Design methods for spiral stirrups confined concrete columns by evaluating the lateral performance of transverse reinforcements

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Abstract

Transverse reinforcements may not yield at the peak stress of confined concrete when the tensile strength and volumetric ratio of lateral steel do not be coordinate with concrete strength. The compressive strength and ductility of confined concrete are closely related to the lateral strain of transverse reinforcement at peak stress. However, determining the lateral strain of transverse reinforcements at peak stress is difficult due to many parameters should be considered. In this paper, a regression analysis model and an artificial neural network (ANN) model were developed to predict the lateral strain in transverse reinforcements and an ANN model was established to determine the volumetric ratio ranges of transverse reinforcements which transverse reinforcements yield at the peak stress of confined concrete. To reach the purpose, 111-group data sets assembled from previous studies were applied to test the effects of influential parameters on the lateral strain and judge whether transverse reinforcements yield at the peak stress of confined concrete. The aspect ratio of specimens, the tensile yield strength and volumetric ratio of transverse reinforcements, the compressive strength of unconfined concrete, as well as longitudinal reinforcements ratio were considered. For lateral strain prediction models, the regression analysis equation was proposed based on theoretical analysis, while the ANN model was determined by collected data; for appropriate volumetric ratio ranges determination model, the outputs of ANN model were based on the classification method to judge the lateral steel yields. The results showed that the prediction models of lateral strain had high efficiency for predicting lateral strain. Besides, the accuracy and the prediction ability of the ANN model was higher than regression analysis model. Furthermore, the appropriate volumetric ratio ranges of transverse reinforcements in different confined concrete were calculated by proposed ANN model. Finally, the recommended lateral strain prediction models and volumetric ratio of transverse reinforcements determination model can be utilized to instruct the design of confined concrete.

Keywords Lateral strain · Transverse reinforcements, confined concrete columns · Prediction model · Appropriate volumetric ratio ranges

1 Introduction

In recent years, high-strength concrete over 100 MPa has been applied to engineer construction. The advantages of the application of high-strength concrete in engineering were evident in construction design, economy, and environment, but high-strength concrete had obvious

brittle characteristic [1, 2]. Applying spiral stirrups to confine concrete was an efficient way to improve the ductility of concrete [3, 4]. However, in confined concrete, if low-strength steel confined high-strength concrete, the steel could not provide effective confining pressure for concrete and steel might rupture at the peak stress of confined concrete; on the contrary, if high-strength

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steel confined normal-strength concrete, steel might not yield at the peak stress of confined concrete causing the strength of steel could not be adequately developed. The strength and number of stirrups should be coordinate with the compressive strength of concrete to ensure that steel yield at the peak stress of confined concrete. The strain of stirrups at the peak stress of confined concrete was an important indicator to evaluate the compatibility between stirrups and concrete. Unfortunately, predicting the lateral strain was a huge challenge due to the complicated mechanism between stirrups and concrete [5].

In past decades, researchers have established the models for evaluating the performance of spiral stirrups confined concrete. The studies was divided into two groups: the one was the predictions of the peak strain, peak stress, and stress–strain curves of confined concrete, the other was the determination of the appropriate ranges of the volumetric ratio of stirrups and the lateral performance evaluation of stirrups. The former group mainly focused on the compressive behavior of confined concrete and was used to instruct the design of confined concrete. Richart et al. [6, 7] proposed the calculation equations of peak stress of confined concrete which was an application of normal-strength concrete; Mander et al. [5] proposed the confined coefficient to evaluate the effects of transverse reinforcements on the peak strain and peak stress of confined concrete based on the experimental results [8–10]. The subsequent researchers focused on modifying the confined coefficient by experimental and theoretical analysis to adapt the normal- and high-strength concrete. The latter one focused on adjusting the volumetric ratio of transverse reinforcements to ensure that transverse reinforcements yield at the peak stress of confined concrete. The calculation equations of minimum volumetric ratio of transverse reinforcements in confined concrete were determined in ACI 318 [11]; Zheng et al. [12] proposed a model for predicting the volumetric ratio of transverse reinforcements in spiral stirrups confined concrete by three-dimension regression analysis by considering the tensile yield strain of stirrups and concrete strength to ensure that transverse reinforcements yield, the model could be used to guide the design of confined concrete less than 60 MPa; Dong et al. [13, 14] proposed a constitute model for predicting the lateral strain of both passive and active confined concrete, which was adapted for the concrete strength ranged from 25 MPa to 120 MPa; Kim et al. [15] modified the minimum volumetric ratio equations of transverse reinforcements based on the ACI 318 to improve the ductility of reinforced concrete columns and to recover their stress; Alacali et al. [16] predicted the lateral confinement coefficient in reinforced concrete columns by neural network models to estimate the confinement degree of stirrups. The recommended model can be

