Conference paper

Goode, C. D. and Lam, D. (2008) *Concrete - filled steel tube columns - tests compared with Eurocode 4.* In: Composite Construction VI, July 20-24, 2008, Devil's Thumb Ranch, Colorado, USA.

Composite Construction VI, July 2008, Colorado, USA.

CONCRETE - FILLED STEEL TUBE COLUMNS - TESTS COMPARED WITH EUROCODE 4

C. Douglas Goode
University of Manchester (retired)
Draughton, Skipton, BD23 6DY, England
e-mail: cdgoode@mypostoffice.co.uk

Dennis Lam
School of Civil Engineering
University of Leeds, LS2 9JT, England
e-mail: d.lam@leeds.ac.uk

ABSTRACT

This paper summarises the data from 1819 tests on concrete-filled steel tube columns and compares their failure load with the prediction of Eurocode 4. The full data is given on the website http://web.ukonline.co.uk/asccs2 . The comparison with Eurocode 4 is discussed and shows that Eurocode 4 can be used with confidence and generally gives good agreement with test results, the average Test/EC4 ratio for all tests being 1.11. The Eurocode 4 limitations on concrete strength could be safely extended to concrete with a cylinder strength of 75 N/mm^2 for circular sections and 60 N/mm^2 for rectangular sections.

INTRODUCTION

The properties (D (or h & b), t, f_y, E_s, f_{cyl}, E_c, L, e) and the failure load in the test (N_u) are given for all 1819 tests on the website http://web.ukonline.co.uk/asccs2 [Goode 2007] together with the Eurocode 4 [BSI 2005] calculation of ultimate load capacity (N_{uEC4}) for each test with the material partial safety factor (γ_m) as unity. The website also contains graphs of all the tests compared with Eurocode 4 and a list of 109 references to the papers from where the data has been obtained. The data is divided into circular section and rectangular section columns, with and without moment, and whether the columns are short (L/D or L/b ≤ 4) or long (L/D or L/b > 4) with separate groups for hollow sections and those with preload on the steel or which were subject to a sustained load. Eleven rectangular columns that were subjected to biaxial bending are also included in the database. Table 1 summarises these results for each type of column and gives the average ratio of Test/EC4 prediction (N_u/N_{uEC4}) and the standard deviation of this ratio for each set. The database website is more comprehensive and gives this information for each author's data.

Composite columns and composite compression members are covered in Section 6.7 of Eurocode 4 and a detailed discussion of these clauses is given in [Goode & Narayanan 1997]. The principal limitations and conditions as far as CFST columns are concerned are that the steel grade should be S235 to S460 (yield strength 235 to 460 N/mm^2) and normal weight concrete of strength classes C20/25 to C50/60 (concrete cylinder strength 20 to 50 N/mm^2, cube strength 25 to 60 N/mm^2) (Clause 6.7.1(2)P). The Code also states that local buckling of the steel tube can be neglected for circular section columns if $t > D/(90*(235/f_y))$ and for rectangular columns if $t > h/(52*\sqrt{(235/f_y)})$, f_y in N/mm^2 (Clause 6.7.1(9)). Tests which were outside these limits have not been excluded from the comparison.

For circular CFST columns enhancement factors ('eta' (η) factors, Clause 6.7.3.2(6)) can be applied to allow for the increase in concrete strength caused by the confining effect of the steel tube which produces a triaxial compressive stress state in the concrete thus increasing its failure load [Hobbs et al 1977]. For rectangular section CFST columns the Code takes the failure stress in the concrete as the cylinder strength, without the 0.85 factor that is applied in unrestrained concrete to relate the concrete's cylinder strength to its uniaxial strength.

Overall buckling is allowed for in the Code by introducing a buckling factor (χ) related to the relative slenderness, $\bar{\lambda}$, by the buckling curve (Clause 6.7.3.5(2)). When there is a moment on the column two methods of analysis are permitted. A 'simplified' method in which the second-order effects (P-Δ effect and member imperfections) are allowed for by multiplying the first-order applied moments by a factor 'k' (greater than unity) and a more exact method where the second-order effect, the lateral deflection due to the end moment, is analysed and allowed for. When comparing with the tests the member imperfections have been assumed to be zero and both the 'simplified' and 'second-order' methods have been used to analyse long columns with an end moment and the results are included in the database and summarised in Table 1 of this paper. In the simplified method the calculated strength has been divided by the 'k' factor to compare with the test result (rather than factoring the test result by 'k') and the failure load predicted by the code is compared with the test result at the same axial load/moment ratio as was used in the test.

