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Evaluation of the Concrete Contribution Factor for Composite Sections with Lightweight Concrete under Axial Compression

[1]Yasser M. Hunaiti, [2]Nabil M. Falah and [3]Issam M. Assi
[1]Department of Civil Engineering, University of Jordan
[2]University of Jordan, [3]Department of Civil Engineering, Al-Isra University, Jordan

Abstract: Tests on hollow steel tubes of square, rectangular and circular sections filled with foamed concrete and lightweight aggregate concrete were conducted to investigate the contribution of these concretes to the strength of cross sections of composite short columns. In addition, these tests aim at understanding the behavior of short columns with lightweight concrete. Thirty short column specimens filled with foamed concrete and lightweight aggregate concrete were tested in this investigation. Fifteen specimens for each type were tested under axial compression. Additional five specimens filled with ordinary concrete and five bare steel sections were also tested and results were compared to those of lightweight concrete filled sections. The test results of this study show that lightweight concrete filled specimens were capable of reaching the ultimate predicted loads in accordance with BS 5400, EC4 and LRFD. On the other hand, foamed concrete filled specimens developed the ultimate axial capacity and significantly enhance the strength of bare steel section. Furthermore, strength of lightweight concrete filled tubular short columns sometimes reached 80% of short columns of same sections filled with ordinary concrete.

Key Words: Axial Compression, Composite Section, Foamed Concrete, Lightweight Concrete, Ordinary Concrete

Introduction

A steel concrete composite column is a compression member, which may be either a concrete encased structural steel section or a concrete filled steel tube. The structural steel and concrete components resist the external loading by interacting together through the interface bond or in special circumstances by the use of mechanical shear connectors (Roeder *et al.*, 1999). A great deal of theoretical and experimental work has been carried out on these types of columns with a view to establishing their behavior, characteristics and load bearing capacities (Schneider, 1998; Saw and Liew, 2000).
Concrete Filled steel Tubular (CFT) columns have become increasingly popular in structural applications. This is partly due to their excellent earthquake resistant properties such as high strength, high ductility and large energy absorption capacity. The enhancement in structural properties is due to the composite action between the constituent elements. The confinement created by steel casing enhances the material properties of concrete due to the triaxial state of stress. Conversely, the inward buckling of the steel tube is prevented by the concrete, thus increasing the stability and strength of the column as a system((Uy, 2001).
Among other advantages of CFT columns are speed of construction, saving formwork for the concrete core and possible use of simple standardized connections(Hunaiti and Abdel Fattah, 1994).
The British Standards Code of practice for the design of composite bridges-BS 5400 dose not permit the use of concerts other than ordinary concrete of a density not less than 2300 kg/m^3. Other codes such as Eurocode 4 permit using lightweight concrete but with characteristic cylinder strength not less than 20 MPa. In addition, Load and Resistance Factor Design Specification-LRFD permit using lightweight concrete with cylinder strength more than 27 MPa. Furthermore, little research can be found on the subject of lightweight concrete in composite section ((Masuo *et al.*, 1991; Hunaiti, 1996; Hunaiti, 1997).
Hunaiti (1996) tested thirty-six specimens of concrete filled square and circular hollow sections to study the bond stress. It was found that the strength of bond in composite sections is significantly affected by the type of concrete. Lightweight aggregate concrete showed higher resistance to push-out loads and thus better composite action. The steel tubes filled with foamed concrete showed low values of bond strength.
Hunaiti (1997) also conducted tests on twenty-two beam and column specimens of square and circular steel hollow sections to investigate the contribution of lightweight aggregate and foamed concrete to strength of cross sections of composite member. The results showed that, Foamed concrete filled column specimens were incapable of reaching the analytically predicted values of the squash load. On the other hand, column specimens filled with lightweight aggregate concrete developed the ultimate axial capacity and significantly enhance the strength of the steel sections. Also beam specimens filled with foamed and lightweight aggregate concrete behave flexurally and developed moments well in excess of the theoretical values.
Schneider (1998) tested fourteen specimens of short concrete filled steel tube columns to investigate the effect of steel tube and wall thickness on the ultimate strength of CFT's .The results showed that; Circular steel tubes offer much more post-yield axial ductility than the square or rectangular tube sections. For small dimensional concrete filled steel tube columns, smaller D/t ratios provide a significant increase in yield load compared to values computed by the AISC/LRFD Specifications (1994). Furthermore, the small D/t ratios exhibited more favorable post-yield behavior. In almost all cases, the AISC/LRFD Specification provides a reasonable, conservative estimate for the axial strength of the concrete filled steel tubes columns.

Roeder *et al.,* (1999) conducted an experimental investigation on 20 specimens to examine the bond stress capacity for circular CFT members. The results showed that shrinkage can be very detrimental to bond stress capacity, and the importance of shrinkage depends upon the characteristics of the concrete. The bond capacity is smaller with large diameter tubes and large D/t ratios.

Uy (2001) studied the effects of both concrete strength and plate slenderness on the strength of concrete filled steel box columns. Thirty specimens were tested, and the experimental results showed that local buckling is significant in thin-walled composite columns.

The experimental program conducted by Hunaiti (1997) was limited to one size of square and circular specimens. In this study different sizes of square, rectangular and circular hollow section will be tested under axial compression.