utilized to predict the concrete within 19.6–56.4 MPa. From previous studies, the existing models were applicable for the design of spiral stirrups confined normal-strength concrete, as for high-strength concrete, the existing models should modify the parameters in models. Besides, in existing models, the lateral strain of transverse reinforcements may not yield at peak stress, the strength of transverse reinforcements could not be fully developed, meanwhile, the proposed models assumed that spiral stirrups totally yielded when confined concrete columns reached peak stress in low volumetric ratio of lateral steel, but proposed models might not applicable for high-strength concrete for its brittle failure. Moreover, high-strength steel might not yield in normal-strength concrete, determining the appropriate ranges of volumetric ratio of transverse reinforcements for different strength concrete was an important procedure for the design of confined concrete. Furthermore, when new experiment data exceeded a specific range of concrete strength was introduced to the existing models, the models should be re-evaluated. Thus, it was necessary to establish the models for predicting the lateral strain of stirrups and determining volumetric ratio of stirrups in appropriate ranges to ensure that lateral steel yield at peak stress.

The objective of this paper was to propose two models for predicting the lateral strain of stirrups and determining the appropriate volumetric ratio ranges of transverse reinforcements. To reach the purpose, a reliable database containing 111-group datasets from previous experimental studies was assembled and the appropriate volumetric ratio ranges of transverse reinforcements were determined by the proposed model.

2 Theoretical analysis and model introduction

2.1 Theoretical analysis

In spiral stirrups concrete columns, the lateral stress of transverse reinforcements provided by confined concrete alongside the edge of confined concrete was affected by the tensile strength and volumetric ratio of transverse reinforcements, as well as concrete strength (In Fig. 1).

Fig. 1 Distribution of lateral stress in transverse reinforcements

Based on experimental researches, many lateral stress calculation equations evaluated the effects of transverse reinforcements on the compressive behaviors of confined concrete were proposed [5, 8–10] and the lateral strain was a crucial parameter to estimate the compressive behavior of confined concrete. In Fig. 1, when concrete columns was under compression, concrete expanded in lateral direction and core concrete pushed spiral stirrups, the lateral strain in transverse reinforcements occurred.

In Fig. 2, the initial diameter of confined concrete was D . When compression load was F , the diameter of confined concrete D changed to $D + \Delta D$, meanwhile, the diameter of spiral stirrups changed with the diameter of confined concrete, so that the lateral strain can be expressed in Eq. (1).

$$\varepsilon_l = \Delta D / D \quad (1)$$

ΔD was related to Poisson's ratio ν and ν was related to the compressive strength of concrete. Equation (1) can be transformed as follows:

$$\varepsilon_l = \Delta D / D = \nu \Delta l / D = \nu L \Delta l / LD = \nu \varepsilon_{cc} L / D = \alpha \varepsilon_{cc} \nu \quad (2)$$

where Δl was the vertical deformation of concrete columns; ε_{cc} was the peak strain of confined concrete related to the compressive strength of concrete, as well as the volumetric ratio and tensile strength of transverse reinforcements. Many studies have researched on predicting the peak strain of confined concrete, however, they did not consider the influence of aspect ratio of specimens. Therefore, in this paper, the lateral strain of transverse reinforcement model was established based on the Eq. (3).

$$\varepsilon_l = \alpha \varepsilon_{cc} \nu = \alpha f(f'_c, \rho_{sv}, f_{sv}) \quad (3)$$

2.2 Model introduction

To predict the lateral strain of stirrups and determine the appropriate ranges of the volumetric ratio of confined concrete, a regression model and an ANN model were

Fig. 2 Lateral deformation in confined concrete

established based on Eq. (3). The introductions of Those two analytical methods were as follows:

2.2.1 Regression analysis

Regression analysis was always applied to establish the calculation models to evaluate the relationship among variables [17]. Regression analysis mainly focused on analyzing the relationships between a dependent variable and one or more independent variables, which meant that the dependent variable changed with a specific independent variable varying and other independent variables held fixed [18, 19]. Regression analysis was widely used for predicting and evaluating the relationships among the independent variables and dependent variable. The techniques for regression analysis had two types: the one was parametric methods, which included linear regression and ordinary least squares regression, the regression function of this type was defined in terms of a finite number of unknown parameters that were estimated from the data; the other one was nonparametric regression that allowed the regression function to lie in a specified set of functions, which may be infinite-dimensional [17]. The regression models involved the following parameters and variables:

- The unknown parameters, denoted as β represents a scalar or a vector;
- The independent variables, X ;
- The dependent variable, Y .

