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Formulation of shear strength of slender RC beams using gene expression programming, part I: Without shear reinforcement

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ABSTRACT

In this study, a new design equation is derived to predict the shear strength of slender reinforced concrete (RC) beams without stirrups using gene expression programming (GEP). The predictor variables included in the analysis are web width, effective depth, concrete compressive strength, amount of longitudinal reinforcement, and shear span to depth ratio. A set of published database containing 1942 experimental test results is used to develop the model. An extra set of test results which is not involved in the modeling process is employed to verify the applicability of the proposed model. Sensitivity and parametric analyses are carried out to determine the contributions of the affecting parameters. The proposed model is effectively capable of estimating the ultimate shear capacity of members without shear steel. The results obtained by GEP are found to be more accurate than those obtained using several building codes. The GEP-based formula is fairly simple and useful for pre-design applications.

1. Introduction

Although several research programs have been conducted to predict the shear capacity of concrete, there is still no clear expression to predict the shear failure mechanisms of concrete elements. Most of the available shear design expressions have different forms and do not provide a consistent factor of safety against shear failure. Thus, the behavior of concrete beams has been extensively investigated during the last three decades. Numerous theoretical models have been established in recent years to investigate the interaction between several forces including axial, shear, bending, and torsion. A modified compression-field theory (MCFT) was proposed by Vecchio and Collins [1] to estimate the capacity of concrete members subjected to both axial and in-plane shear stresses. The role of several factors such as equilibrium conditions, compatibility requirements, and stress–strain relationships was considered in the MCFT formulations. Gregori et al. [2] proposed a 3D numerical model to study the behavior of the reinforced and pre-stressed concrete frames subjected to several different loading patterns. The Timoshenko beam theory was implemented to model the curved 3D frame elements with arbitrary cross-section geometry.

In the field of empirical modeling, artificial neural network (ANN) can be considered as an efficient alternative to traditional techniques. There have been some research studies focusing on the application of this soft computing tool to the evaluation of the shear strength of RC beams without reinforcement [3,4]. Although ANNs are successful in prediction, they are not usually able to produce practical prediction equations. Furthermore, they require the structure of the network to be identified [5].

Genetic programming (GP) [6] is a fairly new soft computing approach for the behavior modeling of structural engineering problems. GP is an extension of genetic algorithms which searches a program space instead of a data space. The main advantage of the GP-based approaches is their ability to generate prediction equations without assuming prior form of the relationship. Many researchers have employed GP and its variants to discover any complex relationships among experimental data (e.g., [5,7,8]). Gene expression programming (GEP) [9] is a recent extension to GP. GEP evolves computer programs of different sizes and shapes encoded in linear chromosomes of fixed length. The GEP chromosomes are composed of multiple genes, each gene encoding a smaller subprogram [10]. The GEP approach is shown to be an efficient alternative to the traditional GP [9,11]. However, there have been limited scientific efforts directed at applying GEP to structural engineering problems (e.g., [10,12]).

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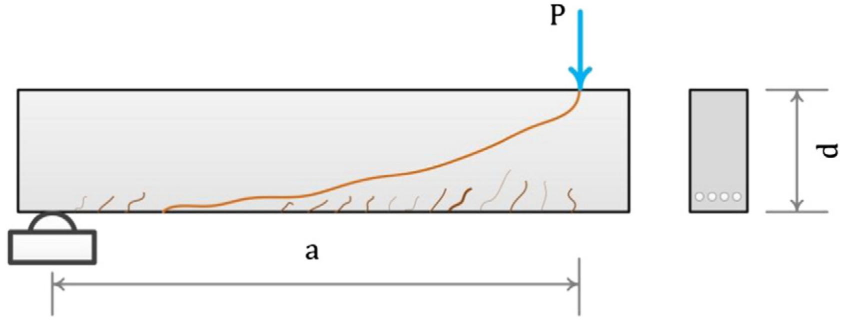

Fig. 1. Shear failure of slender reinforced concrete beams without web reinforcement.

In this study, the GEP approach is utilized to evaluate the shear capacity of RC beams without stirrups. The derived model relates the shear strength to a couple of influencing parameters. The proposed model is developed based on several published shear tests on RC beams. The results generated by the developed model are further compared with those obtained by several codes of practice.

