

Research Article

Ultimate Axial Strength of Concrete-Filled Double Skin Steel Tubular Column Sections

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This study aims at proposing a new model for evaluating the ultimate axial strength of concrete-filled double skin steel tubular (CFDST) composite columns. For this, a total of 103 experimental data regarding the ultimate strength of CFDST columns under axial loading were collected from the previous studies in the literature. All CFDST columns consist of two steel tubes being outer and inner circular hollow section. The model presented herein was developed by using gene expression programming. For this, the yield strength, diameter, and thickness of both outer and inner steel tubes, the compressive strength of annulus concrete, the length of the specimen, and the ultimate axial strength of the columns were utilized as the parameters. Assessment of the obtained results indicated that the generated model had a good performance compared to the existing models by the previous researchers and the equations specified in the design codes. The high value of R^2 and narrow ranged fluctuation of the estimation error for the ultimate axial strength of the CFDST columns were also achieved through the proposed model.

1. Introduction

Concrete-filled steel tube (CFT or CFST) considered as an important structural element is largely used in constructing the composite structures, owing to their high strength and good deformability [1]. Concrete-filled double skin steel tubular (CFDST) members that can be accepted as a new generation of traditional CFST members differ from the conventional ones. CFDST members include outer and inner steel tubes having a concrete infill between them, whereas the traditional CFST members are composed only of a steel tube and concrete infill [2]. Although the double skin composite construction concept had firstly been designed for the utilization in submerged tube tunnels [3], later it was accredited as constructional member due to a potential which may be benefited for nuclear power plants, liquid and gas retaining structures, and blast resistant shelters [4, 5]. Moreover, CFDST members can be applied for vessels to resist the external pressure, for the legs of offshore constructions, for columns and structures with large diameters exposed to the loads caused by ice [6-9].

CFST and CFDST members having the advantage of being economical and quick construction can be built in several shapes as schematically shown in Figure 1. For example, as seen in Figures 1(c) and 1(d), the symbols B_{0} , D_0 and B_i , D_i are used to indicate the dimensions of outer and inner steel tubes, respectively. The thicknesses are represented by t_0 for the former and t_i for the latter. Mainly, CFDST members are composed of two thin steel tubes, which are concentrically situated, and a concrete annulus as a filling material. In the past, a large number of studies were conducted on this kind of elements to examine the possibility to be applied for different practices [1, 7, 9-14]. It was acquired from these studies that the similar behaviors as in the CFST members were observed in the CFDST members [15]. Besides, via the hollow section of CFDST elements, a reduced structure weight is achieved while a large energy absorption capacity is still maintained [1, 15].

In addition to having lower self-weight, CFDST has higher bending stiffness, ductility, strength. and cyclic performance [16–20]. One of the most significant benefits of



FIGURE 1: Concrete-filled tubular columns. (a) Single skin circular section, (b) single skin square section, (c) double skin circular outer and inner tubes, (d) double skin square outer and inner tubes, (e) double skin circular outer and square inner tubes, and (f) double skin square outer and circular inner tubes.

using CFDST members in the structure is that it has a reasonable fire resistance because of the lower temperature of inner tube. This can be provided by the protection of inner tube from the fire by concrete annulus [13, 15, 21]. In high-rise buildings, the architects may use the CFDST columns by configuring the center of the columns in order to be able to utilize for the purpose of some services, such as downspouts or electrical wiring [22].

The study herein aims to obtain a reliable mathematical model that estimates the ultimate axial strength of CFDST columns. For this, a wide experimental dataset was created to improve the sensibility of the developed model. Totally 103 data from the previous studies available in the technical literature were collected. During the development of the model, the axial loading condition for the CFDST column was considered, as shown in Figure 2. The yield strength,



FIGURE 2: Specimen details and loading condition of CFDST columns.

diameter, and thickness of both outer and inner steel tubes, the compressive strength of annulus concrete, and the length of the specimen were selected as input parameters. The output parameter, which is the aim of the model, is the ultimate axial strength of CFDST columns. Gene expression programming (GEP) was used to generate the model that can predict the ultimate axial strength of this type of the columns. The results obtained from this model were comparatively assessed with the results achieved from the experimental tests as well as the equations modified from the design codes and some equations proposed by the other researchers.

2. Previous Equations

One of the assessment criteria for the estimation model in the current study is the comparison of the predicted ultimate axial strength results with the results determined from the equations available in the literature. Therefore, the equations that determine the ultimate axial strength of CFDST columns are summarized as follows.

2.1. ACI Equation. ACI code [23] proffers an equation by which the ultimate axial strength of single skin composite columns containing a reinforcing bar can be determined. However, the concrete confinement effect is disregarded in formula suggested by ACI code. The equation modified from ACI code for determination of the ultimate axial strength of the CFDST stub column involving the contribution of the inner steel tube is expressed as follows [23]:

$$(P_{\rm u})_{\rm ACI} = f_{\rm syo}A_{\rm so} + 0.85f_{\rm c}A_{\rm c} + f_{\rm syi}A_{\rm si}, \tag{1}$$

where $f_{\rm syo}$ and $A_{\rm so}$ are the yield strength and the crosssectional area of the outer steel tube, respectively, $f_{\rm c}$ and $A_{\rm c}$ are the compressive strength and the cross-sectional area of the concrete annulus, respectively, and $f_{\rm syi}$ and $A_{\rm si}$ are the yield strength and the cross-sectional area of the inner steel tube, respectively.

2.2. Eurocode 4 Equation. Eurocode 4 (EC4) [24] suggests equations for estimating the ultimate axial strength of the CFST columns. However, these equations were proposed for column section consisting of the outer steel tube, concrete, reinforcing bars, and also confinement effect. EC4 [24] approach has two different equations according to relative

slenderness criteria. The recommended formula to determine the ultimate axial strength of CFST columns as regards two relative slenderness criteria is given as follows [24]:

When $\overline{\lambda} > 0.5$,

$$P_{\rm u} = f_{\rm yd}A_{\rm a} + f_{\rm cd}A_{\rm c} + f_{\rm sd}A_{\rm s}.$$
 (2)

When $\overline{\lambda} \leq 0.5$,

$$P_{\rm u} = \eta_{\rm a} f_{\rm yd} A_{\rm a} + f_{\rm cd} A_{\rm c} \left[1 + \eta_{\rm c} \left(\frac{t}{D} \right) \left(\frac{f_{\rm y}}{f_{\rm ck}} \right) \right] + f_{\rm sd} A_{\rm s}, \quad (3)$$

where f_{yd} and A_a are the design yield strength and crosssectional area of the structural steel, respectively, f_{cd} and A_c are the design compressive strength and the cross-sectional area of the concrete, respectively, f_{sd} and A_s are the design yield strength and the cross-sectional area, respectively, t and D are the thickness and the diameter of the structural steel, respectively, f_y is the nominal yield strength of the structural steel, and f_{ck} is the characteristic compressive strength of the cylinder concrete at 28 days.

