Advances in Engineering Software 42 (2011) 295–304

Contents lists available at ScienceDirect

Advances in Engineering Software

journal homepage: www.elsevier.com/locate/advengsoft

Prediction of shear strength of FRP-reinforced concrete beams without stirrups based on genetic programming

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ARTICLE INFO

Article history:
Received 31 December 2010
Received in revised form 9 February 2011
Accepted 14 February 2011
Available online 24 March 2011

Keywords:
Gene expression programming
Fibre reinforced polymers
Shear strength
Concrete beams

ABSTRACT

The use of fibre reinforced polymer (FRP) bars to reinforce concrete structures has received a great deal of attention in recent years due to their excellent corrosion resistance, high tensile strength, and good non-magnetization properties. Due to the relatively low modulus of elasticity of FRP bars, concrete members reinforced longitudinally with FRP bars experience reduced shear strength compared to the shear strength of those reinforced with the same amounts of steel reinforcement. This paper presents a simple yet improved model to calculate the concrete shear strength of FRP-reinforced concrete slender beams ($a/d > 2.5$) without stirrups based on the gene expression programming (GEP) approach. The model produced by GEP is constructed directly from a set of experimental results available in the literature. The results of training, testing and validation sets of the model are compared with experimental results. All of the results show that GEP is a strong technique for the prediction of the shear capacity of FRP-reinforced concrete beams without stirrups. The performance of the GEP model is also compared to that of four commonly used shear design provisions for FRP-reinforced concrete beams. The proposed model produced by GEP provides the most accurate results in calculating the concrete shear strength of FRP-reinforced concrete beams among existing shear equations provided by current provisions. A parametric study is also carried out to evaluate the ability of the proposed GEP model and current shear design guidelines to quantitatively account for the effects of basic shear design parameters on the shear strength of FRP-reinforced concrete beams.

1. Introduction

In recent years, fibre reinforced polymer (FRP) bars have been adopted as a potential solution to the corrosion problems in concrete structures. In addition to their excellent non-corrosive characteristics, FRP reinforcements have high strength-to-weight ratio, good fatigue properties and electro-magnetic resistance [1,2]. There are fundamental differences between the steel and FRP reinforcements: the latter has a lower modulus of elasticity and linear stress–strain diagram up to rupture with no discernible yield point and different bond strength according to the type of FRP product. Due to the relatively low modulus of elasticity of FRP bars, concrete members reinforced longitudinally with FRP bars experience reduced shear strength compared to the shear strength of those reinforced with the same amounts of steel reinforcement. This fact is supported by the findings from the experimental investigations on FRP-reinforced concrete beams [3–5].

The applied shear stresses in a cracked reinforced concrete member without transverse reinforcement are resisted by various shear mechanisms. The Joint ASCE-ACI Committee 445 [6] assessed that the quantity of concrete shear strength V_c can be considered as a combination of five mechanisms activated after the formation of diagonal cracks: (1) shear stresses in uncracked compressed concrete; (2) aggregate interlock; (3) dowel action of the longitudinal reinforcing bars; (4) arch action; and (5) residual tensile stresses transmitted directly across the cracks. The contribution of the uncracked concrete in reinforced concrete members depends mainly on the concrete strength, f_c', and on the depth of the uncracked zone, which is function of the longitudinal reinforcement properties. Aggregate interlock results from the resistance to relative slip between two rough interlocking surfaces of the crack, much like frictional resistance. The dowel action refers to the shear force resisting transverse displacement between two parts of a structural element split by a crack that is bridged by the reinforcement. Arching action occurs in deep members or in members in which the shear span-to-depth ratio (a/d) is less than 2.5. This is not a shear transfer mechanism in the sense that it does not transmit a tangential force to a nearby parallel plane, but permits the transfer of a vertical concentrated force to a reaction, thereby reducing the contribution of the other types of shear transfer. The basic explanation of residual tensile stresses is that when concrete first cracks, a clean break does not occur. The residual tension in cracked

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doi:10.1016/j.advengsoft.2011.02.002

concrete has been found to be present for crack widths smaller than 0.15 mm [5,7].

Due to the relatively low modulus of elasticity of FRP composite material, concrete members reinforced with FRP bars will develop wider and deeper cracks than members reinforced with steel. Deeper cracks reduce the contribution to shear strength from the uncracked concrete due to the lower depth of concrete in compression. Wider cracks in turn reduce the contributions from aggregate interlock and residual tensile stresses. Additionally, due to the relatively small transverse strength of FRP bars and relatively wider cracks, the contribution of dowel action can be very small compared to that of steel. Finally, the overall shear capacity of concrete members reinforced with FRP bars as flexural reinforcement is lower than that of concrete members reinforced with steel bars [5].

