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*Research Article*

# Compressive behavior and code based evaluation of normal weight and lightweight concrete filled composite steel tubes

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**Article Info**

***Article History:***

Received 04 Dec 2024

Accepted 07 Feb 2025

***Keywords:***

Compressive behavior;
Concrete filled steel tube;
Design code;
Lightweight concrete;
Normal weight concrete

**Abstract**

The application of lightweight aggregate concrete as a core material for concrete-filled steel tube (CFST) composite columns offer various advantages such as lower self-weight and thermal conductivity, higher fire resistance and durability as well as more resistance against the earthquake loading. In this study, the axial strength of steel tubes filled with normal weight concrete (NWC) and lightweight concrete (LWC) were evaluated by applying two widely used design codes, American Concrete Institute (ACI) and Eurocode 4 (EC4). The assessment included circular steel tubes with variable diameter-to-thickness (D/t) ratios of 30, 60, and 90, coupled with steel yielding strengths of 185, 275, and 450 MPa, while keeping constant wall thickness and length-to-diameter (L/D) ratio. Twelve distinct LWC combinations from the literature, each having verified compressive strength, were employed as infill materials for the steel tubes. A total of 108 results of the ultimate axial strengths predicted by the ACI and EC4 were then investigated and compared to assess their accuracy and applicability to tubes filled with NWC and LWC. A statistical analysis was also conducted to determine the effectiveness of the investigated variables. The findings showed that variations in the D/t ratio had a substantial effect on the ultimate strength of circular steel tube columns filled with NWC and LWC with a contribution rate about 85% according to the statistical evaluation of the ACI and EC4 equations, which is slightly higher in the former. Moreover, the strength predictions by using the EC4 formula gave greater as compared to those obtained by the ACI, ranging from 29 to 54%.

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## 1. Introduction

Composite columns, which have been extensively utilized in engineering fields, provide exceptional ductility and strength characteristics and their development has been the focus of intensive research over the last few decades. When comparing typical reinforced concrete columns to concrete filled steel tube (CFST) columns, noticeable disparities regarding ductility and energy absorption capability are evident [1–4]. Since CFST sections are among the best composite sections and offer numerous benefits over traditional steel and reinforced concrete sections, they have grown in popularity in recent years [5]. By using the combined action of steel and concrete, the CFST sections provide resistance to applied loads. They are created by pouring concrete into a hollow steel tube section [6]. Steel tubes serve as both longitudinal and transverse reinforcement in CFST sections [7]. Because steel has a high elastic modulus, the steel tube that is located at the outside perimeter of the CFST section effectively resists tension and bending moments while also increasing the stiffness of the section. The CFST section's inner concrete core also contributes significantly to improving the section's behavior and postponing the steel tube's inward buckling [8, 9]. Additionally, CFST section's compressive strength is increased by the steel tube's effective

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DOI: http://dx.doi.org/10.17515/resm2025-565me1204rs

containment of the inner concrete core [10, 11]. Therefore, in situations when the columns are subjected to high compressive stresses, CFST sections are beneficial. For a structure situated in an earthquake-prone area, the CFST section's high ductility, strength, and energy absorption capacity is crucial [12]. Another benefit of CFST sections is that its steel tube can be used as formwork during construction, which reduces the need for formwork and the amount of time needed for construction [13].

The weight-bearing capability of the column is greatly impacted by the features of the concrete and steel. The structural parts' cross sections get smaller as steel and concrete's strengths increase. Concrete in CFST columns is contained by steel, which adds to the structural benefit of CFST and increases its load capacity. Additionally, removing the permanent formwork shortens the construction period. Additionally, because of the concrete core, the use of CFST in constructions results in a delayed or inhibited local buckling of steel tube. In summary, the usage of CFST columns is advantageous due to their increased stiffness, ductility, and load carrying capacity as well as their reduction in construction time and cost [2].

CFST columns have been studied experimentally for decades [14–16]. Research has demonstrated that the characteristics and geometry of the materials are key criteria that influence CFST columns' capacity and behavior. In recent years, there have been several theoretical and practical research on circular CFST columns with a variety of diameter-to-thickness (D/t) ratios and material parameters [4,17–21].

The main parameters influencing the behavior and load-bearing capability of CFST columns are presented in a review of the currently published investigations. The behavior and load-bearing capacity were discovered to be affected by the geometrical features including length-to-diameter (L/D) ratio, D/t ratio and the geometry of specimens followed by the mechanical qualities such yield strength of steel and compressive strength of concrete [2]. The lack of understanding of the composite behavior of the concrete and steel in CFST composite columns is one of the main obstacles to their widespread adoption. According to earlier studies on CFST columns, a number of issues impede the study and design of these composite columns [22]. Due to the lack of understanding regarding the actual strength and inelastic performance of the composite columns, the widespread utilization of CFST columns is confined to specific purposes. Despite the extensive research conducted on composite columns in the past, their application has been restricted, and there is a discrepancy between the numerical predictions and the experimental results. Prior research on composite columns has mostly focused on testing different CFST composite columns without any external confinement in order to evaluate the impact of important parameters, such as concrete strength, steel grade, steel yield strength, steel tube D/t ratio, and the bond strength and characteristics at the steel-concrete interface [23].

It is noted that 75–98% of the cross-sectional area of CFST columns is made up of the concrete core. Concrete has a crucial role in determining how strong the output columns are for this. Therefore, the various designs and the availability of concrete materials must be considered while choosing the type of concrete. In this sense, normal-weight concrete (NWC) and lightweight concrete (LWC) would be a sensible option to use in the construction of such columns, especially in nations where natural resources are running low [24]. Gupta et al. [25] investigated 81 specimens to investigate the effects of steel tube diameter and D/t ratio modifications on the axial load bearing capability of the concentrically loaded circular concrete-filled steel tube columns. They found that the D/t ratio dropped with increasing steel tube confinement effectiveness. To examine the columns' failure modes, Ghannam et al. [26] tested rectangular, square and circular tubes filled with NWC and LWC. The test results revealed that the overall buckling of the CFST columns was the reason why both types of filled columns failed. Their research indicates that lightweight aggregate concrete can be used in place of regular concrete for structural purposes because of its low thermal conductivity and specific gravity. Experimental studies on the axial load bearing capacity of CFST columns pique researchers' curiosity, theoretical analysis plays an important role in engineering research and practice. In the literature, Güneyisi and Kadhim [24] assessed and analyzed the load-carrying capacity of recycled aggregate concrete-filled steel tube short columns subjected to axial compression, utilizing 1600 data evaluated based on four international design standards (AIJ, DL/T, EC4 and ACI). The primary factors examined consist of steel tube characteristics (outside diameter, wall thickness, length, yield strength) and concrete core attributes (kind of recycled aggregate, substitution level, and compressive strength). The findings underscore EC4's enhanced efficacy in reducing data dispersion, whereas ACI demonstrated greater variability and deficiencies in addressing steel-concrete confinement effects. The inclusion of recycled aggregates negatively impacted the strength of the concrete and the anticipated $N_u$ across all standards, with the D/t ratio modulating the influence of steel yield strength. In a recent study conducted by Luo et al. [27], the structural performance of ultra-high strength CFST stub columns subjected to combined compression and bending was investigated by using experimental and numerical methods. Twenty specimens, fabricated from steel tubes with yield stresses ranging from 813 to 1153 MPa and concrete with a compressive strength of 146.7 MPa, were subjected to diverse eccentric loads during testing. Critical experimental findings were on failure modes, ultimate load capacity, neutral axis displacements, and strain distribution within the steel tubes. Numerical models were created and confirmed with test data to examine cross-sectional stress behavior and comprehend the eccentric compression process. The research evaluated the appropriateness of design standards including EN 1994-1, AISC 360-16, AIJ-2008, and T/CECS 987–2021 for the columns. Research indicates that EN 1994-1 yields precise predictions in the absence of second-order effects, whereas AIJ-2008 enhances accuracy when these effects are taken into account. T/CECS 987–2021 significantly improves prediction accuracy following the adjustment of axial and bending capacities. Apart from the above studies, Alnemrawi and Al-Rousan [28] examined the performance of lightweight CFST columns subjected to axial compression through 48 simulated models with differing properties. The investigation tested four concrete strengths (30 to 60 MPa), three L/D ratios (3, 6, and 9), and four D/t ratios (36, 31, 26, and 21). Nonlinear finite element analysis was applied to examine load-strain relationships and failure modes. The results were juxtaposed with AISC 360-16 and EC4 design codes, revealing that AISC forecasts were conservative at low L/D ratios, whereas EC4 underestimated performance at elevated L/D ratios by as much as 28%. The results emphasize that steel tubes enhanced the mechanical properties, ductility, and strength of the columns, with failure modes determined by geometrical factors. High-strength concrete exhibited superior performance than increasing tube thickness in improving column behavior.

