ MPa	$f_{y,tie}$ MPa	N kN	N/N_0	$M_{u,exp}$ kN-m	$M_{n,EC4}$ kN-m	$M_{u,exp}$ / $M_{n,EC4}$
S-0.0	280	4	70	-	-	292	26.8	-	0	0.0	172	160	1.08
S-0.2	280	4	70	-	-	317	35.4	-	802	0.2	226	225	1.01
S-0.3	280	4	70	-	-	292	26.8	-	1035	0.3	200	201	1.00
S-0.4	280	4	70	-	-	292	26.8	-	1378	0.4	201	195	1.03
S-0.5	280	4	70	-	-	292	26.8	-	1725	0.5	186	178	1.04
B-3-0.0	280	4	70	*B*/3	9.52	292	26.8	426	0	0.0	179	160	1.12
B-3-0.2	280	4	70	*B*/3	9.52	317	35.4	478	801	0.2	237	225	1.06
B-3-0.3	280	4	70	*B*/3	9.52	317	35.4	478	1201	0.3	256	233	1.10
B-3-0.4	280	4	70	*B*/3	9.52	317	35.4	478	1602	0.4	240	231	1.04
B-3-0.5	280	4	70	*B*/3	9.52	317	35.4	478	2004	0.5	240	217	1.11
B-5-0.0	280	4	70	*B*/5	9.52	317	35.4	478	0	0.0	212	175	1.21
B-5-0.2	280	4	70	*B*/5	9.52	317	35.4	478	806	0.2	254	225	1.13
B-5-0.3	280	4	70	*B*/5	9.52	317	35.4	478	1201	0.3	277	233	1.19
B-5-0.4	280	4	70	*B*/5	9.52	317	35.4	478	1603	0.4	280	231	1.21
B-5-0.5	280	4	70	*B*/5	9.52	317	35.4	478	2004	0.5	276	217	1.27
C-0.0	280	4	70	-	-	292	26.8	-	0	0.0	137	95	1.44
C-0.2	280	4	70	-	-	292	26.8	-	542	0.2	155	125	1.24
C-0.3	280	4	70	-	-	292	26.8	-	812	0.3	164	132	1.24
C-0.4	280	4	70	-	-	317	35.4	-	1202	0.4	183	155	1.18

C-0.5	280	4	70	-	-	292	26.8	-	1354	0.5	172	129	1.33

Fig. 10 to Fig. 14 illustrate the experimental moment-curvature relationships of the tested specimens sorted according to the applied axial load ratios of 0.0, 0.2, 0.3, 0.4, and 0.5, respectively. In these figures, the moment of each specimen is normalized with respect to $M_{0,EC4}$, its moment capacity under zero axial load by the Eurocode 4, and the curvature is non-dimensionalized with respect to the width of specimens B. At the considered B/t value of 70, generally speaking, the C Series specimens seem to perform best flexurally, and then the B-5 Series, and then the B-3 Series, and finally the S Series specimens perform worst. Such tendency is more significant as the applied axial load increases. The curvature ductility of a specimen, no matter circular or square one, decreases as the applied axial load increases.

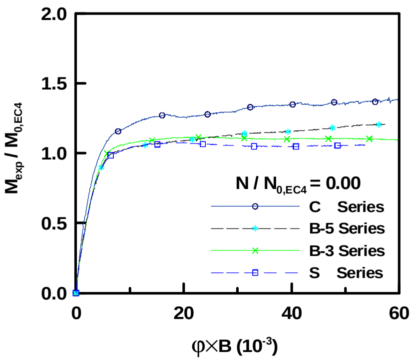

Fig. 10: Moment-curvature relationships for CFT specimens under axial load ratio of 0.0

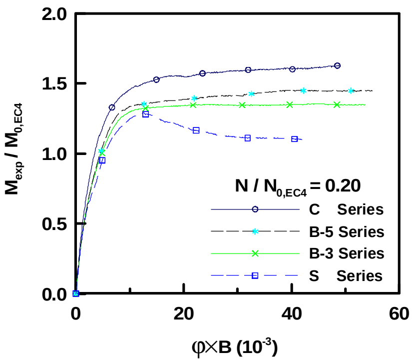

Fig. 11: Moment-curvature relationships for CFT specimens under axial load ratio of 0.2

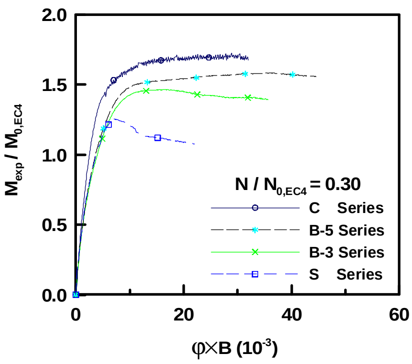

Fig. 12: Moment-curvature relationships for CFT specimens under axial load ratio of 0.3

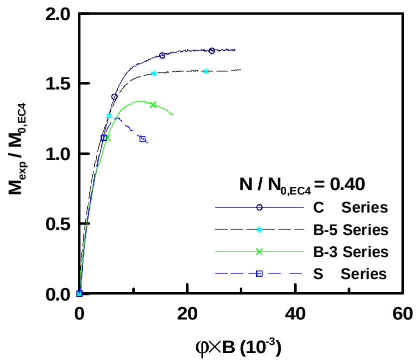

Fig. 13: Moment-curvature relationships for CFT specimens under axial load ratio of 0.4

