Ultimate strength capacity of a square hollow section filled with fibrous foamed concrete

Siti Amirah Azra Khairuddin1, Norashidah Abd Rahman2*, Norwati Jamaluddin2, Zainorizuan Mohd Jaini2, and Noorwirdawati Ali2

1Faculty of Civil and Environmental Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Johor, Malaysia
2Jamilus Research Center, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Johor, Malaysia
Corresponding author: nrashida@uthm.edu.my

Abstract. Concrete-filled sections used as building columns have become popular due to their architectural and structural elements. In recent years, there has been a renewed call for the improvement of materials used as concrete to fill the composite columns. Among these materials, foamed concrete has received great attention due to its structural characteristics and its potential as a construction material used in hollow sections. However, its behaviors as infill material in a hollow section, such as its strength and failure mode, should be investigated. In this study, experimental research was conducted to compare the experimental and theoretical values of its ultimate strength capacity. Eight specimens of hollow steel sections with two different thicknesses were filled with fibrous foamed concrete and then subjected to compression load. The obtained results were compared with those obtained from a hollow section with the same thicknesses, but were filled with normal foamed concrete. Results show that the ultimate strength capacity of the experimental value is the same as that of the theoretical value based on Eurocode 4. The largest percentage values between theoretical and experimental results for thicknesses of 2 and 4 mm are 58% and 55%, respectively.

1. Introduction
The use of a concrete-filled hollow section (CFHS) as a structural component has increased in recent years due to its aesthetically pleasing appearance and its ability to significantly improve axial capacity without increasing the cross-sectional area [1]. In other words, the CFHS offers basic advantages in aesthetic appeal and structural efficiency. Moreover, the CFHS is a structural member that efficiently combines the tensile strength and ductility of steel with the compressive strength of concrete. Chan, Huai, and Wang [2] reported that concrete infill contributed not only to the strength but also to the ductility of CFHS.

Studies on normal concrete and high-strength concrete as infill in CFHS have focused on the dead weight of the structure and the increased construction cost. Therefore, lightweight concrete has been proposed to promote the use of CFHS and minimize the weight of the structure. Extensive research on the use of lightweight aggregate concrete as infill in hollow steel sections have shown that lightweight aggregate concrete provides good compressive and bond strengths to CFHS compared with normal concrete [3–5]. Considerable research on lightweight concrete used as infill in CFHS has been conducted [6,7], and results from past studies indicated that CFHS with lightweight concrete is more ductile than that with normal and high-strength concrete [8]. The use of foamed concrete as infill
material also increases axial load capacity due to the confining effect of the steel tube with concrete core [5,9].

Foamed concrete is a green concrete that is produced using a low amount of water; it optimizes energy, conserves natural resources, generates minimal water, and provides healthy spaces for occupants [10]. Foamed concrete is a type of concrete that includes an expanding agent, which increases the volume of concrete mixture while reducing the dead weight due to the minimal use of coarse aggregate. Despite these advantages, foamed concrete is also known for its brittleness. Thus, the inclusion of fiber has been proposed to improve the brittle properties of foamed concrete. Further research on additional fiber in concrete have contributed to increasing its tensile, flexural, and compressive strengths [11–14]. Awang, Ahmad, and Al-Mulali [15] proved that the compressive strength of foamed concrete increased with the addition of up to 0.4% polypropylene fiber. Subair, Fayas, and Paul [11] conducted an experimental study to determine the optimum percentage of steel fiber. They reported that the compressive strength increased as the percentage of steel fiber increased. However, the compressive strength of lightweight concrete reduced when the steel fiber comprised 1% volume of the concrete. Therefore, the aim of the current research is to investigate the strength of CFHS with fibrous foamed concrete.

