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Shear capacity of reinforced concrete deep beams using genetic algorithm

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Abstract. It is vital to understand the shear behaviour of reinforced concrete (RC) beams in order to avoid a catastrophic shear failure and design for ductile failure. However, due to the complexity in the shear failure mechanism and various parameters influencing the shear behaviour of RC beams, the accuracy in the determination of the shear capacity remains a challenge. In this paper, machine learning and genetic algorithm are utilized to develop an improved shear design equation for RC deep beams without stirrups. The proposed model considers the parameters influencing the shear capacity of beams including concrete compressive strength, cross-sectional dimension of the beams, aspect ratio, and internal reinforcement ratio. The prediction capability of the proposed model has been compared with that of ACI 318 and resulted in a better prediction in terms of safety, accuracy, and economic aspects.

1. Introduction

An extensive research has been carried out to understand the shear behaviour of reinforced concrete (RC) beams. However, due to the complexity in shear failure mechanism and various parameters influencing the shear capacity, its accurate prediction remains a challenge. Several research contributions have been reported on investigating the shear behaviour of RC beams. The modified compression field theory has shown to be an effective and accurate method for predicting the shear capacity of both pristine [1,2] and strengthened beams [3–8]. Recently, Wakjira and Ebead [9] proposed an improved shear design equation for both pristine and fabric reinforced cementitious matrix (FRCM) strengthened slender beams, considering the important parameters.

Beams with the shear span-to-effective depth (a/d) ratio of less than 2.5 are regarded as deep beams according to ACI-ASCE Committee 445 [10]. Several experimental results have been reported on the shear behaviour of RC deep beams [11–14]. The strut and tie model (STM) is generally used for shear capacity determination of RC deep beams and it has been incorporated in international codes and provisions including ACI 318 [15]. The STM is complicated to be used by design practitioners. Thus, the current study deals with investigating the parameters influencing the shear capacity of RC deep beams internally unreinforced with stirrups and proposing an improved and simple shear design equation for such beams based on artificial intelligence and genetic algorithm approaches. The prediction capability of the proposed equation is compared with that of ACI 318.

2. Methodology

2.1. Database

A database of shear-critical RC deep beams that failed in shear prior to flexural failure have been considered in this study [16]. Table 1 presents the statistical characteristics of shear design parameters for the beams considered in this study. As listed in this table, the database contained a wide range of the design parameters. These parameters include compressive strength of concrete ($f_c{}'$), longitudinal reinforcement ratio (ρ_{sx}), yield strength of longitudinal reinforcement (f_{sx}), cross-sectional width of the beam (b_w), effective depth of the beam (d), and shear span-to-depth (a/d) ratio. The scatter plots of the shear capacity versus each parameter is shown in Figures 1a–1f.

Table 1. Statistical characteristics of the test parameters of the beams

Parameters	Deep beams without stirrups (371 beams)			
	Minimum	Maximum	Mean	Coefficient of Variation
a/d	0.2500	2.4900	1.6374	33.92
$f_c{}'$ (MPa)	20.000	103.400	35.166	47.88
b_w (mm)	76.00	500.00	180.46	38.89
d (mm)	132.00	1097.00	361.81	50.86
ρ_{sx} (%)	0.3400	9.2700	2.3680	57.50
f_{sx} (MPa)	267.00	1480.00	470.04	27.01

