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Ultimate moment capacity of foamed and lightweight aggregate concrete-filled steel tubes

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Abstract. An experimental investigation of lightweight aggregate and foamed concrete contribution to the ultimate strength capacity of square and rectangular steel tube sections is presented in this study. Thirty-four simply supported beam specimens, 1000-mm long, filled with lightweight aggregate and foamed concretes were tested in pure flexural bending to calculate the ultimate moment capacity. Normal concrete-filled steel tubular and bare steel sections of identical dimensions were also tested and compared to the filled steel sections. Theoretical values of ultimate moment capacity of the beam specimens were also calculated in this study for comparison purposes. The test results showed that lightweight aggregate and foamed concrete significantly enhance the load carrying capacity of steel tubular sections. Furthermore, it can be concluded from this study that lightweight aggregate and foamed concretes can be used in composite construction to increase the flexural capacity of the steel tubular sections.

Key words: ultimate moment; composite section; lightweight concrete; foamed concrete; concrete contribution factor.

1. Introduction

The term composite construction used randomly can refer to structural systems in which there is interaction between steel and concrete. In this study the term is used solely to refer to interaction between concrete and structural steel in such combinations as a steel beam interacting compositely with a non-reinforced concrete filling. The structural advantages of a composite versus a non-composite construction may thus be summarized as follows:

1. Depth of steel beam is reduced to support a given load.
2. An increase in the capacity (on a static ultimate load basis) is obtained over that of a non-composite beam (fatigue effects may reduce this enhancement of load capacity).
3. For a given load, a reduction in dead loads and construction depth reduces, in turn, the story

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heights, foundation costs, paneling of exteriors, and heating, ventilating and air-conditioning spaces, thus reducing the overall cost of buildings.

The major effect of the composite action is to force the steel and the concrete to act together which shifts the neutral axis of the section upward. This leaves the concrete above the neutral axis in compression and forces almost the whole steel beam below the neutral axis into tension. The composite beam is generally much stiffer than the equivalent non-composite beam, so, the deflection of the composite beam would be less.

There are few studies covering steel tube beams filled with lightweight concretes. Some of the studies considered only the normal weight concrete filled-column tubular rather than using both types of lightweight aggregate and foamed concretes (Knowles and Park 1969, Tomii and Yoshimura 1977, Sakino *et al*. 1985, Shakir-Khalil 1991, Hanbin and Usami 1992, Schneider 1998, Uy 2000).

Hunaiti (1997) conducted a study on the strength of composite sections with foamed and lightweight aggregate concrete. In his research, twenty-two test specimens of steel hollow tubes of square and circular sections filled with foamed and lightweight aggregate concrete were conducted to investigate the contribution of these concretes to the strength of cross sections of composite members.

The use of lightweight aggregate concrete and foamed concrete is increasing faster than the development of appropriate design recommendations. This study presents limited experimental data on the flexural behavior of lightweight aggregate concrete and foamed concrete- filled steel tubular beams.

Lightweight aggregates are produced from a wide variety of raw materials including clay, shale, slate, fly ash, Pumice and Perlite. Pumice and Perlite are the main materials used in the admixture to get the lightweight aggregate concrete in this study.

Foamed concrete is produced by adding admixture to the normal Portland cement, a protein-based foaming agent (NEOPORE) plus Swaileh sand (a mountain sand used extensively in Jordan).

Two main types of concrete filling were used in this study; Lightweight aggregate concrete (designated *L*) and foamed concrete (designated *F*).

Normal weight concrete (designated *N*) was also used in this study for comparison purposes. The British Standards code of practice for design of composite bridges-BS 5400 (steel 1979) does not permit the use of concretes other than normal weight concrete of a density less than 2300 kg/m^3. Other codes such as Eurocode 4 (common 1985) and the European recommendations (composite structures 1981) permit using lightweight concretes of strength not less than 20 MPa.

Testes on steel hollow tubes of square and rectangular sections filled with lightweight aggregate and foamed concrete were conducted to investigate the contribution of these concretes to the strength of the cross section of composite members.

Un-filled steel sections of similar specimens were also tested and results were compared to those of filled specimens. Analytical values of ultimate moment capacities for the test specimens are also included in this study.

2. Analytical considerations

In calculating the capacity of a composite member the strength of the cross section, which is usually expressed in terms of the ultimate moment of resistance is a basic requirement. The computations of these properties are often based on a full plastic stress distribution. The analysis is based on the assumptions that:

- Initially plane sections remain plain after bending and normal to neutral plane.