2. Shear strength mechanisms

The overall geometry of the beam is shown in Fig. 1, where "a" represents the shear span, and d is the effective depth of the beam. In short-span beams with a small aspect ratio, i.e., $\frac{a}{d}$<2–3, the applied loads are mainly transmitted directly to the supports by an arch action mechanism. However, this phenomenon is totally different in long-span or slender beams. The initiation and propagation of the inclined cracking in the slender beams without web reinforcements are the main reasons of the failure (Fig. 1). This type of failure is quite common in slender beams under a concentrated load with $2.5<\frac{a}{d}<5.5$ and beams under a uniform distributed load with $11 < L < 16$. The effective depth of the beam is denoted by d, L is the clear beam span, and a is the distance of the concentrated load from the face of the support [13].

2.1. Shear strength assessment using building codes

Several building codes propose an analytical formulation to determine the shear capacity of reinforced concrete beams. The proposed expressions are mainly formulated based on contributions of both transverse reinforcement and concrete capacity in shear.

ACI building code—The ACI 318-02 [14] presents the following expression to calculate the concrete's contribution of shear capacity (V_c) of beams subjected to combined shear, moment and axial compression:

$$V_c = \left(0.16\sqrt{f_c'} + 17\rho_l\frac{Vd}{M}\right)b_w d,\ f_c < 70\ \text{MPa}; \frac{Vd}{M} \leq 1 \quad (1)$$

where ρ_l is the ratio of the longitudinal reinforcement, b_w and d are the width and effective depth of the section respectively, V is the applied sheer force, and M is the flexural moments.

For most designs, it is convenient to assume that the second term of Eq. (1) equals to $0.01\sqrt{f_c}$ so the simplified ACI code can be found as follows:

$$V_c = \left(\frac{\sqrt{f_c'}}{6}\right)b_w d\ f_c < 70\ \text{MPa}. \quad (2)$$

EC2 building code—The European Committee for Standardization [15] presents the following expression for predicting the failure shear strength:

$$V_{Rd,c} = 18k(100\rho_l f_c)^{1/3} b_w d \geq 0.035 b_w d\sqrt{k^3 f_c}$$

$$k = 1 + \sqrt{\frac{200}{d}} \leq 2.0; \rho_l = \frac{A_l}{b_w d} \leq 0.02. \quad (3)$$

Canadian Standard Code—The Canadian Standard Code [16] proposed the following expression for the shear capacity of a concrete member:

$$V_c = 0.2 b_w d\sqrt{f_c}\ \text{ where } d \leq 300\text{ mm} \quad (4a)$$

$$V_c = \left(\frac{260}{1000 + d}\right)b_w d\sqrt{f_c} \geq 0.1\sqrt{f_c}\ \text{ where } d > 300\text{ mm}. \quad (4b)$$

New Zealand Standard—The New Zealand concrete structure design code [17] is applicable to members not resisting earthquake forces.

$$V_c = (0.07 + 10\rho_l)\sqrt{f_c} b_w d,\ f_c < 100\ \text{MPa} \quad (5)$$

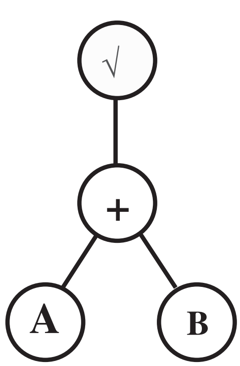

Fig. 2. Representation of a GP model in a tree form (√(A + B)).

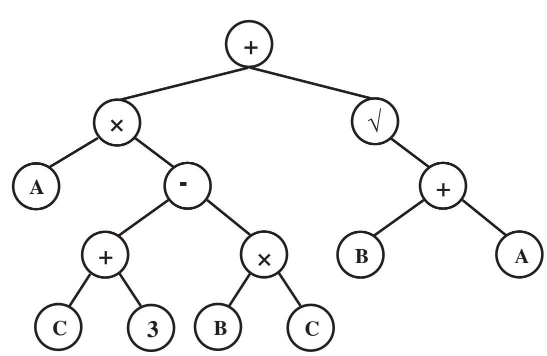

Fig. 3. Example of expression trees (ETs).