DISCUSSION AND COMPARISON WITH EUROCODE 4

General

It can be seen from Table 1 that the average failure load in the test divided by the Eurocode 4 prediction (Test/EC4) value for each type of column is greater than unity indicating that Eurocode 4 predicts a lower value than the test and thus a 'safe' result.

Table 1 – Summary of results for each type of column.

Type of Column		Number of Tests	Average Test/EC4	St Dev of Test/EC4
Short Circular No Moment		368	**1.06**	0.091
Long Circular No Moment		369	**1.17**	0.148
Long (and a few short) Circular with Moment	'k' factor method	254	**1.15**	0.111
	2^{nd} order analysis	254	**1.15**	0.119
Short Rectangular No Moment		330	**1.09**	0.096
Long Rectangular No Moment		212	**1.06**	0.097
Short rectangular with Moment		29	**1.01**	0.108
Long Rectangular with Moment	'k' factor method	96	**1.10**	0.097
	2^{nd} order analysis	96	**1.20**	0.148
Short Hollow Circular No Moment		76	**1.22**	0.095
Circular with Moment and Preload on steel		23	**1.15**	0.123
Rectangular with Moment and Preload on steel		19	**1.03**	0.099
Long Rectangular No Moment with Sustained Load		8	**1.25**	0.051
Square, 8-sided, 16-sided Hollow No Moment		24	**1.16**	0.108
Totals (excluding Biaxial Bending, 'k' factor analysis)		**1808**	**1.11**	0.108
Rectangular with Biaxial Bending	Code straight line interaction	11	**1.52**	0.058
	Elliptical interaction, $\alpha_M = 1$	11	**1.20**	0.041

However, individual tests and test series by some investigators occasionally gave unsafe results (see website for details). Excluding the eleven biaxial bending tests (which gave very safe results) the average Test/EC4 ratio for the 1808 tests analysed in this paper was 1.11 with a standard deviation of 0.108 using the 'k' factor method, and 1.12 with SD of 0.112 when second order analysis is used for the long columns with moment. If the hollow, preload, sustained load and biaxial tests are omitted the average for the remaining 1658 tests is also 1.11. Of these 1658 tests 970 (59%) satisfied all the Code conditions (strength not greater than 50 N/mm^2 or less than 20 N/mm^2 and local buckling criterion satisfied) and the average Test/EC4 for these was 1.15; 173 (18%) of these failed before the Code strength was attained, ie Test/EC4 < 1, the average for these being 0.93, that is 7% below the predicted strength.

Concrete strength

The use of concrete with a cylinder strength greater than 50 N/mm^2 was the main reason the tests did not satisfy the Eurocode 4 criteria. Figure 1 shows all the circular section columns plotted against the cylinder strength (except for 5 tests by Salani, who used mortar as the filling, which gave a very high result Test/EC4 > 2.5; these were omitted to reduce the 'y' axis scale and thus make the graph more readable). The numbers in brackets ( ) indicate the number of tests in each set of results. 21% of tests failed below the Eurocode 4 prediction, points below the line, however there were not significantly more 'unsafe' results when the concrete strength was outside the 20 – 50 N/mm^2 cylinder strength permitted by the Code than when it was within this range. Thus the authors suggest that the Code limitation on concrete strength could be safely extended to a cylinder strength of 75 N/mm^2; and possibly even to 110 N/mm^2 though more tests are required with concrete greater than 100 N/mm^2 to justify this.

