A study on the effect of core concrete strength and aspect ratio on the axial strength of thin wall circular section of concrete-filled steel tubes

Bekalu Gashu Alemu,
PhD Scholar, Dept. of Civil Engineering, AUCE, Visakhapatnam, Andhra Pradesh, India
Mail: (gashub@yahoo.com)
Phone: + 919030432380
K.Srinivasa Rao,
Professor, Dept. of Civil Engineering, AUCE, Visakhapatnam, Andhra Pradesh, India
Mail: (killamsetti@yahoo.com)
Phone: + 919866037087

Corresponding Author
K.Srinivasa Rao,
Professor, Dept. of Civil Engineering, AUCE, Visakhapatnam, Andhra Pradesh, India
Mail: (killamsetti@yahoo.com)
Phone: + 919866037087

Abstract
This study examines the impact of aspect ratio and core concrete strength on the axial strength of thin wall circular section concrete-filled steel tubes. According to the experiment results, the axial load-bearing capacity of 365 mm high specimens filled with M20, M30, and M40 grade core concrete increased by 62.4, 48.2, and 48.2%, respectively, from its theoretical values. In relation to their theoretical values, the load-bearing capability of the 400 mm high specimens increased by 61.9, 47.1, and 49.3%, respectively, with M20, M30, and M40 as the core concrete. Furthermore, specimens filled with M20, M30, and M40 grade core concrete enhanced their axial load-carrying capacity by 5.8, 2.5, and 5.7%, respectively, when the aspect ratio dropped from 5.13 to 4.68. From the study, it is noted that formulas on European code is highly conservative.

Keywords: TCSCFST, aspect ratio, core concrete, axial load, experimental value, theoretical value

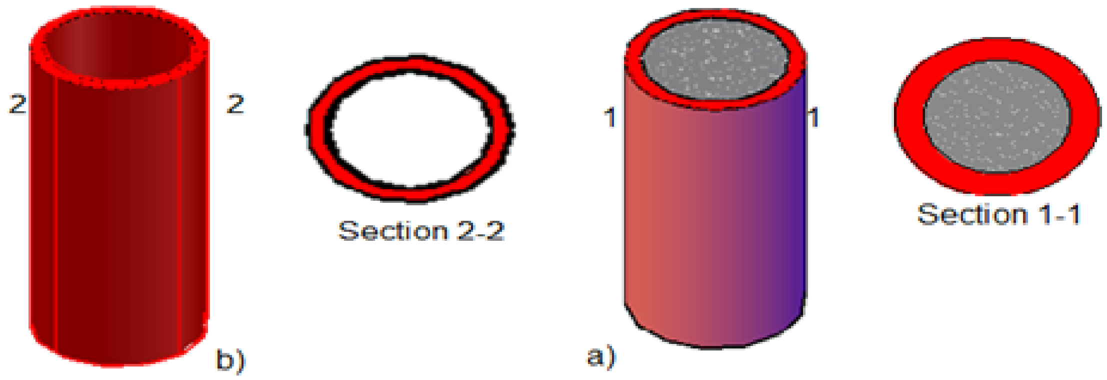
1. Introduction

Many researchers conducted experiments to evaluate the axial performance of confined concrete columns compared to steel and concrete columns. The axial capacity of concrete-filled steel tubes was evaluated for various concrete grades, yield strengths, geometry like diameters, length-to-thickness ratios, aspect ratios, and tube thicknesses. The Architectural Institute of Japan (AIJ) conducted comprehensive studies on circular and square sections of steel tubes in Japan, and several conclusions were drawn [1, 2] The concrete-filled steel tubular (CFST) section provides several structural advantages, such as high strength and fire resistance, ductility, and significant energy absorption capabilities. Furthermore, it decreases the expenses associated with formwork, labor, and time [3, 4, 5]. CFST, being fully compacted, minimizes the use of reinforcement bars and prevents concrete spalling, unlike horizontally aligned hoops [6]. Lin et al. (2018) studied the relationship between the stress path and the compressive strength of CFST [7]. The compressive strength models of confined concrete were established by researchers using experimental tests conducted on actively confined concrete by Richard [8] and Mander [9]. De Nardin S. and El Debs A. L. H. C. (2007) observed that the confinement effect does not enhance the capacity of the columns due to the low axial strain of the high-strength concrete core until the column reaches its maximum load [10]. According to a study on the influence of the rise-to-span ratio, the CFST circular arch bridge's high rise-span ratio led to high ultimate resistance and low deformation [11]. The axial strength of concrete-filled circular tubes surpasses the theoretical value, as demonstrated by many studies [12, 13]. It is advisable to avoid using very large or tiny diameter-to-thickness (D/t) ratios, as well as low-strength steel and high-strength concrete [14]. When the D/t ratio of CFST increased, hoop stress and vertical stress in the steel tube increased [15]. According to Liusheng He et al. [16], low-strength concrete demonstrates superior ductility and confinement compared to high-strength concrete. The biggest design flaw in traditional concrete-filled steel tube columns is the lack of hooped compression under small loads. Since Poisson's ratio of concrete is lower than that of steel, the steel tube detaches from the concrete core during the elastic stage [17].

