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Soft Computing-Based Model for the Ultimate Strength Prediction of Concrete-Filled Circular-Steel Columns

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Abstract:
Concrete-filled steel tube (CFST) columns are popular in construction because of the composite effect between the inside concrete and the outside steel tube, improving structural resistance. Accurately predicting the axial compression capacity of CFST columns is critical to maintaining structural stability and avoiding collapse. This paper uses a grey wolf optimizer (GWO) technique to determine the compressive strength of circular CFST columns. The technique is used to optimize the membership functions of the introduced model. A comprehensive database of 561 experimental tests from the published literature was used to design and validate the model. Several statistical criteria were utilized to evaluate the model's accuracy and robustness. The presented empirical model provides a concise, intuitive, and powerful description of the final load capacity of CFST columns, applicable to both ordinary and high-strength concrete and steel. Comparisons between measured and predicted values of these parameters show the model's accuracy. The designed model is expected to help engineers effectively assess the axial capacity of CFST columns in accordance with design requirements. The proposed maximum-force model yielded a coefficient of variation (CoV%) of 16.89%, an estimate of 1.08, and a correlation coefficient (*R*) of 0.9663, indicating high accuracy and repeatability of the output.

Keywords:
CFST; Circular section; Columns; GWO; Optimization; Strength prediction.

Highlights:
- Ultimate strength model prediction for Concrete-filled steel tube (CFST) columns.
- Optimized strength prediction was considered using the Grey Wolf Optimizer (GWO) technique.
- Optimization and validation were done through intensive experimental data.

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1.INTRODUCTION

Compared with conventional reinforced concrete (RC) or bare steel construction, concrete-filled steel tube (CFST) sections make substantial use of both steel and concrete [1,2]. The steel tube confines the concrete core, whereas the concrete infill prohibits the steel tube from buckling inward [3]. Due to their effectiveness as structural components, CFST elements have been widely used across a range of structural disciplines. According to previous studies such as Wang et al. [4], CFSTs have been used for, for instance, (1) super high-rise buildings with huge columns, (2) long-span bridges that use chord structural components, (3) piers of bridges, (4) piles for a flood-wall, and (5) underground pipeline construction. In these circumstances, the CFST elements primarily serve to accommodate compressive force. There are two strategies to increase the compression resistance of concrete-filled steel tube (CFST) elements [3]. The first strategy is to increase the cross-sectional size of elements. This approach can result in a larger structural weight, further exacerbating earthquake-induced loads and reducing the available area. As a result, this approach can be less workable due to the increasing weight and cost-effectiveness. The second strategy is based on the use of high-strength materials, i.e., high-strength steel and/or high-strength concrete, in accordance with the standard guidelines in AISC 360 [5] and Eurocode 4 part 1-1 [6], resulting in higher load capacity and reduced size and weight, but at a cost-effective level. The selection of both strategies is based on several conditions, such as available space, low- or high-rise buildings, and weight sensitivity. The impact of the enhanced confinement in concrete afforded by the circular steel tube is commonly stated as an improvement in the concrete's contribution to compression capacity, including the concrete's and steel's plastic strength components of CFST elements. Numerous studies have been conducted to assess how the CFST's traditional strength components behave, such as Nishiyama et al. [7], Kim [8], and Han [9]. The performance of high-strength CFST columns has also been examined by several studies, permitting their use in real-world applications. For instance, high-strength rectangular CFST short columns have been experimentally tested by Cederwall et al. [10], Varma [11], Uy [12], Liu et al. [13], Mursi and Uy [14], Sakino et al. [15], Lue et al. [16], Aslani et al. [17], and Xiong et al. [18]. These investigations were reviewed by Lai and Varma [19], who also provided design formulae for determining the cross-sectional capacity of high-strength rectangular CFST columns. Gardner and Jacobson [20], Bergman [21], O'Shea and Bridge [22], Schneider [23], and O'Shea and Bridge [24] performed additional laboratory investigations. They conducted experimental studies to investigate the behavior and performance of concrete-filled steel tube (CFST) columns under various loading conditions. The studies mentioned addressed critical parameters, including axial and lateral load capacity, confinement effects, material interaction, and the failure modes of CFST columns. The present work uses experimental results from published works to construct an integrated dataset. To maintain consistency, this dataset excludes studies using concrete columns reinforced with steel fiber, stainless steel tubing, aluminum tubes, or internally lubricated tubes, as their behavior differs from that of standard CFST columns. Numerous applications of civil engineering, especially in structural engineering, have extensively used optimization and artificial neural network techniques [25–27]. These techniques create models from datasets that can address a variety of linear and nonlinear issues of varying levels of sophistication. To set the maximum strength of circular CFST elements, Sarir et al. [28] developed an optimization and tree-based technique. Ahmadi et al. utilized an intelligent technique (an artificial neural network) to predict the compressive strength of short CFST elements [29]. Both Güneyisi et al. [30] and Ipek and Güneyisi [31] designed a genetic algorithm expression for estimating circular CFST capacity. The load-bearing performance of CCFST was investigated utilizing the fuzzy logic (FL) technique by Moon et al. [32]. Ren et al. [33] investigated the forecasting of square CFST elements for sections other than circular optimization using support vector machine techniques. Tran et al. [34] employed a biological system model (a neural network) to forecast the maximum capacity in a similar section. In addition, Lee et al. [35] predicted the ultimate capacity of CFST elements of circular and rectangular cross-sections with eccentric or concentric loading using a categorical gradient boosting approach. For the same issue, Zarringol et al. [36] employed an artificial neural network (ANN). To conclude, these investigations suggest that optimization techniques are highly effective for examining the mechanical characteristics of CFST-membered systems. Several international steel and composite codes already guide the design of circular CFST columns. Common examples of such requirements can be found in the European EN1994, the American AISC 360, and the Japanese AIJ standards. The key failure mechanism for slender columns is flexural buckling, and the design standards provide methods to predict the strength of this failure mode, as well as the compression capacity essential for short columns. Another noteworthy failure mechanism for thin-walled steel cross-sections is local buckling, in which the steel tube buckles locally. Typically, it is addressed by setting section slenderness restrictions and, based on those limits, either allowing a smaller efficient steel cross-sectional area, e.g., EN1994, or restricting the maximum stress a composite section can sustain, e.g., AISC 360. For the design standards of EN1994, AISC 360, and AIJ, the compression loads are calculated using the following equations, omitting any safety considerations:

$$N_p^{EN1994} = \begin{cases} \eta_a f_y A_s + \left(1 + \eta_c \frac{t f_y}{d \acute{f}_c}\right) \acute{f}_c A_c & ,\bar{\lambda} < 0.5 \\ f_y A_s + \acute{f}_c A_c & ,\bar{\lambda} \geq 0.5 \end{cases} \quad (1)$$

$$N_p^{AISC360} = f_y A_s + 0.95 \acute{f}_c A_c \quad (2)$$

$$N_p^{AIJ} = 1.27 f_y A_s + 0.85 \acute{f}_c A_c \quad (3)$$

where

N_p^{EN1994} =Axial capacity of the CFST column according to Eurocode 4 part 1- 1 [6].

