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Behaviour of Small Diameter Steel Tubes under Axial Compression

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Abstract

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Behaviour of Small Diameter Steel Tubes under Axial Compression

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Abstract

Small diameter steel tubes are used in many civil engineering applications. Recently, the behaviour of concrete columns reinforced with small diameter steel tubes was experimentally and analytically investigated. This study explores the effect of unsupported length to the outside diameter (L/D) ratio on the axial compressive behaviour of small diameter steel tubes, which has not yet been adequately investigated. Galvanized and cold-formed steel tube specimens with L/D ratio of 2 to 12 were tested. It was observed that for specimens with L/D ratio of 2 and 4, the compressive failure occurred due to local elephant's foot buckling. However, the compressive failure mode changed to global buckling for specimens with L/D

ratio ≥ 6 . The ultimate compressive strength was found to be lower than the ultimate tensile strength for specimens with L/D ratio ≥ 6 .

Keywords: Steel tube; axial tension; axial compression; length to outside diameter ratio; stress-strain behaviour.

1. Introduction

Steel tubes are widely used in different structural applications and are subjected to different types of loading [1, 2]. Circular steel tubes are used for the construction of concrete filled steel tube columns and double skin columns, as the steel tube provides a uniform hoop stress [3]. Recently, Hadi et al. [4] used small diameter steel tubes (33.7 mm and 26.9 mm) in lieu of solid steel bars as the main reinforcement in circular reinforced concrete columns. The innovative use of small diameter steel tubes in reinforcing concrete columns was found to be significantly effective, considering the axial load carrying capacity and ductility of the reinforced concrete columns [4]. Small diameter steel tubes are also used in the construction of garage sheds, covered walkways, and pedestrian bridges. The radius of gyration (r) of a steel tube section is significantly higher than the radius of gyration of a solid steel section with similar cross-sectional area. Hence, the slenderness ratio (L/r ratio, where L is the length of the tube and r is the radius of gyration) of the steel tube section is much lower than the slenderness ratio of solid steel sections. The lower L/r ratio of the steel tube results in a higher axial load carrying capacity compared to axial load carrying capacity of solid steel section with the same effective length. In addition, a decrease in the L/r ratio of the steel tube increases the axial load carrying capacity of the tube [5]. The failure modes (local buckling and global buckling) of steel tubes are influenced by the diameter to thickness (D/t) ratio and length to diameter (L/D) ratio. The D/t ratio influences the local buckling and the L/D ratio

influences the global buckling. Steel tubes with larger D and smaller t tend to be more sensitive to local buckling, while steel tubes with larger L and smaller D tend to be more sensitive to global buckling.

Design standards specify limits on the D/t ratio to prevent local buckling of steel tubes [6-8]. Zhao [9] investigated very high strength circular tubes (ultimate tensile strength = 1500 MPa, outside diameter ranged from 31.97 mm to 38.31 mm and thickness ranged from 1.53 mm to 1.99 mm) under axial compression with different D/t ratio and compared the compressive strength with tensile strength. It was found that an increase in the D/t ratio reduced the section capacity (= tensile yield stress $\times$ cross-section area) due to the local buckling of the steel tubes. Sohal and Chen [10] reported that the local buckling influenced the maximum compressive strength of steel tubes with D/t ratio ≥ 36 . Teng and Hu [11] observed that the failure mode of steel tubes with small D/t ratio was outward buckling around the circumference. This local buckling failure occurred at one end of the steel tube, which is commonly known as the elephant's foot buckling. Only a limited number of studies, however, investigated the behaviour of steel tubes (mostly outside diameter larger than 500 mm) under axial compression with different L/D ratios of 0.5, 1.0, 2.36 and 3.0 [12].