2. Methodology

2.1. Test specimens

For this study, 27 short column specimens with core concrete compositions of M20, M30, and M40 were created using thin-walled circular section concrete-filled steel tubes (TCSCFST). The specimens are 78 mm in diameter on the outside, 2.78 mm in thickness, and 365 and 400 mm in height. A 1.4 mm base plate was welded to one end of the TCSCFST in order to stop the concrete from slipping during casting and vibration. We used a 100-ton Universal Testing Machine to measure the steel tube's yield strength. Test specimens were created in compliance with IS 1608:2005 criteria in order to verify the yield strengths of steel tubes [18]. Each core concrete grade has nine specimens, with five specimens measuring 365 mm in height and four specimens measuring 400 mm in height. The compressive strength of TCSCFST was checked for different concrete core grades and aspect ratios (L/D). The layout of concrete-filled and unfilled TCSCFST is shown in Fig. 1.



a) Concrete unfilled steel tubes b) Concrete filled steel tubes

Fig.1 Concrete filled and unfilled thin wall steel tube layout

2.2. Mix design

As seen in Fig. 2, tests were carried out to determine the physical characteristics of each element of concrete, such as gradation, water absorption, organic impurities, and specific gravity. In view of the results, mix design was done in accordance with IS 10262:2009 recommendations to ascertain the proper ratios of concrete ingredients. [19]. The quantity of cement, fine aggregate, coarse aggregate, water, and admixture for M20, M30, and M40 grade core concrete is shown in Table 1. The present investigations were carried out using 42.5-grade OPC cement. Superplasticizer at a dosage of 0.6 % of the weight of cement was used only for M40-grade core concrete.

Table 1 Mix proportions of M20, M30 and M40 grades of concrete

Grade of concrete	Cement (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Admixture (kg/m^3)	Water (kg/m^3)	w/c	Slump (mm)	Mix proportions
M20	329	787	1155	-	233	0.56	36	1:3.29:3.51
M30	407	681	1180	-	231	0.45	36	1:1.67:2.3
M40	460	645	1226	3	209	0.36	75	1:1.4:2.67

a b c

a) Sieve analysis of aggregate b) Saturated surface dry (SSD) checking of sand with cone
c) Glass color standard to check organic impurities of sand

Fig. 2 Physical property checking of concrete ingredients

2.3. Casting, curing, and testing of concrete specimens

Compressive strength, flexural strength, and tensile strength tests were used at 3, 7, 14, 28, 56, and 91 days to ensure the quality of the core material. Figures 3a, 3b, 3c, 3d, and 3e, respectively, depict a number of tests, including slump measurement, casting of specimens, curing of cube specimens, and testing of cubes. Specimens such as cubes, beams, and cylinders were cured in potable water for 3, 7, 14, 28, 56, and 91 days, whereas thin-walled circular section concrete-filled steel tube specimens were cured for 28 days. The compressive, flexural, and splitting tensile strengths of core concrete, were tested by a universal testing machine. The target mean strength and compressive strength of cubes at 7, 14, and 28 days for M20, M30, and M40 concrete grades are shown in Table 2.

Table 2 Compressive strength of M20, M30, and M40 concrete at 7, 14, and 28 days and their target strengths

S.No.	Grade of concrete	Compressive strength in N/mm^2 at			Target strength N/mm^2
		7 days	14 days	28 days	
1	M40	34.65	45.17	52.43	48.25
2	M30	27.69	35.05	48.4	38.25
3	M20	17.6	23.59	28.10	26.6

