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Behaviour of lightweight foamed concrete with pre-tensioning steel straps confinement

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Abstract. Due to its low compressive strength and ductility, lightweight foamed concrete (LFC) cannot be used in structural members such as beams, slabs and columns. One way to improve the strength and ductility of LFC is by confining the concrete laterally by using active external confinement. This research therefore aimed to investigate the effectiveness of external confinement by using low cost steel straps tensioning technique (SSTT) to the LFC columns. A total of 36 cylindrical specimens with 100 mm diameter, 200 mm height and density of 1500 kg/m^3, 1650 kg/m^3 and 1800 kg/m^3 were prepared in this study. The strength of the LFC columns was significantly improved with the increase in number of layers and decrease in spacing of the SSTT confinement. This paper also presents the axial compression stress-strain relationship of the SSTT-confined LFC. SSTT confinement is proven to be effective in increasing the performance of the LFC columns, especially in the specimens with the density of 1500 kg/m^3.

1. Introduction

The technology invention in construction industry nowadays has become more essential as it may enhance the future generation towards greener and sustainable hi-tech system. Reduction of self-weight and size of structural members is important for the construction buildings. Thereby, introducing the lightweight concrete (LWC) to recent construction is able to increase the independency on vast volume of natural resources as well as minimizing dead weight of the building structure. Structural LWC has an in-place density (unit weight) from 1440 to 1840 kg/m^3 compared to normal weight concrete with a density in the range of 2240 to 2400 kg/m^3 [1]. LWC can be defined as a type of concrete which includes an expanding agent in that it increases the volume of the mixture while giving additional quantities such as lessened the dead weight [2]. Lightweight foamed concrete (LFC) and autoclaved aerated concrete are the examples of the cellular concrete. LFC is lighter than the normal weight concrete due to the existence of artificial air bubbles trapped in cement mortar when suitable foaming agent is applied [4]. However, LFC cannot be used as a structural member such as beam, slab and column due to its low compressive strength and ductility. One way to improve the strength and ductility of LWC is by confining the concrete laterally [5]. The pre-tensioning stress applied to LFC column during installation may assist the column to mobilize the confinement material effectively and thus, enhanced the performance of the concrete in term of ductility and strength.

LFC possesses a very low strength of concrete due to its low density. Since the density of the LWC is low, the range of compressive strength that can be produced is from 2 to 30 MPa [3]. Furthermore, LFC with lower compressive strength results in lower ductility. Ductility implies the ability to sustain significant inelastic deformations after the peak load without a significant variation in the resisting capacity prior to collapse [6]. Therefore, knowledge of the complete stress-strain relationship of concrete in compression is necessary to rationally evaluate the ductility of concrete structures [7]. To increase the compressive strength and ductility of the LFC, external wrapping or confinement must be introduced to the LFC. Plenty of research studies have been done for confined column section with internal confinement compared to the external confinement such as fibre reinforced plastic (FRP) and steel straps. It was proven that the mechanical properties of the LWC are improved significantly by using confinement. However, there is still no guideline to estimate the performance of confinement on LFC columns. Lack of understanding in this area will lead to uneconomical design and most importantly is the overestimation in ultimate capacities [8].

The objectives of this study are to investigate the stress-strain behaviour of SSTT-confined LFC with different densities, to determine the effects of SSTT-confinement volumetric ratio on the strength of LFC columns and to examine the performance of SSTT confinement on the mechanical properties of LFC columns such as compressive strength and ductility. This research provides experimental data on the stress-strain behaviour of confined and unconfined LFC. The data produced in this study were generated by considering variables such as number of layers of steel straps confinement and the confinement spacing. Such data are useful in order to compare the stress-strain relationship from the experimental results with the existing models.

2. Material and Methods

2.1 Materials

The materials used to produce the LFC are Ordinary Portland Cement (OPC), oven-dry sand, water, silica fume and Superplasticizer. Superplasticizer was added into the mixes to produce high workability of LFC. The targeted densities for the LFC are 1500 kg/m^3, 1650 kg/m^3 and 1800 kg/m^3 with a tolerance of ±100 kg/m^3. The cement-sand ratio used in this study is 1:1. Only fine aggregate is used in this study. Before being mixed, sand was oven-dried for 24 hours at the temperature of 105 °C. It was then sieved through 600 μm sieve and kept into the sacks for the preparation of specimens. Silica fume was added to the mixture by 10 % of the cement weight in order to improve the concrete properties. Superplasticizer is added to the concrete mixes to increase the workability of the concrete during the casting process. The superplasticizer used in this study was Glenium C380 which is free from chlorides.