The structural performance of CFST columns were thoroughly examined in existing literature, with the majority of studies focusing on the use of conventional concrete as the infill material. However, limited attention has been devoted to exploring the structural behavior of lightweight concrete filled steel tube columns, leaving a significant gap in the understanding of their performance characteristics. For this, the present study aims to investigate the behavior of axially loaded normal and lightweight concrete-filled steel tube composite columns. Additionally, it is objective to identify an appropriate, viable, and precise approach to assess the predictability of two design requirements of the ACI 318 and EC4 [29, 30], including observations on their safety margins and recommendations for necessary modifications. Several factors were taken into account, including different D/t ratios of 30, 60, and 90, coupled with steel yielding strengths of 185, 275, and 450 MPa, while keeping constant wall thickness and L/D ratio. The compressive strength of the normal and lightweight concrete core with three replacement levels of fly ash and micro silica were also considered. A comparison of the analysis findings based on the two design codes was performed for the composite columns that were exposed to compressive loads.

## 2. Details of This Study

Two major design standards were used to assess the behavior of NWC and LWC filled steel tube columns which were exposed to axial compression, as was previously described. In order to achieve this, three steel yield strengths, $f_y$ (185, 275, and 450 MPa), and three D/t ratios (30, 60, and 90) were specified for circular CFST columns. Nonetheless, the specimens had a constant thickness for steel tubes of 4 mm and a L/D ratio of 2.5 for each code. Fig. 1 describing the load placed on the cross section of circular CFST columns. Table 1 shows the parameters have been taken in this study.

A specific methodology was implemented to utilize the compressive strength findings of normal and lightweight concrete as a filling material to evaluate the performance of CFST columns. For the concrete core, the concrete strength utilized in this study was derived from the experimental research of 28 days accomplished by Abbas et al. [32] as shown in Table 2. According to this study, a total of 12 normal and lightweight concrete combinations were created with respect to varied LWA, micro silica, MS (0, 10%) and fly ash, FA (0, 20%) contents. In this investigation, four batch series were examined for the axial compression capacity.

Table 1. Parameters of CFST columns applied in design codes

| Diameter of steel tube (mm) | Diameter of filled concrete (mm) | Length of CFST (mm) | Diameter to thickness ratio | Area of steel ($A_s$) (mm$^2$) | Area of concrete ($A_c$) (mm$^2$) | Steel moment of Inertia ($I_s$) (mm$^4$) | Concrete moment of Inertia ($I_c$) (mm$^4$) |
|---|---|---|---|---|---|---|---|
| 120 | 112 | 300 | 30 | 1457.7 | 9852.04 | 71103641 | 10326440 |
| 180 | 172 | 600 | 60 | 2965.7 | 42273.27 | 1.22E+09 | 84711312 |
| 360 | 352 | 900 | 90 | 4473.63 | 97314 | 6.31E+09 | 2.88E+08 |

The first series contains just regular and lightweight concrete. In the second and third series, micro silica and fly ash were partially substituted with 10% and 20% cement content, respectively. The fourth series involved partial substitution of MS, FA, and artificial aggregate. Their compressive strength findings, measured in cubic units, ranged from 27 to 56 MPa after 28 days. For the designation, for example, LW0MS0FA0 indicates the NWC filled steel tubes without micro silica and fly ash while LW50MS10FA0 presents steel tube filled with LWC having 50% lightweight aggregate, 10% micro silica and 0% fly ash.

Table 2. Transformation of concrete compressive strength according to EC2 [32]

| Series No | Mix ID | $f_c$ cube (MPa) | $f'_c$ cylinder (MPa) |
|---|---|---|---|
| Series 1 | L0M0F0 | 40.30 | 31.43 |
| | L50M0F0 | 33.50 | 27.14 |
| | L100M0F0 | 27.65 | 22.40 |
| Series 2 | L0M10F0 | 56.10 | 46.57 |
| | L50M10F0 | 41.70 | 32.53 |
| | L100M10F0 | 32.30 | 26.16 |
| Series 3 | L0M0F20 | 38.70 | 30.19 |
| | L50M0F20 | 32 | 25.92 |
| | L100M0F20 | 26.96 | 21.84 |
| Series 4 | L0M10F20 | 51.45 | 42.70 |
| | L50M10F20 | 33.80 | 27.38 |
| | L100M10F20 | 30.60 | 24.79 |

The impact of the aforementioned parameters on the ultimate compressive strength ($N_u$) outcomes was examined, contrasted, and thoroughly described in this work. For this, a numerical investigation was conducted into the potential use of NWC and LWC as a concrete core for CFST sections. Two distinct design codes (ACI and EC4) were used to determine the capacity (totally 108 $N_u$ test results) for three distinct D/t ratios, steel tube yield strengths, and twelve distinct concrete core compressive strengths. Between each design code's outcomes, a convenient analysis was carried out. The study also compares and highlights the applicability and prediction capability of the equations given in the design codes for the cases of steel tube filled with both NWC and LWC. It should be noted that Eurocode 2 was used to convert the cubic compressive strength data to cylindrical compressive strength [31], which was then utilized to calculate the ultimate strength of the steel tube columns in accordance with distinct design codes.