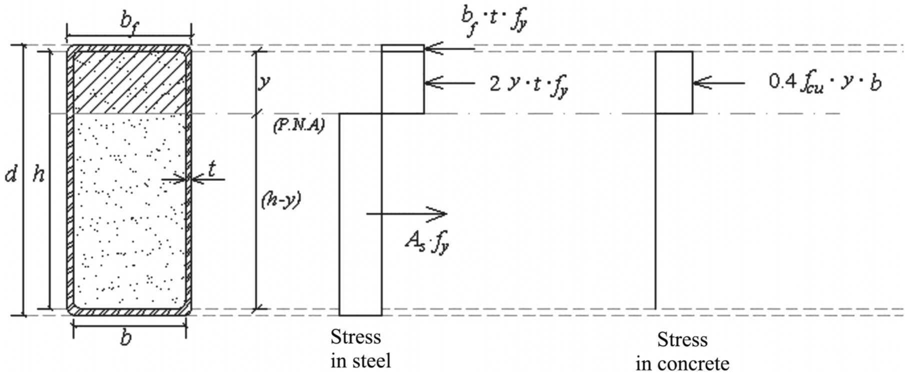


Fig. 1 Stress distribution in concrete- filled rectangular hollow section at M_u

- All steel is at yield stress, which is equal to

$$f_{sk} = f_y / \gamma_{ms}$$

- Concrete in tension is ignored, and the concrete above the neutral axis is under a uniform compressive stress equal to

$$f_{ck} = 0.67\, f_{cu} / \gamma_{mc} \cong 0.4\, f_{cu}$$

As defined by the stress distribution shown in Fig. 1, the depth of the neutral axis can be determined from static equilibrium by equating the compressive and the tensile forces, thus the depth of the neutral axis, y, is given by

$$y = (A_s - 2\, b_f\, t)/(\rho\, b + 4\, t)$$

Where ρ, the concrete-to-steel strength ratio, is given by

$$\rho = f_{ck} / f_{sk} = 0.4\, f_{cu} / f_y$$

Also, from Fig. 1, the ultimate moment of resistance can be obtained by taking moments about the line of action of the compressive force in concrete, and thus ultimate moment of resistance, M_u , is obtained from the following equation:

$$M_u = f_y\,[0.5\, A_s\,(h - y) + b_f\, t\,(t + y)]$$

In calculating the value of M_u, a value of (0.67 f_{cu}) was used for the characteristic concrete strength. Moreover, based *on "Code of practice for design of composite bridges-BS 5400*" (steel 1979) the material partial safety factors of concrete and steel, γ_{mc} and γ_{ms} were taken as 1.50 and 1.00 respectively.

Lightweight aggregate concrete has a good resistance to slippage (Virdi and Dowling 1980, Hamdan and Hunaiti 1991, Hunaiti 1994, 1996, Roeder *et al*. 1999). This may be partly due to the larger aggregate content of the lightweight aggregate concrete, as well as the reserved moisture in the Pumice aggregate and the expanded Perlite, which probably compensate for the loss of water due to external drying, and thus reduce the shrinkage.

Foamed concrete has lower bond strength than lightweight aggregate concrete. The large void content and the large proportion of fine materials in foamed concrete seem to be important factors for bond reduction in foamed-concrete-filled tubes. Moreover, the void content (air bubbles) that reduce the actual area of contact surface, cause more reduction in bond strength.

Generally, mechanical shear connectors are normally unnecessary to develop complete interaction in concrete-filled steel sections.

3. Experimental program

Thirty-four beam specimens of square and rectangular steel hollow sections were tested in this study under flexural bending created by two concentrated loads applied by a compression-testing machine (see Fig. 2). The specimens were divided into four groups, (A, B, C, and D), each one of these groups refers to the steel section dimensions. Cross-sectional dimensions of the test specimens are summarized in Table 1.

Each one of the four groups consists of eight specimens, the first three specimens were filled with lightweight aggregate concrete (designated *L*) and the second three specimens were filled with foamed concrete (designated *F*). The last two specimens of each group were used for a comparison purpose only; one is filled with normal weight concrete (designated *N*) and the other is tested as a bare steel section (designated *H*).