The L/D ratio of steel tubes is an important parameter, as it significantly influences the stability and global buckling of steel tubes. Steel tubes with a large L/D ratio causes global buckling before any significant yielding in the steel tube. For solid steel bars, the ultimate strength and ductility under axial compression decrease with the increase in the L/D ratio [13]. Hence, in the structural applications, to avoid global buckling of steel bars, the L/D ratio is kept limited to 6 [13-15], for which the behaviour under axial tension and compression is similar. The effect of increased L/D ratio on the stability of steel tubes is

significantly important, especially when the D/t ratio is not critical for local buckling. Although the design standards (Eurocode 4-1-1 [6]; Canadian Standards Association [7]; American Institute of Steel Construction [8]) specify factors to reduce the axial compression capacity of steel tubes with large L/D ratio, the design standards are not specifically intended for the small diameter of steel tubes. The Eurocode 4-1-2 specifies a minimum diameter of 160 mm for steel tubes [16], while the other design standards do not specify the limits for the minimum diameter of steel tubes. When the small diameter steel tube is used, the effect of L/D ratio on the reduction of the axial load carrying capacity and ductility becomes more significant. Steel tube with a large L/D ratio may not reach the plastic axial compressive strength and may fail due to global buckling. However, the investigation on effect of L/D ratio on the behaviour of small diameter steel tubes under axial compression is very limited.

This study explores the effect of L/D ratio on the behaviour of galvanized and cold-formed small diameter steel tubes under axial compression. The failure modes of small diameter steel tubes with different L/D ratios were investigated. The behaviour of full section steel tubes under axial tension was also investigated to compare the behaviour of small diameter steel tubes under axial tension and compression.

2. Experimental program

The experimental program contained two different types of steel tubes: galvanized steel tube and cold-formed steel tube. Galvanized and cold-formed steel tubes were chosen as they are commonly used in Australia. Cold-formed steel tubes are extensively used due to their high yield stress [17]. Galvanized steel tubes are also commonly used in structures in coastal areas to avoid damage and deterioration due to corrosion [18]. For cold-formed steel tube specimens, the outside diameter was 26.9 mm and the wall thickness was 2 mm. For cold-

formed steel tube specimens, the outside diameter was 33.7 mm and the wall thickness was 2.6 mm. The nominal tensile strength of both galvanized and cold-formed steel tube was 350 MPa. For tension tests, three specimens were tested for each type of tube. The behaviour of steel tubes under axial compression depends on the unsupported length to outside diameters (L/D) ratio. In the experimental program, galvanized and cold formed steel tube specimens with L/D ratio of 2, 4, 6, 8, 10, and 12 were tested to include a wide range of L/D ratios of the small diameter steel tubes used in various structural engineering applications. It is noted that, for the structural use of steel bars, similar range of L/D ratios were investigated [13-15]. For each L/D ratio, three specimens were tested. A total of 42 steel tube specimens were tested, including 6 specimens under axial tension and 36 specimens under axial compression.

The specimen labels in Tables 1- 3 contain three parts. In the first part of the specimen label, the letters G and C refer to galvanized steel tube and cold-formed steel tube, respectively. In the second part of the specimen label, the letter T refers to the specimens tested under axial tension and the letter C refers to the specimens tested under axial compression. The number associated with letter C represents L/D ratio. The third part of the specimen label refers to the test specimen number, as three specimens were tested from each group. For example, Specimen G-C12-1 refers to galvanized steel tube specimen tested under axial compression with L/D ratio of 12 and the specimen is the first of the three tested specimens.

