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An Interpretable Ensemble Learning Method to Predict the Strength Capacity of CFST Bridge Piers Subjected to Eccentric Loading

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ABSTRACT:

This study investigates into the impact of varying diameter-to-thickness (D/t) ratios (21.22, 25.46, and 31.83) and concrete strengths (40 N/mm2, 50 N/mm2, and 60 N/mm2) on the strength characteristics of concrete-filled steel tubular (CFST) columns. Thirteen experimental models, consisting of nine unique tests, underwent testing to investigate the failure mode, load-deformation behaviour, and ultimate strength capacity of these specimens. As the concrete strength within the columns increased, the confinement of the steel tube on the core weakened, regardless of the D/t ratio. This weakening was attributed to the rise in longitudinal compressive stress within the steel tube as the D/t ratio decreased, leading to a reduction in the inhibition of circumferential tensile stress (fsc). The analysis of variance, represented through Skew plots, revealed that the D/t ratio of the column significantly influenced the strength capacity of CFST columns, with greater impact than the concrete strength within them. The study also evaluated the applicability of proposed design models from various international codes and literature in predicting the strength capacities of CFST columns subjected to axial compression loads. It introduced a simple design model, derived through regression analysis and consideringmaterial strength and column geometry, for predicting the axial strength capacities of short CFST columns. This proposed design model demonstrated superior accuracy and stability compared to other existing and proposed design models.

Keywords: CFST Column, Ensemble Learning, Strength Capacity, Eccentricity

INTRODUCTION:

Concrete-Filled Steel Tube columns, are structural elements widely used in construction of bridge piers. These columns consist of a steel tube filled with high-strength concrete. The combination of steel and concrete creates a composite structure that takes advantage of the strengths of both materials. CFST columns used in bridge piers due to its combination of structural efficiencyand load bearing capacity is good.The process of using mathematical models of data to help a computer learn without direct instruction. This enables a computer system to continue learning and improving on its own, based on experience.Ensemble learning is a machine learning technique that combines multiple models to improve overall performance and accuracy. These models can lead to better results compared to a single model

LITERATURE REVIEW:

1) **Yuying wang, Peng Chen, Changying Liu, Ying Zhang,"** Size effect of circular concrete-filled steel tubular short columns subjected to axial compression", (2017). To evaluate the size effect of circular concrete-filled steel tubular short columns exposed to axial compression, thirty-six short columns with varying diameters (150 mm s d s 460 mm) and steel ratios (4.0% a 10.0%) were tested to failure. The influence of size on peak axial stress, peak axial strain, composite elastic modulus, and ductility coefficient was investigated. The experimental findings revealed that the peak axial stress, peak axial strain, and ductility coefficient of the specimens tended to decrease as the column diameter increased. When the diameter of the specimen was enlarged, the values of the composite elastic modulus remained virtually constant.

2) **Zhi-Wu Yu, Fa-Xing Ding, C.S. Cai**, "Experimental behaviour of circular concrete-filled steel tube stub columns", (2007). The study examines the behaviour of circular concrete-filled steel tube stub columns with self-compacting and normal concrete in compression to failure. Results show that higher strength concrete increases ultimate capacity, but residual capacity remains constant. Steel tubes act more as transverse confinement, and Eurocode 4 predicts reasonable capacity for unnotched CFT stub columns. The sequence of confinement effect changes under different loading conditions.

3) **Kenji Sakino, Hiroyuki Nakahara, Shosuke Morino, Isao Nishiyama, "**Behaviour of centrally loaded concrete-filled steel-tube short columns", (2004). A 5-year research on concrete-filled steel tubular (CFT) column systems was conducted as part of the US-Japan Cooperative Earthquake Research Program. The tests focused on the synergistic interaction between steel tube and filled concrete and determining the load-deformation relationship of CFT columns. 114 specimens were tested on centrally loaded hollow and CFT short columns, with parameters such as tube shape, tensile strength, diameter-to-thickness ratio, and concrete strength. The study concluded that the ultimate axial compressive load

capacities of CFT columns can be estimated as a linear function of tube yield strength. Stress-strain models for concrete in CFT columns were also formulated based on the experimental results.

