Effect of geometrical properties on slenderness ratio of concrete filled multi-skins steel tube column

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Abstract. An experimental and numerical investigation was adopted to estimate the slenderness ratio of concrete filled multi-skin steel tube (CFMST). In this study, 55 specimens composite columns with various heights were fabricated and tested experimentally under axial load. The specimens divided into two main groups depending on the cross-section shape (circular and square cross-section). Both sections have the same external dimension. A new equation was suggested for the predicted slender limit of a composite column with the various number of steel tubes. Some geometrical parameters were studied experimentally and numerically to explain their effect on the slender limit. A number of steel layers, the dimension of cross-section, the thickness of the steel tube, and another parameter were investigated numerically by using the ABAQUS program. It observed that slender limit increase with an increasing number of steel layers and increase of dimension of the column.

Keyword: Composite column; Double skins; Multi skins; Slenderness ratio; Steel tube.

1. Introduction
Concrete-filled steel tube columns CFST have many advantages such as high efficiency, durability, fire resistance, and economics. It has wide use in marine structures, high rise buildings, bridges, and residential structures [1][2][3][4][5][6]. The mechanism of interaction between the components of the CFST column makes the performance of the column high because the steel tube provides the property of confinement on the concrete core, especially in the circular type. This confinement leads to improvement in the compression stresses of concrete filler, which in turn restrict and reduces the bending of the steel tubes, which is the main problem in steel tubes.[7][8][9]. In addition, the distribution of the section has a major role in the resistance of the column, as the steel tube is located at the farthest point from the center where the buckling stresses are less.

The use of CFST is economical because it saves the costs of the mold, as the steel tube is a mold for fresh concrete and provides speed in construction, which saves time and cost. Recently, concrete filled double skin and multi-skin steel tube columns (CFDST, CFMST) appeared as a type of concrete-filled steel tube composite column, it represents the geometric form of a composite compression member. This type has proven to have desirable properties in the case of static and dynamic loading[10]. This type of concrete-filled steel tube composite columns has major benefits, including higher flexibility compared to weight and higher buckling resistance compared to the classic CFST kind[11][12]. In addition, in fire resistance, the CFMST columns are better in two directions: first, due to the multiple layers of steel and the concrete filling between them, it delays the arrival of high temperatures to the inner tube, which in turn makes the exposure time higher for the column before the collapse. Second: in the hollow type, an empty inner tube helps ventilation during a fire[13][14].

This study dealt with CFST, CFDST and CFMST, and the main objective was to study the column parameters, the number of layers of steel tubes, shape of the column section, type of member,
thickness of steel tube, and the external dimensions practically and numerically on the CFST, CFDST and CFMST columns.

2. Experimental Program

1.1. Samples preparation

This program including 28 samples of CFMST of circular section and 27 samples of square section, were manufactured from HSS steel and filled with normal strength of concrete as shown in Figure 1. In each section shape, there are two groups based on the type of member (filled and hollow), in filled section there are three sub groups according to the number of layers (one, two, and three) layers of steel tube. While in the hollow section, there are two sub groups according to a number of layers (two and three) of steel tube. All samples in the circular and square section have a thickness of steel tube =1mm, and outer dimensions of each section were equal (i.e. D of circular = W of square for all layers of steel), in this study using three outer dimensions of tubes (D=W= 76.2, 50.8 and 25.4 mm). Samples have various heights, for the circular section were ranged (400-800 mm) and for the square section between (700-1200mm), with increment (50-100mm). Identification name for the sample contains of three symbols: the first symbol refers to the shape section (circular or square), followed by a number representing the number of layers of steel, while the last symbol indicates the type of member (solid or hollow). The details of specimens are listed and show in Table 1 and Figure 2.

![Figure 1. Fabrication and casting of specimens.](image1.png)

![Figure 2. Cross section of the specimens.](image2.png)

1.2. Loading procedure

All samples of CFMST were subjected to axial compression loads using a universal machine with capacity of 2000 kN. Where the samples was fixed in a vertical form supported at both end by the
bases of the testing machine. To measure the axial displacement (buckling), use two Linear Variable Displacement Transducers (LVDTs) with at the center of column and separate them by 90° angle. Loading on samples was carried out until collapse. Program test show in Figure 3.