3. Instrumentation and testing

A 500 kN universal testing machine in the High Bay laboratory at the University of Wollongong, Australia was used to conduct the tests for all specimens. For tension tests, different wedge grips of the machine jaw were used based on the outside diameters of the steel tube specimens. Tensile testing of steel tubes was conducted according to ASTM A370

[19]. Full-size steel tube section was used to conduct the tensile test. The lengths of the galvanized and cold-formed steel tube specimens tested under axial tension were 302 mm and 324 mm, respectively. The gripping length at each end of the steel tube specimen was 80 mm. To avoid the crushing at the ends of the tube due to gripping, two metal plugs fabricated from solid steel were inserted in both ends of the tube specimen. Figure 1 shows the schematic of the metal plugs for galvanized and cold-formed steel tubes. The gauge length of steel tube specimens tested under axial tension was 50 mm. The gauge length is the unfilled tube distance between the two metal plugs inside the steel tube [19]. Flat grips were used for the compression test, as shown in Figure 2. The ends of steel tube specimen were milled for flat surfaces. The deformation was captured by the Instron testing machine. All specimens were tested under displacement controlled load applications at the rate of 1 mm/min.

4. Results of steel tube tensile tests

Test results of galvanized and cold-formed steel tube specimens under axial tension have been reported in Table 1. Figure 3 shows the stress-strain behaviour of galvanized and cold-formed steel tube specimens under axial tension. It was observed from the stress-strain behaviour of the tested specimens that the galvanized steel tube specimens experienced well-defined yield points and also experienced plastic strain hardening after yield plateau. The cold-formed steel tube specimens did not show clearly defined yield points. Hence, yield stresses were calculated based on 0.2% proof stress [20]. The average ultimate strength to yield stress ratio for galvanized and cold-formed tube specimens was slightly greater than 1.08, which conforms the ductility requirement specified in AISI [20]. The average yield stress of the cold-formed steel tube specimens was 11% higher than the average yield stress of galvanized steel tube specimens. The average ultimate strength of cold-formed steel tube specimens was 14% higher than the average ultimate strength of galvanized steel tube

specimens. Figure 4 shows the typical failure modes of full-section tensile tests for the galvanized and cold-formed steel tube specimens. The failure modes of galvanized and cold-formed steel tubes were characterized by wall tearing of the tubes at the mid-height of the specimens. The planes of wall tearing in the galvanized steel tube specimens were slightly inclined. However, the planes of wall tearing in the cold-formed steel tube specimens were horizontal. The horizontal plane of wall tearing in the cold-formed steel tube was also observed in Jiao and Zhao [21].

5. General behaviour of steel tubes under axial compression

The inelastic buckling behaviour of the steel tubes under compression was found to be significantly influenced by the L/D ratio of the tube specimens (Figure 5). Two failure modes were observed for galvanized and cold-formed steel tubes depending on the L/D ratio of the specimens. The first type of failure mode was local buckling (elephant's foot buckling) which occurred in a ring shape at one end of the steel tube. The second type of failure mode was global buckling which occurred along the entire length of the tube. Global buckling of the tubes occurred with insignificant local buckling at the ends of the tube specimen. After the ultimate load, global buckling failure was observed to occur as a bend in a sharp angle near the mid-height of the tube.

6. Effect of L/D ratio on the compression behaviour of steel tubes

6.1. Galvanized steel tube

Test results of galvanized steel tube specimen under axial compression are reported in Table 2. The stress-strain behaviour of the galvanized steel tube specimens tested under axial compression is shown in Figure 6. For each L/D ratio, three galvanized steel tube specimens were tested. It was observed that the three tested specimens for each L/D ratio experienced

similar stress-strain behaviours. Hence, the axial load-axial deformation behaviour of one of the three tested specimens (the first specimen) for each L/D ratio is shown in Figure 7 for ease of comparison. The initial slopes of stress-strain curves of steel tube specimens tested under axial compression were corrected according to the procedure outlined in Perea et al. [22] and Gustafson et al. [23]. The galvanized tube specimens with L/D ratio ≤ 6 showed two peak stresses: yield stress and ultimate strength. Galvanized steel tube specimens with L/D ratio of 8 to 12 showed one peak stress which is considered ultimate strength in this study. The yield compressive stress was slightly larger than the yield tensile stress for specimens with L/D ratio ≤ 6 . The ultimate compressive strengths for specimens with L/D ratio of 2 and 4 were larger than the respective ultimate tensile strengths by about 9.8% and 8.7%, respectively. For specimens with L/D ratio of 6, the ultimate compressive strength was 2% less than the ultimate tensile strength. The ultimate compressive strength of the galvanized steel tube specimen was 5.3% larger than the compressive yield stress for the L/D ratio of 8.

