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Evolutionary strategies as applied to shear strain effects in reinforced concrete beams

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ABSTRACT

The reinforced concrete beams is a structural member that is widely used in all types of building and civil constructions. These beams are subjected to different external loads that, above a critical value, may cause the collapse of the whole structure, having devastating consequences for civilians. Therefore, the a priori simulation of the internal forces developed within a reinforced concrete beam, when it is subjected to external loads, is mandatory to figure out its progressive structural response, to provide integrated risk assessment for a wide range of constructions such as buildings, bridges, etc. In this paper, we provide a simulation framework to estimate the behavior of reinforced concrete beams when they are subjected to external loads. Of particular interest to us is the simulation of the particularly damaging internal force, called *Shear force*. Several techniques are under study such as regression analysis, Little Genetic Algorithm (LGA) and Covariance Matrix Adaptation Evolution Strategy (CMA-ES), along with different objective functions (lineal, polynomial and rational functions) to provide a solution that satisfies both the physical and computational constraints of the targeted problem. These techniques are empirically optimized by using different parameters and genetic operators such as elitism, penalization for unfeasible individuals, crossing by one point or by linear combination of two individuals, mutation by gen or by individual. Numerical results reveal that CMA-ES algorithm together with a proper objective function, elitism and penalization allows predicting, under a relative error less than 5% (compared to experimental data taken from a tested beam), the shear response of a reinforced concrete beam in the stages near to the structural collapse.

1. Introduction

The transmission of shear through the cracked web of a reinforced concrete beam is a complex phenomenon that has been the subject of several studies in the last decades [1–3]. The formulation of a mechanical model that determines the shear response curve of a reinforced concrete beam requires taking into account, for each level of stress, the inclination of the cracks in the web. *Compression Field Theories* (CFTs) [4–6] establish kinematic relationships between the inclination of these cracks and the strains in the reinforcement and the concrete. The experimental validation of CFTs [5–7] concluded that the consideration of the tension stiffening area prescribed by the international standards significantly underestimates the shear strength of the beam in the load stages near to the structural shear failure (high strains). Therefore, it is interesting to model the strength degradation, which the concrete experiences when the shear force increases, as a function of the member shear strain [6]. Previous works assume the tension stiffening area (denoted as A_c in Fig. 1) to be constant [6–8] which does not fit with the reality. Actually, Gil Martin et al. concluded in [6] that such area decreases as long as crack spacing decreases or the tensile strain increases.

In this paper, we analyze several strategies to perform an inverse analysis of the strain effects in the shear response of reinforced concrete beams to look for an optimal function (κ) that perfectly model the stiffening area (A_c). Fig. 1 summarizes the problem statement and the methodology we use to provide a novel solution to this relevant problem. Firstly, the adjustment of a strength degradation function is attempted by using standard regression through classical least square fitting method. The results of applying this

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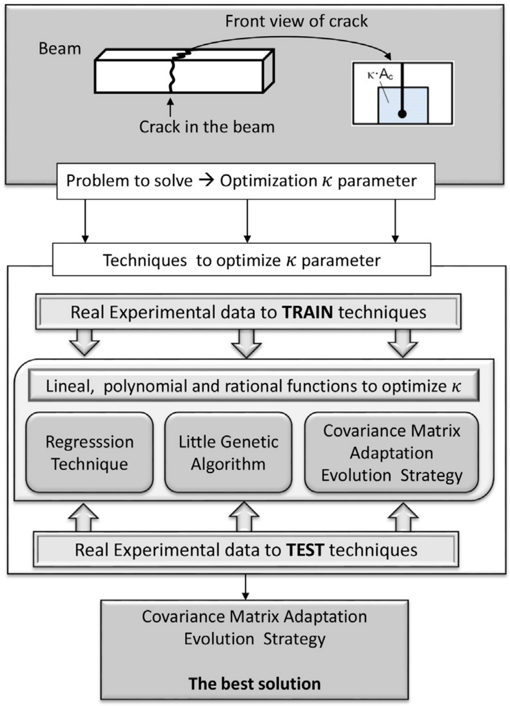

Fig. 1. Problem's statement and methodology to look for an optimal function (κ) that perfectly models the stiffening area (A_c).