Table 1. Specimens Details.

| Type column core | No. of Steel Tube layer | Circular section | Square section |
|------------------|------------------------|------------------|----------------|
|                  |                        | Specimen Designation | Height, mm | Specimen Designation | Height, mm |
|                  | Single layer           | C1S450            | 450         | S1S800            | 800         |
|                  |                        | C1S500            | 500         | S1S850            | 850         |
|                  |                        | C1S550            | 550         | S1S900            | 900         |
|                  |                        | C1S600            | 600         | S1S950            | 950         |
|                  |                        | C1S650            | 650         | S1S1000           | 1000        |
|                  |                        | C1S700            | 700         | S1S1100           | 1100        |
|                  | Double layers          | C2S500            | 500         | S2S800            | 800         |
|                  |                        | C2S550            | 550         | S2S850            | 850         |
|                  |                        | C2S600            | 600         | S2S900            | 900         |
|                  |                        | C2S700            | 700         | S2S950            | 950         |
|                  |                        | C2S750            | 750         | S2S1000           | 1000        |
|                  | Solid section          | C3S500            | 500         | S3S1000           | 1000        |
|                  |                        | C3S550            | 550         | S3S1050           | 1050        |
|                  |                        | C3S600            | 600         | S3S1100           | 1100        |
|                  |                        | C3S650            | 650         | S3S1150           | 1150        |
|                  |                        | C3S700            | 700         | S3S1200           | 1200        |
|                  |                        | C3S750            | 750         | -                 | -           |
|                  |                        | C3S800            | 800         | -                 | -           |
|                  | Triple layers          | C2H400            | 400         | S2H700            | 700         |
|                  |                        | C2H450            | 450         | S2H750            | 750         |
|                  |                        | C2H500            | 500         | S2H800            | 800         |
|                  |                        | C2H550            | 550         | S2H850            | 850         |
|                  |                        | C2H600            | 600         | S2H900            | 900         |
|                  | Hollow                 | C3H500            | 500         | S3H900            | 900         |
|                  |                        | C3H550            | 550         | S3H950            | 950         |
|                  |                        | C3H600            | 600         | S3H1000           | 1000        |
|                  |                        | C3H650            | 650         | S3H1050           | 1050        |
|                  |                        | C3H700            | 700         | S3H1100           | 1100        |

Total No. of samples 28 specimens 27 specimens
1.3. Results of experimental work

The experimental data obtained from the practical study of square and circular section are listed in Table 2. From testing, two type of failure were noted: local and buckling (unstable), depending on the failure pattern, the column behaviour was identification. When the sample failed by compression this mean that the column is non-slimmer column (short type), and the column behaves as a slender column (long type) when unstable failure occurs. Figure 4 show the two pattern of failure.

Table 2. Adopted column specimens with square and circular section.

| Section type | Group of specimens | Specimen designation | Mode failure | P ultimate (kN) |
|--------------|--------------------|----------------------|--------------|-----------------|
| Square section | S1S                | S1S950               | Local Buckling | 338             |
|               |                    | S1S1000              | Global Buckling | 310             |
|               | S2S                | S2S1000              | Local Buckling | 360             |
|               |                    | S2S1100              | Global Buckling | 320             |
|               | S3S                | S3S1100              | Local Buckling | 382             |
|               |                    | S3S1150              | Global Buckling | 379             |
|               | S2H                | S2H800               | Local Buckling | 275             |
|               |                    | S2H850               | Global Buckling | 283             |
|               | S3H                | S3H1050              | Local Buckling | 385             |
|               |                    | S3H1100              | Global Buckling | 370             |
| Circular section | C1S              | C1S450               | Local Buckling | 387             |
|               |                    | C1S500               | Global Buckling | 361             |
|               | C2S                | C2S500               | Local Buckling | 471             |
|               |                    | C2S550               | Global Buckling | 446             |
|               | C3S                | C3S550               | Local Buckling | 487             |
|               |                    | C3S600               | Global Buckling | 484             |
|               | C2H                | C2H450               | Local Buckling | 380             |
|               |                    | C2H500               | Global Buckling | 366             |
|               | C3H                | C3H550               | Local Buckling | 401             |
|               |                    | C3H600               | Global Buckling | 399             |
A mathematical study was also presented in this work to estimate the slenderness limits for each of the samples tested, the slenderness limits of these samples were estimated using Equation No.2, by multiplying the slenderness ratio $\lambda$ which was calculated in Equation No.1 by the average height of two samples in which the failure mode reverses from the local buckling to the global buckling ($h_{av}$)

\[
\lambda = \frac{A_S}{A_c} \quad \text{Eq. 1}
\]

\[
S_L = \lambda \cdot h_{av} \quad \text{Eq. 2}
\]