The approach in EC4 [24] uses an attenuation coefficient, η_{a} , and an improvement coefficient, η_c , for the crosssectional resistance contributed by the steel and the concrete, respectively. These are used to take confinement effect of concrete in account. In these formulations, the reinforcement part was considered as a second steel skin, firstly. For this reason, in equation (3), the strength provided by this section was multiplied with η_a , the factor related to the confinement of concrete as recommended by Pagoulatou et al. [25]. Then, terminological conversion was carried out. Finally, the following expressions were obtained for both conditions:

When $\overline{\lambda} > 0.5$,

$$(P_{\rm u})_{\rm EC4} = f_{\rm syo}A_{\rm so} + f_{\rm c}A_{\rm c} + f_{\rm syi}A_{\rm si}.$$
 (4)

When $\overline{\lambda} \leq 0.5$,

$$(P_{\rm u})_{\rm EC4} = \eta_{\rm a} f_{\rm syo} A_{\rm so} + f_{\rm c} A_{\rm c} \left[1 + \eta_{\rm c} \left(\frac{t_{\rm o}}{D_{\rm o}} \right) \left(\frac{f_{\rm syo}}{f_{\rm c}'} \right) \right] + \eta_{\rm a} f_{\rm syi} A_{\rm si},$$
(5)

where D_o and t_o are the diameter and the thickness of the outer steel tube, respectively, and η_a and η_c are the attenuation coefficient for the cross-sectional resistance provided by the steel and the improvement coefficient of the concrete contribution, respectively.

$$\eta_{\rm a} = 0.25 (3 + 2\overline{\lambda}), \quad (\text{but } \le 1.0),$$
 (5.1)

$$\eta_{\rm c} = 4.9 - 18.5\overline{\lambda} + 17\overline{\lambda}^2, \quad (\text{but} \ge 0), \tag{5.2}$$

where $\overline{\lambda}$ is the relative slenderness and to be determined by the following expression:

$$\overline{\lambda} = \sqrt{\frac{P_{\text{pl,Rd,}(6.30)}}{P_{\text{cr}}}},$$
(5.3)

where $P_{\text{pl,Rd,}(6.30)}$ is the plastic resistance in characteristic value given in EC4 (2004) as 6.30th equation and to be determined by the following expression:

$$P_{\rm pl,Rd,(6.30)} = f_{\rm syo}A_{\rm so} + 0.85f_{\rm c}A_{\rm c} + f_{\rm syi}A_{\rm si}.$$
 (5.4)

 $P_{\rm cr}$ is the elastic critical normal force for relevant buckling mode and to be determined by the following expression:

$$P_{\rm cr} = \frac{\pi^2 \,(\rm EI)_{\rm eff}}{\left(KL\right)^2},\tag{5.5}$$

where *K* is the effective length factor (for pin-pin connection can be taken as 1.0), L is the laterally unbraced length of the member, and EI_{eff} is the effective stiffness of composite section and to be calculated by the following expression:

$$\mathrm{EI}_{\mathrm{eff}} = E_{\mathrm{so}}I_{\mathrm{so}} + K_{\mathrm{c}}E_{\mathrm{cm}}I_{\mathrm{c}} + E_{\mathrm{si}}I_{\mathrm{si}}, \qquad (5.6)$$

where E_{so} and I_{so} are the elastic modulus and the second moments of area of outer steel tube section, respectively, K_c is a correcting coefficient that should be taken as 0.6, $E_{\rm cm}$ and $I_{\rm c}$ are the elastic modulus and the second moments of area of concrete annulus, respectively, and E_{si} and I_{si} are the elastic modulus and the second moments of area of inner steel tube section, respectively.

Herein, the elastic modulus of concrete could be determined by the following empirical expression provided by ACI [23]:

$$E_{\rm cm} = w_{\rm c}^{1.5} 0.043 \sqrt{f_{\rm c}},\tag{5.7}$$

where w_c is the unit weight of the concrete (between 2300 and 2500 kg/m^3).

After calculating the ultimate axial strength of the CFDST columns, the strength value should be multiplied with the reduction coefficient (χ). The formula for the reduction coefficient as regards Eurocode 3 (EC3) [26] is as follows:

$$\chi = \frac{1}{\phi + \sqrt{\phi^2 - \overline{\lambda}^2}}, \quad \text{but } \chi \le 1.0, \tag{6}$$

where

$$\phi = 0.5 \left[1 + \alpha \left(\overline{\lambda} - 0.2 \right) + \overline{\lambda}^2 \right], \tag{6.1}$$

where α is an imperfection factor depending on a buckling curve and can be taken from Table 6.1 given in EC3 [26]. As Hassanein and Kharoob [27] mentioned in their study, the imperfection factor was taken according to buckling curve (b) as 0.34.

2.3. AISC Equation. The equations by AISC [28] are suggested for the single skin composite columns involving reinforcing bars. AISC [28] also recommends two different conditions for the determination of the ultimate axial strength of encased composite columns that subject to axial loading: In the case of $P_{\rm e} < 0.44 P_{\rm o}$,

$$(P_{\rm u})_{\rm AISC} = 0.877 P_{\rm e},$$
 (7)

where

(= 1)

$$P_{\rm e} = \frac{\pi^2 \left({\rm EI} \right)_{\rm eff}}{\left(KL \right)^2},\tag{7.1}$$

where $(EI)_{eff}$ can be calculated by using equation (5.6) with a small alteration in the correction factor, K_c :

$$K_{\rm c} = 0.6 + 2 \left(\frac{A_{\rm so}}{A_{\rm c} + A_{\rm so}} \right) \le 0.9.$$
 (7.2)

In the case of $P_e \ge 0.44P_o$,

$$(P_{\rm u})_{\rm AISC} = P_{\rm o} \left[0.658^{\left(P_{\rm o}/P_{\rm e} \right)} \right], \tag{8}$$

where

$$P_{\rm o} = f_{\rm syo}A_{\rm so} + 0.95f_{\rm c}A_{\rm c} + f_{\rm syi}A_{\rm si}.$$
 (8.1)

Herein, in the calculation of P_{o} and P_{e} , a steel tubular section instead of reinforcing bars was considered as second skin. After these modifications, P_0 and P_e can be expressed as mentioned above.

2.4. Equation Proposed by Uenaka et al. In addition to modifying the formula recommended by the codes, some researchers proposed equations for the calculation of the ultimate axial strength of the CFDST columns. Uenaka et al. [1] are few of these researchers who derived the equation determining the ultimate axial strength of the CFDST columns from the equation that was proposed by AIJ [29] for CFST stub columns. Uenaka et al. [1] elementally superimposed the strengths of both outer and inner steel tubes and the sandwiched concrete. The following expression was first asserted to temporarily predict the ultimate axial strength of CFDST:

$$P_{\rm u} = f_{\rm syo}A_{\rm so} + f_{\rm c}A_{\rm c} + f_{\rm syi}A_{\rm si}.$$
 (9)

After the experimental tests, it was overemphasized that the confinement effect provided by inner tube on the ultimate axial strength of the CFDST columns is not effective as much as that provided by outer tube [1]. Regarding the test results, the estimated ultimate axial strength derived from AIJ [29] is modified to the following expression by Uenaka et al. [1]:

$$(P_{\rm u})_{\rm Uenaka\,et\,al.} = \left(2.86 - 2.59 \left(\frac{D_{\rm i}}{D_{\rm o}}\right)\right) f_{\rm yo} A_{\rm so} + f_{\rm c} A_{\rm c} + f_{\rm yi} A_{\rm si},$$
$$\cdot \left(0.2 < \frac{D_{\rm i}}{D_{\rm o}} < 0.7\right),$$
(10)

where D_i is the diameter of the inner steel tube.

