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A MULTISCALE FRACTURE MECHANICS MODEL FOR PREDICTING DAMAGE EVOLUTION IN LAMINATED COMPOSITES SUBJECTED TO IMPACT LOADING

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ABSTRACT

Laminated polymeric composites are utilized in a variety of structural applications wherein impact loads are a common design consideration. In such circumstances damage is usually observed in the form of a variety of fracture modes including matrix cracking, delamination, and fiber fracture. Multiple cracks with significant energy dissipation are often observed experimentally before complete loss of structural integrity is attained. Therefore, since it is often possible to keep the part in service after the impact event, it is useful to develop models for predicting the post impact performance of the part.

The interaction of crack propagation makes it essential to model the evolution of these damage events during impact loading. In order to capture the physics of all of the fracture events both accurately and efficiently, it is possible to develop a multi-scale continuum mechanics framework in which successively larger scales are utilized to model each of the fracture modes. This approach is taken in the current paper to account for microscale damage ahead of delaminations, mesoscale matrix cracking, local scale delaminations, and global scale part response. The resulting micro-meso-local-global methodology utilizes ductile fracture mechanics on each scale to effect crack growth of the three types described above, with the smaller two scales developed analytically, and the larger two developed computationally by means of the finite element method. Linking between the four different scales is obtained by utilizing damage dependent homogenization theorems that account for energy dissipation due to fracture on the smaller scales.

KEYWORDS

laminated composites, damage evolution, fracture, multi-scale modeling

INTRODUCTION

Much effort has been devoted in recent years towards obtaining improved understanding of damage evolution in composites subjected to impact, as evidenced by numerous publications in the open literature.

Laminated composites impacted at low velocity by blunt objects are susceptible to the development of matrix cracks, fiber cracks, and interply delaminations[1]. While much of this damage may not be readily visible at the surface, it is capable of substantially reducing the residual strength and stiffness of the laminate. The resultant damage induced stress redistribution can lead to the failure of the component. Therefore, it is essential to be able to predict the damage evolution that occurs during the impact event so that the impact resistance, residual strength, and serviceable life of the laminate can be predicted.

While few papers have appeared which attempt to address the three dimensional problem of impact, noteworthy are those of Wu and Springer [2,3] and of Chang and coworkers [4,5]. In these works a three dimensional transient dynamic finite element analysis is presented for the study of impact. However, delamination is not modeled. To the knowledge of the author none of the delamination damage models found in the published literature accounts for the development of the process zone ahead of the delamination front and the resulting nonlinearity in the interfacial mechanical response.

Recently, the author has developed together with coworkers a micromechanics model for predicting the evolution of matrix cracking [6-8], and this model has previously been shown to be accurate when compared to experiment for polymeric composite plates subjected to quasi-static monotonic loading [9-12]. The problem of predicting the evolution of delaminations is much more complicated than that of matrix cracking. We have compared model predictions favorably to experiment for a variety of two dimensional examples [13,14]. While the problem of a single delamination in an elastic medium has successfully been solved [15], the prediction of multiple propagation of planar delaminations has only recently been considered. However, utilizing a cohesive zone model [6-24], the author and coworkers have been able to predict the evolution of up to seven simultaneous delaminations in a two dimensional setting [25], and this has been compared favorably to experimental results. Furthermore, the author and coworkers have also been able to predict the progression of multiple modes of damage in a two dimensional setting, as shown in Fig. 1. In addition, the algorithm has been utilized to predict multiple damage modes in a three dimensional plate with a circular cutout [26]. These predictions are among the most complex attempts known to date for predicting damage progression in composites subjected to impact.

SOLUTION METHODOLOGY

The model is three dimensional and computational in nature, utilizing the finite element method, and this model is implemented to the code SADISTIC [27]. Crack growth is simulated via the cohesive zone model currently under development by the author and coworkers [20-25]. The cohesive zone model for predicting damage evolution in laminated composite plates is cast within a three dimensional continuum finite element algorithm capable of simulating the evolution of matrix, fiber, and delamination cracking in composite structures subjected to ballistic impact. Cracking on vastly differing length scales is accounted for by employing global-local techniques, with appropriate damage dependent homogenization techniques introduced to bridge the disparate scales.