Where:
- $\lambda$ = represent suggested slenderness ratio, dimensionless.
- $A_S$ = Area of steel in cross section of specimen, mm$^2$.
- $A_c$ = Area of concrete in cross section of specimen, mm$^2$.
- $S_L$ = represent slenderness limit for adopted column, mm.
- $h_{av}$ = represent the average height of adjacent specimens when mode failure converted from local buckling to buckling, mm.

Figure 4. Failure mode (local and buckling) of CFST columns.

As shown by the mathematical results of the slenderness ratio $\lambda$ and slenderness limits $S_L$ as which listed in Table 3 and 4, it was found that there is an effect of the variables that were dealt in this study on the values of $\lambda$ and $S_L$ such as type of member. The limits of slenderness for hollow section are higher than that of the steel section in the circular and square sections for the same number of layers of steel tubes. The reason for this that the concrete area of the hollow section is less than of solid, and according to Equation 1, the slenderness ratio will decrease and thus the slenderness limits reduction, also another reason that the solid column is more stiff than the hollow due to the internal filling. Where the percentage increase in the square section was about (8-34.24) % for three and two layers of steel respectively, while increase was about (13.04-64.6) % for three and two layers in circular section.
Table 3. Predicted slenderness limit ($S_L$) for adopted CFST with circular section.

| Group of specimens | *$h_{av}$ (mm) | As (mm$^2$) | Ac (mm$^2$) | $\lambda$ | $S_L$ (mm) |
|--------------------|----------------|-------------|-------------|----------|-----------|
| C1S                | 475            | 236.25      | 4324.12     | 0.055    | 26.12     |
| C2S                | 525            | 392.7       | 4167.7      | 0.094    | 49.35     |
| C3S                | 575            | 469.35      | 4091.02     | 0.115    | 66.12     |
| C2H                | 475            | 392.7       | 2297.3      | 0.171    | 81.22     |
| C3H                | 575            | 469.35      | 3660.96     | 0.13     | 74.75     |

*$h_{av}$ where calculated depending on table 2

Table 4. Predicted slenderness limit ($S_L$) for adopted CFST with square section.

| Group of specimens | *$h_{av}$ (mm) | As (mm$^2$) | Ac (mm$^2$) | $\lambda$ | $S_L$ (mm) |
|--------------------|----------------|-------------|-------------|----------|-----------|
| S1S                | 975            | 300.8       | 5505.64     | 0.055    | 53.62     |
| S2S                | 1050           | 500         | 5306.44     | 0.094    | 98.7      |
| S3S                | 1125           | 597.6       | 5208.8      | 0.115    | 129.4     |
| S2H                | 825            | 500         | 2925        | 0.171    | 132.5     |
| S3H                | 1075           | 597.6       | 4661.28     | 0.13     | 139.75    |

*$h_{av}$ where calculated depending on table 2

3. Numerical Analysis

1.4. Finite Element Modeling

Using commercial software Abaqus version (2017), to simulate the behavior of CFMST columns. Numerical parametric study was conducted. To accurately simulate and analyze the numerical behavior of CFMST columns, an numerical parameters are needed by examining the critical parameters that influence on the slenderness limit ($S_L$) and ultimate strength of CFMST. From modeling samples, material models, boundary conditions, and different geometric were discussed in detail.

Description of CFMST model:
- Concrete core: non-homogeneous solid S3D8
- Steel tube: homogeneous shell S3D8
- Mesh size: 10mm
- “Tie constraint” between steel layers and concrete infill [15]
1.5. Loading and Boundary Condition

The sample of CFMST columns was fixed in two ends and kept free in direction with applied axial loading, to determine the axial load-buckling curves of CFMST columns. Applied axial compression on the top surface of specimen by using the displacement control technique. The geometry and the modelling details of the finite element models of CFMST columns are shown in Figures 5 and 6.

