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Augmented Strain Energy Release Rate (ASER): A novel approach for investigation of mixed-mode I/II fracture of composite materials

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ABSTRACT

In the present research, a comprehensive mixed-mode I/II criterion for fracture investigation of orthotropic materials with arbitrary crack-fibre angle is proposed. The strain energy release rate concept is extended for orthotropic materials based on a Reinforced Isotropic Solid Model (RISM). RISM assumes that the crack growth occurs in isotropic matrix of a composite material. Fibres are defined as reinforcement of the matrix and have appeared in analytical relations as stress reduction coefficients. Since in arbitrary crack–fibre angle case, fracture toughness of the orthotropic material is not measurable, a new material property called 'Equivalent Fracture Toughness' (EFT) is introduced. The ETF is defined in such a manner that it is easy to measure and is not dependent on fracture properties of composite material such as mode II fracture toughness (KIIc) which needs large number of tests. The accuracy of the proposed criterion as well as the coincidence with the nature of fracture of orthotropic materials will be approved by comparing the extracted fracture limit curves for various crack-fibre angles with available experimental data.

1. Introduction

Due to the increasing use of composite structures in various industries, the safety and load caring capacity issues for these kinds of materials have come to acquire great significance. Existence of defects and cracks in the manufacturing process of composite parts, or the creation of defects in the structure of such materials in working environments of the structure is more probable than isotropic materials. Therefore, the fracture mechanics of composite materials has become an important issue in recent research [1].

Fracture of composite materials as quasi-brittle ones is accompanied with the creation of a fracture process zone. This area contains aggregated micro-cracks and toughening mechanisms such as bridging, which, due to energy consumption, will lead to a delay in fracture phenomena. Perhaps Hillerborg was the first researcher who studied the damaged zone and the importance of this area in quasi-brittle materials like concrete [2]. In a separate work, Hillerborg extended the concept of fictitious cracks on the other type of materials [3].

It can be found from the related references that three types of approaches should be used to present orthotropic mixed-mode I/II fracture criterion as follows:

1. Analytical criteria which consider the effects of fracture process zone as a damage factor.

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2. Analytical criteria which are based on the extension of available isotropic fracture criteria in orthotropic materials and;
3. Experimental criteria based on curve fitting on experimental data.

Damage zone effects has not been considered significantly in available mixed-mode I/II fracture criteria. Romanowicz et al. employed nonlocal stress approach for investigation of damage coefficients in the crack tip of orthotropic materials like wood [4], but they were unable to calculate their proposed damage factor appropriately. The nonlocal stress criterion is presented for general case of arbitrary crack–fibre angle. A comprehensive criticism has been expressed in Ref. [5].

Anaraki and Fakoor in 2010 presented an analytical relation for calculation of damage factor considering micro-cracks on a reinforcement isotropic material [6]. In another research, they calculated the introduced damage factor with combination of micro- and macro-approaches, and by utilizing strength properties of orthotropic materials along and perpendicular to fibres [7]. Fakoor and Mehri extended the concept of the damage factor considering micro approach and utilizing experimental methods [8]. Stress approaches have been used in the almost all efforts, such as calculation of fracture process zone effects.

Mixed-mode I/II fracture criteria are also available for fracture investigation of orthotropic materials, which do not contain the effects of fracture process zone directly. These criteria are usually based on extension of famous available isotropic fracture criteria into orthotropic materials. Jernkvist in 2000 extended the well-known Strain Energy Release Rate (SER) [9] and Strain Energy Density (SED) [10] criteria, which are defined for isotropic materials into orthotropic materials [11]. These criteria are able to consider the fracture behavior of orthotropic materials when the crack is perpendicular to fibres. In this special case crack growth is considered by deviation of crack perpendicular from the original notch orientation. This deviation is assumed to take place via a sharp notch. The introduced criteria by Jernkvist have been verified by experimental data in another research by him [12]. The results showed that the energy-based extended criteria were too conservative and could not cover the experimental data. He also extended the Maximum Principal Stress criterion to the orthotropic materials and better results with respect to two later energy-based criteria were achieved [11]. Fakoor and Rafiee extended the Maximum Shear Stress (MSS) criterion to cracked orthotropic materials, leading to the well-known and useful 'Wu' criterion which was presented for investigation of mixed-mode fracture of orthotropic materials [13].

Another category of research is also available for investigation of mixed-mode I/II fracture of orthotropic materials, in which experimental approaches and curve fitting on experimental data are utilized. Most of these criteria are old, and for their utilization, two or three experimental constants are needed that must be prepared with suitable experimental tests. Wu was the first to propose a mixed-mode fracture criterion based on experimental results on the centre notch Balsa wood under mixed-mode I/II loading. The cracks were parallel with fibre direction [14].

Leicester proposed a linear experimental criterion based on orthotropic fracture properties in modes I and II, which is very conservative in comparison with experimental data [15]. Williams and Birch concluded that the shear stress that creates the shear mode does not have any effect on the damage of orthotropic materials under mixed-mode I/II loading. Based on this hypothesis they did not consider mode II fracture toughness in their criterion [16].

Woo and Chow investigated mixed-mode fracture of two species of Kapur and Gagil wood, utilizing single-edge and central-crack specimens. The results showed that fracture under mixed-mode loading is dependent on both modes I and II fracture toughness [17]. However, they couldn't present any fracture criterion.

Mall et al. also presented a mixed-mode fracture criterion which has not any coincidence with experimental data [18]. Moura et al. have done a comprehensive experimental and numerical study on process zone energy [19].

It may be concluded from the above literature review that few references have focused on the important issue of mixed-mode fracture criterion for arbitrary crack-angle of orthotropic materials under mixed-mode I/II. Also, employing all three types of introduced criteria depends on damage zone properties or need mode II fracture toughnessK_{IIc}. Extraction of FPZ properties from the experiment are difficult due to random characteristics of toughening mechanisms [4]. Although there are nowadays several methods for calculating stress intensity factors for various composite materials [20] and fracture tests appropriate for fracture characterization under pure mode II loading, but extraction of K_{IIc} needs large number of tests due to large scatter in test results for composite materials. Mode II fracture characterization of composites and wood is well considered by ENF test specimen [21–23]. ENF test specimen is employed for calculation of G_{IIc} in a composite laminate [24]. Energy release rate is calculated in composite materials employing finite element approach in two-dimensional crack growth condition [25].

In this article, a comprehensive mixed-mode I/II fracture criterion is presented, called 'Augmented Strain Energy Release Rate' (ASER), for orthotropic materials with arbitrary crack–fibre angle. The utilized model is based on several experimental observations in which the crack will propagate in the isotropic matrix of the orthotropic materials. Therefore, in the presentation of the new criterion, the Reinforcement Isotropic Solid Model (RISM) is utilized. Implementation of the presented criterion for fracture investigation of composite materials is possible simply by considering mode I fracture toughness and elastic properties of the material. Comparison of experimental data with fracture limit curves results from the presented criterion is performed, and it proves the accuracy of the new proposed criterion.

2. Problem statement

An efficient mixed-mode I/II fracture criterion for orthotropic materials should be independent from orthotropic fracture properties especially mode II fracture toughness K_{IIc}. The main reason is difficulty of extracting these material properties.