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Abstract

Over the last three decades, fibre has been commonly used in reinforced concrete (RC) columns to enhance their strength and ductility. In the available studies on Steel Fibre Reinforced Concrete (SFRC) columns, axial compressive strength of the columns is expressed as functions of unconfined concrete compressive strength and the lateral confinement pressure. In this study, available experimental investigation results of the axial compressive strength of SFRC square columns have been compiled. This study also proposes axial compressive strength models of the SFRC square columns using artificial neural network (ANN). In the proposed models, axial compressive strength of SFRC columns has been expressed as functions of unconfined concrete compressive strength (fc'), confinement pressure due to lateral reinforcement (fle) and confinement pressure due to the action of steel fibres (flb). The results of the proposed ANN strength models match very well with the available experimental results.

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MODELS FOR PREDICTING THE AXIAL COMPRESSIVE STERNGTH OF STEEL FIBRE REINFORCED NORMAL AND HIGH STRENGTH CONCRETE SQUARE COLUMNS

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ABSTRACT

Over the last three decades, fibre has been commonly used in reinforced concrete (RC) columns to enhance their strength and ductility. In the available studies on Steel Fibre Reinforced Concrete (SFRC) columns, axial compressive strength of the columns is expressed as functions of unconfined concrete compressive strength and the lateral confinement pressure. In this study, available experimental investigation results of the axial compressive strength of SFRC square columns have been compiled. This study also proposes axial compressive strength models of the SFRC square columns using artificial neural network (ANN). In the proposed models, axial compressive strength of SFRC columns has been expressed as functions of unconfined concrete compressive strength (f_c'), confinement pressure due to lateral reinforcement (f_{le}) and confinement pressure due to the action of steel fibres (f_{lb}). The results of the proposed ANN strength models match very well with the available experimental results.

1 INTRODUCTION

In Reinforced Concrete (RC) columns, the concrete core is restrained from lateral expansion by transverse reinforcement in the form of closed tie or helix and longitudinal bars. The increasing lateral strain on the transverse reinforcement results in increasing lateral confining pressure applied to the concrete core. Consequently the strength and ductility of the concrete columns are improved [1]. The expression for the lateral confinement pressure (f_{le}) at peak concrete stress that applies to the nominal concrete core due to the action of the lateral reinforcement, [2, 3] is expressed as:

$$f_{le} = k_e \frac{A_{sh}}{sc} f_h' = \rho_{se} f_h' \quad (1)$$

where c is size of the concrete core (centre to centre spacing of the ties); s is spacing of lateral steel; A_{sh} is cross sectional area of the ties reinforcement; f_h' is lateral reinforcement stress at peak concrete stress; k_e is the confinement effectiveness factor and ρ_{se} is the ratio of the effective section for the confining reinforcement $\rho_{se} = k_e A_{sh}/(sc)$. However, for circular and square columns the value of ρ_{se} is similar in any direction and is equal to half of the effective volumetric lateral reinforcement ratio ($1/2\ k_e \rho_s$) [3].

Inclusion of steel fibre into RC columns can also provide additional confinement pressure to the concrete core, which delays the early cover spalling due to improvement in tensile resistance at cover-core interface. Subsequently, substantial improvement in the strength and ductility of the concrete columns was investigated [3]. It can also reduce the strain on the lateral reinforcement by reducing the expansion in the lateral direction [4]. Thus, the confinement pressure due to the Steel Fibre Reinforced Concrete (SFRC) columns has been proposed and shown below [3]:

$$f_{\mathrm{lb}} = \eta_\theta \tau_{\mathrm{fu}} v_{\mathrm{f}} \left(l_{\mathrm{f}} / d_{\mathrm{f}} \right) \tag{2}$$

where η_θ is the orientation effectiveness factor of the fibre. This factor can be taken as η_θ=1/2 by considering the orientation of fibres at $\theta \geq \pi/6$ [5]; v_{f} is volume content of fibre; ($l_{\mathrm{f}}/d_{\mathrm{f}}$) is the aspect ratio of fibres where l_{f} is the length of fibres and d_{f} is diameter of fibre; $\tau_{\mathrm{fu}} = 0.6(f_c')^{2/3}$ is the bond shear strength of fibres [6].

