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An application for the fracture characterisation of quasi-brittle materials taking into account fracture process zone influence

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ABSTRACT

The paper introduces a Java application programmed for the advanced determination of the fracture characteristics of silicate-based materials failing in a quasi-brittle manner. The tool reconstructs the progress of a quasi-brittle fracture from the measured load–displacement curve and the knowledge of basic mechanical properties of the material. The main contribution of the proposed approach is that it takes the characteristics of the Fracture Process Zone (FPZ, particularly its extent, i.e. its size and shape) evolving at the tip of the propagating crack during the failure process into account and incorporates them into the fracture-mechanical parameter evaluation procedure(s). This approach is expected to substantially diminish the influence of the test specimen's size/shape and the test geometry on the values of the parameters of nonlinear fracture models determined from the records of fracture tests on laboratory specimens. The application implements a developed technique for estimation of the size and shape of the FPZ. The technique is based on an amalgamation of several modelling concepts dealing with the failure of structural materials, i.e. multi-parameter linear elastic fracture mechanics, classical nonlinear fracture models for concrete (equivalent elastic crack and cohesive crack models), and the plasticity approach. The knowledge of the FPZ's extent is employed for the relation of a part of the entire work of fracture to its characteristics within the presented approach. The verification and validation of the developed technique is performed via numerical simulations using the authors' own computational code based on physical discretization of continuum and selected sets of experimental evidence published in the literature. Reasonable agreement is observed between the outputs of the presented semi-analytical technique and both the simulation results and the experimental data.

1. Introduction and motivation

The paper presents a computer application aimed at the thorough and complex processing of records from fracture tests carried out on laboratory-sized specimens made of quasi-brittle materials. These tests are typically performed with the purpose of determining parameters for fracture models describing the softening nature of the quasi-brittle response of civil engineering structures made of such materials. Particular attention is paid to silicate-based, mainly cementitious composites. Fracture tests represent the most convenient way of gaining relevant information on the tensile failure behaviour of the studied materials. However, a number of issues related to the intrinsic relevance of the information gained from laboratory experiments have been intensively researched and reported in the literature for what is already more than 30 years. From these issues the effect of specimen size, shape and boundary conditions on the determined values of fracture characteristics (a topic on which no general consensus between interested researchers has yet been reached) is of particular relevance to this paper. It is unfortunately necessary to know the real values of the fracture characteristics of these materials in order to predict or assess structural response – a typical engineering task – with a reasonable level of accuracy. The importance of the main subject matter of the presented work is thus clear.

Several methods for the estimation of the needed fracture parameters have been established, and even recommended by international authorities [43–45]. These methods are connected with a corresponding fracture model approach, i.e. either the cohesive crack or equivalent elastic crack models (covered in detail e.g. in [6,26,49,55]), or their combination, the double-K/double-$\mathcal{G}$ models [42,68,69]. Except for Bažant's size-shape effect method, promoted by Bažant and his co-workers in a number of publications since the 1990's until the present day (e.g. [5–7,70] among others), the aforementioned methods provide fracture parameter values

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dependent on the size and shape of the tested specimen and the applied boundary conditions. This phenomenon is expressed via several different terms by researchers in this field, e.g. size effect, shape (geometry) effect and boundary effect. Several models have been proposed to explain and capture the phenomenon. Besides Bažant and his co-workers' explanation, other approaches have also been considered that e.g. take into account the non-constant distribution of the fracture energy of the material along the specimen ligament within the determination of the true, size/geometry/boundary-independent fracture properties. The reason for the phenomenon, according to that approach, lies in variations in the FPZ size during the fracture process [10,11,18,28,54]. Another recent concept [2] utilizes a more accurate description of the crack-tip stress field (considering higher order terms of the Williams power expansion) to capture the above-mentioned effect/s. The method presented in this paper is similar in this respect.

The paper presents a (semi-) analytical method which enables modelling of the FPZ existing at the propagating crack tip during the fracture process in quasi-brittle materials, and estimation of its size and shape. The energy dissipated within this zone during fracture can then be related to the extent of this zone of failure, which can result in the refining and better specification of the procedures by which the fracture-mechanical characteristics of quasi-brittle materials may be determined, especially fracture energy [43]. In this paper, an implementation of the said method resulting in a Java application is described, and its function is illustrated in the context of fractures of single edge notched beams in three-point bending (SEN-TPB), and wedge-splitting test (WST) specimens.

2. The fracture process zone – an experimental, modelling and evaluational perspective

The existence of the fracture process zone is the key cause of the nonlinear manner in which quasi-brittle fracture takes place. This zone is formed and evolves around the propagating crack tip during the fracture process; the material of the fracturing structure is damaged at this area via various failure mechanisms on several levels of the material structure which combine to result in energy dissipation. In the case of the quasi-brittle materials relevant to this study, i.e. silicate-based composites in the civil engineering field, the FPZ's size is very large. It may even reach the dimensions of the structure containing it, and depend on the size of the material's basic constituents (i.e. aggregates) [6,26,49,55]. Its length, when we limit only to this dimension, can be expressed as to be proportional to the characteristic length l_{ch} of the material introduced by Hillerborg [16] and the proportionality factor depends on the softening behaviour of the material; its value is roughly between 2 and 5 for concrete [6]. Reported values of l_{ch} for concrete range from 0.15 to 0.5 m [26], the length of FPZ can thus reach values from 0.2 to more than 2 m [6]. So, it is obvious that, in contrast with brittle fracture, the FPZ's size cannot be neglected when creating models of fracture propagation or assessing crack stability.

