Computers and Concrete, *Vol. 14, No. 3 (2014) 327-345*
DOI: http://dx.doi.org/10.12989/cac.2014.14.3.327

Prediction of the bond strength of ribbed steel bars in concrete based on genetic programming

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(*Received July 12, 2013, Revised May 29, 2014, Accepted July 3, 2014*)

Abstract. This paper presents the application of multi-gene genetic programming (MGP) technique for modeling the bond strength of ribbed steel bars in concrete. In this regard, the experimental data of 264 splice beam tests from different technical papers were used for training, validating and testing the model. Seven basic parameters affecting on the bond strength of steel bars were selected as input parameters. These parameters are diameter, relative rib area and yield strength of steel bar, minimum concrete cover to bar diameter ratio, splice length to bar diameter ratio, concrete compressive strength and transverse reinforcement index. The results show that the proposed MGP model can be alternative approach for predicting the bond strength of ribbed steel bars in concrete. Moreover, the performance of the developed model was compared with the building codes' empirical equations for a complete comparison. The study concludes that the proposed MGP model predicts the bond strength of ribbed steel bars better than the existing building codes' equations. Using the proposed MGP model and building codes' equations, a parametric study was also conducted to investigate the trend of the input variables on the bond strength of ribbed steel bars in concrete.

Keywords: genetic programming; bond strength; ribbed steel bars; concrete

Nomenclature

A_b: area of ribbed steel bar
A_{tr}: area of each stirrup crossing the potential plane of splitting adjacent to the ribbed steel bar
c_b: bottom concrete cover for spliced bar
c_{si}: 1/2 of the bar clear spacing
c_{so}: side concrete cover for bar
c_s: minimum (c_{so} , c_{si}+ 6.35 mm)
c_{min}: minimum (c_b, c_s)
c_{max}: maximum (c_b, c_s)
c_{sk}: 2/3 of the center to center of the ribbed steel bars
d_b: diameter of ribbed steel bar
d_{cs}: min (c_{so}+0.5 d_b, c_b+0.5 d_b, c_{sk})
K: constant used in CEB-FIP equation
k_1: bar location factor (in CSA equation)
k_2: coating factor (in CSA equation)
k_3: concrete density factor (in CSA equation)
k_4: bar size factor (in CSA equation)
l_s: splice length
M: ratio of the average yield strength to the design yield strength of the developed bar (in CEB-FIP equation)
n: number of spliced bars
N: the number of transverse stirrups, or ties, within the splice length
R_r: relative rib area of the reinforcement

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http://www.techno-press.org/?journal=cac&subpage=8 ISSN: 1598-8198 (Print), 1598-818X (Online)

f'_c: specified compressive strength of concrete
f_y: yield strength of spliced bar
f_{yt}: yield strength of transverse reinforcement
f_{ctd}: concrete tensile strength (in EC2 equation)
f'_{cd}: design compressive strength of concrete (in JSCE equation)
s: spacing of transverse reinforcement
u_b: bond strength
α_1: bar shape factor (in EC2 equation)
α_2: concrete cover factor (in EC2 equation)
α_3, α_4, α_5 : Confinement factor (in EC2 equation)
η_1: bond quality factor (in EC2 equation)
η_2: bar size factor (in EC2 equation)

1. Introduction

Due to the performance of reinforced concrete structures depending on adequate bond strength between steel bars and concrete, the accurate calculation of splice strength is important. An efficient bond ensures reliable force transfer between reinforcement to the surrounding concrete. According to ACI Committee 408 (2003), in case of a ribbed steel bar, the following mechanisms contribute to force transfer: (1) Chemical adhesion between the bar and the concrete, (2) Frictional forces arising from the roughness of the interface and (3) Mechanical anchorage or bearing of the ribs against the concrete surface.

Orangun *et al*. (1977) reported that the bond failure of ribbed bars normally involves the following phenomena: (1) local crushing of concrete in front of the bar ribs, and/or (2) splitting of the concrete due to radial cracks around the bar. Local crushing dominates when the confinement provided by either surrounding concrete or transverse reinforcement is large and/or the rib height is small. This mechanism of bond failure tends to be ductile and does not cause much size-effect. Splitting of the concrete, so called brittle mechanism, dominates when the confinement is small and/or the rib height is large.

The bond strength and mode of bond failure are affected by many parameters that are well documented in the technical papers. Important among these parameters include diameter, relative rib area and yield strength of steel bar, minimum concrete cover to bar diameter ratio, splice length to bar diameter ratio, concrete compressive strength and transverse reinforcement index (the ratio of the product of the area of each transverse stirrup and its yield strength to the product of stirrup spacing, the number of spliced bars and longitudinal bar diameter). These parameters have been used for quantifying the bond strength in empirical equations of different technical papers (ACI408 2003, Darwin *et al*. 1996a, Darwin *et al*. 1996b, Darwin *et al*. 2001, Ferguson and Thompson 1965, Hacha *et al*. 2006, Harajli *et al*. 2004, Harajli and Mabsout 2002, Hassan *et al*. 2012, Ichinose *et al*. 2004, Lutz and Gergely 1967, Orangun *et al*. 1977, Tepfers 1973, Untrauer 1965, Zuo and Darwin 2000).

Most of the mathematical models used to study the behavior of the reinforced concrete structure consist of mathematical rules and expressions that capture the relationship between different variables. By the way, using mathematical models to take and describe experiences from experimental data are the most reliable, accurate, scientific, and applicable recommended methods. Mathematical models based on experimental data are called “free models”, and are generally in regression forms. However, if the problem contains many independent variables, regression methods cannot be used because of less accuracy and more assumptions in regression form (linear, non-linear, exponential, etc.). In recent years, new modeling techniques based on artificial intelligence methods can approximate non-linear and complex relations due to any phenomena and trial and error processes by learning real record relationships without any presumptions (Dias and Pooliyadda 2001, Ramezanianpour and Davarpanah 2002). Among these methods genetic programming approaches have been successfully applied for engineering applications. Perez *et al*. (2013) applied GP technique in order to enhance the expressions of the FIB. Cevik *et al*. (2010) introduced a GP model for formulating the strength enhancement of CFRP confined concrete cylinders. Kara (2011) used the GP model for predicting the shear strength of FRP- reinforced concrete beams without stirrups. Perez *et al*. (2012) proposed a new GP algorithm for calculating the shear strength of reinforced concrete beams. Kose and Kayadelen (2010) investigated the efficiency of the GP model for determining the transfer length of prestressing strands. Perez *et al*. (2010) used GP for adjusting of EC-2 shear formulation of concrete elements without web reinforcement. Ozbay *et al*. (2008) introduced the GP model as a new tool for the formulation of fresh and hardened properties of self-compacting concrete. Mousavi *et al*. (2012) utilized a type of GP for modeling the compressive strength of HPC. Sarıdemir (2010) proposed a GP model for predicting the compressive strength of concretes containing rice husk ash. Tanyildizi and Cevik (2010) modeled the mechanical performance of lightweight concrete containing silica fume exposed to high temperature using GP. Sonebi and Cevik (2009) developed a GP model for predicting the fresh and hardened properties of self-compacting concrete containing pulverized fuel ash.

Some researchers have applied different branches of artificial intelligence for predicting the bond strength of reinforcing bars in concrete. Golafshani *et al*. (2014) evaluated the bond strength of GFRP bars in concrete using artificial neural network (ANN) and GP. Golafshani *et al*. (2012) developed the ANN and fuzzy logic models for predicting the bond strength of spliced steel bars in concrete. Tanyildizi (2009) devised a fuzzy logic prediction model for the bond strength of lightweigth concrete containing mineral admixtures under different curing conditions. Dahou *et al*. (2009) proposed an ANN model for modelling the bond between conventional ribbed steel bars and concrete.

The aim of this paper is to develop the multi-gene genetic programming model for predicting the bond strength of ribbed steel bar in concrete. A total of 264 records from different technical papers were used in training, validating and testing of the model. A comparison of the developed model's outputs with the target bond strength revealed that the model's results have a good agreement with the experimental data. Also, the obtained results were compared with the different codes' equations to assess the efficiency of the proposed models. Moreover, the proposed MGP model was used to show that it could perform parametric studies to evaluate the effects of the inputs parameters on the bond strength of ribbed steel bar in concrete.

2. Review of current design provisions

Due to the importance of bond strength between steel bars and concrete for design provisions, there are some international efforts to improve design guidelines. These efforts have resulted in the publishing of several codes and design guidelines. Most of the empirical equations used in these publications are based on nonlinear regression analysis of test results. The bond strength between ribbed steel bars and concrete as recommended by some design guidelines are listed in Table 1.

Table 1 Available bond strength equations for ribbed steel bars in concrete

Design method	Expression for bond strength
ACI 318	$u_b = \left(0.125 + 0.25\frac{c_{min}}{d_b} + 4.15\frac{d_b}{l_s} + \frac{A_{tr}f_{yt}}{41.36snd_b}\right)\sqrt{f'_c}$
CSA	$u_b = \frac{0.2768}{\prod_{i=1}^{4} k_i}\left[\frac{A_{tr}f_{yt}}{10.5snd_b} + \frac{d_{cs}}{d_b}\right]\sqrt{f'_c}$
EC2	$u_b = \frac{2.25\eta_1\eta_2 f_{ctd}}{\prod_{i=1}^{5}\alpha_i}$
CEB-FIP	$u_b = \frac{0.353}{M}\frac{(f_c - 2.75)^{2/3}}{\left(1.15 - 0.15\frac{c_{min}}{d_b}\right)(1 - K(N\frac{A_{tr}}{A_b} - 0.25))}$
JSCE	$u_b = 0.31\left[\left(0.318 + 0.795\left(\frac{c_{min}}{d_b} + \frac{15}{s}\frac{A_{tr}}{d_b}\right)\right) + 13.3\frac{d_b}{l_s}\right]\sqrt{f'_{cd}}$

3. Experimental data

The collected experimental data included 264 splice beam tests gathered from different technical papers (Azizinamini *et al*. 1999, Choi *et al*. 1990a, Choi *et al*.1991b, Darwin *et al*. 1996a, Hassan *et al*. 2012, Hagha *et al*. 2006, Hester *et al*. 1991a, Hester *et al*. 1993b, Mathey and Watstein 1961, Rezansoff *et al*. 1991, Seliem *et al*. 2009, Zuo and Darwin 1998, Zuo and Darwin 2000). Based on the previous research studies, some of the important parameters that are thought to affect the bond strength of ribbed steel bars are listed below:

- Diameter of ribbed steel bars (d_b)
- Yield strength of ribbed steel bars (f_y)
- Relative rib area of the reinforcement (R_r)
- Minimum concrete cover to bar diameter ratio ($c_{\min}/d_b$)
- Splice length to bar diameter ratio (l_s/d_b)
- Specified compressive strength of concrete (f'_c)
- Transverse reinforcement index ($A_{tr}f_{yt}/snd_b$)

Among the gathered records from the above-mentioned sources, 184 records were used for training, 40 records for validating, and 40 records for testing of the model. These selections are made by a random process to prevent any man-selection effects on the training process. Table 2 summarizes the range of input and output records for training, validating and testing data. As shown in this table, the ranges of data for validating and testing datasets are within the range of data for training dataset. In other words, the proposed model was developed for interpolation purpose. Furthermore, the database used for training, validating and testing patterns is presented in Table A in Appendix A.