The available research studies on SFRC square columns under concentric loads presented only their own experimental results [4, 5, 8]. However, only a few studies have proposed analytical model to predict axial compressive strength (f_{cc}') [3, 9]. The axial compressive strength model proposed by Ganesan and Muthy [9] did not consider the influence of the steel fibre on the strength of the columns. However, Paultre *et al.* [3] considered the effect of steel fibre on confinement of the concrete columns to predict the axial compressive strength of the 15 SFRC square columns. They used the expression suggested by Cusson and Paultre [2] to determine the axial compressive strength of the SFRC square columns as a function of the effective confinement index at the peak stress of the concrete columns, (I'_{e}). They also reported that the effective confinement index at peak stress of the SFRC square columns should be calculated as functions of confinement pressure due to lateral reinforcement and steel fibre as follows:

$$\frac{f_{cc}'}{f_c'} = 1 + 2.4\left(I'_{\mathrm{e}}\right)^{0.7} \tag{3}$$

$$I'_e = \frac{f_{\mathrm{le}}}{f_c'} + \frac{f_{\mathrm{lb}}}{f_c'} \tag{4}$$

From the available research studies, it has been observed that quite a limited number of research studies are available to predict the axial compressive strength of the SFRC square columns. Thus, it is essential to develop a new axial compressive strength model that accurately covers a wider range of the experimental results of the SFRC square columns. In this study, to predict the axial compressive strength of the SFRC square columns, the confinement pressure due to lateral reinforcement and steel fibres are considered.

In recent years, Artificial Neural Network (ANN) analysis has been used to predict the axial compressive strength of Fibre Reinforced Polymer (FRP) circular columns [10]. ANN has also been used to predict axial strength and strain of FRP square and rectangular columns [11]. This study uses ANN analysis to predict the compressive strength of SFRC square concrete columns for both Normal Strength Concrete (NSC) and High Strength Concrete (HSC) by considering the effect of unconfined concrete compressive strength (f_{c}'), confinement pressure provided by the lateral reinforcement (f_{le}) and confinement pressure provided by the steel fibres (f_{lb}).

2 EXPERIMENTAL DATABASE

A total of 73 experimental results of SFRC square columns have been collected from available research studies of [3, 4, 7, 8]. The SFRC database of square columns includes only reinforced steel columns subjected to concentric load. The research study of Ganesan and Muthy [9] has been excluded due to incomplete information about the values of unconfined concrete compressive strength and the value of yield tensile strength of the lateral reinforcement. In this study, three input parameters *i.e.* f_{c}', f_{le} and f_{lb}, and one target (experimental output) parameter *i.e.* f_{cc}' were used to predict a new f_{cc}' of SFRC square columns. Equations (1) and (2) were used to calculate f_{le} and f_{lb}, respectively. The range of the f_{le} was between 2.7 and 14.5 MPa and the range of the f_{lb} was between 0 and 4.7 MPa. From the experimental results, the values of f_{cc}' of the square columns was calculated by subtracting the load carrying of the longitudinal bars from the total loads divided by concrete core area. The range of the f_c' was between 42 and 155 MPa. Table 1 presents the range of the experimental database.

Table 1. The range of the experimental database.

Selection criteria	Units	Range
Unconfined concrete compressive strength	[MPa]	30-101
Lateral steel reinforcement ratio	[%]	0.32-5.6
Nominal tensile strength of the lateral steel reinforcements	[MPa]	392-856
Longitudinal steel reinforcement ratio	[%]	2-4.52
Nominal tensile strength of the longitudinal steel reinforcement	[MPa]	395-597
Square cross sectional dimensions	[mm]	100-235
Volume content of the fibres	[%]	0-2
Aspect ratio of the fibres	-	0-100
Type of steel fibre	-	Hooked end and crimped
Configuration of lateral steel reinforcement	-	Single and double ties