2.2 Production of Foam

There were two methods to produce LFC which are by pre-foaming method or mixed foaming method [3]. Pre-foaming method is the separate production of a base mix which is slurry concrete and a stably preformed aqueous which is foam agent with water [3]. Foam generator will produce the foam bubbles and immediately added to the base mix and mixed together. The pre-formed foam can be either wet or dry foam. Wet foam is less stable compared to the dry foam [3]. In this study, dry foam was used rather than wet foam. Dry foam was produced by forcing the foaming agent solution through a series of high density restrictions and forcing compressed air simultaneously into the foam generator as shown in Figure 1. Dry foam is stable foam and has a diameter smaller than 1 mm [3]. Pre-foaming method was used in this study as the production of foam of the LFC. In order to produce high quality of LFC, all materials were must be mixed properly and carefully as the bubble foams could be easily destroyed during the mixing process. Over mixing of the slurry concrete was avoided in this study so that stable foam could be maintained in the concrete. Foam agent was weighted according to the foam-to-water ratio which was 1:25 by volume. Then, it was diluted in the water in the foam generator for about 5-10 minutes. For each process, the foam bubbles were taken out from the foam generator and directly added into the concrete mixer. Each time the foam was taken out, it was weighted. The volume of foam bubbles added was dependent on the target density. The more the foam bubbles added to the mixture, the lower the density being produced and vice versa.

Figure 1. The production of dry foam.

Table 1. Details of specimens prepared for the experimental works.

Density (kg/m^3)	Spacing of Confinement (mm)	Layer of Confinement		
		x = 0 Unconfined	**x = 1 Confined**	**x = 2 Confined**
1500	15	CC1-0-1(1) CC1-0-1(2)	CC1-1-1(1) CC1-1-1(2)	CC1-2-1(1) CC1-2-1(2)
	0	CC1-0-2(1) CC1-0-2(2)	CC1-1-2(1) CC1-1-2(2)	CC1-2-2(1) CC1-2-2(2)
1650	15	CC2-0-1(1) CC2-0-1(2)	CC2-1-1(1) CC2-1-1(2)	CC2-2-1(1) CC2-2-1(2)
	0	CC2-0-2(1) CC2-0-2(2)	CC2-1-2(1) CC2-1-2(2)	CC2-2-2(1) CC2-2-2(2)
1800	15	CC3-0-1(1) CC3-0-1(2)	CC3-1-1(1) CC3-1-1(2)	CC3-2-1(1) CC3-2-1(2)
	0	CC3-0-2(1) CC3-0-2(2)	CC3-1-2(1) CC3-1-2(2)	CC3-2-2(1) CC3-2-2(2)

2.3 Preparation of the LFC Columns

To identify the behaviour of confined LFC with pre-tensioned steel straps, 36 specimens were prepared in this study. The water to cement ratios used were 0.40 for the density of 1500 kg/m^3, 0.42 for the density of 1650 kg/m^3 and 0.42 for the density of 1800 kg/m^3. Each targeted density consists of 12 LFC columns which were allocated for particular parameters such as number of confinement layers and spacing used during the confining works. In every type of densities, there were unconfined and confined samples. For the confined samples, columns were wrapped with one or two layers of steel straps and spacing of 0 mm or 15 mm. The details of the specimens prepared for the experimental works is tabulated in Table 1. The specimens ID are denoted as CCt-x-y(m) where;

t is the density of the LFC column (1 = 1500 kg/m^3; 2 = 1650 kg/m^3; 3 = 1800 kg/m^3)

x is the number of layer of confinement using steel straps (0, 1, 2)
y is the parameter of spacing being used for the steel straps confinement (1 = 15 mm; 2 = 0 mm)
m is the number of sample(s) in one group

2.4 SSTT-confining Work

SSTT-confining work was carried out by warping steel straps around the specimens and tensioning the straps by using a pneumatic tensioner, PT-52. The straps hoops were secured in place by using connection clips made of the similar steel straps. The details of the connection clips are illustrated in Figure 2. This connection clips enabled self-regulation among the multi-layers of steel straps and this is one of the advantages of using the connection clips. This innovation of connection clips was pioneered in University Technology Malaysia, Malaysia. The straps were tensioned around the column by a pressure of approximately 10 – 15 MPa by using the commercially available strapping equipment [8]. Having a consistent value of tensioning pressure ensures effective utilisation of the straps and avoids early crushing of the confined concrete, which could have occurred without properly tightened straps. The steel straps and the pneumatic tensioner used in this study are as shown in Figure 3(a) and 3(b), respectively. To prevent early cracking on the loading surface during the compressive load test, confinement was installed near both the loading surfaces of the specimens.