2. Analytical consideration

In this study, the stability of a short column structure is referred to as the ultimate capacity of the compression member to reach the maximum load without buckling, also known as squash load. The column must be perfectly straight and subjected only to axial load [4]. Meanwhile, Eurocode 4 [16] is an international standard code of practice in composite structure, which covers not only concrete-encased and partially encased steel section, but also concrete-filled section with or without reinforcement. The ultimate axial load of a composite column can be analyzed using an equation based on Eurocode 4, known as plastic resistance to compression (squash load). The equation also includes the limit state concept to achieve serviceability and safety by including the partial safety factor of material properties

\[ N_u = A_t f_{yd} + A_c f_{cd}, \]  

where \( f_{yd} \) is the design value of the yield strength of steel, \( f_{cd} \) is the design value of the compressive strength of concrete, and \( f_c \) is the 28-day strength of concrete. The value of 0.83 \( f_c \) is recommended by the European Convention for Constructional Steelwork for experimental work.

The strength index (SI) is defined as the ratio of the ultimate strength capacity of the CFHS column to the sum of the strengths of the composite column. Values of SI that are higher than 1.0 suggest a positive interaction between the steel tube and the concrete core, and good concrete confinement [17] SI is described as

\[ SI = \frac{N_u}{N_{uc}} \]  

where \( N_u \) is the experimental value of ultimate strength capacity of CFHS and the summation of the load-bearing capacity of the steel tube and core concrete, \( N_{uc} \).

3. Experimental program

The aims of the experimental study were to determine the maximum load capacity of specimens and compare the result with theoretical value analyses based on the code of practice. In this study, 12 specimens were cast with different types of concrete and thicknesses.

3.1. Material properties

The strength properties of mild steel hollow steel section were determined for each side of the steel section. The geometry of the coupon specimen was specified according to BS EN ISO 6892-1-2016
Table 1 shows the detail of the dimension and value of yield strength steel section. The cross section of the hollow steel section is shown in Figure 1.

Table 1. Details of section properties.

| Dimension (h × b × t) (mm) | Length (mm) | $f_{yk}$ (MPa) |
|---------------------------|-------------|-----------------|
| 100 × 100 × 2            | 350         | 349             |
| 100 × 100 × 4            | 350         | 387             |

Figure 1. Cross section of the specimen.

The material components of the foamed concrete included used in this study included ordinary Portland cement, sand, water, preforming agent, and fiber. The mix design of foamed concrete was calculated based on the design of environmental method. The proposed density was 1600 kg/m$^3$. The optimum percentages of steel and polypropylene fibers used in foamed concrete were 0.8% and 0.4%, respectively. With the addition of steel fiber, a slight increase in density (~4%) was achieved. To achieve the targeted density, the quantities of cement and sand proportions in fibrous foamed concrete for 1 m$^3$ were 550 and 756 kg, respectively. Furthermore, the ratios of water–cement, foam–water, and foam–cement were 0.55, 0.05, and 0.07, respectively.

3.2. Testing

Twelve specimens with a size of 100 mm × 100 mm × 350 mm and thicknesses of 2 and 4 mm were tested under static load test. The displacement of the specimens was measured by two linear variable differential transformers. Each specimen was filled with various types of foamed concrete, which were polypropylene fiber foamed concrete (PF), steel fiber foamed concrete (SF), and normal foamed concrete (FC). A strain gauge with a size of 10 mm was used to capture the deformation value of the specimens. The universal testing machine was set up to the minimum speed of 1 mm/min to provide sufficient time for specimens to fail. The loading rate was maintained, and the strain and displacement reading was recorded at each load increment. Figure 2 shows the equipment setup for the CFHS specimens.

Figure 2. Testing specimen setup.
Cube specimens with a size of 100 mm × 100 mm × 100 mm were tested according to BS EN12390-3:2009 [19] in order to determine the compressive strength of fibrous foamed concrete. The cube specimens were tested at 7, 14, and 28 days of air-curing age. Before testing, the cube specimens were weighed to determine the density of each specimen.