3 ARTIFICIAL NEURAL NETWORKS (ANN) ANALYSIS

Artificial neural network (ANN) is an analysis toolbox available in MATLAB. It can be used for pattern recognition, model prediction and data classification. The ANN analysis consists of input and target (experimental output), weight factor and activation functions. The ANN output is generated in three layers. In the first layer *i.e.* input layer, the input scalar (I) is multiplied with weight scalar (W) to form (IW) known as input weight matrix and bias matrix of input layer (b_I) is added to IW to obtain input function. In the second layer *i.e.* hidden layer, the input function is subjected to activation function, such as Purelin, Tansig and Logsig functions, by multiplying the input function with LW, which is the output weight matrix of the hidden layer, and the second bias matrix of output layer (b_2) is added to obtain output function. In the third layer *i.e.* output layer, outputs are obtained as a function of the input function and output function.

In this study three input parameters (f_c', f_{le} and, f_{lb}) and one target parameter (f_{cc}') were used to design the network. After designing, the neural network is configured. A feed-forward back propagation type of network was used. A Levenberg-Marquardt (LM) algorithm type of back propagation was used. The Trainlm function of training, the Learngdm adaption learning function and the MSE performance function were used. Two types of activation functions *i.e.* Purelin and Tansig functions were used to develop and train neural network. All input and target data were randomly divided into training (70%), testing (15%), and validation (15%). The network architecture of the proposed ANN strength models is illustrated in Figure 1.

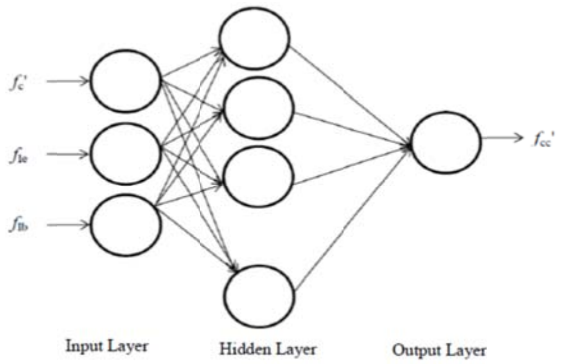

Figure 1 Architecture for the ANN models.

4 MATHEMATICAL DERIVATIONS

Two activation functions (Purelin and Tansig) were used in the ANN analysis to develop strength models. All input and target data were normalized. Bias (b_1 and b_2) and weight factors (input weight (IW) and output weight (LW)) were formulated using neural network Equations (5-8).

$$y_1 = IW \times X_n + b_1 \tag{5}$$

$$y_2 = \text{Activation Function}(y_1) \tag{6}$$

$$y_3 = LW \times y_2 + b_2 \tag{7}$$

$$y = \text{Activation Function}(y_3) \tag{8}$$

where, X_n is the input matrix; y_1 is the output of the input layer; y_2 and y_3 are the outputs of the hidden layer; y is the ANN output. The Purelin and Tansig activation functions are used in this study to train the neural network.

5 PROPOSED COMPRESSIVE STRENGTH MODEL

5.1 Purelin strength model

The Purelin function was developed to predict the f_{cc}' of square NSC and HSC columns. After training, the input weight matrix (IW), the layer weight matrix (LW) and bias matrices b_1 and b_2 were obtained. Equation 8 was used to modify the Purelin strength model as given below:

$$y = LW \times IW \times X_n + LW \times b_1 + b_2 \tag{9}$$

$$y = \sum_{n=1}^{3} W \times X_n + LW \times b_1 + b_2 \tag{10}$$

Based on the trained ANN, Equations 9 and 10 can be used to develop the Purelin strength model for the 73 SFRC square columns and is expressed as follows:

$$f_{cc}' = \begin{bmatrix} 1.16 & 0.87 & 2.09 \end{bmatrix} \begin{bmatrix} f_c' \\ f_{\text{le}} \\ f_{\text{lb}} \end{bmatrix} - 7.5 \tag{11}$$