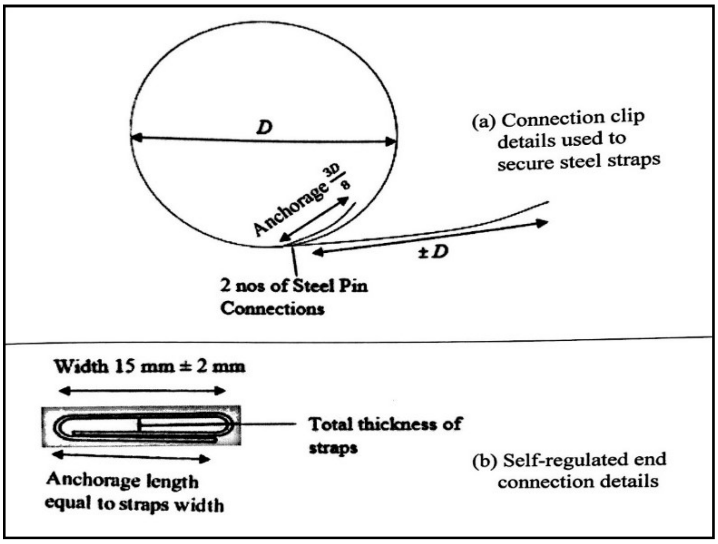


Figure 2. Self-regulated steel straps hoop and connection details (reproduced from Awang, 2013).

(a)

(b)

Figure 3. Steel straps and the tensioner (a) Steel straps hoops (b) Pneumatic tensioner.

2.5 Testing Configuration
In this research, axial compression test was carried out to the specimens. This test was conducted immediately after the confining works so that any loss of pre-tensioning force was avoided. Figure 4 depicts the configuration of axial compression test in Laboratory of Structures and Materials, Faculty of Civil Engineering, University Technology Malaysia. Two (2) omega strain gauges were attached to each of the specimens and were connected to the data logger and computer for data acquisition as shown in Figure 5(a) and (b), respectively.

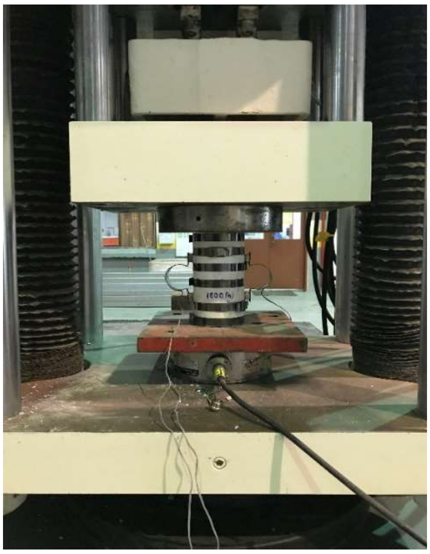


Figure 4. Test setup and configuration.

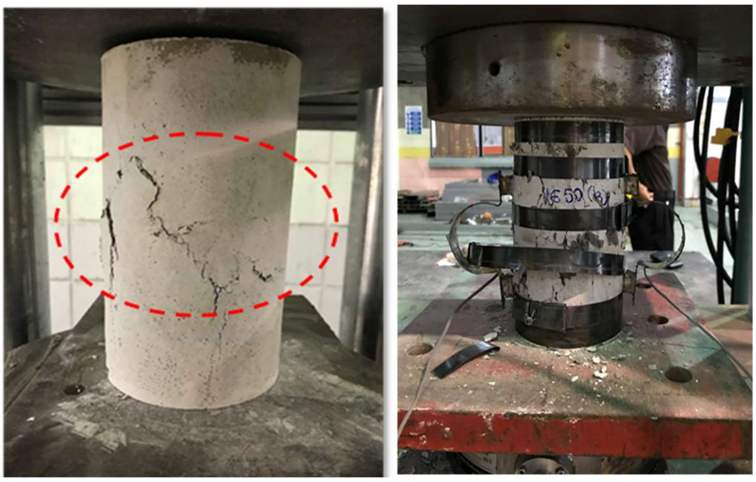
(a) (b)

Figure 5. Strain acquisition setup (a) Data logger (b) Omega strain gauges on specimens.