Increasing the L/D ratio of galvanized steel tube specimens from 2 to 6 decreased the ultimate compressive strength and corresponding strain by 11.6% and 49.3%, respectively. However, no reduction in the compressive yield stress of the galvanized steel was observed for the specimens with L/D ratio ≤ 6 . The average ultimate compressive strength to yield compressive stress ratio of the galvanized tube specimens was greater than 1.08 for specimens with L/D ratio of 2 and 4.

Figure 7 shows that for specimens with L/D ratio of 8 to 12, the strain hardening of the galvanized steel tube did not occur. Only one peak stress was observed for the specimens with L/D ratio of 8 to 12. The stress-strain curve of galvanized steel tube changed from strain hardening to strain softening for L/D ratio of 8 to 12. In addition, it was observed that the

compressive failure mode of steel tube changed from local elephant's foot buckling to global buckling at L/D ratio of 6. Compressive failure in galvanized steel tube specimens with L/D ratio of 2 and 4 occurred due to local elephant's foot buckling. After the yield stress, the stress-strain behaviour of the steel tubes exhibited strain hardening due to further reduction in effective length, which occurred from the initiation of the elephant's foot buckling. For the specimen with L/D ratio of 6, galvanized steel tubes underwent yielding before insignificant local buckling at ends. Afterwards, global buckling took place and resulted in the failure of the steel tubes. For specimens with L/D ratio of 8 to 12, the compressive failure was observed to be more rapid due to the global buckling of the steel tube. Figure 8 shows the typical failure modes of galvanized steel tube specimens.

6.2. Cold-formed steel tube

Test results of cold-formed steel tube specimens under axial compression are reported in Table 3. The stress-strain behaviour of cold-formed steel tube specimens tested under axial compression is shown in Figure 9. For each L/D ratio, three cold-formed steel tube specimens were tested. It was observed that the three tested specimens for each L/D ratio experienced similar stress-strain behaviours. Hence, the axial load-axial deformation behaviour of one of the three tested specimens (the first specimen) for each L/D ratio is shown in Figure 10. The stress-strain behaviour of the cold-formed steel tubes under axial compression showed no clear yield points. Therefore, the yield stresses of the cold-formed steel tubes were calculated by using 0.2% proof stress [20]. For the specimens with L/D ratio of 2, the yield compressive stress was slightly larger than the yield tensile stress. However, the yield compressive stress was 5.5% less than the yield tensile stress for specimens with L/D ratio of 4. The ultimate compressive strengths for specimens with L/D ratio of 2 and 4 were larger than the respective ultimate tensile strengths by about 9.6% and 2.3%,

respectively. For specimens with L/D ratio of 6, the ultimate compressive strength was less than the ultimate tensile strength by only 3%.

Increasing the L/D ratio of the cold-formed steel tube specimens from 2 to 12 decreased the ultimate compressive strength and corresponding strain by 26.6% and 87.7%, respectively. When, the L/D ratio increased from 2 to 10, the yield compressive stress decreased by 10%. For specimens with L/D ratio of 2, the ultimate compressive strength was 18% larger than the yield compressive stress. This percentage reduced to only 6% for specimens with L/D ratio of 10. The average ultimate compressive strength to yield compressive stress ratio of cold-formed tube specimens was greater than 1.08 for specimens with L/D ratio of 8 and below. The initial slope of stress-strain behaviour in the cold-formed steel tube specimens with L/D ratio ≥ 6 was steeper than the initial slope of specimens with L/D ratio of 2 and 4.