Table 2 Range of input-output parameters in database and their normalization values

Parameters	Minimum			Maximum			Mean			Standard deviation		
	Training data	Validating data	Testing data	Training data	Validating data	Testing data	Training data	Validating data	Testing data	Training data	Validating data	Testing data
d_b (mm)	12.70	15.87	12.70	63.50	63.50	63.50	27.89	27.97	28.60	8	7.66	8.59
f_y (MPa)	413.79	413.79	452.00	827.59	827.59	827.59	632.43	602.06	661.11	150.10	142.76	144.27
R_r	0.06	0.07	0.07	0.18	0.18	0.18	0.10	0.10	0.10	0.03	0.03	0.03
$c_{\min}/d_b$	0.60	0.60	0.60	3.50	3.20	3.50	1.55	1.59	1.61	0.51	0.48	0.67
l_s/d_b	7.00	16	12	94.00	58.40	64.54	30.28	29.00	29.82	16.61	12.65	14.66
f'_c (MPa)	24.10	25.96	27.96	110.36	108.25	107.93	51.78	49.74	48.59	25.87	23.94	22.85
$A_{tr}f_{yt}/snd_b$	0.00	0.00	0.00	271.21	93.06	271.21	18.21	12.12	23.27	36.28	14.93	55.13
u_b	1.52	2.61	1.92	11.36	8.40	10.92	5.28	5.20	5.57	1.63	1.34	2.14

4. Genetic programming

Genetic programming, proposed by Koza (1992), is a subset of solution search techniques enshrined within the term of evolutionary computation (EC). EC includes a set of methods based on models that emulate certain characteristics of nature, mainly the capacity that living beings possess to adapt themselves to their environment. This feature of living beings had been captured by Darwin (1859) to make his theory of evolution according to the species natural selection principle. Darwin (1859) holds that those individuals in a population who possess the most advantageous characters will leave proportionally more descendants in the following generation, and if such characters are due to genetic differences that can be transmitted to the descendants, the genetic composition of the population will tend to change, raising the number of individuals with such characteristics. In this way, the complete population of living beings adapt themselves to the changeable circumstances of their environment. The final result is that living beings tend to perfect themselves in relation to the circumstances that surround them.

The GP solutions are computer programs represented as tree structures. Each of these trees will be a possible solution to the problem in question. The fitness function is used to evaluate its goodness. In GP, each solution is called individual, and the set of individuals with whom it works is called population. This population, that is initially random, is made to evolve through a number of iterations that are called generations in which new individuals who will be part of the current population are created from the individuals of a previous generation. These new individuals are created combining the genetic material of some selected individuals, using the selection, crossover and mutation algorithms. Fig. 1 describes the GP general functioning. This outline is the same for any evolutionary algorithm (Perez *et al*. 2012).