4. Result and analysis

Figure 3 shows the compressive strengths of various types of foamed concrete. As can be seen, the compressive strength of FC is 14.5 MPa, which complies with the compressive strength of foamed concrete determined by the British Cement Association [20]. Rahman, Jaini, and Zahir [21] reported a relatively high fracture energy for the compressive strength of foamed concrete at 14.7 MPa with a density of 1600 kg/m³. The compressive strengths of foamed concrete with the addition of polypropylene and steel fibers increase by up to 17.2 and 17.9 MPa, respectively. Furthermore, with the addition of fiber in foamed concrete, the strength of foamed concrete compared with that of FC increases at the range of 19% to 23%. Hence, the inclusion of fiber improves the mechanical properties of foamed concrete. This finding agrees with the results reported by Subair et al. [11], Mydin et al. [12], and Awang et al. [13], who concluded that the addition of fiber improved the structural strength and the impact resistance of foamed concrete.

Table 2 shows the comparison of the theoretical and experimental results. As can be seen, the CFHS with fibrous foamed concrete with a density of 1600 kg/m³ achieved the theoretical value. The maximum ultimate strength of the CFHS with additional fiber in foamed concrete for a thickness of 2 mm is 542 kN, and that of CFHS with FC is 520 kN. Moreover, the ultimate strength capacity for 4 mm thickness increases to a maximum (as much as 971 kN) compared with the CFHS with FC, which yields a value of 910 kN. The experimental result indicates that the value of ultimate strength capacity with additional fiber increases by up to 6% for 2 mm thickness, and that for 4 mm thickness increases in the range of 7% to 9%. Both thicknesses are compared with CFHS with FC. The result proves that the addition of fiber contributes to the increment of the ultimate strength capacity of CFHS.

The inclusion of steel fiber in CFHS with foamed concrete also shows higher experimental value due to the higher compressive strength of concrete with FC. Further, the inclusion of steel fiber in concrete core also significantly increases the ultimate strength of capacity of CFHS. Hence, the addition of steel fiber definitely improves the ductility and deformation behavior of CFHS specimen [22]. Meanwhile, a minimal increment in the ultimate strength capacity of CFHS with PF is observed compared with that of CFHS with FC. The experimental value of CFHS with polypropylene fiber shows an unstable result, because polypropylene fiber is a hydrophobic type of fiber that tends to absorb water and cause the generation of numerous pores [15,23].

The maximum value for the ultimate strength capacity of CFHS with fibrous foamed concrete for 4 mm thickness is 971 kN. The percentage difference between the experimental and theoretical values

![Figure 3. Compressive strength of various types of foamed concrete.](image-url)
for 4 mm thickness for each type of foamed concrete as an infill ranges between 46% and 55%. For 2 mm thickness, the high value of experimental result is 535 kN, which ranges between 57% and 58%. The two thicknesses are compared with CFHS with FC due to the increasing thickness of the steel section. As previously mentioned, the ultimate strength capacity is influenced not only by concrete strength, but also by the thickness of steel section. The ultimate strength capacity of CFHS for 4 mm thickness increases in the range of 75% to 81% compared with that for 2 mm thickness. This result is due the decreased b/t ratio. An investigation conducted by Geetha and Swedha [24] showed that the percentage difference in ultimate strength capacity between 2 and 3 mm thicknesses was 48%. The ultimate strength capacity is also affected by b/t ratio, which agrees with the previous work conducted by Al-Mazini and Chkhewier [25]. Theoretically, SI value is affected by concrete strength and b/t ratio. The experimental result also shows that SI value is influenced by concrete strength, thus proving that fibrous foamed concrete ensures good confinement. Kassoul et al. [26] reported that the parameters influencing confinement can significantly improve the strength and ductility of local sections.

Table 2. Comparison of CFHS test results.