A regression model related Y to a function of X and β :

$$Y \approx f(X, \beta) \quad (4)$$

The procedures for regression analyzing were as following:

- Determine variables. Determine the independent variable and dependent variables from experimental data, and select the primary dependent variables for independent variable;
- Establish a prediction model. Establish a regression analysis prediction model based on the theoretical analysis;
- Analyze correlation. The correlation analysis between the independent variable and dependent variables is determined by the correlation coefficient to judge the degree of correlation relationship between independent variable and dependent variables;
- Calculate prediction errors. To test the reliable and the predictable of the regression analysis prediction model, the errors between predicted values and experimental values should be calculated.

The method of regression analysis for estimating the relationships among variables was the least square regression analysis. The regression analysis prediction models included linear regression and nonlinear regression [20].

2.2.2 Artificial neural network model

Artificial neural networks (ANN) is a computer model that simulates the structure and working principle of the biological nervous systems. Similar to the biological nervous system, the ANN model consisted of a great number of highly interconnected neurons, and acquires intelligent characteristics after training. The topological structure of typical ANN was multi-layer feed forward perception network, in which the numerous neurons are distributed into three or more layers, including an input layer, one or more hidden layers, and an output layer, as shown in Fig. 3. In this network, all neurons in each layer are connected to next layer, and no connection among neurons at the same layer. The conversion between input and output layer is through adjusting the weights and thresholds among layers. Eventually, if the problem can be learned, a set of weights will be stable and a good result will be obtained.

The Back-Propagation (BP) neural network is one of the ANN solving the nonlinear problems. Generally, the BP neural network has three layers: the input layer, hidden layers, and the output layer (In Fig. 4). The neurons are distributed into three layers, all neurons are linked with each other in different layers, while there are no links among neurons in the same layer. The training processes of a BP network has two stages: the forward stage and the backward stage. The forward stage calculates the network outputs through the given initial connection weights and input data. In the process, the input data is passed from the input layer to the hidden layer. Then the neurons in the hidden layer calculate a weighted sum of the input data, processes the sum by using an activation function, and finally pass the activation results to the output layer; in the backward stage, the errors between the calculated

Fig. 4 System of typical BP model. A typical BP model has input, sum function, log-sigmoid activation function, and output

outputs and the experimental results are calculated, and the errors are passed back to the network to modify the connection weights and bias. This process is repeated until the errors reach an acceptable level [21–23].

In this study, the training method of the ANN model used the LM (Levenberg–Marquardt) algorithm, because the LM algorithm combined the advantages of the Quasi-Newton algorithm and the Steepest Descent Backpropagation, which was suitable for solving non-linear least square problems [23].

3 Experimental database and model establishment

3.1 Experimental test database

A reliable database was established by assembling the experimental test data under axial compression [24–30]. In the database, the diameter, the spacing, the tensile strength, the yield stress, and the volumetric ratio of transverse reinforcements, as well as the compressive strength

Fig. 3 System of typical ANN model

unconfined concrete were considered to establish the model for predicting the lateral strain of stirrups. Table 1 shows the collected experimental test data.

In the database, the diameter and height of specimens varied from 102×203 mm to 440×1500 mm; the diameter, the spacing, the tensile strength, and the volumetric ratio of transverse reinforcements varied from 5.1 to 12 mm, 13 to 135 mm, 307 to 1318 MPa, 0.082 to 0.703%, and 0.36 to 14.8%, respectively; the compressive strength of unconfined concrete were 25.04–151 MPa; the lateral strain of stirrups in confined concrete varied from 0.027 to 1.488%.

3.2 Establishing models

3.2.1 Regression analysis prediction model

To develop the regression prediction model, the aspect ratio of specimens, the volumetric ratio and strength of stirrups, the compressive strength of concrete, as well as longitudinal reinforcements ratio were considered. Based on the previous study [5], the form of calculation model for the lateral stress of stirrups is listed as following:

$$f_l = k \rho_{sv} f_{sv} \quad (5)$$

where k was the coefficient related to the space and diameter of stirrups, as well as the ratio of longitudinal reinforcements.