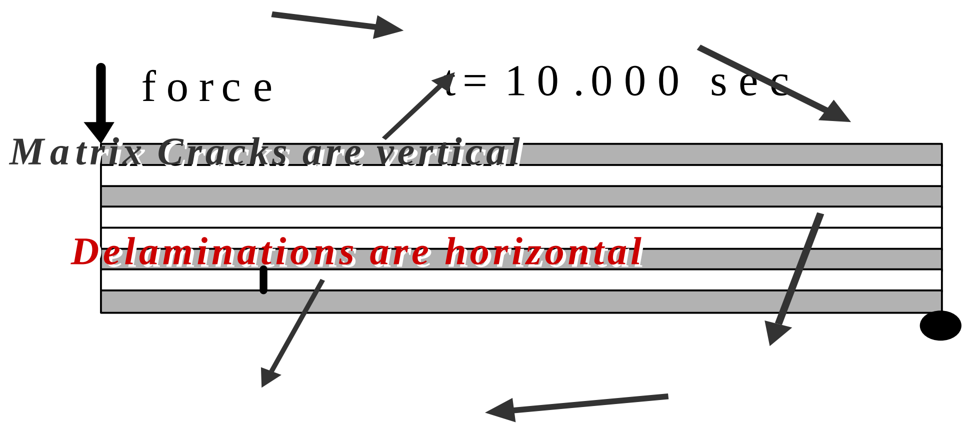

Fig. 1. Evolution of damage in right half plane of $[0,90,0,90]_s$ beam subjected to transverse loading

In order to describe this technique, consider a scenario in which damage exists simultaneously in a solid on two (or more) significantly different length scales. Of course, one way to analyze such a problem is to consider the possibility of cracks extending everywhere and at all length scales simultaneously in the continuum. However, this is untenable by both analytic and computational means for all but a few simple scenarios at the current state of the art. Alternatively, suppose we define the length scale of the microcracks to be l_1, and the length scale of the macrocracks to be l_2. Then, under the circumstance that $l_2 >> l_1$, it can be shown that continuum scale analyses can be carried out on the smaller and larger scales separately (so long as other geometric length scales are also widely separated) and linked together by a homogenization principle without significant loss of accuracy. This may be accomplished by completing the following tasks in succession: 1) perform a continuum scale analysis of the microscale problem; 2) homogenize the results of the microscale analysis, thus producing a damage dependent macroscale constitutive theory; and 3) solve the macroscale continuum problem (including crack propagation) using the damage dependent constitutive theory produced in 2). This procedure will obviate the presence of microscale induced stress concentrations on the macroscale, so that some loss of accuracy is inevitable. However, this loss of accuracy may not be significant when the length scales are significantly different. Furthermore, the savings in computational and/or analytical difficulties gained by employing homogenization techniques will in many cases make a heretofore untractable problem solvable. Note also that if the homogenization process is performed correctly, then the total energy dissipation predicted by the macroscopically homogenized constitutive equations will be identical to that predicted on the microscale, except that the homogenization process will result naturally in a dissipative damage parameter on the macroscale. Similar situations exist in other fields of applied physics, such as the process of linking continuum mechanics to molecular dynamics. Although temperature and entropy do not exist as state variables at the molecular scale, the process of homogenizing the effect of many molecular motions results naturally in the introduction of these variables at the continuum scale.

It is possible to employ this procedure on multiple scales at one time, where the number of scales, n, is essentially determined by the physics of the problem. Thus, we can say

$$l_{m+1} \gg l_m \qquad m = 1, \ldots, n \tag{1}$$

The solutions to the problems on each of these length scales is then linked to the solutions on the adjacent length scales by utilizing homogenization techniques such as those recently developed by the author and coworkers for damaged media [28-30]. These solutions can then be used to model damage evolution on several differing length scales simultaneously.

CONCLUSION

While the technique described herein is too complicated to present in detail in such a short space, the technique has been shown to lead to accurate solutions that are computationally efficient for several problems that involve damage evolution on widely differing length scales. The interested reader will find these results documented in references [20-30].

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