| Specimen | Thickness (mm) | b/t | Compressive strength, $f_c$ (MPa) | Theoretical value, $N_u$ (kN) | Experimental value, $N_e$ (kN) | Strength index, SI |
|----------|----------------|-----|----------------------------------|-------------------------------|-------------------------------|-------------------|
| FC21     | 2              | 50  | 14.5                             | 323                           | 495                           | 1.53              |
| FC22     | 2              | 50  | 14.5                             | 323                           | 520                           | 1.61              |
| FC41     | 4              | 25  | 14.5                             | 608                           | 870                           | 1.44              |
| FC42     | 4              | 25  | 14.5                             | 608                           | 910                           | 1.50              |
| PF21     | 2              | 50  | 17.2                             | 336                           | 513                           | 1.52              |
| PF22     | 2              | 50  | 17.2                             | 336                           | 538                           | 1.60              |
| PF41     | 2              | 50  | 17.2                             | 336                           | 513                           | 1.52              |
| PF42     | 2              | 50  | 17.2                             | 336                           | 538                           | 1.60              |
| SF21     | 4              | 25  | 17.9                             | 621                           | 954                           | 1.54              |
| SF22     | 4              | 25  | 17.9                             | 621                           | 949                           | 1.53              |
| SF41     | 4              | 25  | 17.9                             | 621                           | 971                           | 1.56              |
| SF42     | 4              | 25  | 17.9                             | 621                           | 964                           | 1.54              |

FC: CFHS with normal foamed concrete  
PF: CFHS with polypropylene fiber foamed concrete  
SF: CFHS with steel fiber foamed concrete

Figure 4 shows the typical modes of failure experienced by short-column CFHS with fibrous foamed concrete subjected to compression load. The failure modes of specimens show an outward buckling at the top and at the bottom of the stub specimens. According to Jayaganesh et al. [27], the steel section in the outer limit directly carries the applied load and ensures confinement to the inner concrete core, thus avoiding damage to the inner concrete core that can lead to the buckling of the steel section. However, the buckling effect cannot be seen clearly because the fiber can postpone the buckling effect of CFHS. Tao [28] reported that SI values greater than 1 effectively postpone the local buckling effect of specimens.
5. Conclusion
This paper presents the experimental results of testing CFHS with fibrous foamed concrete, from which the following conclusions can be derived:

1) Normal concrete can be replaced with fibrous foamed concrete as infill material in steel hollow sections in order to reduce the dead weight of the concrete infill.
2) The confinement of the fibrous concrete infill improves its strength and delays the local buckling of the steel section.
3) The ultimate strength capacity is influenced by b/t. When b/t is reduce, the ultimate strength capacity increases.
4) CFHS with fibrous foamed concrete can achieve the theoretical value based on Eurocode 4, in which 58% is the largest percentage difference between the experimental and theoretical results of ultimate strength capacity due to the thickness of wall section.

6. References
[1] Testo N and Lam D 2011 Composite Construction in Steel and Concrete VI (USA: American Society of Civil Engineers) pp 252-262
[2] Chan T M, Huai Y M, and Wang W 2015 Experimental investigation on lightweight concrete filled cold-formed elliptical hollow section stub columns Journal Construction Steel Research 115 434–444
[3] Roseline K J and Tensing D 2013 State of The Art Report on Steel- Concrete Infilled Composite Column International Journal of Scientific & Engineering Research 4 677–684
[4] Mouli M and Khelafi H 2007 Strength of short composite rectangular hollow section columns filled with lightweight aggregate concrete Eng. Struct. 29 (8) 1791–1797
[5] Hunaiti Y M 1997 Strength of Composite Sections with Foamed and Lightweight Aggregate Concrete J. Mater Civil Eng. 9 58–61
[6] Ghamnam S, Al-Rawi O and El-Khatieb 2011 Experimental Study on Light Weight Concrete-Filled Steel Tubes Jordan Journal of Civil Engineering 5 1-9
[7] Fu Z Q, Ji B H, Lei L., and Zhou W J 2011 Behavior of lightweight aggregate concrete filled steel tubular slender columns under axial compression Advanced Steel Construction 7 144–156
[8] Chu K 2014 Axial load behaviour of steel tube columns in-filled with various high-performance concretes Thesis (Ryerson University, Toronto, Ontario)
[9] Hunaiti M Y, Nabil M F and Issam M A 2002 Evaluation of the Concrete Contribution Factor for Composite Section with Lightweight Concrete under Axial Compression Journal of Applied Science 10 990–999
[10] Moon A S, Varghese V., Waghmare S S and Moon A S 2015 Foam Concrete as A Green Building Material International Journal For Research In Emerging Science And Technology 2(9) 25–32
[11] Subair M D, Fayas C and Paul 2016 An experimental study on the mechanical properties of steel fibered sand replaced of foamed concrete *Int. Res. J. Engenieneering Technol.* 3 14

