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GP-BASED PREDICTION FOR PUNCHING SHEAR CAPACITY OF FRP-REINFORCED TWO-WAY SLABS

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***Abstract*—In this study, a new genetic programming (GP) based design model for the prediction of punching shear capacity of FRP-reinforced two-way slabs is proposed. The proposed model is an empirical model based on 53 experimental studies available in the literature. As opposed to existing equations in the literature, the span length of slab (L) has been included in the proposed formulation in order to increase the performance of prediction. The generalization capability of the model is verified by means of extensive parametric studies. The proposed model is also compared with existing design codes and formulations available in the literature and is found to be more accurate. The results are illustrated both in tabular and graphical form.**

***Keywords*—genetic programming, punching shear, concrete slabs, FRP**

I. Introduction

For the construction industry, service life and durability of concrete structures are substantial issues. The corrosion risk of steel reinforcement is considered to be one of the main concerns that should be solved. Additionally, steel reinforced structures that are built, particularly, in wet environments generally require a comprehensive care. Recently, fiber-reinforced polymer (FRP) materials that are free of these problems appear to offer useful solutions as a substitute material for reinforcement. The user-friendly and nonmetallic nature, high tensile strength and low density make FRPs advantageous [4].

Various solutions such as concrete surface protective coatings to terminate the entering of CO2 and soluble chemicals, corrosion inhibitor admixtures at the wet phase, epoxy coating of reinforcement and galvanizing of reinforcement are offered for the reduction of the corrosion risk in extremely aggressive environments. The cathodic protection is a more forward-looking approach adopted in late decades. This method, which was initially produced as a rehabilitation measure, utilizes an electric current or a sacrificial anode to protect the main reinforcement. In some cases, stainless steel reinforcement provides the strongest anti-corrosion solution. Yet, most such solutions have either had failures or are costly [3].

In this study, an application of FRP reinforcement in RC slabs is introduced. A new design code for punching shear capacity of FRP reinforced two-way slabs is proposed based on a genetic programming approach.

II. FRP Reinforcement in RC Structures

The use of FRP bars as an alternative of the traditional mild-steel reinforcement provides some main advantages such as; resistance for corrosion, high unidirectional strength, high fatigue endurance, lightweight, magnetic transparency, low conductivity of heat and electricity (for glass and aramid fibers). [6]

Yet, the applications of FRP reinforcements have restrictions because of the unwanted characteristics as follows; brittle nature, low transverse strength, low elastic modulus (varies with fiber type), reduction of durability in acid/salt, moist and alkaline environments, low shear strength, high thermal expansion coefficient, fire resistance (varies with type of matrix) [6]

FRP bars show elastic behaviors up to rupture and fail in brittle nature. All existing design provisions and equations for reinforced concrete design and analysis are based on the yield properties of steel reinforcement. Typical stress-strain relations of FRP and steel reinforcement are shown in Figure 1 to demonstrate the different properties.

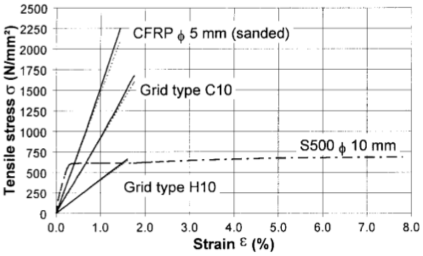

Fig. 1 Stress strain behavior of FRP bars

III. FRP-reinforced Two-Way Slabs

It is essential to comprehend the advantages and limitations of FRPs as well as which materials work and which shapes or forms suit best in order to successfully apply FRP reinforcement in slab construction. It has been observed that FRPs display a brittle-elastic behavior under direct tension and are much more flexible than steel in most cases. FRP reinforced concrete slabs are also likely to exhibit greater deflections and crack widths at the serviceability limit state level, owing to the low stiffness of FRP reinforcement [13].