As was mentioned above, the existence of this zone influences the values of fracture-mechanical properties determined by the standardised evaluation procedures from records of fracture tests. The work-of-fracture method [43] is mainly focused on in this paper; it is the most often used method for the determination of fracture energy, a basic parameter for cohesive crack model-based computational tools. Within this method, the main reason for the dependence of the determined fracture energy on the specimen size/shape/free boundaries is the change in the FPZ's extent (and subsequently in the distribution of the intensity of energy dissipation within it). Although this explanation is widely accepted [4,11,19,28], the characteristics of the FPZ are not included in the procedures for fracture parameter determination. On the contrary, the FPZ's description (usually only partial, in most cases only involving its length or a parameter linked to its length, e.g. Bažant's c_{f} [6], Hillerborg's l_{ch} [16], Hu–Duan's a^*_∞ [18]; and rarely its width, e.g. h_{FPZ} [17]) are among outputs of the procedures. However, no specific consideration is given to the real extent of the FPZ, i.e. its size and shape, in these procedures. The authors of this paper are therefore providing an introduction to a (part of a) method which eliminates this disadvantage with the vision of diminishing the size/shape/boundary effect on fracture properties.

The proposed method described hereafter needs to be validated by experimental data. However, only a limited amount of works available in the literature can be directly used for such a task. This is in most cases due to the incompleteness (for our purpose) of the reported data or because the analyses the works contain have a different focus than is needed for the comparison of the FPZ parameters used with the results of the developed technique. Reports exist in the literature regarding several experimental techniques based on various physical phenomena for the determination of either the propagating crack tip position or rather the entire FPZ extension during the fracture process in quasi-brittle materials (summarised e.g. in [37,49,55]). Among the most relevant are the holographic interferometry technique [49,55], X-ray radiation [23,40] (in combination with digital image correlation analysis, e.g. [21], and computational tomography, e.g. [56]), acoustic emission scanning [33,35,36,38,40,41,50,58], infrared vibro-thermography [34,55], ultrasonic measurement [46] and micro/nano-indentation [61].

3. Theoretical background

3.1. Multi-parameter fracture mechanics approach

Multi-parameter fracture mechanics is based on the utilisation of several initial terms of the Williams power series approximating the stress and displacement fields in an elastic isotropic homogeneous 2D body with a crack. Williams' solution [67] provides, for mode I, the following formulas for the stress tensor and displacement vector:

$$\sigma_{ij} = \sum_{n=1}^{\infty} A_n \ \frac{n}{2} \ r^{\frac{n}{2}-1} \ {}^{\sigma}f_{ij}(n,\theta), \quad i,\ j = \{x, y\}, \tag{1}$$

$$u_i = \sum_{n=1}^{\infty} A_n \ \frac{n}{2} \ r^{\frac{n}{2}-1} \ {}^{u}f_i(\theta, n, E, \nu), \quad i = \{x, y\}, \tag{2}$$

where r and θ are the polar coordinates with their origin centred at the crack tip (considering the direction of crack propagation along the positive x-axis), coefficients A_n are constants for a particular crack propagation stage and ${}^{\sigma}f_{ij}(n,\theta)$, ${}^{u}f_i(\theta,n,E,\nu)$ are known functions which can be found, apart from in the source paper [67], in classical textbooks on fracture mechanics (e.g. [1]) as well as in recent relevant papers (e.g. [30,3]). E and ν are Young's modulus and Poisson's ratio.

Stress tensor components are used within the presented approach, and therefore the detailed form of Eq. (1) is given here for the convenience of the interested reader:

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = \sum_{n=1}^{\infty} A_n \ \tfrac{n}{2} \ r^{\frac{n}{2}-1} \cdot \begin{Bmatrix} \left[2+(-1)^n+\frac{n}{2}\right]\cos\left[\left(\frac{n}{2}-1\right)\theta\right] - \left(\frac{n}{2}-1\right)\cos\left[\left(\frac{n}{2}-3\right)\theta\right] \\ \left[2-(-1)^n-\frac{n}{2}\right]\cos\left[\left(\frac{n}{2}-1\right)\theta\right] + \left(\frac{n}{2}-1\right)\cos\left[\left(\frac{n}{2}-3\right)\theta\right] \\ -\left[(-1)^n+\frac{n}{2}\right]\sin\left[\left(\frac{n}{2}-1\right)\theta\right] + \left(\frac{n}{2}-1\right)\sin\left[\left(\frac{n}{2}-3\right)\theta\right] \end{Bmatrix}. \tag{3}$$

The first and second term of the series expansion are singular and constant, respectively, with regard to the distance r from the crack tip. The constants A_1 and A_2 from these terms correspond to the stress intensity factors K and T-stress, respectively. The rest of the terms take finite values for arbitrary r and converge to zero