Figure 2 shows the ratio for all the rectangular section columns plotted against cylinder strength. For rectangular columns a decrease in this ratio when high strength concrete was used is evident. However, the authors suggest that the Code limitation on concrete strength could, for square and rectangular sections, be safely extended to concrete with a strength of 60 N/mm^2. This is also illustrated in Table 2, showing a slight increase in the average Test/EC4 (Av.) values when only columns containing concrete with a cylinder strength less than 60 N/mm^2 are considered and unsafe results for short columns with concrete greater than 60 N/mm^2. The last column in Table 2 shows that safe results are achieved for these rectangular columns when f_{cyl} is replaced by 0.85 f_{cyl}; thus the 0.85 factor, which the Code says can be omitted for concrete filled sections (Clause 6.7.3.2(1)), should be included for rectangular columns when concrete with a cylinder strength greater than 60 N/mm^2 (cube strength 75 N/mm^2) is used.

Table 2 – The use of 0.85 factor for rectangular section columns when f_{cyl} > 60 N/mm^2

Type of Rectangular Section Column	All Columns		fcyl ≤ 60 N/mm^2		fcyl > 60 N/mm^2		
						fcyl	$0.85f_{cyl}$
	No.	Av.	No.	Av.	No.	Av.	Av.
Short no Moment	330	1.09	277	1.12	53	0.97	1.06
Long no Moment	212	1.06	169	1.06	43	1.09	1.19
Short with Moment	29	1.01	25	1.02	4	0.93	1.01
Long with Moment 'k'	96	1.10	64	1.10	32	1.11	1.25
Long with Moment 2^{nd} order	96	1.17	64	1.17	32	1.18	1.29
Overall Average ('k' factor)	667	1.08	535	1.09	132	1.04	1.15

Note: No. is the number of tests, Av. is the average for each set of tests of the ratio Test/EC4

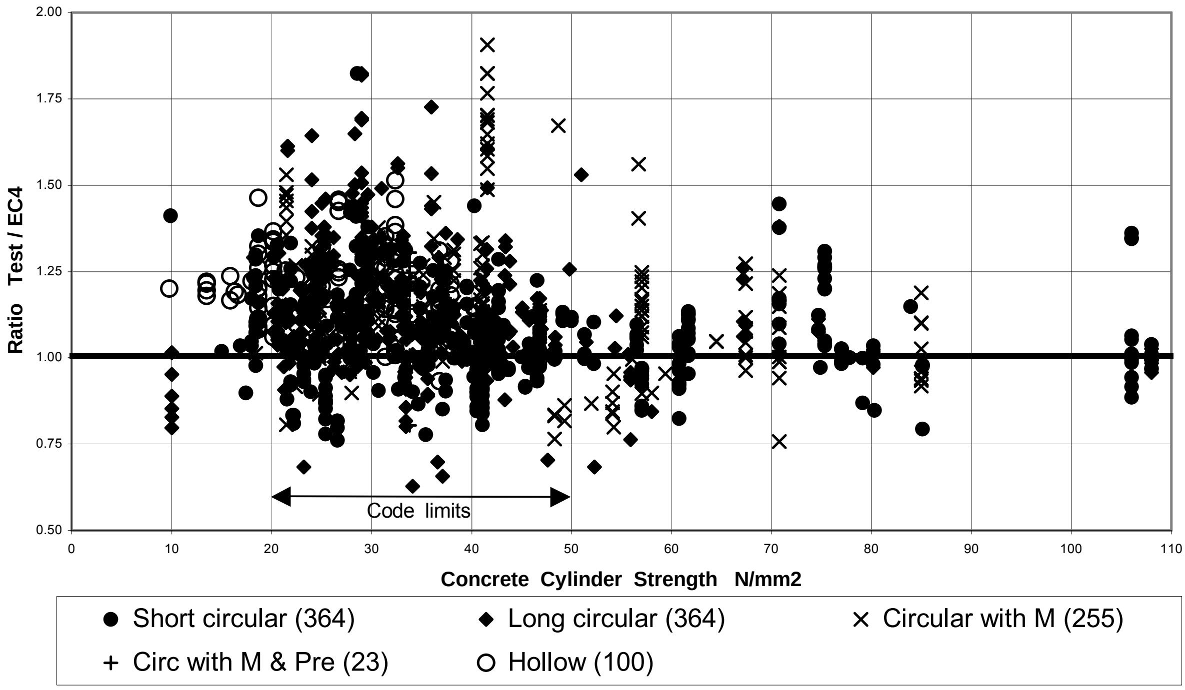

Figure 1. Circular section columns. Ratio Test/EC4 against Concrete cylinder strength

Because of the number of tests involved the separate groups cannot be distinguished in the more densely tested zones in these black and white figures. However, the general trend is clear; the individual tests can be distinguished in the coloured graphs on the website.