The standardization institutions provide many expressions for various conditions. The formulas utilized in this article are those proposed by ACI 318 and EC4. This formula evaluates concrete core and steel tube separately, ignoring concrete confinement and contact. The predicted axial load capacity is expected to be less than comparable codes. The ACI code [29] employs the observing formula to calculate the directional load capacity of circular CFST columns.

$$N_u = 0.85 f_c^{'} A_c + f_y A_s \tag{1}$$

This relation overlooks the influence of concrete confinement and the interaction between the steel tube and concrete core. On the other hand, EC4 takes into consideration the confinement effect in addition to the contributions of the concrete core and steel tube. The coefficients of confinement for concrete ($\eta_c$) and steel tube ($\eta_a$) are applied. The triaxial state of stress increases concrete strength by $\eta_c$, while hoop stresses lower steel tube strength by ηa. EC4 proposes the following expression:

$$N_u = \left(1 + \eta_c \frac{t}{D}\frac{f_y}{f_y'}\right) f_c' A_c + \eta_a f_y A_s \tag{2}$$

$$\eta_c = 4.9 - 18.5 \acute{\lambda} + 17 \acute{\lambda}^2 \; (\eta_c \geq 0) \tag{3}$$

$$\eta_a = 0.25 \left(3 + 2 \acute{\lambda}\right) \quad (\eta_a \leq 1.0) \tag{4}$$

$$\acute{\lambda} = \sqrt{\frac{N_{PIR}}{N_{cr}}} \tag{5}$$

$$N_{PIR} = f_y A_s + f_c^{'} A_c \tag{6}$$

$$N_{cr} = \frac{\pi^2 (EI)_{eff2}}{l^2} \tag{7}$$

$$(EI)_{eff2} = E_s I_s + K_e E_{c2} I_c \tag{8}$$

$$P_{0,EC4} = \left(1 + 4.9 \frac{t}{D}\frac{t_y}{f_c'}\right) f_c' A_c + 0.75 f_y A_s \; (If \acute{\lambda} = 0) \tag{9}$$

Where:

$f_y'$: the compressive strength transferred from 100 ×100 mm cube strength;

$f_y$: steel tube yield strength;

$A_s$, $A_c$: concrete and steel tube cross section area, respectively

$\acute{\lambda}$ : the relative slenderness;

$N_{PIR}$: characteristic value of the plastic resistance;

$N_{cr}$ : the elastic critical force for the relevant buckling mode;

$K_e$ : correction factor equal to 0.6;

$I_c$, $I_s$: second moment of inertia of concrete and steel, respectively

l: column buckling length;

$E_s$: elastic modulus of steel.

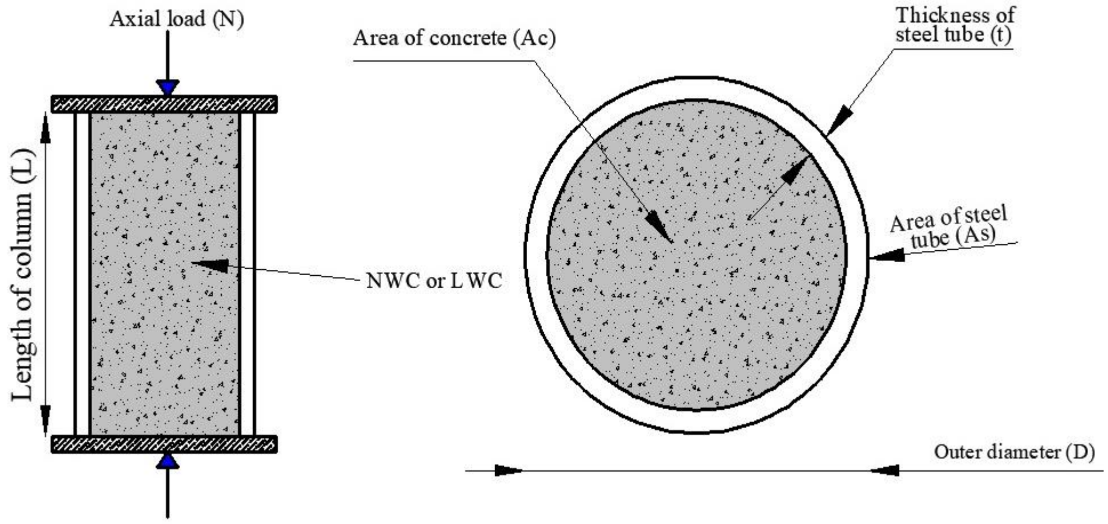



Fig. 1. Test configuration indicating the load placed across a circular CFST cross section

## 3. Results and Discussion

### 3.1 Effect of Material Strength and Type

The 28-day compressive strength of normal and lightweight concrete mixtures was applied to compute the ultimate strength of steel tube columns using ACI and EC4 techniques. Fig. 2 depicts the axial load applied capacity for the lightweight concrete and normal concrete with and without micro-silica (MS) and fly ash (FA) contents, specifically for a D/t ratio of 30 and a steel yield strength of 185 MPa. Similar results are presented in Figs. 3 and 4 for D/t ratios of 60 and 90, with steel yield strengths of 275 and 450 MPa.

The data reveal that the axial strength of steel tube filled with NWC and LWC is considerably impacted by the concrete's compressive strength. Incorporating LWA up to a 50% replacement level decreased the ultimate axial strength, which, in turn, led to decline in column ultimate strength. However, when the LWC substitution reached 100%, a fall in concrete compressive strength was found across all concrete mixtures, leading in lower ultimate strengths for CFST columns as determined by both ACI and EC4 formulas. Unlike LWC, the addition of MS often enhanced LWC compressive strength, resulting to higher ultimate strengths of the steel tube columns. The use of MS significantly improved the mixes' strength properties [32, 33], which raised the composite columns' ultimate strength, as seen in Figs 2–4. In actuality, MS is known to strengthen the transition zone and improve the link between the matrix and aggregate [34]. Regardless of MS and aggregate type, Figs. 2–4 also show that Nu decreased when the FA replaced with cement. This behavior was explained that FA developed a higher concrete strength after 28 days of water curing.

It is clear that tube columns filled with normal concrete can bear heavier weights than those loaded with LWC. For example, when evaluating conventional concrete-filled steel tube columns against their lightweight counterparts, both designed with a yield strength of 185 MPa and a diameter-to-thickness ratio of 30, the conventional columns achieved an axial strength of 533 kN as per ACI and 746 kN according to EC4. In comparison, the lightweight columns exhibited axial strengths of 457 kN and 661 kN under ACI and EC4 assessments, respectively. This disparity is attributable to the inherently higher strength of normal-weight concrete compared to lightweight concrete when all other parameters remain constant as shown in Figs. 2-4. Additionally, the ultimate strengths projected by ACI were frequently lower than those calculated from EC4. The investigation further found that raising the concrete surface area, by adjusting D/t ratios, enhances the ultimate strength, and the use of steel tubes with higher yield strengths greatly boosts the columns' ultimate strength.