[12] Mydin N M, Othuman M A, Sahidun, N S, Yusof M. and Noordin, 2016 Compressive, Flexural and Splitting Tensile Strength of Lightweight Foamed Concrete with Inclusion of Steel Fibre *Journal Teknologi* 5 45–50

[13] Awang M H, Hanizam and Ahmad 2014 Durability Properties of Foamed Concrete with Fiber Inclusion *International Journal of Civil, Environmental, Structural, Construction and Architectural Engineering* 8 273–276

[14] Myd in A O and Soleimanzadeh S 2012 Effect of polypropylene fiber content on flexural strength of lightweight foamed concrete at ambient and elevated temperatures *Advances in Applied Science Research* 3 2837–2846

[15] Awang H, Ahmad M H, and Al-Mulali M Z 2015 Influence of kenaf and polypropylene fibres on mechanical and durability properties of fibre reinforced lightweight foamed concrete *J. Eng. Sci. Technol.* 10(4) 496–508

[16] EN 1994 1-1 2009 Design of composite steel and concrete structures *British Standard Institution*

[17] Jamaluddin N, Lam D, Dai X H and Ye J 2013 An experimental study on elliptical concrete filled columns under axial compression *Journal of Constructional Steel Research* 87 6–16.

[18] EN ISO 6892-1 2016 Metallic Materials-Tensile Testing Part 1: Method of test at room temperature *British Standard Institution*

[19] EN 12390-3 2009 Testing hardened concrete (compression) *British Standards Institution* vol. 3 pp. 420–457

[20] British Cement Association 1994 *Foamed Concrete: Composite and properties* Report ref46042 Slough:BCA.

[21] Rahman N A, Jaini Z M, and Zahir N N M 2015 Fracture Energy of Foamed concrete by means of the three-point bending tests on notched beam specimens *ARPN J. Eng. Appl. Sci.* 10 6562–6570

[22] Tokgoz S and Dundar C 2010 Experimental Study on Steel Tubular Columns In-filled with Plain and Steel Fiber Reinforced Concrete *Thin-Walled Struct.* 48 414–422

[23] Roslan H, Ahmad F and Awang H 2014 Effects of Various Additives on Drying Shrinkage, Compressive and Flexural Strength of Lightweight Foamed Concrete (LFC):*Advanced Material Research* (Switzerland) vol 2013(Trans Tech Publication) pp. 594-604

[24] Geetha H and Swetha T 2015 An Experimental study on Concrete Filled Tubular Columns Using Varying Steel Materials *International Journal of Innovative Science, Engineering & Technology* 2(5) 737–742

[25] Al-mazini M A and Chkhewier A H 2017 Behavior of Concrete Filled Aluminum Square and Rectangular Hollow Section Columns under Axial Loads: Experimental and Analytical Study *Journal of Babylon University* 25(2) 712–726

[26] Kassoul A, Bougara A, and Abdesselam H 2014 Analysis of Confinement Effect on Strength and Ductility in Reinforced Concrete Structure *Earthquake Engineering And Seismology, European Conference (Istanbul)* vol 3 (European Association for Earthquake Engineering (EAEE ))pp. 2584-2593

[27] Jayaganesh S, Murugadoss J R, Prabhu G G, and Jegan J 2015 Effects of Concentrical Partial (Local) Compression on the Structural Behavior of Concrete Filled Steel Tubular Column

[28] Tao Z, Han L, and Wang D 2008 Strength and Ductility of stiffened thin-walled hollow steel structural stub columns filled with concrete *Thin-walled Structure* 46 1113-1128

**Acknowledgments**

The author would like to thank the Universiti Tun Hussein Onn Malaysia (UTHM) for the continuous support in terms of facilities and the Center for Graduate Studies UTHM as a sponsor for this paper. This study also was conducted under FRGS Vot 1625.