Performance of square steel tubular stub columns in-filled with fly ash and silica fume self-compacting concrete under concentric loading

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Abstract. Concrete filled steel tube (CFST) column is a composite member comprising of structural hollow steel tube and concrete core. This paper evaluates the effect of fly ash (FA) and silica fume (SF) on square CFST stub columns’ behavior under concentric loading. The self-compacting concrete (SCC) grade used is M60 with the addition of 50% FA and 10% SF as a partial replacement of Portland cement. The performances of the fly ash-silica fume self-compacting (FSS) CFST columns are examined through the axial compression capacity, the load-shortening response, and the failure mode of stub columns. The axial load of the FSS CFST columns is compared with the international design codes to validate the available design codes’ accuracy. The results yield that the FSS CFST columns’ ultimate axial load capacities range between 1408.80 kN and 808.70 kN, while the reference CFST columns’ capacities range between 1332.80 kN and 789.20 kN. FSS concrete improves the concrete contribution ratio and strength index of the square CFST stub columns. However, reference CFST columns demonstrate better ductility than FSS CFST columns. This is attributed to the brittleness of the FSS concrete. All the square CFST stub columns fail via local buckling. Eurocode 4 slightly over predicts the square CFST columns' ultimate capacity by an average of 4.58%. The American Concrete Institute (ACI) code, on the other hand, over predicts the axial capacity of the CFST stub columns by an average of 17.46%.

1. Introduction

In recent years, the use of waste materials and by-products in construction materials has been increasingly emphasized [1, 2] as a partial solution for ecological and environmental problems. The usage helps lower the cost of cement and concrete production [3]. Still, it also has other indirect benefits, such as reducing the expense of waste, saving energy, and protecting the atmosphere from potential emissions. The key benefits of the CFST column are that the steel tube serves as permanent confinement for the concrete and prevents the concrete from spalling. Likewise, the concrete core avoids the steel tube from local buckling and increases the column strength. CFST columns display excellent static and earthquake-resistant properties. It possesses high strength, high ductility, improved capacity to absorb energy, etc. To enhance the compactness of the concrete in steel tubes, SCC is used. The SCC will increase the working efficiency, compactness, and suitability for pumping and pouring the concrete core [4].
Several researchers have established a better awareness of the behavior of CFST columns. Nevertheless, there is little knowledge about adding FA and SF on the behavior of CFST columns. A literature review highlights that few studies have explored the combined usage of FA and SF in SCC as infill material in steel tubular columns. Herein are some of the previous studies focused on the structural behavior of CFST columns with FA and SF. Xu et al. [5] explored the influence of tube thickness, length-to-diameter ratio, self-stress level, and concrete strength on the uniaxial compressive behavior of a self-stressing and self-compacting high-strength CFST column. In producing the self-stressing and self-compacting high-strength concrete, mineral admixtures, like fly ash, slag, silica fume, microspheres, and expansion agents were used. The mineral admixtures were added at different dosages to obtain concrete grades of 60, 70, 80 MPa, and self-stresses of 0, 3, and 5 MPa. The results indicated that increasing the concrete strength can make a meaningful contribution to the ultimate bearing capacity. However, there is no apparent improvement in the post-peak ductility due to the high brittleness of core concrete.

Furthermore, Li et al. [6] studied the performance of M40 fly ash and silica fume self-compacting (FSS) concrete as filled in-line multi-cavity steel tube bundle shear wall. They conclude that the confinement effect improves the deformation resistance of FSS concrete. Likewise, Liu et al. [7] explored the interaction between steel tubes and reactive powder concrete (RPC) core. Silica fume, ground granulated blast-furnace slag, and fly ash were incorporated as supplementary cementing materials to prepare the 170 MPa RPC. Their findings indicated that the utilization of RPC as core concrete in CFST stub columns improves the ductility of high strength concrete. Moreover, Chen et al. [8] examined the square CFST columns' behavior under concentric loading. The effect of the thickness of the steel tube, the grade of concrete, and the amount of expansive agent on the load-carrying capacity of CFST columns were explored. Concrete with design strengths of 20 MPa and 50 MPa were produced using fly ash and silica fume as pozzolanic materials with Portland cement. Results suggested that the failure mode of CFSTs depends on the strength of the concrete core. Furthermore, the load-carrying capacity of CFSTs improves with an increase in the thickness of the steel tube.