## 3.2 Effect of Diameter to Thickness Ratio

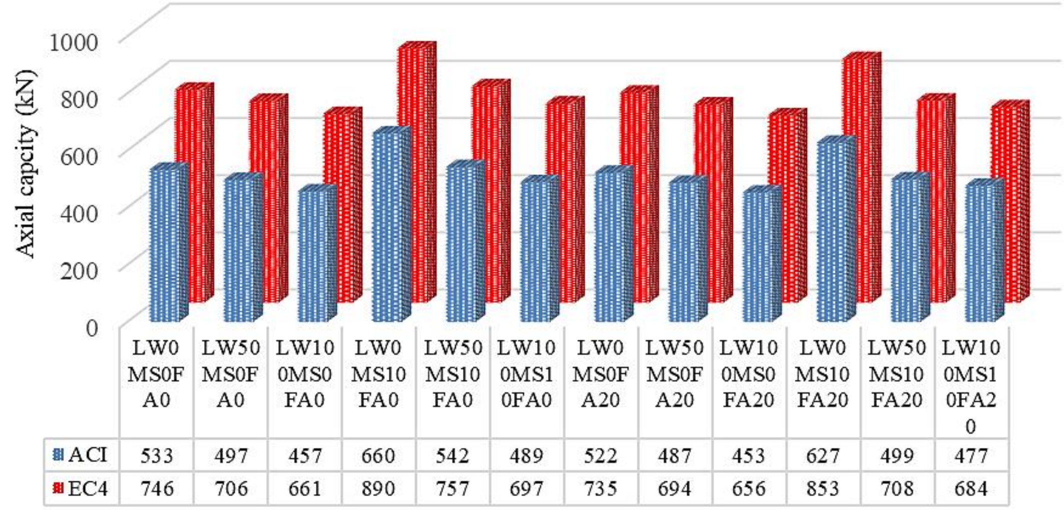
The effects of the D/t ratio on axial strength were analyzed under controlled variables, including compressive strength and yielding steel strength (fy). For the reference mix (LW0MS0FA0), the initial axial strengths were determined as 533 kN and 746 kN according to the ACI Code and EC4, respectively, with a yielding steel strength of 185 MPa. When the D/t ratio was set to 60, the axial strength increased significantly, reaching 1678 kN for the ACI code and 2305 kN for EC4 with an increase percentage 214.82% and 208.98 %, respectively. Further increasing the (D/t) ratio to 90 resulted in axial strengths of 3427 kN and 4581 kN, with a rise percent of 542% and 514% as per the ACI and EC4, respectively. These results indicate that the axial strength of the system improves substantially with an increased (D/t) ratio, highlighting the critical influence of geometric parameters on structural performance. These findings highlight the effect of the steel tube's D/t ratio on axial ultimate strength. Between the codes, the ACI formulas yielded the lowest Nu values, impacted by the D/t ratio and yield steel tube strength. Specifically, the projected Nu values with ACI varied from 453 kN to 5865 kN, substantially lower than the 656 kN to 8187 kN range obtained using EC4. That means the ultimate strength ratings estimated using the ACI formula are lower compared to those obtained using EC4. Furthermore, it has been observed that the percentage increase in results predicted by the ACI is more pronounced compared to those of EC4 when the (D/t) ratio is increased.

In normal weight concrete filled steel tube (NWCFST), the dense concrete core provides stronger confinement due to higher lateral pressure. NWCFST rely more on the composite action between the steel tube and concrete core. In NWC, lower D/t enhances strength and confinement, making the composite action more efficient. Lightweight concrete filled steel tube (LWCFST) depend more on the steel tube, especially at high D/t ratio, because the concrete core contributes less to load resistance. In LWCFST, lower D/t also improves performance, but the gains are primarily limited to steel tube stability, as the concrete core contributes less to the overall strength. In LWCFST, the confinement effect is weaker because of the lower density and lateral pressure.

## 3.3 Effect of Steel Yielding Strength

The influence of $f_y$ on axial strength was investigated while maintaining constant variables such as compressive strength and D/t ratio. Using the mix LW100MS0FA0, initial axial strengths were observed as 453 kN and 656 kN for the ACI and EC4, respectively, with a D/t ratio of 30 and $f_y$ of 185 MPa. An increase in $f_y$ to 275 MPa yielded axial strengths of 584 kN and 860 kN, corresponding to percentage increases of 24.58% for the ACI and 27.21% for EC4, respectively.

A further increase in $f_y$ to 450 MPa resulted in a significant escalation in axial strengths, achieving 839 kN for the ACI, reflecting a percentage increase of 72.42%, and 1243 kN for EC4, corresponding to a rise of 78.42%. These findings demonstrate a strong correlation between the yielding steel strength and the axial load-carrying capacity, emphasizing the critical role of material properties in the performance of structural elements. A comparable trend is observed in Figs. 4 and 5, which depict results with identical parameters. It has been determined that the EC4 exhibits a more significant percentage increase in results compared to the ACI when variations in $f_y$ are introduced. Furthermore, the correlation of design codes for composite sections with various LWCs mixtures was provided in Fig. 5. The Figure showed a good correlation between the EC4 equations and the ultimate axial strength determined by ACI.

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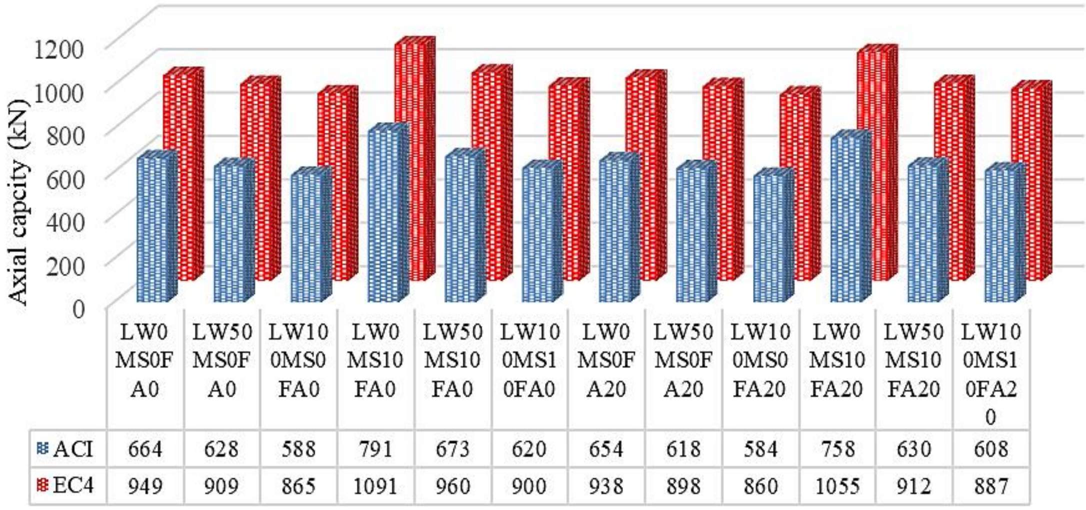