Combining Eq. (3) with Eq. (5), the regression analysis model for predicting the lateral strain of stirrups is expressed in Eq. (6).

$$\varepsilon_l = k \alpha^a f_c^b f_{sv}^c \rho_{sv}^d \rho_c^e \quad (6)$$

where k, a, b, c, d, e were regression coefficients.

By regression analysis, the regression analysis prediction model was obtained.

$$\varepsilon_l = 0.6163 \alpha^{-1.7752} f_c^{-0.7031} f_{sv}^{0.5979} \rho_{sv}^{0.4926} (1 - \rho_c)^{-13.0923} \quad (7)$$

3.2.2 ANN model

Similarly, ANN model was adopted to predict the lateral strain of stirrups. Based on the collected data, the ANN model was trained and tested. Because there was no analytical model for calculating the number of hidden layer and the neural nodes of hidden layers in ANN model, the proposed ANN model should be trained many times for its prediction and accuracy. When ANN model had acceptable results, the weights and the thresholds were stable. In this paper, 80% (88 groups) of collected data sets were selected to train the ANN model while remaining data sets (23 groups) were tested the accuracy of the proposed

model. The inputs parameters included the compressive strength of unconfined concrete, the tensile strength and the volumetric ratio of transverse reinforcements, the aspect ratio of specimens, as well as longitudinal reinforcements ratios, while the output values was the lateral strain of transverse reinforcements. After a series of trials, an acceptable ANN model for predicting the lateral strain of stirrups in confined concrete was obtained and the indicators reach the satisfactory values. Table 2 lists the parameters of the proposed models.

There were three indicators for evaluating the prediction performance of the models: the root-mean-square error (RMSE), average absolute error, and the determine coefficient (R^2). The calculation equations of indicators were described as following.

$$\text{RMSE} = \sqrt{\frac{1}{N} \left(\sum_{i=1}^N \left(\frac{o_i - x_i}{x_i} \right)^2 \right)} \quad (8)$$

$$\text{AAE} = \frac{1}{N} \sum_{i=1}^N \frac{|o_i - x_i|}{x_i} \quad (9)$$

$$R^2 = 1 - \frac{\sum_{i=1}^N (o_i - x_i)^2}{\sum_{i=1}^N x_i^2} \quad (10)$$

where N was the total number of data sets; o_i and x_i were the outputs of the proposed models and the experimental test results, respectively.

4 Results and discussion

To evaluate the predictable and accuracy of proposed models, the predicted values from recommended models should compare with collected data sets. Figure 5 and Table 3 show the comparison between predicted results from the proposed models and experimental results and the indicators for evaluating the prediction performance of proposed models, respectively. As for the proposed regression analysis prediction model and the ANN model, the almost predicted values from the regression analysis model and ANN model were both within -10 to $+10\%$. Meanwhile, the RMSE, AAE and R^2 for regression analysis model and ANN model are 1.1590 and 0.8542, 0.6689 and 0.5077, and 0.7840 and 0.9206, respectively. It indicated that those two proposed models had high accuracy for predicting the lateral strain of stirrups in confined concrete. Besides, the ANN model was more suitable for predicting the lateral strain than regression analysis model for its high predictable and high accuracy.

