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The Design for Local Buckling of Concrete Filled Steel Tubes

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Summary

From the analysis of carefully controlled experiments, the influence of local buckling on the behaviour of short circular thin-walled concrete filled steel tubes has been examined. Two possible failure modes of the steel tube have been identified, local buckling and yield failure. These were found to be independent of the diameter to wall thickness ratio. Instead, bond (or lack of it) between the steel and concrete infill determined the failure mode. A proposed design method has been suggested based upon the recommendations in Eurocode 4 (1992).

1. Introduction

Circular concrete filled steel tubes have been found to be an economical column alternative (Watson and O'Brien, 1990). Further economies are possible if high strength concrete infill is used in conjunction with thin-walled steel tubes, with just sufficient steel to support the floors while under construction (Webb and Peyton, 1990).

It has been recognised that the capacity of thin-walled circular steel tubes may be reduced by local buckling effects, with their post ultimate response exhibiting little ductility. Conservative predictions of the local buckling strength can be made using currently available design methods (O'Shea and Bridge, 1996) such as AISI-LRFD (1991) and AISC-LRFD (1994) while the unloading response is dependent upon the specimen length. The behaviour of high strength concrete has also been shown to exhibit a rapid unloading response in the postultimate region with strain reversal evident at strengths of 115 MPa (O'Shea and Bridge, 1994). For thick-walled steel tubes filled with low to medium strength concrete, enhancement of the concrete has been found to occur for short axially loaded specimens due to the confining pressures exerted by hoop stress in the steel tube. However, this then reduces the axial capacity of the steel tube which is recognised in Eurocode 4. For thin-walled circular concrete filled steel tubes, both hoop stress and local buckling effects have to be considered. Due to these effects, the summation of the individual ultimate strengths of the steel and the concrete, even taking strain compatibility into account, is not likely to be appropriate or valid for design purposes. As few tests have been carried out on axially loaded thin walled concrete filled steel tubes, tests were performed to evaluate the issues identified above.

2. Axially Loaded Steel Tubes

Ten axially loaded steel tubes were examined with properties as shown in Table 1. Five diameter to thickness ratios (D/t) were selected. The specimens were all short with a length (L) to diameter ratio of 3.5. Material coupon tests were conducted to determine yield strength (f_y) and elastic modulus (E_s). Two series of tests were performed. In the series labelled BS, the specimens were axially loaded with no internal restraint. In the other series labelled BSC, the specimens were filled with unbonded concrete to restrain the possible formation of internal buckles. The local strains in the steel tube were measured using three internal and external strain rosettes placed at midheight.

Specimen	D (mm)	t (mm)	D/t	f_y (MPa)	E_s (MPa)	L (mm)		Strength (kN)	
						BS	BSC	BS	BSC
S30	165	2.82	58.6	363.3	200600	580.0	575.0	522.6	n.a.
S20	190	1.94	98.2	256.4	204700	665.0	657.0	284.4	279.9
S16	190	1.52	125.1	306.1	207400	665.0	657.5	239.2	283.8
S12	190	1.13	168.1	185.7	178400	665.0	659.5	109.1	109.3
S10	190	0.86	220.4	210.7	177000	665.0	658.5	92.9	91.0

n.a. not available

Table 1 Test results for axially loaded steel tubes

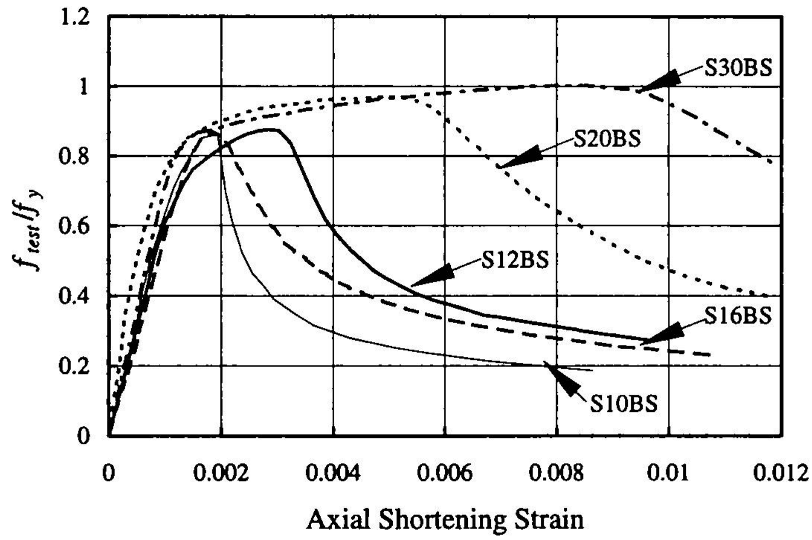

Figure 1 Normalised load axial shortening response for axially loaded unfilled steel tubes

