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Optimal adjustment of EC-2 shear formulation for concrete elements without web reinforcement using Genetic Programming

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ABSTRACT

This paper presents the improvement of the EC-2 shear strength formulation for concrete beams without shear reinforcement. The method used is based on the modification of the Genetic Programming (GP) technique configured to generate symbolic regression from a set of experimental data. Starting from the EC-2 formulation, several points of the equation are subject to optimization, together with the set of restrictions that must be fulfilled, achieving in this way to control and direct the searching process. It is specifically pursued to improve the term of size effect, the influence of the amount longitudinal reinforcement and the bending-moment–shear-force interaction. For the development and checking of the models it has been used in about 1200 experimental tests on concrete beams from the literature. The four expressions obtained are analyzed in depth through GP and, finally, three expressions of great simplicity are proposed that improve, significantly, the shear strength prediction with respect to the proposals of the Eurocode 2 and ACI 318-05 Code.

1. Introduction

The shear strength in concrete beams without shear reinforcement has been, undoubtedly, one of the most controversial aspects bound to the Ultimate Limit States. It exists a wide range of theoretical models of high complexity that, due to the difficulty of capturing the importance of all the variables involved, they result in different ruling proposals, being to a great extent about formulation cases of empirical origin, as is the case of the European code EC-2 [1] and the American code ACI 318-05 [2].

Once the diagonal tension cracks develop in the web of a slender beam without shear reinforcement, there exists several transfer mechanisms: the shear stress in the no-cracked concrete of the compression head, the shear transferred in the surface of the fissures and the dowel action of the longitudinal reinforcement [3,4]. These different mechanisms are translated in a simplified way into the internal strength developed in a cracked beam, as is shown in Fig. 1.

Kani showed the importance of arch action in not very slender beams [5]. Its importance is inversely proportional to the relation between the shear span and the effective depth, a/d. In beams with a coefficient a/d lower than 2.5, slanting fissures are developed and, after an internal redistribution of stress, the beams are capable of resisting a significant load increase because the applied strength can be transmitted directly to the supports through the appearance of compressed struts in the concrete. In the case of beams with a/d higher or equal to 2.5, this effect loses importance, as is observed in Fig. 2.

The importance of the size effect was not suggested until 1967. Kani [7] showed experimentally that raising the depth of a beam, keeping the rest of the parameters constant, reduced the failure shear stress. Raising the depth of the beam, the fissure width tends to increase. Some authors consider that this entails a reduction of the effect of aggregate interlock leading to a decrease of the shear strength [8]. Fig. 3 shows the result of Shioya's test [9] in which the great influence of the size effect can be observed. Besides, some authors [8,10,11] relate the size effect to the compression resistance of the concrete, suggesting that the higher the concrete compressive strength the more the reduction of tangential stress at cracking due to the size effect is emphasized.

The influence of the aggregate maximum size is also shown in Fig. 3. A decrease of the aggregate maximum size produces a fall of the shear crack stress. However, this parameter is not always perfectly known to engineers during the designing process, and most concrete codes do not take into account this influence in the shear strength formulations. This is the case for the Eurocode 2 [1], the ACI 318-05 Code [2] and the Spanish Concrete Code EHE-08 [12]. However, this influence is considered in more complex models [13,14].

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Notations

A_s	Area of the tensile reinforcement;
a/d	Shear span to depth ratio;
b_w	Web width;
d	Effective depth;
f_c	Concrete compressive strength;
M	Moment at critical section;
V	Shear force at critical section;
V_c	Shear resistance of the member without shear reinforcement;
V_{pred}	Shear strength predicted by a given formulation;
V_{test}	Failure shear strength for a tested element;
ρ_l	Amount of longitudinal reinforcement, $\rho_l = \frac{A_S}{b_w \cdot d}$.

According to the experimental results, the different transfer mechanisms depend mainly on the concrete resistance, on the ratio of longitudinal reinforcement, on the effective depth and on the shears span to depth ratio a/d.

Due to its simplicity and the generally acceptable correlation against experimental results, the equation given in the Eurocode 2 is being extended to different national codes of practice, as it is the case of the Spanish Concrete Code EHE-08 [12]. However, one of the limitations that pose for elements without shear reinforcement, is the fact that the EC-2 procedure does not take into account the bending-moment–shear-force interaction, except for the need to check that the longitudinal tension reinforcement is able to resist the additional tensile force caused by shear. To a given section, according to the EC-2 formulation, the shear strength is independent from the concomitant bending moment if the last is kept away from which produces the plastification of the longitudinal reinforcement. On the contrary, most complex models as the Modified Compression Field Theory (MCFT) [13] predict a reduction in the shear strength as the concomitant bending moment increases for any value of the bending moment (Fig. 4).