η_a =Reduction factor for the steel section.

f_y =Yield strength of the steel.

A_s =Cross-sectional area of the steel tube.

η_c =Reduction factor for the concrete.

t =Thickness of the steel tube.

d =Diameter of the steel tube.

f_c =Compressive strength of the concrete.

A_c =Cross-sectional area of the concrete core.

λ =Slenderness ratio of the column.

$N_p^{AISC360}$ =Axial capacity of the CFST column according to AISC 360.

N_p^{AU} =Axial capacity of the CFST column according to the Australian Standard (AS 5100).

N_p =Nominal axial capacity of the CFST column.

Factors η_a and η_c are explanations for the element slenderness l.o. The compression loads listed above do not accurately depict the maximum compressive load for slender columns. When the global column slenderness is high, buckling phenomena develop, leading to early failure. In this context, the approaches outlined in the earlier design guidelines are distinguished. However, because of space constraints, the required expressions are not repeated here. All guidelines impose limitations on their variety of applications. Limits on material strength, global or overall slenderness, or the proportion of steel to concrete are among these. The applicable usage restrictions for the codes considered are shown in Table 1.

Table 1 Restrictions of the Application of Design Guidelines, Concerning CCFSTs.

Code	f_y, MPa	f'_c, MPa	Section slenderness	Other
EN1994	$235 \leq f_y \leq 460$	$25 \leq f_y \leq 50$	$\frac{d}{t} \leq 90 \frac{235\,MPa}{f_y}$	$0.2 \leq \frac{f_y A_s}{N_p} \leq 0.9$
AISC 360	$f_y \leq 525$	$21 \leq f_y \leq 69$	$\frac{d}{t} \leq \frac{0.31 E_s}{f_y}$	$A_s \leq 0.01 A_{sc}$
AIJ	$235 \leq f_y \leq 355$	$18 \leq f_y \leq 60$	$\frac{d}{t} \leq 1.5 \frac{23500\,MPa}{\sqrt{min\{f_y; 0.7 f_u\}}}$	$\frac{L_e}{B} \leq 50$

The present study aims to develop an optimization model to predict the axial compression capacity of CFST columns, particularly in composite structural buildings. The proposed model differs from previously developed models by considering a large number of data sets with CFST and concrete compressive strength to construct a new design model with a higher level of description, achieved using the grey wolf optimization algorithm. Steel tube thickness and column cross-sectional size, as well as steel yield stress and concrete compressive strength, are included in the input data. The suggested model was built and tested using existing test samples to identify the optimal prediction model for the topic under consideration.

2.RESEARCH SIGNIFICANCE

CFST design can be achieved utilizing a variety of approaches and codes worldwide. Developing a new type of analysis method, such as a soft computing-based surrogate model, is necessary to mitigate the drawbacks of the traditional design codes and empirical-based models, which are also commonly based on analytical and conservative approximations and calculations that do not necessarily capture all the interactions between the steel tube and concrete core in the CFST columns. Besides, the behavior of CFST columns is highly nonlinear and dependent on parameters, such as confinement and material properties, as well as geometric imperfections. It is not easy to predict them accurately with conventional methods. Therefore, the target of this research is to provide a workable solution to the aforementioned problem using the most recent computational techniques established by the grey wolf optimizer (GWO) approach. The GWO can achieve a higher accuracy by learning from experimental data and handling uncertainty, variability, and complex relationships. It is possible to create a new predictive model to analyze CFST designs more efficiently and precisely using GWO. The optimal solution to the suggested model, which satisfies these requirements, could be applied to new circumstances and yield results suitable for actual industrial implementations. The present model's key benefit is that it considers a broader range of data than earlier models, such as a wide range of compressive strengths and concrete and steel tube cross-section sizes (diameters).

3.METHODOLOGY

3.1.Data Setup

Through an extensive literature search, 561 circular specimens were collected and used to verify the proposed model. The parameters of these specimens are summarized in Table 2.

These sources comprise axial compression measurements of circular CFST columns. In these experiments, several geometric and mechanical characteristics were used to investigate the failure of CCFST columns under compressive loading. These geometric input variables are column diameter (D) and thickness (t). Moreover, the yield stress (f_y) is a material-specific characteristic that indicates mechanical qualities and the compressive strength of the filling concrete, denoted by the symbol (f_c'). The CFST column's ultimate experimental compressive load is the only output of the issue. A statistical analysis of the dataset is presented in Table 3.

Table 2 Summary of Test Data of Circular CFST Columns.