Table 1 The details of collected data sets for establishing model

Literature	D (mm)	H (mm)	d (mm)	S (mm)	f_{sv} (Mpa)	ρ_{sv} (%)	ε_{sv} (%)	f'_c / MPa	ε_l (%)	Lateral strain ANN model	Appropriate volumetric ratio ANN model
Mander [24]	440	1500	12	52.00	310	1.99	0.15	24	0.483	Testing	Training
	440	1500	12	52.00	340	1.99	0.17	30	0.261	Training	Training
	440	1500	12	52.00	340	1.99	0.17	32	0.183	Training	Training
	440	1500	12	41.00	340	2.52	0.17	29	0.681	Training	Testing
	440	1500	12	69.00	340	1.50	0.17	29	0.185	Training	Training
	440	1500	12	103.00	340	1.00	0.17	29	0.291	Training	Testing
	440	1500	10	119.00	320	0.60	0.16	29	0.182	Training	Training
	440	1500	10	36.00	320	1.98	0.16	29	0.351	Training	Training
	440	1500	16	93.00	307	1.97	0.15	29	0.332	Training	Training
	440	1500	12	52.00	340	1.99	0.17	32	0.443	Training	Training
	440	1500	12	52.00	340	1.99	0.17	30	0.203	Training	Testing
	440	1500	12	52.00	340	1.99	0.17	32	0.182	Training	Training
	440	1500	12	52.00	340	1.99	0.17	30	0.173	Training	Training
	440	1500	12	52.00	340	1.99	0.17	30	0.226	Testing	Training
	440	1500	12	52.00	340	1.99	0.17	32	0.388	Testing	Testing
Antonius [25]	110	550	6.25	35.00	488	4.38	0.1584	44.55	0.185	Training	Training
	110	550	6.25	35.00	488	4.38	0.1584	54.98	0.145	Testing	Training
	110	550	5.5	35.00	315	3.19	0.082	54.98	0.131	Training	Testing
	110	550	5.5	55.00	315	2.03	0.082	54.98	0.0936	Training	Training
	110	550	6.25	35.00	488	4.38	0.1584	62.5	0.0228	Testing	Training
	110	550	6.25	35.00	587	4.38	0.1737	62.5	0.11	Training	Training
	110	550	6.25	55.00	587	2.79	0.1737	62.5	0.285	Training	Testing
Assa [26]	145	300	6.25	27.75	1296	3.05	0.67	25.04	1.37	Training	Training
	145	300	6.25	44.17	1296	1.92	0.67	25.04	0.92	Training	Training
	145	300	6.25	20.40	1296	4.15	0.67	34.13	1.48	Training	Testing
	145	300	6.25	27.80	1296	3.04	0.67	34.13	1.13	Testing	Training
	145	300	6.25	46.90	1296	1.80	0.67	34.13	0.61	Training	Training
	145	300	6.25	50.00	909	1.69	0.44	34.13	0.61	Training	Training
	145	300	6.25	75.00	909	1.13	0.44	34.13	0.28	Training	Training
	145	300	6.25	27.75	1296	3.05	0.67	41.38	1.02	Testing	Training
	145	300	6.25	44.17	1296	1.92	0.67	41.38	0.61	Training	Testing
	145	300	6.25	27.75	1296	3.05	0.67	49.75	0.99	Training	Training
	145	300	6.25	44.17	1296	1.92	0.67	49.75	0.56	Training	Testing
	145	300	6.25	28.00	1296	3.02	0.67	64.40	0.77	Training	Training
	145	300	6.25	27.75	1296	3.05	0.67	64.40	0.63	Training	Training
	145	300	6.25	44.17	1296	1.92	0.67	64.40	0.53	Testing	Training
	145	300	6.25	28.00	1296	3.02	0.67	70.10	0.64	Training	Training
	145	300	6.25	44.17	1296	1.92	0.67	70.10	0.27	Training	Training
	145	300	6.25	20.40	1296	4.15	0.67	83.03	0.93	Training	Testing
	145	300	6.25	28.12	1296	3.01	0.67	83.03	0.55	Training	Training
	145	300	6.25	46.60	1296	1.82	0.67	83.03	0.29	Testing	Training
	145	300	6.25	50.00	909	1.69	0.44	83.03	0.24	Training	Testing
	145	300	6.25	75.00	909	1.13	0.44	83.03	0.21	Training	Training
	145	300	6.25	25.00	1296	3.38	0.67	75.04	0.53	Training	Training
	145	300	6.25	38.00	1296	2.23	0.67	75.04	0.23	Training	Training
	145	300	6.25	25.00	1296	3.38	0.67	74.49	0.48	Testing	Testing
Li [27]	210	720	6	20.00	445	2.69	0.255	63	0.429	Training	Training
	210	720	6	35.00	445	1.54	0.255	63	0.45	Training	Training

Table 1 (continued)