In this study, multi-gene genetic programming (MGP), a novel branch of standard GP proposed by Hinchliffe *et al*. (1996), was used for modeling the bond strength of ribbed steel bars in concrete. It is a new feature that makes the GP approach more powerful for modeling non-linear problems. Contrary to standard GP, each computer program in MGP is presented as a number of detached genes such that each one is a symbolic regression. The main difference between standard and MGP is the amount of tree-based structures that can be employed. Applying the multi-gene feature noticeably improves the ability of GP and allows better results to be obtained. In MGP, each prediction of the output variable is formed linearly by the weighted output of each of the genes plus a bias term. Each tree is a function of the input variables. Mathematically, a multi-gene regression model can be written as (Searson 2009)

```
1. Initializing the population
2. Population evaluation
3. Whereas the termination criterion is  not satisfied
       a.  Selecting individuals for the reproduction
       b.  Creation of new individuals from the ones that
           are selected (crossover)
       c.  Individuals mutation (with probability p)
       d.  New individuals evaluation
       e.  Replacement of all/some of the individuals from
           the current population with the new individuals
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Fig. 1 Outline of an evolutionary algorithm (Perez *et al*. 2012)

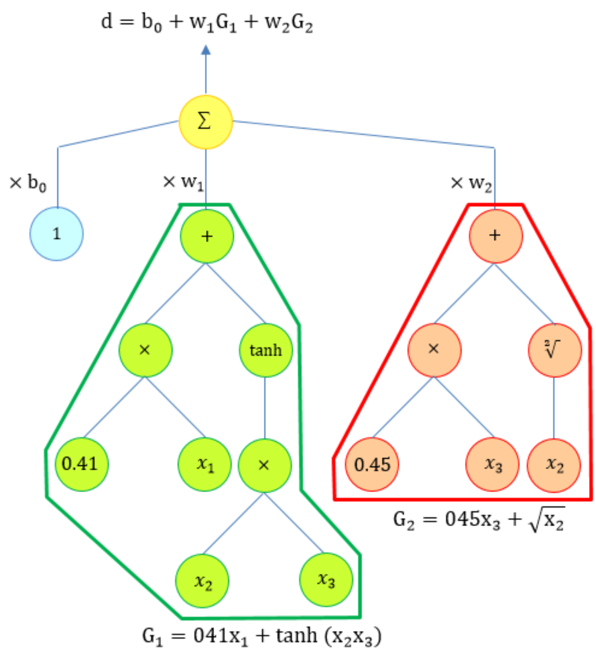

Fig. 2 Example of a MGP model

$$y = \sum_{i=1}^{n} \omega_i G_i + b_0 \quad (1)$$

where y is the predicted output, G_i is the value of the ith gene and is, in general, a function of one or more of the input variables, ω_i is the ith weighting coefficient, n is the number of genes and b_0 is a bias term. The gene weights are determined by a least squares procedure to minimize the RMSE between the predicted and output actual outputs. Fig. 2 shows an example of the MGP model using input variables x_1, x_2 and x_3 (Searson 2009).

5. MGP results

The fundamental aim of developing the MGP model was to generate the mathematical functions for predicting the bond strength of ribbed steel bars in concrete. The best model was chosen on the basis of a multi-objective strategy as follows:

i. Selecting the simplest model using simple functions and least depth and number of genes.

ii. Providing the best fitness values on the training, validating and testing data.

In this regard, different MGP models with different number of genes (2 and 3 genes) and different genes' tree depth (3, 4 and 5) were developed. All of these models were tested and ten replications for each architecture were carried out. The performance and the simplicity of each model (the number of nodes and the applied functions) were considered for its evaluation. The optimized parameters used in the MGP model development were summarized in Table 3. Also, the expression tree of formulation for the u_b is shown in Fig. 3.

Table 3 Parameters of MGP approach model

Parameter definition	MGP model
Population size	10000
Number of generations	500
Max genes	3
Max genes' tree depth	5
Function set	Multiple, Minus, Plus, Divide, Abs, $\sqrt[2]{\ }$, $\sqrt[2]{\ }$, $\sqrt[4]{\ }$,Power 2, Power 3, Power 4, sin, cos, tan
Probability of GP mutation event	0.10
Probability of GP crossover event	0.85
Probability of GP direct copy event	0.05

Table 4 The u_b statistical values of the proposed MGP model

Proposed model	Data sets	MAPE	RMSE	R^2
The MGP model	Training	8.8302	0.5152	0.9912
	Validating	8.2982	0.5473	0.9892
	Testing	8.9161	0.5671	0.9909

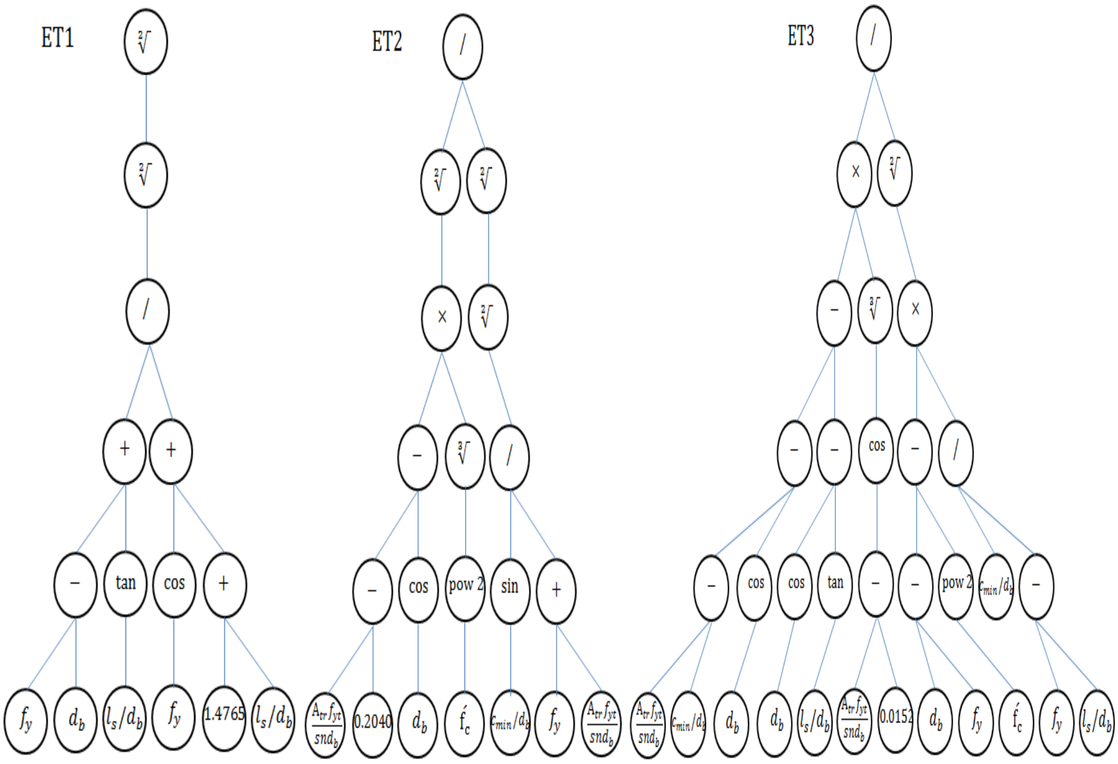

Fig. 3 Expression trees of the proposed MGP model

6. Results and discussion

Maximum absolute percentage error (MAPE), Root mean squared error (RMSE) and the absolute fraction of variance (R^2) are statistical values that were used for comparative evaluation of the performance of the proposed model and empirical equations. These statistical values are calculated according to Eqs. (6)-(8), respectively.

$$\mathrm{MAPE} = \frac{1}{N}\sum_{i=1}^{N}\frac{|O_i - t_i|}{t_i} \times 100 \tag{6}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(O_i - t_i)^2} \tag{7}$$

$$R^2 = 1 - \left(\frac{\sum_{i=1}^{N}(O_i - t_i)^2}{\sum_{i=1}^{N}(O_i)^2}\right) \tag{8}$$

where t_i is the bond strength of ribbed steel bars in concrete, O_i is the predicted value and N is the total number of data points in each set of data.

The statistical values for the bond strength of ribbed steel bar in concrete obtained from training, validating and testing sets in the proposed MGP model are given in Table 4. While the statistical values MAPE, RMSE and R^2 from training in the proposed model were obtained as 8.8302%, 0.5152 and 0.9912, respectively, these values were obtained in validating as 8.2982%, 0.5473 and 0.9892, respectively and for testing data as 8.9161%, 0.5671 and 0.9909 respectively.

For the proposed model, the comparisons of the measured and predicted bond strength versus data samples are shown in Figs. 4-6 for training, validating and testing stages, respectively. Figs. 7–9, present the measured bond strengths versus predicted bond strengths by MGP model. Also, the linear least square fit line and its equation are given in these figures.

As it is visible in Figs. 4, 7 and Table 4, the values obtained from the training set in the proposed MGP model are much closer to the experimental data. It can be concluded that the proposed model could learn the relationship between the different input parameters and the output parameter, which is expected, since the proposed model were constructed using these data. Also, the results of the validating stage in Figs. 5, 8 and Table 4 show that the proposed model was capable of generalizing between input variables and the output. Finally, Figs. 6 and 9 and Table 4 reveal that the developed model is able to model the bond strength of ribbed steel bars in concrete.

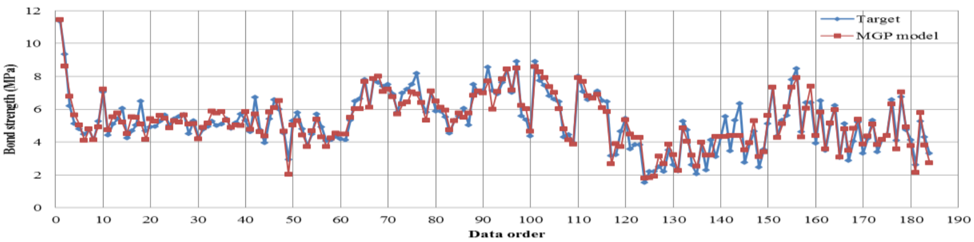

Fig. 4 Predicted bond strengths through the proposed MGP model for training set

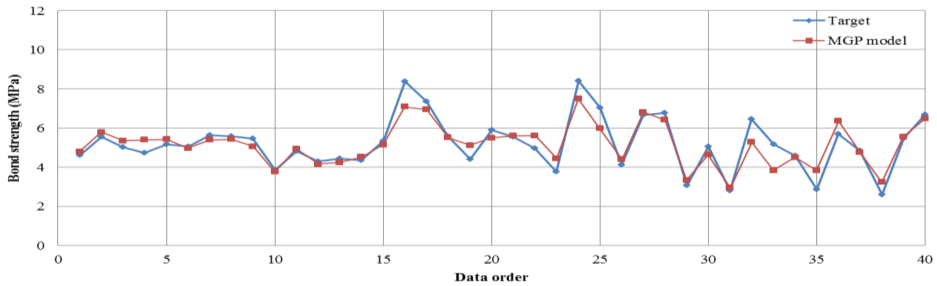

Fig. 5 Predicted bond strengths through the proposed MGP model for validating set

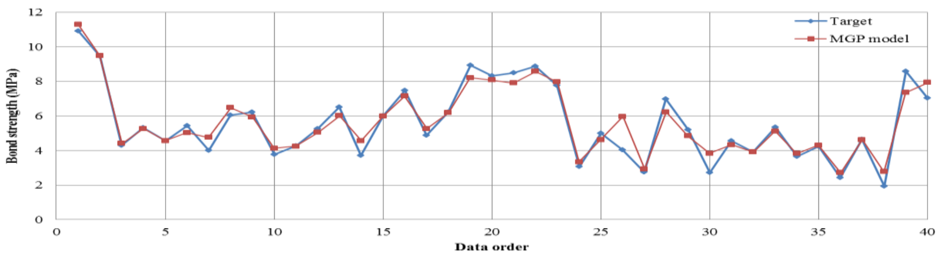

Fig. 6 Predicted bond strengths through the proposed MGP model for testing set

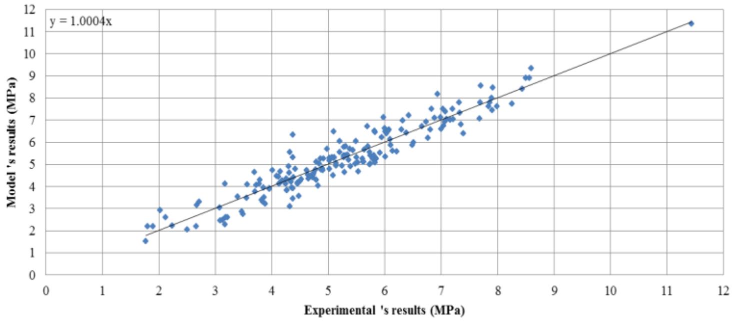

Fig. 7 The correlation of the measured and predicted bond strengths in training stage for the proposed MGP model

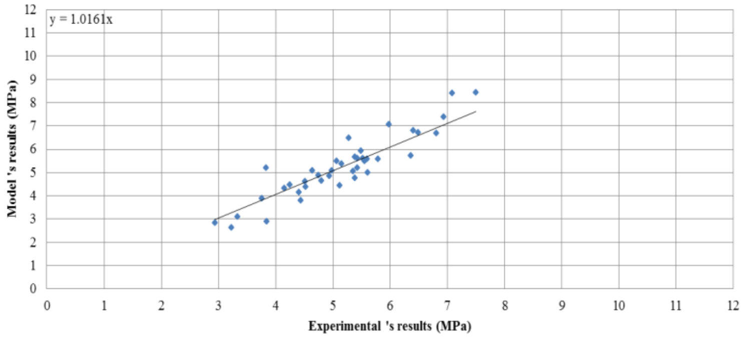

Fig. 8 The correlation of the measured and predicted bond strengths in validating stage for the proposed MGP model

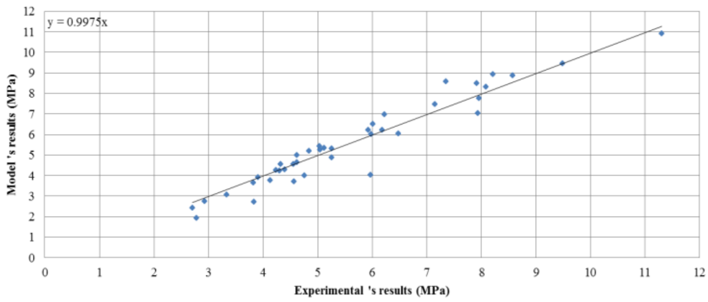