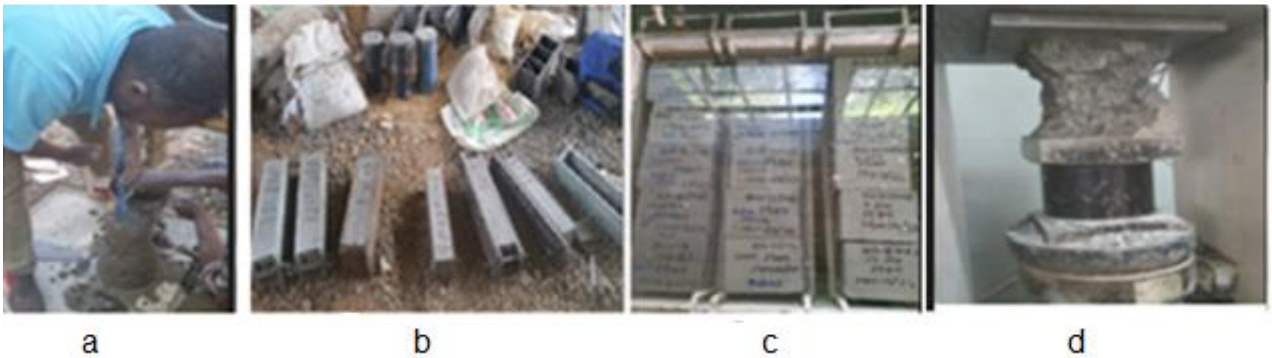


Fig. 3 a) Slump test b) Cylindrical and flexural specimens c) Curing of specimens d) Compression test on cubes

2.4. Experimental investigation of TCSCFST

The specimens of thin-walled circular-section concrete-filled steel tubes were cast, cured, and tested at the end of 28 days. During the axial compressive strength test, the column was positioned in the loading frame and subjected to a concentric load, as shown in Figs. 4 and 5. In addition, the TCSCFST specimens ready for compressive testing are shown in Fig. 5a. The bearing capacity and measured axial shortening of TCSCFST are shown in Table 5.

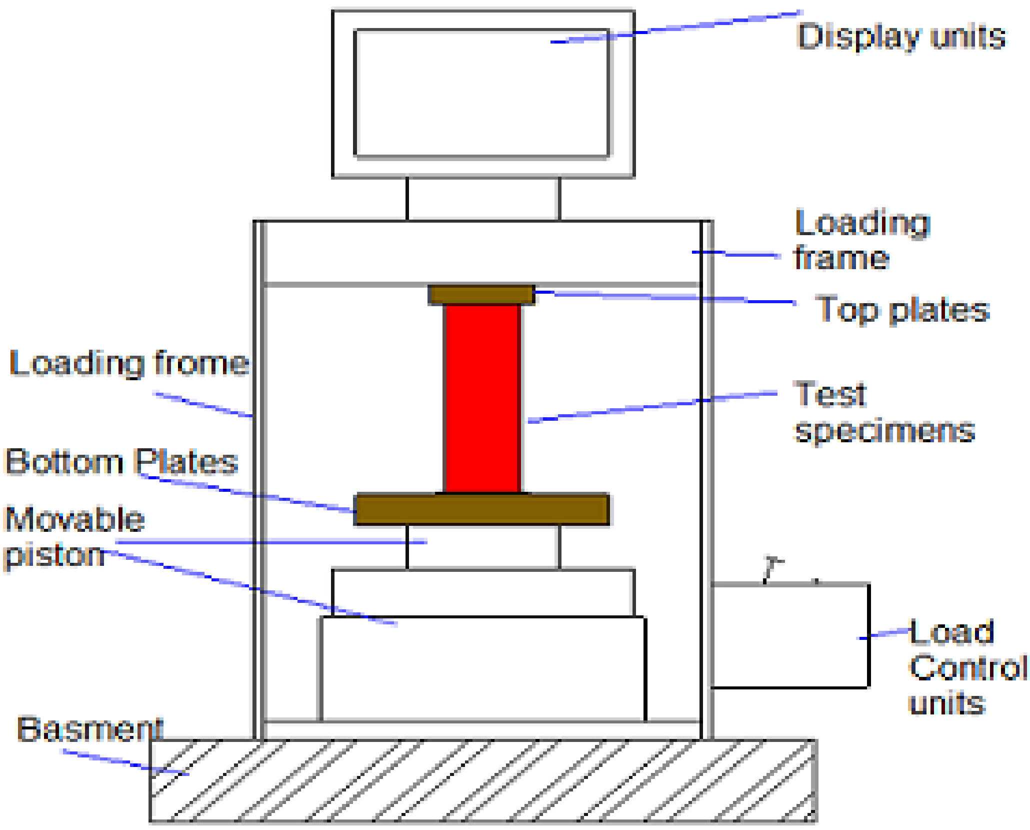


Fig.4 Compression testing machine schematic view

a) TCSCFST specimens b) Axial compression test set up

Fig. 5 TCSCFST test specimens

2.5. Theoretical investigation of TCSCFST

Theoretical studies were conducted and their findings are compared to the experimental data. The Eurocode-4, EN 1994-1-1 (2004) Part 1-1 [20], was used to assess the axial load-carrying capability of TCSCFST columns.