Given the preceding, fly ash concrete filled steel tubes have a strong load-bearing potential, but not much work is currently underway on FSS CFST columns. Therefore, it is essential to study the axial compression behavior and failure mechanism of steel tubular columns filled with FSS concrete. The research objective presented is twofold: firstly, to carry out an experimental testing program to study and monitor the FSS CFST stub columns' performances. The performances of the FSS CFST columns are examined through the axial compression capacity, the load-shortening response, and the failure mode of stub columns. Three yield strengths and four D/t ratios of steel tubes were considered. Secondly, the axial load capacities of the FSS CFST columns are compared with the international design codes to validate the accuracy of the available design codes. The grade of SCC used is M60 concrete with 50% and 10% addition of FA and SF, respectively, as partial replacement of Portland cement.

2. Experimental program

2.1. Materials
The concrete mixes were made using CEM 1 ordinary Portland cement (OPC) with a specific gravity of 3.15 and a strength of 42.5 MPa. The low calcium FA per ASTM C618-12a [9] Class F with a gravity of 2.1, collected at Johor Bahru from the Tanjung Bin power plant, was used to achieve the required workability and uniformity of SCC while cutting down on the likelihood of segregation and hydration heat. To account for the comparatively weak early FA concrete strength, densified silica fume (SF) with a bulk density of 550–650 kg/m³ and gravity of 2.1–2.4 was used. As suggested by Muller et al. [10], 10% of SF was added. Class F FA comprises a composition of 70% silicon dioxide (SiO₂), aluminium oxide (Al₂O₃), and iron oxide (Fe₂O₃), while the total composition of calcium oxide (CaO) is less than 7%, according to ASTM C618-12a [9]. Natural river sand with a relative density (SSD) of 2.65 kg/m³, fineness modulus of 3.17, and water absorption of 1.15% was used as the fine aggregate in the mixture. A well-graded 10 mm aggregate was used as the coarse aggregate, with a water absorption value and an SSD of 1.0% and 2.66 kg/m³, respectively. The third generation
Superplasticizer based on polycarboxylate ether termed Sika Viscocrete-2044, which meets ASTM C494 [11], was used to achieve the necessary consistency.

2.2. Specimens

A total of 12 square specimens were formed and tested under axial compressive loads. The main parameters varied in the tests are (1) breadth to thickness ratio of the tube (from 18 to 33.33) and (2) yield strength of steel (from 275.83 MPa to 350.51 MPa). The specimens had a length of three times the diameter to diminish the end impacts and ensure the samples were stub columns with the least slender effect. All steel tubes were manufactured from cold-formed steel. Each tube was cast from a plate and then bent and welded. The steel tube ends were cut to the required length and machined. A wire was rubbed into the insides of the tubes to eliminate any possible loose debris and rust. Steel coupon samples were tested in tension to obtain the stress-strain relationship and yield strength.

A self-compacting concrete mix was designed for compressive cube strength ($f_{cu}$) at 28 days of 60 MPa. An axial extensometer was used to obtain the static modulus of elasticity of 100 x 200 mm concrete cylinders at 28 days, of which the average value is 56,130 MPa. The concrete was poured into the steel tubes in a vertically upright position to form the CFST stub columns after mixing. Six samples of square hollow steel tubes were cast with the FSS, while the remaining six samples were filled with ordinary Portland cement (OPC) concrete as reference. Since all the concrete studied herein were self-compacting, no additional compaction was needed as the concrete was self-flowing. To compensate for a potential concrete shrinkage, an additional 5 mm layer was cast on top of the columns. The SCC mix proportions are presented in Table 1, and the summary of the specimen details is given in Table 2.

| Concrete mixes       | Proportion in kg/m³ |
|----------------------|---------------------|
| W/B = 0.31           |                     |
| 100%OPC              | 188                 |
| 40%PC;50%FA;10%SF    | 188                 |

The symbols used for naming the CFST specimens in Table 2 have the following meanings: letter 'R' and 'P' represent FSS concrete infill and reference concrete infill. All the square steel tubes are 300 mm in length. For each of the hollow steel tubes, at the mid-height of the specimens, two strain gauges perpendicular to each other in the transverse and longitudinal directions were glued to monitor the hoop and axial strains. One of the strain gauges is fixed horizontally, and the other was mounted vertically with a small gap between the gauges. The steel tube's outer surface was scrub with sandpaper to remove any paint and then cleaned with Acetone chemical to remove rust and dust before gluing the strain gauges. Figure 1(a) illustrates the sample preparation, while Figure 1(b) shows the strain gauges' location and orientation.