No. of specimens	D (mm)	t (mm)	f_y (MPa)	f_c' (MPa)	Source
6	140-300	2.0-6.5	232-350.4	27.15-31.15	[37] El-Heweity, 2012
3	114-219	2.19-2.86	335.7-350.4	42.7	[38] Yang and Han, 2006
1	120	1.77	286.7	63.4	[39] Yang and Ma, 2013
1	199.3	3.63	465	47.2	[40] Xiao et al., 2012
3	133-140	2.71-4.57	302-335	50.6	[41] Wang et al., 2015
2	139.1-168.9	2.79-2.86	339.6-388.5	41.2	[42] Tam et al., 2014
2	88.34-112	1.78-2.66	357.2	31.1	[43] Chen et al., 2014
1	114	1.74	300	42.6	[44] Shi et al., 2010
18	165-190	0.86-2.82	185.70-363.3	38.20-108	[24] O'Shea and Bridge, 2000
3	200-300	2-5	265.8-341.7	27.2-31.2	[45] Huang et al., 2002
9	150	2-4.29	268.21-311.17	18-28.7	[46] Tomii et all., 1977
8	300	4.5-11.88	348.1-420	27.8-42.6	[47] Sato, 1995
24	114.85-193.7	3-3.5	345.2-488.2	25.6-32.1	[48] Dundu, 2012
67	101.5-318.4	0.86-10.37	185.7-452	29.5-167.87	[28] Sarir et al., 2021
24	38.1-216	2.77-6.5	286.3-524	17.9-29.8	[49] Klöppel, 1957
11	38.1-76.2	1.24-2.77	524	17.9-27.9	[50] Salani and Sims, 1964
8	114.3-152.4	1.55-3.18	330.9-413.7	21-35.2	[51] Furlong, 1967
11	168.1-169.2	5-2.64	317.2-221.3	17.9-34.1	[52] Gardner, 1968
8	82.6-88.9	1.4-5.84	399.9-482.6	37-40.9	[53] Knowles and Park, 1969
17	95.3-218.5	3.7-6.5	281.5-302	37.1-42.2	[54] Guiaux and Janss, 1970
6	152	1.7	270-328	73-85	[55] Prion and Boehme, 1994
14	114	1.78-6.14	266-486	24-37	[56] Fujii, 1994
2	323.9	5.6	478	92.3	[21] Bergmann, 1994
5	165.2	4.5	413.90	40.9	[57] Matsui and Tsuida, 1996
10	133-108	1-4.7	232-368	77.4-84.7	[58] Tan et al., 1990
1	305.7	3	371	51.3	[59] Kilpatrick and Rangan, 1999
15	165-190	0.86-2.82	185.7-363.3	41-108	[24] O'Shea and Bridge, 2000
3	157.5-158.7	0.9-2.2	221-308	18.7	[60] Uenaka et al., 2003
12	114.4-114.9	5-3.82	343-365	34.7-104.9	[61] Giakoumelis and Lam, 2004
12	110-165	1.9-4.7	350-355	10-23.4	[62] Ghannam et al., 2004
26	122-450	2.96-6.47	279-843	25.4-85.1	[15] Sakino et al., 2004
17	100-200	3	303.5	58.5	[63] Han and Yao, 2004
6	165-219	2.72-4.78	350	42.6-77.2	[64] Yu et al., 2008
10	100	1.9	404	121.6	[65] Lee et al., 2011
2	159.00	6.00	235.00	37.7-120.1	[66] Yang and Han, 2012
2	114.30	2.70	235.00	56.2-66.8	[67] Chang et al., 2013
3	114.30	2.74	235.00	56.2-107.2	[68] Portolés et al., 2011
15	114.30	2.74-6	235	56.2-107.2	[69] Ekmekyapar and Al-Eliwi, 2016
10	159-1020	5.07-13.25	291.4-381.5	16.9-46	[70] Luksha and Nesterovich, 1991
12	174-179	3-9	249-383	22.1-45.7	[71] Sakino and Hayashi, 1991
10	297-301.5	4.5-11.88	347.9-399.8	27.7-82.40	[72] Kato, 1995
19	101.6-139.8	2.37-3	341-465.6	25.4-117	[73] Saisho and Nakaya, 1999
7	101.3-318.5	3.02-10.38	339-452	33.2-52.2	[74] Yamamoto et al., 2002
23	149-165	1-8	338-438	87.1-91.8	[75] Yu et al., 2002
6	114.3-115	3.75-5	365-365	38-105	[61] Giakoumelis and Lam, 2004
36	133.1-167.8	3.28-5.51	325-392	44.6-77.1	[76] Zhang and Wang, 2004
26	60-250	1.85-2	282-404	85-90	[63] Han et al., 2005
12	108-133	3.5-7	352-429	106-116	[77] Tan, 2006

3.2.Modeling Approaches

To create the best two-dimensional model for the ultimate strength of CCFST columns, optimization is required, and its creation must consider three crucial factors: (a) the formulation of the objective function; (b) the necessity for a precise approach to address the optimization issue; and (c) the definition of convergence criteria. The following subsections discuss these itemized points. The proposed approaches for axial strength forecast of CCFST columns consider the various considerations:

1) As closely as feasible, the formulas should match the experimental results.
2) The equations should be as user-friendly and straightforward as possible to use in any analysis.
3) The proposed formula corresponds to the relevant current design standards, allowing engineers to employ them with ease in the process of engineering design.

3.3.Fitness (Objective) Function

GWO's main purpose is to optimize the ultimate strength of the CCFST column model and to find the best set of unknown factors within the solution space. When applying the final form of the suggested model, the observed and forecasted ultimate capacities of the CCFST columns showed small differences. Convergence of the suggested model is achieved, and the search procedure is stopped once the coefficient that minimizes the objective function is found. To optimize the ultimate capacity of the circular CFST columns model, the proposed model is simulated using MATLAB 2021 [78]. As a result, there is little discrepancy between the measured ultimate strength and that determined using the optimized equations in their final form. The objective function of mean absolute error (MAE) is employed [79,80]. The following expression can be used to find this objective function:

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|NA - NP| \quad (4)$$

where NP is the estimated value, NA is the observed value, and n is the specimen's size for the datasets.

3.2.1. Grey Wolf Optimizer

The grey wolf optimizer (GWO) draws inspiration from the social system and the way those wolves hunt [44]. In the process of designing the GWO, the solution deemed to be the fittest is considered to be the alpha (α) wolf, achieved by imitating the social hierarchy found in grey wolves. The beta (β) and delta (δ) wolves, accordingly, represent the second- and third-best answers. The remaining candidate solutions have been given the designation of being the omega (ω) wolves. They have a very rigid social dominance hierarchy, as shown in Fig. 1, which is particularly relevant. The exploration (hunt) technique is governed by α, β, and δ, which are accompanied by the ω wolves. The primary stages of grey wolf hunting, based on Muro et al. [81], are as shown

- Following, chasing, and reaching the target (prey).
- Harassing, chasing, and circling the target till it comes to a stop.
- Attack on the target.

Figure 2 depicts these actions in detail. The social structure of grey wolves and their hunting approach is simulated in this work to create GWO and conduct optimization. When hunting, the grey wolves frequently circle their target. The following are the formulas that model this encircling behavior.

$$D = \left|C \cdot X_p(t) - X(t)\right| \quad (5)$$

$$X(t+1) = X_p(t) - A \cdot D \quad (6)$$

where t stands for the recent epoch, X_p represents the prey's location vector, and X describes the location vector of the grey wolf. The coefficient vectors A and C are evaluated from the following formulas:

$$A = 2 \cdot a \cdot r_1 - a \quad (7)$$

$$C = 2 \cdot r_2 \quad (8)$$

where during the search process, the elements of a linear decrease from 2 to 0, and the random vectors r_1 and r_2 are in the range [0, 1]. The GWO assumes that the α, β, and δ wolves have a greater understanding of the location of the target because the place of the best (target) in an abstract search space is unknown. Figure 2 illustrates potential prey positions for a grey wolf. The potential solutions in the GWO require using the equations below to update their locations following the locations of α, β, and δ.