$$N_{pl,Rd} = \eta_s A_a\ f_{yd} + A_c\ f_{cd}\,(1+\eta_{cc}\frac{(t)}{d}\frac{\left(f_{yd}\right)}{f_{ck}} \qquad (1)$$

Where

$N_{pl,Rd}$ is the design plastic resistance to compression,η_s and η_{cc} are the confinement ratios for steel and concrete respectively. A_a and A_c are the areas of steel and concrete respectively, d is the outer diameter of steel tube, t is the thickness of the steel tube, f_{yd} is the yield strength of steel tube, and f_{ck} is characteristic compressive strength of concrete.

$$\eta_{cc} = 0.25(3+2\bar{\lambda}) \le 1 \qquad (2)$$

$$\eta_s = \left(4.9 - 18.5\bar{\lambda} + \bar{\lambda}^2\right) \ge 0 \qquad (3)$$

$$\bar{\lambda} = \sqrt{\frac{N_{pl,Rk}}{N_{cr}}} \qquad (4)$$

$$N_{pl,Rk} = A_a\ f_{yd} + 0.85\ A_c\ f_{cd} \qquad (5)$$

$$\left(EI\right)_{eff} = E_a I_a + K_e\ E_{cm} I \qquad (6)$$

$N_{pl,Rk}$ is characteristic plastic resistance, N_{cr} is critical normal force at elastic stage ,$(EI)_{eff}$ is effective stiffness, K_e =0.6 is a correction factor , I_a and I, are the moment of inertia for steel and uncracked concrete section, E_{cm} is the youngous modulus of concrete section (uncracked).

3. Results

A total of 27 specimens were used for the investigation. Of these, 12 were 400 mm tall, and 15 were 365 mm tall. M20, M30, and M40 are different grades of concrete used as the core material. Four specimens are 400 mm tall, and five specimens are 365 mm tall in each grade of core concrete. From the investigation, specimens with M40 grade of core concrete and 365 mm height measured an average experimental axial strength ($P_{exp.365}$) of 480.28 kN while its average theoretical strength (P_{u365}) is 317.67 kN. Similarly, specimens with M40 grade of core concrete and 400 mm height measured an average experimental axial strength ($P_{exp.400}$) of 467.75 kN while its average theoretical strength ($P_{u\ 400}$) was 313.28 kN. Specimens with M30 grade of core concrete and 365 mm height measured an average experimental axial strength ($P_{exp.365}$) of 426.24 kN while its average theoretical strength ($P_{u\ 365}$) was 287.60 kN. Likewise, the average experimental axial strength of M30 grade core concrete specimens with 400 mm height ($P_{exp.400}$) measured 415.93 kN, while their average theoretical values ($P_{u\ 400}$) were 282.82 kN. Furthermore; the experimental study found that the average experimental axial strength of M20 grade core concrete specimens with 365 mm height measured an average experimental axial strength ($P_{exp.365}$) of 418.54 kN while its average theoretical strength ($P_{u,365}$) was 257.75 kN. Finally, the average experimental axial strength of M20 grade core concrete specimens with 400 mm height (Pexp.400) measured 409.33 kN while their average theoretical values (Pu, 400) was 252.80 kN as shown in Table 3 and Fig 6.