2.5. Equation Proposed by Han et al. [30] also proposed an equation regarding the inner tube capacity and a capacity containing the concrete annulus with the outer steel tube. The formula suggested is as follows:

$$(P_u)_{\text{Han et al.}} = P_{\text{osc,u}} + P_{i,u}, \qquad (11)$$

where $P_{i,u}$ is the strength capacity supplied by the inner steel tube and to be calculated by the following expression:

$$P_{i,u} = f_{syi}A_{si}, \qquad (11.1)$$

where $P_{\text{osc,u}}$ is the strength capacity supplied by the outer steel tube and concrete annulus and to be determined by the following expression:

$$P_{\rm osc,u} = f_{\rm osc} A_{\rm soc}, \qquad (11.2)$$

where f_{osc} is the characteristic strength provided by outer steel tube and concrete annulus and to be determined by the following expression:

$$f_{\rm osc} = C_1 \chi^2 f_{\rm syo} + C_2 (1.14 + 1.02\xi) f_{\rm ck}, \qquad (11.3)$$

where C_1 is the coefficient of strength for the outer steel tube and to be determined by the following expression:

$$C_1 = \frac{\alpha}{1+\alpha},\tag{11.4}$$

where α can be determined by the following expression:

$$\alpha = \frac{A_{\rm so}}{A_{\rm c}}.$$
(11.5)

 χ is the hollow section ratio and to be determined by the following expression:

$$\chi = \frac{D_{\rm i}}{D_{\rm o} - 2t_{\rm o}}.$$
 (11.6)

 C_2 is the coefficient of strength for the concrete annulus and to be determined by the following expression:

$$C_2 = \frac{1 + \alpha_n}{1 + \alpha},$$
 (11.7)

where α_n can be determined by the following expression:

$$\alpha_n = \frac{A_{\rm so}}{A_{\rm c,nominal}}.$$
 (11.8)

 ξ is the nominal confinement factor and to be determined by the following expression:

$$\xi = \frac{f_{\rm syo}A_{\rm so}}{f_{\rm ck}A_{\rm c,nominal}},\tag{11.9}$$

where f_{ck} is the concrete characteristic compressive strength and to be determined by the following expression:

$$f_{\rm ck} = 0.67 f_{\rm cu}.$$
 (11.10)

 $A_{c,nominal}$ is the nominal cross-sectional area of the concrete and to be determined by the following expression:

$$A_{\rm c,nominal} = \frac{\pi (D_{\rm o} - 2t_{\rm o})^2}{4},$$
 (11.11)

where f_{cu} is the concrete characteristic cube strength.

 A_{soc} is the summation cross-sectional area of the outer steel tube and concrete annulus and to be determined by the following expression:

$$A_{\rm soc} = A_{\rm so} + A_{\rm c}.$$
 (11.12)

2.6. Equation Proposed by Yu et al. Yu et al. [31] proposed an equation confirming the experimentally obtained test results of the ultimate axial strength. The formula was for the single skin solid and hollow section CFST columns and presented as follows:

$$P_{\rm u} = \left(1 + 0.5 \frac{\xi}{1 + \xi} \Omega\right) \left(f_{\rm sy}A_{\rm s} + f_{\rm ck}A_{\rm c}\right),\tag{12}$$

where ξ is the confinement coefficient and to be determined by the following expression:

$$\xi = \frac{f_{\rm syo}A_{\rm so}}{f_{\rm ck}A_{\rm c}}.$$
(12.1)

 Ω is the solid ratio and to be determined by the following expression:

$$\Omega = \frac{A_{\rm c}}{A_{\rm c} + A_{\rm k}}.$$
(12.2)

 f_{sy} is the yield strength of steel tube, f_{ck} is the concrete characteristic strength, and A_k is the cross-sectional area of the hollow part.

Herein, the formula proposed by Yu et al. [31] was modified to be applicable on the CFST columns including double steel skin. As Hassanein and Kharoob [32] recommended, the modified formula includes the combination of circular hollow CFST column and inner steel tube as follows:

$$(P_{\rm u})_{\rm Yu\ et\ al.} = \left(1 + 0.5\frac{\xi}{1+\xi}\Omega\right) (f_{\rm syo}A_{\rm so} + f_{\rm ck}A_{\rm c}) + P_{\rm i,u},$$
(13)

where $P_{i,u}$ is the capacity of the inner steel tube and to be determined by equation (11.1).

2.7. Equation Proposed by Hassanein et al. Hassanein et al. [33] proposed a model that could be used in the estimation of the ultimate axial strength of CFDST circular stub columns. The proposed equation by Hassanein et al. [33] was based on the design model developed by Liang and Fragomeni's [34] that estimates the ultimate axial strength of CFST circular stub columns. In addition, this model is developed regarding to design model previously suggested by Hassanein et al. [35] in order to predict the ultimate axial strength of CFDST stub columns including stainless and carbon steels. The new design model developed by Hassanein et al. [33] is presented as follows:

$$(P_{\rm u})_{\rm Hassanein\,et\,al.} = \gamma_{\rm so} f_{\rm syo} A_{\rm so} + (\gamma_{\rm c} f_{\rm c} + 4.1 f_{\rm rp,so}') A_{\rm c} + \gamma_{\rm si} f_{\rm syi} A_{\rm si},$$
(14)

where γ_{so} is the coefficient used to explain the strain hardening effect on the outer steel and to be determined by the following expression:

$$\gamma_{\rm so} = 1.458 \left(\frac{D_{\rm o}}{t_{\rm o}}\right)^{-0.1}, \quad 0.9 \le \gamma_{\rm so} \le 1.1.$$
 (14.1)

 γ_c is the strength attenuation coefficient recommended by Liang [36] and to be determined by the following expression:

$$\gamma_{\rm c} = 1.85 D_{\rm c}^{-0.135}, \quad 0.85 \le \gamma_{\rm c} \le 1.0,$$
 (14.2)

where Dc is the diameter of the concrete annulus and to be determined by the following expression:

$$D_{\rm c} = D_{\rm o} - 2t_{\rm o}.$$
 (14.3)

 $f^{\,\prime}_{\rm rp,so}$ is the lateral confining pressure and to be determined by the following expressions:

$$f_{\rm rp,so}' = \begin{cases} 0.7(\nu_{\rm o} - \nu_{\rm s}) \frac{2t_{\rm o}}{D_{\rm o} - 2t_{\rm o}} f_{\rm syo}, & \text{for } \frac{D_{\rm o}}{t_{\rm o}} \le 47, \\ \\ \left(0.006241 - 0.0000357 \frac{D_{\rm o}}{t_{\rm o}} \right) f_{\rm syo}, & \text{for } 47 < \frac{D_{\rm o}}{t_{\rm o}} \le 150. \end{cases}$$

$$(14.4)$$

 v_{o} is Poisson's ratio of concrete-filled steel tube and to be calculated by Tang et al.'s [37] equation given as follows:

$$\nu_{o} = 0.2312 + 0.3582\nu'_{o} - 0.1524 \left(\frac{f_{c}}{f_{syo}}\right) + 4.843\nu'_{o} \left(\frac{f_{c}}{f_{syo}}\right) - 9.169 \left(\frac{f_{c}}{f_{syo}}\right)^{2},$$
(14.5)

where

$$\nu_{o}' = 0.881 \times 10^{-6} \left(\frac{D_{o}}{t_{o}}\right)^{3} - 2.58 \times 10^{-4} \left(\frac{D_{o}}{t_{o}}\right)^{2} + 1.953 \times 10^{-2} \left(\frac{D_{o}}{t_{o}}\right) + 0.4011.$$
(14.6)

 $v_{\rm s}$ is Poisson's ratios of steel tube without concrete infill and at the maximum strength point, and it is taken as 0.5.

 γ_{si} is the coefficient used to explain the strain hardening effect on the inner steel and to be determined by the following expression:

$$\gamma_{\rm si} = 1.458 \left(\frac{D_{\rm i}}{t_{\rm i}}\right)^{-0.1}, \quad 0.9 \le \gamma_{\rm si} \le 1.1,$$
(14.7)

where t_i is the thickness of inner steel tube.

3. Effective Parameters on CFDST Column Capacity

Uenaka et al. [1] investigated experimentally the behavior of CFDST columns with different outer steel tube yield strengths and thicknesses. Additionally, various inner steel

tube yield strengths, diameters, and thicknesses were examined. However, the concrete compressive strength, outer steel tube diameter, and length of specimen were kept constant in that study. They observed that the CFDST columns fail in local buckling mode which occurs at both tubes due to the vulnerability to shear failure of the concrete annulus.

