Accurate Prediction of Axial Capacity of Octagonal Concrete Filled Steel Tube Columns Using Artificial Neural Network

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Abstract
The predicting of the ultimate axial capacity of concrete-filled steel tube (CFST) columns is essential in the design process. To reach an accurate estimation of the column capacity it needs to involve all the important parameters that affect the behavior. One of the most recent tools that has been progressively used for this objective is machine intelligence. The present study has been dedicated in order to construct an appropriate artificial neural network (ANN) model that can give accurate predictions to the ultimate capacity of octagonal concrete-filled steel tube columns. The model is constructed using a back-propagation and optimizing Levenberg-Marquardt algorithms. The ANN model depends on experimental data collected from previous researches. To show the reliability of the model, the results were verified and compared with previous methods presented in previous researches and codes. The ANN results showed good agreement with experimental ones. The ANN model has been used in exploring various parameters that may affect the strength of octagonal CFST columns. The results have shown that a careful portioning of geometrical ad material properties should be followed to achieve the most .optimum design

Keywords: CFST, axial capacity, confinement, ANN, composite

Introduction

The ability to anticipate column capacities is critical because it provides the designer with the most important component in determining the capability of the structural element to sustain specified loads. The interaction of two material components in concrete-filled steel tube (CFST) columns may cause certain complications in the design process. The effect of the lateral confining pressure induced on the concrete core by the outer steel tube should be accurately implied, which can be complicated further by the cross-sectional .shape

The octagonal sections are one of the most commonly utilized shapes in columns due to aesthetic and functional reasons. In comparison to other polygonal designs, circular sections of steel tubes in CFST columns provide the maximum lateral confining pressure on concrete cores, according to an earlier study [1, 2]. This could be owing to the geometry of circular sections in translating lateral internal pressures caused by axial concentric load through Poisson's effect, as shown in Fig. 1. The transverse confinement pressure (frp) will aid in improving the strength of core concrete by making it behave in a triaxial state, which will then be reverted on the outside steel tube as hoop stresses (fsr), causing delays .[in cases of local buckling [2

The composite columns of octagonal sections have scarcely been documented in the literature. Ding et al. [3], however, presented a study on the mechanical performance of octagonal CFST columns that incorporated theoretical, numerical, and experimental work. They recommended a confinement coefficient of 1.5 to forecast final strength due to the confinement effect on the behavior of octagonal CFST columns. It should be emphasized that the amplification factor provided by Ding et al. [3] for the confinement effect is independent of different material or geometrical characteristics, which is the topic of the .article

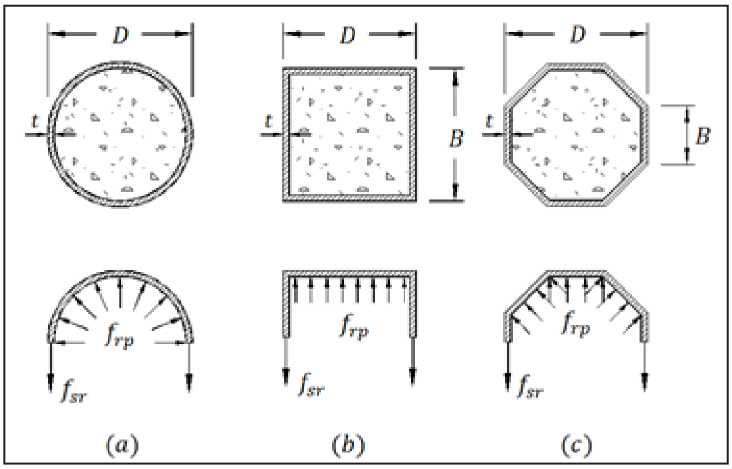


Fig. 1 distribution of lateral internal pressures of different shapes: (a) circular, (b) rectangular, and (c) octagonal

Attempts have been made to develop a unifying formula for predicting the final capacity of various CFST column shapes including octagonal [4, 5]. Susantha et al. [4] used a finite element analysis program to evaluate the lateral confining pressure in circular, box (square), and octagonal composite columns and found that circular parts have the most influence, while box sections have the least. Yu et al. [5] proposed a method to estimate the load strength of circular and polygonal CFST columns utilizing circular sections as a special case of polygonal sections by splitting elastic deformation in circular sections into .axial compression and plane strain problems