Fig. 9 The correlation of the measured and predicted bond strengths in testing stage for the proposed MGP model

7. Comparison of building code equations

In this part, the results of the proposed MGP model were compared with different building codes' equations for the existing data in the database. Fig. 10 shows the performance of the model produced by MGP and those provided by commonly used bond strength's equations. The ratio of experimentally measured to analytically calculated bond strength ($u_{b,\text{ experimental}}/u_{b,\text{ model}}$) for all data in the database is shown in this figure. Also, Table 5 reports the average and standard deviation

Table 5 Performance of the bond strength's equations considered in this study

Model	MAPE (%)	RMSE	R^2	$u_{b,\text{ experimental}}/u_{b,\text{ model}}$	
				Average	SD
ACI 318	15.3245	1.2524	0.9429	1.0242	0.2573
CSA	17.3066	1.2224	0.9500	1.1202	0.2867
EC2	19.0323	1.2148	0.9431	1.0701	0.2415
CEB-FIP	24.4721	1.4716	0.9261	1.0708	0.2946
JSCE	13.6997	0.9981	0.9693	1.0315	0.1934
MGP	8.7619	0.5283	0.9909	0.9983	0.1153

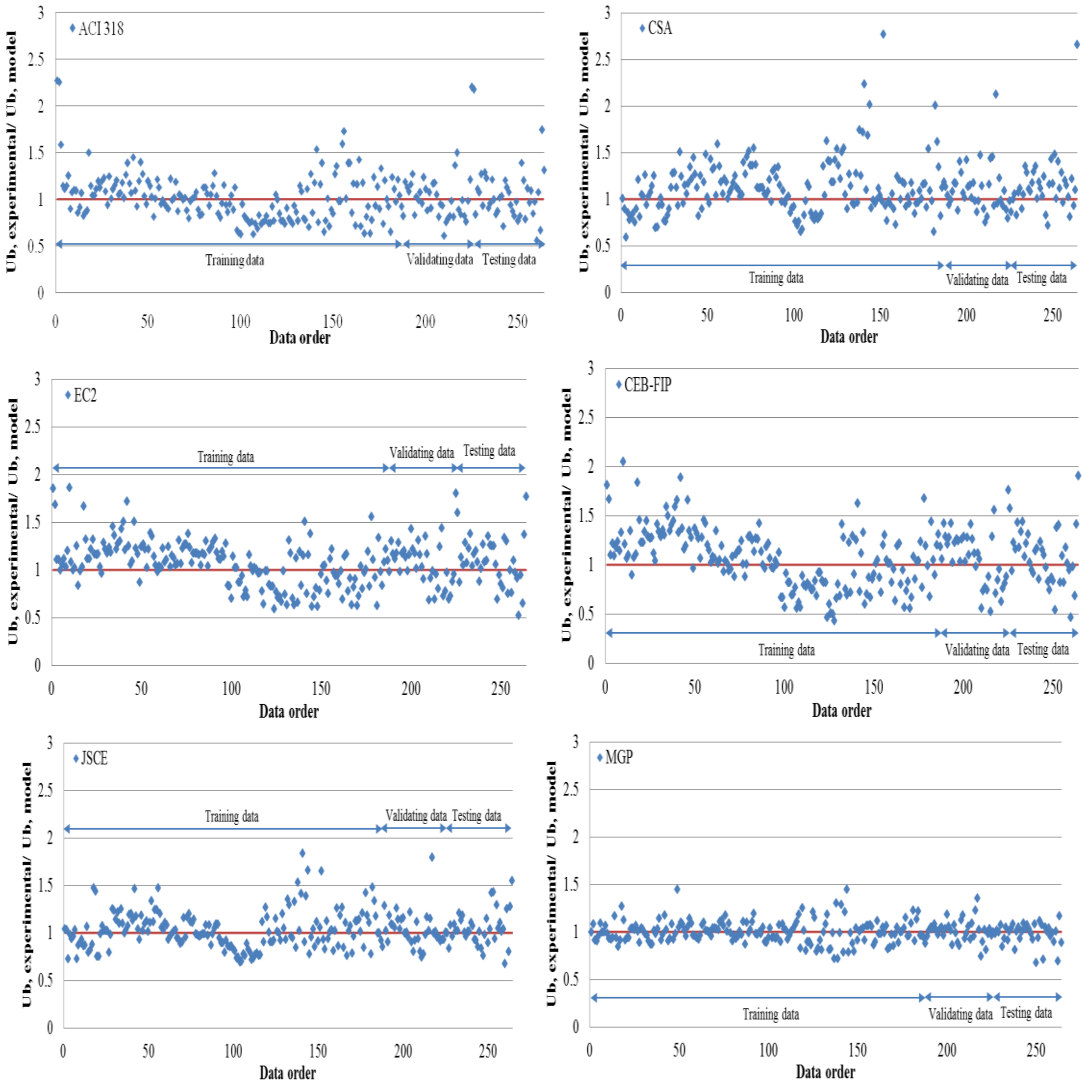

Fig. 10 Performance of the proposed MGP model and different design equations in calculating bond strength of steel bars in concrete using all data

(SD) for $u_{b,\ \mathrm{experimental}}/u_{b,\ \mathrm{model}}$ and the statistical values of all design equations and the proposed model. It can be seen that the MGP model has the lowest MAPE of 8.76% compared to 15.32% for ACI 318's equation, 17.31% for CSA's equation, 19.03% for EC2's equation, 24.47% for CEB-FIP's equation and 13.70% for JSCE's equation. Also, the average value of the ratios of the experimental bond strengths to the predicted bond strengths is 1.02, 1.12, 1.07, 1.07, 1.03 and almost 1 in ACI 318, CSA, EC2, CEB-FIP, JSCE and the proposed MGP models, respectively. Thus, the proposed MGP model provides the best average ratio of experimentally measured to analytically calculated bond strength ($u_{b,\ \mathrm{experimental}}/u_{b,\ \mathrm{model}}$) value. As shown in Fig. 10 and Table 5, the variations of $u_{b,\ \mathrm{experimental}}/u_{b,\ \mathrm{model}}$ from the expected value for MGP model is lower compared to other design codes' equations. Also, all building code equations averagely underestimate the bond strength of ribbed steel bars in concrete. However, dispersion of results for JSCE's equation is lower compared to other building codes' equations and it provides better results than other traditional models. Moreover, dispersion of results and the error of prediction for CEB-FIP's equation are higher than other building codes' equations.

8. Parametric study

The effectiveness of the proposed model is dependent on the weight of each parameter conducting the phenomena. In this paper, the parametric study was employed to examine the effect of the main input parameters on the bond strength of ribbed steel bars in concrete. This study will be carried out by simply varying one input parameter and keeping the others constant. The bond strength of a set of beams having geometrical and mechanical properties similar to those of beams selected from the database have been also calculated for different amounts of d_b, R_r, $C_{\min}/d_b$, l_s/d_b, f_c, $(A_{tr}.f_{yt})/(s.n.d_b)$ and f_y using the building codes' equations and the proposed MGP model considered herein. Also, the selection of beams from the database are made by a random process among those of experimental data that their values are not at the extremes of the whole range for each parameter and also occur within the band for which there is a high frequency.

Furthermore, taking into account the performance of empirical equations, the parametric study can be useful as a basis for determining the most influential parameters in the problem under study with the purpose of proposing future modifications to the empirical equations. In this regard, the proposed model’s predictions have been compared with theoretical predictions of the different empirical equations.

8.1 Influence of d_b

Fig. 11 shows the effect of ribbed bar diameter on the bond strength for the proposed MGP model and different building codes' equations. It is seen that the bond strength of smaller steel bars is more than bigger ones. Interestingly the proposed MGP model and most design codes do not consider d_b to be a notable influencing parameter on the bond strength of ribbed steel bar in concrete. However, the result of MGP model is consistent with the result provided by Ichinose *et al* (2004).

8.2 Influence of R_r

The influence of surface deformations of ribbed steel bars on the bond strength is presented in Fig. 12. It is observed that the bond strength of ribbed steel bar in concrete is not much influenced

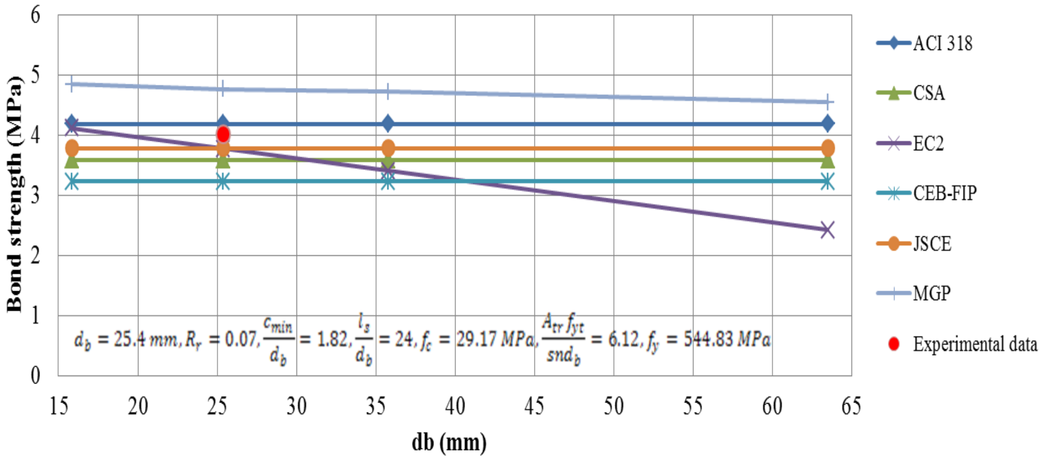

Fig. 11 Effect of the db on the bond strength in the different predictions

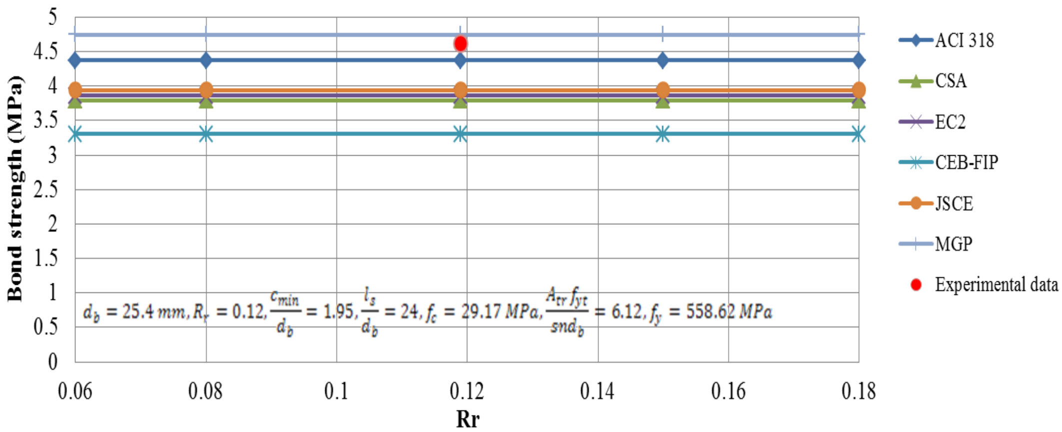

Fig. 12 Effect of the R_r on the bond strength in the different predictions

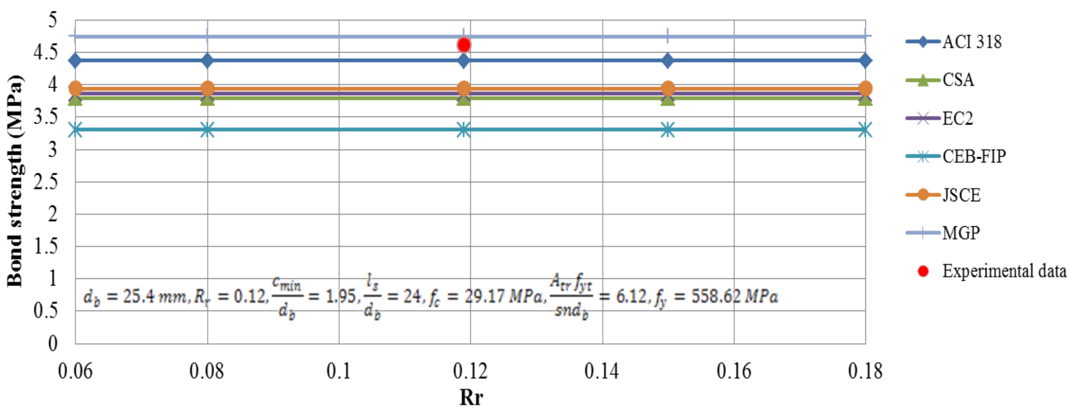

Fig. 13 Effect of the c_{min}/d_b on the bond strength in the different predictions

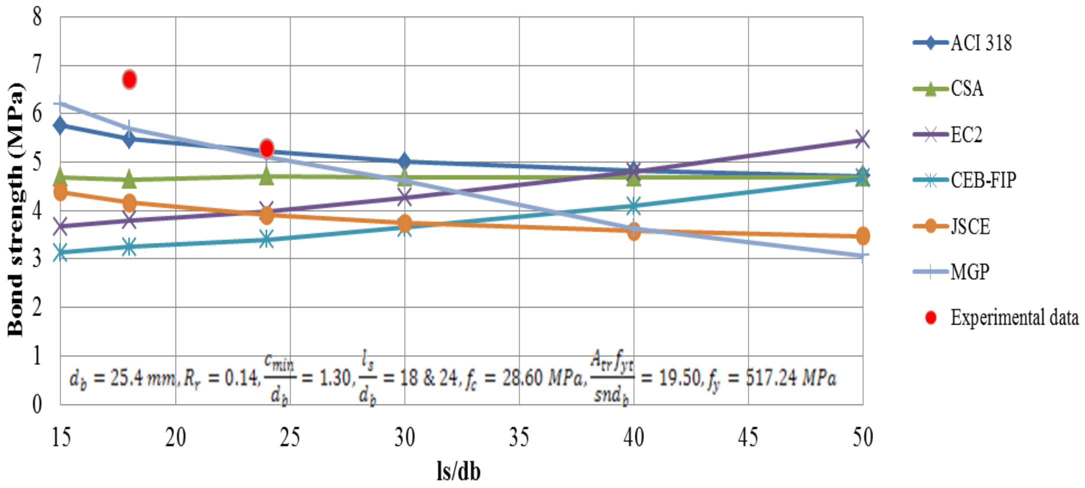

Fig. 14 Effect of the l_s/d_b on the bond strength in the different predictions

by its R_r. However, more experimental works will be needed for accurate assessment of this parameter considering bond failure mechanism.

8.3 Influence of C_{min}/d_b

Fig. 13 shows the influence of C_{min}/d_b ratio on the bond strength of ribbed steel bars in concrete. It is shown that all empirical equations, experimental results and the MGP model consider the effect of C_{min}/d_b, but they vary in the magnitude of such an effect. When increasing C_{min}/d_b ratio, the bond strength of ribbed steel bars and concrete increases, since the confinement of ribbed steel bars in concrete increases.

8.4 Influence of l_s/d_b

Fig. 14 shows the effect of l_s/d_b ratio on the bond strength of ribbed steel bars in concrete. As shown in this figure, the bond strength equations provided by EC2 and CEB-FIP assumes that the bond strength of ribbed steel bars in concrete increases as l_s/d_b increases, whereas ACI318, JSCE and the MGP model predicts the well-known trend of bond strength of ribbed steel bars in concrete, i.e. lower bond strength for higher l_s/d_b ratios and higher bond strength for lower l_s/d_b ratios. The result of the proposed model is compatible with the experimental results.

8.5 Influence of f_c

Fig. 15 shows the variation in bond strength of ribbed steel bars with variable concrete compressive strength. The figure illustrates the effect of f_c as estimated by the proposed model, various empirical bond strength equations considered in this study and the experimental results. It is shown that all design codes' equations consider effect of f_c, but they vary in the magnitude of such an effect. The proposed MGP model and design codes' equations assume that the bond strength of ribbed steel bars in concrete increases with an increase of compressive strength and this relationship is non-linear for all models.