Experimental program: Forty short column specimens were prepared and tested under concentric axial compression. Eight were circular, sixteen were square and sixteen were rectangular steel tube shapes. For convenience, circular tubes were designated with C, S for square and R for rectangular. The specimens have a length of 400 mm.

The column specimens comprised four different groups. The first group, fifteen specimens filled with lightweight aggregate concrete. The second group also fifteen specimens filled with foamed concrete. Five specimens in the third group were filled with ordinary concrete for comparison. Finally, the fourth group, another five specimens was bare steel sections for comparison. The arrangement and properties of all specimens are listed in Table 1.

The specimens were filled vertically with concrete in three layers. The process was similar to that used for the concrete cubes. Due to the shrinkage of concrete core the steel tube was not in the same level with the concrete core, therefore, to overcome this problem, a thin layer of non-shrinkage cementitions precision grout (conbextra HF with 56 MPa strength at 28 days) was poured on the top surface of concrete. This is to ensure that the concrete core and steel tube were loaded simultaneously. Three different mixes of concrete were used in this investigation. Details of the concrete mixes are given in Table 2.

Electric strain gauges (10mm length with resistance 120 ± 0.3Ω) were used to the steel measure strains in tubes to monitor the onset of local buckling. Linear Variable Differential Transducers (LVDT-0.001mm precision) were used to measure axial deformations of the test specimens. Fig. 1 shows the instrumentation of test specimens.

The applied loads were electronically measured by a built-in load cell of 2000 kN capacity DARTEC M1000/RD universal testing machine at Jordan University of Science and Technology.

Experimental procedure: The specimens were set in the testing machine between two flat bearing plates. These plates were thick enough to ensure a uniform distribution of load through the specimen. All specimens were prepared and placed under the applied load with a high degree of accuracy to ensure the load application to the required positions.

The loading process was conducted at two phases. At the initial phase, a load-controlled type of loading was used with rate of 0.5 kN/sec. This type of loading was used until the proportional limit is reached (end of elastic range), then a displacement-controlled loading was applied with a rate of 0.01mm/sec. During the testing process the plotter attached to the testing machine monitored the elastic range. Before applying the load, the LVDTs were adjusted to ensure that there was full contact between the head of LVDTs and the top bearing plate as shown in Fig. 1.

Strains and deformations were recorded with the corresponding load every three-seconds in the elastic range and every one-second after the elastic range by a computerized data acquisition system. Loading was continued until the load had decreased to about 20%-30% of the ultimate load.

Review of Results: Failure loads of specimens filled with lightweight concrete specially foamed concrete showed good agreement with the predictions of BS 5400, EC4 and LRFD. The results showed that the design loads were generally lower than the test results. Tables 4 to 6 show that for lightweight concrete filled steel tubes, EC4 gives better agreement between the test and the design loads than BS 5400 and LRFD. The higher test/design ratio for BS 5400 is due to the reduction factor 0.85 that being applied to the squash load.

Furthermore, results of this investigation showed that foamed concrete contribution factor to axial capacity of composite cross section was higher than the contribution factor of lightweight aggregate concrete. This can be attributed to the homogeneity of the concrete mix and probably the higher voids ratio. The foamed concrete contribution factors varied between 18% and 27%, while the contribution factor for lightweight aggregate concrete ranged between 8% and 19%. It should be mentioned that the limits of the contribution factor, α, according to BS 5400 should lie between 10% and 80%.

It has been observed that the experimental ultimate axial load of foamed concrete filled test specimens was larger than the sum of uncoupled steel and concrete failure load ($A_sF_y+A_cF_{cu}$). The increase in axial load capacity is caused by the confining effect of the steel tube on the concrete. It is worth mentioning that the confined compressive strength F_{cu}' was two times the cube compressive strength F_{cu} of foamed concrete for most cross sections. It was noted that there was no confining effect of steel tube on the lightweight aggregate concrete.

The confinement ratio (F_{cu}'/F_{cu}) for ordinary concrete was less than that for foamed concrete for small *D/t* ratios, this is because as the compressive strength increases the stiffness of concrete also increases resulting in less confining pressure. It was found that the concrete exhibited larger confined compressive strength F_{cu}' with smaller diameter to wall thickness ratio or breadth to wall thickness (i.e., thicker tubes). Generally, it can be concluded that; the load carrying capacity increases with decreasing *D/t* ratio.

Referring to the test results (Fig. 2 to 6), it is observed that the strength of foamed concrete filled tubular short columns (200×100 and 140×140) reached 80% of the strength of columns filled with ordinary concrete of same section. Also the strength of foamed concrete filled tubular short columns (150×90, 100×100 and 114.5×2) reached between 68% and 50% of strength of columns filled with ordinary concrete of the same section. On other hand, the strength of lightweight aggregate concrete filled tubular short columns reached between 70% and 41% of the strength of columns filled with ordinary concrete of same section. However, it should be mentioned that the cube compressive strength of ordinary concrete was six times the cube compressive strength of lightweight concrete.