The rapid advancement of artificial intelligence (AI) techniques has resulted in a wide range of structural engineering applications. AI is a machine-based replica of human intellect that goes through three main phases: learning, reasoning, and correcting. The artificial neural network (ANN) is a process that is carried out by interconnected nodes known .[as neurons as part of AI [6

As recently as Ahmadi et al. [6], Jayalekshmi et al. [7], Tran et al. [8], and Sarir et al. [9] employed this form of analysis in circular and square CFST columns. Du et al. [10] used ANN models to forecast the axial strength capacity of rectangular CFST columns, which .they compared to several international codes

Due to the combined influences of mechanical characteristics such as modulus of elasticity and Poisson's ratio, as well as additional factors such as bond strength, boundary, and constraining conditions, the mechanism of interactions between steel and concrete is still not entirely understood. The artificial intelligence (AI) approach has been applied in this study to explore the behavior of octagonal CFST columns. Rare studies have investigated the behavior of CFST columns using ANN approaches. The ANN model of the present .study has been found to provide better predictions of ultimate strengths than codes

Experimental Database

A series of experimental findings on octagonal concrete-filled steel tube columns under axial loading were collected to develop the proper network for estimating the steel-concrete compressive strength. There are 20 test results in the data acquired from the litera- .[ture [3, 11, 12

The material strength ratio (f_c'/f_y) of the specimens in Table 1 ranges from 0.05 to 0.15, and the depth-to-thickness of the tube (D/t) is between 38 and 126. Normal strength concrete with compressive values ranging from 17 to 45 MPa and steel tubes with yield .strengths ranging from 294 to 341 MPa

Ultimate Strength of Octagonal CFST Columns

The axial strength (P) of a CFST column can be easily determined in the early phases of loading by

$$P = A_c f_c' + A_s f_s \quad \text{.........} \quad 1$$

where f_c' and A_c represent the strength and cross-sectional area of the concrete core, and f_s and A_s represent the strength and cross-sectional area of the steel tube, respectively. When stresses are increased to the point of failure, instantaneous crushing in the concrete core and yielding of the steel tube is expected to result in squash load (P_{u0}) by

$$P_{u0} = A_c f_c' + A_s f_y \quad \text{.........} \quad 2$$

.where f_c' and f_y are the compressive strength of concrete and the yield strength of steel

Table 1 Data from experimental tests of octagonal CFST columns

No.	Specimen	L (mm)	B (mm)	t (mm)	fy (MPa)	fc′ (MPa)	Nu (kN)	Reference
1	OST1-A	1500	201.0	3.85	311.0	31.08	9297	Ding et al. [3]
2	OST1-B	1500	199.0	3.98	311.0	31.08	9311	
3	OST2-A	1500	200.0	6.02	321.0	31.08	10502	
4	OST2-B	1500	197.0	5.89	321.0	31.08	10713	
5	OST3-A	1500	200.0	3.92	311.0	45.40	12362	
6	OST3-B	1500	199.0	4.02	311.0	45.40	12357	
7	OST4-A	1500	197.0	5.88	321.0	45.40	12992	
8	OST4-B	1500	198.0	5.98	321.0	45.40	13263	
9	2HN	-	62.1	2.00	341.3	30.10	1003	Tomii et al. [11]
10	3HN	-	62.1	3.20	300.2	30.10	1100	
11	4HN	-	62.1	4.00	294.3	30.10	1273	
12	2MN	-	62.1	2.00	341.3	21.90	782	
13	3MN	-	62.1	3.20	300.2	21.90	946	
14	4MN	-	62.1	4.00	294.3	21.90	1108	
15	2LN	-	62.1	2.00	341.3	16.70	650	
16	3LN	-	62.1	3.20	300.2	16.70	803	
17	4LN	-	62.1	4.00	294.3	16.70	968	
18	CFST-1	-	80.0	5.00	295.8	28.90	1916	Zha [12]
19	CFST-2	-	80.0	5.00	295.8	28.90	1907	
20	CFST-3	-	80.0	5.00	295.8	28.90	1906	