For group (B), in which the steel section is rectangular, two additional specimens were tested under minor axis bending. One of these specimens was filled with lightweight aggregate concrete and the other was filled with foamed concrete. The rest of specimens are similar to the other groups. It should be mentioned that due to certain limitation in the testing program, all specimens of groups' (B) and (D)

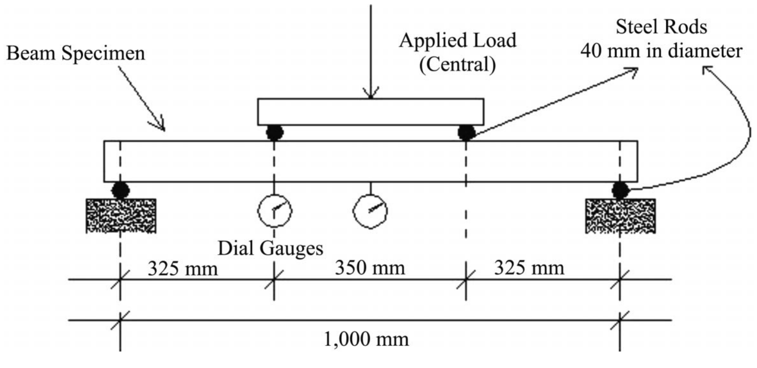


Fig. 2 Details of loading system for beam specimens

Table 1 Group designations of the test specimens

Group designation	Dimensions (mm) (depth · breadth · thickness)
A	(100×100×2.00)
B	(150×90.0×2.80)
C	(140×140×3.90)
D	(200×100×4.70)

Table 2 Detail of test specimens

Group	Specimen designation	Dimensions (mm) ($d \cdot b_f \cdot t$)	Area of steel, A_s (mm^2)	Area of concrete A_c (filled section) (mm^2)	Type of filled concrete†
A	B_1A-SL	100×100×2.00	784	9216	*L*
	B_2A-SL	100×100×2.00	784	9216	*L*
	B_3A-SL	100×100×2.00	784	9216	*L*
	B_1A-SF	100×100×2.00	784	9216	*F*
	B_2A-SF	100×100×2.00	784	9216	*F*
	B_3A-SF	100×100×2.00	784	9216	*F*
	B_1A-SN	100×100×2.00	784	9216	*N*
	B_1A-SH	100×100×2.00	784		*H*
B	B_1B-RL	150×90×2.80	1313	12187	*L*
	B_2B-RL	150×90×2.80	1313	12187	*L*
	B_3B-RL	150×90×2.80	1313	12187	*L*
	B_4B-RL *	90×150×2.80	1313	12187	*L*
	B_1B-RF	150×90×2.80	1313	12187	*F*
	B_2B-RF	150×90×2.80	1313	12187	*F*
	B_3B-RF	150×90×2.80	1313	12187	*F*
	B_4B-RF *	90×150×2.80	1313	12187	*F*
	B_1B-RN	150×90×2.80	1313	12187	*N*
	B_1B-RH	150×90×2.80	1313		*H*
C	B_1C-SL	140×140×3.90	2123	17477	*L*
	B_2C-SL	140×140×3.90	2123	17477	*L*
	B_3C-SL	140×140×3.90	2123	17477	*L*
	B_1C-SF	140×140×3.90	2123	17477	*F*
	B_2C-SF	140×140×3.90	2123	17477	*F*
	B_3C-SF	140×140×3.90	2123	17477	*F*
	B_1C-SN	140×140×3.90	2123	17477	*N*
	B_1C-SH	140×140×3.90	2123		*H*
D	B_1D-RL	200×100×4.70	2732	17268	*L*
	B_2D-RL	200×100×4.70	2732	17268	*L*
	B_3D-RL	200×100×4.70	2732	17268	*L*
	B_1D-RF	200×100×4.70	2732	17268	*F*
	B_2D-RF	200×100×4.70	2732	17268	*F*
	B_3D-RF	200×100×4.70	2732	17268	*F*
	B_1D-RN	200×100×4.70	2732	17268	*N*
	B_1D-RH	200×100×4.70	2732		*H*

*Specimens tested under minor axis bending
†*L*-lightweight aggregate concrete, *F*-foamed concrete, *N*-normal weight concrete, *H*-bare steel section

(rectangular section) were tested under major axis bending except the two additional specimens, which were mentioned for group (B).

