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Prediction of shear strength of FRP-reinforced concrete flexural members without stirrups using artificial neural networks

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ABSTRACT

A theoretical model based on an artificial neural network (ANN) was presented for predicting shear strength of slender fiber reinforced polymer (FRP) reinforced concrete flexural members without stirrups. The model takes into account the effects of the effective depth, shear span-to-depth ratio, modulus of elasticity and ratio of the FRP flexural reinforcement and compressive concrete strength on shear strength. Comparisons between the predicted values and 106 test data showed that the developed ANN model resulted in improved statistical parameters with better accuracy than other existing equations. From the 2^k experiment, the influence of parameters was identified in the order of effective depth, axial rigidity of FRP flexural reinforcement, shear span-to-depth ratio and compressive concrete strength. Using the ANN model and based on the results of the 2^k experiment, predictive formulas for shear strength of slender FRP-reinforced concrete beam without stirrups were developed for practical applications. These formulas were able to predict the shear strength better than other existing equations.

1. Introduction

Fiber-reinforced polymers (FRPs) have several advantages over steel, including being non-corrosive and non-magnetic and having higher tensile strength. They are also lighter than steel, which enables easier handling and reduces self-weight of structures. However, they also have the disadvantages of linear elastic tensile behavior that is prone to rupture with lower ductility, lower modulus of elasticity and lower shear strength than steel.

Concrete flexural members that are reinforced with longitudinal steel bars for flexure without stirrups resist the applied shear stresses via a number of mechanisms [1–4], including: (1) shear resistance of uncracked concrete, (2) interlocking action of aggregate, (3) dowel action of the longitudinal reinforcement, (4) arch action, and (5) residual tensile stresses across cracks. Although the basic shear resistance mechanism may be similar to that of steel reinforced concrete members, the distinctive material property of FRPs could significantly alter the relative contribution of each mechanism to the total shear resistance [5–8].

In a beam longitudinally reinforced with less stiff FRP bars, flexural cracks could penetrate deeper into the section and wider cracks will form compared to those in a beam reinforced with an equal amount of longitudinal steel bars with higher stiffness. Deeper flexural cracks with FRP bars would decrease the depth of the compression zone, thereby reducing the contribution of the uncracked concrete to the shear strength [9]. The development of wider and deeper cracks also reduces the resistance by aggregate interlock and the residual tension in cracked concrete. The dowel resistance of longitudinal bars that limit the shearing displacement along the cracks was considered negligible for FRP bars due to their low transverse modulus and smaller size together with relatively wider cracks [1,8].

For the flexural members with a shear span-to-depth ratio a/d of approximately less than 2.5, the arch action occurs [1], in which a and d are the shear span and effective depth of a beam, respectively. Compared to the amount of research on the arch actions for flexural members that are longitudinally reinforced with steel bars, a limited number of studies were reported for the beams with FRP bars [10]. For the slender flexural members with a/d greater than 2.5, the shear strength of flexural members with longitudinal steel bars is a function of a/d as well [11–13]. For these members, a/d represents the interacting effect of the moment (M_f) and shear (V_f) at a section or the quantity $(V_f \cdot d/M_f)^{-1}$ on the shear strength of that section. El-Sayed et al. [14] reported that the experimental shear capacity of the test beams increased as the concrete compressive strength (f_c') increased.

Various design equations have been developed to determine the shear strength of FRP-reinforced concrete flexural members without stirrups [2,6–8,15–21]. Their accuracy, however, seems

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limited as these equations were empirically developed using predefined forms and with the test data mainly generated for a limited number of influential parameters.

An artificial neural network (ANN) is a generalized mathematical model of human neural biology. The main feature of an ANN is its ability to classify the data and determine the relationships between the input values (or parameters affecting shear strength) and their outcome (or shear strength). This feature enables an ANN to generalize the effect of each parameter on the shear strength, even if large portions of the data were generated for the purpose of identifying the effects of a limited number of influential parameters. An ANN does not require a predetermined form of equation as in the case of the most empirical approaches. In this study, the development of an ANN model is presented to predict the shear strength of slender FRP-reinforced concrete flexural members without stirrups (V_{cf}).

2. Design equations for shear strength of FRP-reinforced concrete beams without stirrups

2.1. Design equations

The existing equations for V_{cf} are presented in Eqs. (1)–(3), (4a), (4b), (5a), (5b), (6)–(11). Significant gaps exist in selecting the main parameters and their effects on V_{cf} because these equations have been empirically derived. In the following equations, b_w = member web width; d = member effective depth; E_c, E_s and E_f = moduli of elasticity for concrete, steel and FRP, respectively; f_{cu} = cube compressive strength of concrete; $n = E_f/E_c$; β_1 = rectangular compressive stress block parameter for flexure; and ρ_f = flexural FRP reinforcement ratio.