Once external loads are raised, the concrete expands gradually as micro-cracks emerge, which is opposed by the outside steel tube. The transverse confining pressure will be applied to the concrete core, which will be in a tri-axial compressive condition with a confined strength of f_{cc}' and can be expressed as

$$f_{cc}' = \gamma_c f_c' + k_1 f_{rp} \qquad \text{.........} \quad 3$$

where the scale reduction γ_c ranges between 0.85 and 1.0, k_1 is a confinement factor given .by Richart et al. [13] as 4.1. f_{rp} is the confining pressure

The following formulas were proposed by Patel et al. [14] to determine the confining pressure

$$f_{rp} = \begin{cases} (250.8 - 3.977\frac{D}{t}) \times 10^{-4} f_y & 17 < \frac{D}{t} < 47 \\ (4465 - 1.5\frac{D}{t}) \times 10^{-6} f_y & 47 \le \frac{D}{t} < 150 \\ 0 & \frac{D}{t} \ge 150 \end{cases} \qquad \text{.........} \quad 4$$

where D is the distance between outside surfaces of two opposite sides of the octagonal section as shown in Fig. 1 and can be taken as D=2.414B, in which B is the side length of .the octagonal section and t is the thickness of the tube
The effect of the confinement can be taken into account as proposed by Patel et al. [14] that the bearing capacity of a CFST column be

$$P_{u,1} = A_c f'_{cc} + A_s f_y \qquad \text{.........} \quad 5$$

Ding et al. [3] presented a method to account for the effect of confinement by magnifying the steel tube strength resulting from composite interactions between concrete and steel, which can be expressed as

$$P_{u,2} = A_c f'_c + 1.5 A_s f_y \qquad \text{.........} \quad 6$$

By modifying the specific case formula of circular sections, Yu et al. [5] developed a unified formula to estimate the final strength of circular and polygonal CFST columns, which is given as

$$P_{u,3} = \left(1 + 0.5\frac{\xi}{1+\xi}\right)\left(A_c f'_c + A_s f_y\right) \qquad \text{.........} \quad 7$$

.where ξ is the stiffness ratio and it equals $f_y A_s / f_c' A_c$
Abbas and Ali [15] proposed a formula as

$$P_{u,4} = A_c\left(f'_c + f_{rp}\right) + A_s f_y \qquad \text{.........} \quad 8$$

[The confining pressure in Eq. 8 can be given as [16

$$f_{rp} = \left(\nu_e - \nu_s\right)\frac{2t}{D-2t} f_y \qquad \text{.........} \quad 9$$

ν_e is the Poisson's ratios of steel tubes with concrete fill can be expressed as

$$\nu_e = 3.346 + 5.579\nu'_e - 32.066\left(\frac{f'_c}{f_y}\right) + 97.493\nu'_e\left(\frac{f'_c}{f_y}\right) - 212.305\left(\frac{f'_c}{f_y}\right)^2 \qquad \text{.........} \quad 10$$

where

$$\nu'_e = 2.446 \times 10^{-7}\left(\frac{D}{t}\right)^3 - 7.139 \times 10^{-5}\left(\frac{D}{t}\right)^2 + 9.000 \times 10^{-3}\left(\frac{D}{t}\right) + 0.497 \qquad \text{.........} \quad 11$$

.[At the maximum strength point, ν_s can be assumed to be equal to 0.5 [4

Strength of CFST Columns Using Artificial Neural Network

In the past few years, the artificial neural network (ANN) has been used in composite columns successfully. One of the most important steps in ANN analysis is training the neural network using test results. In CFST columns, this step is essential to develop a model that capable to estimate the ultimate strength of the composite column of a similar environment. Due to the lack of test results in the literature that carried out on octagonal CFST columns, the ANN model is limited to 20 column specimens shown in Table 1. The present ANN model was constructed with different layers which are one layer for input parameters, one or more hidden layers, and an output results layer. Various input nodes and hidden layers have been tried to get the most accurate and efficient model. Trial and error can be used to determine the number of neurons and hidden layers, which has an impact on the efficiency of the model. In the present ANN model four input neurons, one hidden layer with five neurons, and a single output neuron as shown in Fig. 2. The input parameters are the side length, the tube thickness, the compressive strength of concrete, yield strength of steel while the output layer is giving the ultimate strength of the CFST column. It is found that adopting a back-propagation algorithm in parallel with an optimization technique using the Levenberg-Marquardt algorithm gives the most efficiency .in the training process