Tao et al. [13] studied on the influence of various outer and inner steel tube yield strengths, diameters, and specimen lengths on the CFDST stub columns while keeping the concrete compressive strength, outer, and inner steel tubes thicknesses constant. They concluded that the diameter-tothickness ratio (D_i/t_i) of the inner tube is the effective parameter on the failing mode of the inner tube rather than that of outer tube. Moreover, it was revealed that increasing the D_i/t_i ratio changed the failure mode from no sign of buckling towards the buckling. They also attributed the ductility of the columns to the diameter-to-thickness ratio of the outer tubes (D_o/t_o) . This means when the smaller ratio is used, a lower ductility is obtained.

In the study of Essopjee and Dundu [22], the yield strength, diameter, and thickness of the inner steel tube as well as the concrete strength were kept constant, while various outer steel tube yield strengths and diameters with different specimen lengths were utilized in the experimental program. It was concluded that CFDST columns with the length of 1 m failed due to only the yielding of the outer steel tube and the crushing of concrete core, whereas the columns with the length of more than 1 m failed because of only overall buckling. In addition, they revealed that decreasing the column length directly increased the ultimate axial capacity of CFDST columns, whilst increasing the diameters resulted in an increment of CFDST ultimate axial capacities.

Two important parameters, the effects of the inner steel tube and concrete annulus diameters, were investigated in the study of Han et al. [30]. It could clearly be inferred that decreasing the inner steel tube diameter and the increasing the concrete annulus diameter resulted in the increment of the ultimate axial capacity of CFDST columns.

Another significant parameter on the load carrying capacity of CFDST columns is the length-to-diameter (L/D) ratio, because the higher L/D ratio induces the different failure mode of specimen and increases the slenderness of column. This type of failure, namely, failing due to bending of column, was reported in the studies of Tao et al. [13], Essopjee and Dundu [22], and Han et al. [38]. This type of failure was well explained in the study of Rodriguez-Gutierrez and Aristizabal-Ochoa [39]. The slender composite columns were examined in that study, and the slenderness of column, type of applied load, influence of complex support condition, and cross section of column were stated as a reason for bending failure mode.

In the study of Wang et al. [40], the influence of the concrete compressive strength on the ultimate axial strength of CFDST columns was obviously explained. Their results revealed that increasing the compressive strength of concrete annulus remarkably increased the ultimate axial strength of CFDST columns.

Additionally, under the axial compression loading in the initial stage, it is thought that the interaction between the steel tube and concrete can be neglected or can be considered to have no interplay. The steel with higher Poisson's ratio could initially expand more than the concrete in the lateral direction that may induce a little space between steel and concrete. When the concrete expansion in the lateral direction by the increasing of axial strain exceeds the steel tube expansion in the lateral direction, the contact between steel tube and concrete establishes again. The interplay between steel tube and concrete arises, and this would induce a confinement pressure on the concrete provided by the steel tube. By this way, the concrete performs higher compressive strength when compared with unconfined condition. Yet, as Rodriguez-Gutierrez and Aristizabal-Ochoa [41, 42] stated, the confinement effect provided by steel tube may be insignificant in the case of slender column and/or large eccentricity.

4. Details of Parametric Study and Discussion

4.1. Overview of Gene Expression Programming (GEP). Soft computing could be described as a summation of techniques which are purposed to utilize the toleration for erroneous and uncertainness to attain tractability, robustness, and low solution cost [43]. Engineering problems, financial estimations, diagnostic tools in medicine etc. are some of the application areas of soft computing techniques. Genetic programming and genetic algorithms are two of the most popular soft computing techniques. Genetic algorithms use the populations of individuals and choose these populations regarding the formation and submit the genetic variation by handling one or more genetic operators. Genetic programming also accomplishes the same operations as genetic algorithms but genetic programming, which was firstly asserted by Koza [44], is a generalization form of genetic algorithms [45]. Application of the genetic algorithms to computer programs is basically "genetic programming." Gene expression programming (GEP) can be accepted as the development of genetic programming and algorithms, owing to the utilization of the same mechanism [46].

GEP was firstly devised by Ferreira [46] as a novel technique to conceive the computer programs by utilizing the statement of learned models or discovered knowledge [47]. The main idea lying beneath genetic programming and algorithms is that the problem must be described at the beginning; thereafter, the solution of the problem is endeavored in a problem-independent mode by the program [44, 45]. On the other hand, GEP generates the computer programs of which sizes are different and shapes are encoded in linear chromosomes of fixed length, then the chromosomes are predicated, and the fitness of each individual is evaluated depending on the solution quality that is represented. Thereby, it can be said that GEP is a developed form of genetic programming and algorithms. On the basis of the solution, all aforementioned techniques use almost the same genetic operator with minor differences [48].

4.2. Proposed Model. The data presented herein were compiled from the experimental studies available in the literature [1, 10, 13-15, 20, 22, 31, 38, 40, 49-54]. Table 1 illustrates the summary of the experimental data with their sources for the concrete-filled double skin steel circular tubular columns under axial loading. As seen in Table 1, a total of eight crucial parameters were used. These parameters consist of the 28-day compressive strength of concrete infill (f_c) , yield strengths (f_{svo}, f_{svi}) , diameters (D_o, D_i) and thicknesses (t_0, t_i) of the outer and inner steel tubes, and the length of the specimen (L). The model for the CFDST columns was proposed by the utilization of these predictive parameters. In Figure 2, the details of the cross section and loading of the columns were given. It was noted that the concrete compressive strength performed on $Ø150 \times 300 \text{ mm}$ cylindrical specimen was used in the databases, but some compressive strength values reported in the studies were measured on different geometric samples. For this reason, the compressive strength measured on different geometric samples were transformed from the given specimen geometry to $Ø150 \times 300 \text{ mm}$ cylindrical specimens regarding coefficients recommended by Ersoy et al. [55]. Moreover, during the testing, all of the specimens considered for the generation of the GEP model were directly placed into the testing machine, and two steel plates were utilized at the ends of the specimens.

Totally, 103 data were gathered from the available studies in the literature. They were utilized in the derivation of the model via using the software named as GeneXproTools 5.0 [56]. The data sources were arbitrarily divided into two groups as train and test subdatasets. The training dataset was handled to be employed for the enhancement of the developed model, whereas the test dataset was used to observe the robustness and repeatability of the proposed mathematical model. The test set constitutes approximately 25% of the total data samples. Both datasets were also statistically evaluated and are introduced in Table 2. The statistical analysis results indicated that both of the training and testing datasets represent whole data given in Table 1. Moreover, there is a good agreement between the training and testing datasets such that both datasets reflect the nearly same populations. Besides, Table 3 presents the GEP parameters utilized in the derivation of the mathematical model. Table 3 obviously illustrates that, in order to be able to increase the accuracy of the model; several mathematical operations were used in the derivation. The equation attained from the software is given as equation (15). The expression trees of this predictive model, which were employed to present the GEP model formulation, are indicated in Figure 3. Some mathematical terms given in the expression tree were abbreviated in the presentation of the formula. As an example, $2f_c$ was used instead of writing $f_c + f_c$ in Sub-ET7. However, some input parameters can sometimes be neglected by software owing to their negligible influence on the entire model when the optimum model evaluation was trained for best fitness. All input variables were used in the current study for the generation of GEP model:

	Munhou		Outer steel			Inner steel		Concerto commence	ا مسمطام مو	I Thimata arrial
Reference	of data	Yield strength f _{syo} (MPa)	Diameter D _o (mm)	Thickness $t_{\rm o}~({\rm mm})$	Yield strength f _{syi} (MPa)	Diameter $D_{\rm i}$ (mm)	Thickness t _i (mm)	concrete compressive strength f_c (MPa)	Lengun or specimen L (mm)	Ultimate axial strength P _u (kN)
Uenaka et al. [1]	6	221.0-308.0	157.0-159.0	0.90 - 2.14	221.0 - 308.0	38.0-115.0	0.90 - 2.14	18.7	450	378.3-968.2
Zhao et al. [10]	9	395.0-454.0	114.2-165.3	2.80 - 3.10	410.0 - 425.0	48.4 - 101.8	2.90 - 5.90	63.4	400	1110.0 - 1705.0
Tao et al. [13]	14	275.9-294.5	114.0 - 300.0	3.00	294.5 - 396.1	48.0 - 165.0	3.00	40.0	342-1770	595.0 - 3331.0
Zhao et al. [14]	6	395.0-454.0	114.3 - 165.1	1.70 - 6.00	394.0-425.0	48.3-101.6	2.90 - 3.20	63.4	400	1145.0 - 1665.0
Li et al. [15]	2	439.3	350.0	3.82	396.5	231.0	2.92	50.0	1050	5396.0-5499.0
Lin and Tsai [20]	2	250.0	300.0	2.00 - 4.00	250.0	180.0	2.00	28.0	1100	2311.0-2750.0
Essopjee and Dundu [22]	32	391.0-549.0	139.2–193.7	3.00 - 3.50	324.0	76.0	2.00	30.8	998-2503	729.0-2030.0
Han et al. [30]	4	319.6	220.0	3.62	380.6	106.0 - 159.0	3.72	60.0	660	2537.0-3506.0
Han et al. [38]	б	311.0	120.0	1.96	380.0	60.0	1.96	39.3-66.4	1324	578.0-789.0
Wang et al. [40]	10	300	140.1 - 140.3	2.86–2.92	433.0-1029.0	22.1-89.1	3.91 - 10.76	40.5-79.9	350	1450.0 - 2775.0
Hastemoğlu and Erkan [49]	б	250.0	139.0	2.00	250.0	75.0	3.00	55.0	351-585	807.0-877.0
Dong and Ho										
Dong and Ho [51]	5	360.0-450.0	168.3	5.00	360.0-450.0	88.9-114.3	5.00	50.0-85.0	330	2674.0-3218.0
Abbas et al. [52]	1	307.0	150.0	6.00	307.0	26.7	2.87	40.0	600	1805.0
Wang et al. [53]	2	350.0	165.0	1.70	350.0	76.0-114.0	1.20 - 1.70	28.1	500	715.0-980.0
Lu et al. [54]	1	426.0	219.1	5.00	426.0	101.6	3.20	46.6	800	3333.0

TABLE 1: Summary of the experimental datasets used in the derivation of the model.

TABLE 2: Statistics of the experimental data used in the model derivation.

	f _{syo} (MPa)	$D_{\rm o}~({\rm mm})$	$t_{\rm o} \ ({\rm mm})$	f _{syi} (MPa)	D _i (mm)	$t_{\rm i} \ ({\rm mm})$	f _c (MPa)	L (mm)	$P_{\rm u,exp}$ (kN)
Total data									
Number of data	103	103	103	103	103	103	103	103	103
Mean	374.9	167.1	3.02	380.6	81	2.99	37.1	938.1	1608
Standard deviation	93.2	47.2	0.93	137.4	38.2	1.64	18.4	686.5	929.4
COV	0.25	0.28	0.31	0.36	0.47	0.55	0.50	0.73	0.58
Min. value	221	114	0.9	221	22.1	0.9	18.7	330	378.3
Max. value	549	350	6	1029	231	10.76	85	2503	5499
Training data									
Number of data	77	77	77	77	77	77	77	77	77
Mean	375	169.5	3.08	373.5	81.6	2.97	37.4	955.2	1642.9
Standard deviation	93.1	47.5	0.97	127.6	37.6	1.56	19.1	691.6	901.5
COV	0.25	0.28	0.31	0.34	0.46	0.52	0.51	0.72	0.55
Min. value	221	114	0.9	221	22.1	0.9	18.7	330	378.3
Max. value	549	350	6	1029	231	10.62	85	2503	5499
Testing data									
Number of data	26	26	26	26	26	26	26	26	26
Mean	374.7	159.7	2.87	401.6	79.3	3.03	36.3	887.5	1504.9
Standard deviation	95.5	46.7	0.80	164.1	40.8	1.90	16.5	682.1	1019.3
COV	0.25	0.29	0.28	0.41	0.51	0.63	0.45	0.77	0.68
Min. value	221	114	0.9	221	32	0.9	18.7	330	578
Max. value	549	350	5	1029	231	10.76	77.6	2500	5396

TABLE 3: The parameters used in the proposed model.

P_1	Function set	+, -, *, /, Sqrt, Exp, Sin, Cos,
- 1 D	NTh	Arctan
P_2	Number of generations	499999
P_3	Chromosomes	140
P_4	Head size	10
P_5	Linking function	Addition
P_6	Number of genes	8
P_7	Mutation rate	0.00206
P_8	Inversion rate	0.00546
D	One-point recombination	0.00277
P9	rate	0.00277
D	Two-point recombination	0.00277
P_{10}	rate	0.00277
P_{11}	Gene recombination rate	0.00277
P_{12}	Gene transposition rate	0.00277
P_{13}	Constants per gen	5
D	Lower/upper bound of	50/60
P_{14}	constants	-50/60

$$(P_{\rm u})_{\rm GEP} = P_1 + P_2 + P_3 + P_4 + P_5 + P_6 + P_7 + P_8, \quad (15)$$

where $(P_u)_{GEP}$ is the ultimate axial strength of CFDST columns proposed with help of GEP, and the subfunctions from P_1 to P_8 are given as follows:

$$P_{1} = D_{o}t_{o} - D_{o}\cos\left(t_{o} - D_{i} - \frac{f_{c}}{47.401621}\right),$$
(15.1)

$$P_{2} = \sqrt{f_{syo}} - [D_{i}(t_{o} - 1.9217768) + f_{c}]\cos(27.565796L),$$
(15.2)

$$P_3 = \frac{D_{\rm i}}{18.452453e^{t_{\rm o}}\left[\cos\left(D_{\rm o}\right) - 0.779304\right]},\tag{15.3}$$

$$P_4 = (L + 98.2384615t_i - 20.245728) \left(\frac{-25.1921737}{D_i}\right),$$
(15.4)

$$P_{5} = D_{o} - f_{c} \tan^{-1} \left(\frac{2D_{i} - D_{o} + 0.470241}{\sin(D_{o})} \right),$$
(15.5)

$$P_{6} = D_{o} \left[t_{o} + t_{i} + \sin \left(\sqrt{D_{i}} + t_{o} \right) \right],$$
(15.6)

$$P_7 = (-1.5067511) \left(D_{\rm i} + 67.7034842 - 2f_{\rm c} - \frac{f_{\rm syi}}{t_{\rm o}} \right),$$
(15.7)

$$P_8 = \sqrt{D_{\rm i} \ L + f_{\rm c} f_{\rm syi} - 52.9959407 - 485.5475433 D_{\rm i}}.$$
(15.8)

In Figure 4, the experimental and predicted ultimate axial strength of CFDST columns were compared with respect to the coefficient of determination R^2 value. The coefficient of determination is the measurement proportion of a predicted outcome variance. It could be between 0 and 1 that indicates the performance of prediction. When this value approaches to 1, a good accuracy of the scatter of the data is obtained, whereas moving away from 1 can be considered as worse prediction performance. As seen in Figure 4, the R^2 values of 0.987 were achieved for the both train and test, respectively. This may be an indication of a strong correlation between actual and predicted values. In addition, the robustness and appropriate precision of the GEP model could be manifested by obtaining the proximate correlation coefficients.