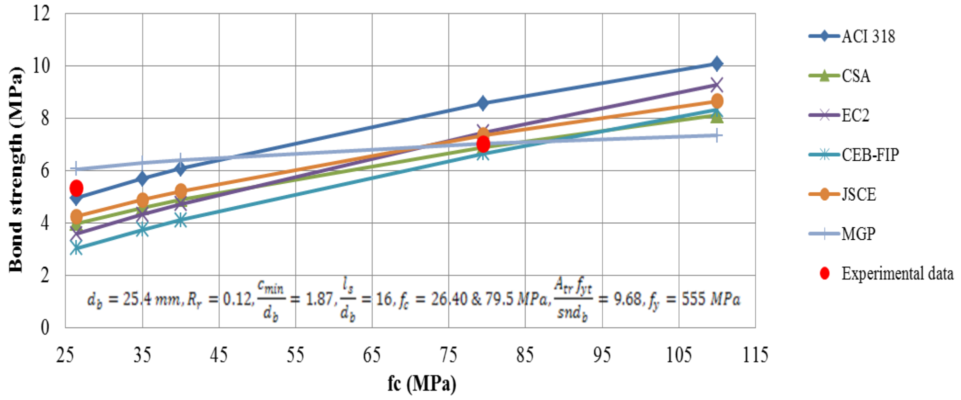

Fig. 15 Effect of the f'_c on the bond strength in the different predictions

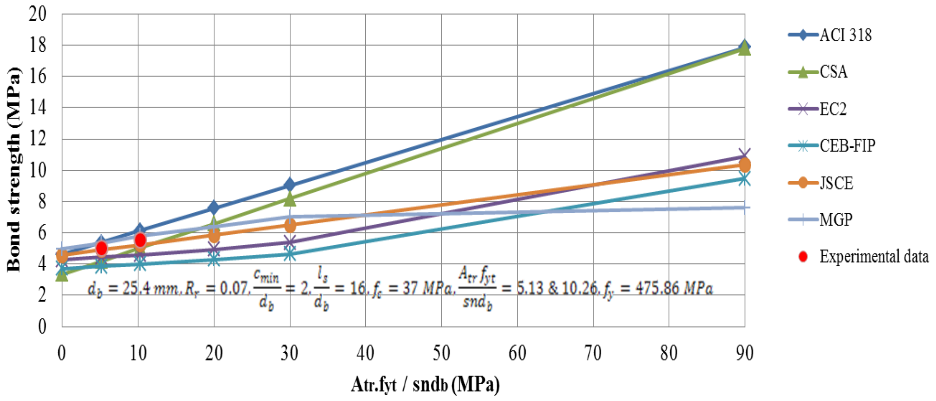

Fig. 16 Effect of the $A_{tr}f_{yt}/\underline{snd_b}$ on the bond strength in the different predictions

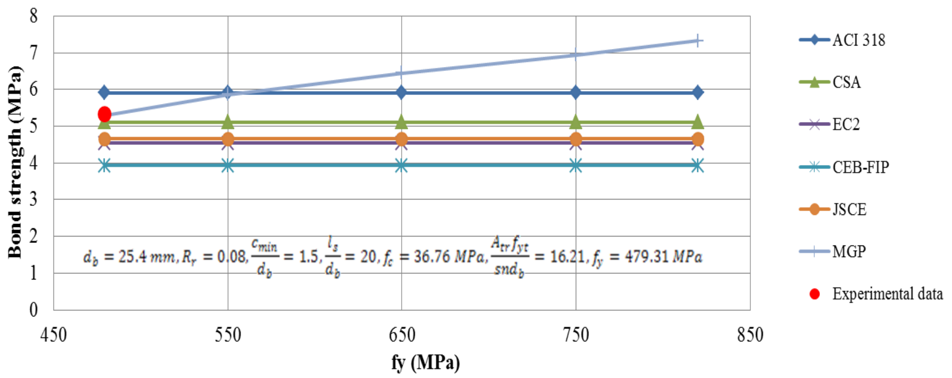

Fig. 17 Effect of the f_y on the bond strength in the different predictions

8.6 Influence of ($A_{tr}.f_{yt}$)/($s.n.d_b$)

The effect of lateral confinement on the bond strength of ribbed steel bars in concrete is shown in Fig. 16. It is obvious that well-confined steel bars with steel stirrups exhibit higher bond strength with concrete than the unconfined steel bars.

8.7 Influence of f_y

Fig.17 shows the relationship between the bond strength of ribbed steel bars and its yield strength in concrete. Although not considered by different design codes' equations, the proposed MGP model have shown that as the yield strengths of ribbed steel bar increases, the bond strength of bar in concrete increases. However, more experimental works will be needed for investigating this condition in future.

It is now proved that the proposed MGP model takes correctly into account the influence of the most different parameters conducting the bond strength of ribbed steel bars in concrete that confirms the potential generalization capability of this model.

9. Conclusion

In this study, multi-gene genetic programming (MGP) method was used for predicting the bond strength of ribbed steel bars in concrete. Statistical values such as MAPE, RMSE and R^2 were applied for comparing experimental results with the results of the proposed model and different design codes' empirical equations. The following conclusions were drawn from this investigation:

- The proposed MGP model is very good for interpolating and it is more accurate and reliable than those obtained from design codes' equations for predicting the bond strength of ribbed steel bars in concrete, especially in cases where it is difficult to model the complex interactions among the multiple variables.
- Compared to all other artificial intelligence methods, the proposed MGP model is so simple that it can be used by anyone not necessarily being familiar with GP. The model also gives a practical way for predicting the bond strength of ribbed steel bars in concrete to obtain accurate results, and encourages use of GP in other aspects of civil engineering studies.
- All considered design codes' equations underestimate averagely the bond strength of ribbed steel bars in concrete. However, comparison between the design codes' equations in terms of statistical values shows that the JSCE equation provides better results than all other empirical equations' results.
- The proposed model was also used to perform parametric studies in modeling physical processes. The results of parametric studies for the proposed model had good agreement with the experimental results and codes' predictions. However, more experimental works will be needed for evaluating some phenomena.

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CC

Appendix A

Table A Experimental data.

No.	d_b	R_r	C_{min}/d_b	l_s/d_b	$(A_{tr}f_{yt}/snd_b)$	f_c	f_y	u_b	ACI 318	CSA	EC2	CEB-FIP	JSCE	MGP
1 Tr	12.70	0.10	3.50	14.00	271.21	29.41	791.03	11.36	5.00	11.26	6.13	6.26	10.92	11.44
2 Tr	12.70	0.10	3.50	21.00	241.08	25.34	791.03	9.34	4.14	10.46	5.55	5.60	9.07	8.60
3 Tr	12.70	0.10	3.50	28.00	226.01	25.59	791.03	6.20	3.91	10.51	5.58	5.64	8.58	6.77
4 Tr	25.40	0.09	1.50	21.00	90.40	29.21	668.97	5.10	4.45	5.99	4.61	4.21	5.19	5.63
5 Tr	25.40	0.09	1.50	28.00	90.40	30.93	668.97	4.79	4.30	6.16	4.79	4.39	5.10	5.03
6 Tr	25.40	0.09	1.50	28.00	90.40	25.52	668.97	4.47	3.91	5.60	4.22	3.81	4.64	4.09
7 Tr	25.40	0.09	1.50	34.00	93.06	25.83	668.97	4.75	3.80	5.63	4.25	3.84	4.60	4.78
8 Tr	25.40	0.09	1.50	14.00	113.00	24.72	668.97	4.13	4.58	5.51	4.02	3.62	5.67	4.13
9 Tr	25.40	0.09	1.50	14.00	113.00	27.97	668.97	5.25	4.87	5.86	4.36	3.96	6.04	4.92
10 Tr	25.40	0.09	1.50	7.00	135.61	27.62	668.97	7.05	6.40	5.82	3.79	3.44	7.86	7.22
11 Tr	25.40	0.09	1.50	21.00	90.40	24.10	668.97	4.40	4.04	5.44	4.06	3.65	4.72	4.72
12 Tr	25.40	0.07	2.00	16.00	6.53	44.48	490.34	5.07	5.90	4.84	5.10	4.76	5.91	5.52
13 Tr	25.40	0.07	2.00	16.00	8.71	44.48	490.34	5.39	5.90	5.23	5.26	4.91	6.21	5.75
14 Tr	25.40	0.08	2.00	16.00	7.33	41.31	440.00	6.05	5.68	4.80	4.85	4.51	5.69	5.20
15 Tr	25.40	0.07	2.00	22.75	6.01	40.34	475.86	4.23	5.13	4.53	5.09	4.73	5.34	4.51
16 Tr	25.40	0.07	2.00	16.00	6.84	37.86	475.86	4.68	5.44	4.52	4.72	4.37	5.73	5.53
17 Tr	25.40	0.07	2.00	16.00	6.53	41.52	490.34	5.01	5.70	4.68	4.87	4.53	5.71	5.48
18 Tr	19.50	0.08	1.30	20.05	19.46	26.80	499.99	6.47	4.31	5.66	3.89	3.52	4.40	5.09
19 Tr	19.50	0.08	1.30	28.77	7.75	27.90	499.99	4.67	4.06	3.73	3.53	3.21	3.25	4.15
20 Tr	15.88	0.08	1.33	16.00	28.04	28.41	448.28	4.92	4.71	7.07	4.41	4.01	6.57	5.40
21 Tr	15.88	0.11	1.33	16.00	28.04	28.41	441.38	4.92	4.71	7.06	4.40	4.01	6.56	5.24

No.	d_b	R_r	C_{min}/d_b	l_s/d_b	$(A_{tr}f_{yt}/snd_b)$	f_c	f_y	u_b	ACI 318	CSA	EC2	CEB-FIP	JSCE	MGP
22 ^{Tr}	15.88	0.08	2.07	16.00	10.45	28.41	448.28	5.24	4.71	5.65	4.31	3.92	5.30	5.61
23 ^{Tr}	15.88	0.11	2.02	16.00	10.45	28.41	441.38	5.63	4.71	5.57	4.28	3.89	5.25	5.44
24 ^{Tr}	15.88	0.11	2.08	19.20	8.71	28.34	441.38	5.03	4.48	5.37	4.32	3.93	4.91	4.84
25 ^{Tr}	15.88	0.08	1.94	19.20	19.59	28.97	448.28	5.41	4.53	7.08	4.68	4.27	5.31	5.28
26 ^{Tr}	15.88	0.11	2.04	19.20	19.59	28.97	441.38	5.55	4.53	7.28	4.77	4.35	5.43	5.21
27 ^{Tr}	25.40	0.10	1.88	16.00	24.40	34.62	413.79	5.66	5.20	6.84	5.50	5.07	7.14	5.65
28 ^{Tr}	25.40	0.07	1.33	24.00	17.68	36.21	482.76	4.51	4.80	5.02	4.69	4.34	4.62	5.08
29 ^{Tr}	25.40	0.14	1.31	24.00	19.89	28.21	517.24	5.28	4.24	4.72	4.11	3.74	4.22	5.10
30 ^{Tr}	25.40	0.10	1.22	24.00	11.05	28.21	413.79	4.28	4.24	3.34	3.52	3.20	3.48	4.19
31 ^{Tr}	25.40	0.14	1.36	24.00	11.79	28.90	517.24	4.76	4.29	3.69	4.06	3.70	4.17	4.87
32 ^{Tr}	25.40	0.14	1.28	24.00	17.68	28.90	517.24	4.95	4.29	4.41	4.01	3.65	4.07	5.15
33 ^{Tr}	25.40	0.14	1.31	22.00	26.61	28.90	517.24	5.27	4.37	5.68	4.45	4.05	4.81	5.86
34 ^{Tr}	25.40	0.14	1.34	16.00	9.18	29.10	517.24	5.00	4.77	3.31	3.44	3.14	4.01	5.74
35 ^{Tr}	25.40	0.14	1.88	16.00	9.18	28.69	517.24	5.07	4.74	4.08	3.72	3.39	4.60	5.83
36 ^{Tr}	25.40	0.10	1.31	18.00	38.94	28.69	413.79	5.40	4.58	5.66	4.43	4.03	5.42	5.31
37 ^{Tr}	25.40	0.10	1.94	16.00	9.18	28.69	413.79	4.81	4.74	4.17	3.76	3.43	4.67	4.89
38 ^{Tr}	25.40	0.07	0.95	24.00	29.21	26.41	544.83	5.18	4.10	4.91	3.99	3.59	4.82	5.03