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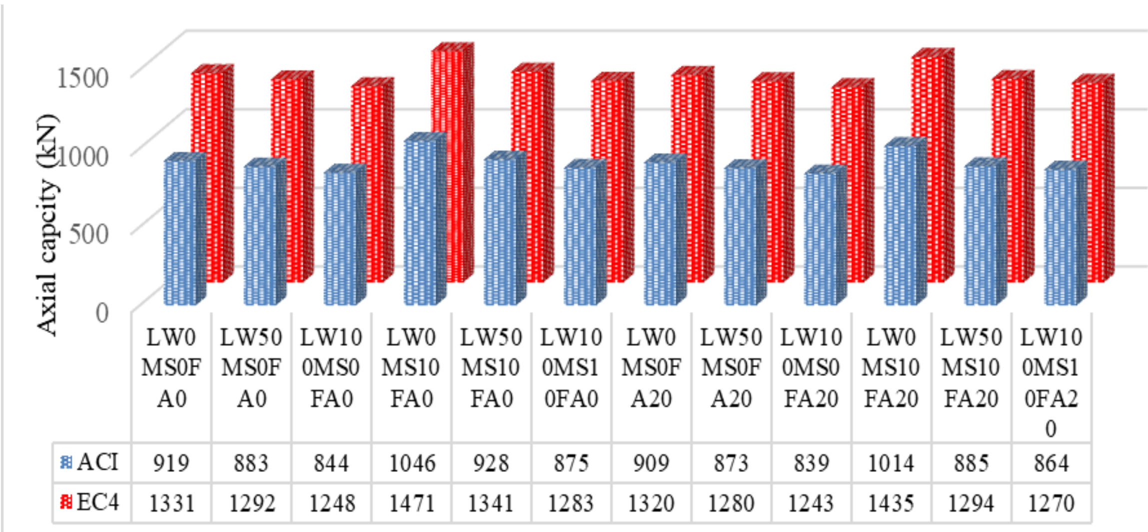
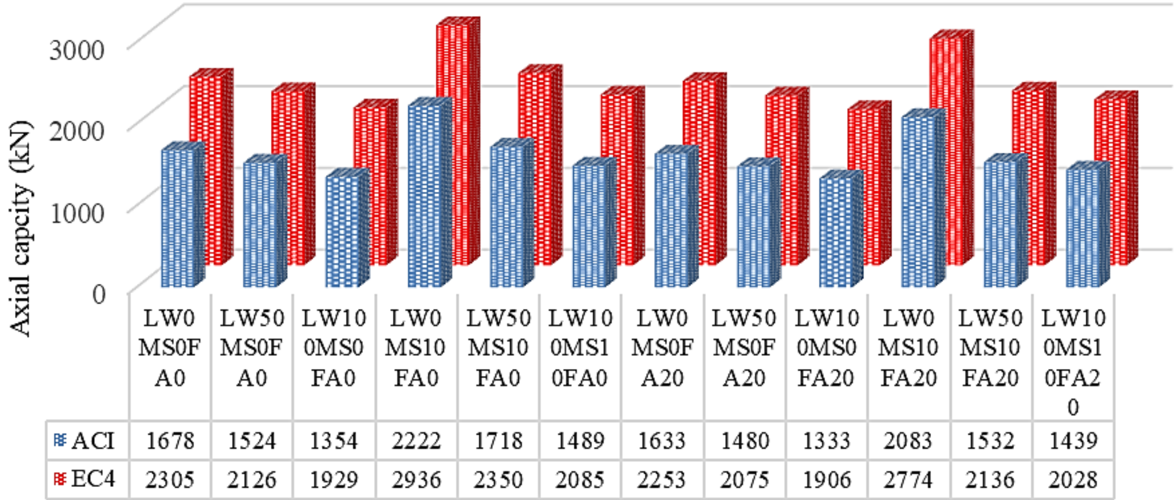



(c)

Fig. 2. Axial compression capacity of CFST with D/t ratio of 30 and fy of a) 185, b) 275, c) 450 MPa having NWC and LWC mixtures based on ACI and EC4

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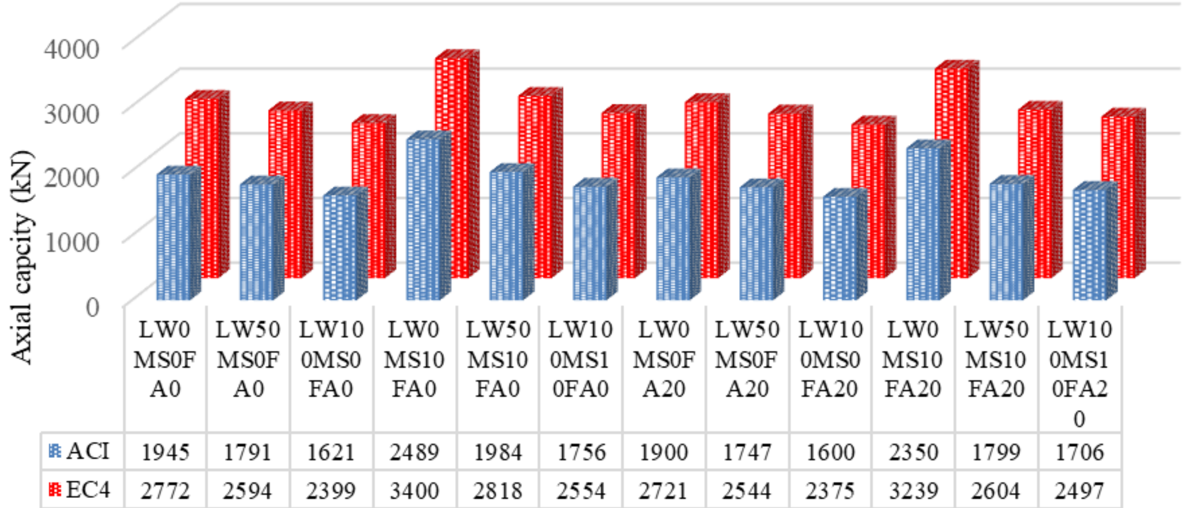


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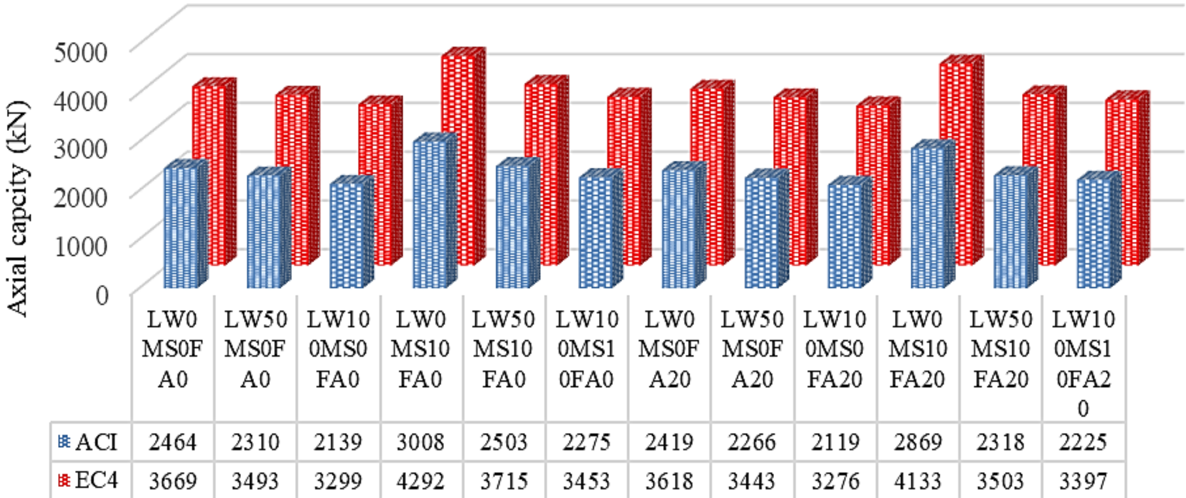
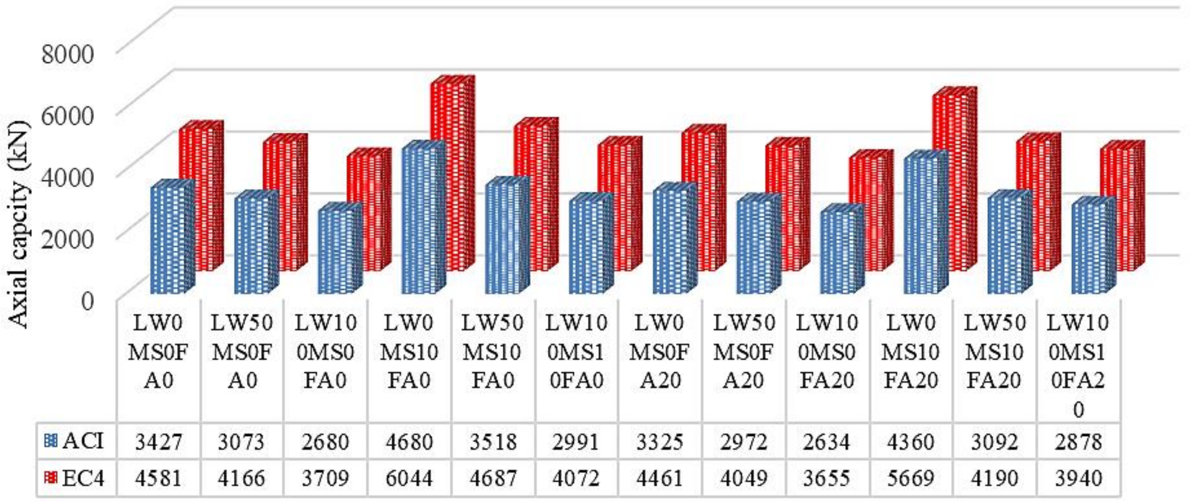