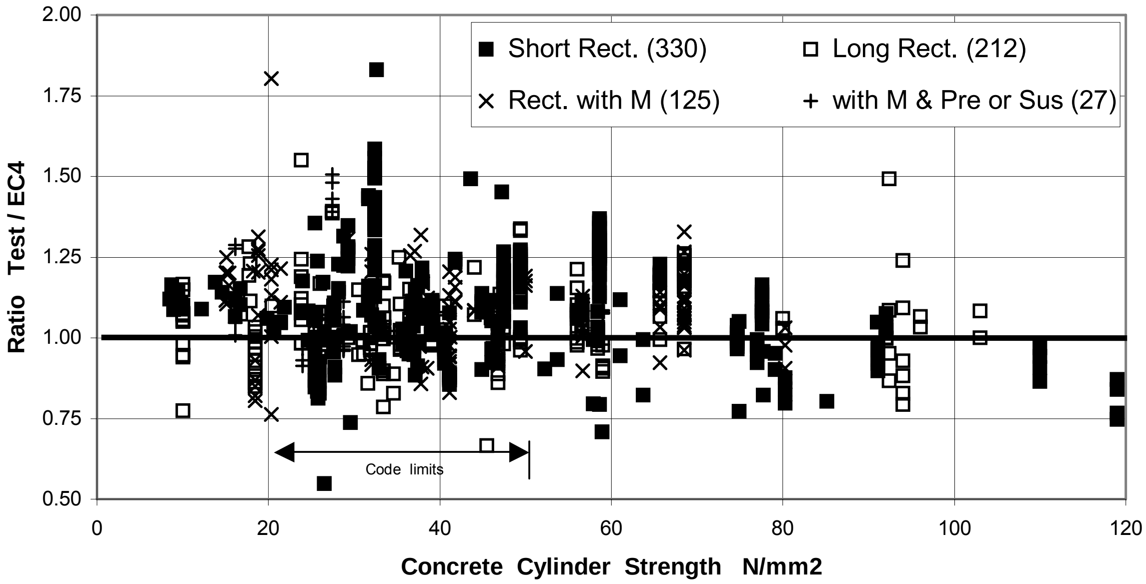

Figure 2. Rectangular section columns. Ratio Test/EC4 against Concrete cylinder strength