Figure 5. A typical CFMST columns of square section a finite element meshing, b and c boundary conditions.

Figure 6. A typical CFMST columns in circular section a finite element meshing, b and c boundary conditions.
1.6. Parameters Considered in the Numerical Analysis (F.E.M)

Other parameters that not studied in the practical program, were studied their effect in the ABAQUS program, these parameters are: influence of the steel tube thickness, influence of the increase in the number of steel tube layers, and increase the cross section dimension of the steel tube. For each of these parameters, two samples of the CFMST columns were analysed based on the failure patterns considered in this study, local, and buckling (i.e. two samples non-slender and slender column) in each section.

1.6.1. Influence of the Steel Tubes Thickness

The thickness of samples used in experimental work was (1mm), in the numerical study changed to (t=0.5, and t=2) mm and the other geometric parameters remain constant. Tables 5 and 6 and Figure 7, 8 explain numerical results for circular and square sections respectively. Adopted parametric study to show the effect of thickness of the steel tube on slenderness limit and ultimate capacity of load. In each case of changing the thickness, two non-slender and slender samples were used, in circular and square section; each sample composed of three layers of steel and completely filled with concrete (C3S, S3S).

Table 5. Effect of steel tube thickness on slenderness limit for circular section.

| Specimen Designation | Height of specimens mm | Average Height of specimens $h_{av}$ mm. | Mode failure | Slenderness ratio ($\lambda$) | Slenderness Limit ($S_L$) mm | Difference $S_L^*$ (%) |
|----------------------|------------------------|----------------------------------------|--------------|-----------------------------|-----------------------------|-------------------------|
|                      |                        | t = 0.5 mm                             |              |                             |                             |                         |
| C3S300               | 300                    | 350                                    | Local        | 0.054                       | 18.9                        | -71                     |
| C3S400               | 400                    | 575                                    | Local        | 0.115                       | 66.125                      | 0                       |
|                      |                        | t = 1 mm (Reference specimens)         |              |                             |                             |                         |
| C3S550               | 550                    | 575                                    | Local        | 0.115                       | 66.125                      | 0                       |
| C3S600               | 600                    | 575                                    | Buckling     |                             |                             |                         |
|                      |                        | t = 2 mm                               |              |                             |                             |                         |
| C3S900               | 900                    | 1000                                   | Local        | 0.26                        | 260                         | 293.2                   |
| C3S1100              | 1100                   | 1000                                   | Buckling     |                             |                             |                         |

* Difference $S_L^* = \left( \frac{S_{Lt,0.5 or 2} - S_{Lt1}}{S_{Lt1}} \right) * 100$
Table 6. Effect of steel tube thickness on slenderness limit for square section.

| Specimen Designation | Height of specimens mm | Average Height of specimens $h_{av}$ mm. | Mode failure | Slenderness ratio ($\lambda$) | Slenderness Limit ($S_L$) mm | Difference $S_L$ (*) (%) |
|----------------------|------------------------|-----------------------------------------|--------------|-------------------------------|-----------------------------|----------------------------|
|                      |                        | t = 0.5 mm                              |              |                               |                             | 85.4                       |
| S3S300               | 300                    | 350                                     | Local        | 0.054                         | 18.9                        | -85.4                      |
| S3S400               | 400                    |                                         | Buckling     |                               |                             |                            |
|                      |                        | t = 1 mm (Reference specimens)          |              |                               |                             |                            |
| S3S1100              | 1100                   | 1125                                    | Local        | 0.115                         | 129.4                       | 0                          |
| S3S1150              | 1150                   |                                         | Buckling     |                               |                             |                            |
|                      |                        | t = 2 mm                                |              |                               |                             |                            |
| S3S1400              | 1400                   | 1450                                    | Local        | 0.26                          | 377                         | 191                        |
| S3S1500              | 1500                   |                                         | Buckling     |                               |                             |                            |

* Difference $S_L$ = \( \frac{(S_{L,t=0.5 \text{ or } t=2} - S_{L,t=1})}{S_{L,t=1}} \) \times 100

Figure 7. The effect of changing the wall thickness of the steel tube on ultimate strength in the circular section.
From the above results, it is significant that the thickness has a clear effect on the resistance of the column and its limit of slenderness, as it increases with increasing thickness and decreases by reducing it. The decrease in slenderness limit was by -85.4% and -71.4% for square and circular sequentially. While the effect is reversed in the case of increasing the thickness of specimens. The increase of the slenderness limit was 191%, 293% for square and circular sequentially.