(c)

Fig. 3. Axial compression capacity of CFST with D/t ratio of 60 and fy of a) 185, b) 275, c) 450 MPa having NWC and LWC mixtures based on ACI and EC4

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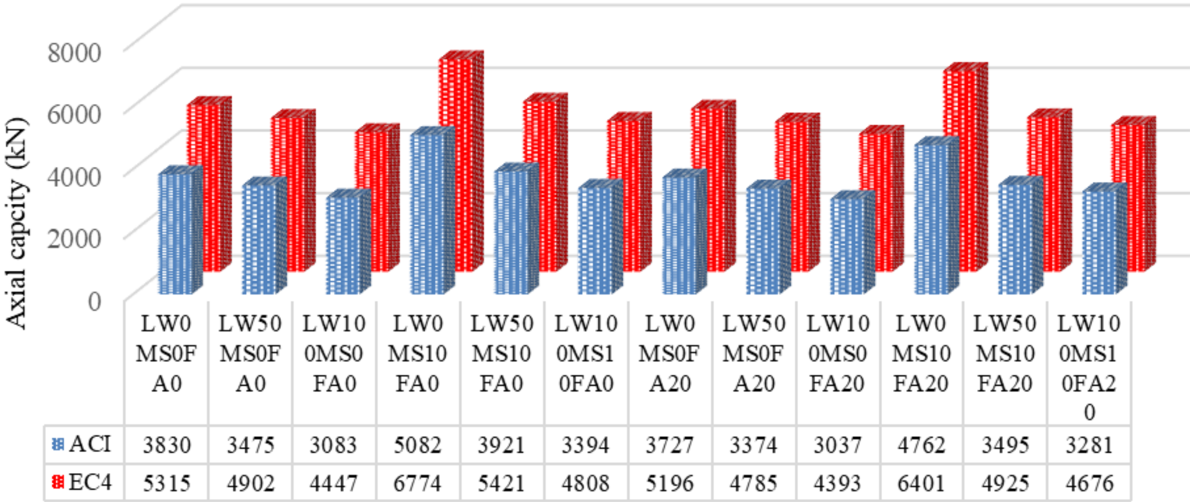


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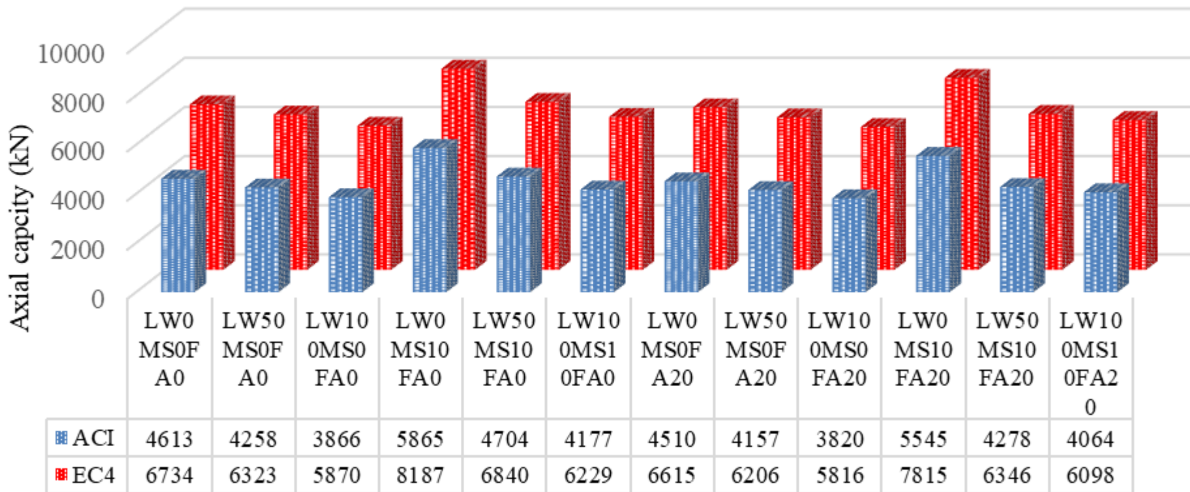


(c)

Fig. 4. Axial compression capacity of CFST with D/t ratio of 90 and fy of a) 185, b) 275, c) 450 MPa having NWC and LWC mixtures based on ACI and EC4

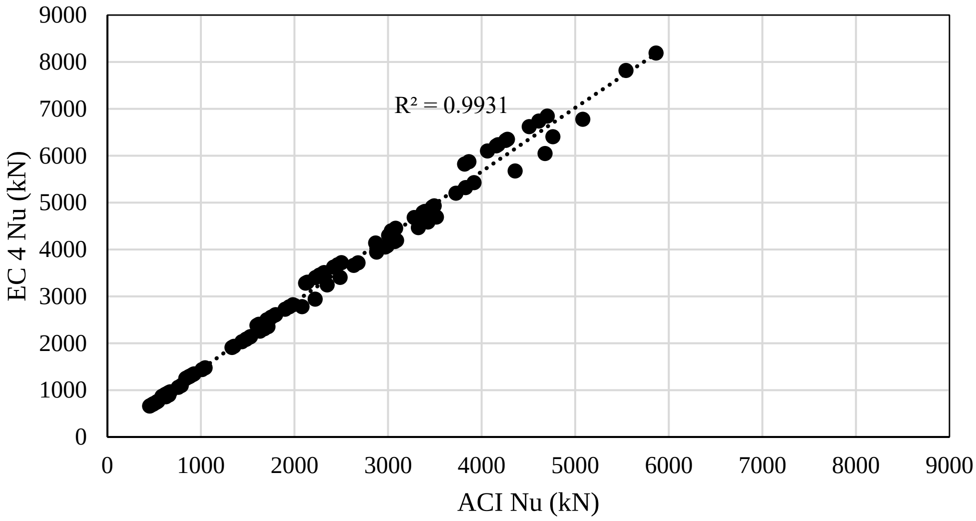


Fig. 5. Correlation between the predicted axial capacity of CFST based on the design codes

## 4. Statistical Analysis

Table 3 displays the findings of the analysis of variance (ANOVA), which indicates whether or not the status of an independent variable affects the dependent variables. Minitab 19 software was used for the statistical evaluation of the GLM-ANOVA approach was used for the multiple linear regression method. Ultimate strength data from ACI (Nu) and from EC4 (Nu) were designated as dependent variables and investigated. The general linear model analysis of variance (GLM-ANOVA) was used to calculate the experimental parameter validation. However, LWA, MS, FA, $f_y$, and D/t were the independent criterion.