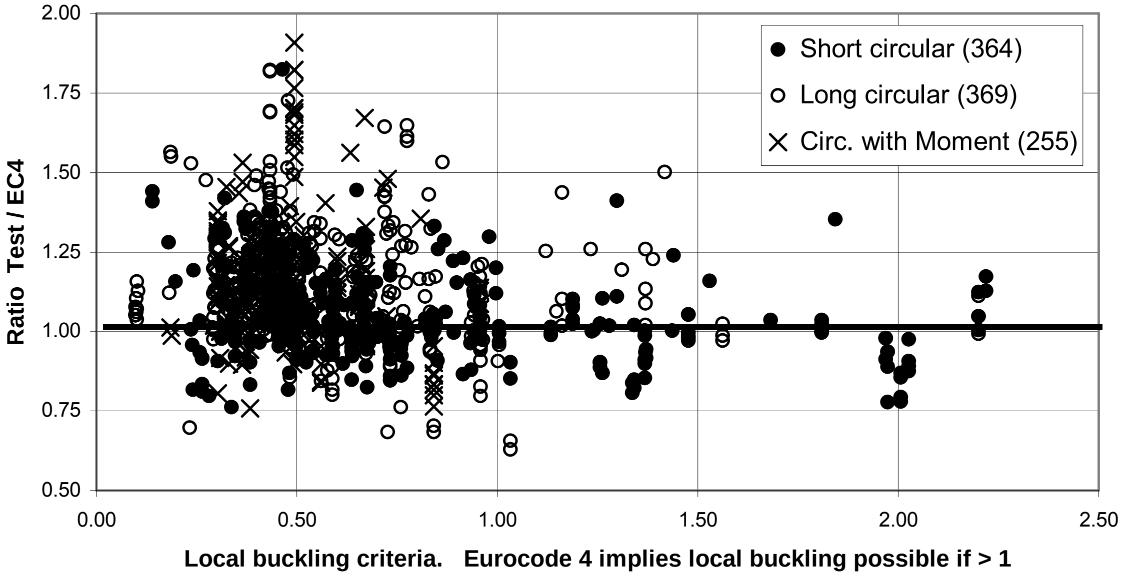

Figure 3. Circular Columns. Ratio Test/EC4 against Eurocode 4 local buckling criteria

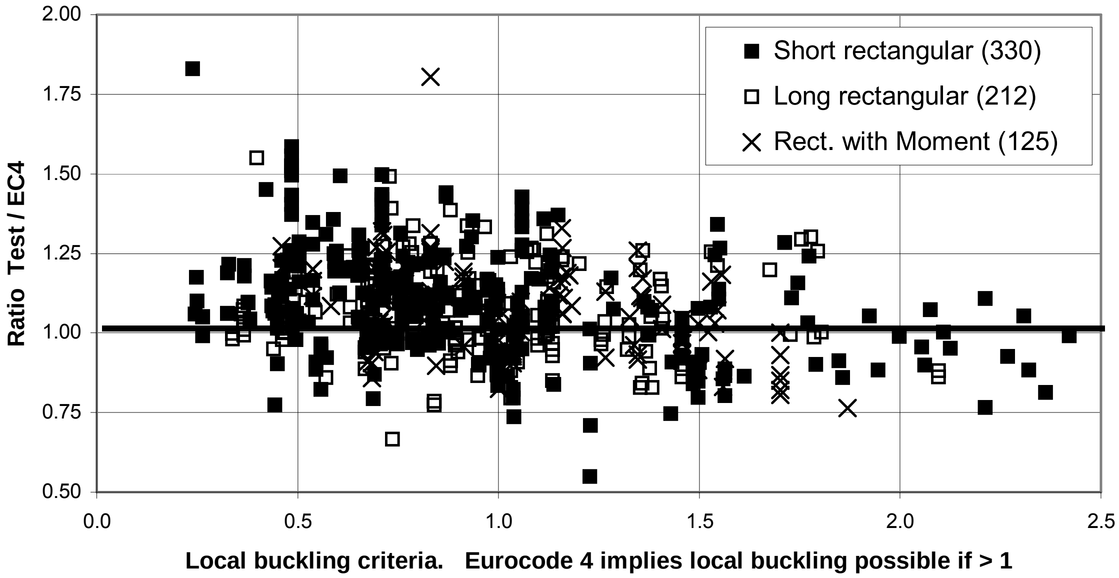

Figure 4. Rectangular Columns. Ratio Test / EC4 against local buckling criteria

Local buckling

The Test/EC4 ratio plotted against the local buckling criteria is shown in Figure 3 for the circular section columns and in Figure 4 for the rectangular section columns. There is a general downward trend in the results for both circular and rectangular section columns when the local buckling criteria is exceeded (> 1.0) so it is probably desirable to keep the existing limits. In some tests the steel would have had to be over twice as thick to satisfy the Code criteria;

however, in all cases where the Code condition is exceeded, if a 0.75 factor were applied to the Eurocode 4 prediction the tests would be safe.

Slenderness

Figure 5 (short columns without moment), Figure 6 (long columns without moment) and Figure 7 (columns with an end moment) show the ratio Test/EC4 against slenderness. They all show that the Code method of allowing for slenderness is satisfactory. Indeed, as Figure 6 shows, for circular columns without moment there is a slight upward trend in the ratio as the columns become more slender; this could be because the buckling factor (χ) used in the code is conservative when the columns are slender. However, it would be prudent for no changes to be made to the Eurocode 4 buckling factor unless further tests confirm this trend.