The normalised load axial shortening curve for the BS specimens has been included in Figure 1 where f_{test} is the experimentally applied stress. For clarity the BSC specimens have not been included as they exhibited an experimentally similar response. This can also be seen in the principal strains for specimen S10 in Figure 2 with both S10BS and S10BSC having the same strain response. The elastic unloading of the tube in the post ultimate region can be clearly seen with the vertical and circumferential strains reducing. For this to occur the axial shortening must occur in the locally buckled region. The ultimate strengths of the companion BS and BSC tubes in Table 1 are similar. Consequently the internal concrete was found to have no influence on the buckling mode of the axially loaded steel tube. The only exception was specimen S16BSC. In this case the local buckle occurred at mid-height compared to an end for all other specimens.

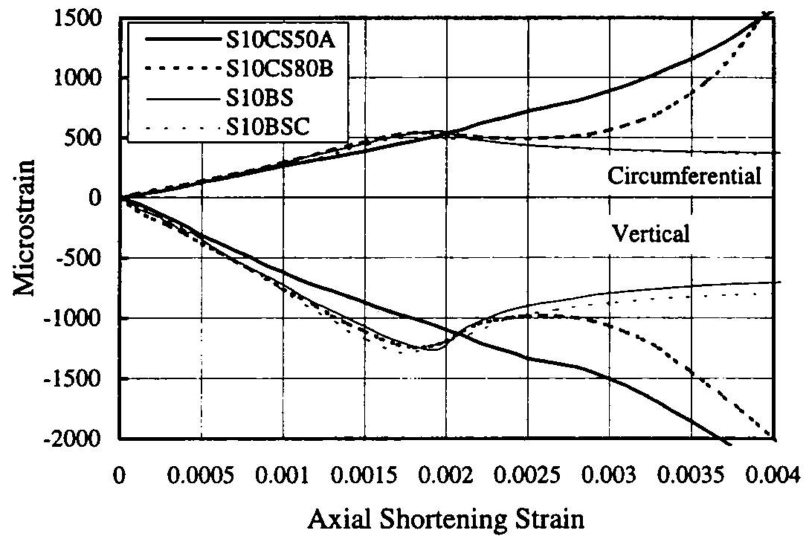

Figure 2 Local strains for Specimen S10BS, S10BSC, S10CS50A and S10CS80B

The incremental Poisson's ratio for each specimen was calculated from the principal vertical and circumferential strains. Three curves of best fit, reflecting the different material properties were obtained as in Figure 3. An upper limit of 0.5 was used to indicate full plasticity.

