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Modeling of dynamic crack propagation using rate dependent interface model

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ABSTRACT

Influence of crack tip separation rate-dependent cohesive zone modeling at mesoscale and macroscale behaviors are investigated for sub-Rayleigh, intersonic and sub-Rayleigh to intersonic dynamic delamination growth speeds. A simple rate-dependency factor, k, is proposed for bilinear cohesive zone model (CZM) using the interface model of Corigliano et al. (2006). The factor is defined by the ratio of dynamic to static fracture toughness which is found to be related to the square of the ratio of pure-mode interfacial strengths for the selected bilinear CZM. Experimental cases from the literature with different loading rates are parametrically studied by varying the rate-dependency factor from unity, which is rate-independent, to infinity, a non-physical but theoretical condition. The first case is the three-point impact bending test that exemplifies the low-speed mode-I dynamic fracture. Next, asymmetric impact loading of polymer–composite experiment providing a mode-II dominated high speed intersonic propagation is simulated with various k. After comparing with mode-I low speed and mode-II dominated high-speed dynamic fracture experiments, an parametric analysis is carried out for a mixed-mode sub-Rayleigh to intersonic dynamic delamination in composite L-beams and compared with the experiments from Gozluklu et al. (2015). For this case, it is observed that the macroscopic aspects of fracture do not change with the rate-dependency factor. The effect of rate-dependency on crack growth kinetics is also found to be negligible for crack initiation and early stages of propagation, although the energy release rate increases. For one of the crack tips growing at intersonic speeds, the crack tip slows to sub-Rayleigh as the rate-dependency factor goes to infinity. The crack tip speeds for $k > 1$ provides slightly better results compared with the experiments. In conclusion, rate-dependency is observed to be necessary in accurately modeling low speed, and low-to-high speed crack propagation cases but not in high-speed intersonic crack propagation.

1. Introduction

One of the main failure modes in laminated composite structures is *delamination*, which is an interfacial crack separating individual plies of the laminate. In delamination, the crack propagates along a weak interface, which is the bonding surface of the plies. As the crack is forced to grow along a predetermined path, the interfacial crack cannot change its direction by branching. Under dynamic loading, Washabaugh and Knauss [1] showed that mode-I crack growth along a weak interface can reach the Rayleigh wave speed (C_R) of the material, which is faster than a crack growing in a bulk medium that can barely reach half of the C_R [2] due to crack branching. It can be stated that interfacial crack growth is expected to be faster than a crack growth in a bulk medium. Under mode-II loading, Rosakis et al. [3] showed that the speed of crack growth exceeds the shear wave speed of the material (C_s), becoming *intersonic*, if sufficient external energy is supplied. Intersonic crack growth changes the stress distribution in front of the crack tip with shear Mach waves emanating from the crack tips being observed. For isotropic materials, the crack growth speed under mode-I loading cannot exceed C_R, whereas mode-II crack growth speed can exceed the shear wave speed (C_s) [4–6] where the crack travels at a sustained speed of $\sqrt{2}\,C_s$ [7–9]. Similarly, for orthotropic materials, Coker and Rosakis [4] reported that intersonic interfacial crack was attained in unidirectional composite laminates propagating at a material specific sustained speed [4,6,10,11]. In these studies, intersonic crack propagation is achieved using “sudden loading”; impact loading was used in Refs. [3,4] or small

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explosions under uniform-constant compressive loading was used to initiate the sliding in Ref. [12]. Moreover, intersonic crack growth is attained under mode-II dominated ideal loading conditions and using special specimens.

In the aerospace industry, delamination is considered to be an insidious type of damage because it may propagate undetected until the catastrophic failure of the whole part. Due to this reason, regulations in civil aviation focuses on inhibiting the initiation of delamination and not allowing the propagation of delamination [13]. As the propagation or fatigue crack growth is not permitted, the majority of composite design is based on static sizing that concerns initiation of delamination [14,38]. The process of delamination, which occurs rapidly under quasi-static loading in the development tests, are an unexplored area for the industry. Recently, Gozluklu et al. [15] experimentally observed the dynamic delamination in L-shaped composite laminates used in aircraft wings with a high-speed camera. They showed that the delamination process is very dynamic and that the crack tip speed exceeds the shear wave speed of the material, becoming *intersonic*. Under quasi-static shear loading, delamination in mode-I is initiated. Delamination then gradually transitions to pure mode-II while the crack tips accelerate from sub-Rayleigh to intersonic speed regime. In Ref. [15], the propagation of intersonic delamination is found to cause shear Mach waves similar to the case of Coker and Rosakis [4]. In the numerical modeling of this problem [15–19], static material properties were used. The current study was initially motivated by using crack tip separation rate-dependent interface properties in this unique case of intersonic interface crack propagation under quasi-static loading.