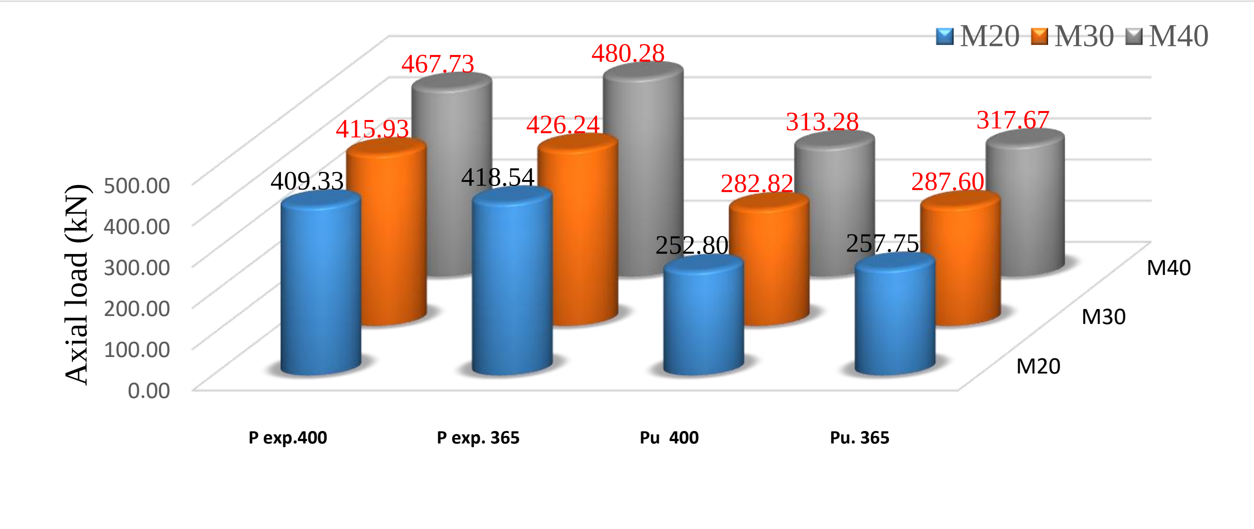


Fig.6 Experimental and theoretical axial strength of TCSCFST withM20, M30, and M40 grade core concrete for 365 and 400 mm high specimens

Table 3 Experimental and theoretical values of axial strength of specimens

Grade of concrete	Axial strength			
	Experimental value (kN)		Theoretical value (kN)	
	$P_{exp.365}$	$P_{exp.400}$	$P_{u.365}$	$P_{u.400}$
M40	480.28	467.73	317.67	313.28
M30	426.24	415.93	287.60	282.82
M20	418.54	409.33	257.75	252.80

4. Discussion

4.1. **Effect of grade of concrete**

In comparison to theoretical values for 400 mm high (H400) columns, the axial load-bearing capacity of specimens with M20, M30, and M40 grades of core concrete increased by an average of 61.9, 47.1, and 49.3%, respectively. Additionally, the results for 365 mm high specimens (H365) indicated that, with respect to its theoretical value, the axial load carrying capacity of TCSCFST columns rose by 62.4, 48.2, and 51.2% for M20, M30, and M40 grade of core concrete, respectively.In both 365 and 400 mm high test specimens, M20 grade of core concrete specimens bear more load than the other with respect to their theoretical value as shown in Fig 7. This indicates that thin-walled circular section concrete-filled steel tube columns are more effective for lower-grade core concrete.

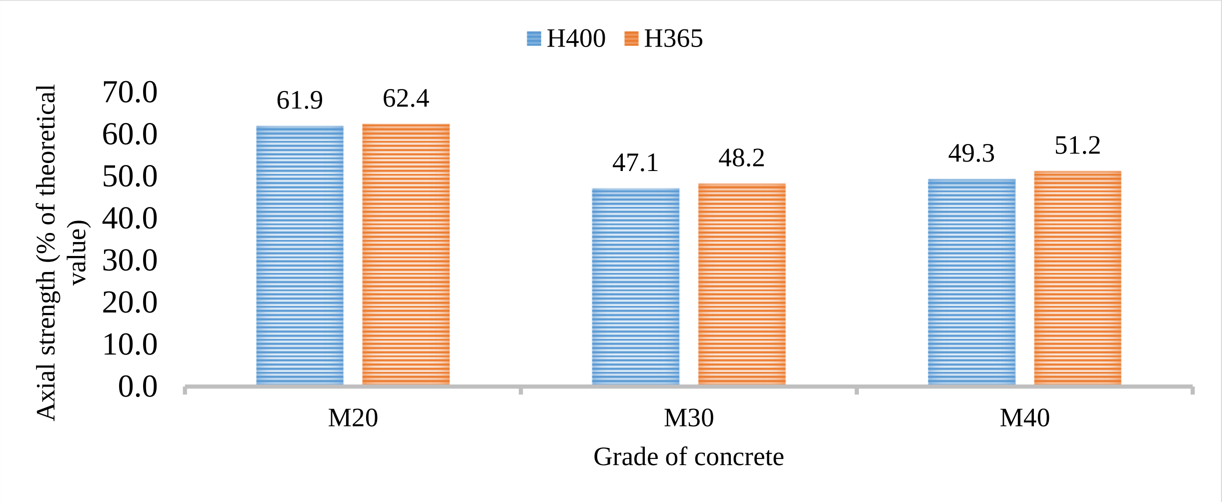


Fig.7 Axial strength of different grade of concrete (% of theoretical values)