It was observed that the *D/t* ratio has a significant effect on the local buckling of the steel tube. The test results showed that the code requirements for the upper limits of the *D/t* ratio to prevent local buckling are unnecessarily restrictive for ordinary concrete-filled

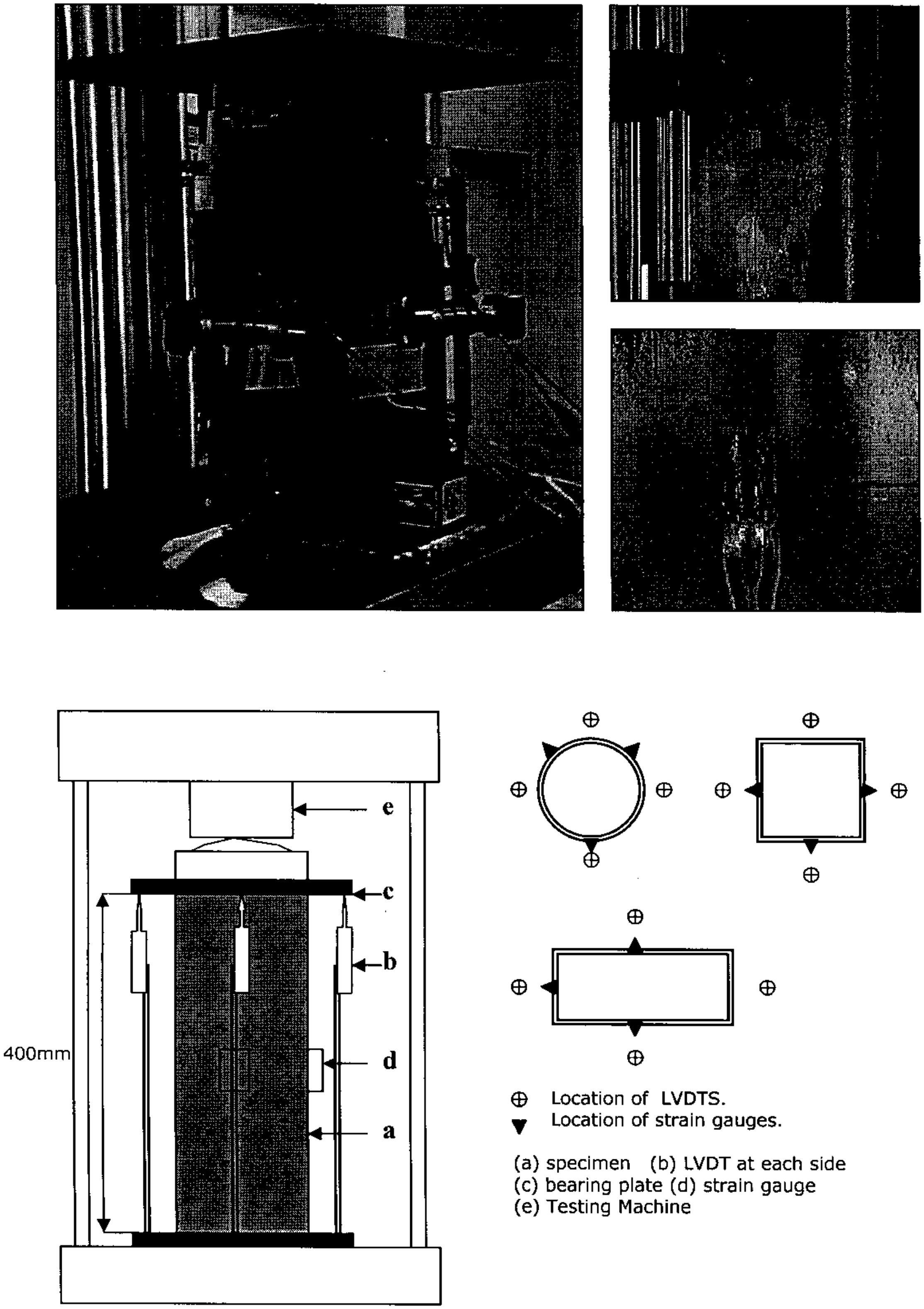

Fig.1: Instrumentation of Test Specimens

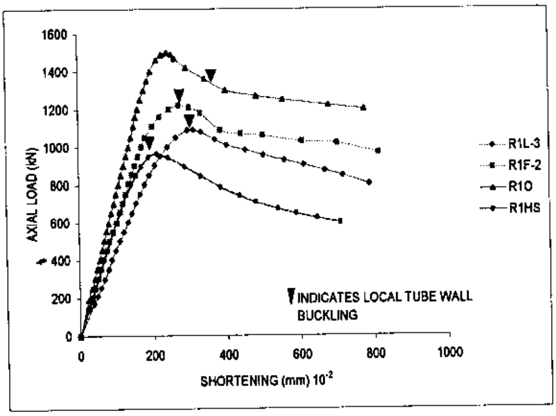

Fig. 2: Comparison of Lightweight Concrete with Ordinary Concrete and Bare Section

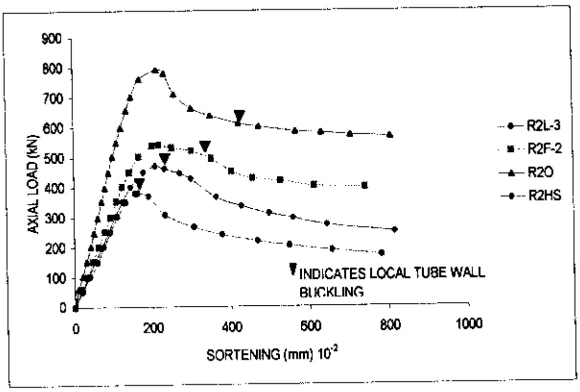

Fig. 3: Comparison of Lightweight Concrete with Ordinary Concrete and Bare Section