4) **J.Y. Richard Liew, Mingxiang Xiong, Dexin Xiong**, “Design of Concrete Filled Tubular Beam-columns with High Strength Steel and Concrete”, (2016). A design guide for concrete filled steel tubular members has been proposed, based on an extension of Eurocode 4 method for concrete compressive strength up to 150 N/mm and high tensile steel with yield strength up to 550 N/mm². The guide is intended for CFTS members with at least Class 3 steel section and should match grades of steel and concrete materials. A strength reduction factor should be applied for high strength concrete with cylinder strength greater than 50 N/mm² but less than 90 N/mm², and the secant modulus of concrete should be modified. For ultra-high strength concrete with compressive cylinder strength higher than 90 N/mm² but less than 190 N/mm2, a conservative approach is adopted, with steel with yield strength greater than 550 N/mm² allowed.

5) **Suliman Abdalla, Farid Abed, Mohammad AlHamaydeh**, “Behaviour of CFSTs and CCFSTs under quasi-static axial compression”, (2013). This paper investigates the behaviour of circular Concrete Filled Steel Tubes (CFST) and Confined Concrete Filled Steel Tubes (CFST) with Glass Fiber-Reinforced Polymers (GFRP) wrapping sheets under concentric compressive quasi-static loads. The study tested 35 specimens with two concrete compressive strengths and three diameter-to-thickness ratios. The dominant failure mode was the explosive rupture of GFRP wraps at the mid-height region. The CCFST section's axial load-carrying and ductility capacities increased due to GFRP additional confinement. The study found that increasing the concrete strength increased the axial capacity of both elements, but had minimal effect on their stiffness.

6) **Qing Yu, Zhong Tao, Wei Liu, Zhi-Bo Chen**, “Analysis and calculations of steel tube confined concrete (STCC)stub columns”, (2010). This study uses a finite element analysis (FEA) model to predict the mechanisms of STCC stub columns under axial compression. The model shows good agreement with measurements. The interaction between the steel tube and concrete core was analyzeds, showing that the sectional capacity of circular and square columns is slightly higher than CFST columns. A simplified model was developed for calculating section capacities.

7) **Martin D. O’Shea, Russell Q. Bridge**, “Design of circular thin-walled concrete filled steel tubes”, (2000). This paper presents design methods for conservatively estimating the strength of circular thin-walled concrete-filled steel tubes under various loading conditions. Tests on short specimens were conducted to validate the methods. The bond between steel and internal concrete was crucial in determining the formation of a local buckle.

8) **Shiming Zhou, Qing Sun, Xiaohong Wu**, “Impact of D/t ratio on circular concrete –filled high strength steel tubular stub columns under axial compression”, (2018). The paper presents an experiment program on concrete-filled high-strength steel stub columns under concentric loading to understand the behaviour of Concentric High-Strength Steel Structural Tension (CFHST) with a large D/t ratio. Results show that the strength and ductility of confined concrete increase due to the steel tube's confinement. A plastic section design can still be applied in CFHST with a D/t ratio less than 125.

9) **Stephen P. Schneider**, “Axially loaded concrete-filled steel tubes”, (1998). This study investigates the influence of steel tube shape and D/t ratio on concrete-filled steel tube columns. Circular steel tubes offer more post-yield axial ductility than square or rectangular tubes, with strain-hardening characteristics for small D/r ratios. Measured perimeter-to-longitudinal strains show no significant confinement for most specimens until the axial load reaches 92% of the column's yield strength. Local wall buckling for circular tubes occurs at axial ductility of 10 or more, while most local wall buckling occurs between 2 and 8. Smaller D/t ratios increase yield load compared to computed AISC/LRFD Specifications. AISC/LRFD Specification provides a conservative estimate for axial strength.

10) **Lin-Hai Han, Guo- Huang Yao**, “Experimental behaviour of thin-walled hollow structural steel (HSS) columns filled with self-consolidating concrete (SCC)”, (2004). The study explores the use of thin-walled HSS columns filled with SCC in practice. Results show similar features between specimens compacted without vibrations, compacted with a poker vibrator, and compacted by hand. Stub columns with SCC compacted without vibration had slightly lower section capacity values. Good concrete compaction resulted in slightly higher beam-column member capacities , with ultimate strengths higher for members compacted with a poker vibrator.