FIGURE 3: Expression trees for the proposed model. (a) Function 1. (b) Function 2. (c) Function 3. (d) Function 4. (e) Function 5. (f) Function 6. (g) Function 7. (h) Function 8.



FIGURE 4: Ultimate axial strength prediction performance of the proposed model. (a) Train dataset. (b) Test dataset.

In order to compare the estimation capability of predicted and experimental ultimate axial strengths, the normalized ultimate axial strength values of both train and test dataset with respect to experimental ultimate axial strength values are exhibited in Figure 5. The $\pm 10\%$ limit values were selected for the normalized line that may help to indicate the prediction performance of the proposed GEP model. Analysis of Figure 5 exhibits that the scatter of normalized value is good, and this can be comprehended by distribution of the almost all data in the designated normalized line limits. According to good scatter of values and higher correlation of determination values, it could be inferred that the prediction performance of the GEP model can be accepted as good.

In addition to comparison of the estimation capability of the proposed GEP model regarding the experimental ultimate axial strength values, the prediction capability of the proposed model was evaluated with respect to specimen properties such as hollow ratio (χ), length-to-outer steel diameter ratio (L/D_o) , outer steel diameter-to-inner steel diameter ratio (D_0/D_i) , outer steel diameter-to-thickness ratio (D_0/t_0) , and inner steel diameter-to-thickness ratio $(D_{\rm i}/t_{\rm i})$. These are graphically illustrated in Figures 6(a)-6(e). In these figures, the normalized values were also used for comparison. The figures were plotted in order to perceive the effectiveness of the specimen properties. It can be clearly seen from Figure 6(a) that the data used in the study presented herein have the hollow ratio values changing between 0.1 and 0.8, and the proposed GEP model has a good prediction performance at almost all values of the hollow ratio. The same conclusion can be done on the comparisons between the normalized ultimate axial strength values and the other specimen properties. It can be concluded that although the data were accumulated at some certain values for each specimen properties, the predicted values had only several distributions of overestimation and underestimation performance. To understand the effectiveness of the strength parameters such as the compressive strength of infill concrete and yield

strength of steel tubes, Figures 6(f)–6(h) are also plotted. From the analysis of these figures, it can be observed that the proposed GEP model cannot be unequivocally attached to specified specimen properties and material strengths. For this reason, it could be overemphasized according to these findings that both specified specimen properties and materials strengths utilized in the modeling had impartially effectiveness on the proposed model. This demonstrates that the proposed model by GEP had a generalized prediction capability.

4.3. Comparing the Proposed Model with Existing Ones. The results of the proposed model were also compared and discussed with those calculated by some existing relations given by the researchers in the literature and the formulas based on the codes. Table 4 indicates the comparison of the proposed models in accordance with the normalized ultimate axial strength values. The average of the normalized values and their coefficient of variations (COV) are tabulated in Table 4 at the end of the normalized values. The proposed model with an average normalized value of 1.003 and coefficient of variation value of 0.084 performed the best estimation capability among the other models. Furthermore, to comprehend the prediction performance of the models, the results were statistically examined through the mean absolute percent error (MAPE), mean square error (MSE), and root-mean-square error (RMSE) values. These are calculated according to the following formulas:

MAPE =
$$\frac{1}{n} \sum_{i=1}^{n} \left| \frac{m_i - p_i}{m_i} \right| \times 100,$$

MSE = $\frac{\sum_{i=1}^{n} (m_i - p_i)^2}{n},$ (16)

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (m_i - p_i)^2}{n}}$$



FIGURE 5: Prediction capability of the proposed model on the ultimate axial strength of CFDST columns.





FIGURE 6: Interaction between the prediction capability of the proposed model and specimen properties. (a) Hollow ratio (χ). (b) Length-toouter steel diameter ratio (L/D_o). (c) Outer steel diameter-to-inner steel diameter ratio (D_o/D_i). (d) Outer steel diameter-to-thickness ratio (D_o/t_o). (e) Inner steel diameter-to-thickness ratio (D_i/t_i). (f) Concrete compressive strength (f_c). (g) Outer steel yield strength (f_{syo}). (h) Inner steel yield strength (f_{syi}).

TABLE 4: Comparison of the experimental ultimate axial strength of CFDST columns with the proposed and existing models.

Reference	Puerp	$P_{\rm u,exp}/$	$P_{\rm u,exp}/$	$P_{\rm u,exp}/$	P _{u,exp} /	P _{u,exp} /	P _{u,exp} /	P _{u,exp} /	P _{u,exp} /
	ц,схр	$P_{u,GEP}$	$P_{u,ACI}$	$P_{u,EC4}$	$P_{u,AISC}$	P _{u,Uenakaetal.}	$P_{\rm u,Hanetal.}$	$P_{u,Yuetal.}$	$P_{u, Hassaneinetal.}$
	635.0	1.13	1.56	1.19	1.44	1.09	1.40	1.41	1.49
	540.0	1.03	1.41	1.13	1.32	1.11	1.28	1.30	1.37
	378.3	1.08	1.20	1.04	1.14	1.11	1.11	1.12	1.21
	851.6	1.04	1.51	1.12	1.43	0.96	1.37	1.28	1.35
Uenaka et al. [1]	728.1	1.08	1.29	1.03	1.24	0.99	1.19	1.13	1.20
	589.0	0.90	1.12	1.01	1.08	1.07	1.06	1.02	1.09
	968.2	1.00	1.50	1.09	1.43	0.92	1.34	1.24	1.31
	879.1	1.11	1.32	1.06	1.28	1.00	1.22	1.14	1.20
	703.6	0.71	1.10	1.01	1.08	1.08	1.04	1.00	1.05
Zhao et al. [10]	1415.0	0.99	1.22	1.06	1.18	0.90	1.09	1.06	0.98
	1380.0	1.01	1.29	1.11	1.25	0.95	1.15	1.13	1.03
	1210.0	0.95	1.17	0.98	1.13	0.84	1.03	1.00	0.92
	1110.0	0.90	1.13	0.94	1.09	0.81	0.99	0.97	0.89
	1705.0	1.01	0.99	0.85	0.95	0.85	0.90	0.89	0.91
	1605.0	0.95	1.01	0.86	0.97	0.86	0.91	0.91	0.93
Tao et al. [13]	1790.0	1.11	1.46	1.12	1.39	0.96	1.29	1.25	1.30
	1791.0	1.11	1.46	1.12	1.39	0.96	1.29	1.25	1.30
	1648.0	1.03	1.36	1.03	1.29	0.89	1.20	1.16	1.20
	1650.0	1.03	1.36	1.03	1.29	0.89	1.20	1.16	1.21
	1435.0	0.91	1.19	0.91	1.13	0.78	1.05	1.02	1.06
	1358.0	0.86	1.13	0.86	1.07	0.74	1.00	0.97	1.00
	904.0	0.99	1.33	1.12	1.29	1.03	1.20	1.15	1.09
	898.0	0.98	1.32	1.11	1.29	1.02	1.19	1.14	1.08
	2421.0	0.95	1.33	1.07	1.26	1.02	1.20	1.19	1.24
	2460.0	0.96	1.35	1.09	1.28	1.04	1.22	1.21	1.26
	3331.0	1.07	1.32	1.09	1.25	1.08	1.20	1.20	1.28
	3266.0	1.05	1.29	1.07	1.22	1.06	1.18	1.18	1.25
	620.0	1.19	0.91	0.99	0.97	0.71	0.82	0.79	0.75
	595.0	1.14	0.88	0.95	0.93	0.68	0.79	0.76	0.72
	1665.0	1.03	1.16	0.95	1.14	0.76	0.95	0.93	0.92
	1441.0	1.11	1.19	0.97	1.16	0.80	1.00	0.98	0.93
	1243.0	1.03	1.12	0.92	1.08	0.77	0.97	0.93	0.88
	1145.0	0.94	1.11	0.91	1.07	0.78	0.97	0.94	0.87
Zhao et al. [14]	1629.0	0.87	0.93	0.79	0.90	0.79	0.84	0.83	0.85
	1613.0	1.01	1.01	0.87	0.97	0.87	0.92	0.91	0.93
	1487.0	1.19	1.02	0.88	0.97	0.88	0.93	0.93	0.94
	1328.0	0.99	0.96	0.84	0.92	0.84	0.88	0.89	0.89
	1236.0	0.95	0.93	0.82	0.88	0.81	0.85	0.87	0.86