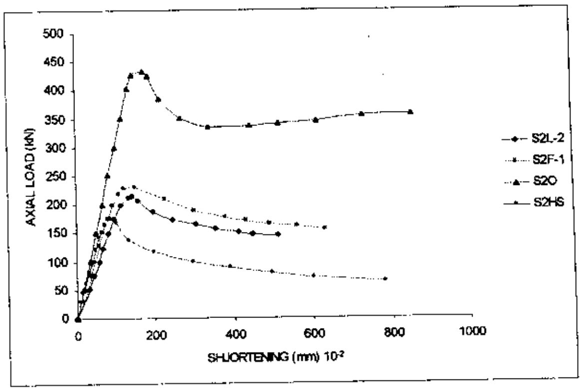

Fig. 5: Comparison of Lightweight Concrete with Ordinary Concrete and Bare Section

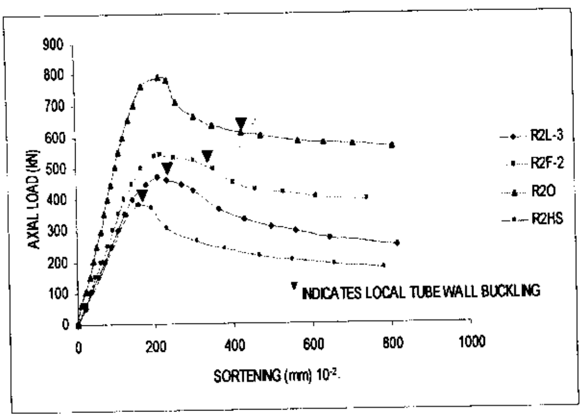

Fig. 4: Comparison of Lightweight Concrete with Ordinary Concrete and Bare Section

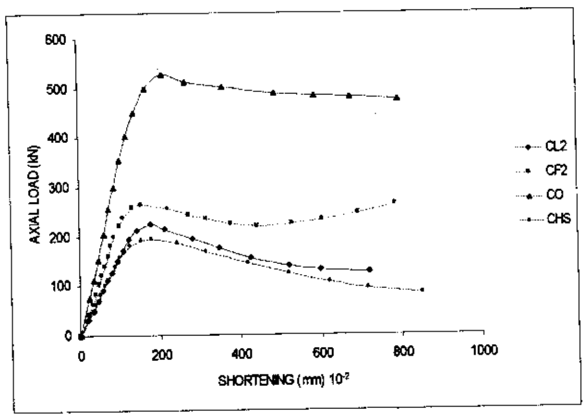

Fig. 6: Comparison of Lightweight Concrete with Ordinary Concrete and Bare Section

Table 1: Properties of Test Specimens *Specimen Designation is as Follows: L-Lightweight Aggregate Concrete; F-Foamed Concrete; O-Ordinary Concrete

Specimen Designation*	Actual Dimension *(mm)*	Steel Properties			Concrete Properties		
		A_S *(mm^2)*	F_y *(MPa)*	E_s *(MPa)*	A_c *(mm^2)*	f_{cu} *(MPa)*	E_c *(MPa)*
R1L-1	200×100×4.7	2732	360	205874	17268	6.7	4978
R1L-2	200×100×4.7	2732	360	205874	17268	6.7	4978
R1L-3	200×100×4.7	2732	360	205874	17268	6.7	4978
R1F-1	200×100×4.7	2732	360	205874	17268	5.6	4497
R1F-2	200×100×4.7	2732	360	205874	17268	5.6	4497
R1F-3	200×100×4.7	2732	360	205874	17268	5.6	4497
R1O	200×100×4.7	2732	360	205874	17268	39	29351
R1HS	200×100×4.7	2732	360	205874	-	-	-
S1L-1	140×140×3.9	2123	350	209023	17477	6.7	4978
S1L-2	140×140×3.9	2123	350	209023	17477	6.7	4978
S1L-3	140×140×3.9	2123	350	209023	17477	6.7	4978
S1F-1	140×140×3.9	2123	350	209023	17477	5.6	4497
S1F-2	140×140×3.9	2123	350	209023	17477	5.6	4497
S1F-3	140×140×3.9	2123	350	209023	17477	5.6	4497
S1O	140×140×3.9	2123	350	209023	17477	39	29351
S1HS	140×140×3.9	2123	350	209023	-	-	-
R2L-1	150×90×2.8	1313	320	198500	12187	6.7	4978
R2L-2	150×90×2.8	1313	320	198500	12187	6.7	4978
R2L-3	150×90×2.8	1313	320	198500	12187	6.7	4978
R2F-1	150×90×2.8	1313	320	198500	12187	5.6	4497
R2F-2	150×90×2.8	1313	320	198500	12187	5.6	4497
R2F-3	150×90×2.8	1313	320	198500	12187	5.6	4497
R2O	150×90×2.8	1313	320	198500	12187	39	29351
R2HS	150×90×2.8	1313	320	198500	-	-	-
S2L-1	100×100×2	784	260	210063	9216	6.7	4978
S2L-2	100×100×2	784	260	210063	9216	6.7	4978
S2L-3	100×100×2	784	260	210063	9216	6.7	4978
S2F-1	100×100×2	784	260	210063	9216	5.6	4497
S2F-2	100×100×2	784	260	210063	9216	5.6	4497
S2F-3	100×100×2	784	260	210063	9216	5.6	4497
S2O	100×100×2	784	260	210063	9216	39	29351
S2HS	100×100×2	784	260	210063	-	-	-
CL-1	114.5×2	707	260	204619	9590	6.7	4978
CL-2	114.5×2	707	260	204619	9590	6.7	4978
CL-3	114.5×2	707	260	204619	9590	6.7	4978
CF-1	114.5×2	707	260	204619	9590	5.6	4497
CF-2	114.5×2	707	260	204619	9590	5.6	4497
CF-3	114.5×2	707	260	204619	9590	5.6	4497
CO	114.5×2	707	260	204619	9590	39	29351
CHS	114.5×2	707	260	204619	-	-	-