$$D_\alpha = |C_1 \cdot X_\alpha(t) - X(t)|$$
$$D_\beta = |C_2 \cdot X_\beta(t) - X(t)| \quad (9)$$
$$D_\delta = |C_3 \cdot X_\delta(t) - X(t)|$$

$$X_1 = X_\alpha(t) - A_1 \cdot D_\alpha$$
$$X_2 = X_\beta(t) - A_2 \cdot D_\beta \quad (10)$$
$$X_3 = X_\delta(t) - A_3 \cdot D_\delta$$

$$X(t+1) = \frac{X_1+X_2+X_3}{3} \quad (11)$$

Due to its straightforward parameters and mechanism, the GWO can be easily implemented and begins with a random group of grey wolves. In a 2D search space, a search agent, which represents the wolf, updates its position following the top three wolves: alpha, beta, and delta, as shown in Fig. 3. Noting that alpha is the first best solution, beta is the second best solution, and delta is the third best solution. By directing the other wolves' movements, these three leaders conduct their search. In particular, each wolf determines how far away it is from alpha, beta, and delta, and then uses a weighted average of these influences to modify its position within a circle that is established by the locations of alpha, beta, and delta in the search space. The final location appears to have been chosen at random. This procedure successfully reduces the search region around the anticipated target position, as shown in Fig. 3, mimicking the encircling behavior observed in grey wolf hunting, in which the wolves gather around the prey's most likely position (the optimal solution). Alpha, beta, and delta thereby predict where the target will be, while other wolves update their positions randomly around the target.

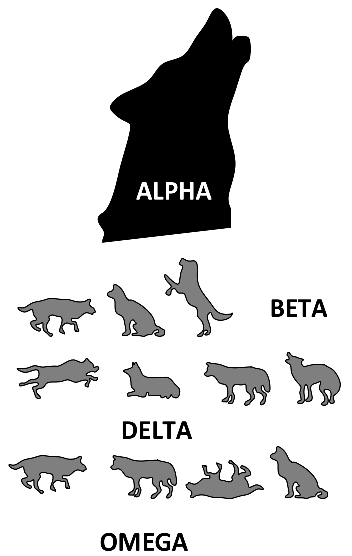

Fig. 1 The Order of the Grey Wolf Pack's Social Structure.

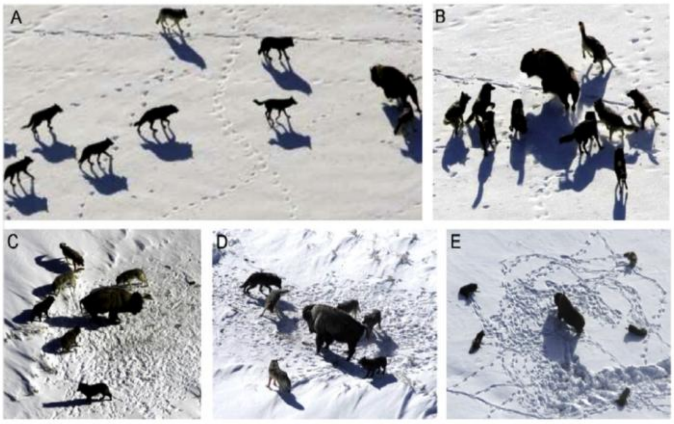

Fig. 2 Grey Wolf Hunting Techniques:
(A) Chasing, Reaching, and Tracking the Target, (B-D) Harassing, Encircling, and Pursuing, and (E) Fixed Situation and Attack [45].

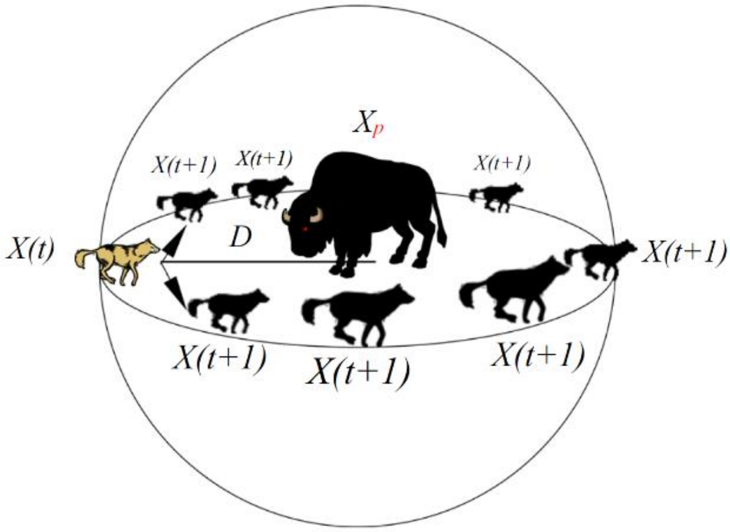

Fig. 3 The Numerical Formulas that Enable Location Updating Around a Pivot Point. Equation (5) Mathematically Models the Location Updating of a Grey Wolf (X(t)) Around a Prey (Xp). Depending on the Distance between the Wolf and the Prey (D), a Wolf can be Relocated in a Circle (in a 2D Space), Sphere (in a 3D Space), or a Hypersphere (in an N-D Space) Around the Prey (Xp) Using Eq. 5.

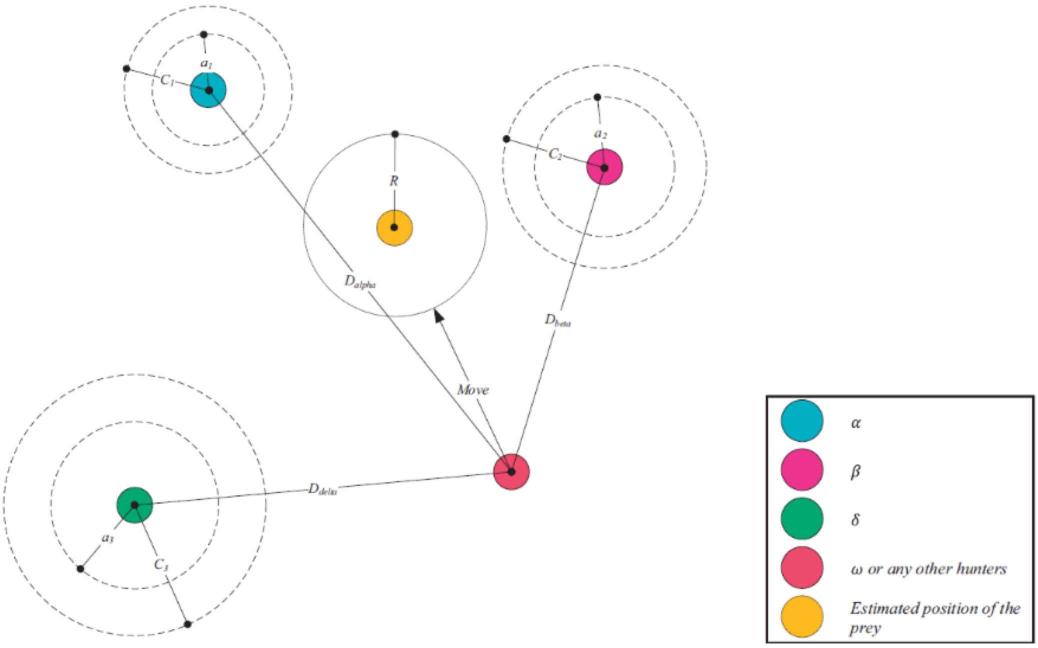

Fig. 4 Position Updating in GWO.