Description of Database

Because the It is well known that the collection and the precision of the data is machine learning modelling. A database of 105 experimental dataset on circular CFST columns under axial compression was retrieved from various literatures and the details of the literatures are summarized in Table 1. The axial compression setup used to test the CFST column is shown in Figure 1. The independent variables of the ML model are includes shape parameters (diameter, thickness and height of the steel tube), and material properties (‘*fck*’ – Compressive strength of Concrete and ‘*fy*’ – Yield strength of Steel Tube). The cube compressive strength considered for the ML modelling. Though, few of the literatures utilized cylinder compressive strength as concrete strength, those are converted in to cube compressive strength, and those compressive strength was adopted in this study for ML modelling.

Statistical details of the data used in this study

Since the quality of data is determining the accuracy and precision of the ML model, quality data has been collected from various literatures. The database contains a total of 192 data objects and with six different attributes. Since the descriptive statistics allow us to understand the data and it will be very helpful during interpreting the ML model, detailed descriptive data analysis includes data frequency distribution, histograms were made and to identify the mean, standard deviation, IQR and outliers, five point summary and box plot were made on all data attributes. The descriptive statistics of 192 data objects are summarized in Table 1. The data frequency distribution and the five point summary are shown in Figure 1. With respect to material properties, the data base covering the compressive strength of concrete is ranging from 25.40N/mm2 to 89.16N/mm2 and the steel yield strength is ranging from 185.70N/mm2 to 724N/mm2. Though the material properties data was covered wide range of data, the yield strength of steel tube somewhat followed the normal distribution, whereas, in concrete strength, could able identify the relative uniform distribution. From the histogram it can be understood that the data frequency distribution of yield strength of steel tube is right skewed, implies that most of the data objects are concentrated in the range of 200N/mm2 to 400N/mm2, and only few data objects are falling in the range of 200N/mm2 to 400N/mm2. Further, from the five point summary and box plot it can be understood that the Yield strength of steel tube is having few outliers as well. With respect the concrete strength, the compressive strength of concrete is following relative uniform distributions and it is not having any outliers as well.

Considering the shape parameters of the column, the data base covering the diameter, thickness and height ranging from 101mm to 247mm, 0.86mm to 6.58mm and 203mm to 741mm, respectively. From the frequency distribution (Figure 1), it can be understood that all the shape parameters are following normal distribution. Considering shape parameters, though the diameter followed the normal distribution, the data distribution is slightly right skewed. With respect to steel tube, most of the diameters are concentrated in the range of 100mm to 180mm, and few data are falling beyond 200mm. Further, shape parameters are having very few outliers, further; the column thickness is not having any outliers.

Five highly relevant features related with axial strength capacity of CFST column was considered and the target variable of the ML model is axial strength capacity of CFST column. The target variable of ML model is followed the normal distribution and the data is slightly rightly skewed. The database covering the data objects ranging from 610kN to 4166kN, further, from the box plot it can be seen that the target variable is having few outliers as well.

It is well documented that the standard deviation of the data attributes are very important in ML modelling. For precise modelling, the data attributes are should have a minimum deviation. The standard deviation of the present study data set is summarized in Table 1, and from Table 1, it can be understood that data attributes steel tube diameter, thickness and compressive strength of infilled concrete are having low standard deviation implies that the values of the data set is consistent, whereas the data attributes column height and Yield strength of steel tube are having slightly higher standard deviation. Since the data set are having slightly higher standard deviation, there may not be possibility for overfitting. Since the present study utilizing ensemble ML model with hyper parameter tuning, the possibility of overfitting can be avoided.