The treatment of the influence of the longitudinal reinforcement also varies noticeably from one code of practice to another. The formulation given by the Eurocode 2 propounds that shear strength is proportional to the amount of longitudinal reinforcement. However, other models propose that the shear strength is proportional to the $\rho_l Vd/M$ value, as in the case of one of the methods proposed in the ACI Code. In the real sizing of beams, the amount of longitudinal reinforcement grows proportionally with the concomitant bending moment, and for that reason, the $\rho_l Vd/M$ parameter is practically constant. However, it is usual in laboratory test to use disproportionately raised ρ_l values to avoid bending failures and, even to make series of tests in which a/d decreases, therefore decreasing the concomitant bending moment, without varying the longitudinal reinforcement. For this reason, some authors [14] supports that the adjustment of equations with these unrealistic tests can cause deviations for real elements with the usual combinations of the different variables. In the case of the

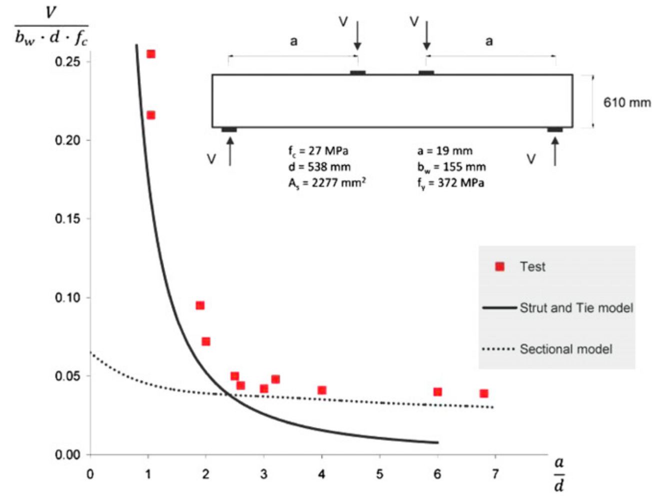

Fig. 2. Strength calculated and observed in concrete beams tested by Collins and Mitchell [6].

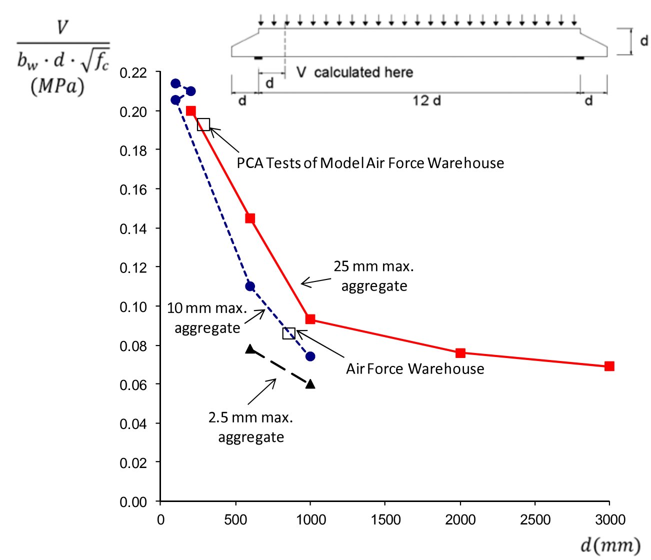

Fig. 3. Influence of the beam depth and the aggregate maximum size in the shear crack stress [6].

given formulation by the Eurocode 2, an increase of the longitudinal amount would always mean an increase in the shear strength regardless of the concomitant bending moment.

In the most of the studies it is necessary to analyze test databases. In order to do this, A.I. techniques can be used, which are no longer unconnected with the field of the Civil Engineering. In scientific literature there are several contributions that use different techniques applied to the model of shear strength of concrete beams without shear reinforcement. It is important to mention examples of three different techniques: in the first place,

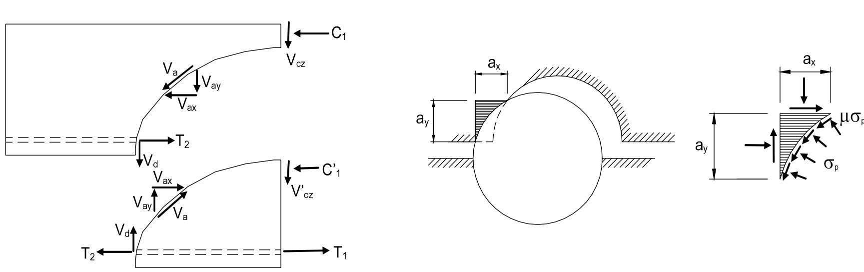

Fig. 1. Internal forces in a cracked concrete beam without shear reinforcement.