4.2. Effect of aspect ratio

The study examined the effect of aspect ratio on the axial strength of TCSCFST for the prescribed grades of core concrete. When the aspect ratio increased from 4.68 to 5.13 for the M20 grade of core concrete, the experimental value decreased from 418.54 to 409.33kN, and the theoretical values decreased from 217.75 to 252.80kN. Specimens filled with M30 grade core concrete depicted that the experimental axial capacity reduced from 426.24 to 415.93 kN, and its theoretical value reduced from 287.6 to 282.82 kN when the aspect ratio increased from 4.68 to 5.13. Moreover, specimens filled with M40 grade of core concrete and its aspect ratio changed from 4.68 to 5.13, the axial load carrying capacity reduced from 480.28 to 467.73kN, and the theoretical value reduced from 317.67 to 313.28kN. Generally, when the aspect ratio increased from 4.68 to 5.13, the experimental bearing capacity of TCSCFST decreased by 5.4, 2.4, and 5.4%, and the theoretical value decreased by 1.4, 1.7, and 1.9% for M20, M30 and M40 grade of core concrete respectively as shown on Table 4.To sum up, when the aspect ratio increased, the axial bearing capacity of the thin-walled circular section concrete-filled steel tube columns decreased.

Table 4 Axial strength of TCSCFSTs for different aspect ratios

Grade of concrete	Axial strength			
	Experimental value (kN)		Theoretical value (kN)	
	Aspect ratio 4.68	Aspect ratio 5.13	Aspect ratio 4.68	Aspect ratio 5.13
M20	418.54	409.33	257.75	252.8
M30	426.24	415.93	287.6	282.82
M40	480.28	467.73	317.67	313.28

4.3. Failure mode

Fig. 8 illustrates how the specimens failed during testing due to local buckling and bending in single and double curvatures. Sixteen of the twenty-seven TCSCFST specimens failed the single and double curvature mode of bending. The specimen's mid-height was almost where the local buckling was located for the remaining specimen. A shell in the test specimen prevented the concrete from crushing. Furthermore, the core concrete prevents the shell from bowing locally. Among the samples, one specimen experienced axial shortening of 41.62 mm and local buckling mode failure at an ultimate load of 415.10 kN.Tri-axial stress is produced on concrete as a result of the axial load's lateral pressure. The hoop stress circumferentially resists the radial stress, which causes the shell to expand radially and push outward as the axial stress rises. At this point, the shell continues to enlarge and the core concrete begins to crush as the column achieves its greatest ultimate capacity.

a b c

a) Single curvature b) Double curvature c) Local buckling

Fig.8 Different failure modes of the TCSCFST

4.4. Axial shortening of TCSCFST

The test specimens are designated with letter and numbers. The letter and numbers describe the grade of core concrete, sequence, height, and diameter of the specimens. For example, from test specimen M40-1-365-78, M denotes mix design,40 denotes the grade of concrete, 1 denotes the first specimen, 365 denotes the height of the specimen in millimetres, and 78 denotes the diameter of the specimen in millimetres. The experimental ($P_{exp.}$) to theoretical load (P_u) ratio, axial shortening, and ultimate strain values are tabulated in Table 6.

For M40 core concrete and 365 mm high specimens, the maximum strain value is 2.6% at the axial load of 481.10 kN, and the minimum strain is 2% at 472.20 kN axial load. Similarly, for M40 grade core concrete with 400 mm high specimens, the maximum strain is 2.4% at a 469.2 kN axial load, and the minimum strain is 1.7% at an axial load of 482.50 kN. On specimens filled with M30 core concrete, a maximum of 3.9% and a minimum of 2% strain is attained for a 365 mm high column. The same grade of core concrete with 400 mm high specimens measures a maximum of 2.2% strain at the load of 405.40 kN and a minimum of 2% strain at the load of 428.80 kN. For the M20 grade of core concrete at a maximum load of 475.10 kN and minimum load of 419 kN, the corresponding maximum strain of 11.4% and minimum strain of 1.3%, were measured for 365 mm high column specimens. For a 400 mm high column of M20 core concrete, a maximum of 2.9% strain at 482.80 kN and a minimum strain of 1.8% at 451.40 kN load were measured.Fig.9 shows the comparison of the experimental load to the theoretical value for each test specimen. It is observed that all experimental values exceed the theoretical value.