Table 2: Details of Concrete Mixes*

Type of concrete	Cube strength f_{cu}: *(MPa)*	Density ρ: *(kg/m^3)*	Concrete mix
Lightweight aggregate concrete	6.7	1260	cement : sand† : pumice 1.0: 0.45 : 2.55 /0.83 expanded perlite : 0.7 *l/kg* of pumice
Foamed concrete	5.6	1250	cement : sand, 1 : 3 /0.5 Aercel : protein based foaming agent in a 2% solution
Ordinary concrete	39	2200	cement : sand : crushed limestone gravel 1 : 1.5 : 3 /0.5

*Ordinary Portland Cement produced in Jordan was used in all mixes
†Mountain sand (Swaileh) instead of river sand used in construction in Jordan

Table 3: Summary of Specimens' Behavior

Specimen	Section dimension *(mm)*	Type of filled-in concrete	Ratio between experimental Squash load and theoretical Load *(%)*			Ratio between experimental Squash load and design Load *(%)*			Axial shortening at ultimate load *(mm)*	Strain at ultimate load *(10^-3)*	Inelastic behavior (load-shortening)	Failure mode
			BS-5400	*EC4*	*LRFD*	*BS-5400*	*EC4*	*LRFD*				
R1L	200 × 100 × 4.7	L aggregate	99	96	98	111	108	115	2.72	6.30	strain-softening	Local buckling then crushing
R1F	200 × 100 × 4.7	Foamed	114	111	113	128	125	133	2.61	5.70	strain-softening	Crushing then local buckling
R1O	200 × 100 × 4.7	Ordinary	105	91	98	126	112	115	2.42	3.20	strain-softening	Crushing then local buckling
R1HS	200 × 100 × 4.7	Bare sec	99	99	100			118	2.11	3.50	degrading stiffness	Local buckling
S1L	140 × 140 × 3.9	L aggregate	95	91	93	107	104	110	2.97	4.30	strain-softening	Crushing then local buckling
S1F	140 × 140 × 3.9	Foamed	117	113	115	132	128	136	3.16	5.90	strain-softening	Crushing then local buckling
S1O	140 × 140 × 3.9	Ordinary	99	85	91	121	105	107	2.17	3.20	strain-softening	Crushing then local buckling
S1HS	140 × 140 × 3.9	Empty	94	94	95			117	2.22	3.50	degrading stiffness	Local buckling
R2L	150 × 90 × 2.8	L aggregate	95	90	93	108	103	110	2.26	4.10	degrading stiffness	Local buckling then crushing
R2F	150 × 90 × 2.8	Foamed	113	108	111	127	123	131	2.53	3.10	strain-softening	Crushing then local buckling
R2O	150 × 90 × 2.8	Ordinary	108	89	98	134	114	115	2.17	2.50	degrading stiffness	Crushing then local buckling
R2HS	150 × 90 × 2.8	Bare sec	95	95	96			113	1.64	1.20	degrading stiffness	Local buckling
S2L	100 × 100 × 2	L aggregate	88	82	87	102	96	103	1.48	1.40	degrading stiffness	Local buckling then crushing
S2F	100 × 100 × 2	Foamed	97	90	93	110	104	110	1.37	1.80	degrading stiffness	Local buckling then crushing
S2O	100 × 100 × 2	Ordinary	98	77	86	127	102	102	1.74	2.60	degrading stiffness	Crushing then local buckling
S2HS	100 × 100 × 2	Bare sec	87	87	87			103	1.00	0.55	degrading stiffness	Local buckling
CL	114.5 × 2	L.aggregate	97	88	92	112	104	110	1.67	1.60	degrading stiffness	Local buckling then crushing
CF	114.5 × 2	Foamed	118	109	113	135	127	134	1.76	1.60	strain-softening	Crushing than local buckling
CO	114.5 × 2	Ordinary	123	96	107	159	128	126	2.13	3.70	elasto-plastic	Crushing than local buckling
CHS	114.5 × 2	Bare sec	106	107	107			127	1.8	2.40	degrading stiffness	Local buckling

specimens. The in-filled concrete adds stiffness to the steel tube and prevents its inward buckling. It can be seen from Fig. 2 to 6 that after the local buckling has occurred, the concrete filled steel tubular short columns have a large load-deformation capacity. For bare steel section, rapid deterioration of axial load is observed after the initiation of local buckling. The main reason for local buckling to appear in an inclined plane was the crushing of the concrete core.