3.2.3.Convergence Criteria

Due to the GWO exploration's iterative process, conditions can be used to terminate the optimization. The number of epochs in the GWO algorithm and the minimum acceptable error required to determine the optimal value of the objective function are the two most well-known and widely used convergence criteria. The total number of iterations is determined by the level of complexity of the optimization problem, whereas the second criterion relies on the background experience of the overall perfect value. Mathematical problems can be utilized to evaluate or fine-tune an algorithm when the optimal value is known a priori. This technique, however, does not apply to real-world structural optimization issues where the optimum is unknown beforehand. Table 3 lists several key GWO parameters.

Table 3 Main GWO Parameters.

Description	Details
Number of agents, N	The usual range is 10 to 40 agents. The range can be raised to 50–100 for some particularly difficult or unique issues.
Dimension of agents, D	It is evaluated by the optimization issue.
Vectors comprising the peak (upper) and lowest (lower) values of the n design variables.	The problem that needs to be optimized determines them. In general, different ranges can be applied for agents with different dimensions.

3.2.4.GOW for the Ultimate Strength of The Circular CFST Column

The effects of several factors, i.e., steel tube thickness (t), column cross-sectional diameter (D), steel yield stress (f_y), and concrete compressive strength (f_c), were considered when developing the model to provide a precise assessment of the compressive strength of the CCFST column. The GWO technique was used in the present study to establish the following meaningful connection between the axial compression capacity of the CFST column (N_{GWO}) and the aforementioned variables:

$$N_{GWO} = f\left(t, D, f_y, f_c\right) \quad (12)$$

To improve the ultimate strength model, the suggested system is modeled utilizing MATLAB 2021 [78]. The following describes the final model that will be optimized:

$$N_{GWO} = \left(F_1\, f_c\, A_c + \frac{F_2\, t}{(D+F_3\, t)} f_y\, A_s\right) \times 10^{-3} \quad (13)$$

where N_{GWO} is the forecast ultimate strength of the CCFST column, t is the steel tube section's thickness, D is the diameter of the circular steel tube section, f_y and f_c are the steel tensile yield strength and concrete compressive strength, respectively. Three elements are considered for each agent (wolf) in the suggested model: F_1, F_2, and F_3. The proposed model utilizes the values obtained for these variables to reduce forecast error in the ultimate capacity of CCFST columns. The suggested model's flowchart is depicted in Fig. 5.

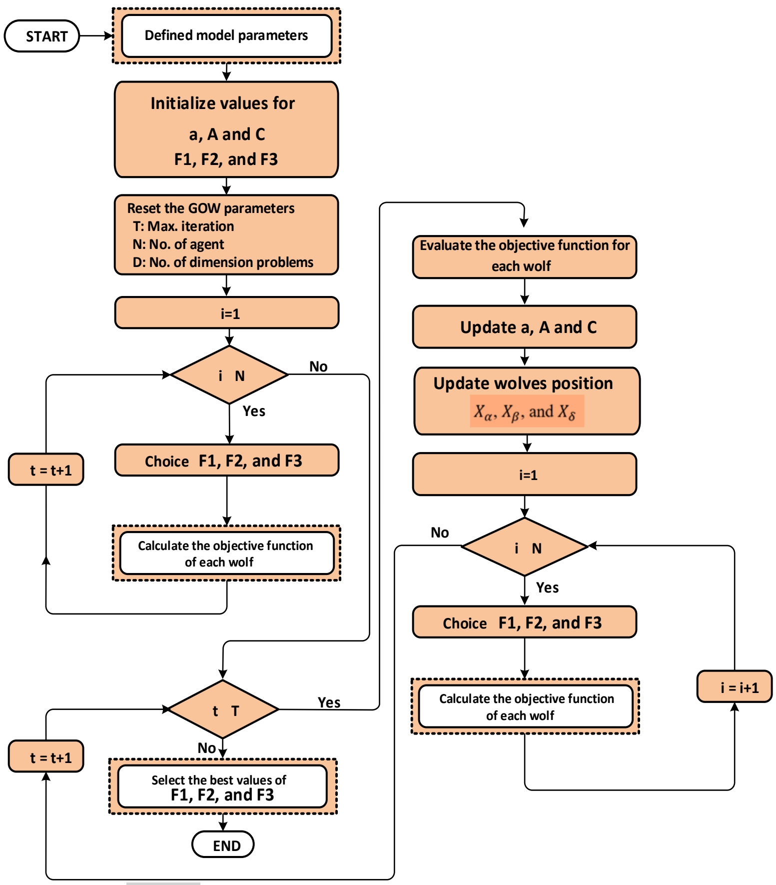

Fig. 5 Flowchart of the Proposed Algorithm.

4.RESULTS AND DISCUSSION

4.1.Establishing The Proposed Model

The main objective herein is to develop a reliable and robust model using the GWO approach to predict the ultimate strength of CFST connections. The ability of models developed employing computational intelligence techniques to estimate within the data range used for their development is well established. Therefore, the dataset size utilized during simulation is a crucial factor, as it significantly affects the accuracy of the final model. A building dataset and a validation dataset used to validate the model after development were created from the entire database. 449 of the 561 investigated (Table A1) CCFST specimens (or 80%) were used to model construction, and the residual 112 samples (or 20%) were applied to evaluate the proposed model [27]. To overcome this restriction, Frank and Todeschini [95] claimed that the optimal number of objects specified for a model to be considered acceptable is 3. They argue that considering a number of 5 is better. In the present study, this proportion is considerably greater and equals 449/4, or about 112.25. By establishing the objective function for 40, 60, 80, and 100 wolves, as shown in Fig. 5, the GWO algorithm was applied. To enable the GWO algorithm to select wolves that achieve the lowest inaccuracy (error) and time duration, multiple wolf sizes are incorporated. The mean absolute error (MAE) was applied as the objective function to select an appropriate objective. In addition, the sizes of four wolves, i.e., 40, 60, 80, and 100, were studied. The GWO search algorithm continues until the specified convergence criterion is satisfied. Due to the changes in the objective functions, the number of epochs in the present investigation was restricted to 5000. As shown in Fig. 5, the search was steady after 4100 epochs. To determine which wolf size minimizes error and convergence time, a variety of wolves were investigated. Figure 5 depicts that the 100 wolves provide the optimal GWO solution, achieving the minimum objective function value, as presented in Table 4. The optimal values for the coefficient factors demonstrated in the proposed model are listed in Table 4. Based on the observed findings, this table indicates that the suggested model's load capacity of CCFST column prediction is reliable. The reasonable assumption of Pimentel-Gomes [96] states that when the CoV value of a model is less than 10%, it denotes high accuracy, while values of 10-20% state good accuracy, values between 20-30% reflect minimal sensitivity, and values over 30% are thought to reflect minimal accuracy. This criterion is displayed between the forecasted and observed values. For the designed suggested models, an adequate CoV of roughly 16.89% (100 wolves) was observed, indicating better accuracy and confirming the correctness of the target value. Additionally, the suggested model's close mean value, i.e., 1.08, in Table 6 demonstrates its correctness and robustness. Considering the relationship between the observed and estimated values in light of the following considerations, Smith [97] proposed restrictions to measure the precision of the mathematical model's efficiency by applying the correlation coefficient (R) in 1986:

