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Full Length Article

Maximum tangential stress coupled with probabilistic aspect of fracture toughness of hybrid bio-composite

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ABSTRACT

The statistical aspect of mode I, mode II and mixed mode I/II fracture toughness of epoxy based bio-composite reinforced with 20 wt% walnut shell particle and 10 wt% coconut fiber is studied. The bio-composite is fabricated by the squeeze casting method. A series of fracture tests are conducted on hybrid bio-composite using three point bend, four point bend and semicircular arc bend specimen. The statistical distribution of normalized geometry parameters, T stress, crack tip plastic zone size, particle and fiber size are studied. Generalized maximum tangential stress criterion is modified considering the stochastic nature of the geometry and strength parameters assuming them to follow two parameters Weibull probability distribution. The model developed is applied to the bio-composite and predicted results are compared with the experimental values. Very good agreement is found between the experimental results and predicted results. The variability in the fracture toughness values are correlated with the particle and fiber size determined from scanning electron microscopy.

1. Introduction

In the recent years, bio-fiber and bio-particle reinforced bio-composites have raised great interest due to the growing concern for the environment and biopolymers, i.e., biodegradable polymers, and bio-composites have been the topic of many researchers. In practice, short fiber composites are considered an isotropic material and their expected behaviour is similar to a homogeneous material whereas for long fiber composites, the mechanical properties are orthotropic, i.e. strongly dependent on orientation of the fibers. Similarly particulate composite can be considered homogeneous if the particles of uniform size and shape are uniformly dispersed in the matrix. In composite material the fiber or particle volume fraction, their distribution, shape and size, surface texture of the fiber etc. are important parameters which can control the damage tolerance properties. The effects of each variable are well reviewed by many researchers [1–4].

Due to involvement of several factors, the properties of bio-composites vary significantly from specimen to specimen. Fiber or particulate reinforced biocomposites also exhibit an inherent uncertainty due to their complex manufacturing processes. Over the years, a range of stochastic analysis methods have been developed to account for the uncertainties at different scales in the field of various science and engineering. Accounting for the variability in fracture toughness of bio-composites is an important aspect of mechanical design that requires knowledge of the statistical distributions of fracture toughness. The experimental quantification of these distributions can be time consuming and expensive, so the statistical modelling can be an appropriate solution to decrease the number of experiments needed to evaluate fracture toughness of bio-composites even at low probability of failure. The problem has received considerable attention for metals, but, a very limited research has been conducted for bio-composite. Many authors have investigated the fracture behaviour of the biocomposite materials [5–13]. Shear yielding, crack deflection and crack bridging are some of the fracture mechanisms which were discussed thoroughly by Shadlou et al. [14]. The various mechanisms such as crack pinning [15], crack path deflection [16,17], particle debonding and subsequent void growth [18] and plastic deformation [19–21] and shear induced mechanism [22] have been proposed to address the enhancement in toughness in particle and/or fiber reinforced composites. In fact in case of fiber reinforced composites, several mechanisms act together and contribute to the fiber composites toughness, although one particular mechanism can be dominant. A common realization is that no single mechanism or criterion can accomplish best performance for all possible conditions and materials. It is, therefore, more work is needed in this direction. The desire for increasing understanding of failure of bio-composite materials, it is essential to work on the aspect of fracture mechanism and failure criteria of bio-composite.

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Several failure criteria for engineering design that protect material structures against failure have been proposed by many investigators over the past century. The physical foundation for these failure criteria might be different, and their individual validity may be restricted to specified type of material and structural applications. These fracture criteria describe brittle failure in linear elastic bodies when subjected to mode I, mode II or mixed mode (I/II) loading. Under mixed mode loading conditions, fracture of cracked components and structures may grow along curvilinear paths and not necessarily along the direction of original crack. Furthermore, when an estimate of crack arrest is required, the direction of fracture initiation from existing cracks must be determined particularly under mixed mode loading. Therefore, the investigation of the fracture initiation angle and the fracture propagation path under mixed mode loading is an interesting subject for researchers. There are a number of theoretical models and various experimental techniques to investigate mixed mode crack growth. Theoretical fracture criteria such as the maximum tangential stress (MTS) criterion [23], the minimum strain energy density criterion [24], the maximum energy release rate criterion [25], and the cohesive zone model [26] have been frequently used by researchers to predict the resistance and the direction of mixed mode fracture growth. These fracture models are usually developed based on the state of stress, strain, energy etc. in front of the crack tip and often use the stress intensity factors (K_I and K_{II}) for predicting the crack growth direction. More recently, increasing attention has been devoted to study the effect of higher order terms of Williams' series expansion on the initiation of fracture. Recently the effect of T stress on fracture process and crack growth have been reviewed by Gupta et al. [27]. Authors provided a critical review for the role of T-stress in predicting crack. paths stability and concluded with a concise summary of the research on T-stress.