3. Test Results and Discussion
The specimens were tested using the Tinius Olsen Compression Machine by using a displacement-controlled load of 0.05 mm/s. The following sections describe the findings from the experimental test.

3.1 Failure Modes
All of the plain or unconfined LFC columns, minor vertical cracks were observed shortly on the outer surface of the concrete right after the loading was initiated. The specimens slightly bloated at the mid height section as the load continuously increased as shown in Figure 6(a). Eventually major surface cracks were observed on the surface of the concrete. Since there was no coarse aggregate involved in

the specimens, null incline cracks occurred on the concrete surface. At the ultimate axial load, the specimens were observed to be absolutely failed and cracking sound can be heard clearly at this stage. Minor surface cracks were observed at the upper and lower part of the specimens. As the specimens progressively loaded, the external protection from SSTT confinement appeared to prevent the columns from failure. When the load approaches the ultimate axial load, major cracks were observed, and the cracks continue to implode in both upper and lower direction. 'Popping' noise was heard especially on the specimens with 0 mm of spacing and two layers of SSTT confinement. The surface of the specimens with one layer of confinement was slightly damaged and the steel straps ruptured or yielded at the ultimate load. This indicates that single layer of steel straps confined LFC columns exerted insufficient confining pressure to the concrete core. As the applied load was about to reach peak axial force, a noise associated with brittle rupture was clearly seen, followed by an immediate extremely loud explosive noise when the steel straps was broken and failed at the middle section of the test columns, as shown in Figure 6(b). From the confined LFC, it showed that SSTT confinement functions well in reserving the column's strength and preventing the column from short time collapse.



(a) (b)

Figure 6. Failure modes of the LFC under load testing (a) Unconfined LFC (b) Confined LFC.

3.2 General Behaviour of SSTT-confined LFC

After applying the steel straps confinement, the strength of the LFC columns was found to be significantly improved by a rate related to the number of layer and spacing of the confinement used. The stiffness and spacing of straps strongly influenced the extent of uniformity of confinement of the concrete [9]. In fact, steel straps confinement may be functioning in slowing down the losses of concrete's strength and column failure at vigorously ultimate strain will be preceded by more visible strain of distresses. After confining the LFC columns with one layer of steel straps, the strength of the columns in group CC1, CC2 and CC3 was improved to 1.808, 1.092 and 1.011 times the strength of the plain LFC columns, respectively. After confining with two layers of steel straps, the strength of the LFC columns in group CC1, CC2 and CC3 was improved drastically to 1.859, 1.156 and 1.179 times the strength of the plain concrete columns, respectively. The results show that the lower the strength of the LFC, the higher the increase rate, and the greater the number of confinement layers, the higher the increase rate. Meaning to say, the result seems to be more significant to the columns with low strength of LFC and it is apparently enhanced the strength of the columns by approximately twice of the strength of the plain LFC. After confining the LFC columns with 15 mm of confinement spacing, the strength of the LFC columns in group CC1, CC2 and CC3 was improved to 1.808, 1.092 and 1.011 times the strength of the plain concrete columns, respectively. However, after confining the columns with 0 mm of confinement spacing, the strength of the LFC columns in group CC1, CC2 and CC3 was significantly improved to 1.936, 1.199 and 1.393 times the strength of the plain concrete columns, respectively.

Results from Table 2 indicated that external steel straps confinement is proven to be effective in increasing the performance of the LFC columns, especially to the concrete with density of 1500 kg/m^3.