The specimens were filled with concrete in many layers and carefully compacted by a steel rod to

Table 3 Yields and ultimate stress of steel sections

Group designation	Dimension of steel section (mm)	Yield stress f_y (MPa)	Ultimate stress f_u (MPa)
A	100×100×2.00	250	384
B	150×90.0×2.80	250	391
C	140×140×3.90	350	446
D	200×100×4.70	360	470

Table 4 Properties of aggregates

Property	Pumice	Sand	Limestone
Specific gravity (G_s)	1.6	2.4	2.6
Nominal maximum size (mm)	4 (50%) 8-16 (50%)	0-4	4 (50%) 10 (50%)
Dry unit weight (kg/m^3)	800	1550	1400
Absorption, 24 hr submerged %	21	1.5	3.5

Table 5 Details of concrete mixes

Type of concrete (designation)	28-d Cube strength, f_{cu} (MPa)	28-d Density ρ (kg/m^3)	Concrete mix proportions
Lightweight aggregate concrete	6.70	1250	cement : sand : pumice 1.0 : 0.45 : 2.55/0.83 expanded perlite: 0.7 l/kg of pumice and water -cement ratio
Foamed concrete	5.60	1245	cement : sand, 1 : 3/0.5, neopore: protein-based foaming agent in a 2% solution
Normal weight concrete	39.0	2200	cement: sand: aggregate, 1 : 1.5 : 3

*Normal Portland pozzolana cement produced in Jordan was used in all mixes
†Mountain sand (Swaileh) instead of river sand used in construction in Jordan

avoid any gaps that may occur inside the specimens. Three 150-mm cubes were prepared for each type of concrete to determine the average compressive strength. These cubes were cured in water tanks and tested at almost the same time of the corresponding beam specimens. Table 2 shows the designation, properties and the type of concrete filler for each test specimen.

In order to determine the material properties that used in load calculations, a set of material tests were carried out for both the steel and the concrete used in the experiments.

Coupon tests were carried out to determine the tensile yield strength. Two coupons were selected from each group of steel, thus, eight coupons were tested and the mean value of the yield stress for each group was used. The coupons were prepared and tested according to ASTM E8 (see Table 3).

The specimens were filled with three different types of concrete with properties and proportions as shown in Tables 4 and 5. Proportions suggested by Sabaleish (1988) were used to produce the lightweight aggregate concrete. For foamed concrete; a protein-based foaming agent (NEOPORE) was used in a 2% concentration to produce the foamed concrete with cement to sand ratio of 1:3. This mix proved to produce stronger foamed concrete (Jaradat 1993).

The test specimens were instrumented to measure loads and deflections. Ultimate loads of the tested beams measured by built-in load cells. The in-plane and lateral deflections were measured by dial

Fig. 3 Experimental setup

gauges of (0.25-mm) precision at points of expected maximum deflection. For the purpose of this investigation in which the ultimate loads were of the major concern, no strain measurements were taken in the tests.

Beams were tested under two-point loading in a 600-kN capacity-testing machine controlled and calibrated according to the BS-1610 specifications.

All beam specimens were of a span length of 1,000 mm loaded and simply supported by 40-mm diameter steel rods as shown in Fig. 2. The beams were tested under two-point loading applied at the center of a very rigid plate, to ensure the distribution of the load (which was applied by the compression testing machine) into two equal concentrated loads as shown in Fig. 3. 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 built-in load cells of the testing machine measured failure loads of the tested specimens. Load-deflection curves of the beam specimens were produced during testing by the plotter attached to the testing machine.

Deflections of the beam specimens were measured by two dial gauges one is used at the location of the concentrated load and the other is used at the mid-span of the specimen as shown in Fig. 3. Similar dial gauge is used to detect any lateral movement. The deflection readings were recorded at a load increment of 5-kN for small sections and at a load increment of 10-kN and 20-kN for other sections.

All beam specimens behaved in purely flexural manner. Primary tension failure occurred in all beams with no lateral deformation or any other form of instability. All specimens exhibited a ductile failure, which highlighted good performance of this type of composite beam.

4. Discussion of results

The experimental results of this study demonstrated the predominant failure mechanism of the beam specimens to be excessive deflection accompanied with some local distortions near the points of load application at stages very close to the maximum load.