39 ^{Tr}	25.40	0.12	0.93	24.00	29.21	26.41	558.62	5.70	4.10	4.88	3.99	3.57	4.79	4.98
40 ^{Tr}	25.40	0.12	1.91	16.00	9.18	26.41	558.62	5.32	4.55	3.96	3.54	3.21	4.45	5.83
41 ^{Tr}	25.40	0.12	1.95	24.00	6.12	29.17	558.62	4.61	4.31	3.79	3.82	3.48	4.08	4.75

No.	d_b	R_r	C_{min}/d_b	l_s/d_b	$(A_{tr}f_{yt}/snd_b)$	f_c	f_y	u_b	ACI 318	CSA	EC2	CEB-FIP	JSCE	MGP
42 [Tr]	25.40	0.14	1.29	18.00	19.04	29.17	517.24	6.71	4.62	4.64	3.90	3.55	4.59	5.69
43 [Tr]	25.40	0.14	1.92	24.00	6.12	29.17	517.24	4.73	4.31	3.74	3.79	3.46	4.03	4.62
44 [Tr]	25.40	0.07	1.80	26.00	5.65	29.31	544.83	3.94	4.25	3.50	3.73	3.40	3.80	4.35
45 [Tr]	25.40	0.07	1.92	20.00	35.05	29.31	544.83	5.40	4.51	6.62	4.96	4.52	5.84	5.81
46 [Tr]	25.40	0.14	0.95	18.00	30.29	30.21	517.24	6.56	4.70	5.26	4.36	3.96	5.53	6.08
47 [Tr]	25.40	0.07	1.88	18.00	32.45	30.21	544.83	5.99	4.70	6.67	4.89	4.47	5.84	6.51
48 [Tr]	25.40	0.14	1.93	24.00	6.12	30.21	517.24	4.54	4.39	3.82	3.89	3.55	4.12	4.64
49 [Tr]	25.40	0.10	0.98	36.00	3.63	28.97	413.79	2.93	3.09	1.98	3.36	3.05	2.60	2.02
50 [Tr]	25.40	0.10	0.97	21.00	29.67	28.97	413.79	5.27	4.43	5.17	4.24	3.85	5.22	5.03
51 [Tr]	35.81	0.07	1.14	19.15	30.69	36.21	441.38	5.79	5.06	6.07	4.56	4.38	5.23	5.28
52 [Tr]	35.81	0.13	1.11	28.37	9.55	36.21	558.62	4.80	4.69	3.36	3.94	3.78	3.59	4.42
53 [Tr]	35.81	0.07	1.31	28.37	4.34	35.72	482.76	3.76	4.61	2.85	3.66	3.52	3.38	3.70
54 [Tr]	35.81	0.13	1.34	26.95	8.23	32.48	558.62	4.48	4.44	3.35	3.68	3.51	3.62	4.69
55 [Tr]	35.81	0.13	1.36	21.28	22.10	32.48	558.62	5.68	4.67	5.46	4.10	3.92	4.57	5.39
56 [Tr]	35.81	0.13	1.05	28.37	9.55	32.41	558.62	4.92	4.36	3.09	3.63	3.46	3.33	4.30
57 [Tr]	35.81	0.07	1.33	28.37	6.08	32.41	482.76	4.05	4.27	3.00	3.55	3.39	3.38	3.72
58 [Tr]	25.40	0.12	1.90	30.00	4.35	29.31	555.66	4.11	4.13	3.47	3.91	3.57	3.89	4.25
59 [Tr]	35.81	0.13	1.30	28.37	12.43	35.03	536.34	4.32	4.57	4.08	4.42	4.24	4.19	4.53
60 [Tr]	35.81	0.13	1.29	28.37	8.29	35.03	536.34	4.16	4.57	3.41	4.01	3.85	3.77	4.46
61 [Tr]	35.81	0.13	1.32	28.37	8.29	35.03	536.34	4.11	4.57	3.47	4.03	3.87	3.81	4.46

No.	d_b	R_r	C_{min}/d_b	l_s/d_b	$(A_{tr}f_{yt}/snd_b)$	f_c	f_y	u_b	ACI 318	CSA	EC2	CEB-FIP	JSCE	MGP
62 ^{Tr}	25.40	0.12	0.98	24.00	26.18	29.86	555.66	5.31	4.36	5.26	4.33	3.95	5.71	5.50
63 ^{Tr}	25.40	0.12	1.93	21.00	8.58	62.62	555.66	6.48	6.51	6.02	5.99	6.37	6.75	6.01
64 ^{Tr}	25.40	0.12	1.90	21.00	8.58	62.62	555.66	6.61	6.51	5.96	5.96	6.34	6.70	6.01
65 ^{Tr}	25.40	0.12	1.21	17.50	20.47	57.72	555.66	7.79	6.55	6.65	6.28	6.54	7.66	7.69
66 ^{Tr}	25.40	0.12	0.98	22.50	11.21	74.55	545.31	6.13	6.99	4.91	5.93	6.60	5.93	6.10
67 ^{Tr}	25.40	0.12	0.96	17.50	20.47	74.55	545.31	7.80	7.44	6.96	6.79	7.53	8.23	7.86
68 ^{Tr}	25.40	0.07	0.96	17.50	20.47	74.55	537.66	7.61	7.44	6.95	6.79	7.52	8.22	7.99
69 ^{Tr}	25.40	0.12	1.43	18.00	16.58	74.55	545.31	7.38	7.39	7.19	7.06	7.87	8.32	7.08
70 ^{Tr}	25.40	0.07	1.43	18.00	16.58	74.55	537.66	7.51	7.39	7.20	7.06	7.88	8.33	7.21
71 ^{Tr}	35.81	0.13	1.04	17.73	9.20	86.97	536.34	6.93	7.86	4.96	5.29	6.40	5.99	6.74
72 ^{Tr}	35.81	0.13	1.35	19.86	4.56	86.97	536.34	5.82	7.29	4.60	5.46	6.61	6.11	5.71
73 ^{Tr}	25.40	0.12	0.99	20.00	10.81	73.24	545.31	6.98	7.12	4.79	5.69	6.31	6.00	6.32
74 ^{Tr}	25.40	0.07	0.98	20.00	10.81	73.24	537.66	7.21	7.12	4.77	5.69	6.30	5.99	6.43
75 ^{Tr}	25.40	0.12	0.98	18.00	14.01	73.24	545.31	7.49	7.32	5.50	5.89	6.52	6.71	7.03
76 ^{Tr}	25.40	0.12	1.46	16.00	11.26	73.24	545.31	8.17	7.57	6.01	5.92	6.57	7.35	6.93
77 ^{Tr}	35.81	0.13	0.99	17.73	6.13	91.17	536.34	6.42	7.20	4.16	5.19	6.37	5.63	6.39
78 ^{Tr}	35.81	0.13	1.34	19.86	2.74	91.17	536.34	5.81	7.02	4.23	5.39	6.62	5.89	5.31
79 ^{Tr}	25.40	0.07	1.44	16.00	10.13	88.90	537.66	7.03	8.34	6.28	5.98	7.02	7.20	7.09
80 ^{Tr}	25.40	0.12	0.93	18.00	23.22	36.97	545.31	5.87	5.20	5.28	4.99	4.57	6.08	6.50
81 ^{Tr}	25.40	0.09	0.89	18.00	23.22	36.97	479.31	5.88	5.20	5.23	4.99	4.55	6.04	6.11

No.	d_b	R_r	C_{min}/d_b	l_s/d_b	$(A_{tr}f_{yt}/snd_b)$	f_c	f_y	u_b	ACI 318	CSA	EC2	CEB-FIP	JSCE	MGP
82 ^{Tr}	25.40	0.12	1.97	18.00	10.01	36.97	545.31	5.52	5.20	4.92	4.77	4.42	5.58	5.92
83 ^{Tr}	25.40	0.09	1.89	22.00	7.37	36.07	479.31	4.54	4.89	4.31	4.35	4.02	4.58	4.74
84 ^{Tr}	25.40	0.09	1.50	20.00	16.22	36.76	479.31	5.32	5.05	5.11	4.54	4.20	4.92	5.28
85 ^{Tr}	25.40	0.12	0.98	21.00	22.74	34.90	545.31	5.56	4.86	5.15	4.81	4.42	5.75	5.74
86 ^{Tr}	25.40	0.14	0.98	21.00	22.74	33.10	520.14	6.06	4.73	5.02	4.64	4.25	5.60	5.49
87 ^{Tr}	25.40	0.12	0.98	21.00	22.74	35.03	545.31	5.02	4.87	5.16	4.82	4.43	5.76	5.75
88 ^{Tr}	25.40	0.10	1.02	16.00	11.26	99.66	466.83	7.52	8.83	5.77	6.24	7.57	7.60	6.83
89 ^{Tr}	35.81	0.13	1.04	16.31	8.33	107.93	536.34	7.04	8.75	5.29	5.66	7.32	6.74	7.10
90 ^{Tr}	25.40	0.12	1.52	16.00	10.13	70.21	555.66	7.13	7.41	5.77	5.51	6.04	6.55	6.99
91 ^{Tr}	25.40	0.12	0.96	16.00	18.66	70.21	555.66	8.55	7.41	6.35	6.44	7.03	7.82	7.71
92 ^{Tr}	25.40	0.09	1.98	16.00	6.76	72.41	479.31	7.11	7.53	6.18	6.03	6.67	7.49	5.98
93 ^{Tr}	25.40	0.07	1.86	16.00	10.13	82.28	537.66	6.93	8.02	7.11	6.22	7.14	7.76	7.07
94 ^{Tr}	25.40	0.07	1.00	16.00	18.66	82.28	537.66	7.62	8.02	6.97	6.88	7.89	8.54	7.84
95 ^{Tr}	25.40	0.07	1.00	16.00	28.05	82.28	537.66	8.40	8.02	8.79	7.07	8.10	10.58	8.44
96 ^{Tr}	25.40	0.12	1.84	16.00	10.13	79.52	555.66	7.00	7.89	6.94	6.12	6.95	7.59	7.16
97 ^{Tr}	25.40	0.12	1.00	16.00	28.05	79.52	555.66	8.91	7.89	8.64	6.97	7.92	10.40	8.50
98 ^{Tr}	25.40	0.07	1.00	25.00	13.07	110.37	499.31	5.57	8.31	6.53	6.68	8.37	6.55	6.22
99 ^{Tr}	25.40	0.07	1.00	25.00	10.89	108.37	499.31	5.33	8.23	5.87	6.42	8.00	6.19	6.02
100 ^{Tr}	25.40	0.07	1.00	32.00	6.81	108.26	499.31	4.36	6.96	4.75	6.21	7.74	5.29	4.65
101 ^{Tr}	25.40	0.07	2.00	15.00	21.79	108.37	499.31	8.90	9.39	11.75	7.81	9.73	10.97	8.57

No.	d_b	R_r	C_{min}/d_b	l_s/d_b	$(A_{tr}f_{yt}/snd_b)$	f_c	f_y	u_b	ACI 318	CSA	EC2	CEB-FIP	JSCE	MGP
102 ^{Tr}	25.40	0.07	2.00	15.00	18.16	108.37	499.31	7.73	9.39	10.75	7.55	9.41	10.47	8.25
103 ^{Tr}	25.40	0.07	2.00	15.00	14.53	108.37	499.31	7.45	9.39	9.75	7.31	9.11	9.97	7.90
104 ^{Tr}	25.40	0.07	2.00	19.00	17.20	109.54	497.59	6.82	8.83	10.55	7.84	9.80	9.86	7.36
105 ^{Tr}	25.40	0.07	2.00	19.00	14.33	109.54	497.59	6.60	8.83	9.75	7.58	9.48	9.46	7.00
106 ^{Tr}	25.40	0.07	2.00	19.00	8.60	100.54	491.03	6.46	8.46	7.83	6.89	8.39	8.31	6.03
107 ^{Tr}	35.81	0.06	0.98	28.37	5.79	108.69	488.28	4.30	6.83	4.41	5.99	7.74	5.66	4.79
108 ^{Tr}	35.81	0.06	0.98	31.91	4.01	102.41	488.28	4.44	6.03	3.80	5.68	7.20	4.99	4.12
109 ^{Tr}	35.81	0.06	0.98	31.91	2.86	102.69	488.28	3.96	5.76	3.50	5.51	7.00	4.77	3.85
110 ^{Tr}	35.81	0.09	2.13	14.18	11.59	110.37	492.76	8.01	9.64	9.40	6.92	9.02	10.09	7.90
111 ^{Tr}	35.81	0.09	2.13	14.18	9.66	110.37	492.76	7.08	9.64	8.87	6.82	8.88	9.83	7.68
112 ^{Tr}	35.81	0.09	2.13	17.02	9.66	100.54	492.76	6.58	8.71	8.46	6.68	8.46	8.95	6.81
113 ^{Tr}	35.81	0.09	2.13	17.02	8.05	100.54	492.76	6.72	8.71	8.04	6.58	8.33	8.74	6.66