Reference	P	$P_{\rm u,exp}/$	P _{u,exp} /	P _{u,exp} /	P _{u,exp} /	$P_{\rm u,exp}/$	$P_{\rm u,exp}/$	$P_{\rm u,exp}/$	P _{u,exp} /
	1 u,exp	$P_{u,GEP}$	$P_{u,ACI}$	$P_{u,EC4}$	$P_{u,AISC}$	$P_{u,Uenakaetal.}$	$P_{\rm u,Hanetal.}$	P _{u,Yuetal.}	$P_{u, Hassaneinetal.}$
Li et al. [15]	5499.0 5396.0	1.01 0.99	1.26 1.24	1.08 1.06	1.21 1.19	1.11 1.09	1.16 1.14	1.14 1.12	1.24 1.21
	2311.0	0.91	1.47	1.24	1.39	1.24	1.35	1.35	1.49
Lin and Isai [20]	2750.0	1.06	1.38	1.13	1.32	1.13	1.26	1.21	1.34
	1059.2	0.94	1.23	1.14	1.23	0.94	1.13	1.02	1.07
	1056.1	0.95	1.23	1.14	1.22	0.93	1.12	1.02	1.07
	905.5	1.03	1.05	1.07	1.07	0.80	0.96	0.87	0.92
	901.6	1.08	1.05	1.07	1.07	0.80	0.96	0.87	0.91
	831.7	0.89	0.97	1.04	1.02	0.74	0.88	0.80	0.84
	837.4	0.96	0.97	1.05	1.02	0.74	0.89	0.81	0.85
	732.1	1.12	0.85	0.95	0.93	0.65	0.78	0.70	0.74
	729.0	0.96	0.85	0.95	0.93	0.64	0.77	0.70	0.74
	1263.5	0.97	1.10	0.99	1.09	0.78	1.00	0.88	0.98
	1254.9	1.13	1.09	0.98	1.09	0.77	1.00	0.88	0.97
	1195.6	1.02	1.04	1.04	1.06	0.73	0.95	0.84	0.93
	1191.2	1.16	1.04	1.04	1.06	0.73	0.95	0.83	0.93
	1047.3	0.99	0.91	0.98	0.96	0.64	0.83	0.73	0.81
	1041.6	0.93	0.91	0.98	0.95	0.64	0.83	0.73	0.81
E	941.4	1.00	0.82	0.92	0.90	0.58	0.75	0.66	0.73
Essopjee and Dundu	949.0	1.10	0.85	1.092	0.91	0.58	0.75	0.66	0.74
[22]	1512.5	1.02	1.24	1.08	1.22	0.84	1.13	0.99	1.10
	1310.0	1.14	1.24	1.07	1.22	0.84	0.96	0.99	1.10
	1200.4	1.06	1.05	1.02	1.00	0.72	0.90	0.83	0.94
	1275.1	0.94	0.97	1.01	1.05	0.71	0.95	0.84	0.93
	1107.2	0.94	0.98	1.02	1.01	0.67	0.89	0.78	0.87
	1028.0	0.93	0.84	0.92	0.90	0.57	0.77	0.68	0.75
	1026.5	1.03	0.85	0.92	0.91	0.58	0.77	0.68	0.76
	2010.0	1.04	1.45	1.17	1.41	0.93	1.30	1.17	1.29
	2030.0	1.12	1.46	1.18	1.42	0.94	1.31	1.18	1.30
	1730.0	0.94	1.25	1.10	1.23	0.80	1.12	1.00	1.11
	1720.0	1.04	1.24	1.10	1.22	0.80	1.11	1.00	1.10
	1581.6	0.94	1.14	1.09	1.14	0.73	1.02	0.92	1.01
	1584.1	0.91	1.14	1.10	1.14	0.74	1.03	0.92	1.02
	1451.4	0.96	1.04	1.07	1.07	0.67	0.94	0.84	0.93
	1458.7	1.05	1.05	1.07	1.07	0.68	0.94	0.85	0.94
	2537.0	0.98	1.20	1.11	1.16	1.14	1.11	1.11	1.15
Ham at al [20]	2566.0	0.99	1.21	1.12	1.17	1.16	1.13	1.12	1.16
Han et al. [50]	3436.0	1.03	1.47	1.22	1.40	1.14	1.32	1.32	1.36
	3506.0	1.05	1.50	1.24	1.43	1.17	1.35	1.34	1.39
	578.0	0.84	1.02	1.01	1.02	0.79	0.92	0.89	0.91
Han et al. [38]	789.9	0.99	1.11	1.10	1.11	0.88	0.99	1.00	0.99
	715.4	0.90	1.00	1.00	1.01	0.79	0.90	0.91	0.89
	1450.0	0.98	1.47	1.12	1.40	0.90	1.29	1.25	1.28
	1562.0	0.89	1.46	1.16	1.40	0.97	1.30	1.26	1.28
	1838.4	0.99	1.68	1.36	1.62	1.15	1.51	1.46	1.48
	2724.0	1.08	1.48	1.44	1.46	1.23	1.40	1.37	1.33
Wang at al [40]	2024.9	1.04	1.20	1.22	1.18	1.12	1.15	1.13	1.10
wallg et al. [40]	1845.1	0.97	1.25	0.99	1.17	0.85	1.08	1.12	1.10
	2012.5	1.03	1.31	1.06	1.23	0.93	1.14	1.18	1.16
	2083.4	1.03	1.35	1.10	1.27	0.98	1.17	1.22	1.19
	2775.0	0.98	1.23	1.16	1.19	1.02	1.12	1.15	1.10
	2107.4	1.02	1.07	1.06	1.04	0.98	1.00	1.02	0.98
Hastemoğlu and	807.0	1.01	1.07	0.89	1.01	0.88	0.96	0.98	0.96
Frkan [49]	810.0	0.93	1.07	0.91	1.02	0.88	0.97	0.98	0.97
	877.0	0.95	1.16	1.01	1.11	0.95	1.05	1.06	1.05
Dong and Ho [50]	2852.0	0.94	1.37	1.14	1.32	1.08	1.22	1.19	1.12

TABLE 4: Continued.