All beams behaved as predicted during testing. All beams have reached ultimate moments with no signs of lateral movement of the cross-section or any other form of instability. In other words, the beam

Table 6 Results of beam specimens of group (A)

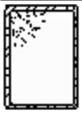
	Failure load	Ultimate moment of resistance			Moment ratio	
Beam specimen	P_{ue} (kN)	M_{ue} (kN.m)	M_{uf} (kN.m)	M_{up} (kN.m)	M_{ue} / M_{uf}	M_{ue} / M_{up}
(Lightweight aggregate concrete-filled beams)						
B_1A-SL	48.50	7.88	7.47	7.20	1.06	1.09
B_2A-SL	50.50	8.21	7.47	7.20	1.10	1.14
B_3A-SL	47.50	7.72	7.47	7.20	1.03	1.07
{Mean}	{48.83}	–	–	–	{1.06}	{1.10}
(Foamed concrete-filled beams)						
B_1A-SF	45.50	7.39	7.43	7.20	0.99	1.03
B_2A-SF	52.00	8.45	7.43	7.20	1.14	1.17
B_3A-SF	53.00	8.61	7.43	7.20	1.16	1.20
{Mean}	{50.17}	–	–	–	{1.10}	{1.13}
(Normal weight concrete-filled beam)						
B_1A-SN	77.00	12.51	8.19	7.20	1.53	1.74
(Bare steel section)						
B_1A-SH	47.00	7.64	7.20	7.20	1.06	1.06

 Square Sections 100×100×2.00 [mm] f_y = 250 MPa

Table 7 Results of beam specimens of group (B)

	Failure load	Ultimate moment of resistance			Moment ratio	
Beam specimen	P_{ue} (kN)	M_{ue} (kN.m)	M_{uf} (kN.m)	M_{up} (kN.m)	M_{ue} / M_{uf}	M_{ue} / M_{up}
(Lightweight aggregate concrete filled beams)						
B_1B-RL	137.00	22.26	17.12	16.57	1.30	1.34
B_2B-RL	123.50	20.07	17.12	16.57	1.17	1.21
B_3B-RL	117.00	19.01	17.12	16.57	1.11	1.15
{Mean}	{125.83}	–	–	–	{1.19}	{1.23}
B_4B-RL *	100.00	16.25	11.95	11.65	1.36	1.39
(Foamed concrete filled beams)						
B_1B-RF	127.00	20.64	17.03	16.57	1.21	1.25
B_2B-RF	117.00	19.01	17.03	16.57	1.12	1.15
B_3B-RF	112.00	18.20	17.03	16.57	1.07	1.10
{Mean}	{118.67}	–	–	–	{1.13}	{1.17}
B_4B-RF*	97.00	15.76	11.91	11.65	1.32	1.35
(Normal weight concrete filled beam)						
B_1B-RN	230.00	37.38	18.91	16.57	1.98	2.26
(Bare Steel Section)						
B_1B-RH	110.00	17.88	16.57	16.57	1.08	1.08

*, Specimens Tested Under Minor Axis Bending

 Rectangular sections 150×90×2.80 [mm] f_y = 250 MPa

specimens developed the full flexural strength of the section.

Theoretical values of the ultimate moment of resistance are compared with the experimental results as shows in Tables 6 to 9. It could be observed from the test results that the ultimate moments are sufficiently close to the analytically predicted values. This is clear when considering the average of the mean values of the ratio M_{ue} / M_{uf}.

The test results of square sections of groups (A) and (C) in Tables 6 and 8, respectively, showed that beam specimens filled with lightweight aggregate and foamed concrete failed at moments of about 110% of the analytically obtained values. Furthermore, the test results for rectangular sections of groups (B) and (D) in Tables 7 and 9, respectively, showed that beam specimens filled with lightweight aggregate concrete failed at moments of about 120% of the analytically predicted values. While beams filled with foamed concrete failed at moments of about 114% of the analytically obtained values.

In addition, the ultimate moment capacity of filled beams is compared to the bare steel sections by considering the ratio of M_{ue} / M_{up}, as shown in Tables 6 to 9.

Results of group (A) in Table 6 showed that the enhancement of the ultimate moment capacity of filled beams, due to the use of lightweight aggregate concrete, was in the range of 7 to 14%. While due to the use of foamed concrete, the enhancement was in the range 3 to 20%. And for the larger square sections of group (C) shown in Table 8, the enhancement of the ultimate moment capacity was in the ranges of 6 to 24% and 6 to 15% due to the use of lightweight aggregate and foamed concrete, respectively.