Table 3. Statistical analysis of the predicted results

| Dependent variables | Independent variables | Sequential sum of squares | Computed F | P-value | Significance | Contribution (%) | R²-value |
|---|---|---|---|---|---|---|---|
| $N_u$ (ACI) | LWA (%) | 6529976 | 37.02 | 0.000 | Yes | 3.129 | 95.8 |
| | MS | 2283458 | 25.89 | 0.000 | Yes | 1.094 | |
| | FA | 241797 | 2.74 | 0.101 | No | 0.115 | |
| | $f_y$ | 11498839 | 65.19 | 0.000 | Yes | 5.51 | |
| | D/t | 179370857 | 1016.94 | 0.000 | Yes | 85.964 | |
| | Error | 8730993 | - | - | Yes | 4.184 | |
| | Total | 208655919 | - | - | - | - | |
| $N_u$ (EC4) | LWA (%) | 8741655 | 25.69 | 0.000 | Yes | 2.103 | 96.0 |
| | MS | 3058146 | 17.98 | 0.000 | Yes | 0.735 | |
| | FA | 323715 | 1.90 | 0.171 | No | 0.077 | |
| | $f_y$ | 34829306 | 102.37 | 0.000 | Yes | 8.379 | |
| | D/t | 351868129 | 1034.21 | 0.000 | Yes | 84.652 | |
| | Error | 16841324 | - | - | Yes | 4.051 | |
| | Total | 415662275 | - | - | - | - | |

Furthermore, while assessing the input parameters' contribution, it is evident that the D/t ratio and $f_y$ influence the analytical outcomes' fluctuation more than the other factors. Furthermore, information on the percentage relationship between each experimental result and one or more input components is provided by the R-squared values displayed in Table 6's last column. These R squared values demonstrate a strong correlation between the input and output variables, hence confirming the significance of the analytical findings.

The statistical research shows that the D/t ratio significantly affects the axial capacity for two codes. The analysis found that this variable is the principal driver of ultimate strength values, with little effect from $f_y$. Table 3 shows that LWA percentage and MS have a small but considerable impact on the ultimate strength capacity values from the ACI and EC4, while FA has no effect. The D/t value has a significant impact axial strength capacity, contributing 86.0% and 84.7% for ACI and EC4, respectively.

The influence of the examined parameters and their interactions on the response is depicted in a Pareto chart, as shown in Figs. 6 and 7. This chart displays the absolute values of the standardized effects, arranged from the most impactful to the least. It also includes a reference line to identify effects that are statistically significant. The position of this reference line is determined by the chosen significance level, commonly referred to as α. The longest bar signifies the most influential factor, followed by progressively shorter bars for less impactful factors. A reference line is included to identify statistically significant factors, those bars extending beyond this line are deemed significant at a 95% confidence level. Furthermore, the Pareto chart clearly demonstrates that all analyzed parameters are statistically significant except fly ash. Among these, D/t exhibits the highest effect, followed sequentially by $f_y$, LWA, and MS.