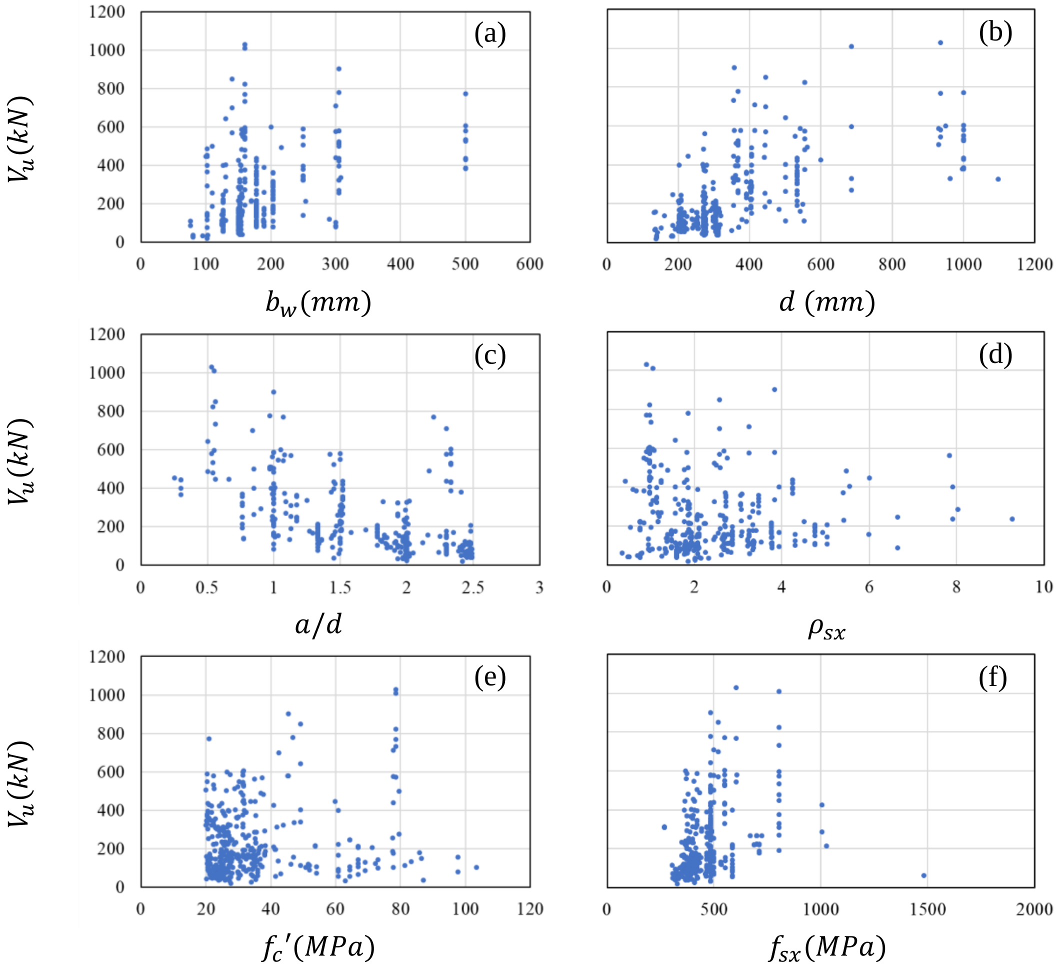


Figure 1. Variation of shear capacity with respect to the design parameters.

2.2. Shear design equation

Machine learning using genetic algorithm (GA) has gained popularity in solving complex nonlinear problems. The GA is a global search procedure for gradually improving the solution in succeeding populations using genetic operators, namely, mutation, selection, and crossover as inspired by Darwin's theory of evolution and the natural law of survival of the fittest [17]. Figure 2 shows the basic steps of the GA.

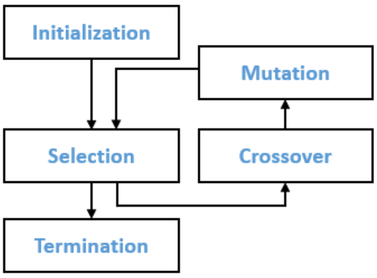


Figure 2. Variation of shear capacity with respect to the design parameters.

Explaining the fundamental basis of GAs is beyond the scope of this paper and details on how to build a genetic algorithm model for optimization can be found elsewhere Goldberg 1989 [18]. In this study, the GA algorithms approach is used herein as an optimization technique to develop equation for the shear capacity of RC deep beams. Thus, an original form of the equation defining the overall shear behaviour with the significant parameters that influence the shear capacity of concrete beams is required [19]. The objective function for the shear capacity of RC beams is defined in terms of the independent variables as follows:

$$V_u = c_1 {f_c}^{c_2} (\rho_{sx} f_{sx})^{c_3} (a/d)^{c_4} b_w d \tag{1}$$

where, c_1, c_2, c_3, and c_4 are the equation unknown coefficients that are to be estimated.

The GA technique is utilized to develop the shear equation based on the database of 371 shear-critical RC deep beams. From the database, 50% was selected randomly and used for training the model, while the remaining 50% was used for validating the model. The result of the GA model is given in equation below.

$$V_{th} = 0.0456 {f_c}^{0.619} {\rho_{sx}}^{0.411} (a/d)^{-0.874} b_w d \tag{2}$$

Figures 3a and 3b show the correlation between the predicted and experimental shear capacities based on the proposed equation and ACI 318, respectively. The exact match between the test results and predicted values for shear capacity is shown using the 45^0 line.