Table 4 list the strain values of steel tubes at failure load (ultimate load) based on the average of strain gauges readings. It can be observed that the strain values of steel tubes at failure load for lightweight concrete filled specimens were higher than ordinary concrete-filled specimens. This is because local buckling occurred at the ultimate load for most lightweight concrete filled specimens. Bare steel tubes had strain values at failure load less than the concrete filled steel tubes. These high strain values provide an indication of a good performance of specimens (short column) in resisting the applied load and a high ductility of such a composite section. Such higher strains occurred as a result of the mutual restraint of both the concrete and the steel tube. As shown in the axial load-strain diagrams the decrease in the strain value occurred at the onset of local buckling. The axial load-strain results provide useful information on the local buckling behavior of the steel tubes.

Short columns filled with lightweight concrete exhibited good behavior as shown in the axial load-strain relationships. The ordinary concrete filled tubular short column had elasto-plastic behavior. It is worthy to note that the cross-sectional shape, diameter to wall thickness ratio and the concrete strength remarkably affect the axial load-strain relationships of the tested specimens.

Table 4: Results of Tested Specimen: BS 5400

Specimen	D/t ratio	Experimental results		Theoretical results			Load ratio		
		N_{ue} (kN)	α (%)	N_{ut} (kN)	α (%)	N_d (kN)	N_{ue}/N_{ut}	N_{ue}/N_p	N_{ue}/N_d
R1l-1	40.5	1053	7.6	1060	7.3	946	0.99	1.07	1.11
R1l-2	40.5	1005	3.2	1060	7.3	946	0.95	1.02	1.06
R1l-3	40.54	1098	11.4	1060	7.3	946	1.03	1.12	1.16
R1f-1	40.5	1188	18.1	1048	6.2	938	1.13	1.21	1.27
R1f-2	40.5	1227	20.7	1048	6.2	938	1.17	1.25	1.31
R1f-3	40.5	1187	18	1048	6.2	938	1.13	1.21	1.27
R1O	40.5	1510	35.6	1434	31.5	1197	1.05	1.54	1.26
R1HS	40.5	973		983			0.99	0.99	
S1L-1	33.8	792	11.6	821	9.5	728	0.96	1.07	1.09
S1L-2	33.8	792	11.6	821	9.5	728	0.96	1.07	1.09
S1L-3	33.8	760	7.8	821	9.5	728	0.93	1.02	1.04
S1F-1	33.8	958	26.9	808	8.1	720	1.18	1.29	1.33
S1F-2	33.8	940	25.5	808	8.1	720	1.16	1.27	1.31
S1F-3	33.8	950	26.3	808	8.1	720	1.17	1.28	1.32
S1O	33.8	1191	41.2	1199	38	982	0.99	1.60	1.21
S1HS	33.8	700		743			0.94	0.94	
R2L-1	51.5	461	13.2	474	11.5	418	0.97	1.09	1.10
R2L-2	51.5	420	4.8	474	11.5	418	0.88	1.00	1.00
R2L-3	51.5	473	15.4	474	11.5	418	1.00	1.17	1.13
R2F-1	51.5	558	28.3	465	9.8	412	1.20	1.33	1.35
R2F-2	51.5	546	26.7	465	9.8	412	1.17	1.30	1.33
R2F-3	51.5	471	15.1	465	9.8	412	1.01	1.12	1.14
R2O	51.5	800	50	738	43.1	596	1.08	1.90	1.34
R2HS	51.5	400		420			0.95	0.95	
S2L-1	48	220	20	245	16.8	213	0.89	1.08	1.03
S2L-2	48	216	18.5	245	16.8	213	0.88	1.06	1.01
S2L-3	48	216	18.5	245	16.8	213	0.88	1.06	1.01
S2F-1	48	233	24.4	238	14.5	208	0.98	1.15	1.12
S2F-2	48	230	23.5	238	14.5	208	0.97	1.13	1.11
S2F-3	48	225	21.8	238	14.5	208	0.95	1.11	1.08
S2O	48	436	58.9	444	54.2	347	0.98	2.15	1.27
S2HS	48	176		203			0.87	0.87	
CL-1	55.2	226	13.3	226	18.8	196	1.00	1.23	1.15
CL-2	55.2	220	11	226	18.8	196	0.97	1.2	1.12
CL-3	55.2	211	7.1	226	18.8	196	0.93	1.15	1.08
CF-1	55.2	250	21.6	219	16.4	191	1.14	1.37	1.31
CF-2	55.2	267	26.6	219	16.4	191	1.22	1.46	1.40
CF-3	55.2	257	23.7	219	16.4	191	1.17	1.40	1.35
CO	55.2	532	63.2	434	57.6	335	1.23	2.91	1.59
CHS	55.2	196		183			1.06	1.06	