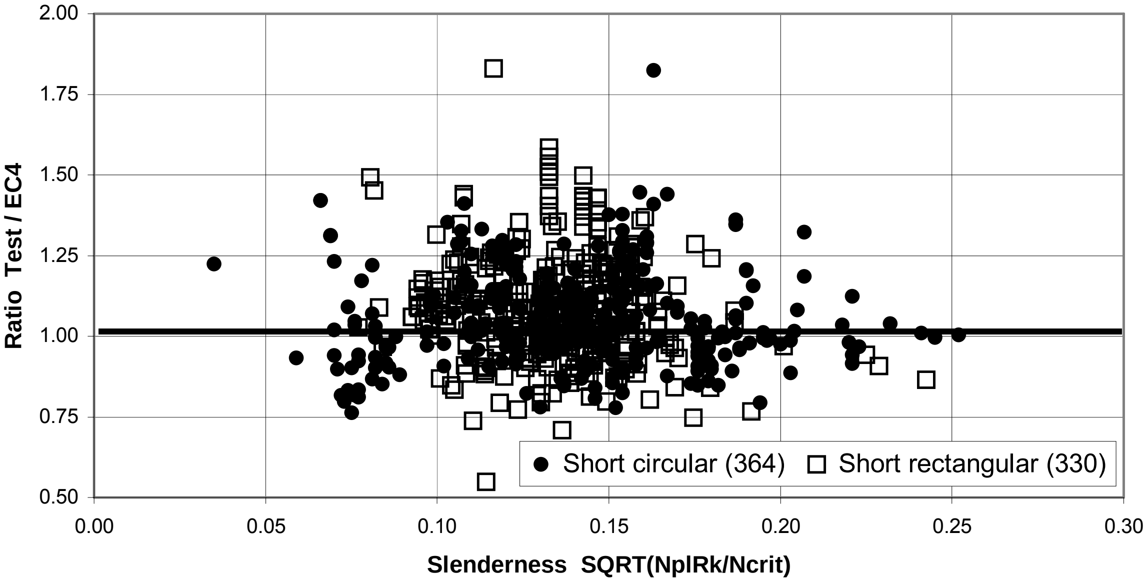

Figure 5. Short columns without moment. Ratio Test/EC4 against Slenderness

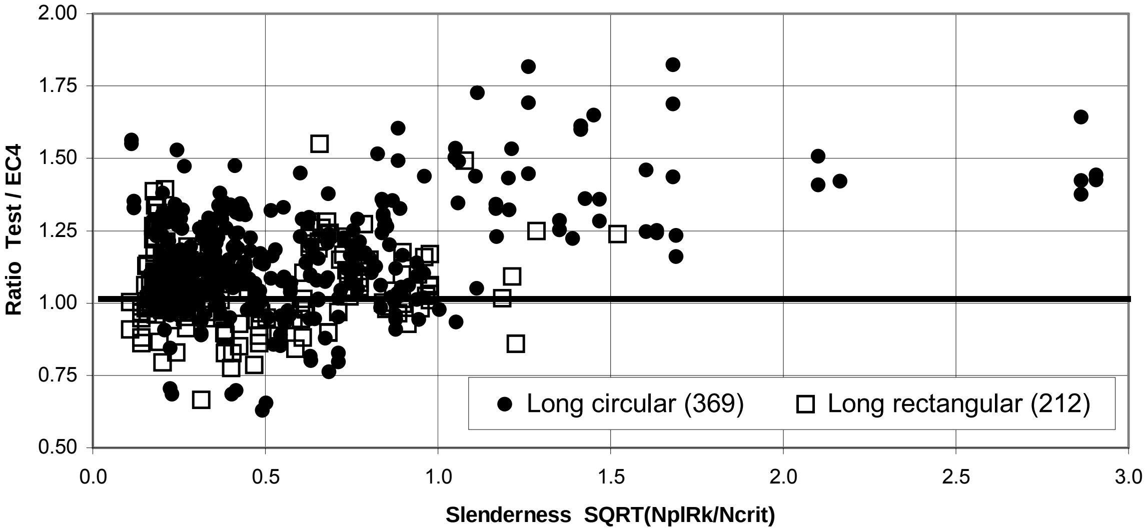

Figure 6. Long columns without moment. Ratio Test/EC4 against Slenderness

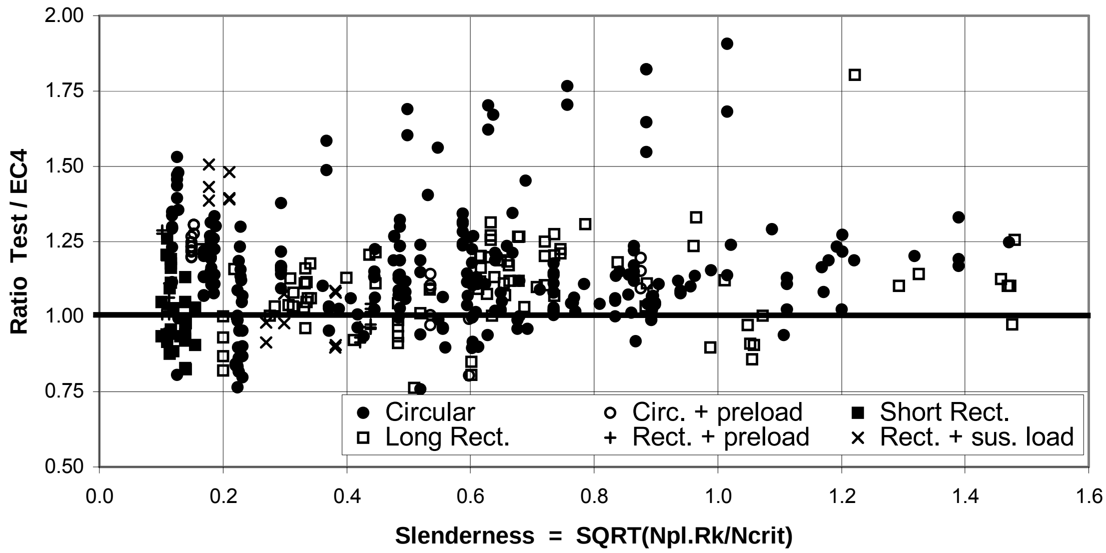

Figure 7. Columns with moment. Ratio Test/EC4 against Slenderness

Hollow sections (rows 10 and 14 in Table 1)
Hollow sections were formed by spinning the steel tube with some concrete in it so that centrifugal force leaves a hole in the concrete. All the hollow sections used low strength concrete, none greater than 40 N/mm^2, and gave column strengths about 20% greater than predicted. This may be due to the difficulty of measuring the true strength of the spun concrete which might be higher than the measured cylinder strength. However, it appears that hollow sections can be designed safely using Eurocode 4 if the hole is allowed for.

Preload and sustained load (rows 11, 12, 13 in Table 1)
Pre-load (up to 60% of the capacity of the steel) on the steel tube before filling with concrete seems to have had no effect on the strength; the average Test/EC4 for the 23 circular columns (11 short and 12 long) being 1.15 (SD 0.123) and for the 19 rectangular columns (10 short and 12 long) being 1.03 (SD 0.099). The eight tests which sustained an average load of between 53% and 63% of their capacity for 120 or 180 days before being loaded to failure carried a slightly higher load before failing (average Test/EC4 = 1.25) than their six comparison tests without sustained load (average Test/EC4 = 1.08); these six companion tests are included in the 212 tests of row 6 of Table 1.

Biaxial bending
Only eleven tests on rectangular columns with biaxial bending are reported and these all failed at much higher loads than predicted by Eurocode 4, average Test/EC4 was 1.52. The Code uses a straight line interaction for the bending resistance between the two axes with an additional safety factor α_M, (with α_M as 0.9 for steel grades S235 to S355 and 0.8 for steel grades S420 and S460, Clause 6.7.3.7). Using an elliptical interaction between the moments about the two axes and omitting this additional safety factor, ie. α_M = 1, gives much closer agreement with the test failure load, an average Test/Prediction of 1.20 for these eleven tests; see the last two rows of Table 1.