Moreover, beams of group (B) in Table 7 showed that the enhancement of the ultimate moment capacity of filled beams due to the use of lightweight aggregate concrete was in the range of 15 to 34% while due to the use of foamed concrete the range was 10 to 25%. For the larger rectangular sections of

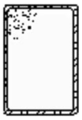
Table 8 Results of beam specimens of group (C)

	Failure load	Ultimate moment of resistance			Moment ratio	
Beam specimen	P_{ue} (kN)	M_{ue} (kN.m)	M_{uf} (kN.m)	M_{up} (kN.m)	M_{ue} / M_{uf}	M_{ue} / M_{up}
(Lightweight aggregate concrete filled beams)						
B_1C-SL	268.80	43.68	38.66	37.94	1.13	1.15
B_2C-SL	246.40	40.04	38.66	37.94	1.04	1.06
B_3C-SL	288.85	46.94	38.66	37.94	1.21	1.24
{Mean}	{268.02}	–	–	–	{1.13}	{1.15}
(Foamed concrete filled beams)						
B_1C-SF	263.00	42.74	38.55	37.94	1.11	1.13
B_2C-SF	268.80	43.68	38.55	37.94	1.13	1.15
B_3C-SF	247.75	40.26	38.55	37.94	1.04	1.06
{Mean}	{259.85}	–	–	–	{1.09}	{1.11}
(Normal weight concrete filled beam)						
B_1C-SN	342.00	55.58	41.21	37.94	1.35	1.46
(Bare steel section)						
B_1C-SH	235.00	38.19	37.94	37.94	1.01	1.01

Square Sections 140×140×3.90 [mm] f_y = 350 MPa

Table 9 Results of beam specimens of group (D)

	Failure load	Ultimate moment of resistance			Moment ratio	
Beam specimen	P_{ue} (kN)	M_{ue} (kN.m)	M_{uf} (kN.m)	M_{up} (kN.m)	M_{ue} / M_{uf}	M_{ue} / M_{up}
(Lightweight Aggregate Concrete Filled Beams)						
B_1D-RL	447.00	72.64	64.84	63.78	1.12	1.14
B_2D-RL	498.00	80.93	64.84	63.78	1.25	1.27
B_3D-RL	494.00	80.28	64.84	63.78	1.24	1.26
{Mean}	{479.67}	–	–	–	{1.20}	{1.22}
(Foamed concrete filled beams)						
B_1D-RF	451.00	73.29	64.67	63.78	1.13	1.15
B_2D-RF	442.00	71.83	64.67	63.78	1.11	1.13
B_3D-RF	469.00	76.21	64.67	63.78	1.18	1.20
{Mean}	{454.00}	–	–	–	{1.14}	{1.16}
(Normal weight concrete filled beams)						
B_1D-RN	597.00	97.01	69.09	63.78	1.40	1.52
(Bare Steel Section)						
B_1D-RH	408.00	66.30	63.78	63.78	1.04	1.04



Rectangular Sections 200×100×4.70 [mm] f_y = 360 MPa

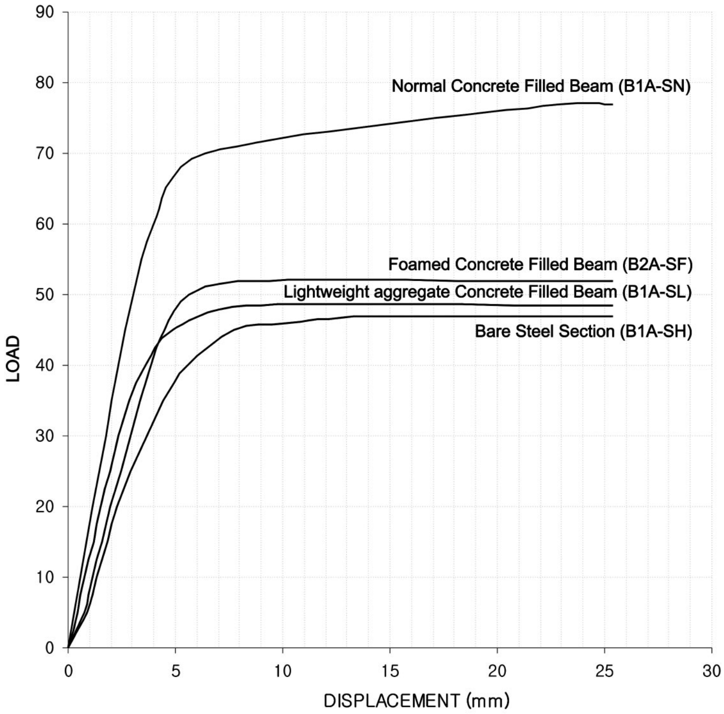


Fig. 4 Comparison chart of group (A)