1.6.2. Effect of the increasing in the number of layers of steel
The highest number of steel layers achieved in the practical study is three layers, in the numerical analysis, the number of these layers was increased to four and five with external dimensions (W=D=101.6 mm) and (W=D=127 mm) respectively as well as preserving the thickness of all steel layers (1 mm) in square and circular section. From the results shown in Tables 7 and 8 and Figures 9 and 10 it was found that the SL and Pult. Of the column improved with the increase of the steel layers. The amount of increase in the $S_L$ for circular was by 58%, 60% for (4, and 5) layers respectively. In the square was by 3.55%, 12.06% for (4, and 5) layers respectively.

Table 7. Effect of increase the layers of steel tube on slenderness limit (circular section).

| Specimen Designation | Height of specimens mm | Average Height of specimens hav, mm | Mode failure | Slenderness ratio ($\lambda$) | Slenderness Limit ($S_L$) mm | Difference $S_L$ (%) |
|----------------------|------------------------|------------------------------------|--------------|-----------------------------|-----------------------------|-------------------|
| C3S550               | 550                    | 575                                | Local        | 0.115                       | 66.125                      | 0                 |
| C3S600               | 600                    |                                    | Buckling     |                             |                             |                   |
| Number of steel layers=3, D = 76.2 mm (Reference specimens) |
| C4S900               | 900                    | 950                                | Local        | 0.11                        | 104.5                       | 58%               |
| C4S1000              | 1000                   |                                    | Buckling     |                             |                             |                   |
| Number of steel layers=4, D = 101.6 mm |
| C5S1000              | 1000                   | 1050                               | Local        | 0.1                         | 105                         | 60%               |
| C5S1100              | 1100                   |                                    | Buckling     |                             |                             |                   |
| Number of steel layers=5, D = 127 mm |
Table 8. Effect of increase the layers of steel tube on slenderness limit (square section).

| Specimen Designation | Height of specimens mm | Average Height of specimens $h_{av}$ mm | Mode failure | Slenderness ratio ($\lambda$) | Slenderness Limit ($S_L$) mm | Difference $S_L^*$ (%) |
|----------------------|------------------------|-----------------------------------------|--------------|----------------------------|----------------------------|--------------------------|
| Number of steel layers = 3, $W = 76.2$ mm (Reference specimens) | | | | | | |
| S3S1100 | 1100 | 1125 | Local | 0.115 | 129.4 | 0 |
| S3S1150 | 1150 | 1200 | Buckling | 0.110 | 134 | 3.55% |
| Number of steel layers = 4, $W = 101.6$ mm | | | | | | |
| S4S1200 | 1200 | 1300 | Local | 0.111 | 134 | 3.35% |
| S4S1400 | 1400 | 1450 | Buckling | 0.100 | 145 | 12.06% |
| Number of steel layers = 5, $W = 127$ mm | | | | | | |
| S5S1400 | 1400 | 1450 | Local | 0.100 | 145 | 12.06% |
| S5S1500 | 1500 | | Buckling | | | |

* Difference $S_L = \frac{(S_{L4 or 5} - S_{L3})}{S_{L3}} \times 100$

![Figure 9](image.jpg)

**Figure 9.** Effect of changing the number of layers of steel tube on ultimate strength and slenderness limit in circular section.
1.6.3. *Increase The Cross-Section Dimension of The Steel Tube*

Two samples of CFMST columns were analysed, each sample consisting of two layers of steel with the thickness (1mm) and filled with concrete completely for each circular section and square (C2S, S2S). The original dimensions have been twice the reference column dimension, (i.e. W = D = 152.4 mm) for external steel tubes and (W=D= 101.6 mm) for the internal tube, to see the effect of multiplying the dimensions on the slenderness limit $S_L$ and ultimate capacity of load. It was noticed that the obtained ($S_L$) and load-buckling curves increase as shown in Tables 9 and 10. As a result of the increase in dimensions of steel tubes, the increase in ($S_L$) for circular 18.54 % and the square was 36 %.