The compressive failure modes of cold-formed and galvanized steel tubes were similar. For specimens with L/D ratio of 2 and 4, the compressive failure of cold-formed steel tube specimens occurred due to the local elephant's foot buckling. After the yield stress, strain hardening occurred due to further reduction in the effective length, which occurred from the initiation of the elephant's foot buckling. For the L/D ratio of 6, cold-formed steel tube specimens underwent yielding before insignificant local buckling at ends followed by the global buckling of the entire tube specimens. Although the cold-formed steel tube specimens exhibited no clear yield point unlike galvanized steel tube specimens, the stress-strain behaviour of cold-formed steel tube specimens exhibited a rapid decrease in the stress with strain after the ultimate strength for L/D ratio of 8 to 12. Figure 11 shows the typical failure modes of cold-formed steel tube specimens.

In general, to avoid global buckling of galvanized and cold-formed steel tubes in the structural applications, the L/D ratio needs to be less than 6. It is noted that for the use of small diameter steel tubes in reinforcing concrete columns, the effect of infill concrete together with the confinement provided by the surrounding concrete needs to be adequately investigated. Such investigations are considered beyond the scope of this paper and are considered part of the future research investigations by the authors.

8. Conclusion

Based on the experimental investigation presented in this study, the following conclusions and observations can be drawn:

1. The behaviour of galvanized and cold-formed small diameter steel tubes under axial compression is significantly influenced by the L/D ratio. For the L/D ratio of 2 and 4, the compressive failure in the steel tube specimens occurred due to local elephant's foot buckling. For the L/D ratio ≥ 6 , the compressive failure modes of galvanized and cold-formed steel tube specimens changed from local elephant's foot buckling to global buckling. In structural applications, steel tubes with $L/D < 6$ should be used to prevent global buckling and to increase the ductility.

2. The stress-strain behaviour of galvanized steel tube specimens with L/D ratio ≤ 6 exhibited strain hardening after the yield stress. It is noted that the cold-formed steel tube specimens exhibited no clear yield point under axial tension and also under axial compression. However, the ultimate compressive strength of cold-formed steel tube specimen was higher than the yield compressive stress for specimens with L/D ratio of 10 and below.

3. The average ultimate compressive strength to yield compressive stress ratios of galvanized tube specimens were greater than 1.08 for the specimens with L/D ratio ≤ 4 . The average

ultimate compressive strength to yield compressive stress ratios of cold-formed tube specimens were greater than 1.08 for the specimens with L/D ratio ≤ 8 .

4. The yield compressive stress was slightly larger than the yield tensile stress for galvanized steel tube specimens with L/D ratio ≤ 6 . The yield compressive stress was slightly larger than the yield tensile stress for cold-formed steel tube specimens with L/D ratio of 2. The ultimate compressive strength of galvanized and cold-formed steel tube was found to be less than the ultimate tensile strength for specimens with L/D ratio ≥ 6 .

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Table 1: Test results of galvanized and cold-formed steel tube specimens under axial tension

Specimen	Yield ^a stress (MPa)	Strain ^a corresponding to yield stress (%)	Ultimate strength (MPa)	Strain corresponding to ultimate strength (%)	Young's modulus (GPa)
G-T-1	408	0.27	440	5.7	190
G-T-2	411	0.27	448	5.53	210
G-T-3	410	0.29	441	5.51	185
Average (G-T)	410	0.28	443	5.58	195
C-T-1	450	0.65	501	3.27	180
C-T-2	455	0.66	505	3.72	190
C-T-3	460	0.67	511	3.41	195
Average (C-T)	455	0.66	506	3.47	190

^a Yield stress and yield strain of C-T specimens were calculated based on 0.2% proof stress.