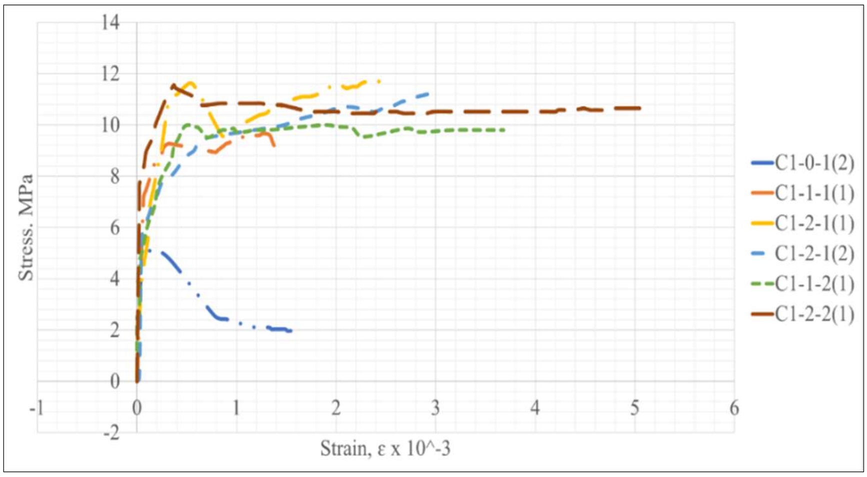
Table 2. Test results of SSTT-confined LFC columns.

Specimen ID	F (kN)	f_{co} (MPa)	f_{cc} (MPa)	ε_{co} (%)	ε_{cc} (%)	ρ_v
CC1-0-1(1)	40.513	5.263	-	0.183	-	0.000
CC1-0-1(2)	38.997	5.128	-	0.137	-	0.000
CC1-1-1(1)	70.503	-	9.271	-	0.328	1.087
CC1-1-1(2)	73.636	-	9.683	-	0.427	1.041
CC1-2-1(1)	77.066	-	10.134	-	0.636	1.882
CC1-2-1(2)	72.503	-	9.534	-	0.733	2.001
CC1-1-2(1)	75.499	-	9.928	-	0.578	1.861
CC1-1-2(2)	78.324	-	10.175	-	0.496	1.815
CC1-2-2(1)	89.001	-	11.562	-	0.370	3.025
CC1-2-2(2)	87.646	-	11.386	-	0.413	3.071
CC2-0-1(1)	155.801	20.240	-	0.117	-	0.000
CC2-0-1(2)	152.998	20.119	-	0.099	-	0.000
CC2-1-1(1)	166.998	-	21.960	-	0.393	0.459
CC2-1-1(2)	172.028	-	22.348	-	0.374	0.451
CC2-2-1(1)	179.002	-	23.254	-	0.531	0.820
CC2-2-1(2)	180.200	-	23.696	-	0.625	0.805
CC2-1-2(1)	183.501	-	24.130	-	0.393	0.766
CC2-1-2(2)	199.531	-	26.238	-	0.421	0.704
CC2-2-2(1)	238.003	-	31.297	-	0.231	1.117
CC2-2-2(2)	238.236	-	30.949	-	0.278	1.130
CC3-0-1(1)	377.062	49.583	-	0.084	-	0.000
CC3-0-1(2)	366.598	48.207	-	0.050	-	0.000
CC3-1-1(1)	386.216	-	50.173	-	0.093	0.201
CC3-1-1(1)	386.216	-	50.173	-	0.093	0.201
CC3-1-1(2)	370.598	-	48.733	-	0.066	0.207
CC3-2-1(1)	432.097	-	56.820	-	0.069	0.336
CC3-2-1(2)	427.809	-	56.256	-	0.093	0.339
CC3-1-2(1)	508.955	-	66.927	-	0.121	0.276
CC3-1-2(2)	510.600	-	67.143	-	0.109	0.275
CC3-2-2(1)	542.602	-	70.489	-	0.139	0.496
CC3-2-2(2)	540.016	-	70.153	-	0.159	0.498