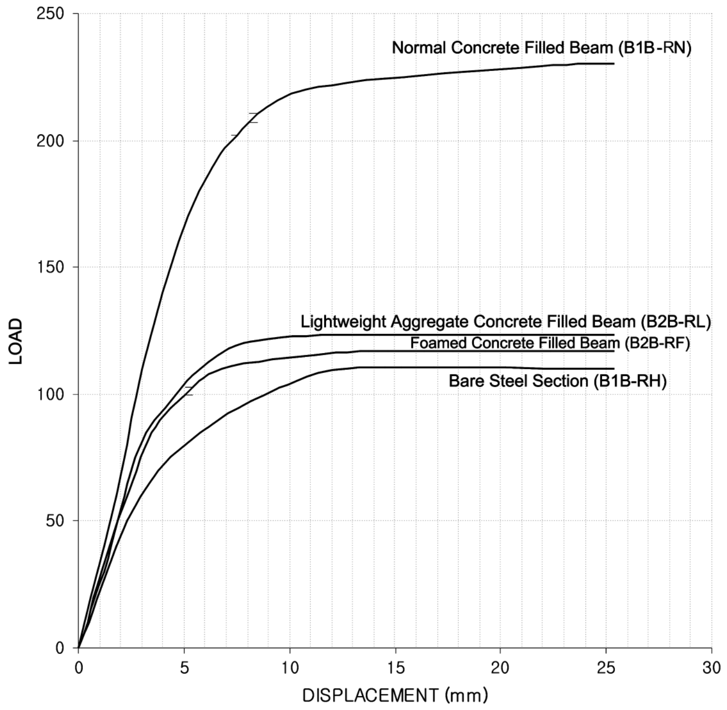


Fig. 5 Comparison chart of group (B)

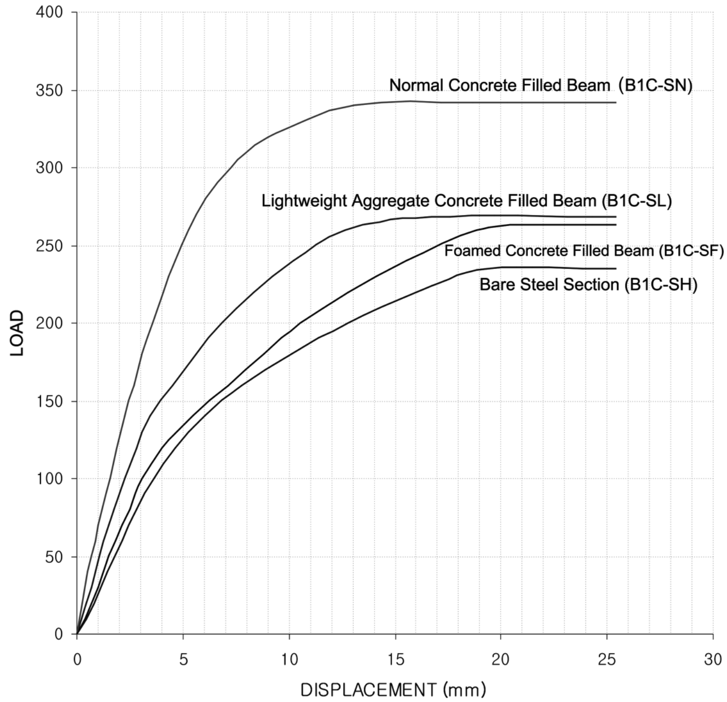


Fig. 6 Comparison chart of group (C)