114 ^{Tr}	35.81	0.09	2.13	19.86	11.04	106.32	517.24	7.09	8.60	9.08	7.04	9.07	9.07	6.88
115 ^{Tr}	35.81	0.09	2.13	19.86	6.90	108.26	492.76	6.50	8.68	8.02	6.77	8.77	8.59	6.07
116 ^{Tr}	35.81	0.09	2.13	19.86	5.52	108.26	492.76	6.45	8.68	7.64	6.67	8.64	8.40	5.84
117 ^{Tr}	28.58	0.18	1.28	56.89	0.00	43.45	754.99	3.15	3.41	2.34	4.06	3.79	2.84	2.67
118 ^{Tr}	28.58	0.18	1.28	49.78	4.33	43.45	754.56	3.22	4.17	3.09	5.06	4.71	3.57	3.89
119 ^{Tr}	28.58	0.18	1.28	40.89	0.00	64.83	751.11	4.64	4.40	2.85	4.68	5.02	3.67	3.70
120 ^{Tr}	28.58	0.18	1.28	35.56	4.72	64.83	757.27	5.43	5.44	3.86	5.52	5.92	4.67	5.34
121 ^{Tr}	28.58	0.18	1.28	28.44	0.00	51.45	753.51	3.58	4.24	2.54	4.22	4.27	3.54	4.48

No.	d_b	R_r	C_{min}/d_b	l_s/d_b	$(A_{tr}f_{yt}/snd_b)$	f_c	f_y	u_b	ACI 318	CSA	EC2	CEB-FIP	JSCE	MGP
122 ^{Tr}	28.58	0.18	1.28	26.67	3.60	51.45	753.51	3.81	4.93	3.22	4.61	4.67	4.22	4.27
123 ^{Tr}	28.58	0.18	1.28	26.67	3.60	51.45	753.51	3.81	4.93	3.22	4.61	4.67	4.22	4.27
124 ^{Tr}	63.50	0.16	0.60	94.00	0.00	41.38	733.86	1.52	2.05	1.07	2.58	3.31	1.65	1.78
125 ^{Tr}	63.50	0.16	0.60	82.80	2.08	41.38	731.45	2.19	2.41	1.42	2.83	3.63	1.90	1.80
126 ^{Tr}	63.50	0.16	0.60	82.80	2.08	53.10	731.45	2.19	2.74	1.61	3.08	4.33	2.15	1.90
127 ^{Tr}	63.50	0.16	0.60	74.00	3.94	57.93	737.93	2.49	3.24	2.05	3.49	5.01	2.51	3.13
128 ^{Tr}	63.50	0.16	0.60	66.40	0.00	77.93	732.76	2.21	2.98	1.47	3.31	5.16	2.41	2.66
129 ^{Tr}	63.50	0.16	0.60	52.40	4.04	69.66	737.93	3.52	3.77	2.28	3.57	5.38	2.93	3.87
130 ^{Tr}	15.88	0.08	1.20	52.80	0.00	35.86	827.59	2.61	3.02	2.49	3.53	3.26	2.50	3.21
131 ^{Tr}	15.88	0.08	1.20	70.40	0.00	35.86	827.59	2.23	2.90	2.49	3.53	3.26	2.40	2.24
132 ^{Tr}	15.88	0.08	2.00	28.80	0.00	35.86	827.59	5.27	4.61	4.15	4.03	3.72	3.89	4.86
133 ^{Tr}	15.88	0.08	2.00	40.00	0.00	35.86	827.59	4.74	4.36	4.15	4.03	3.72	3.68	4.02
134 ^{Tr}	15.88	0.08	1.28	51.20	0.00	37.86	827.59	2.59	3.24	2.73	3.71	3.43	2.69	3.18
135 ^{Tr}	15.88	0.08	1.12	68.80	0.00	32.21	827.59	2.05	2.64	2.20	3.25	2.98	2.18	2.50
136 ^{Tr}	15.88	0.08	1.57	40.00	0.00	32.21	827.59	3.92	3.52	3.08	3.49	3.20	2.95	3.97
137 ^{Tr}	25.40	0.08	1.50	62.00	0.00	32.41	827.59	2.28	3.23	2.36	3.46	3.18	2.69	3.17
138 ^{Tr}	25.40	0.08	1.50	62.00	0.00	32.41	827.59	4.12	3.23	2.36	3.46	3.18	2.69	3.17
139 ^{Tr}	25.40	0.08	1.50	40.00	0.00	35.86	827.59	3.10	3.62	2.49	3.70	3.42	3.02	4.32
140 ^{Tr}	25.40	0.08	1.50	40.00	0.00	35.86	827.59	4.27	3.62	2.49	3.70	3.42	3.02	4.32
141 ^{Tr}	25.40	0.08	1.50	40.00	0.00	35.86	827.59	5.56	3.62	2.49	3.70	3.42	3.02	4.32

No.	d_b	R_r	C_{min}/d_b	l_s/d_b	$(A_{tr}f_{yt}/snd_b)$	f_c	f_y	u_b	ACI 318	CSA	EC2	CEB-FIP	JSCE	MGP
142 Tr	25.40	0.08	1.50	40.00	0.00	57.24	827.59	3.45	4.57	3.14	4.59	4.77	3.82	4.37
143 Tr	25.40	0.08	1.50	40.00	0.00	57.24	827.59	5.30	4.57	3.14	4.59	4.77	3.82	4.37
144 Tr	25.40	0.08	1.50	40.00	0.00	57.24	827.59	6.34	4.57	3.14	4.59	4.77	3.82	4.37
145 Tr	25.40	0.08	1.50	54.00	0.00	53.79	827.59	2.75	4.23	3.05	4.46	4.56	3.53	3.50
146 Tr	25.40	0.08	1.50	54.00	4.60	53.79	827.59	3.90	5.05	3.94	5.43	5.56	4.06	3.96
147 Tr	25.40	0.08	1.40	47.00	14.07	41.72	827.59	4.66	4.61	4.90	5.76	5.36	4.47	5.29
148 Tr	25.40	0.08	1.41	63.00	0.00	40.97	827.59	2.46	3.48	2.50	3.99	3.71	2.89	3.09
149 Tr	25.40	0.08	1.50	63.00	5.25	32.55	827.59	3.53	3.95	3.16	4.51	4.14	3.17	3.40
150 Tr	25.40	0.08	2.30	27.00	0.00	59.72	827.59	5.11	6.02	4.92	5.37	5.64	5.59	5.62
151 Tr	25.40	0.08	2.17	27.00	15.38	55.10	827.59	7.34	5.78	7.47	7.04	7.25	6.96	7.33
152 Tr	25.40	0.08	0.77	36.00	0.00	55.10	827.59	4.36	3.21	1.58	4.17	4.15	2.64	4.26
153 Tr	25.40	0.08	2.39	36.00	4.60	53.72	827.59	5.32	5.43	5.74	5.97	6.11	5.73	5.11
154 Tr	25.40	0.08	2.31	36.00	11.41	59.72	827.59	5.60	5.72	7.27	7.46	7.84	6.74	6.14
155 Tr	25.40	0.08	2.50	31.00	20.69	41.52	827.59	7.79	4.89	7.98	6.96	6.48	6.94	7.32
156 Tr	25.40	0.08	2.50	31.00	41.38	41.52	827.59	8.45	4.89	8.92	6.96	6.48	9.04	7.92
157 Tr	25.40	0.08	2.50	41.00	0.00	40.14	827.59	4.63	4.60	4.39	4.76	4.43	4.57	4.31
158 Tr	25.40	0.08	2.50	41.00	16.55	40.14	827.59	6.39	4.60	7.15	6.81	6.32	6.22	6.04
159 Tr	25.40	0.08	2.50	41.00	33.10	40.14	827.59	6.39	4.60	8.77	6.81	6.32	7.88	7.39
160 Tr	25.40	0.08	1.50	40.00	0.00	57.93	827.59	3.92	4.60	3.16	4.61	4.81	3.84	4.38
161 Tr	25.40	0.08	1.50	40.00	11.03	57.93	827.59	6.51	5.55	5.38	6.57	6.84	5.17	5.82

No.	d_b	R_r	C_{min}/d_b	l_s/d_b	$(A_{tr}f_{yt}/snd_b)$	f_c	f_y	u_b	ACI 318	CSA	EC2	CEB-FIP	JSCE	MGP
162 ^{Tr}	25.40	0.08	1.50	54.00	0.00	70.34	827.59	3.48	4.84	3.48	5.01	5.50	4.04	3.56
163 ^{Tr}	35.81	0.08	1.95	35.46	7.05	34.48	827.59	5.06	4.36	4.26	4.43	4.24	4.26	5.15
164 ^{Tr}	35.81	0.08	1.95	35.46	14.08	34.48	827.59	6.22	4.36	5.35	5.35	5.12	4.92	5.95
165 ^{Tr}	35.81	0.08	1.95	47.52	0.00	37.24	827.59	3.05	4.27	3.30	3.94	3.79	3.59	3.08
166 ^{Tr}	35.81	0.08	1.95	47.52	10.52	37.24	827.59	5.12	4.35	4.99	5.63	5.42	4.61	4.79
167 ^{Tr}	35.81	0.08	1.34	41.13	0.00	64.62	827.59	2.85	4.51	2.98	4.53	5.06	3.76	3.48
168 ^{Tr}	35.81	0.08	1.16	41.13	4.05	64.62	827.59	4.02	4.93	3.43	4.91	5.48	3.95	4.82
169 ^{Tr}	35.81	0.08	1.42	41.13	9.03	59.86	827.59	5.20	5.62	4.88	5.76	6.30	4.85	5.37
170 ^{Tr}	35.81	0.08	1.43	56.03	2.97	68.34	827.59	3.29	5.19	3.91	5.25	5.94	4.21	3.85
171 ^{Tr}	35.81	0.08	1.42	56.03	6.71	59.86	827.59	4.22	5.41	4.41	5.78	6.32	4.39	4.34
172 ^{Tr}	35.81	0.08	1.42	48.94	19.56	36.83	827.59	5.32	4.31	5.52	5.11	4.91	4.73	5.07
173 ^{Tr}	35.81	0.08	1.42	64.54	7.34	28.00	827.59	3.39	3.65	3.10	4.21	3.98	3.01	3.82
174 ^{Tr}	35.81	0.08	1.42	64.54	14.67	28.00	827.59	4.14	3.65	4.13	4.26	4.02	3.62	4.15
175 ^{Tr}	35.81	0.08	2.13	30.50	0.00	41.86	827.59	4.41	4.92	3.81	4.40	4.25	4.34	4.39
176 ^{Tr}	35.81	0.08	2.13	30.50	10.67	41.86	827.59	6.56	4.92	5.63	5.50	5.32	5.43	6.30
177 ^{Tr}	35.81	0.08	2.13	40.43	0.00	57.79	827.59	4.09	5.53	4.48	4.93	5.34	4.87	3.57
178 ^{Tr}	19.05	0.11	1.99	16.00	0.00	40.01	827.59	6.73	5.59	4.37	4.33	4.02	4.74	7.05
179 ^{Tr}	19.05	0.11	1.99	32.00	0.00	39.41	827.59	4.73	4.73	4.33	4.29	3.98	3.99	4.91
180 ^{Tr}	19.05	0.11	1.84	48.00	0.00	44.01	827.59	4.13	4.45	4.22	4.49	4.19	3.74	3.78
181 ^{Tr}	19.05	0.11	1.84	80.00	0.00	39.41	827.59	2.60	3.99	3.99	4.17	3.87	3.35	2.12

No.	d_b	R_r	C_{min}/d_b	l_s/d_b	$(A_{tr}f_{yt}/snd_b)$	f_c	f_y	u_b	ACI 318	CSA	EC2	CEB-FIP	JSCE	MGP
182 [Tr]	25.40	0.08	1.50	24.00	0.15	39.41	827.59	5.26	4.24	2.63	3.94	3.66	3.55	5.79
183 [Tr]	25.40	0.08	1.38	47.00	0.19	47.41	827.59	4.29	3.87	2.66	4.37	4.09	3.21	3.80
184 [Tr]	25.40	0.08	1.38	72.00	0.17	41.01	827.59	3.32	3.40	2.47	3.97	3.69	2.81	2.72
185 [Va]	25.40	0.09	1.50	34.00	93.06	25.97	668.97	4.62	3.81	5.64	4.27	3.86	4.62	4.80
186 [Va]	25.40	0.07	2.00	16.00	10.26	36.14	475.86	5.56	5.32	4.96	4.58	4.23	5.59	5.78
187 [Va]	25.40	0.07	2.00	16.00	5.13	37.86	475.86	5.02	5.44	4.24	4.58	4.24	5.45	5.36
188 [Va]	25.40	0.07	1.83	16.00	5.13	42.76	475.86	4.74	5.78	4.20	4.82	4.49	5.55	5.39
189 [Va]	19.50	0.08	1.30	23.64	14.15	29.50	499.99	5.16	4.35	4.98	3.97	3.63	4.03	5.43