Literature	D (mm)	H (mm)	d (mm)	S (mm)	f_{sv} (Mpa)	ρ_{sv} (%)	ε_{sv} (%)	f'_c / MPa	ε_l (%)	Lateral strain ANN model	Appropriate volumetric ratio ANN model
	210	720	6	50.00	445	1.08	0.255	63	0.154	Training	Training
	210	720	6	65.00	445	0.83	0.255	63	0.341	Testing	Training
	210	720	6	20.00	445	2.69	0.255	72.3	0.466	Training	Testing
	210	720	6	35.00	445	1.54	0.255	72.3	0.369	Training	Training
	210	720	6	50.00	445	1.08	0.255	72.3	0.0756	Training	Training
	210	720	6	65.00	445	0.83	0.255	72.3	0.0897	Training	Training
	210	720	6.4	20.00	1318	2.94	0.634	52	1.46	Training	Testing
	210	720	6.4	35.00	1318	1.67	0.634	52	1.15	Testing	Training
	210	720	6.4	50.00	1318	1.17	0.634	52	1.49	Training	Training
	210	720	6.4	20.00	1318	2.94	0.634	82.5	1.13	Training	Testing
	210	720	6.4	35.00	1318	1.67	0.634	82.5	1.11	Testing	Training
	210	720	6.4	50.00	1318	1.17	0.634	82.5	1.09	Training	Training
	210	720	6.4	35.00	1318	1.68	0.634	35.2	0.87	Training	Training
	210	720	6.4	53.00	1318	1.10	0.634	35.2	0.71	Testing	Testing
	210	720	6.4	70.00	1318	0.84	0.634	35.2	0.48	Training	Training
Montgomery [28]	254	1016	11.3	41.00	522	1.17	0.24	69.7	0.193	Training	Training
	254	1016	11.3	53.00	522	3.62	0.24	69.7	0.101	Training	Testing
	254	1016	11.3	79.00	522	2.43	0.24	69.7	0.244	Testing	Training
	254	1016	11.3	109.00	522	1.76	0.24	69.7	0.22	Training	Training
	254	1016	8	41.00	666	2.23	0.653	69.7	0.166	Training	Training
	254	1016	8	53.00	666	1.73	0.653	69.7	0.114	Training	Training
	254	1016	8	79.00	666	1.16	0.653	69.7	0.0467	Testing	Testing
	254	1016	8	109.00	666	0.84	0.653	69.7	0.0656	Training	Training
	254	1016	5.7	41.00	583	1.17	0.488	69.7	0.132	Training	Training
	254	1016	5.7	53.00	583	0.91	0.488	69.7	0.25	Testing	Training
	203	813	11.3	64.00	522	3.77	0.24	69.7	0.515	Training	Testing
	203	813	9.5	43.00	508	3.96	0.275	69.7	0.627	Training	Training
	203	813	9.5	64.00	508	2.66	0.275	69.7	0.206	Training	Training
	203	813	9.5	86.00	508	1.98	0.275	69.7	0.225	Training	Training
	203	813	8	64.00	666	1.79	0.491	69.7	0.113	Training	Testing
	203	813	6.4	43.00	646	1.76	0.524	69.7	0.0306	Testing	Training
	203	813	6.4	64.00	646	1.18	0.524	69.7	0.167	Training	Training
	203	813	6.4	86.00	646	0.88	0.524	69.7	0.0411	Training	Training
	203	813	4.8	43.00	692	0.96	0.653	69.7	0.359	Training	Training
	203	813	11.3	43.00	522	5.61	0.24	89.8	0.856	Training	Testing
	203	813	11.3	64.00	522	3.77	0.24	89.8	0.216	Testing	Training
	203	813	11.3	86.00	522	2.81	0.24	89.8	0.148	Training	Training
	203	813	9.5	43.00	508	3.96	0.275	89.8	0.25	Training	Training
	203	813	9.5	64.00	508	2.66	0.275	89.8	0.167	Training	Testing
	203	813	9.5	86.00	508	1.98	0.275	89.8	0.204	Testing	Training
	203	813	8	43.00	666	2.67	0.491	89.8	0.208	Training	Training
	203	813	8	64.00	666	1.79	0.491	89.8	0.142	Training	Testing
	203	813	8	86.00	666	1.33	0.491	89.8	0.422	Testing	Training
	203	813	6.4	43.00	646	1.76	0.524	89.8	0.0957	Training	Training
	203	813	6.4	64.00	646	1.18	0.2524	89.8	0.0471	Training	Training
	203	813	6.4	86.00	646	0.88	0.524	89.8	0.307	Training	Training
	203	813	4.8	43.00	692	1.74	0.653	89.8	0.0321	Testing	Training
Razvi [29]	240	1500	6.3	70.00	660	0.8	0.529	60	0.0625	Training	Testing

Table 1 (continued)

