Engineering Fracture Mechanics 186 (2017) 466–482

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech

A new empirical formula for prediction of fracture energy of concrete based on the artificial neural network

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ARTICLE INFO

Article history:
Received 17 June 2017
Received in revised form 31 October 2017
Accepted 3 November 2017
Available online 4 November 2017

Keywords:
Neural networks
Fracture energy
Concrete
Empirical formula

ABSTRACT

Assessment of energy needed for crack growth in concrete structures has been an interesting topic since the use of fracture mechanics to concrete. For concrete as a quasi-brittle material, the fracture energy has been demonstrated to be an effective index in the safe design of structures and the failure behavior modeling. Since the nonlinear behavior of concrete in fracture process is very complicated, intensive debates on the precise prediction of fracture energy by means of available estimating formula have never ended. In the present study, a new empirical method to determine the fracture energy of concrete is explored. With an extensive experimental database including 246 fracture tests, a new artificial neural network (ANN) model relating the fracture energy to different effective parameters such as compressive strength, water to cement ratio, maximum aggregate size and age is trained and validated. Using the generalization capabilities of the ANN, an empirical design plot and some correcting equations are extended to make a user-friendly formula to determine the fracture energy of concrete in practical design. Results showed that predicted values from ANN are in rationally good agreement with the experimental data and also ANN give higher accuracy than existing regression models, especially with overcoming the high scattered predictions. The use of the new empirical method as an efficient technique for determining the fracture energy of concrete is thus proved.
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1. Introduction

Nowadays, it is obvious that employing fracture mechanics theory for designing concrete elements to remedy all kinds of brittle failures, results in more reliable, cost-effective, and safer concrete structures [1]. This concept is stated by numerous experimental and analytical types of research [2–4]. Moreover, well-known structural disastrous events, such as the failure of the Cypress Viaduct in Oakland, CA caused by the 1989 Loma Prieta earthquake, the failure of the Malpasset Arch Dam in the French Maritime Alps in 1959, the failure of the Hanshin Viaduct in Kobe as a result of the Hyogo-Ken Nambu earthquake in 1995, the failure of Schoharie Creek Bridge on New York Thruway, and the sudden explosive failure of Sleipner A oil platform in 1991 due to submergence test in a Norwegian, reveal the necessity of considering fracture mechanics for designing concrete structures [5]. Although fracture mechanics was pioneered by Griffith already in 1921 [6], this concept was held

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https://doi.org/10.1016/j.engfracmech.2017.11.010
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List of symbols

f_c	concrete cylinders compressive strength (MPa)
f_{cm}	mean value of compressive strength of concrete (MPa)
f_{ck}	the characteristic value of compressive strength of concrete (MPa)
$d_{\max}$	maximum aggregate size (mm)
w/c	water to cement ratio
α_0	correction factor for aggregate shape
G_F	total fracture energy (N/m)
G_f	initial fracture energy (N/m)
C_{f_c}	correction factor of the compressive strength
$C_{d_{\max}}$	correction factor of the maximum aggregate size
C_{Age}	correction factor of the age of concrete
$C_{w/c}$	correction factor of the water to cement ratio
NMSE	normalized root-mean-square error
R	correlation coefficient
ANNs	artificial neural networks
LEFM	linear elastic fracture mechanics
FPZ	fracture process zone
CBM	crack band model
TPM	two parameter model
SEM	size effect model
ECM	effective crack model
WFM	work-of-fracture method
F	correction function

inapplicable for concrete due to inadequate development of the individual fracture mechanics theory for concrete as a heterogeneous material compared to homogeneous materials such as steel or ceramics [5]. Kaplan in 1961 [7] conducted the first experimental study regarding fracture mechanics of concrete by using linear elastic fracture mechanics (LEFM) concept. In addition, Kesler et al. in 1972 [8] demonstrated that the classical LEFM of sharp cracks with only one fracture parameter, the fracture energy G_F, was inadequate for concrete structures due to the presence of an inelastic zone with remarkable scale and full micro cracks in front of the crack tip in concrete, namely fracture process zone (FPZ). Researchers showed at least two fracture parameters are needed for describing concrete fracture [9]. In order to eliminate LEFM deficiencies regarding concrete, numerous investigations were carried out for proposing the best nonlinear concrete fracture model based on FPZ [10,11]. According to Yan et al. [12], these models can be divided into two main categories. Firstly, the cohesive or fictitious crack model and the crack band model (CBM) that are available for numerical analysis. Secondly, the two-parameter model (TPM), the size effect model (SEM), the effective crack model (ECM), and the double-K model which are suitable for analytic computation. One of the most important parameters to describe cohesive crack model is specific fracture energy (G_F). The specific fracture energy, adopted by the RILEM TC 50-FMC [13] is defined as the total work required to create one unit area of a crack, namely work-of-fracture method (WFM). As the beam is broken into two parts, the fracture energy can be computed by estimating the total area under the load-displacement curve of the specimen and calculated by dividing the total dissipated energy by the initial ligament area. The obtained G_F by WFM method is specimen size and shape dependent and this drawback, nevertheless, could perhaps be avoided by thorough measurement of the tail of the load-displacement curve and the whole energy dissipation sources in the experiment [14]. In contrast to G_F, initial fracture energy (G_f), representing the area under initial tangent of the softening curve, is independent of the specimen size and geometry [15]. As a matter of fact, both types of fracture energies, G_F and G_f, are two unique materials' characteristics. Researchers mentioned that these two parameters are weakly correlated with each other owing to higher scatter of G_F quantities than G_f due to more uncertainty in the tail of the softening curve in comparison with the initial part of the curve [5]. As reported by Planas et al. [16], a very rough approximation could be assigned to the ratio between G_F and G_f, ranging from 2 to 2.5. These two definitions of fracture energy could be employed for different purposes. In order to quantify consumption of energy in total failure of structures, and to predict the entire post-peak softening load-displacement curve of a structure, G_F is appropriate and requisite, whereas, regarding G_f, it is quite adequate to predict the maximum load of structures and the softening curves up to their peak point [17]. Up to now, several researchers have studied the parameters affecting G_f in different types of concrete. Jenq and Shah [10] reported that in NVC, G_f increases from 21.1 to 35.4 N/m by an increase in maximum aggregate size from 4.75 to 19 mm. investigating concretes with w/c ratios of 0.4 and 0.29 at ages of 1–28 days, Shah et al. [18] stated that G_f varies from 20.6 to 37.5 N/m and from 36.7 to 62.3 N/m respectively. Bharatkumar et al. [19] also resulted that in HPC, an increase in the w/c ratio from 0.36 to 0.5 leads G_f to decrease from 46.3 to 40.4 N/m. Moreover, regarding the effect of the w/c ratio in SCC containing limestone powder, Beygi et al. [3] reported that with a increase in the w/c ratio from 0.35 to 0.7, the value of G_f decreases from 52.3 to 29.5 N/m. Yu and Ansari [20] also showed that variation of G_f

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