The operation in the hidden layer can be controlled by a transfer function f *(u)* which is a nonlinear tan-sigmoid function. The independent variable here is coming from the weighted sum given as

$$u=\sum W_i x_i+b$$

where x_i is an input vector received by each input neuron, W_i is the weight and b is a bias

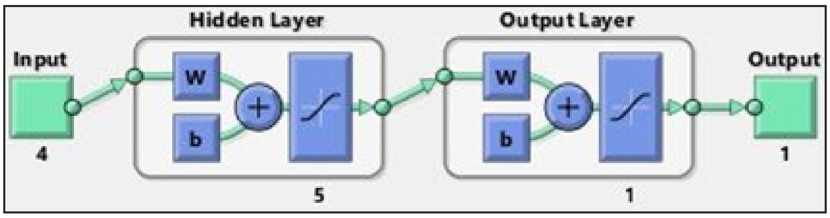


Fig. 2 The architecture of a neural network

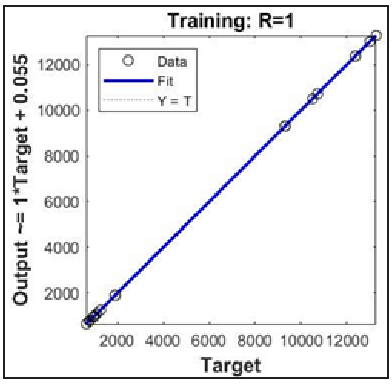
The ANN model is used in training 70% of test data and 15% of test data in the validation process and the remainder 15% is used in the self-correcting test process. Evaluation and performance of regression accuracy of ANN model can be seen in Figs. 3 and 4 which show good accuracy

Ultimate Strengths of Octagonal CFST Columns Using Different Methods

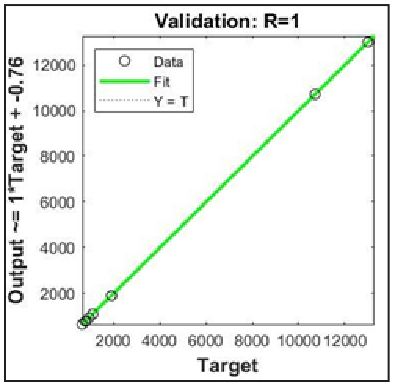
A comparative analysis of ultimate strength ratio *($P_u/P_{u,exp}$)* using formulas proposed by Ding et al. [3], Yu et al. [5], and Abbas and Ali [15], in addition to the present ANN model as shown in Table 2. To compare accuracy amongst different approaches, the mean, standard deviation (SD), and coefficient of variation (COV) of the outcomes were obtained, as shown in Table 3. As can be observed, Abbas and Ali's formula and the ANN model are comparable and provide the most accurate results when compared to other available formulas for a wide variety of material and geometric variations of octagonal CFST columns. Even with lower values of SD, the formula proposed by Ding et al. [3] has a mean that somewhat far from unity. As it is known that the standard deviation shows how .results are closer to the mean value

Analysis of Parameters Using ANN

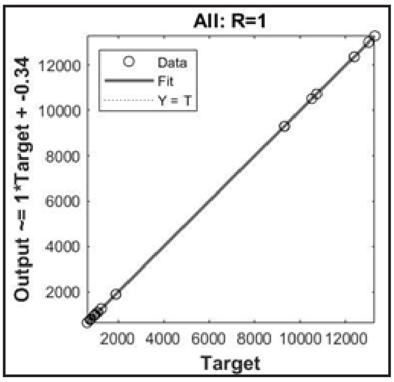
Once the artificial neural network (ANN) model has been constructed it will be a useful and fast tool in predicting the ultimate strengths of CFST columns. This feature will be employed to check how variation in geometrical and material properties affects the column capacities. Eighteen columns with varying material and geometrical parameters have been studied by using the ANN model that was previously created and verified to .show the impact of various parameters on CFST column strength capacity