Two linear variable displacement transducers (LVDTs) were placed at the adjacent faces, at mid-height of the column, and perpendicular to each other, as shown in Figure 1(c). The LVDTs were used to monitor the overall deformation at symmetric locations. A 2000 kN capacity load cell was used in the testing, whereas the data logger recorded and stored all data from the LVDTs, load cell, and strain gauges. The axial compressive test on the CFST column specimens was conducted using a 2000 kN capacity Tinius Olsen Universal Testing Machine. The load actuator is servo-controlled for consistent load increments. To soundly obtain the confinement performance of the column, the axial compressive load was applied only to the concrete core through a bearing plate. When the axial load is acting solely on the concrete, lateral dilation of the concrete core creates friction between the steel tube and the concrete core resulting in axial stress and strain on the steel tube.

The CFST specimens experienced axial loading at an initial rate of 0.01 mm/sec until the load applied exceeded 70% of the expected maximum load. The speed was then decreased to 0.005 mm/sec.
and kept constant until the load point equal to 90% of the peak load was reached, which was already on the descending branch of the load versus strain curve. In the final part of the test, the rate was then raised to 0.01 mm/sec and then to 0.02 mm/sec. It took about 20-30 minutes for the whole process. The ultimate experimental loads ($N_{exp}$) along with the other results from the test are presented in Table 2. The abbreviation $CCR$, $SI$, and $DI$ in Table 2 denote the concrete contribution ratio, strength index, and ductility index. These results will be discussed further.

### Table 2. Specimen details and member capacities of CFST stub columns.

| Specimen label | Thickness (t) (mm) | Breadth (B) (mm) | B/t ratio | Steel yield strength $f_y$ (MPa) | L/B ratio | Concrete cylinder strength $f_c$ (MPa) | $N_{exp}$ (kN) | $CCR$ | $SI$ | $DI$ |
|----------------|-------------------|-----------------|-----------|-------------------------------|-----------|--------------------------------|----------------|-------|------|------|
| S5AR           | 5.0               | 90              | 18.00     | 350.51                        | 3.33      | 62.23                          | 1152.20     | 1.93  | 1.16 | 1.723 |
| S5AP           | 5.0               | 90              | 18.00     | 350.51                        | 3.33      | 62.64                          | 1116.70     | 1.87  | 1.12 | 2.187 |
| S4AR           | 4.0               | 90              | 22.50     | 320.36                        | 3.33      | 62.23                          | 808.70      | 1.83  | 0.94 | 1.671 |
| S4AP           | 4.0               | 90              | 22.50     | 320.36                        | 3.33      | 62.64                          | 885.20      | 1.84  | 0.98 | 6.068 |
| S4BR           | 4.0               | 100             | 25.00     | 320.36                        | 3.00      | 62.23                          | 970.70      | 1.97  | 0.95 | 2.385 |
| S4BP           | 4.0               | 100             | 25.00     | 320.36                        | 3.00      | 62.64                          | 1006.20     | 2.04  | 0.98 | 2.818 |
| S4.5AR         | 4.5               | 100             | 22.22     | 335.43                        | 3.00      | 62.23                          | 1282.80     | 2.22  | 1.17 | 2.020 |
| S4.5AP         | 4.5               | 100             | 22.22     | 335.43                        | 3.00      | 62.64                          | 1332.80     | 2.31  | 1.22 | 4.213 |
| S4.5BR         | 4.5               | 100             | 22.22     | 335.43                        | 3.00      | 62.23                          | 1408.80     | 2.44  | 1.29 | 2.894 |
| S4.5BP         | 4.5               | 100             | 22.22     | 335.43                        | 3.00      | 62.64                          | 1298.30     | 2.25  | 1.19 | 3.004 |
| S3BR           | 3.0               | 100             | 33.33     | 275.83                        | 3.00      | 62.23                          | 1006.40     | 3.13  | 1.16 | 1.571 |
| S3BP           | 3.0               | 100             | 33.33     | 275.83                        | 3.00      | 62.64                          | 789.20      | 2.46  | 0.90 | 2.825 |

![Figure 1](image-url)  
**Figure 1.** (a) Sample preparation and location of strain gauges cleanly scrubbed before gluing (b) Schematic view of the orientation of strain gauges, and (c) Test setup and instrumentation for CFST square stub column.