CONCLUSIONS

a) Eurocode 4 can be used with confidence for the design of concrete filled steel tube columns. The average Test/EC4 ratio from 1808 tests being 1.11.

b) For circular section columns the Code limitation on concrete cylinder strength could be safely extended to 75 N/mm^2 (cube 94 N/mm^2). Even columns with cylinder strengths above 100 N/mm^2 (cube 125 N/mm^2) were safe, though more tests with such high strength concrete are desirable to justify using the Code with such high strength concrete.

c) For rectangular section columns the concrete strength limitation could be safely extended to 60 N/mm^2. When higher strength concrete is used its cylinder strength should be factored by 0.85, equivalent to assuming no enhancement of concrete strength due to containment.

d) Sections, both circular and rectangular, which have a wall thickness thinner than permitted by the local buckling Clause 6.7.1(9) could be used if a factor of 0.75 was applied to the strength predicted by Eurocode 4.

e) Hollow sections can be designed using Eurocode 4 provided allowance is made for the hole.

f) Neither preload on the steel tube nor sustained load on the filled column had any significant effect on the failure strength of the column.

g) More testing of rectangular columns under biaxial bending is needed. The eleven tests reported show the straight line interaction used in Eurocode 4 to be very safe (Test/EC4 = 1.52) and an elliptical interaction might be preferable (Test/Prediction = 1.20).

REFERENCES

BSI 2005. British Standards Institution. *Eurocode 4: Design of composite steel and concrete structures – Part 1-1: General rules and rules for buildings. BS EN 1994-1-1:2004.* Milton Keynes, BSI, 2005.

Goode 2007. Website with database of all 1819 tests and 109 references to this data: http://website.ukonline.co.uk/asccs2 (also available for £5 as a CD with all data, supplementary calculations and analysis from Douglas Goode, e-mail: cdgoode@mypostoffice.co.uk)

Goode & Narayanan 1997. Goode C. D. and Narayanan R. 'Design of concrete filled steel tubes to EC4', *International Conference on Composite Construction – Conventional and Innovative, Seminar by ASCCS on Concrete Filled Steel Tubes,* Innsbruck, 18 September 1997, p 1-25.

Hobbs et al 1977. Hobbs D. W., Pomeroy C. D. & Newman J. B. 'Design stresses for concrete structures subject to multi-axial stresses', *The Structural Engineer,* **55**/4, 1977, p 151-164.

NOTATION

D	outer diameter of the circular steel tube
h	larger dimension of the rectangular steel tube
b	smaller dimension of the rectangular steel tube
t	thickness of the steel tube
f_y	yield stress of the steel
E_s	modulus of elasticity of the steel (E_a in EC4) = 200 N/mm^2 if not given by the tester
f_{cyl}	cylinder strength of the concrete = $0.8f_{cu}$ if cube strength given by the tester
f_{cu}	cube strength of the concrete
E_c	secant modulus of elasticity of the concrete to $0.4f_{cyl}$ $= 22*((f_{cyl} + 8)/10)$^$^{0.3}$ if E_c was not given by the tester
L	length of the column
e	eccentricity of load on the end of the column, causing end moment
N_{uEC4}	ultimate load capacity of the column as calculated using Eurocode 4
N_u	axial load at failure in the test
χ	buckling factor = $1/(\varphi + \sqrt{}(\varphi^2 - \bar{\lambda}))$ where $\varphi = 0.5*(1 + 0.21*(\bar{\lambda} - 0.2) + \bar{\lambda}^2)$
$\bar{\lambda}$	slenderness ratio = $\sqrt{}(N_{plRk}/N_{cr})$
N_{plRk}	plastic resistance of the composite section
N_{cr}	elastic critical load = $\pi^2(EI)_{eff}/L^2$
$(EI)_{eff}$	effective flexural stiffness of the composite section = $E_aI_a + 0.6*E_cI_c$
k	factor to take account of second order effects in the simplified analysis, which, for columns with equal end moment, = $1/(1 – N_u/N_{cr,eff})$ where $N_{cr,eff}$ uses $(EI)_{eff,II} = 0.9*(E_aI_a + 0.5*E_cI_c)$ to obtain the elastic critical load