- A strong relationship is identified if |R| > 0.8.
- A good relationship is identified if 0.2 |R| > 0.8.
- A weak relationship is identified if |R| is 0.2.

Figure 6 depicts the correlation between the measured and the predicted strength capacity of concrete-filled steel tube (CFST) columns based on the proposed GWO-based model. The regression coefficient (R) of 0.9663 indicates a strong correlation between the observed and forecast values, and thus, the model's predictive accuracy is very high. This high value of R indicates that the model efficiently captures the intricate relationships among model input parameters, e.g., geometric dimensions, material properties, and the final strength capacity of CFST columns. The close alignment of the data points along the diagonal line, where predicted values equal actual values, further confirms the model's reliability. The small scatter of data points around this line suggests that the model can consistently and accurately predict across a wide range of experimental measurements. This behavior is especially relevant to the differences in material characteristics and geometrical arrangements of the CFST column entries in the dataset. The excellent performance of the GWO-based model can be attributed to the optimization of membership functions and model parameters, which were fine-tuned using the grey wolf optimizer. This optimization procedure ensures that the model has the lowest prediction error, thereby making it robust and reliable for real applications. Additionally, the findings demonstrate the advantage of the proposed model over conventional statistical and empirical approaches and design codes that typically rely on approximate assumptions and fail to explicitly account for the nonlinearities of CFST columns. The high R-value and low error measures (RMSE, MAE) indicate the model's robustness for complex real-world applications, such as high-strain materials and non-axisymmetric shapes. In conclusion, Fig. 7 demonstrates that the GWO-based model provides a highly accurate and reliable tool for predicting the ultimate strength capacity of CFST columns. This tool is effective for engineers and designers who want to maximize the performance and safety of $CFST$ structures in contemporary construction.

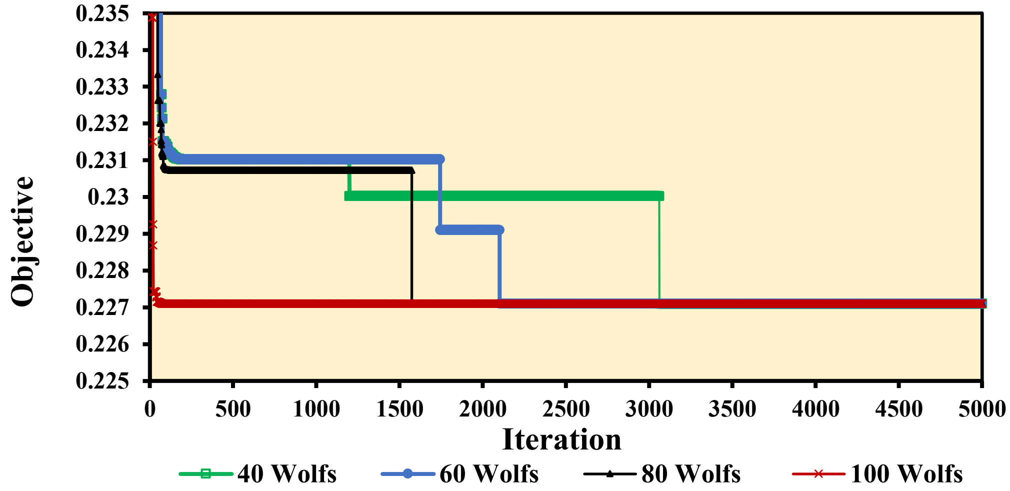

Fig. 6 Convergence Procedure for Various Sizes of Wolves.

Table 4 The GWO Algorithm's Best Estimates of the Unknown Coefficients' Values.

Parameters	100 Wolfs
F_1	1.21
F_2	2.66
F_3	9.33
M	1.08
SD	0.18
CoV %	16.89

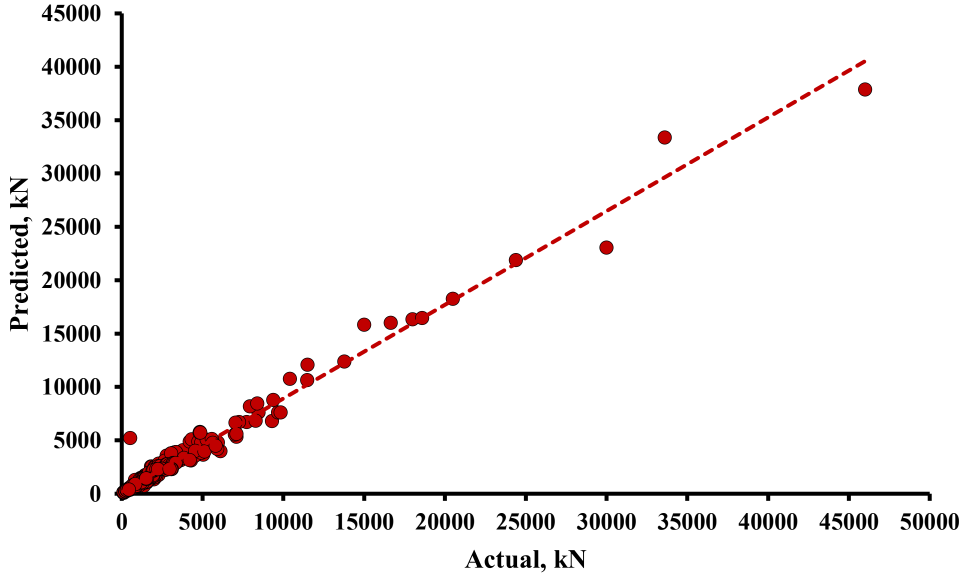

Fig. 7 Comparison Utilizing the Suggested Model between the Estimated and Actual Ultimate Load of the CCFST Column Capacity.