Table 1 Descriptive statistics of data objects

Descriptive Statistics	**Diameter (mm)**	**Thickness (mm)**	**Compressive strength of Concrete (f_{ck}) (N/mm^2)**	**Yield strength of steel tube (fy) (N/mm^2)**	**Column Height(mm)**	**Axial strength capacity of CFST column (kN)**
Mean	149.46	3.57	59.19	371.44	450.31	1801.35
Standard Deviation	32.22	1.13	18.16	100.62	119.28	651.23
IQR	(127, 165)	(2.9, 4.54)	(44, 77.1)	(312.8, 362.5)	(378, 512)	(1377, 2075)
Outliers	Yes	No	Yes	No	Yes	Yes

Table 2 Five point summary

Data Attributes	**min**	**25%**	**50%**	**75%**	**max**
Diameter (mm)	101.70	127.0	139.8	165.00	247.00
Thicknes (mm)	0.86	2.9	3.4	4.54	6.58
Yield strength of steel tube (fy) (N/mm^2)	185.70	312.8	350.0	362.50	724.00
Compressive strength of Concrete (f_{ck}) (N/mm^2)	25.40	44.0	60.0	77.10	89.16
Column Height(mm)	203.00	378.0	430.0	512.00	741.00
Axial strength capacity of CFST column (kN)	610.00	1377.0	1710.0	2075.00	4166.00

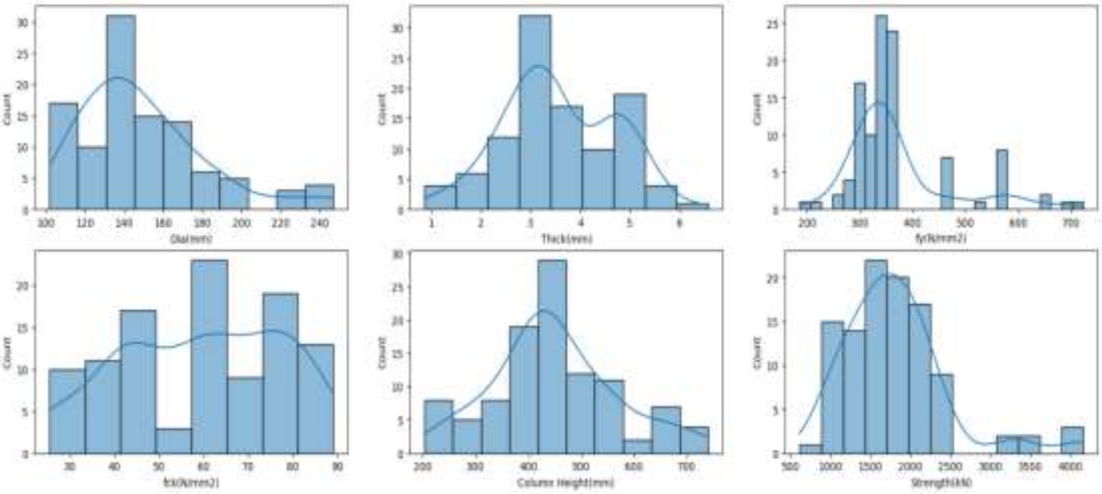


Figure 1 Frequency distribution of all data attributes

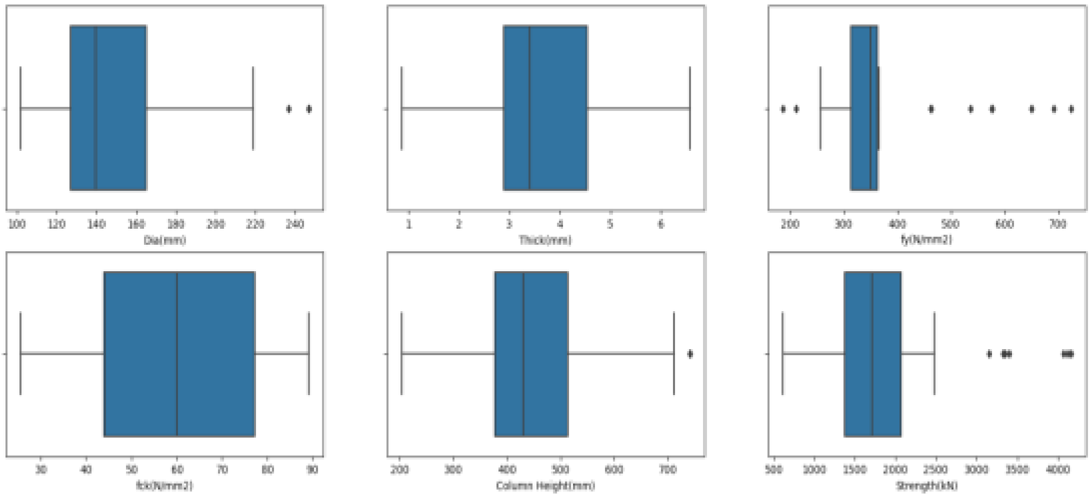


Figure 1 Five point summary of all data attributes

RESULTS AND DISCUSSIONS:

Considering the linear regression model, the model shown an accuracy of 96% in train and 92% in test. It was expected that the higher standard deviation of the features may lead to the overfitting. As expected, the higher standardization of the features led to the overfitting of the model. It is well known that the ensemble model will have a less possibility of model overfitting, so, the same ensemble models are used here to predict the strength capacity of the CFST column.

The model statistics and the feature importance of the features are summarized in Table 1 and presented in Figure 1. The predicted strength and actual strength comparison is shown in Figure 2.

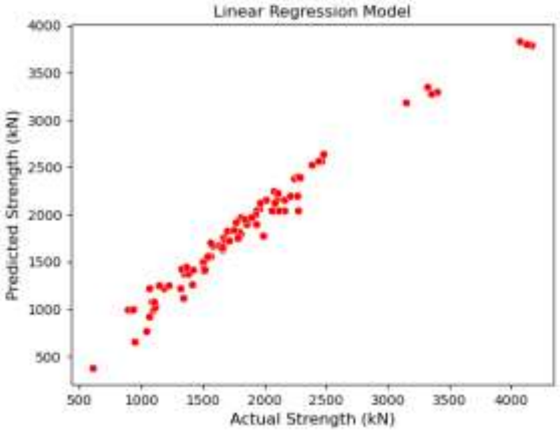
Table 2 ML model statistics

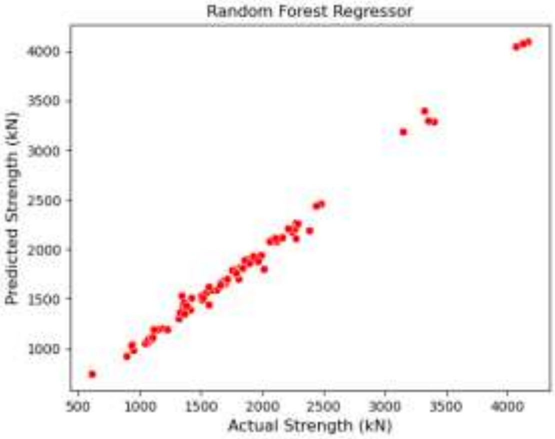
Ensemble Techniques		**R2**	**Mean absolute percentage error (MAPE)**	**Root mean squared error (RMSE)**
Linear Regression	Train	0.96	0.06	121.47
	Test	0.81	0.21	325.85
Random Forest	Train	0.99	0.02	65.62
	Test	0.97	0.04	88.56
Ada Boost Regression	Train	0.97	0.06	118.25
	Test	0.95	0.11	110.21
Gradient Boost Regression	**Train**	**0.99**	**0.02**	**52.24**
	Test	**0.98**	**0.03**	**71.41**

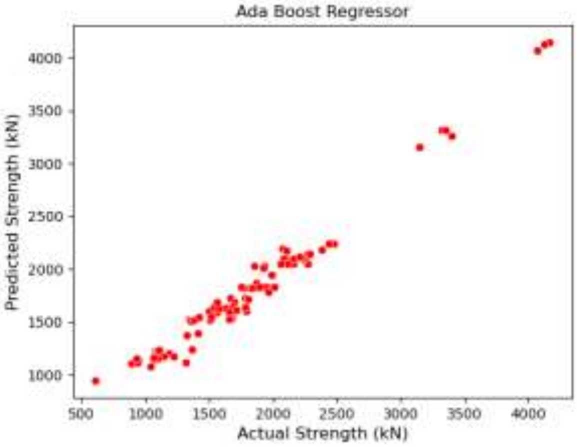
Not like, the performance of the ensemble model was too better than the linear regression model. It is well documented that the model which is having accuracy score more than 92% and Mean absolute percentage error (MAPE) less than 15% can be considered as a good model. In this condition, all the ensemble model were shown more than 96% accuracy score and the MAPE score were less than 11%. So, the entire ensemble model can be considered as fair model predict the strength capacity of the column. Though all three ensemble models were shown relatively similar performance, considering the 'R^2' of all three ensemble models, the performance of Gradient Boost Regression is relatively better than other ensemble models includes Random Forest and Ada Boost Regression. The score value of the Gradient Boost Regression is 98% in test, whereas, the other models Random Forest and Ada Boost Regression shown a score value of 97% and 95% in test. From, Figure 1, it can be understood that the predicted strength capacity of Gradient Boost Regression is fairly agreed with the actual strength capacity of the CFST column. Whereas, in other model, though few data objects are fairly agreed with the actual strength, few of the data objects are not fairly agreed with the actual strength and those points falling away from the centre line which is evident from Figure 1.