technique show low correlation coefficients because of, among other reasons, the high non-linearity of the problem and the large number of variables involved. Therefore, more complex optimization techniques are required to deal with such challenging problem. We propose the use of evolutionary techniques as they are gaining increasing acceptance, and they are now used in a wide variety of application domains where the computational cost is not affordable by traditional machines [9]. In these disciplines, *NP-complete* problems; i.e., problems that cannot be targeted by exact resolution algorithm as its computational cost saves a polynomial relation to the size of the input, emerge very often. The task becomes even more difficult whenever the problem to solve has a high dimensionality by the presence of a large number of features or input variables like the problem targeted here. The major findings of this paper include the following:

1 An inverse analysis of the strain effects in the shear response of reinforced concrete beams is proposed to better estimate the shear strength of the beam in the load stages near to the structural shear failure.
2 A preliminary analysis of the physical problem is performed using regression techniques.
3 Two different genetic algorithms; the Little Genetic Algorithm (LGA) and the Covariance Matrix Adaptation Evolution Strategy (CMA-ES) are proposed using a polynomial approximation as degradation function of the tension stiffening area.
4 To improve the results obtained by our strategies, a new rational degradation function of the tension stiffening area is adjusted, obtaining up to 95% of adjustment compared to experimental data from a shear test of a reinforced concrete beam.

The rest of the paper is organized as follows. Section 2 shows a related work about the shear model considered in this work before introducing the strength degradation as a function of the shear strain. In Section 3 the equations of the physical problem under consideration are presented and the numerical complexity of the model to optimize is justified. Next, in Section 4 a preliminary analysis of the problem is shown using the least square fitting technique, before the two evolutionary approaches are described to solve this challenging problem (Section 5). Section 6 discusses the results obtained by the different computationally techniques targeted in this paper. Finally, Section 7 provides some conclusions and directions for future work, and in Appendix, Table 2 shows the characteristics of the specimens used for the different experiments performed along this paper.

2. Related work

In 1986 Vecchio and Collins developed an analytical model, the Modified Compression Field Theory (MCFT) [4], that predicted the full load-strain response of a reinforce concrete member subjected to shear, taking into account the equilibrium, compatibility and constitutive relationships of the involved materials; in particular, the stress–strain relationship for the steel was then assumed elastic-perfectly plastic, resulting in a elastic modulus constant up to the steel yield stress and then zero. The use of this constitutive relationship requires performing a crack checking in order to avoid that stresses exceed the maximum strength in the crack. To admit new increments of shear force, the MCFT introduced the concept of local shear stresses at the crack interface. Nevertheless, if an embedded bar model is considered, then crack checking is not necessary.

In 1994 Belarbi and Hsu presented in [5] a constitutive law for steel stiffened by the surrounding concrete (embedded bar model), in the context of the so-called Rotating Angle Softened Truss Model (RA-STM), in order to predict the in-plane shear response of reinforced concrete membranes. To this aim, an experimental campaign was performed, and it was shown that the concrete develops tensile stresses after even extensive cracking; consequently, the stress–strain curve of a steel bar embedded in the concrete admit new increments of shear force after yielding. Following this trend, Gil Martín et al. proposed in [6,10] a refinement of the above-mentioned compression field theories (RCFT), which consisted of the consideration of the reinforcement elastic modulus as a gradually-varying function based on equilibrium, within a tension stiffening-type formulation. The main contribution of this refinement is the formulation of an embedded bar model based on the traditional formulation of the MCFT, but without need of crack stresses checking. Numerical results obtained in this work show a better fitting of the experimental results, in particular near the peak point in the shear response curve, where the MCFT significantly deviates from the experimental evidences.

In the embedded bar models above cited, the area of concrete contributing to tension stiffening (or tension stiffening area) has been assumed to be constant; nevertheless, Gil Martin et al. concluded in [6] that such area decreases as long as crack spacing decreases or the tensile strain increases. In 2013 Palermo et al. [7] made use of the RCFT to calibrate the load-deflection response of three full-scale thin low reinforced concrete panels subjected to cyclic loading. At this time, the tension stiffening area was estimated through a squared least procedure in order to fit the envelope of the cyclic behavior of the specimens; numerical results revealed a strongly dependence between the tension stiffening area and the applied axial load, in such a way that the concrete area decreased as the axial load increased. Under analogous considerations, in 2014 Palermo et al. [8] predicted the ultimate shear strengths of plastered straw bale walls through the previous calibration of the tension stiffening area in the RCFT; as conclusion of this work, the refinements introduced (and the corresponding experimental calibration) allow the RCFT to accurately predict the