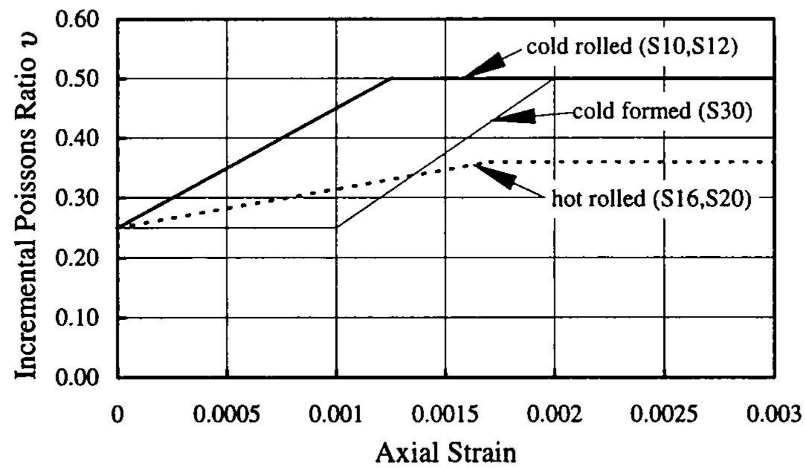

Figure 3 Poisson's ratio used in the analysis

3. Axially Loaded Concrete Filled Steel Tubes

Ten concrete filled steel tubes (CFT) labelled CS were tested with dimensions as shown in Table 2. They were identical to their companion axially loaded steel tubes but were filled with concrete. Two nominal concrete strengths of 50 or 80 MPa were selected with two mixes of each type. After filling, the CFT ends were sealed with plastic and stored in the concrete laboratory at ambient room temperature until testing. Ten 100 mm diameter material property cylinders were cast for each mix. After demoulding, half the material cylinders were stored in a lime bath at a constant temperature of 20 degrees, the rest were sealed in plastic and stored with the tubes. The latter were used for the indicative concrete properties, strength (f_c) and elastic modulus (E_c), as the CFT environment was accurately simulated. Prior to testing, the specimen ends were ground square and flat to ensure that the steel and concrete were loaded together. Three strain rosettes evenly spaced at midheight were attached to each CFT.

Specimen	D (mm)	t (mm)	D/t	L (mm)	f_c (MPa)	E_c (MPa)	f_y (MPa)	E_s (MPa)	Strength (kN)
S30CS50B	165	2.82	58.6	580.5	48.3	21210	363.3	200600	1662
S20CS50A	190	1.94	98.2	663.5	41.0	17810	256.4	204700	1678
S16CS50B	190	1.52	125.1	664.5	48.3	21210	306.1	207400	1695
S12CS50A	190	1.13	168.1	664.5	41.0	17810	185.7	178400	1377
S10CS50A	190	0.86	220.4	659	41.0	17810	210.7	177000	1350
S30CS80A	165	2.82	58.6	580.5	80.20	28450	363.3	200600	2295
S20CS80B	190	1.94	98.2	663.5	74.7	27580	256.4	204700	2592
S16CS80A	190	1.52	125.1	663.5	80.2	28450	306.1	207400	2602
S12CS80A	190	1.13	168.1	662.5	80.2	28450	185.7	178400	2295
S10CS80B	190	0.86	220.4	663.5	74.7	27580	210.7	177000	2451

Table 2 Test results for axially loaded concrete filled steel tubes

Two different failure modes were observed from the tests. In yield failure, bond between the steel and the concrete was maintained. This can be observed in Figure 2 for specimen S10CS50A with the principal strains increasing with axial shortening strain. However in buckling failure, bond was not maintained with local buckling of the steel occurring as in specimen S10CS80B in Figure 2.

4. Analysis of Tests

An incremental elastic analysis was chosen to determine the vertical stress and the hoop stress from the measured strains. A failure surface defined by the maximum energy distortion theory (Higdon et. al., 1977) was used. The intersection point with the failure surface was assumed to remain constant with increasing axial shortening strain.

The response of the confined concrete was calculated by subtracting the steel load component in the vertical direction from the applied load. The peak confined concrete strength (f_{cc}) has been included in Table 3 and plotted in Figure 4 and 5, normalised with concrete strength (f_c). Clearly the nominal 50 MPa concrete has had significant improvement in strength and ductility while for the 80 MPa mix this only occurred for the thicker tubes. Ductility improvement compared to the unconfined behaviour is clearly visible in Figure 5, especially for specimen S30CS80A. An unexpected result occurred for specimen S10CS80B with a high confined concrete strength. However, this was due to buckling of the steel tube allowing greater confinement of the concrete to occur in the elastic region away from the locally buckled region.

From Table 3, Eurocode 4 generally provides a good prediction of the enhanced concrete strength. However a conservative estimate of the vertical steel strength was obtained from Eurocode 4. The inclusion of local buckling as recommended by Eurocode 4 would yield even more conservative results. The high axial steel strengths obtained in the CS tests were due to the influence of bond. This forces the steel to yield by preventing local buckles. If one does form as in specimen S10CS80A then a *higher* axial load can be obtained as greater confinement is possible. This is supported by Orito et. al. (1987) with tests on unbonded concrete filled tubes.