Previous studies [4,8–10] concluded that current shear design guidelines are very conservative in calculating the shear capacity of FRP-reinforced concrete beams. Consequently, the excessive amount of FRP needed to resist shear could be both costly and likely to create reinforcement congestion problems [8]. Accordingly, the purpose of this paper is to develop a simple yet accurate model for predicting the shear strength of FRP-reinforced concrete slender beams ($a/d > 2.5$) without stirrups. GEP approach is also used to build empirical model. For building the model, shear capacity results of 104 specimens used in training, testing and validation sets for GEP model were obtained from the literature. Six main parameters that affect the shear strength of FRP-reinforced concrete members were selected for input variables. In the sets of the model, the concrete compressive strength (f_c'), beam width (b_w), effective depth (d), shear span-to-depth ratio (a/d), reinforcement ratio (ρ_f) and the ratio of modulus of elasticity of FPR to steel reinforcement (E_f/E_s) were entered as input variables, while shear strength value (V_{cf}) was used as output variable. The performance of the model was subsequently compared to results obtained from different shear design guidelines namely, the provisions of the American Concrete Institute (ACI) [11,12], the Canadian Standards Association (CSA) [13], the Japan Society of Civil Engineers (JSCE) [14], and The Canadian Network of Centres of Excellence on Intelligent Sensing for Innovative Structures (ISIS) [15]. A parametric study was also carried out to evaluate the ability of the proposed GEP model and current shear design guidelines to quantitatively account for the effects of basic shear design parameters on the shear strength of FRP-reinforced concrete beams.

2. Review of current design provisions

Due to the rapid increase of using FRP materials as reinforcement for concrete structures, there are international efforts to develop design guidelines. These efforts have resulted in the publishing of several codes and design guidelines. Most of the shear design provisions incorporated in these codes and guides on shear capacity of FRP-reinforced concrete beams have focused on modifying existing shear design equations for steel-reinforced concrete beams to account for the substantial differences between FRP and steel reinforcement. These provisions are generally based on the parallel truss model with 45° constant inclination diagonal shear cracks. This model identifies the shear strength of a reinforced concrete flexural member as the sum of the shear capacity of the concrete component V_{cf} and the shear reinforcement component V_s. In this paper, the concrete shear strength component V_{cf} of members longitudinally reinforced with FRP bars as recommended by ACI 440, ISIS Canada, CSA S806, and JSCE are reviewed and they are listed in Table 1. Note that all strength reduction factors used in the equations listed in the table for design purposes are set equal to one for comparison.

3. Genetic programming approach

Genetic programming (GP) is proposed by Koza [16]. It is a generalization of genetic algorithms (GAs) [17]. The most general form of a solution to a computer-modelled problem is a computer program. GP takes cognizance of this and attempts to use computer programs as its data representation. Similarly to GA, GP needs only the problem to be defined. Then, the program searches for a solution in a problem-independent manner [16–18].

GP breeds computer programs to solve problems by executing the following three steps:

(1) Generate an initial population of random compositions of the functions and terminals of the problem.
(2) Iteratively perform the following substeps until the termination criterion has been satisfied:
    (A) Execute each program in the population and assign it a fitness value using the fitness measure.

Table 1
Shear design equations for FRP-reinforced concrete beams without stirrups.

ACI 440-03	$V_{cf} = \frac{\rho_f E_f}{90\beta_1 f_c'} V_c \leqslant V_c$ V_c is calculated using ACI 318; $\beta_1 = 0.85 - 0.05\left(\frac{f_c' - 28}{7}\right) \geqslant 0.65$
ACI 440-06	$V_{cf} = \frac{2\sqrt{f_c'}}{5} b_w C \quad C = Kd$ $K = \sqrt{2\rho_f n_f + (\rho_f n_f)^2} - \rho_f n_f$ and $n_f = \frac{E_f}{E_c}$
CSA S806-02	$V_{cf} = 0.035 b_w d\left(f_c' \rho_f E_f \frac{V_f d}{M_f}\right)^{1/3}$ $0.1 b_w d\sqrt{f_c'} \leqslant V_{cf} \leqslant 0.2 b_w d\sqrt{f_c'}$ for $d \leq 300$ mm $V_{cf} = \frac{130}{1000+d} b_w d\sqrt{f_c'} \geq 0.08 b_w d\sqrt{f_c'}$ for $d > 300$ mm, and $\frac{V_f d}{M_f} \leqslant 1$
JSCE-97	$V_{cf} = \frac{\beta_d \beta_p \beta_n f_{vcd}}{\gamma_b} b_W d \quad \beta_p = 3\sqrt{\frac{100\rho_f E_f}{E_S}} \leq 1.5 \quad \beta_d = 4\sqrt{\frac{1000}{d}} \leq 1.5$ $f_{vcd} = 0.23\sqrt{f_{cd}} \leq 0.72$(MPa) γ_b and β_n are factors to account for strength reduction and axial force, respectively
ISIS Canada-01	$V_{cf} = 0.2 b_w d\sqrt{f_c' \frac{E_f}{E_s}}$ for $d \leqslant 300$ mm $V_{cf} = \frac{260}{1000+d} b_w d\sqrt{f_c' \frac{E_f}{E_s}} \geqslant 0.1 b_w d\sqrt{f_c' \frac{E_f}{E_s}}$ for $d > 300$ mm

Note: f_c' = compressive strength of concrete, b_w and d = beam's width and effective width, respectively, ρ_f = longitudinal reinforcement ratio; E_c, E_s and E_f = modulus of elasticity of concrete, steel and FRP longitudinal bars, respectively; M_f and V_f = moment and shear force at critical section, respectively.