Table 5: Results of Tested Specimen: EC4

Specimen	D/t ratio	Experimental results		Theoretical results			Load ratio		
		N_{ue} (kN)	α (%)	N_{ut} (kN)	α (%)	N_d (kN)	N_{ue}/N_{ut}	N_{ue}/N_p	N_{ue}/N_d
R1I-1	40.5	1053	7.6	1099	10	972	0.96	1.07	1.08
R1I-2	40.5	1005	3.2	1099	10	972	0.91	1.02	1.03
R1I-3	40.54	1098	11.4	1099	10	972	1.00	1.12	1.13
R1f-1	0.5	1188	18.1	1080	9	959	1.10	1.21	1.24
R1f-2	40.5	1227	20.7	1080	9	959	1.14	1.25	1.28
R1f-3	40.5	1187	18	1080	9	959	1.10	1.21	1.24
R1O	40.5	1510	35.6	1656	41	1346	0.91	1.54	1.12
R1HS	40.5	973		983			0.99	0.99	
S1L-1	33.8	792	11.6	860	13	754	0.92	1.06	1.05
S1L-2	33.8	792	11.6	860	13	754	0.92	1.06	1.05
S1L-3	33.8	760	7.8	860	13	754	0.88	1.02	1.01
S1F-1	33.8	958	26.9	841	11	741	1.14	1.29	1.29
S1F-2	33.8	940	25.5	841	11	741	1.12	1.26	1.27
S1F-3	33.8	950	26.3	841	11	741	1.13	1.13	1.28
S1O	33.8	1191	41.2	1424	47	1132	0.84	1.60	1.05
S1HS	33.8	700		743			0.94	0.94	
R2L-1	51.5	461	13.2	501	16	436	0.92	1.10	1.06
R2L-2	51.5	420	4.8	501	16	436	0.84	1.00	0.94
R2L-3	51.5	473	15.4	501	16	436	0.94	1.13	1.08
R2F-1	51.5	558	28.3	488	14	427	1.14	1.33	1.31
R2F-2	51.5	546	26.7	488	14	427	1.12	1.30	1.28
R2F-3	51.5	471	15.1	488	14	427	0.97	1.12	1.10
R2O	51.5	800	50	895	53	700	0.89	1.90	1.14
R2HS	51.5	400		420			0.95	0.95	
S2L-1	48	220	20	265	23	226	0.83	1.09	0.97
S2L-2	48	216	18.5	265	23	226	0.82	1.07	0.96
S2L-3	48	216	18.5	265	23	226	0.82	1.07	0.96
S2F-1	48	233	24.4	255	20	220	0.91	1.15	1.06
S2F-2	48	230	23.5	255	20	220	0.90	1.14	1.05
S2F-3	48	225	21.8	255	20	220	0.88	1.11	1.02
S2O	48	436	58.9	563	63	426	0.77	2.16	1.02
S2HS	48	176		204			0.86	0.86	
CL-1	55.2	226	13.3	248	25	210	0.91	1.23	1.08
CL-2	55.2	220	11	248	25	210	0.89	1.20	1.05
CL-3	55.2	211	7.1	248	25	210	0.85	1.15	1.00
CF-1	55.2	250	21.6	237	22	203	1.05	1.36	1.23
CF-2	55.2	267	26.6	237	22	203	1.13	1.45	1.32
CF-3	55.2	257	23.7	237	22	203	1.08	1.40	1.27
CO	55.2	532	63.2	557	67	417	0.96	2.89	1.28
CHS	55.2	196		184			1.07	1.07	