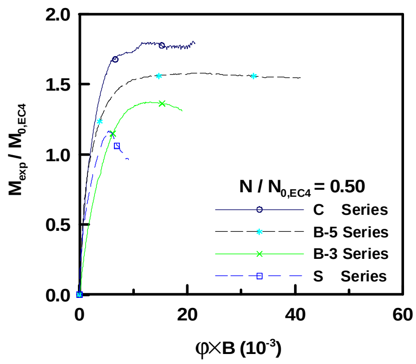

Fig. 14: Moment-curvature relationships for CFT specimens under axial load ratio of 0.5

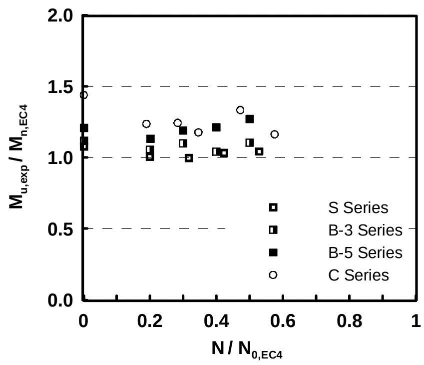

Fig. 15: The moment capacity ratios of CFT beam-columns under various axial loads

Fig. 15 depicts the attained ratios of ultimate moment capacity $M_{u,exp}$ to nominal moment capacity $M_{n,EC4}$ (predicted by the Eurocode 4) of all CFT beam-columns. For the S-Series specimens, the moment capacity predicted by the Eurocode 4 seems very close to the experimental value under all axial loads. The maximum error reads only 8%. Enhancement up to 20% is possible if they are stiffened into B-3 or B-5 Series. Such enhancement in moment capacity is shown to be more remarkable as the applied axial load increases. The curvature ductility of S Series specimens is shown to decrease more significantly too as the applied axial load increases. However, if they were tie-bar stiffened into B-3 or B-5 Series, then their curvature ductility could be significantly improved even under high axial load (e.g. ratio of 0.4 or 0.5). Their flexural performance thus could be improved very close to those of C series specimens.

In summary, tie-bar stiffened specimens demonstrate a better moment capacity and significantly improved curvature ductility, especially while under high axial load ratios.

CONCLUSIONS

Experimental investigation on the effectiveness of "tie-bar stiffening scheme" has been carried out successfully. According to the test results, we have the following observations: (1) The axial load strength and ductility of square CFT columns can be enhanced by the proposed stiffening scheme, and the spacing instead of diameter of the tie bars is the dominant factor to the scheme's effectiveness. (2) Stiffened square CFT beam-columns have a better flexural behavior, in terms of moment capacity and curvature ductility, than unstiffened ones. Such improvement in flexural behavior is more significant as the beam-column is subject to higher axial load. It is recommended that the upper limit to the square tube's width-to-thickness ratio imposed by various codes should be relieved if they could be adequately stiffened.

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REFERENCES

American Institute of Steel Construction (AISC) (1994), *Manual of Steel Construction: Load and Resistance Factor Design (LRFD)*, 2nd Ed., Chicago.

American Institute of Steel Construction (AISC) (1997), *Seismic Provisions for Structural Steel Buildings*, Chicago.

Architectural Institute of Japan (AIJ) (1997), *Recommendations for Design and Construction of Concrete Filled Steel Tubular Structures*, Tokyo.

British Standards Institute (BSI) (1994), *Design of Composite Steel and Concrete Structures, Eurocode 4, ENV 1994-1-1*, London.

Ge, H. B. and Usami, T. (1992), "Strength of Concrete-filled Thin-walled Steel Box Column: Experiment", *J. Construct. Steel Res.*, 30, 179-186.

Huang, C. S., Yeh, Y.-K., Liu, G.-Y., Hu, H.-T., Tsai, K. C., Weng, Y. T., Wang, S. H., and Wu, M.-H. (2002), "Axial Load Behavior of Stiffened Concrete-Filled Steel Columns," *J Structural Eng., ASCE*, 128(9), 1222-1230.

Kwon, Y. B. and Song, J. Y. (1998), "A Study on the Structural Behavior of Concrete-filled Steel Box

Sections", *Proc. 6th Asia-Pacific Confer. Struct. Eng. Construct.*, 701-706, Taipei, Taiwan, January 14-16, 1998.

Lin, T. I., Huang, C. M., and Chen, S. Y. (1993), "Concrete-filled Tubular Steel Columns Subjected to Eccentric Axial Load", *J. Chinese Instit. Civil Hydraulic Eng.*, 5(4), 377-386 (in Chinese).

Liu, G.-Y., Huang, C. S., Yeh, Y.-K., Weng, Y.-T., Wang, S.-H., and Tsai, K.-C. (2000), "Effectiveness of Interior Stiffeners on Axially Loaded Concrete-Filled Square Tubular Steel Columns," *Proc. 6th ASCCS Int. Confer. Steel-Concrete Composite Struct.*, 521-528, Los Angeles, March 22-24, 2000.

Liu, G.-Y., Yeh, Y.-K., Tsai, K. C., Su, S.-C., and Sun, W.-L. (2003), *A Study on the Behavior of Concrete-Filled Steel Tubular Beam-Columns Subjected to Axial Load and Bending Moment*, Technical Report NCREE-03-009, National Center for Research on Earthquake Engineering, Taipei, Taiwan (in Chinese).

Yeh, Y.-K., Liu, G.-Y., Su, S.-C., Huang, C. S., Sun, W.-L., and Tsai, K. C. (2001), "Experimental Behavior of Square Concrete-Filled Steel Tubular Beam-Columns Stiffened by Interior Tie Bars," *Proc. 1st Int. Confer. Steel & Composite Structure*, 1171-1178, Pusan, Korea, June 14-16, 2001.