ACI Committee 440 [15]:

$$V_{cf} = \frac{\rho_f \cdot E_f}{90\beta_1 f_c'}\left(\frac{\sqrt{f_c'}b_w d}{6}\right) \quad (1)$$

ACI440.1R-06 [16]:

$$V_{cf} = \frac{2}{5}k_n\sqrt{f_c'}b_w d \quad (2)$$

where $k_n = \sqrt{2\rho_f n + (\rho_f n)^2} - \rho_f n$

BISE design guidelines [17]:

$$V_{cf} = 0.79\left(100\rho_f\frac{E_f}{E_s}\right)^{1/3}\left(\frac{400}{d}\right)^{1/4}\left(\frac{f_{cu}}{25}\right)^{1/3}b_w d \quad (3)$$

CSA S806-02 [18]:

$$\text{For } d \leqslant 300\text{ mm}: \quad V_{cf} = 0.035\lambda\phi_c\left(f_c'\rho_f E_f\frac{V_f}{M_f}d\right)^{1/3}b_w d$$
$$0.1\lambda\phi_c\sqrt{f_c'}b_w d \leqslant V_{cf} \leqslant 0.2\lambda\phi_c\sqrt{f_c'}b_w d \quad (4a)$$

$$\text{For } d > 300\text{ mm}: \quad V_{cf} = \left(\frac{130}{1000+d}\right)\lambda\phi_c\sqrt{f_c'}b_w d$$
$$\geqslant 0.08\lambda\phi_c\sqrt{f_c'}b_w d\frac{V_f}{M_f}d \leqslant 1.0 \quad (\lambda = 1.0 \text{ and } \phi_c = 1.0 \text{ for the present study}) \quad (4b)$$

ISIS-M03-01 [19]:

$$\text{For } d \leqslant 300\text{ mm}: V_{cf} = 0.2\lambda\phi_c \cdot \sqrt{f_c'}b_w d\sqrt{\frac{E_f}{E_s}} \quad (5a)$$

$$\text{For } d > 300\text{ mm}: \quad V_{cf} = \left[\frac{260}{1,000+d}\right]\lambda\phi_c \cdot \sqrt{f_c'}b_w d\sqrt{\frac{E_f}{E_s}} \geqslant 0.1\lambda\phi_c\sqrt{f_c'} \cdot b_w d\sqrt{\frac{E_f}{E_s}} \quad (5b)$$

JSCE shear design method [20]:

$$V_{cf} = \beta_d\beta_\rho\beta_n f_{vcd}b_w d/\gamma_b \quad (6)$$

where

$$V_{cf} = \beta_d\beta_\rho\beta_n f_{vcd}b_w d/\gamma_b$$

$$f_{vcd} = 0.2(f_c')^{(1/3)} \leqslant 0.72$$

$$\beta_d = \left(\frac{1000}{d}\right)^{(1/4)} \leqslant 1.5$$

$$\beta_\rho = \left(100\rho_f\frac{E_f}{E_s}\right)^{(1/3)} \leqslant 1.5$$

$$\beta_n = \begin{cases} 1 + \frac{M_o}{M_d} \leqslant 2 \text{ for the } N_d' \geqslant 0 \\ 1 + \frac{M_o}{M_d} \geqslant 0 \text{ for the } N_d' < 0 \end{cases}$$

γ_b = 1.0 for the present day.

Michaluk et al. [7]:

$$V_{cf} = \frac{E_f}{E_s}\left(\frac{1}{6}\sqrt{f_c'}b_w d\right) \quad (7)$$

Deitz et al. [6]:

$$V_{cf} = 3\frac{E_f}{E_s}\left(\frac{1}{6}\sqrt{f_c'}b_w d\right) \quad (8)$$

Tureyen and Frosch [21]:

$$V_{cf} = \frac{5}{12}k_n\sqrt{f_c'}b_w d \quad (9)$$

El-Sayed et al. [2]:

$$V_{cf} = \left(\frac{\rho_f E_f}{90\beta_1 f_c'}\right)^{1/3}\left(\frac{\sqrt{f_c'}}{6}b_w d\right) \leqslant \frac{\sqrt{f_c'}}{6}b_w d \quad (10)$$

Razaqpur and Isgor [8]:

$$V_{cf} = 0.035k_m k_s k_a(1+k_r)\sqrt{f_c'}b_w d \leqslant 0.2k_s\sqrt{f_c'}b_w d \quad (11)$$

where

$$k_m = \left(\frac{V_F d}{M_F}\right)^{2/3}$$

$$k_r = (E_f\rho_f)^{1/3}$$

$$k_a = \begin{cases} 1.0 & \text{for } \left(\frac{M_f}{V_f d}\right) \geqslant 2.5 \\ \frac{2.5}{(M_f/V_f d)} & \text{for } \left(\frac{M_f}{V_f d}\right) < 2.5 \end{cases}$$

$$k_s = \begin{cases} 1.0 & \text{for } d \leqslant 300\text{ mm} \\ \frac{750}{450+d} & \text{for } d > 300\text{ mm} \end{cases}$$

2.2. Limitations of the existing equations

Table 1 summarizes the parameters included in Eqs. (1)–(3), (4a), (4b), (5a), (5b), (6)–(11). The error metrics in terms of the