The test results on punching shear capacity of two-way FRP-reinforced slabs are reported by several researchers [1,2,5,7,8,10-12,14-16]. All of these researchers tested slabs with FRP reinforcing bars or two-dimensional grids except for those tested by Ahmad et al. (1993). The slabs tested by Ahmad et al. (1993) had three-dimensional carbon-FRP (CFRP) grids. All of the slabs had unrestrained edges and were subjected to a central column load. Glass (GFRP), carbon (CFRP) or a hybrid of carbon and glass (HFRP) types of fibers were used [14].

In order to predict the punching shear capacity of FRP-reinforced slabs, several researchers and design codes proposed various formulations given in Table 2.

IV. Overview of Genetic Programming

Koza [9], as an extension to Genetic Algorithms (GA), has proposed a new tool called as genetic programming (GP). GP is defined as a problem-solving technique based on Darwinian principle of reproduction and survival of the fittest and analogs of naturally occurring genetic operations (i.e. mutation and sexual recombination) and it is implemented by evolution of computer programs for the purpose of solving, or approximately solving, problems.

In this study, gene expression programming (GeneXproTools) software is used. Using GeneXproTools software, computer programs with different sizes and shapes are evolved and coded in chromosomes of predetermined length. These linear chromosomes include several genes and each gene encodes a smaller subprogram. Additionally, the linear chromosomes allow the operation of essential genetic operators such as recombination, transposition and mutation. GEP approach has two main strengths: the first is that, since the genetic operators function at the chromosome level, a significant simplification for the formation of genetic diversity is provided. The second strength of GEP approach is that, thanks to its unique functionality, more complex programs containing several subprograms can be evolved.

V. Numerical Application

In this study, the main focus is to obtain a new formulation for punching strength of FRP reinforced two-way slabs by use of GP. The formulation is based on experimental results collected from the literature. Thus, an extensive literature review has been conducted for on FRP reinforced two-way slabs. Experimental database given in Table A1 was used as testing and training sets for GP formulation. The comparison of proposed GP formulation results and experimental database is presented in Table A1. 20% of the experimental database was used as testing set and 80 percent was used training set during GP process. The statistical parameters of training, testing and total sets are given in Table 1.

TABLE I. STATISTICAL PERFORMANCE OF THE GEP MODEL

	R^2	Standard deviation	Mean test/equation	RMSE
Train set	0.916	0.12	0.99	24.35
Test set	0.89	0.18	0.993	22.55
Total Set	0.906	0.12	0.99	23.95

Figure 2 shows the expression tree (ET) of the formulation, which is actually:

P = (d0^(1/3))* (d5^(1/3))*(d3^c7)*(d2^(1/2))* (d4^c11) *(d1^c15)* (c19^(1/5))*(c3/c17)*(c13^(1/2))

where

d(0) = c (mm); d(1) = d (mm); d(2) = EFRP (GPa); d(3) = fc (MPa); d(4) = L (mm); d(5) = ρ (%)

and constants of the equation are

c3 = 0.84; c7 = 0.009977; c11 = -0.196; c13 = 0.5051;
c15 = 1.684, c17 = 133.91; c19 = 1.96

Rearranging the corresponding values and simplifying the terms, the final equation becomes:

$$P = \frac{0.005716\sqrt[3]{c}\,\sqrt{E_{FRP}}\,\sqrt[3]{\rho}\,d^{1.684} f_c^{0.09977}}{L^{0.1963}} \qquad (10)$$

where P is ultimate punching load (kN), ρ is reinforcement ratio (%), fc is compressive strength of concrete (MPa), c is dimension of column section (mm), L is span length of slab (mm), E_{FRP} is elastic modulus of FRP bars and d is effective flexural slab depth (mm).