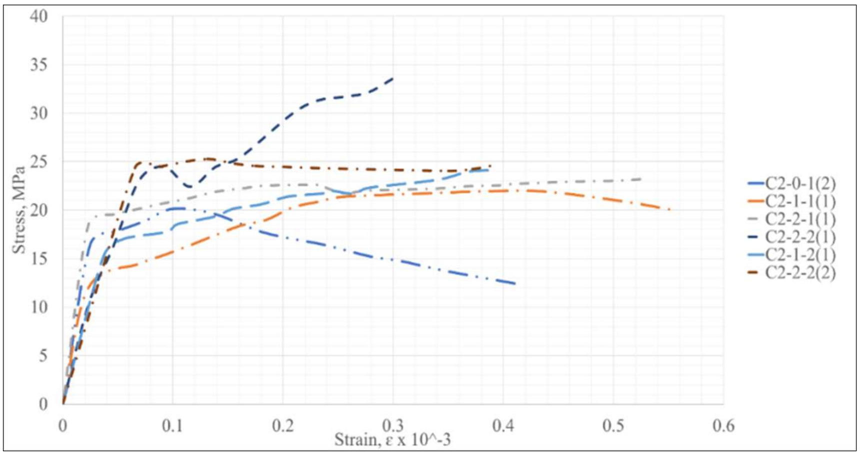
F is the ultimate axial load;
f_{co}, f_{cc} are the ultimate strength of unconfined concrete and confined concrete, respectively;
ε_{co}, ε_{cc} are the ultimate strain of unconfined concrete and confined concrete, respectively;
ρ_v is SSTT-confinement volumetric ratio = $V_s f_y / V_c f_{co}$,
V_s, V_c are volume of steel straps used and concrete, respectively;
f_y is yield stress of steel straps;

3.3 Stress-strain Behaviour of SSTT-confined LFC

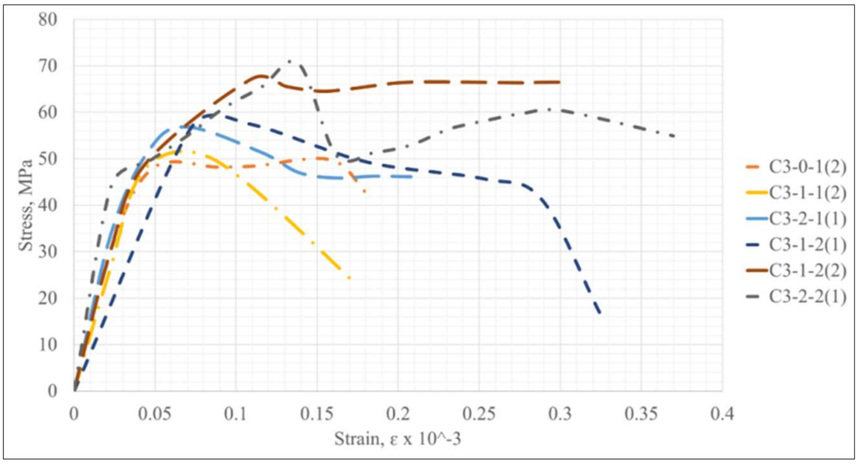
Figure 7 shows comparisons of the axial stress-strain curves of the LFC columns. The stress-strain relationship graphs were plotted from the experimental data recorded during the experimental test, by referring to the load applied from Tinius Olsen Compression Machine and the corresponding deflection reading from the omega strain gauge through the data logger. Under the pre-stressed confinement, the strength and ductility of the LFC columns were significantly improved compared to the unconfined columns. The steel straps confinement was not observed to have a significant effect on the stress-strain curve during the initial stage of the applied loading. Most of the columns are having the increasing linear constant slope until peak point. The linear constant slope can be classified as elastic zone whereby all columns within this zone would be able to return to their original form once the load is released. Figure 7 also indicates that the stress-strain graph of the confined LFC columns had significant steeper slopes with the increment of concrete's strength compared to the unconfined columns. In the plastic zone where the columns sustained more deformation and deflection although the ultimate load has been reached. In summary, it can be concluded that the steel straps confinement yielded the best improvement in the strength and ductility of the lower-grade of the LFC which referred to the low density of concrete. Additionally, most of the experimental results showed that confining the LWC columns with any types of confinement will drastically enhanced the compressive strength and ductility of the specimens.



(a)



(b)



(c)

Figure 7. Stress-strain curves of each type of groups: (a) CC1; (b) CC2; and (c) CC3.