4.2. Verification of The Proposed Model

The designed model's effectiveness was evaluated to validate the data. 130 tested samples in total (20% of all datasets) were assessed. Their data were used for the model's verification rather than for the proposed model's optimization phase. Figure 8 reveals that the ultimate capacity estimated by the proposed model agrees with the experimental results. The suggested model accurately and consistently estimated a mean value of 1.04, a standard deviation of 0.18, and a coefficient of variation (*CoV*) of 17.5%. Comparisons between the predicted and observed results are shown in Fig. 7. These comparisons imply that the proposed model is reasonably reliable. A *CoV* value of 17.5%, as shown in the preceding subsection, denotes that the suggested model's anticipated results are extremely precise and consistent. The proposed model's mean value was extremely close to 1.0 (1.04), and the R-value (0.9843) in Fig. 7 demonstrates a strong relationship between the observed and predicted ultimate strengths. To accurately forecast the capacity of a CCFST column while accounting for various material properties, the proposed model was developed.

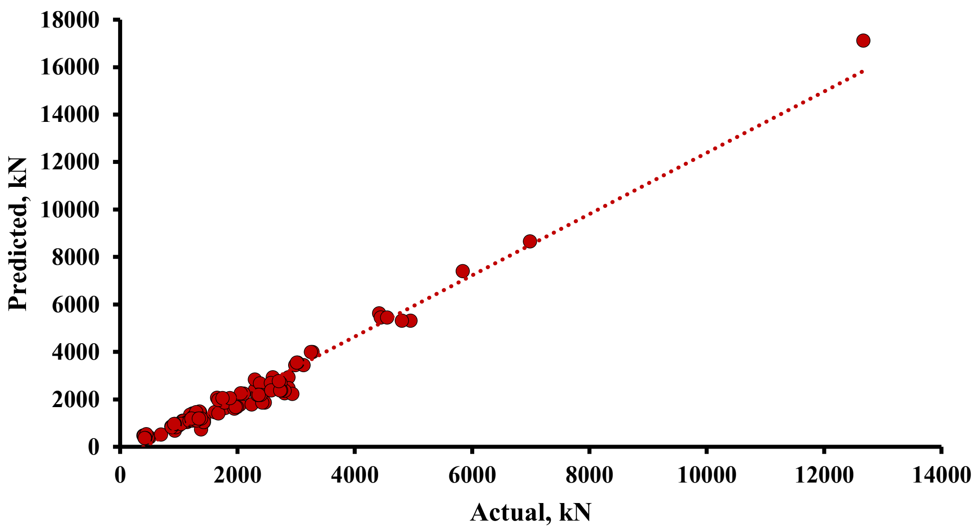

Fig. 8 Comparison of the Observed and Expected Values for the CCFST's Ultimate Capacity.

4.3. Model Validity

The proposed model was externally verified on the testing datasets using the new requirements suggested by [82]. Regression lines (k or k') across the origin seem to require at least one slope to be closer to 1.0 [83]. A confirmatory index of additional model reliability (R_m) was established [84]. The criterion is met if R_m > 0.5. The coefficient of correlation (R) ought to be near 1.0 between simulated and experimental values. Table 5 displays the appropriate model findings as well as the validation criteria considered. As seen, the constructed model meets the essential conditions. All suggested conditions are satisfied by the constructed GWO model.

Table 5 The Suggested Model's Statistical Specifications for Extra Verification.

Item	Equation	Condition	Suggested model
1	$R = \frac{\sum_{i=1}^{n}(PDA_i - \overline{PDA_i})(PDE_i - \overline{PDE_i})}{\sqrt{\sum_{i=1}^{n}(PDA_i - \overline{PDA_i})^2 \sum_{i=1}^{n}(PDE_i - \overline{PDE_i})^2}}$	$R > 0.8$	0.9843
2	$k = \frac{\sum_{i=1}^{n}(PDA_i \times PDE_i)}{{PDA_i}^2}$	$0.85 < k < 1.15$	1.20
3	$\acute{k} = \frac{\sum_{i=1}^{n}(PDA_i \times PDE_i)}{{PDE_i}^2}$	$0.85 < k' < 1.15$	0.84
4	$R_m = R^2 \times \left(1 - \sqrt{\lvert R^2 - R_o^2 \rvert}\right)$	$R_m > 0.5$	0.70

Where: $R_o^2 = 1 - \frac{\sum_{i=1}^{n}(PDE_i - PDA_i^o)^2}{(PDE_i - \overline{PDE_i})^2}$, $PDA_i^o = k \times PDE_i$

4.4. Error Evaluation

The proposed model, as previously mentioned, was developed to forecast the maximum strength of a CCFST column. It was suggested that the distribution of the relative errors be evaluated when comparing model prediction abilities [85]. Therefore, the following formula is used to calculate the absolute relative error (ARE) %:

$$ARE\% = \left|\frac{NA_i - NP_i}{NA_i}\right| \times 100 \qquad (14)$$

The ARE variation, including the suggested model, is displayed in Fig. 9. The frequency depicted in the figure should reduce as ARE increases. The designed model has the lowest number of ARE values that are significant (ARE > 30 %) and the highest number of ARE values that are less significant (ARE 25 %). The designed model provides reasonable error levels, as shown in Fig. 9.

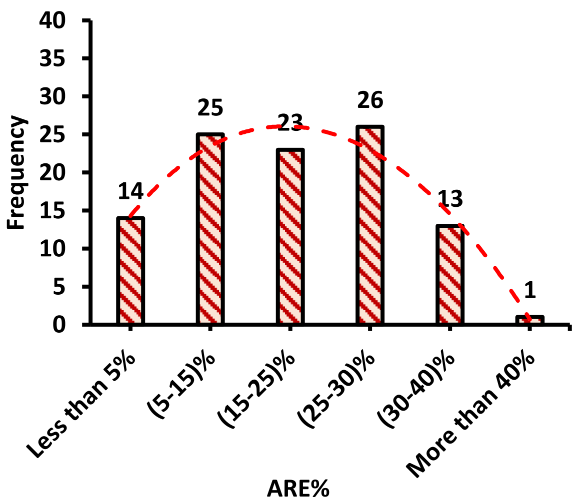

Fig. 9 ARE Distribution of the Proposed Model.