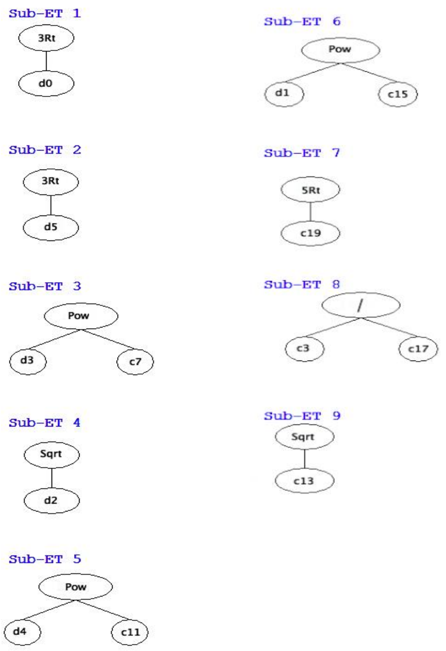

Fig. 2 Expression tree of proposed GP formulation

VI. Discussion & Results

An evaluation process has been performed to test the accuracy of the GP formulation by means of numerical results of the same experimental database and empirical equations available in the literature. The accuracy of proposed GP formulation is found to be higher than numerical results and existing analytical equations available in the literature. The performance of the proposed GP model is shown in Figure 3.

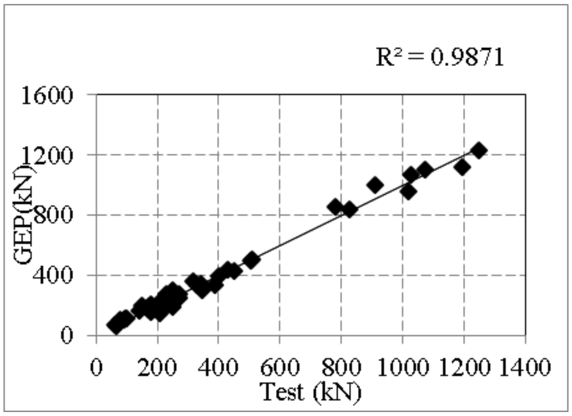

Fig. 3 Performance of proposed GP model (Eq. 10) vs. test results for punching shear load

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TABLE II. EXISTING FORMULAS FOR ESTIMATION OF PUNCHING SHEAR RESISTANCE OF FRP REINFORCED TWO-WAY SLABS

Source	Formula	Remarks
ACI 318 (Eq. 1)	$P = 0.33\sqrt{f_c}\, b_{0,0.5d}\, d$	$b_{0,0.5d} = 4(c+d)$
BS 8110-97 (Eq. 2)	$P = 0.79(100\rho)^{1/3}\left[\frac{400}{d}\right]^{1/4}\left[\frac{f_{ck}}{25}\right]^{1/3} b_{0,1.5d}\, d$	$b_{0,1.5d} = 4(c+3d)$ f_{ck} = cubic compressive strength of concrete
El-Ghandour et al. (ACI) (Eq. 3)	$P = 0.33\sqrt{f_c}\left[\frac{E_f}{E_s}\right]^{1/3} b_{0,0.5d}\, d$	$b_{0,0.5d} = 4(c+d)$ $E_s = 210GPa$
El-Ghandour et al. (BS) (Eq. 4)	$P = 0.79\left[100\rho(1.8)\frac{E_f}{E_s}\right]^{1/3}\left[\frac{400}{d}\right]^{1/4}\left[\frac{f_{ck}}{25}\right]^{1/3} b_{0,1.5d}\, d$	$b_{0,1.5d} = 4(c+3d)$ $E_s = 210GPa$
Matthys et al. (Eq. 5)	$P = 1.36\frac{\left[100\rho\frac{E_f}{E_S}f_{cm}\right]^{1/3}}{d^{1/4}} b_{0,1.5d}\, d$	$b_{0,1.5d} = 4(c+3d)$ $E_s = 210GPa$ f_{cm} = mean concrete compressive strength of cylinder specimens at 28 days
Ospina et al. (Eq. 6)	$P = 2.77\left(\rho f_c\right)^{1/3}\left[\frac{E_f}{E_s}\right]^{1/2} b_{0,1.5d}\, d$	$b_{0,1.5d} = 4(c+3d)$ $E_s = 210GPa$
Zaghloul et al. (Eq. 7)	$P = 0.07\left(\rho f_c E_f\right)^{1/3} b_{0,0.5d}\, d$	
El-Gamal (Eq. 8)	$P = 0.33\sqrt{f_c}(1.2)^N b_{0,0.5d}\, d\alpha$	$b_{0,0.5d} = 4(c+d)$ $\alpha = 0.62(\rho E_f)^{1/3}\left[1+\frac{8d}{b_{0,0.5d}}\right]$
Theodorakopoulos et al. (Eq. 9)	$P = \frac{1}{2}0.234 f_{cu}^{2/3}\left[\frac{100}{d}\right]^{1/6}\left[\frac{2\alpha_f\lambda_f}{1+\alpha_f\lambda_f}\right] b_{0,1.5d}\, d$ for $\alpha_f > 0.33$ $\alpha_f = \rho_f E_f\left[\frac{0.0105}{0.145 f_{cu}}\right]$ with $f_{cu} = f_c/0.8$ $\lambda_f = (k_f/6)(-1+\sqrt{1+48/\alpha_f} < 1$ with $k_f = 0.55$	$b_{0,1.5d} = 4(c+3d)$ $E_s = 210GPa$ f_{cu} = ultimate compressive strength of concrete.