Table 5 Load ratio, axial shortening and ultimate axial strain

S.No.	Specimen	H_o (mm)	$P_{exp.}$ (kN)	$P_{exp.}/P_u$	Δ_{exp}. (mm)	ε_{ult} (%)
1	M40-1-365-78	365	493.80	1.55	9.14	2.50
2	M40-2-365-78	365	472.20	1.49	7.14	1.96
3	M40-3-365-78	365	474.30	1.49	9.14	2.50
4	M40-4-365-78	365	480.00	1.51	7.70	2.11
5	M40-5-365-78	365	481.10	1.51	9.36	2.56
6	M40-6-400-78	400	471.90	1.51	7.71	1.93
7	M40-7-400-78	400	469.20	1.50	9.71	2.43
8	M40-8-400-78	400	482.50	1.54	6.64	1.66
9	M40-9-400-78	400	447.30	1.43	9.14	2.29
10	M30-1-365-78	365	417.40	1.45	7.14	1.96
11	M30-2-365-78	365	435.60	1.51	12.14	3.33
12	M30-3-365-78	365	415.30	1.44	14.14	3.87
13	M30-4-365-78	365	430.20	1.50	8.71	2.39
14	M30-5-365-78	365	432.70	1.50	7.71	2.11
15	M30-6-400-78	400	405.40	1.43	8.71	2.18
16	M30-7-400-78	400	399.50	1.41	8.21	2.05
17	M30-8-400-78	400	430.00	1.52	8.14	2.04
18	M30-9-400-78	400	428.80	1.52	7.71	1.93
19	M20-1-365-78	365	425.00	1.88	27.35	7.49
20	M20-2-365-78	365	415.10	1.84	41.62	11.40
21	M20-3-365-78	365	413.40	1.76	8.64	2.37
22	M20-4-365-78	365	416.10	1.85	9.71	2.66

23	M20-5-365-78	365	423.10	1.63	4.71	1.29
24	M20-6-400-78	400	422.80	1.91	11.71	2.93
25	M20-7-400-78	400	411.60	1.87	8.21	2.05
26	M20-8-400-78	400	391.40	1.79	7.20	1.80
27	M20-9-400-78	400	411.50	1.87	8.70	2.18