4.5.Analysis of Factors Influencing Axial Load Capacity in CFST

Figure 10, which presents the Pareto chart [86], shows the normalized effect of the various factors on the experimental axial load capacity (P_{exp}) of concrete-filled steel tube (CFST) with a significance level (α) of 0.05. The chart may be employed to identify which factors contribute most to the response variable (P_{exp}). The factors analyzed include the diameter of the column (D), length (L), thickness of the steel tube (t), cross-sectional area of the steel tube (A_s), cross-sectional area of the concrete core (Ac), yield strength of the steel (f_y), and compressive strength of the concrete (f_c). The vertical line at 1.97 represents the statistical significance level; any variable with a standardized effect value greater than this is considered significant. Obviously from Fig. 10, the diameter (D) and thickness (t) of the column and steel tube have the greatest standardized effect, indicating that these parameters may be the principal influencing factors of the axial load capacity of the CFST columns, which is not surprising because larger diameters and thicker steel tubes usually have better load-resistance properties due to larger volumes and tighter confinement effects. The yield strength of the steel (f_y) and the compressive strength of concrete (f_c) are also notable, however, less dominant, influences compared to D and t, and are directly responsible for column strength; the greater the strength, the larger the load capacity. The values in the column length (L) and the cross-sectional areas (A_s and A_c) appear to have a relatively small influence and appear to suggest that although they are part of the structural behavior, their contribution to the axial load-carrying capability is not as important as that of the other parameters. In conclusion, the Pareto chart provides valuable insights into the relative importance of different factors affecting the axial load capacity of CFST columns. The results show that the geometrical parameters, namely the steel tube diameter and thickness, and material parameters, e.g., steel modulus of elasticity and concrete compressive strength, are the primary controlling parameters. For the engineer/designer, this data is of great importance because it informs the optimization of CFST columns and guides the selection of parameters that improve structural performance and efficiency. The ability to learn these relationships allows for more accurate predictions and ultimately more informed decisions about structure design, a process that can eventually lead to safer and cheaper structures.

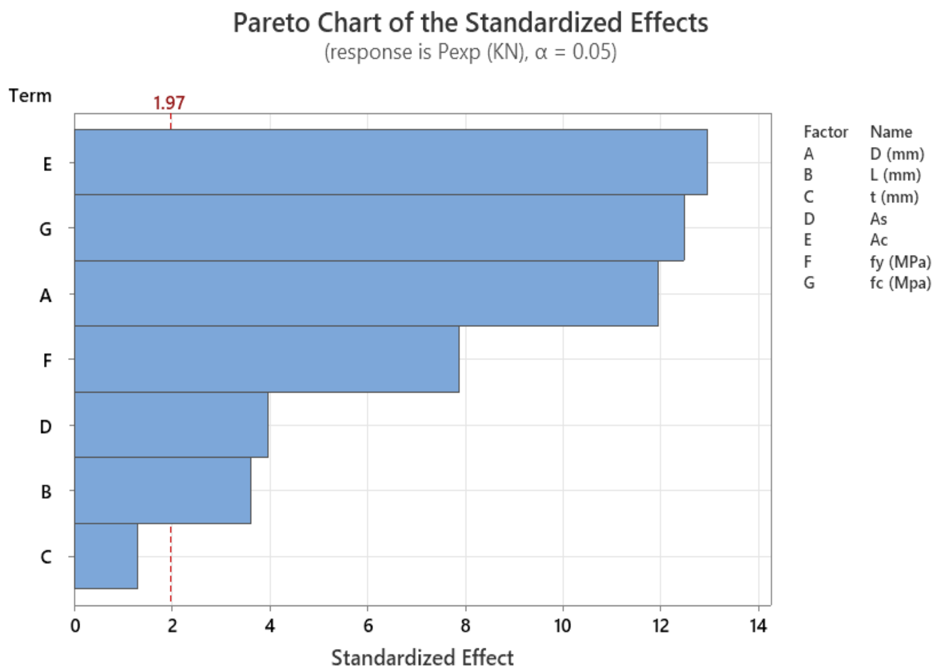

Fig. 10 Pareto Chart for the Normalized Effect of the Various Factors on the Axial Load Capacity of Concrete-Filled Steel Tube (CFST).

4.6.Limitations and Future Works

The GWO technique was used in the present study to develop the best possible model for forecasting the maximum axial strength of CCFST columns. This model is based on datasets from previously conducted laboratory studies. The types of parameters must be considered when collecting and analyzing such data, because the number of parameters substantially affects the structure of the models. Moreover, the goal of this research is to develop a nonlinear model to achieve greater precision in evaluating the target parameter. As a result, it is necessary to balance the dataset inputs and their statistical features, enabling the analysis of a broader range of data and the creation of models with greater capability. The final strategic goal of the current study is to design a new model with greater generality, for instance, by increasing the dataset size with a circular cross-section.

5.CONCLUSIONS

In the present research, the ultimate strength of CCFST columns is accurately assessed using a novel GWO-based prediction model. A large database of 561 laboratory investigations on circular CFST columns was compiled from publicly accessible literature. The effectiveness and accuracy of the findings were assessed using statistical and visual explanations, and the aforementioned conclusions can be drawn.

- The study effectively developed a GWO-based model for accurately predicting the final strength of circular CFST columns. It can offer an optimal solution for predicting ultimate strength values utilizing a variety of parameters with acceptable precision.
- 130 experimental test samples were used to validate the suggested model, and the results showed a high degree of agreement between the anticipated and observed values, indicating the model's suitability for practical use.
- Using the suggested model for ultimate strength, the coefficient of variation (CoV), mean, and correlation coefficient (R) were found to be 16.89, 1.08, and 0.9663, respectively, demonstrating the high precision and consistency of the results. As a result, it has been hypothesized that the proposed model can accurately predict CCFST's ultimate strength.
- The screening analysis of the Pareto chart shows that the steel tube diameter (D) and thickness (t) are the dominating controllable variables that determine the axial load capacity (P_{exp}) of CFST columns, followed by the steel yield strength (fy) and concrete compressive strength (f_c). Length (L) and cross-sectional areas (A_s and A_c) have a relatively modest influence. These outcomes emphasize the need to characterize the geometric constraints and material properties that enhance CFST column performance. To address the following challenges, the designer can increase design efficiency, accuracy, and structural security, thereby enabling more economical and reliable construction.
- Additional experimental studies should be conducted to examine and revise the suggested ultimate strength of the CFST model and to analyze a wider range of variables.
- The model's final results, however, might be significantly affected by a more complex and expansive database. Additionally, the proposed models in the present research can also be used to investigate the geometries of various CFTS sections, including squares and squares with round ends. Using an optimization model based on closed-form formulas for this problem will be very helpful to engineering in the future.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Suha Rasheed Abbas: Original writing, Investigation, Funding, writing &editing. *Ammar N. Hanoon*: Project administration, Conceptualization, Methodology, Resources. *Ali A. Abdulhameed*: Administration Writing & editing, Supervision, review, Resources. *Mahir M. Hason*: Correspondence, Administration, Investigation, Review & editing, Resources. *Haitham Jameel Abed*: Writing, Resources, Methodology, Review & editing.

DECLARATION OF COMPETING INTEREST

The authors declare no conflict of interest.

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