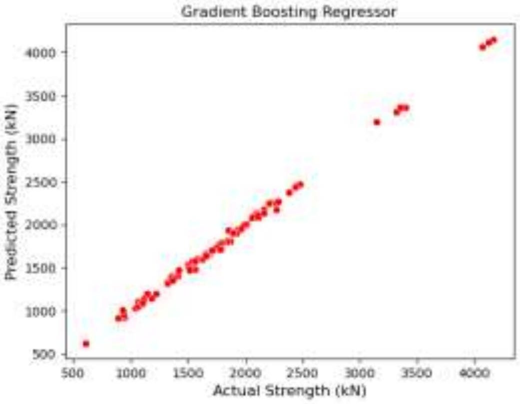
Feature importance

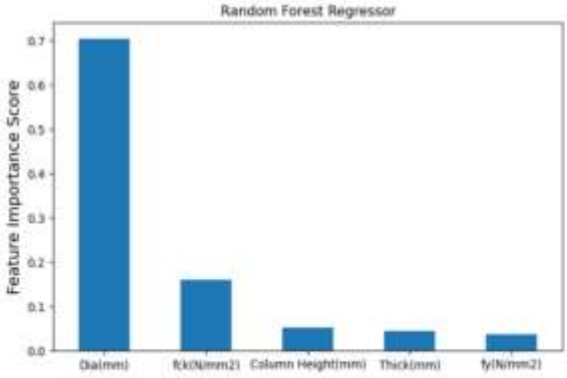
The advantage of ensemble models are it will provide the feature importance means provide the order of parameter contributing the target variable. The feature importance provided by the all three ensemble model is presented in Figure 2. From Figure 1, it can be understood that the diameter of the steel tube and the strength of infilled concrete are most important factor with respect to the strength capacity of the CFST column followed by the steel tube thickness and column height are the most important factors.

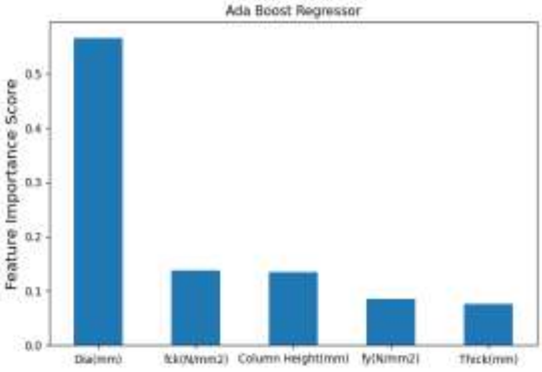


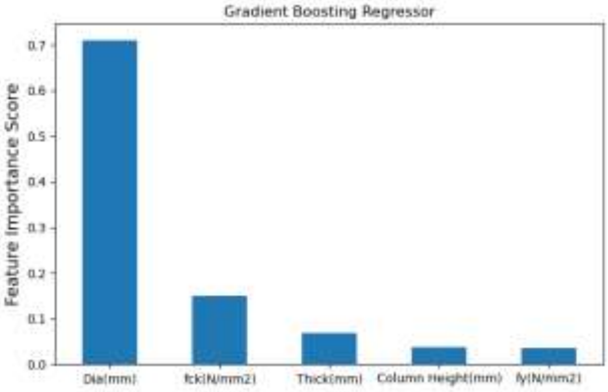












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