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Mixed mode I/II fracture criterion for orthotropic materials based on damage zone properties

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ABSTRACT

In the present paper, by definition of a damage parameter, a new mixed mode I/II fracture criterion is presented for predicting the initiation and propagation of cracks in orthotropic materials. Damage parameter can be obtained with respect to micromechanics consideration that inferred from the residual tensile and shear strength of fracture process zone at crack tip vicinity. Numerical and experimental approaches are employed for estimation of material properties in damage zone. A new approach named in this research as "Representative Circular Elements (RCEs)" is proposed for simulation of variety in directions and dimensions of damage zone micro-cracks. Comparison with experimental results is demonstrated the capability of the presented criterion.

1. Introduction

According to advantages of composite materials and widely application of these kinds of materials in various industries and applications, prediction of material fracture and failure using suitable and reliable criterion seems to be necessary.

Since, the mechanical behavior of orthotropic composite materials is commonly in the form of quasi-brittle materials, the fracture of these kinds of materials is generally associated with emerges of considerable damaged zone in crack tip vicinity.

Although damage area has very complex and non-linear behavior, ignoring the effects of this area on prediction of the fracture, is equivalent to forgoing of considerable energy which is wasted by the appearance and growth of micro-cracks. Also, without consideration of the damaged zone, several parameters are ignored that causing error in prediction of failure.

Despite the several efforts that have been made to propose the fracture criteria for orthotropic materials, but till now in the proposed criteria, damaged zone has not been considered properly or due to the complex mechanical behavior of this region, these criteria are associated with general and unrealistic approximation from fracture process zone.

Among the proposed fracture criteria for investigation of the orthotropic materials, the failure criteria that are considered the existence of the damage zone have better estimation of failure. In other words, successful fracture criteria for quasi-brittle materials should have a suitable method for including the behavior and properties of the damaged zone.

Due to the complexity of the fracture behavior of orthotropic materials, especially in mixed mode I/II loading, the primary proposed criteria in this context are generally based on curve fitting on experimental data [20]. Also, since wood is a natural orthotropic material, often has been tried to use this material as specimen [13].

Wu examined Balsa wood panels with central notch under mixed mode I/II loading, which notches were cut parallel to the fiber direction. He proposed an interactive equation as a criterion for crack growth in mixed mode I/II loading, based on

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Nomenclature

E, G	elastic and shear modulus
v	Poisson's ratio
$\bar{E}$, $\bar{G}$	elastic and shear modulus of damaged zone
$\bar{v}$	Poisson's ratio of damaged zone
w	crack density parameter
β_i	coefficient depends on elastic properties
c_{ij}	compliance matrix
ρ	orthotropic damage factor (odf)
ζ	location vector
C_R, C_{RL}	extensional and sliding compliance
$v_{ij},\ i,j = L,R,K$	Poisson's ratio on an orthotropic plane
$G_{ij},\ i,j = L,R,K$	shear modulus on an orthotropic plane
$E_i,\ i = L,R,K$	elasticity modulus
λ_{ij}	coefficients in the non-local stress fracture criterion
$T_M,\ T_m$	the strength along and across the fiber direction
$K_I,\ K_{II}$	mode I and II stress intensity factor
$K_{Ic},\ K_{IIc}$	mode I and II fracture toughness
s^o	compliance tensor of matrix
s^c	compliance tensor by participating α-th micro-crack in the matrix
s^{co}	compliance tensor without any attention to interaction
$\bar{A}$	interference surface between two micro-cracks
A	summation of micro-crack surfaces
$\bar{V}$	volume of interference between two micro-cracks
V	summation of micro-crack volume
γ	interference parameter
θ	micro-crack orientation with respect to normal direction
φ	orientation of the micro-crack in direction of micro-crack surface
H	general effective compliance tensor
$\mu_\theta,\ \mu_a$	variance of micro-crack orientation and size
$\sigma_\theta^2,\ \sigma_a^2$	mean micro-crack orientation and size
V_d	volume of damaged zone
V_m	volume of micro-cracks
N	number of micro-crack

curve fitting on experimental data. This criterion is often presented as a general fracture criterion for anisotropic composite materials [36].

In 1974, Leicester proposed a first order interactive equation within stress intensity in mode i and mode II based on the experimental results on pine wood (Pinus radiate) for investigation of the fracture of wood [19]. His criteria, recalls as a conservative mixed mode I/II fracture criterion in standard wood specimens.

Williams and Birch studied on fracture phenomena of two species of Utile (Entandrophragma utile) and Scots pine (Pinus-sylvestris) wood by considering the straight and angular cracks. They came into the conclusion that shear stress which creates the slip does not have any effects on mixed mode I/II fracture [35].

In 1979, Woo and Chow, investigated the mixed mode I/II fracture for Kapur (Dryobalanops) and Gagil (Hopesegal) specimens of wood with central and edge cracks. Their results indicated that mixed mode I/II fracture of wood depends on both stress intensity factors K_I and K_{II}. They did not provide any fracture criteria due to lack of information related to the pure mode II fracture toughness [37].

In 1982, Hunt and Croager [13] proposed an experimental equation for study the mixed mode I/II fracture of wood timber.

In 1983, Mall et al. applied wide number of mixed mode I/II fracture tests on Red Spruce (Picearubens) in the TL crack orientation and declared the interaction between K_I and K_{II} at the fracture, conclusively. They also introduced an interactive equation proposed by Wu [36] as the best criterion based on experimental results [20].

Recently, extended fracture theories have been offered by applying some modifications on well-known isotropic fracture criteria, including Strain Energy Release rate (SER) [11], Strain Energy Density (SED) and Maximum Tangential Stress (MTS) theory [27]. Major of research in this region, has been performed by Jernkvist in 2001 [16,17].

He tried to generalize the proposed isotropic fracture criteria for prediction of the mixed mode I/II fracture of wood specimens by considering the cracks along and perpendicular to wood fibers.