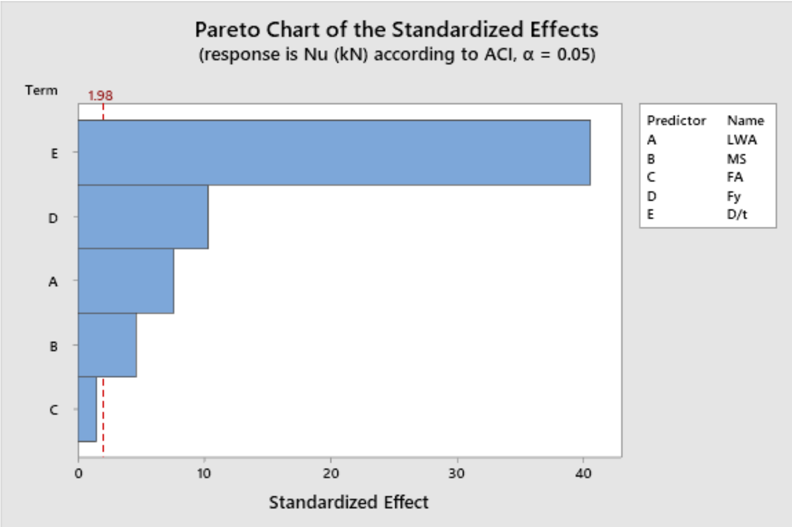


Fig. 6. Pareto chart of Nu (ACI) vs. variables

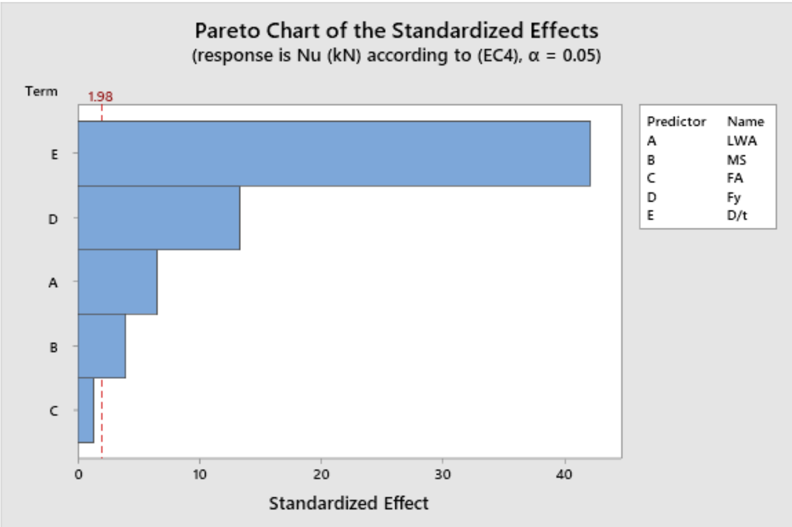


Fig. 7. Pareto chart of Nu (EC4) vs. variables

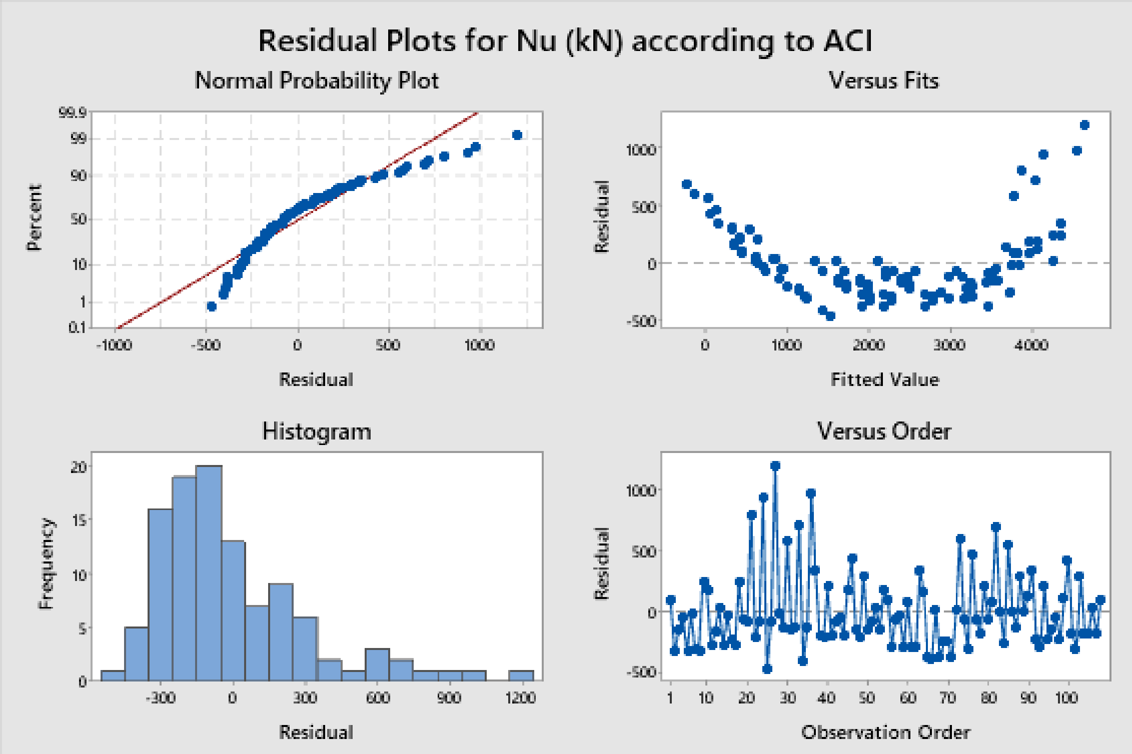


Fig. 8. Residual plots for $N_u$ predicted by ACI

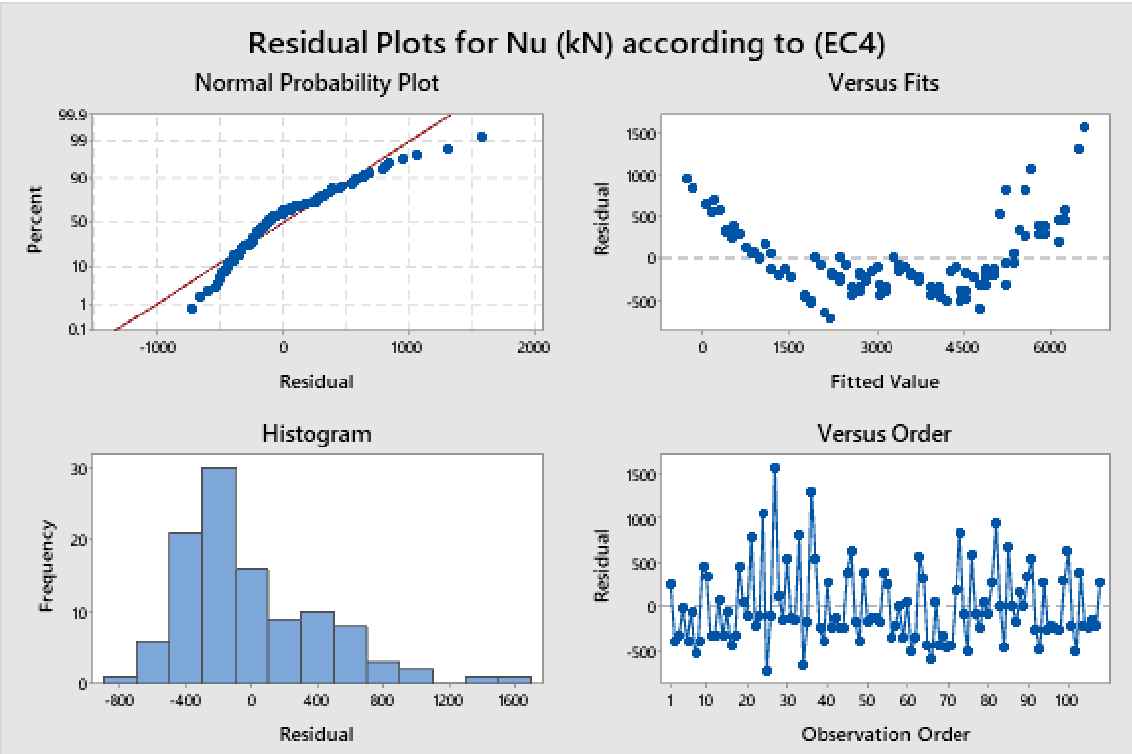


Fig. 9. Residual plots for $N_u$ predicted by EC4

Additionally, the chart provides insights into the relative significance of factor combinations. The red line in the chart represents the cumulative percentage, indicating the running total of occurrences as the progress from the highest-impact category to the lowest. Residual plots are valuable diagnostic tools for determining the validity of assumptions in regression models and other statistical analysis. They assist in determining if the model fits the data adequately and whether assumptions like as normality and constant variance hold. The normal probability plot evaluates if the residuals conform to a normal distribution. According to Figs. 8 and 9, the points align closely along a straight line, the residuals have a normal distribution, and the assumption of normality is satisfied. Residuals versus fit plot investigates whether the residuals are randomly distributed near zero across the range of fitted values. The histogram provides a visual view of the pattern of residuals. A bell-shaped curve situated at zero implies normalcy. In summarize, residual plots collectively offer a comprehensive diagnostic tool for analyzing the hypotheses of regression models. If any of the plots reveal variations from predicted trends, it may be essential to modify the model, change variables, or investigate alternate analytical approaches. Using these techniques supports the reliability and validity of statistical inferences.

## 5. Conclusions

In this study, the axial strength of normal weight concrete filled steel tube (NWCFST) and lightweight concrete filled steel tube (LWCFST) were evaluated by applying ACI and EC4 with different D/t ratios and steel yielding strengths. The properties of the concrete core were also changed. The outcomes of this research led to the main crucial conclusions:

- Examining the behavior of axially loaded NWCFST and LWCFST columns requires the deployment of specialized setup, advanced equipment, and precision testing machinery. This process involves considerable time and financial resources, making it economically impractical for widespread application. Consequently, it becomes imperative to develop an effective, feasible, and accurate methodology for evaluating the predictive capabilities of the two prominent design standards, ACI and EC4, in meeting structural performance requirements.
- The ultimate strength of circular steel tube columns filled with concrete is greatly affected by the compressive strength of the concrete and the yield strength of the steel.
- NWCFST and LWCFST columns exhibit comparable trends in their behavior, and tubular columns filled with normal concrete could bear more load than those having lightweight aggregate concrete.
- The contents of lightweight aggregate and microsilica have a substantial impact on the concrete strength and CFST columns.
- Variations in the D/t ratios demonstrate a substantial effect rather than compressive strength on the ultimate strength of circular steel tube columns filled with normal and lightweight concrete.
- The ultimate strength ratings estimated using the ACI formula are lower compared to those obtained using EC4.
- In NWCFST, the dense concrete core provides stronger confinement due to higher lateral pressure. In NWCFST, lower D/t enhances strength and confinement, making the composite action more efficient. While LWCFST depend more on the steel tube, especially at high D/t ratios, because the concrete core contributes less to load resistance. In LWCFST, lower D/t also improves performance, but the gains are primarily limited to steel tube stability, as the concrete core contributes less to the overall strength. In LWCFST, the confinement effect is weaker because of the lower density and lateral pressure.
- A high correlation exists between the ultimate strength values generated from the ACI and EC4 equations.
- The statistical evaluation showed that ultimate strength is more significantly impacted by the D/t with a contribution rate with 85% according to the statistical evaluation.
- Further study is also recommended using other codes such as American code AISC 360, Chinese code GB 50936, and Japanese code AIJ to deepen the comparative analysis and provide more comprehensive insights into the differences between these standards.

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