3.4 Performance of SSTT Confinement on Ultimate Strength

Apparently, as the SSTT-confinement volumetric ratio increased, the ultimate strength increased with slightly linear relationship exists to the specimens with the density of 1500 kg/m^3. Table 3 summarises the effects of steel straps confinement spacing on the ultimate strength of the confined LFC. Theoretically, decreasing the spacing of the confinement to the columns will increase the volume of the steel straps being used, V_s and increasing the SSTT-confinement volumetric ratio, ρ_v and thus, enhancing the ultimate strength of the specimens. Confining the column with 15 mm of spacing results in lower ultimate strength compared to the confinement spacing of 0 mm. Increasing the number of steel straps confinement layers to the LFC columns will increase the SSTT-confinement volumetric ratio and resulting in the improvement of the ultimate strength of the confined columns. From experimental test, the ultimate strength of the LFC columns increased as the spacing of the steel straps confinement is reduced. A reverse relationship exists between the spacing of each steel straps and stress-strain behaviour of the confinement, where the smaller the spacing between the steel straps, the higher the ultimate capacity can be achieved [10].

Table 3. Relationship of ultimate strength with the spacing of confinement.

Density (kg/m^3)	Spacing (mm)	No. of Sample	f_{cc} (MPa)	ρ_v, volumetric ratio	Enhancement (%)
1500	unconfined	CC1-0-1(2)	5.128	0.000	-
	15	CC1-1-1(1)	9.271	1.087	80.792
	0	CC1-1-2(1)	9.928	1.861	93.604
1650	unconfined	CC2-0-1(2)	20.119	0.000	-
	15	CC2-1-1(1)	21.960	0.459	9.151
	0	CC2-1-2(1)	24.130	0.766	19.936
1800	unconfined	CC3-0-1(2)	48.207	0.000	-
	15	CC3-1-1(2)	48.733	0.207	1.091
	0	CC3-1-2(2)	67.143	0.275	39.281

3.5 Performance of SSTT Confinement on Ductility

The deformability of a structural member prior to the failure can be measured through ductility. The ratio of two displacements which is the yield displacement, ε_y and the ultimate displacement, ε_{cc} (i.e. $\varepsilon_{cc} / \varepsilon_y > 1.0$) is considered as one of the ductility measurement parameters for the ductility ratio of a confined specimen. According to the test results, the ductility ratio varies for all number of layers and spacing of the confinement. All specimens with two layers of steel straps confinement having the higher value of ductility ratio compared to the unconfined specimens or the LFC columns that were confined with one layer of steel straps. In addition, for the confined LFC columns with 0 mm of spacing exhibited higher ductility ratio compared to the unconfined specimens or the columns with 15 mm of confinement spacing. Furthermore, the ductility ratio is significantly influenced by the amount of tensile reinforcement as well as by the amount of confining reinforcement [6]. The higher the confinement ratio, the higher the ductility and toughness of the material. Increasing ductility promises a safer structure as it slows down the strength loss beyond peak and prevents column failure at a very much higher ultimate strain. Therefore, from all analysis of the effects of the SSTT-confined LFC, it is obvious that the external steel straps confinement is more effective in increasing the strength and ductility of the low density LFC columns.

4. Conclusions

In this paper, the mechanical properties of SSTT-confined LFC were experimentally and theoretically studied, and the following conclusions were obtained:

(1) SSTT confinement is proven to be effective in increasing the performance of the LFC columns, especially to the columns with the density of 1500 kg/m^3; the enhancement in axial stress of confined columns is 80% and 94% for the volumetric ratio of 1.087 and 1.861, respectively. The deformability of the columns also increased when the density of the concrete is increased.

(2) The enhancement of the external steel straps confinement is way better in enhancing the deformability of the LFC columns drastically compared to the increasing of concrete’s strength which is relatively small from 80% to 94% by overall.

(3) The increase in ductility of LFC columns as well as its strength due to the lateral confinement is a desired benefit. Moreover, the effectiveness of the SSTT confinement yielded the best improvement for the lower-grade of LFC as it possessing to the highest value of the ductility ratio compared to the other densities.

(4) Confining LFC columns with two layers of steel straps exhibit significant improvement compared to the one layer of confinement and unconfined LFC. Same goes to the parameter of confinement spacing whereby column that is confined with closer spacing between steel straps will yielded to the biggest improvement of mechanical properties especially to the ultimate resisting capacity.

(5) The existing theoretical model for the comparison with the experimental results seems to be less accurate especially when it relates to the higher density of the LFC. Thus, a new theoretical model for the SSTT-confined LFC should be developed to make verification and satisfaction between the previous and current experimental tests.

(6) Steel strapping is a new and innovative technique of applying pre-tensioning force. The cheapness of materials used, the ease and speed of application make this technique very competitive for improving the ductility of new and existing concrete structures.

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