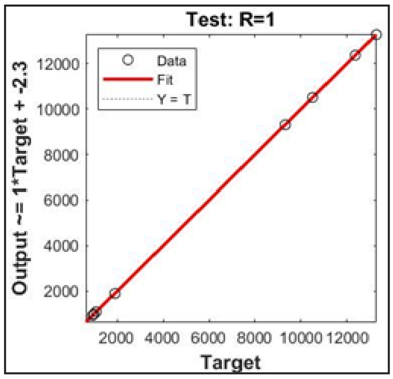
a) Regression of training



b) Regression of validation



d) Regression of all



c) Regression of test

Fig. 3 Regression analysis of ANN

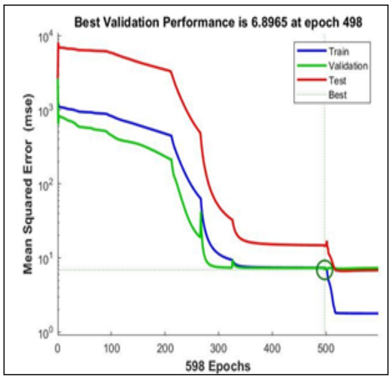


Fig. 4 Performance of ANN model

Table 2 Bearing capacity *(Pu/Puexp)* ratio using different formulas

No.	Patel et al. [14]	Ding et al. [3]	Yu et al. [5]	Abbas and Ali [15]	ANN
1	0.85	0.96	0.87	1.00	0.99
2	0.84	0.95	0.86	0.99	1.00
3	0.85	1.00	0.90	1.00	1.01
4	0.81	0.95	0.85	0.95	0.99
5	0.82	0.98	0.89	1.01	1.00
6	0.82	0.97	0.89	1.00	1.00
7	0.83	1.01	0.93	1.00	1.02
8	0.83	1.00	0.92	0.99	1.01
9	0.94	1.03	0.90	1.03	0.93
10	0.99	1.10	0.97	1.06	0.94
11	0.98	1.06	0.94	0.98	1.02
12	1.03	1.14	1.00	1.03	1.02
13	1.01	1.14	1.00	1.03	0.93
14	1.01	1.10	0.98	0.98	0.94
15	1.11	1.22	1.08	0.98	1.14
16	1.09	1.23	1.09	1.02	1.01
17	1.07	1.17	1.04	0.96	0.98
18	1.04	0.96	1.01	1.05	1.00
19	1.04	0.95	1.01	1.06	1.01
20	1.04	1.00	1.01	1.06	1.01

Table 3 Statistical analysis of results

Criteria	Patel et al. [14]	Ding et al. [3]	Yu et al. [5]	Abbas and Ali [15]	ANN
Mean	0.95	1.060	0.96	1.01	1.00
Standard Deviation (SD)	0.105	0.094	0.072	0.032	0.046
the Coefficient of Variation (COV)	0.111	0.088	0.075	0.032	0.046

Table 4 shows the material and geometrical properties of the columns and their results. All columns are 1500 mm long. Three different side lengths 100, 150, and 200 mm lengths which give depths (D) of 241, 362, and 483 mm, in addition to two thicknesses of steel tubes of 4 and 6 mm have been used. The compressive strengths of core concrete are 25, 35, and 45 MPa, while the yield strengths of steel tubes are 290 and 340 MPa. All these properties are within the range of the input data used in the training of the neural network .to guarantee accurate results

Table 4 ANN model results of octagonal CFST columns

Variable properties				*fy* (MPa)	
				290	340
fc' (MPa)	B (mm)	t (mm)	B/t	*Nu* (kN)	
25	100	4	25	2427	2549
		6	16.7	2877	3106
	150	4	37.5	4702	4837
		6	25	5461	5735
	200	4	50	7655	7778
		6	33.3	8710	9007
35	100	4	25	2960	3182
		6	16.7	3269	3645
	150	4	37.5	6036	6322
		6	25	6661	7160
	200	4	50	10118	10444
		6	33.3	11034	11635
45	100	4	25	3268	3622
		6	16.7	3327	3899
	150	4	37.5	7025	7514
		6	25	7352	8150
	200	4	50	12120	12717
		6	33.3	12674	13677