### 3. Results and discussions

#### 3.1. Compressive strength of FSS CFST columns

Improvements in the FSS CFST columns ultimate axial capacities are observed compared to the reference columns, as illustrated in Table 2. The ultimate axial load capacities of the FSS CFST columns are range from 808.70 kN to 1408.80 kN, while those of the reference columns are range from 789.20 kN to 1332.80 kN. This indicates that FSS CFST columns have higher compressive strength than reference columns. Moreover, the incorporation of FA and SF in concrete effectively reduces the porosity of concrete. It improves the transition zone structure of the concrete due to the
micro filler effect of FA and SF or their inhibition of calcium hydrate crystal growth [12], therefore, enhancing the ultimate axial capacities of the FSS CFST columns.

3.2. Concrete Contribution Ratio
The concrete contribution ratio (CCR) was used to analyse the concrete core's contribution to the performance of CFST stub columns. CCR is defined by Ibáñez et al. [14] as follows:

\[
CCR = \frac{N_{\text{exp}}}{A_{s,\text{eff}} f_y}
\]

where \(N_{\text{exp}}\) is the experimental ultimate axial load, \(f_y\) is the yield strength of the steel tube, and \(A_{s,\text{eff}}\) is the effective cross-sectional area of the steel tube corresponding to EN1993-1-5 provisions [13].

For each of the CFST columns, the CCR is measured, and the values are shown in Table 2. The CCR values of CFST columns with reference concrete are below 2.46. Column S3BR has the largest CCR of 3.13. There is an inherent improvement in the CCR value due to the addition of FA and SF. Moreover, the CCR value increases as the thickness of steel tubes decreases. The CFST columns with thin walled have the highest CCR values since the concrete core prevents the steel tubes from local buckling, which is likely to occur in these cases. Vice versa, the CCR value decreases as the thickness increases because of the rise in the steel tube's cross-sectional area. Similar observations were reported by Ibáñez et al. [14].

3.3. Strength index
Strength index (SI) was used to compare the confinement effect of the square CFST columns under axial load. The SI is an appropriate measure for confinement evaluation and composite action in CFST columns. It refers to the ultimate experimental load ratio to the potential cross-section capacity of the composite column. The SI, as defined by Ibáñez et al. [14], was used herein to quantify the section strength, which is:

\[
SI = \frac{N_{\text{exp}}}{A_s f_y + A_c f_c}
\]

where \(N_{\text{exp}}\) is the ultimate experimental load, \(A_s\) and \(A_c\) are the cross-sectional area of steel tube and concrete respectively, \(f_y\) is the yield strength of steel tube, and \(f_c\) is the strength of concrete.

For each column, the SI was calculated, and the values were summarized in Table 2. The SI value greater than unity indicates that the cross-section capacity can reach the yield load. It can be observed that S4AR, S4BR, S4AP, S4BP, and S3BP have SI lower than unity, which implies that the cross-sectional capacity overestimates the test result. Compared with reference CFST columns, all CFST columns infilled with FSS concrete have greater SI. This could be due to the beneficial effect of the change in concrete volume arising from free lime hydration in FSS concrete. As the volume expansion of concrete was constrained by the steel tube, the microstructure was modified, and as a result, improving the steel tube’s confinement.

3.4 Ductility index
Ductility frequently refers to the ability of a structural member or section to withstand plastic deformation beyond the elastic limit while maintaining a sufficient capacity for bearing the load before complete failure. The axial ductility performance index is used to evaluate the axial ductility of CFST columns under axial compression. A ductility index (DI) defined by Zhong Tao [15] is used.

\[
DI = \frac{\varepsilon_{\text{est}}}{\varepsilon_y}
\]
where $\varepsilon_{85\%}$ is the actual axial strain when the load falls to 85% of the peak load, $\varepsilon_y$ is equal to $\varepsilon_{75\%}/0.75$, and $\varepsilon_{75\%}$ is the nominal axial strain when the load reaches 75% of the peak load in the pre-peak stage. The values of $\varepsilon_{85\%}$ and $\varepsilon_y$ are obtained from axial load-axial strain curves. The estimated ductility index ($DI$) is given in Table 2. In general, the reference CFST columns show better ductility. This is attributed to the brittleness of FSS concrete in comparison to the reference concrete. All CFST columns with FSS concrete had a ductility index below 2.896. while column S4AP with reference concrete showed a member ductility index of 6.068. The higher the ductility index, the more ductile is the CFST column [15].