Literature	D (mm)	H (mm)	d (mm)	S (mm)	f_{sv} (Mpa)	ρ_{sv} (%)	ε_{sv} (%)	f'_c / MPa	ε_l (%)	Lateral strain ANN model	Appropriate volumetric ratio ANN model
Silva [30]	240	1500	6.3	70.00	660	0.8	0.529	60	0.0457	Training	Training
	240	1500	6.3	60.00	660	0.93	0.529	124	0.053	Training	Training
	240	1500	7.5	60.00	1000	1.32	0.703	124	0.0175	Testing	Training
	240	1500	7.5	60.00	1000	1.32	0.703	92	0.0069	Training	Training
	240	1500	7.5	100.00	1000	0.79	0.703	92	0.0445	Training	Training
	240	1500	6.3	100.00	660	0.56	0.529	92	0.0208	Testing	Training
	240	1500	11.3	135.00	400	1.35	0.423	92	0.0375	Training	Training
	305	1600	11.3	100.00	440	1.40	0.21	35.5	0.0628	Training	Training
	305	1600	9.5	100.00	560	1.00	0.25	35.5	0.0477	Testing	Training
	305	1600	11.3	100.00	440	1.40	0.21	39.5	0.0512	Training	Testing
	305	1600	9.5	100.00	560	1.00	0.25	39.5	0.0638	Training	Training
	305	1600	11.3	75.00	440	1.86	0.21	59.6	0.0578	Testing	Training
	305	1600	9.5	80.00	560	1.24	0.25	59.6	0.0273	Training	Training
	305	1600	11.3	45.00	440	3.11	0.21	119.9	0.0442	Training	Training
	305	1600	9.5	50.00	560	1.99	0.25	119.9	0.0568	Training	Training

Table 2 The parameters of proposed ANN model

Parameters	Lateral Strain Model
Number of input layer nodes	5
Number of hidden layers	1
Number of hidden layer nodes	15
Number of output layer nodes	1
Momentum factor	0.8
Learning rate	0.3
Target error	0.00001
Learning cycle	10,000

5 Appropriate volumetric ratio ranges of transverse reinforcements

The appropriate volumetric ratio ranges of stirrups in different strength confined concrete were essential to design confined concrete. For a specific strength stirrups and a specific strength concrete, if the volumetric ratio of transverse reinforcements was low, concrete could not be confined effectively, on the contrary, if the volumetric ratio of transverse reinforcements was too high, it was hard for casting concrete and the strength of lateral steel could not be fully developed. Thus, it was critical to determine the appropriate volumetric ratio of spiral stirrups for designing

Fig. 5 Comparison between predict results from lateral strain prediction models and Experimental results from collected data. **a** Regression analysis model, **b** ANN model

Table 3 Indicator values of proposed model

Indicators	Regression analysis model	ANN model
RMSE	1.1590	0.8542
AAE	0.6689	0.5077
R^2	0.7840	0.9206

confined concrete. In collected data sets, there were 45-group datasets represented that the stirrups yielded at the peak stress of confined concrete.

To establish the models for determining the appropriate volumetric ratio ranges of stirrups in different strength confined concrete, an ANN model was established. The authors defined that stirrups yielded at the peak stress was one, while stirrups did not yield was zero. As mentioned in Sect. 2, the ANN model for determining the appropriate volumetric ratio ranges of transverse reinforcements in different strength confined concrete was developed as follows:

- Select 80% (88 groups) of collected data sets to train the model and remaining data sets (23 groups) were applied to test the reliability of proposed ANN model;
- The inputs parameters included the compressive strength of unconfined concrete, the tensile strength and the volumetric ratio of transverse reinforcements, the aspect ratio of specimens, as well as longitudinal reinforcements ratios, while the output values was one or zero representing the stirrups yield or not;
- The different strength lateral steel confined different strength concrete were tested the ANN model;
- Determine the appropriate volumetric ratio ranges of different strength concrete.

Table 4 lists the structure parameters of ANN model for determining the appropriate volumetric ratio ranges of

Table 4 Parameters in ANN models

Parameters	Lateral strain model
Number of input layer nodes	5
Number of hidden layers	2
Number of hidden layer 1 nodes	12
Number of hidden layer 2 nodes	3
Number of output layer nodes	2
Momentum factor	0.8
Learning rate	0.01
Target error	0.00001
Learning cycle	50,000

Fig. 6 Comparison between Experimental values and Predicted values from the proposed ANN model

transverse reinforcements in confined concrete and Fig. 6 shows the comparison between experimental values and predicted values from the proposed ANN model. In Fig. 6, 104-group datasets from the proposed ANN model of were equaled to experimental datasets, only 7-group datasets were different. Therefore, the proposed ANN model had high accuracy in determining whether stirrups yields at the peak stress of confined concrete.