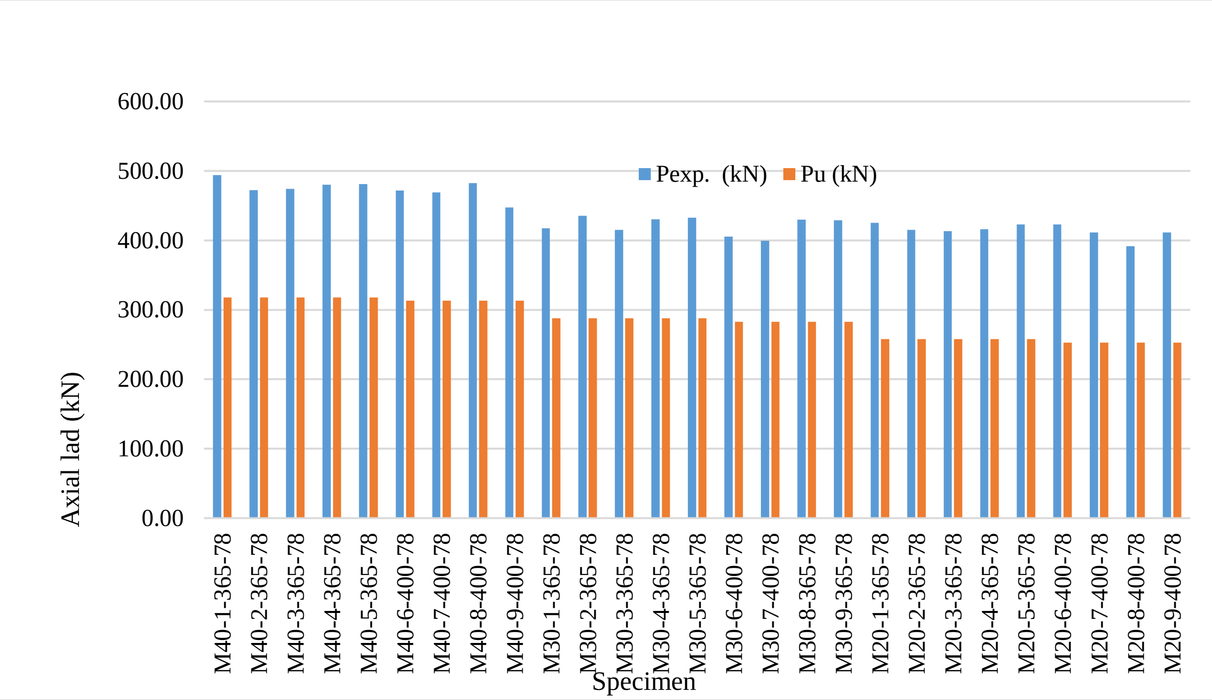


Fig.9 Experimental and theoretical values of specimens

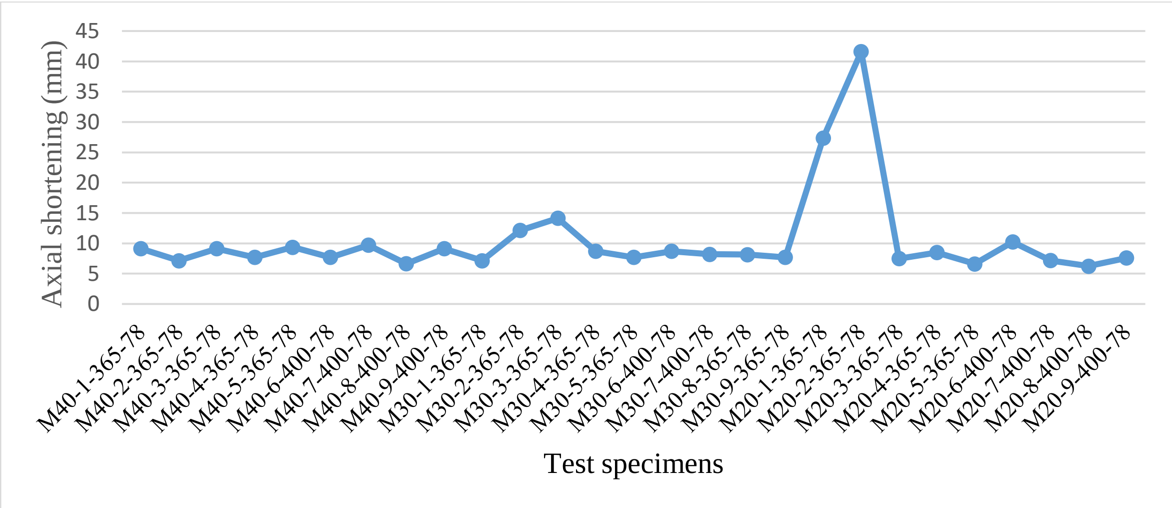


Fig. 10 Axial shortening of specimens

5. Conclusion

The study included a comparison between the theoretical and experimental values. The experimental value had greater axial capacity than the theoretical value, according to the results. Aspect ratio and the grade of core concrete are the variables taken into account in this study. The following findings are enumerated from the investigation;

1. The load-bearing capacity of TCSCFST with M20 grade core concrete exhibited 62.2% more capacity than its theoretical value.
2. The load-bearing capacity of TCSCFST with M30 grade core concrete exhibited 47.7% more capacity than its theoretical value.
3. The load-bearing capacity of TCSCFST with M40 grade core concrete exhibited 50.4% more capacity than its theoretical value.
4. During testing, the TCSCFST exhibits buckling in both concavity and convexity shapes, without displaying any indications of core concrete crushing. Seldom do specimens break down in the crushing mode. The specimens' shells' confining effect is to blame for this.
5. The axial strength of TCSCFST specimens filled with M20 grade core concrete increased by 5.6% when the aspect ratio decreased from 5.13 to 4.68.
6. The axial strength of TCSCFST specimens filled with M30 grade core concrete increased by 2.5% when the aspect ratio decreased from 5.13 to 4.86.
7. The axial strength of TCSCFST specimens filled with M40 grade core concrete increased by 5.7% when the aspect ratio decreased from 5.13 to 4.86.
8. The maximum strain of 3.9% is registered for M30 grade core concrete while the minimum strain of 1.3% is registered for M40 grade core concrete.

In general, the experimental result and the theoretical value for the axial strength of circular section concrete-filled steel tubes, as determined by EN 1994-1-1 (2004) part 1-1, are very different. The construction industry that used TWCSCFST as a building material would now incur higher costs as a result. Therefore, it is advisable to think about going over the equation in EN 1994-1-1 (2004) part 1-1.

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