2.3. Assessment of the predictive performance

The prediction of the proposed equation is compared with that of ACI 318-14 [15] in terms of safety, accuracy, and economic aspects based on the modified version of the demerit points classification (DPC) [20] proposed by Collins [21]. In this approach, a penalty is assigned to each value of V_{th}/V_{ex} ratio according to the criteria presented in Table 2 and the total penalty of the model indicates its performance.

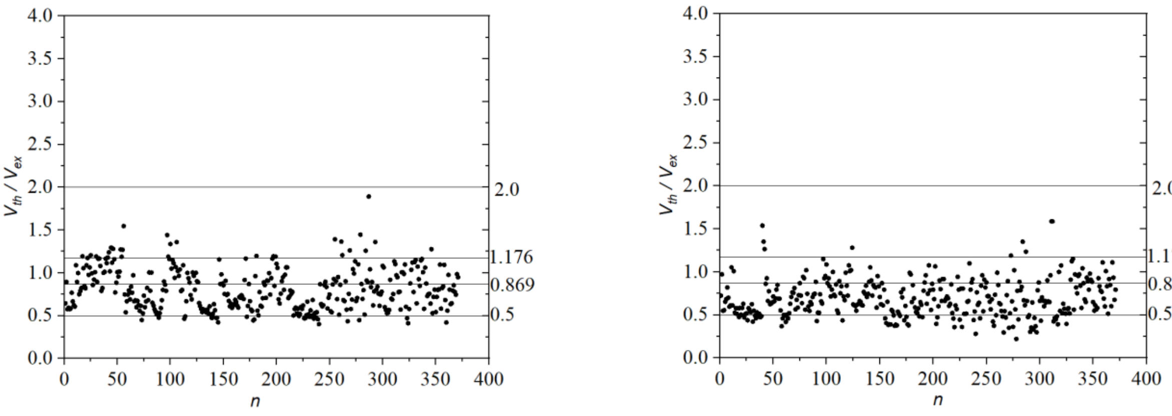
Table 2. Demerit Points Classification [20]

Range	Classification	Penalty
$V_{th}/V_{ex} \geq 2$	Extra dangerous	10
$1.176 \leq V_{th}/V_{ex} < 2$	Dangerous	5
$0.869 \leq V_{th}/V_{ex} < 1.176$	Appropriate safety	0
$0.5 \leq V_{th}/V_{ex} < 0.869$	Conservative	1
$V_{th}/V_{ex} \leq 0.5$	Extra conservative	2

Table 3 as well as Figures 3a and 3b show the predictive performance of the proposed model and ACI 318-14 [15]. As can be seen in this figure, the proposed design equation using the GA model provides better predictions than that of ACI 318 with an average V_{th}/V_{ex} of 0.82 and standard deviation (STD) of 0.25. The ACI 318 provision resulted in a lower average of the V_{th}/V_{ex} ratio of 0.79 and higher STD of 0.27, as listed in Table 3. Moreover, the proposed equation resulted in a lower total penalty of 390 compared to that for the ACI 318, which was 403, as listed in Table 3. Thus, it can be concluded that the proposed equation resulted in a better prediction capability compared to that of ACI 318.

Table 3. Prediction capability of different models based on the modified DPC [20].

Model	Total #	V_{th}/V_{ex}							Total Penalty
		Average	STD	Extra dangerous	Dangerous	Appropriate safety	Conservative	Extra conservative	
Proposed model	371	0.82	0.25	–	27	113	207	24	390
ACI 318-14	371	0.79	0.27	–	9	70	226	66	403



(a) (b)

Figure 3. Prediction capability of the proposed equation (a) and ACI 318 (b) based on the DPC [20].

3. Conclusion

In this paper, an improved shear design equation for RC deep beams is proposed based on genetic algorithm. Total of 371 shear-critical RC deep beams was used in the database. Half of the total database has been used for training the GA model, while the remaining was used for validation. The study considered the important parameters that influence the shear capacity of the RC deep beams including compressive strength of concrete, longitudinal reinforcement ratio, yield strength of longitudinal reinforcement, cross-sectional width of the beam, effective depth of the beam, and shear span-to-depth ratio. The prediction performance of the proposed model has been compared to the existing ACI 318-14 provision and resulted in a better prediction capability in terms of safety, accuracy, and economic aspects.

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