The interfacial fracture toughness, G_c, and interfacial strength, T_0, are reported as rate-dependent material properties [20,21]. These properties logarithmically increase at higher crack tip speeds and/or the crack tip separation velocities in delamination of composite laminates. Corigliano and Ricci [22] reported a slight increase in the failure load in mode-I fracture toughness in Double Cantilever Beam (DCB) tests, where the delamination grows stably. In fact, the effect of rate-dependency at high-speed dynamic fracture is still under discussion for delamination. There are numerous studies successfully simulated intersonic delamination experiments without using rate-dependency [23–26]. Along with the uncertain influences of rate-dependent interface modeling, rate-dependent interface properties are hard to obtain since they are very sensitive to the experimental setup [22]. Consequently, in the current study, a simple "rate-dependency factor" that defines the ratio of rate-dependent interface properties on the static values is proposed and parametrically used for assessing the effects of rate-dependency.

Cohesive zone modeling (CZM) is used to model delamination. Cohesive zone modeling was first suggested by Dugdale [27] and Barenblatt [28] as a local transition/process zone between traction free and elastic zones in front of a crack tip. It was proposed to be constitutive law of the process zone in terms of *crack tip separations* and *tractions*. These constitutive laws are implemented by interface elements into finite element codes. Delamination is a good candidate for using CZM since the crack grows along a predefined interface where the interface elements can be confidently located.

In the literature, CZM has been widely used in the forms of piecewise-linear [29], polynomial [30], linear-polynomial [31], linear-decaying [32], rigid-linear [33], bilinear [34–36] and exponential [24] traction-separation laws. Bilinear CZM has been successfully applied to modeling of delamination in laminated composite materials under static loading [34–36,40–46]. CZM was also used to model intersonic fracture in composite materials. For example, Dwivedi and Espinosa [46] used CZM for impact loading of composites and Gozluklu et al. [15] did the same for quasi-static loading. In this study, *Bilinear CZM* proposed by Mi et al. [36] was modified to involve a rate-dependent behavior based on crack tip separation speed.

There are numerous studies that used crack tip speed or crack tip separation rate-dependent CZMs for modeling of crack propagation along a weak interface. Rahul-Kumar et al. [47] proposed a model based on the inverse power of the separation velocity and delamination of composite laminates under contact. Landis et al. [48] derived a rate-dependent interface formulation for the piece-wise linear Tvergaard and Hutchinson [29] type of CZM. They reported enhancement of fracture toughness and maximum stress at higher loading rates for the fracture of epoxy materials. Later, Corigliano and Ricci [22] proposed a rate-dependent bilinear CZM for implicit (static) finite element scheme. They simulated stable crack propagation in DCB and End-Notch Flexure (ENF) experiments at different loading rates using their rate-dependent bilinear CZM. Similarly, Corigliano and Mariani [49,50] and Corigliano and Allix [51] applied rate-dependent CZMs to the delamination growth analysis using implicit FEA. Samudrala et al. [52] used a rate-dependent CZM, specifically with a linear dependency for the mode-II separation velocity, for the simulation of sub-Rayleigh and intersonic crack propagations along the weak interface of two bonded PMMA plates [53]. In their study, the fracture energy was proportional to the loading rate and acceleration of the crack tip. Samudrala et al. [52] showed that the fracture energy was considerably rate-sensitive in the PMMA plates. Kubair et al. [54] developed a rate-dependent polynomial type of CZM which was used in conjunction with spectral method [54]. Anvari et al. [55] proposed a rate-dependent interface cohesive model composed of polynomial and piecewise linear parts for ductile fracture in aluminum. Recently, May [56] used four different types of rate-dependent cohesive zone models to numerically model the delamination formed under low-velocity impact. May [56] concluded that the delamination area induced by the impact is significantly affected by rate-dependent material properties in the cohesive zone model. Corigliano et al. [57] proposed an elementary definition of rate-dependency behavior for delamination in composite laminates. This rate-dependent interface model was embedded into several existing cohesive constitutive laws such as the CZMs proposed by Rose et al. [59,60], Camacho and Ortiz [33] and Xu–Needleman [61]. Due to the simplicity and its application to the delamination of composite laminates, the rate-dependent model proposed by Corigliano et al. [57] is used in our study.

In this paper, influences of crack tip separation based rate-dependent interface modeling to low-speed, high-speed and low-to-high speed delamination cases are studied. Initially, the rate-dependent interface model of Corigliano et al. [58] is embedded into bilinear CZM of Mi et al. [36]. The rate-dependent bilinear CZM is implemented into ABAQUS/Explicit via VUEL user-subroutines [62]. A rate-dependency parameter denoted by "k" is defined by the ratio of dynamic fracture toughness attainable by infinitely fast separations to quasi-static fracture toughness. For the bilinear CZM, it is shown that this factor inherently relates the ratio of interfacial tractions in the power of ½. The factor of "k" eventually represents the amount of toughening and strengthening that can be attained by the interface under high-speed crack tip separations. Afterward, parametric studies based on "k" are performed for mode-I low-speed and mode-II high-speed interfacial crack propagation experiments taken from literature. These cases are also used to validate the rate-dependent cohesive interface element. The major focus is given to the delamination of L-shaped composite laminates studied by Gozluklu et al. [15] where low-to-high speed delamination under mode-I, mode-II and mixed-mode quasi-static loading is attained. In the results, micro-mechanical and macro-mechanical responses of the delamination process were compared and contrasted. The experimental

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