Table 6: Results of Tested Specimen: AISC/LRFD

Specimen	A_s/A_t (%)	Experimental results		Theoretical results			Load ratio		
		N_{ue} (kN)	E_m (MPa)	N_{ut} (kN)	E_m (MPa)	N_d (kN)	N_{ue}/N_{ut}	N_{ue}/N_p	N_{ue}/N_d
R1l-1	13.6	1053	199686	1074	218461	912	0.98	1.08	1.15
R1l-2	13.6	1005	199686	1074	218461	912	0.94	1.03	1.10
R1l-3	13.6	1098	199686	1074	218461	912	1.02	1.13	1.20
R1f-1	13.6	1188	201986	1058	217245	899	1.12	1.22	1.32
R1f-2	13.6	1227	201986	1058	217245	899	1.16	1.26	1.36
R1f-3	13.6	1187	201986	1058	217245	899	1.12	1.22	1.32
R1O	13.6	1510	324085	1543	280093	1311	0.98	1.55	1.15
R1HS	1.00	973		976		829	1.00	1.00	1.18
S1L-1	10.8	792	251982	839	225413	713	0.94	1.07	1.11
S1L-2	10.8	792	251982	839	225413	713	0.94	1.07	1.11
S1L-3	10.8	760	251982	839	225413	713	0.91	1.03	1.07
S1F-1	10.8	958	259191	823	223829	699	1.16	1.29	1.37
S1F-2	10.8	940	259191	823	223829	699	1.14	1.27	1.34
S1F-3	10.8	950	259191	823	223829	699	1.15	1.28	1.36
S1O	10.8	1191	290056	1316	305665	1118	0.91	1.61	1.07
S1HS	1.00	700		740		629	0.95	0.95	1.17
R2L-1	9.7	461	236377	485	216987	412	0.95	1.11	1.12
R2L-2	9.7	420	236377	485	216987	412	0.87	1.01	1.02
R2L-3	9.7	473	236377	485	216987	412	0.97	1.14	1.15
R2F-1	9.7	558	250252	474	215201	402	1.18	1.34	1.39
R2F-2	9.7	546	250252	474	215201	402	1.15	1.31	1.36
R2F-3	9.7	471	250252	474	215201	402	0.99	1.13	1.17
R2O	9.7	800	295783	816	307506	693	0.98	1.92	1.15
R2HS	1.00	400		416		353	0.96	0.96	1.13
S2L-1	7.8	220	224827	250	233469	212	0.88	1.09	1.04
S2L-2	7.8	216	224827	250	233469	212	0.86	1.07	1.02
S2L-3	7.8	216	224827	250	233469	212	0.86	1.07	1.02
S2F-1	7.8	233	241709	246	231208	209	0.95	1.15	1.11
S2F-2	7.8	230	241709	246	231208	209	0.93	1.14	1.10
S2F-3	7.8	225	241709	246	231208	209	0.91	1.11	1.08
S2O	7.8	436	317420	505	348074	429	0.86	2.16	1.02
S2HS	1.00	176		202		171	0.87	0.87	1.03
CL-1	6.8	226	253265	236	231633	200	0.96	1.24	1.13
CL-2	6.8	220	253265	236	231633	200	0.93	1.21	1.10
CL-3	6.8	211	253265	236	231633	200	0.89	1.16	1.06
CF-1	6.8	250	252589	228	229023	193	1.10	1.37	1.30
CF-2	6.8	267	252589	228	229023	193	1.17	1.46	1.38
CF-3	6.8	257	252589	228	229023	193	1.13	1.41	1.33
CO	6.8	532	356287	497	363902	422	1.07	2.92	1.26
CHS	6.8	196		182		154	1.07	1.07	1.27

Notation

A_c	cross-sectional area of concrete
A_s	cross-sectional area of steel
α_c	concrete contribution factor
D/t	diameter to wall thickness ratio or breadth to wall thickness (aspect ratio)
E_c	modulus of elasticity of concrete
E_s	Young's modulus of elasticity of steel
F_{cr}	critical stress
f_{cu}	characteristic cube strength of the concrete.
f_y	nominal yield strength of the steel
$f_y^{/}$	reduced nominal yield strength of the steel casing
N_d	design load.
N_p	plastic load of bare steel section
N_p	plastic resistance design load
N_u	squash loads.
N_{ue}	ultimate axial load (Failure load)
N_{ut}	ultimate predicted load.

Conclusion

On the basis of this study the following conclusions may be drown:

1. Lightweight aggregate concrete filled tubular short column specimens were capable of reaching the theoretical predicted values of the squash loads. On the other hand, short column specimens filled with foamed concrete developed the ultimate axial capacity and significantly enhance the strength of steel sections. Lightweight aggregate concrete filled tubular short columns behaved well under axial load and exhibited more ductility than bare steel sections.
2. Lightweight concrete contribution to the strength of cross sections of composite short column exhibited a good agreement with limits of contribution factors according to BS 5400. The foamed concrete contribution to the squash load was higher than that of lightweight aggregate

concrete. The lightweight concrete contribution factors were affected by homogeneity of the concrete mix and voids ratio. Thus, special care must be given to the casting of the concrete.

3. There was an increase in axial capacity due to triaxial effects in specimens which filled with foamed concrete. However, for lightweight aggregate concrete filled column specimens, there were no increases in axial capacity due to triaxial effects despite the fact that they had nearly the same values of cube strength of concrete.
4. It was observed that for small *D/t* ratios, the confinement ratio for ordinary concrete was less than that for foamed concrete. This is an important factor that must be considered to optimize the usage of high-strength concrete in concrete filled steel tubular columns. It is noteworthy that triaxail stress is affected by *D/t* ratio (aspect ratio).
5. The test results showed that the strength of foamed concrete filled tubular short columns reached 80% of the strength of short columns filled with ordinary concrete. While the strength of lightweight aggregate concrete filled tubular short columns reached 70% of the strength of short columns filled with ordinary concrete. These ratios decrease with the decrease in the thickness of steel cross section.
6. Axial load versus shortening relations for lightweight concrete filled short column specimens can be classified as degrading stiffness type or strain softening type. The cross-sectional shape, diameter to wall thickness ratio (*D/t*) and concrete strength, remarkably affected axial load-shortening behavior of short columns.
7. Local buckling significantly influenced by the type of concrete and *D/t* ratio. In concrete filled steel tubes the wall buckled outward in all faces; i.e. inward buckling has been prevented by the filled-in concrete. For the same cross section, ordinary concrete showed more resistance against local buckling than lightweight concrete. In addition, the upper limits of the *D/t* ratio to prevent local buckling according to composite codes did not agree with ordinary concrete filled specimens. Local buckling of circular cross sections was due to a radial expansion, but other cross sections showed wall bulging.
8. The concrete filled steel tubular short column specimens had two failure modes, the first failure mode was initiated by concrete crushing and followed by local wall buckling, in the second failure mode, local wall buckling occurred then followed by crushing of concrete. Cross-sectional shape and *D/t* ratios were important factors affecting the amount of distortion.

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