Specimen	Steel reduction f_{test}/f_y			Concrete enhancement f_{cc}/f_c		CS Test / EC 4		
	CS test	BS test	EC 4	CS test	EC 4	Steel	Concrete	Composite
S30CS50B	0.91	1.00	0.80	1.24	1.42	1.14	0.87	0.93
S20CS50A	0.94	0.97	0.80	1.26	1.21	1.18	1.04	1.06
S16CS50B	0.87	0.87	0.80	1.09	1.16	1.09	0.94	0.96
S12CS50A	0.94	0.88	0.80	1.11	1.08	1.17	1.02	1.04
S10CS50A	0.87	0.86	0.81	1.11	1.07	1.07	1.03	1.03
S30CS80A	0.92	1.00	0.81	1.18	1.24	1.14	0.95	0.96
S20CS80B	n.a.	0.97	0.81	1.13	1.11	n.a.	1.02	1.04
S16CS80A	n.a.	0.87	0.81	1.06	1.10	n.a.	0.97	0.99
S12CS80A	0.92	0.88	0.81	0.98	1.04	1.13	0.95	0.95
S10CS80B	0.73	0.86	0.82	1.14	1.04	0.90	1.10	1.09

n.a. Not available

Table 3 Comparison of tests to Eurocode 4 (EC 4)

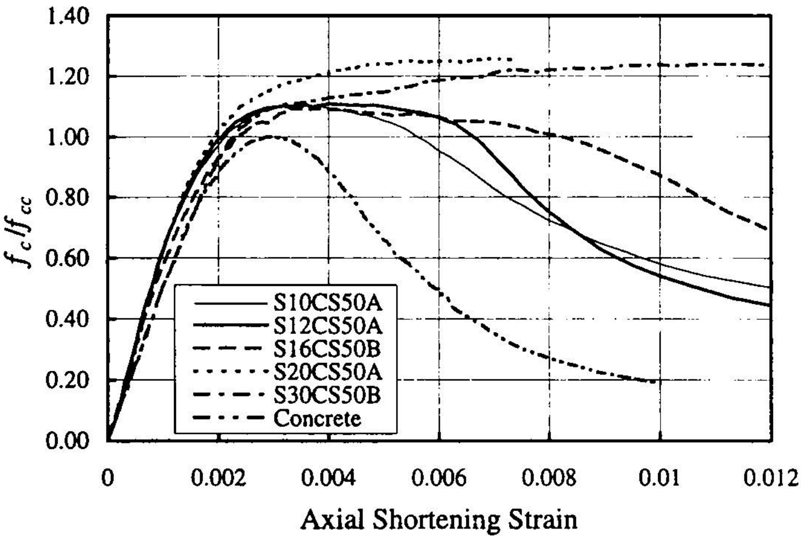

Figure 4 Confined concrete response for nominal 50 MPa mix

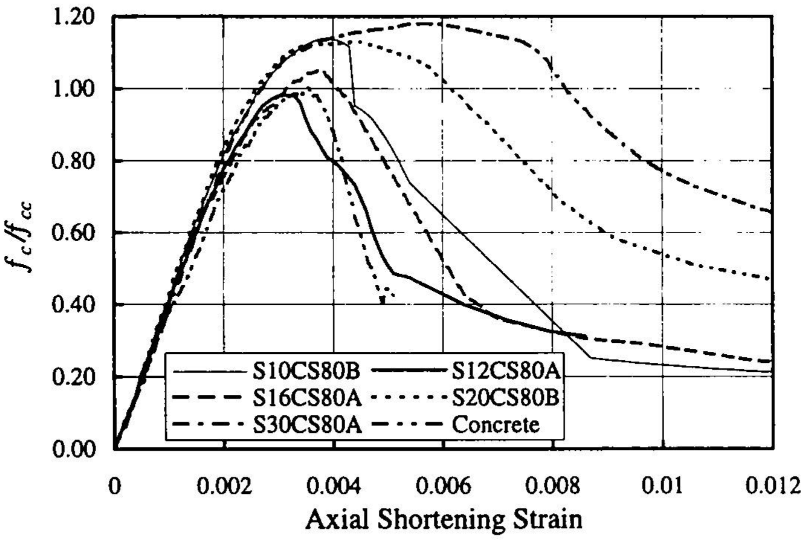

Figure 5 Confined concrete response for nominal 80 MPa mix

5. Conclusions

The ductility of high strength concrete can be significantly improved from the confining action of thin-walled circular steel tubes. Enhancement of the concrete can occur for some combinations of *D/t* ratio and concrete strength. Failure of the steel tube can occur by yielding or buckling. In yield failure, the steel tube reaches yield with the vertical capacity reduced by confining action. In buckling failure, the bond between the steel and concrete is not maintained allowing greater concrete confinement and capacity. Eurocode 4 accounts for both effects giving conservative results for thin-walled tubes filled with concrete. Less conservative predictions can be obtained by excluding the influence of local buckling.

6. Acknowledgements

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