Based on the proposed ANN model, the volumetric ratio of the different strength stirrups confined different strength concrete was determined to ensure that stirrups yield at the peak stress of confined concrete. To reach the purpose, the appropriate volumetric ratio ranges of stirrups confined concrete were evaluated by the proposed ANN model. Among test specimens, the tensile yield strength of transverse reinforcements included 300, 335, 400, 500, 600, 800, 970, and 1270 MPa, the strength of concrete included 30, 40, 50, 60, 70, 80, 90, and 100 MPa, the aspect ratio of specimens was 3, and longitudinal reinforcements ratio was 0%. The appropriate volumetric ratio ranges of different strength stirrups confined concrete are listed in Table 5. In Table 5, the volumetric ratio of stirrups in different strength stirrups confined a specific strength concrete could determine that stirrups yielded at the peak stress of confined concrete. The volumetric ratio ranges of transverse reinforcements increased with concrete strength. The minimum volumetric ratio of stirrups in low strength concrete was 0.8%, but in high strength concrete was 0.6%. Table 5 can provide a referee for the design of spiral stirrups confined concrete.

6 Conclusion

In this paper, the lateral performance of stirrups in confined concretes was evaluated. The lateral performance evaluation of stirrups included the prediction of the lateral

Table 5 Appropriate Volumetric ratio ranges of stirrups in confined concrete

ρ_{sv} (%)	f_c /MPa								
		30	40	50	60	70	80	90	100
f_{sv} (MPa)	300	0.9–2.0	0.8–2.0	0.8–2.0	0.8–2.0	0.6–2.0	0.6–2.0	0.6–2.0	0.6–2.0
	335	1.0–2.3	1.0–2.3	1.0–2.3	0.9–2.3	0.9–2.3	0.9–2.3	0.9–2.3	0.9–2.3
	400	1.2–2.8	1.2–2.8	1.2–2.9	1.2–2.9	1.1–2.9	1.1–2.9	1.1–2.9	1.1–2.9
	500	1.5–3.7	1.5–3.7	1.5–3.7	1.5–3.7	1.5–3.7	1.5–3.8	1.5–3.8	1.5–3.8
	600	1.8–4.5	1.8–4.5	1.8–4.6	1.8–4.6	1.8–4.6	1.8–4.6	1.8–4.6	1.8–4.6
	800	2.5–6.2	2.5–6.2	2.5–6.3	2.5–6.3	2.5–6.3	2.5–6.3	2.5–6.3	2.5–6.3
	970	3.2–7.7	3.2–7.7	3.1–7.7	3.1–7.7	3.0–7.7	3.0–7.7	3.0–7.8	3.0–7.8
	1270	4.1–10.2	4.1–10.2	4.1–10.2	4.1–10.2	4.0–10.2	4.0–10.3	4.0–10.3	4.0–10.3

strain and the determination of appropriate volumetric ratio ranges. To reach the purpose, the theoretical analysis on the lateral strain of stirrups in confined concrete was carried out to determine the effects of main influential parameters on lateral strain. Based on theoretical analysis and a reliable database consisting of 111-group data sets, a regression analysis model and an ANN model were established to predict lateral strain of stirrups at the peak strain of confined concrete. Besides, an ANN model for determining the appropriate volumetric ratio of confined concrete was established to instruct the design of spiral stirrups confined concrete. The conclusions were drawn as follows:

- (1) The effects of main influential parameters of the lateral strain of transverse reinforcements included the aspect ratio of specimens, the volumetric ratio and the tensile strength of transverse reinforcements, the ratio of longitudinal reinforcements, as well as the compressive strength of concrete on the lateral strain of stirrups in confined concrete were determined by analyzed;
- (2) A regression analysis model was established based on theoretical analysis and an ANN model was established to predict the lateral strain of confined concrete. Both those proposed two models high accuracy for predicting the lateral strain of confined concrete. Besides, the predicted values from the ANN model were more accurate and more reliable than the regression analysis model, while the formula of regression analysis model was more specific than ANN model;
- (3) The ANN model was established to determine the volumetric ratio ranges of transverse reinforcements to ensure that transverse reinforcements yield at the peak stress of confined concrete. This model had a high significance in predicting the peak strain and the peak stress of confined concrete in existing analytical models, meanwhile, the appropriate volumetric ratio ranges of transverse reinforcements can provide

a referee for the design of spiral stirrups confined concrete.

- (4) The ANN model was first applied to evaluate the lateral strain of stirrups in confined concrete. Determining the appropriate volumetric ratio ranges of stirrups in confined concrete was important to judge stirrups yield at the peak stress of confined concrete.

Compliance with ethical standards

Conflicts of interest The authors declare that they have no conflict of interest.

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