Slab	*Shape of column*	*c (mm)*	*d (mm)*	*E_{FRP} (Gpa)*	*f_c (Mpa)*	*L (mm)*	*ρ (%)*	*P_{test} (kN)*	*$P_{test}/P_{predicted}$*									
									ACI318 (Eq.(1))	BS8110 (Eq.(2))	El-Ghandour (ACI) (Eq. (3))	El-Ghandour (BS) (Eq. (4))	Matthys (Eq. (5))	Ospina (Eq.(6))	Zaghloul (Eq. (7))	El-Gamal (Eq.(8))	Theodorakopoulos (Eq. (9))	GP model (Eq. (10))
Ahmad et al.																		
CFRC-SN1	S	75	61	113	42.4	600	0.95	93	1.30	1.00	1.58	0.92	1.07	0.96	1.12	1.34	1.05	1.09
CFRC-SN2	S	75	61	113	44.6	600	0.95	78	1.07	0.82	1.29	0.76	0.88	0.79	0.93	1.10	0.87	1.32
CFRC-SN3	S	100	61	113	39	600	0.95	96	1.19	0.96	1.43	0.89	1.03	0.93	1.01	1.32	1.02	1.10
CFRC-SN4	S	100	61	113	36.6	600	0.95	99	1.26	1.02	1.53	0.93	1.09	0.98	1.06	1.40	1.09	1.04
Banthia et al.																		
I	S	100	55	100	41	500	0.312	65	0.90	1.07	1.14	1.03	1.20	1.13	1.16	1.56	1.13	0.94
II	S	100	55	100	52.9	500	0.312	61	0.75	0.93	0.94	0.89	1.04	0.98	1.01	1.29	0.97	1.09
El-Ghandour et al.																		
SGI	S	200	142	45	33.3	1700	0.22	170	0.46	0.70	0.76	0.96	1.03	0.87	0.92	1.09	1.00	1.12
SCI	S	200	142	110	34.7	1700	0.18	229	0.61	1.00	0.74	1.01	1.09	0.79	0.96	1.14	1.06	1.16
SG2	S	200	142	45	46.6	1700	0.47	271	0.62	0.78	1.02	1.05	1.13	0.96	1.00	1.14	0.99	1.01
SG3	S	200	142	45	30.3	1700	0.47	237	0.67	0.79	1.10	1.05	1.14	0.97	1.01	1.23	1.00	1.00
SC2	S	200	142	110	29.6	1700	0.43	317	0.91	1.09	1.11	1.09	1.18	0.86	1.03	1.27	1.05	1.07
Matthys et al.																		
C1	C	150	96	91.8	36.7	900	0.26	181	0.96	1.31	1.58	1.28	1.51	1.25	1.32	1.74	1.42	0.79
C1'	C	230	96	91.8	37.3	900	0.26	189	0.75	1.15	1.24	1.12	1.33	1.10	1.03	1.52	1.24	0.92
C2	C	150	95	95	35.7	900	1.05	255	1.39	1.19	2.27	1.16	1.36	1.12	1.19	1.57	1.28	0.88
C2'	C	230	95	95	36.3	900	1.05	273	1.11	1.07	1.82	1.05	1.22	1.01	0.95	1.40	1.16	1.00
C3	C	150	126	92	33.8	900	0.52	347	1.30	1.39	2.15	1.37	1.60	1.24	1.41	1.74	1.42	0.79
C3'	C	230	126	92	34.3	900	0.52	343	0.99	1.19	1.63	1.18	1.37	1.06	1.08	1.48	1.22	0.98
CS	C	150	95	147.6	32.6	900	0.19	142	0.81	1.21	1.14	1.02	1.19	0.91	1.04	1.39	1.07	1.04
CS'	C	230	95	147.6	33.2	900	0.19	150	0.64	1.07	0.90	0.90	1.05	0.81	0.83	1.23	0.95	1.20
H1	C	150	95	37.3	118	900	0.64	207	0.62	0.77	1.38	1.03	1.19	1.15	1.05	1.13	1.14	0.90
H2	C	150	89	40.7	35.8	900	3.78	231	1.38	0.77	2.98	1.00	1.16	1.13	1.02	1.37	1.17	0.91
H2'	C	80	89	40.7	35.9	900	3.78	171	1.44	0.68	3.11	0.89	1.03	1.00	1.06	1.21	1.04	1.02
H3	C	150	122	44.8	32.1	900	1.21	237	0.95	0.76	2.00	0.96	1.12	0.99	0.98	1.23	1.00	1.04
H3'	C	80	122	44.8	32.1	900	1.21	217	1.18	0.81	2.47	1.01	1.19	1.04	1.20	1.31	1.06	0.94