3.5. Failure modes
During testing, the stub columns failed by concrete crushing and steel tube yielding. The concrete core prevented inward buckling from occurring. Bulges at the mid-height of the columns are simple proofs of local outward buckling. The steel walls were pushed out by the concrete core in this crushing failure mode. A similar observation was documented by Kibriya [16] and Ekmekyapar and Al-Eliwi [17]. The typical failure mode of the specimens is displayed in Figure 2. The CFSTs filled with reference concrete exhibited severe local buckling compared to FSS CFSTs. Local buckling occurred near the mid-section, top half, and bottom half section of the column for reference CFSTs, whereas, for FSS CFSTs, the local bucking occurred near the column's mid-section.

![Figure 2. Typical failure modes of square reference CFST and FSS CFST columns.](image)

3.6. Axial load-deformation curves
Axial load versus deformation curves describe the ductility, stiffness, and toughness behavior of CFST columns. The axial load-deformation curves can be used to apprehend the behavior of the concrete core. Figure 3 presents the axial load-deformation curves of FSS CFSTs and reference CFSTs. There are some standard features about the column failure behavior, of which dissimilarities in steel properties and concrete cause diverse reactions in load-shortening curves.

Figure 3(a) depicts the load-shortening curves of CFSTs with FSS concrete. Specimens S4BR, S4AR, S5AR, and S3BR demonstrated inelastic softening failure with a gross axial deformation of 9.48 mm, 1.04 mm, 3.44 mm, and 3.84 mm, respectively. In contrast, specimens S4.5AR and S4.5BR demonstrated inelastic hardening failure. Moreover, the load-shortening curves of stub column S4.5AR and S4.5BR are very smooth with a maximum deformation of 2.81 mm and 5.31 mm, respectively.
respectively. Specimen S4.5BR possesses the highest axial load capacity of 1408.80 kN for this category.

Figure 3(b) highlights the load-shortening curves of steel tubes filled with reference concrete. The load-shortening curves of S4BP, S4.5BP, and S3BP specimens show a smooth curve, with axial deformations of 16.68 mm, 6.85 mm, and 9.30 mm, respectively. Similarly, the axial deformation of specimen S5AP is 6.30 mm, while S4AP is 5.42 mm. Specimen S4.5AP possesses the highest ultimate axial capacity of 1332.80 kN for this category, with an axial deformation of 5.39 mm. All the CFST stub columns in this category displayed an inelastic hardening failure. It should be noted that strain hardening tends to increase the specimen's strength and decrease its ductility.

![Figure 3(a)](image_url)

**Figure 3(a).** Axial load-deformation curve of concrete filled steel tubular column (a) CFST columns with FSS concrete and (b) CFST columns with reference concrete.

3.7. *Analysis of axial load-strain relationships*

The axial load versus axial and hoop strains based on the strain gauge readings at mid-height of the CFST stub columns are shown in Figures 4(a) to (c). In the figures, the hoop strain is shown to be positive, whereas the axial strain is shown to be negative. Reference column S5AP demonstrates early strain development compared to FSS column S5AR, as shown in Figure 4(a). Although the early strain
increase of S5AP is more significant, the column can withstand more loads even after the steel has yielded due to strain hardening. The axial and hoop strain of 0.0252 and 0.1063, respectively, in column S5AP, are greater than 0.0083 and 0.0489 in column S5AR. However, column S5AR retains a much higher axial load with an increment of 3.18%. Due to the strain hardening, column S4AP sustains a greater axial load with an increment of 8.64%. The axial and hoop strain of 0.0065 and 0.0296 in column S4AP are greater than 0.0033 and 0.0226 in column S4AR, as shown in Figure 4 (b). Furthermore, column S4.5AP supports a greater load due to strain hardening with a load increment of 3.83%. The axial and hoop strain of 0.0177 and 0.0383 in column S4.5AP are more than 0.0142 and 0.0183 in column S4.5AR, as illustrated in Figure 4 (c). This implies that concrete confinement in CFST columns infilled with reference concrete is significant compared to CFST columns infilled with FSS concrete. The low confinement in FSS CFST columns can be due to the dense matrix of the FSS concrete. Moreover, FA chemically reacts with the non-durable calcium hydroxide (lime) formed by the hydration of Portland cement concrete. This reaction converts the calcium hydroxide into calcium silicate hydrate (C-S-H) gel, which is the source of hardened concrete [18].