5.2 Tansig strength model

The Tansig strength model was trained using Tansig activation function. The Tansig strength model cannot be simplified to the form of Purelin strength model. The input weight matrix (IW), the layer weight matrix (LW) and bias matrices b_1 and b_2 were obtained. The Tansig strength model was developed using Equations (5-8) and expressed as follows;

$$f'_{cc} = \tanh\left[LW^T \left[\tanh\left[\sum_{n=1}^{3} IW \times (X_n)^T + b_1 \right] \right] + b_2 \right] \tag{12}$$

where;

$$LW^T = \begin{bmatrix} 0.6 \\ 0.18 \\ -1.14 \\ -1.38 \\ 0.54 \\ -0.53 \\ -1.17 \\ 1.19 \\ -0.78 \\ -1.45 \\ 0.12 \\ 0.66 \end{bmatrix} \quad IW = \begin{bmatrix} 3.42 & 2.21 & 1.1 \\ 2.77 & 0.29 & 1.32 \\ -1.86 & 3.81 & 1.26 \\ 2.16 & -4.55 & -0.39 \\ 1.95 & -1.21 & 2.05 \\ -2.54 & 2.27 & -0.76 \\ -1.45 & 1.71 & 2.64 \\ 0.77 & 2.97 & -1.43 \\ 2.52 & 1.54 & -1.18 \\ 1.87 & -2.32 & -1.55 \\ -1.61 & 1.91 & -2.38 \\ 2.19 & 1.73 & 1.41 \end{bmatrix} \quad b_1 = \begin{bmatrix} -2.69 \\ -2.69 \\ 1.37 \\ -0.61 \\ -0.78 \\ -0.35 \\ -1.35 \\ 2.3 \\ 0.51 \\ 2.6 \\ -2.3 \\ 3.25 \end{bmatrix} \quad b_2 = 0.24$$

6. RESULTS AND DISCUSSION

In Purelin strength model, the contribution of the input parameters *i.e.* f_c', f_{le} and f_{lb} to the ANN output can be investigated based on the weight matrix of (W) as presented in Equation 12. The three input parameters (f_c', f_{le}, f_{lb}) significantly influence the axial compressive strength of the square columns (f_{cc}'). It was observed that the contribution of the input f_{lb} to the f_{cc}' is greater than that of the f_{le}. Consequently, increasing the amount of the steel fibre has significantly influenced the strength of square concrete columns compared with increasing amount of lateral reinforcement.

The performance of the developed Purelin, Tansig strength models and available strength model that was proposed by Paultre *et al.* [3] are shown in Figure 2 (a, b and c). This figure shows that the developed Purelin and Tansig strength models for a wider range of the database of SFRC square columns provide prediction values that fit the experimental results very well. The performance of the developed Purelin and Tansig strength models are compared with available strength model. This comparison could be identified by a correlation factor between predicted and experimental values. It was observed that the correlation factor for Purelin strength model is the same that of the available strength model *i.e.* 0.72 (R^2=72%). Whereas, the correlation factor for the Tansig strength model is 0.93 (R^2=93%), which is significantly higher than the Purelin and available strength models. As both Paultre *et al* [3] and Purelin models are based on linear regression analysis, it appears that these linear models can predict the strength up to 115 MPa. However, nonlinear Tansig model can accurately predict the strength for all tested data

Two statistical indicators Mean Square Error (MSE) and Mean Absolute Error (MAE) were used to verify the performance of the strength models. The developed Purelin strength model for a wider range of data point shows slightly lower error than the available strength model. MSE of 1.14% and MAE of 8.56% for the Purelin strength model were observed, while, MSE of 1.19% and MAE of 8.75% for the available strength model were observed as shown in Figure 2 (d). However, Tansig strength model presents quite lesser error of 0.72% of MSE and 6.4% of MAE compared with the Purelin strength model and available strength model as shown in Figure 2 (d).