Ospina et al.																		
GFR_1	S	250	120	34	29.5	1831	0.73	217	0.68	0.73	1.23	0.95	1.03	1.08	0.85	1.32	1.03	0.92
GFR-2	S	250	120	34	28.9	1831	1.46	260	0.83	0.70	1.49	0.91	1.12	1.04	0.81	1.26	1.01	0.96
NEF-1	S	250	120	28.4	37.5	1831	0.866	206	0.57	0.60	1.10	0.88	1.03	0.98	0.79	1.11	0.91	1.02
Rashid																		
GS1	S	250	100	42	40	1830	1.183	249	0.85	0.82	1.43	1.03	1.19	1.11	0.92	1.37	1.10	0.85
GS2	S	250	100	42	35	1830	1.052	218	0.80	0.78	1.34	1.00	1.16	1.05	0.89	1.33	1.05	0.89
GS3	S	250	100	42	29	1830	1.671	240	0.96	0.78	1.62	0.99	1.15	1.05	0.88	1.38	1.10	0.89
GS4	S	250	100	42	26	1830	0.947	210	0.89	0.86	1.50	1.09	1.27	1.16	0.97	1.54	1.17	0.81
Mean									0.93	0.93	1.52	1.01	1.17	1.02	1.02	1.34	1.09	0.99
Standard deviation									0.27	0.20	0.58	0.12	0.15	0.12	0.14	0.17	0.13	0.12
Coefficient of variation (COV), %									29.22	21.96	38.30	12.10	12.72	11.77	13.67	12.87	11.73	12.27
Mean squared error									6348.9	3438.1	6797.7	630.4	1746.7	647.4	902.0	3412.7	913.6	573.9
Coefficient of correlation (R-square)									0.536	0.656	0.420	0.903	0.890	0.887	0.848	0.871	0.898	0.906

TABLE A1 EXPERIMENTAL DATABASE