**Table 9. Effect of increase dimensions in steel tube for circular section.**

| Specimen Designation | Height of specimens mm | Average Height of specimens $h_{av}$ mm. | Mode failure | Slenderness ratio ($\lambda$) | Slenderness Limit ($S_L$) mm | Difference $S_L$ (%) |
|----------------------|------------------------|------------------------------------------|--------------|-----------------------------|-----------------------------|---------------------|
| Dimension; outer tube (D= 76.2mm), inner tube(D= 50.8mm) (Reference specimens) |          |                                          |              |                             |                             |                     |
| C2S500               | 500                    |                                          | Local        | 0.094                       | 49.35                       | 0                   |
| C2S550               | 550                    | 525                                      | Local        | 0.094                       | 49.35                       | 0                   |
| Dimension; outer tube (D= 152.4mm), inner tube(D= 101.6mm) |          |                                          | Buckling     |                             |                             |                     |
| C2S1200              | 1200                   | 1300                                     | Local        | 0.045                       | 58.5                        | 18.54%              |
| C2S1400              | 1400                   |                                          | Local        | 0.045                       | 58.5                        | 18.54%              |

* Difference $S_L = \frac{(S_{L2D} - S_{LD})}{S_{LD}} * 100$
Table 10. Effect of increase dimensions in steel tube for square section.

| Specimen Designation | Height of specimens mm | Average Height of specimens $h_{av}$ mm. | Mode failure | Slenderness Limit ($S_L$) mm | Slenderness ratio ($\lambda$) | Difference $S_L^*$ (%) |
|----------------------|------------------------|------------------------------------------|--------------|----------------------------|-----------------------------|------------------------|
| Dimension; outer tube (W= 76.2mm), inner tube(W= 50.8mm) (Reference specimens) |
| S2S1000              | 1000                   | 1050                                     | Local        | 0.094                      | 98.7                        | 0                      |
| S2S1100              | 1100                   |                                          | Buckling     |                            |                             |                        |
| Dimension; outer tube (W=D=152.4mm), inner tube(W=D=101.6mm) |
| S2S1300              | 1300                   | 1400                                     | Local        | 0.045                      | 63                          | -36%                   |
| S2S1500              | 1500                   |                                          | Buckling     |                            |                             |                        |

* Difference $S_L^* = \left(\frac{S_{L_{ZW}} - S_{L_{W}}}{{S_{L_{W}}}}\right) \times 100$

Figure 11. Effect of the increase of external dimensions of steel tube on ultimate strength in circular section.

Figure 12. Effect of the increase of external dimensions of steel tube on ultimate strength in square section.
Because the heights required finding the slenderness limits $S_L$ for one, two and three layers of steel tube respectively, and for the hollow square section are (132.5 and 139.75 mm) for two and three layers of steel respectively.

2. The maximum resistance of the column decreases as the height increase.

3. In circular section, for filled section the slenderness limits are (26.12, 49.35, and 66.12 mm) for one, two and three layers while in hollow section are (81.22, 74.75).

4. Increasing the thickness of the steel tube wall from (0.5 to 1 and 2 mm) leads to an increase in the slenderness limit by about 191%, 293% for square and circular sequentially.

5. The greater the number of steel layers, the slenderness limit and resistance of column improved, as the amount of increase in $S_L$ of four tubes of steel was by (58 %, 3.55 %) for circular and square. While when the number of layers increased to five, the $S_L$ increase to (60%, 12.06 %) in circular and square section respectively.

6. The $S_L$ increased for circular 18.54 % and in the square was decrease by 36 %, when the origin external dimensions of steel tube (W=D) are doubled.

7. The square section showed higher and better resistance than the circular section of the same external dimensions and the details of the cross section. Because the heights required finding the limits of slenderness were higher in the square than in the circular as previously shown, and this indicates that the square section is stiffer.

4. Conclusions

From experimental and numerical investigations, it concluded that:

1. Slenderness Limits $S_L$ for filled square section are (53.62, 98.7, and 129.4 mm) for one, two and three layers of steel tube respectively, and for the hollow square section are (132.5 and 139.75 mm) for two and three layers of steel respectively.

*where Dref. = original dimensions for tubes of steel

Dstudy= dimensions were used in this study

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