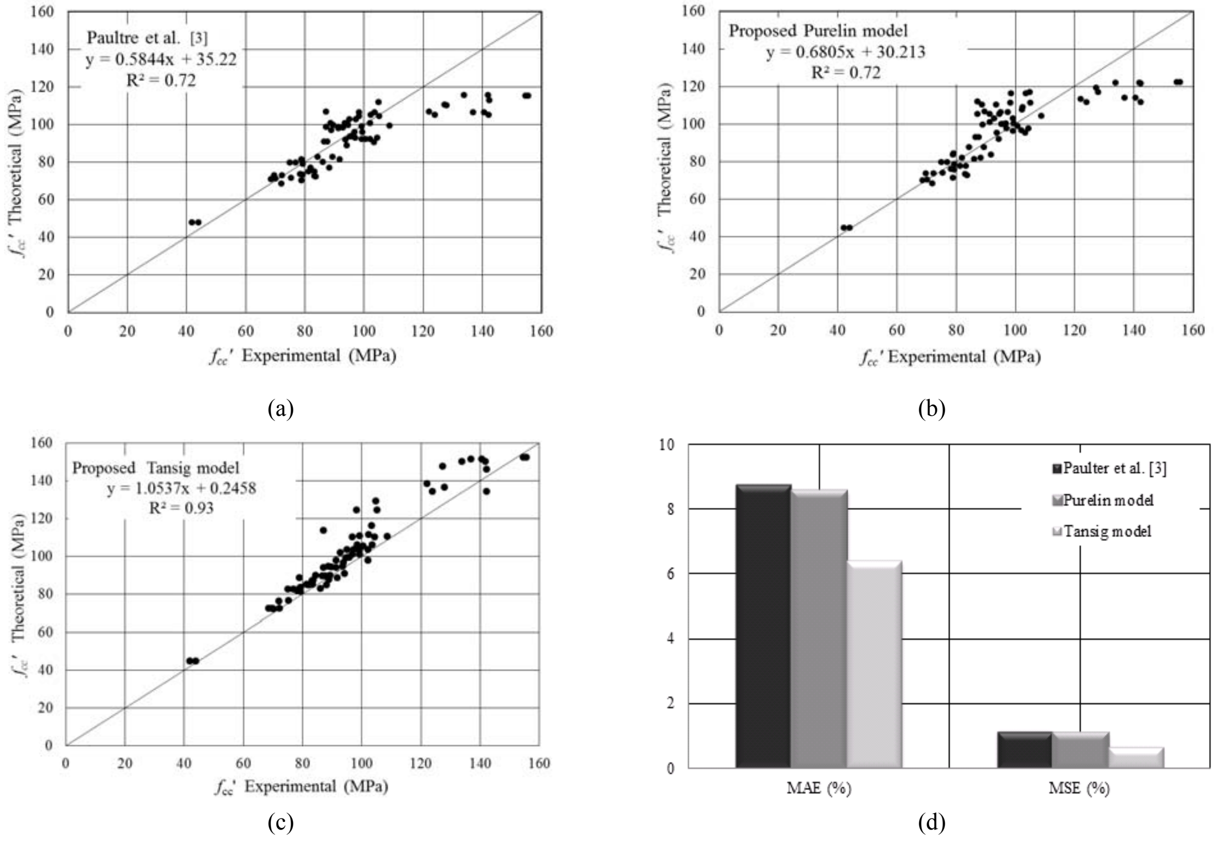

Figure 4 Performance of the available and proposed strength models.

7 CONCLUSIONS

The Purelin and Tansig strength models are developed to predict the axial compressive strength of steel fibre reinforced NSC and HSC square columns. The findings in this paper are summarized as follows:

- The prediction values of the developed ANN strength models fit very well with the experimental results.
- The performance of the Purelin strength model is similar to the available strength model. However the performance of the Tansig strength model is significantly higher than the performance of the Purelin and available strength models.
- The contribution of confinement pressure provided by the steel fibre could be higher than the contribution of confinement pressure of the lateral reinforcement on the compressive strength of the SFRC square columns.
- The error of the Tansig strength model is quite less than the Purelin strength model and the available strength model and consequently, the Tansig strength model is more accurate than the Purelin and available strength models.

The ANN has been successfully applied for predicting the axial compressive strength of SFRC square columns for both NSC and HSC. It is found that the developed strength models provide better accuracy in estimating the axial compressive strength of SFRC square columns than the available strength models.

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