Reference	$P_{u,exp}$	$P_{\rm u,exp}/$	$P_{\rm u,exp}/$	$P_{\rm u,exp}/$	$P_{\rm u,exp}/$	$P_{\rm u,exp}/$	$P_{\rm u,exp}/$	$P_{\rm u,exp}/$	$P_{\rm u,exp}/$
	. 1	$P_{u,GEP}$	$P_{u,ACI}$	$P_{u,EC4}$	P _{u,AISC}	Pu,Uenakaetal.	P _{u,Hanetal} .	$P_{u,Yuetal.}$	Pu,Hassaneinetal.
	2865.0	0.96	1.30	1.05	1.27	1.00	1.16	1.11	1.07
Dong and Ho [E1]	2674.0	0.96	1.26	1.12	1.24	1.16	1.16	1.12	1.08
Doing and Ho [51]	3218.0	1.03	1.24	1.00	1.19	0.96	1.08	1.08	1.00
	2994.0	1.02	1.25	1.10	1.21	1.14	1.12	1.13	1.06
Abbas et al. [52]	1805.0	1.02	1.30	0.96	1.26	0.68	1.05	1.01	0.99
Wang at al [52]	980.0	1.25	1.38	1.08	1.32	1.01	1.26	1.19	1.27
wallg et al. [55]	715.0	0.81	1.00	0.90	0.98	0.93	0.95	0.91	0.97
Lu et al. [54]	3333.0	1.01	1.17	0.96	1.13	0.84	1.04	0.99	0.97
Ave		1.003	1.182	1.042	1.157	0.889	1.066	1.021	1.053
COV		0.084	0.163	0.105	0.139	0.186	0.160	0.180	0.178

TABLE 4: Continued.

where *m* and *p* are the values of measured (m_i) and the predicted (p_i) values, respectively.

MAPE, MSE, and RMSE values of the proposed GEP model as well as the models modified from the codes and proposed by the researchers are tabulated in Table 5. In addition to these parameters, the coefficient of determination (R^2) value of each model is presented in Table 5. As clearly observed in the table, the lowest MAPE, MSE, and RMSE values were achieved for the training dataset of GEP model. When the all dataset was considered, the proposed GEP model had again the lowest MAPE, MSE, and RMSE values, which is the indication of a good prediction performance. Among the existing models, the nearest estimation capability was observed in EC4 model with MAPE value of 8.68 and R^2 value of 0.960. Although the statistical results of some models were near to that of the GEP model, the proposed GEP model was still the best when compared to any other proposed model with respect to estimation performance.

Besides, the percent error regarding the ultimate axial strength intervals obtained from each model was determined and is plotted in Figure 7. For this reason, the ultimate axial strength values were divided into five groups in the range of 750 kN. Also, the number of data falling in each interval class is demonstrated in Figure 7. It could be clearly seen that EC4 model showed lower percent error value only in the case of the ultimate axial strength value \leq 750 kN, while the proposed GEP model indicated lower percent error values in the other intervals. For the ultimate axial strength values of lower than 1500 kN, the higher percent error results were obtained from the model by Uenaka et al. [1], while for the strength values higher than 1500 kN, the worst percent error results were attained from the model by ACI [23]. The percent error values of the proposed GEP model decreased with increasing of the ultimate strength, and the lowest percent error value of 2.98% was achieved at the ultimate axial strength higher than 3000 kN. It can be noted that, in the high strength CFDST columns, the proposed model has better prediction capability.

The comparison of the models through the experimental results is graphically presented in Figure 8. The figure illustrates that the generalization ability of the proposed model for the estimation of the ultimate axial strength of CFDST can be claimed for 0 and 3000 kN interval. It may be comprehended from the figure that the scattering of the results obtained from the proposed GEP model was around the 100% agreement line, whilst the results of the other models were dispersed to the wider area. Particularly, as the ultimate axial strength increases, the predictions of the other models fell apart from the agreement line. Moreover, almost all existing expressions underestimated the strength through the ultimate axial strength values of greater than 3000 kN, while the proposed model by GEP had approximately 100% precision. The most extreme overestimated results were observed in the model of Uenaka et al. [1], whereas the underestimated values were seen in the model of ACI [23].

5. Conclusions

The study herein exhibited an explicit equation for the ultimate axial capacity (P_u) of the CFDST composite columns. For the derivation of the proposed model, a soft computing technique named GEP was used. To this, the results of the experimental test results available in the literature were compiled and used as the dataset. With reference to aforementioned discussion, evaluation, and comparison the following conclusions could be drawn:

- (i) It is shown that GEP technique could be a beneficial tool in the derivation of empirical mathematical formulation for the ultimate axial strength of CFDST columns based on the several section sizes and material properties. The valid results were achieved by the proposed model, namely, the predicted result values were not zero or less than zero. The proposed model comprises of many mathematical functions that need to be transferred to the computer in order to save time and eliminate the human factor. Through development of a user friendly interface, the proposed model can practically be used by the practitioners.
- (ii) The developed model was firstly evaluated by comparing the derived model via a testing dataset that was not used during the training of the model. It was revealed by this comparison that the test dataset with the coefficient of determination value of 0.987 was obtained, and it could be accepted as a good prediction capability of the model.

Madala		Statistical parameters		
Widdels	Mean absolute percent error (MAPE)	Mean square error (MSE)	Root-mean-square error (RMSE)	R^2
Proposed model				
Train dataset	5.72	10860	81.0	0.987
Test dataset	8.52	13567	99.9	0.987
All dataset	6.43	11543	85.7	0.987
ACI [23]	16.81	168726	301.0	0.936
EC4 [24]	8.68	45291	151.4	0.960
AISC [28]	14.41	129403	262.5	0.950
Uenaka et al. [1]	21.47	128636	291.2	0.888
Han et al. [30]	13.48	87481	220.6	0.939
Yu et al. [31]	15.43	90708	234.3	0.917
Hassanein et al. [33]	14.54	104162	232.5	0.917

TABLE 5: Statistical parameters of the proposed and existing models.



FIGURE 7: Error analysis of the proposed and existing models.



FIGURE 8: Comparison of the proposed model with the existing ones.

- (iii) The results of the proposed model were statistically and graphically compared with the modified expressions of the codes and some existing models by various researchers. The statistical results indicated that the proposed model estimates the ultimate axial strength of the CFDST columns with a better performance than the others. Especially, when the coefficient of determination, R^2 , and mean absolute percent error values were compared, the estimation capability of the GEP model can be clearly observed.
- (iv) The percent error values for various ultimate axial strength intervals were also used to evaluate the prediction capability of the models. It can be professed that, while the other models indicated fluctuating estimation capability with respect to the strength intervals, the proposed model showed a stable prediction performance with no matter what the strength intervals are.
- (v) Even though the proposed model with 103 data compiled from the available experimental researches in the literature had a reliable and better prediction performance than existing ones, the robustness and accuracy as well as the generalization capability of such model can be improved by extending the dataset utilized in the training of the model.

Data Availability

Previously reported (experimental test results) data were used to support this study and are available at doi: https:// doi.org/10.1016/j.tws.2009.08.001, https://doi.org/10.12989/ scs.2002.2.2.129, https://doi.org/10.1016/j.jcsr.2003.11.008, https://doi.org/10.1016/j.engstruct.2009.11.015, https://doi. org/10.1016/j.tws.2012.03.019, https://doi.org/10.1016/j. compstruct.2015.08.033, https://doi.org/10.1016/j.tws.2011. 08.001, https://doi.org/10.12989/scs.2014.17.4.431, https:// doi.org/10.1002/cepa.252, https://doi.org/10.4172/2168-9717.1000194, https://doi.org/10.12989/scs.2012.13.6.587, https://doi.org/10.1680/macr.13.00041, https://doi.org/10. 1007/s12205-016-0852-3, https://doi.org/10.1016/j.jcsr. 2010.09.010, and https://doi.org/10.1016/j.jcsr.2010.03.004 and http://citeseerx.ist.psu.edu/viewdoc/download?doi=10. 1.1.529.4433&rep=rep1&type=pdf. These prior studies (and datasets) are cited at relevant places within the text as references [1, 10, 13-15, 20, 22, 30, 38, 40, 49-54].

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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