Considering the relationship between the T-stress and the fracture resistance of materials, two-parameter models for mode I cracks and three-parameter models for mixed mode cracks have been now well established for a reliable fracture prediction in cracked components [28–30]. Smith et al. suggested a generalized maximum tangential stress (GMTS) criterion and studied the role of T-stress in mixed mode brittle fracture [28]. Through their study, they showed that mixed mode brittle fracture is significantly affected by the T-stress. Subsequently, Ayatollahi and his co-workers conducted a large number of experiments and found very good agreement between the results predicted by the GMTS criterion and the experimental results [31–33]. However, the GMTS criterion suggests that within the framework of LEFM, the T-stress has no influence on mode I fracture resistance of brittle materials. The use of these conventional fracture criteria for isotropic and homogeneous materials is well documented and these conventional fracture mechanics methodologies can still be applied to composite materials with certain limitations.

The development of appropriate fracture theories for biocomposites has received relatively little attention from the scientific community until now and the scatter analysis of fracture toughness and the appropriate probabilistic model is yet not addressed. Scatter is an inherent characteristic of mechanical properties including fracture toughness. This characteristic is related to the reliability of structure and the safety factor in design. It is well addressed that in case of particle reinforced or fiber reinforced bio-composites improper adhesion or mixing of the reinforcing materials with the matrix causes defects or pores, agglomeration, etc. It is recognized that these defects affect the fracture toughness variability. The scatter behaviour of fracture toughness is influenced by diversity, nature, size and the distribution of such defects. These defects act as the sites of crack nucleation and influence the fracture toughness values leading to a significant scatter.

In the present study, the scatter behaviour of fracture toughness of 20 wt% of walnut shell particle and 10 wt% of coconut fiber reinforced hybrid bio-composite has been investigated in detail. These fiber and particles are selected due to their plenty availability. They are also light weighted, environment friendly and provide high specific properties when used as reinforcing material. The optimum mechanical and thermal properties are found to be with about 10–20 wt% of the plant fiber particulate materials reinforced with epoxy resin [34,35]. The work of Singh [36], Nitin and Singh [37] on walnut shell particle reinforced composites reveals that the mechanical properties increase with the increase of wt% of walnut shell particle up to 20 wt% and thereafter the properties decrease. The results of Romli et al. [38], Naveen and Yasaswi [39], and Udaykumar et al. [40] on the effect of weight percentage of coconut fiber on the mechanical properties reveal that 10–15 wt % of coconut fiber is optimum for best mechanical properties. Similarly researchers have shown that both fiber length and weight percentage of the fiber plays a vital role in the enhancement of the mechanical, thermal, etc. properties. The studies of various researchers [41,42] with coconut fiber/coir fiber of length 2 mm to 15 mm with various weight percentage shows that more the length with lesser weight percentage or lesser the fiber length with higher weight percentage shows better mechanical properties. It has been shown that small ratio between matrix/reinforcement particle sizes resulted in more uniform distribution of the particles in the matrix and resulted in higher yield strength, ultimate tensile strength and elongation due to homogenous particle distribution [43,44]. According to Baiardo et al. [45] the mechanical properties of short fiber reinforced composites are expected to depend on (i) the intrinsic properties of matrix and fibers, (ii) aspect ratio, content, length distribution and orientation of the fibers in the composite, and (iii) fiber-matrix adhesion that is responsible for the efficiency of load transfer in the composites. Thus, the present study is aimed at the two selected weight percentages of the particle and fiber matrix material with varying sizes. The failure mechanism also depends upon the particulate or fiber size, volume percentage, etc. It is therefore, the role of particle or fiber pull out, fiber breaking and particle size distribution on the fracture toughness scatter has been discussed in this work. The fracture toughness results obtained from three point bend, four point bend and semicircular arc bend tests are used to model the generalized two parameter Weibull distribution and subsequently the generalized maximum tangential stress criterion is modified considering the stochastic nature of the geometry and strength parameters. The developed probabilistic model is validated with the experimental results and found to be reasonably good even at very low probability of failure.

2. Materials and methods

The raw materials used in this study are walnut shell, coconut fiber, epoxy and hardener. After cleaning the walnut shells, they are chipped by a knife ring flaker and the chipped shells are converted to particle form by Wily mill. Particles thus prepared are oven dried at 100 ± 5 °C to reach the target moisture content (less than 2%) before using them as reinforcing material. Coconut fibers are extracted from exocarp, washed with distilled water and dried at 100 °C for 24 h. The length of coconut fibers used in the present investigation vary from 1.0 mm to 1.5 mm. CY 230 resin is used as an adhesive in the preparation of biofibres and particles reinforced bio composite. HY-950 is used as the hardener. CY 230 and HY 950 are supplied by M/s Fine Finish Organics Pvt. Limited, Chennai, India. The bio-composite is fabricated by squeeze casting method. The detailed procedure of casting is described in the references [46–48].