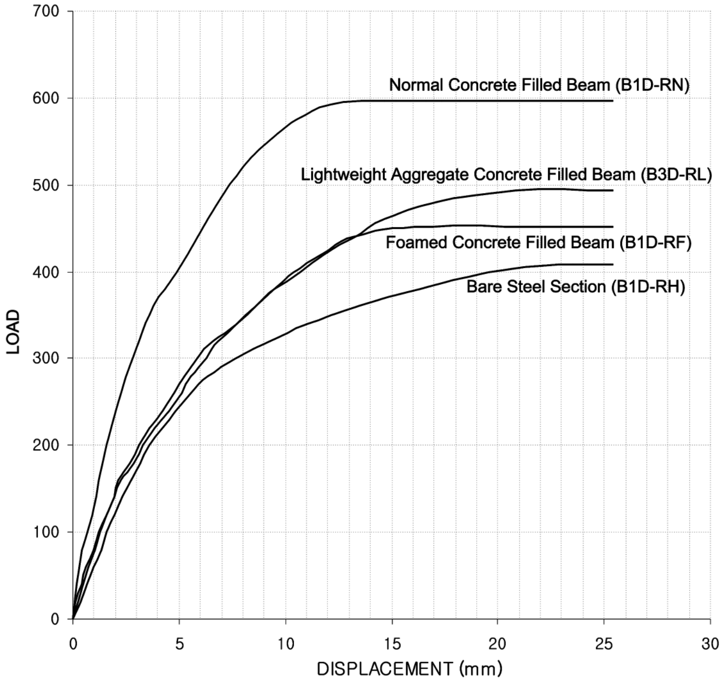


Fig. 7 Comparison chart of group (D)

group (D) (see Table 9), the enhancement of the ultimate moment capacity was in the ranges of 14 to 27% and 13 to 20% due to the use of lightweight aggregate and foamed concrete, respectively.

According to the test results shown in Tables 6 to 9, it is observed that the strength of lightweight concrete-filled tubular sections is varied between, 55% and 80% of the strength of normal weight concrete-filled specimens, for all specimens (all groups).

For additional specimens of group (B), B_4B-RL and B_4B-RF, the contribution to the strength capacity of the steel sections, due to the use of lightweight aggregate and foamed concrete is 39% and 35%, respectively, as shown in Table 7 compared to the bare steel sections. Actually, these were much higher values when compared to the specimens of the same sections tested under major axis bending. The reason is that the width of these two specimens (150-mm) is large enough compared to the depth (90-mm) where the load is applied, so the local distortion dose not take place at the region of the concentrated loads, thus, specimens failed by the effects of excessive bending (developing the full flexural strength of the section).

It was observed that beam specimens filled with lightweight aggregate concrete have ultimate loads at failure more than those filled with foamed concrete, as shown in Figs. 4 to 7. Group (A) in Fig. 4 showed opposite results. The reason is that the specimens of group (A) are small and in casting these specimens, manual compaction of the lightweight aggregate concrete was used, which may cause voids to form inside some specimens. However, in practice it is required to use a special mechanical vibrator during casting.

5. Conclusions

From the tests conducted in this study on foamed and lightweight aggregate concrete filled square and rectangular steel hollow sections, the following conclusions may be drawn:

1. Beams filled with foamed and lightweight aggregate concrete behave flexurally and were capable of developing the full flexural strength of their sections. Moreover, loads supported by the tested beams were in close agreement with the theoretical predictions and thus foamed and lightweight aggregate concrete enhance the ultimate moment capacity of the steel hollow sections.

2. The experimental results of this investigation demonstrated the predominant failure mechanism of the beam specimens to be excessive deflection with no lateral distortions or any other form of instability.

3. The load-deflection curves produced during the tests showed that all beam specimens filled with lightweight aggregate and foamed concrete exhibited similar behavior to that of the bare steel sections but with increasing ductility.

4. The test results of this study showed that the enhancement of the ultimate moment capacity of filled beams reached values of up to 34% when using lightweight aggregate concrete and values up to 25% when using foamed concrete.

Finally, the tests conducted in this investigation confirm that foamed and lightweight aggregate concrete can be used in composite construction to increase the flexural capacity of steel sections.

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Notation

A_c : cross-sectional area of concrete
A_s : cross-sectional area of steel
b : internal breadth of the section
b_f : external breadth of the section
d : external depth of the section
f_{ck} : characteristic strength of concrete
f_{cu} : characteristic 28-day cube strength of concrete
f_{sk} : characteristic strength of structural steel
f_y : yield strength of structural steel
h : internal depth of the section
M_u : ultimate moment of resistance
M_{ue} : experimental failure moment
M_{uf} : ultimate moment calculated by stress blocks
M_{up} : plastic moment of bare steel section
t : wall thickness of steel section
y : depth of neutral axis
γ_{mc} : material partial safety factor for concrete
γ_{ms} : material partial safety factor for steel
ρ : concrete-to-steel strength ratio, is given by $\rho = f_{ck} / f_{sk}$

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