Table 2: Test results of galvanized steel tube specimens under axial compression

Specimen	Yield stress (MPa)	Strain corresponding to yield stress (%)	Ultimate strength (MPa)	Strain corresponding to ultimate strength (%)
G-C2-1	410	0.78	492	7.21
G-C2-2	410	0.77	489	7.04
G-C2-3	416	0.80	492	7.15
Average (G-C2)	412	0.78	491	7.14
G-C4-1	410	0.78	491	6.06
G-C4-2	410	0.70	487	6.10
G-C4-3	412	0.77	476	6.2
Average (G-C4)	411	0.75	485	6.12
G-C6-1	411	0.73	434	3.59
G-C6-2	412	0.71	434	3.62
G-C6-3	410	0.68	433	3.64
Average (G-C6)	411	0.71	434	3.62
G-C8-1	-	-	426	0.69
G-C8-2	-	-	426	0.7
G-C8-3	-	-	426	0.5
Average (G-C8)	-	-	426	0.63
G-C10-1	-	-	426	0.39
G-C10-2	-	-	426	0.45
G-C10-3	-	-	425	0.47
Average (G-C10)	-	-	426	0.44
G-C12-1	-	-	424	0.40
G-C12-2	-	-	423	0.38
G-C12-3	-	-	424	0.41
Average (G-C12)	-	-	424	0.40

Table 3: Test results of cold-formed steel tube specimens under axial compression

Specimen	Yield ^a stress (MPa)	Strain ^a corresponding to yield stress (%)	Ultimate strength (MPa)	Strain corresponding to ultimate strength (%)
C-C2-1	458	1.4	562	6.63
C-C2-2	460	1.86	557	6.25
C-C2-3	455	1.52	560	6.42
Average (C-C2)	458	1.59	560	6.43
C-C4-1	430	1.17	515	4.51
C-C4-2	430	0.96	521	4.52
C-C4-3	429	1.01	518	4.49
Average (C-C4)	430	1.05	518	4.51
C-C6-1	420	0.87	483	2.45
C-C6-2	421	0.86	495	2.61
C-C6-3	420	0.68	496	2.64
Average (C-C6)	420	0.80	491	2.57
C-C8-1	418	0.64	452	1.51
C-C8-2	421	0.65	459	1.67
C-C8-3	419	0.65	457	1.55
Average (C-C8)	419	0.65	456	1.58
C-C10-1	413	0.64	438	1.22
C-C10-2	413	0.59	439	1.12
C-C10-3	411	0.55	439	1.12
Average (C-C10)	412	0.59	439	1.15
C-C12-1	405	0.57	412	0.73
C-C12-2	406	0.58	408	0.76
C-C12-3	405	0.57	413	0.88
Average (C-C12)	405	0.57	411	0.79

^a Yield stress and yield strain were calculated based on 0.2% proof stress.

(a) Galvanized steel tube plug

(b) Cold-formed steel tube plug

Figure 1: Metal plugs: (a) Galvanized steel tube plug; and (b) Cold-formed steel tube plug

Figure 2: Testing of specimen under axial compression

Figure 3: Stress-strain behaviour of galvanized and cold-formed steel tube specimens under axial tension

(a) Galvanized steel tube

(b) Cold-formed steel tube

Figure 4: Typical failure modes of specimens under axial tension: (a) Galvanized steel tube;
and (b) Cold-formed steel tube

(a) Galvanized steel tube specimen with $L/D=4$

(b) Galvanized steel tube specimen with $L/D=8$

Figure 5: Failure modes of galvanized steel tube specimens: (a) local buckling; and (b) global buckling

Figure 6: Galvanized steel tube specimens with different L/D ratios under axial compression

Figure 7: Stress-strain behaviour of galvanized steel tube specimens under axial compression

Figure 8: Typical failure modes of galvanized steel tube specimens

Figure 9: Cold-formed steel tube specimens with different L/D ratios under axial compression

Figure 10: Stress-strain behaviour of cold-formed steel tube specimens under axial compression

Figure 11: Typical failure modes of cold-formed steel tube specimens