![Figure 4](image-url)

**Figure 4.** Axial load-strain relationships of CFST stub columns for (a) tube thickness of 5.0 mm, and (b) tube thickness of 4.0 mm, and (c) tube thickness of 4.5 mm.

### 4. Prediction of axial load capacity

Eurocode 4 [19] and the American Concrete Institute (ACI 318) [20] design standards are used to predict the ultimate axial load capacity of FSS CFST columns. Eurocode 4 assumes a limit state design to ensure safety and serviceability by applying some partial safety factors to material properties and load. Whereas the ACI 318 formulations do not compensate for the concrete confinement’s effectiveness and the interaction between the steel tube and concrete core. The ultimate axial load capacities of the specimens examined were compared with that predicted from Eurocode 4 and ACI 318, as shown in Tables 3. Eurocode 4 slightly over predicts the ultimate capacity of the CFST columns by an average of 4.58%, the mean and standard deviation are 1.046 and 0.138. On the
contrary, ACI 318 over predicts the axial capacity of the square CFST stub columns by an average of 17.46%, with a mean and standard deviation of 1.175 and 0.134.

| Specimen | $N_{\text{EXP}}$ (kN) | $N_{\text{EC4}}$ (kN) | $N_{\text{ACI 318}}$ (kN) | $N_{\text{EXP}}/N_{\text{EC4}}$ | $N_{\text{EXP}}/N_{\text{ACI 318}}$ |
|----------|-----------------------|-----------------------|--------------------------|-----------------------------|-----------------------------|
| S5AR     | 1152.2                | 1001.77               | 942.04                   | 1.150                       | 1.22                        |
| S4AR     | 808.7                 | 906.91                | 796.50                   | 0.892                       | 1.02                        |
| S4BR     | 970.7                 | 1071.99               | 939.79                   | 0.906                       | 1.03                        |
| S4.5AR   | 1281.8                | 1125.57               | 1014.65                  | 1.139                       | 1.26                        |
| S4.5BR   | 1408.8                | 1125.57               | 1014.65                  | 1.252                       | 1.39                        |
| S3BR     | 1006.4                | 963.08                | 788.47                   | 1.045                       | 1.28                        |
| S5AP     | 1116.7                | 1004.4                | 936.62                   | 1.112                       | 1.19                        |
| S4AP     | 885.2                 | 909.67                | 840.31                   | 0.973                       | 1.05                        |
| S4BP     | 1006.2                | 1075.46               | 942.73                   | 0.936                       | 1.07                        |
| S4.5AP   | 1332.8                | 1128.97               | 1017.52                  | 1.181                       | 1.31                        |
| S4.5BP   | 1298.3                | 1128.97               | 1017.52                  | 1.150                       | 1.28                        |
| S3BP     | 789.2                 | 966.71                | 791.53                   | 0.816                       | 1.00                        |
| Average  |                      |                       |                          | 1.046                       | 1.175                       |
| Std      |                      |                       |                          | 0.138                       | 0.134                       |

5. Conclusions
This paper presents an experimental analysis on square CFST stub columns with fly ash and silica fume self-compacting concrete under axial compressive load. Based on the experimental results, the following conclusions were drawn:

- The ultimate axial load capacities of the FSS CFST stub columns range between 808.70 kN to 1408.80 kN, while those of the reference CFST stub columns range between 789.20 kN to 1332.80 kN. This shows that FSS CFST stub columns have higher compressive strength than reference CFST stub columns.
- The CCR values of CFST stub columns infilled with reference concrete are below 2.46. Column S4BR has the largest CCR of 3.13. The addition of fly ash and silica fume has improved the CCR values of the CFST stub columns.
- All CFST stub columns infilled with FSS concrete have a greater SI index than the reference CFST stub columns. This can be due to the beneficial effect of the change in concrete volume arising from free lime hydration in FSS concrete.
- The reference CFST stub columns show better ductility than the FSS CFST stub columns. This is attributed to the brittleness of FSS concrete.
- All CFST stub columns fail via local buckling failure.
- Eurocode 4 slightly over predicts the CFST stub columns' ultimate capacities by an average of 4.58%. The mean and standard deviation are 1.046 and 0.138. The ACI 318 over predicts the CFST stub columns' axial capacities by an average of 17.46%. With a mean of 1.175 and a standard deviation of 0.134.

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