The impacts of various diagonal depth-to-thickness ratios (*B/t*), yield strength of steel walls (f_y), and compressive strength of concrete core (f_c') on the ultimate strength of columns have been investigated. Fig. 5 illustrates that the effect of increasing the slenderness ratio of the section (*B/t*) on the ratio of strength capacity (P_u/P_{u0}) where the squash strength P_{u0} is given in Eq. 2. It can be seen that an increase in strength due to composite action and confinement effects may reach up to approximately 9%. Also, it can be noted that the larger sizes of octagonal CFST columns gained greater strength. This is maybe owed to the buckling vulnerability of the columns with slender sections of higher *B/t* ratios. To show the effect of the variation of the compressive strength of core concrete, Fig. 6 was plotted. The increase in axial capacity of the column is increasing with increasing the compressive strength. For higher yield strength steel tubes the rate of increase in ultimate strengths is larger.

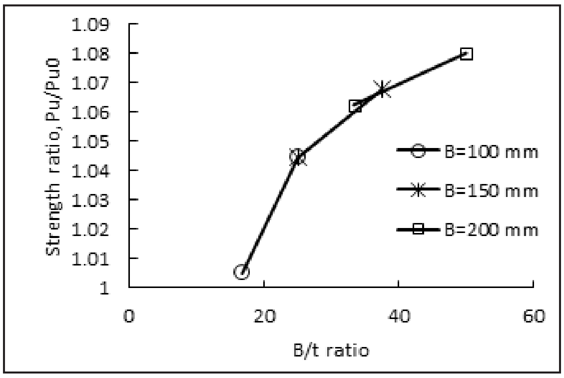


Fig. 5 Effect of the section slenderness (*B/t*) on the ultimate strength ratios f_y=290 MPa

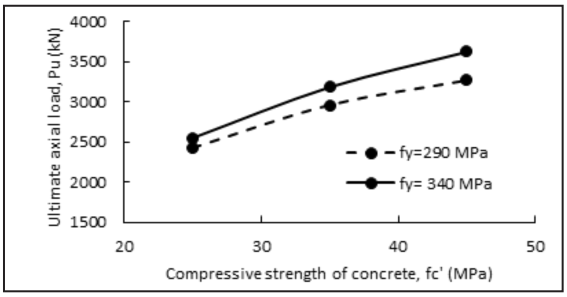


Fig. 6 Effect of the compressive strength of concrete on the ultimate strength

Conclusions

:Based on the present study, the following conclusions can be taken

1-An ANN model was created and utilized to add verify the proposed formula and to expand the database of various parameters

2-Comparison with other available equations literature showed that the present ANN model gives more accurate results with exception the method proposed by Abbas [and Ali [15

3-The side length-to-thickness ratio is shown to be important in the confinement effect on the strength capacity of octagonal CFST columns

4-No significant effect to high yield strength tube of the octagonal CFST columns with a .normal concrete core. This may be owed to the earlier failure of the concrete core
5-The composite action will be more effective in CFST columns with slender cross-sections than columns with compact sections

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Appendix

Nomenclatures	
Ac	area of concrete core cross-section
As	area of steel tube cross-section
B	width of the section
D	length of the section
D'	diagonal depth of the section
Es	modulus of elasticity of steel
fc'	compressive strength of concrete core
fcc'	confined strength of concrete core
frp	lateral confining pressure
fsr	hoop stresses
fy	yield strength of steel tube
L	length of the column
Nu	ultimate capacity
T	thickness of steel tube
Greek Symbols	
γc	scale (dimensional) factor for concrete core
ve	Poisson's ratios of steel tube with concrete fill,
vs	Poisson's ratios of steel tube without concrete fill
ξ	Stiffness ratio
Abbreviations	
ANN	Artificial Neural Network
CFST	Concrete-Filled Steel Tube
FEM	Finite Element Method