190 [Va]	15.88	0.08	2.10	19.20	8.71	28.34	448.28	5.06	4.48	5.41	4.33	3.94	4.94	4.98
191 [Va]	25.40	0.10	1.94	16.00	16.26	34.62	413.79	5.64	5.20	5.68	5.06	4.66	6.26	5.39
192 [Va]	25.40	0.14	1.41	24.00	17.68	36.21	517.24	5.59	4.80	5.15	4.75	4.39	4.72	5.43
193 [Va]	25.40	0.14	0.94	24.00	22.90	29.10	517.24	5.47	4.30	4.66	4.26	3.85	5.04	5.06
194 [Va]	35.81	0.07	1.08	28.37	9.55	36.21	441.38	3.85	4.64	3.31	3.92	3.76	3.55	3.76
195 [Va]	35.81	0.07	1.35	21.28	22.10	32.48	482.76	4.81	4.67	5.46	4.10	3.91	4.56	4.94
196 [Va]	35.81	0.13	1.36	28.37	6.08	32.41	558.62	4.29	4.31	3.05	3.57	3.40	3.42	4.15
197 [Va]	25.40	0.12	1.90	30.00	4.35	29.31	555.66	4.44	4.13	3.47	3.91	3.57	3.89	4.25
198 [Va]	35.81	0.13	1.31	28.37	12.43	35.03	536.34	4.36	4.57	4.09	4.43	4.24	4.20	4.53
199 [Va]	25.40	0.12	1.42	25.00	21.49	29.86	555.66	5.33	4.32	5.25	4.62	4.22	4.68	5.16
200 [Va]	25.40	0.07	1.41	16.00	11.26	73.24	537.66	8.38	7.57	5.89	5.87	6.51	7.26	7.09
201 [Va]	25.40	0.12	1.52	16.00	10.13	88.90	545.31	7.35	8.34	6.49	6.06	7.11	7.37	6.94

No.	d_b	R_r	C_{min}/d_b	l_s/d_b	$(A_{tr}f_{yt}/snd_b)$	f_c	f_y	u_b	ACI 318	CSA	EC2	CEB-FIP	JSCE	MGP
202 [Va]	25.40	0.09	1.94	18.00	10.01	36.97	479.31	5.59	5.20	4.86	4.75	4.39	5.54	5.52
203 [Va]	25.40	0.12	1.93	22.00	7.37	36.07	545.31	4.42	4.89	4.37	4.38	4.04	4.63	5.12
204 [Va]	25.40	0.14	1.45	20.00	16.22	36.76	520.14	5.90	5.05	5.03	4.51	4.17	4.86	5.49
205 [Va]	25.40	0.12	0.98	24.00	26.18	34.90	545.31	5.56	4.71	5.69	4.81	4.42	6.17	5.60
206 [Va]	25.40	0.12	1.00	24.00	26.18	35.03	545.31	4.95	4.72	5.73	4.82	4.44	6.20	5.61
207 [Va]	25.40	0.12	1.75	26.00	6.24	35.03	545.31	3.77	4.64	3.85	4.17	3.84	4.10	4.44
208 [Va]	25.40	0.07	0.99	16.00	11.26	99.66	537.66	8.40	8.83	5.70	6.22	7.54	7.54	7.50
209 [Va]	25.40	0.09	1.98	16.00	6.76	72.41	479.31	7.05	7.53	6.19	6.03	6.67	7.51	5.98
210 [Va]	25.40	0.07	1.00	32.00	6.81	100.54	491.03	4.11	6.71	4.58	6.04	7.36	5.10	4.41
211 [Va]	25.40	0.07	2.00	19.00	11.47	108.26	499.31	6.65	8.78	8.91	7.31	9.11	9.01	6.81
212 [Va]	35.81	0.09	2.13	19.86	8.28	106.32	517.24	6.76	8.60	8.33	6.83	8.79	8.70	6.41
213 [Va]	28.58	0.18	1.28	53.33	1.80	43.45	753.07	3.07	3.73	2.65	4.44	4.14	3.14	3.34
214 [Va]	28.58	0.18	1.28	38.22	2.51	69.66	757.27	5.05	5.13	3.51	5.27	5.77	4.35	4.64
215 [Va]	63.50	0.16	0.60	58.40	2.04	76.55	712.14	2.80	3.46	1.92	3.49	5.40	2.73	2.94
216 [Va]	15.88	0.08	3.20	32.00	0.00	39.31	827.59	6.47	4.73	6.95	5.20	5.04	5.63	5.28
217 [Va]	25.40	0.08	1.50	47.00	0.00	34.48	827.59	5.17	3.45	2.44	3.61	3.32	2.89	3.83
218 [Va]	25.40	0.08	1.50	54.00	9.20	53.79	827.59	4.60	5.15	4.83	6.37	6.52	4.60	4.51
219 [Va]	25.40	0.08	1.40	47.00	0.00	36.28	827.59	2.86	3.39	2.34	3.67	3.39	2.83	3.84
220 [Va]	25.40	0.08	2.26	27.00	6.13	53.72	827.59	5.68	5.71	5.77	5.83	5.96	5.95	6.36
221 [Va]	25.40	0.08	1.50	54.00	7.88	70.34	827.59	4.85	5.89	5.23	7.04	7.73	5.08	4.75

No.	d_b	R_r	C_{min}/d_b	l_s/d_b	$(A_{tr}f_{yt}/snd_b)$	f_c	f_y	u_b	ACI 318	CSA	EC2	CEB-FIP	JSCE	MGP
222 [Va]	35.81	0.08	1.42	48.94	0.00	36.83	827.59	2.61	3.43	2.38	3.58	3.44	2.86	3.23
223 [Va]	35.81	0.08	2.13	40.43	8.38	57.79	827.59	5.46	5.53	6.16	6.24	6.76	5.88	5.56
224 [Va]	35.81	0.08	2.13	40.43	19.56	57.79	827.59	6.70	5.53	8.40	7.05	7.63	7.22	6.49
225 [Te]	12.70	0.10	3.50	14.00	271.21	29.03	791.03	10.92	4.96	11.19	6.07	6.20	10.85	11.31
226 [Te]	12.70	0.10	3.50	21.00	241.08	27.97	791.03	9.46	4.35	10.98	5.92	6.03	9.53	9.49
227 [Te]	25.40	0.07	2.00	22.75	4.81	40.34	475.86	4.29	5.13	4.32	4.93	4.58	5.14	4.40
228 [Te]	25.40	0.14	1.97	24.00	11.05	36.21	517.24	5.32	4.80	5.03	4.71	4.35	4.92	5.26
229 [Te]	25.40	0.07	1.25	24.00	28.46	28.21	482.76	4.55	4.24	5.52	4.33	3.94	4.74	4.56
230 [Te]	25.40	0.14	0.90	24.00	29.21	28.69	517.24	5.42	4.27	5.04	4.22	3.78	4.95	5.03
231 [Te]	25.40	0.07	1.82	24.00	6.12	29.17	544.83	4.01	4.31	3.59	3.73	3.40	3.92	4.76
232 [Te]	25.40	0.12	1.94	18.00	32.45	30.21	558.62	6.05	4.70	6.76	4.95	4.52	5.91	6.48
233 [Te]	35.81	0.13	1.07	19.15	30.69	36.21	558.62	6.22	5.06	5.96	4.51	4.34	5.15	5.93
234 [Te]	35.81	0.13	1.27	28.37	4.34	35.72	558.62	3.77	4.15	2.79	3.64	3.50	3.32	4.13
235 [Te]	35.81	0.07	1.32	26.95	8.23	32.48	482.76	4.27	4.44	3.33	3.67	3.50	3.60	4.24
236 [Te]	25.40	0.12	1.08	25.00	21.54	29.86	555.66	5.26	4.32	4.74	4.38	4.00	5.21	5.04
237 [Te]	25.40	0.12	1.93	21.00	8.58	62.62	555.66	6.50	6.51	6.02	5.99	6.37	6.75	6.01
238 [Te]	25.40	0.12	1.16	30.00	8.41	34.18	545.31	3.71	4.42	3.17	4.24	3.91	3.67	4.57
239 [Te]	25.40	0.07	0.98	22.50	10.21	74.55	537.66	6.02	6.91	4.66	5.93	6.60	5.92	5.98
240 [Te]	25.40	0.07	0.99	18.00	14.01	73.24	537.66	7.47	7.32	5.51	5.89	6.53	6.72	7.15
241 [Te]	25.40	0.12	1.45	24.00	15.77	35.03	545.31	4.87	4.72	4.84	4.52	4.17	4.53	5.26

No.	d_b	R_r	C_{min}/d_b	l_s/d_b	$(A_{tr}f_{yt}/snd_b)$	f_c	f_y	u_b	ACI 318	CSA	EC2	CEB-FIP	JSCE	MGP
242 [Te]	35.81	0.07	1.03	16.31	8.33	107.93	452.00	6.22	8.71	5.24	5.64	7.30	6.71	6.19
243 [Te]	25.40	0.12	0.97	16.00	28.05	70.21	555.66	8.95	7.41	8.05	6.62	7.23	9.71	8.22
244 [Te]	25.40	0.07	0.98	16.00	28.05	70.21	537.66	8.33	7.41	8.09	6.62	7.25	9.74	8.08
245 [Te]	25.40	0.12	1.00	16.00	18.66	79.52	555.66	8.49	7.89	6.86	6.78	7.70	8.39	7.91
246 [Te]	35.81	0.09	2.13	14.18	17.38	104.77	517.24	8.87	9.39	10.72	7.11	9.12	10.62	8.58
247 [Te]	35.81	0.09	2.13	17.02	17.71	104.77	517.24	7.77	8.89	10.81	7.35	9.42	10.22	7.96
248 [Te]	28.58	0.18	1.28	53.33	1.80	43.45	753.07	3.07	3.73	2.65	4.44	4.14	3.14	3.34
249 [Te]	28.58	0.18	1.28	38.22	2.51	69.66	757.94	5.01	5.13	3.51	5.27	5.77	4.35	4.62
250 [Te]	28.58	0.18	1.28	24.89	4.82	51.45	754.72	4.02	5.22	3.45	4.73	4.79	4.49	5.97
251 [Te]	63.50	0.16	0.60	58.40	2.04	71.03	728.84	2.75	3.33	1.85	3.38	5.12	2.63	2.93
252 [Te]	15.88	0.08	3.20	24.00	0.00	39.31	827.59	6.97	5.00	6.95	5.20	5.04	4.91	6.23
253 [Te]	15.88	0.08	1.74	28.80	0.00	37.86	827.59	5.21	4.34	3.71	4.00	3.70	3.65	4.85
254 [Te]	25.40	0.08	1.50	47.00	0.00	34.48	827.59	2.71	3.45	2.44	3.61	3.32	2.89	3.83
255 [Te]	25.40	0.08	1.57	47.00	7.04	32.55	827.59	4.55	4.07	3.54	4.56	4.19	3.53	4.33
256 [Te]	25.40	0.08	1.50	63.00	10.50	34.55	827.59	3.91	4.06	4.07	5.16	4.76	3.75	3.90
257 [Te]	25.40	0.08	2.50	31.00	0.00	41.52	827.59	5.34	4.89	4.46	4.87	4.53	4.83	5.12
258 [Te]	35.81	0.08	1.95	35.46	0.00	34.48	827.59	3.65	4.28	3.17	3.74	3.59	3.61	3.82
259 [Te]	35.81	0.08	1.95	47.52	5.25	37.24	827.59	4.25	4.35	4.14	4.66	4.48	4.10	4.31
260 [Te]	35.81	0.08	1.31	56.03	0.00	68.34	827.59	2.43	4.36	3.00	4.62	5.23	3.62	2.70
261 [Te]	35.81	0.08	1.42	48.94	9.03	36.83	827.59	4.65	4.31	3.83	4.92	4.73	3.72	4.62

No.	d_b	R_r	C_{min}/d_b	l_s/d_b	$(A_{tr}f_{yt}/snd_b)$	f_c	f_y	u_b	ACI 318	CSA	EC2	CEB-FIP	JSCE	MGP
262 Te	35.81	0.08	1.42	64.54	0.00	28.00	827.59	1.92	2.88	2.08	2.98	2.82	2.40	2.78
263 Te	35.81	0.08	2.13	30.50	23.48	41.86	827.59	8.59	4.92	7.82	6.28	6.08	6.74	7.35
264 Te	25.40	0.08	1.50	12.00	0.15	40.01	827.59	7.04	5.37	2.65	3.98	3.70	4.54	7.94

Tr: Training data set; Va: Validating data set; Te: Testing data set.