Transactions on the Built Environment vol 32, © 1998 WIT Press, www.witpress.com, ISSN 1743-3509

Micromechanics based modeling of damage in composites under high velocity impact – a review

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Abstract

This paper presents a review on the status of micromechanical and engineering modeling of polymeric matrix composites under shock and impact loading conditions. The various stages of projectile penetration mechanisms, damage mechanisms, and modeling approaches are briefly reviewed. In the modeling efforts, an outline of the various relationships developed for individual damage mechanisms followed by phenomenological constitutive relations used in modeling the penetration process is presented.

1. Introduction

Understanding and modeling of the complex damage failure processes in fiber reinforced polymeric composite laminates are very critical for the successful use of these composites in penetration-resistant light weight armor applications. Most often, the damage mechanisms in polymeric composites subject to shock and high velocity impact loading include fiber fracture, matrix cracking, interfacial debonding and ply level delamination. In addition, one type of damage may influence the initiation and propagation of another type of damage. The mechanics of projectile penetration through fiber-reinforced composite targets is still not fully understood; however, several experimental investigations have been undertaken to document the dominant failure mechanisms in composite targets. For example, Bless, et al., [1-3] summarized various penetration mechanisms into graphite/epoxy and S-2 Glass/phenolic composites. In the material modeling of polymeric composites, an approach in which the total effects of various damage mechanisms can be described through a reduced number of internal state variables is essential.

2. Penetration Mechanisms

The penetration process of a blunt impactor can be divided into three stages: impact, entry, and exit.

In the ***impact phase***, shock waves are generated in both the projectile and target. The maximum intensity of the shock wave depends on the impact velocity and the shock impedance of the target and projectile. During the impact phase, the release waves from the stress-free lateral surfaces can cause delamination of composite targets. In the ***entry phase***, the target material suffers mostly compressive failure in the contact region. The fibers and matrix fail around the penetration cavity. The dominant failure mechanisms seem to be shear cutting of fibers and cavity expansion, which refers to the radial expansion of the target material. A schematic of selected damage processes in a composite laminate is shown in Figure 1 [4]. This radial expansion is usually accompanied by local buckling of the fibers and microcracking of the matrix material. The matrix suffers mostly compressive and shear failure during this stage.

In the ***exit phase***, a transition from compressive failure to tensile failure seems to occur, usually accompanied by extensive delamination. The time dependent delamination process is initiated during the earlier time of the impact phase. However, the delamination growth (propagation) will continue until the arrival of the projectile near the delaminated areas. The plies are pushed ahead of the projectile and tensile failure of fibers may occur away from the projectile nose. Fiber pull-out may also occur in this stage. Projectile energy is absorbed mainly due to fiber failure, fiber pull-out and delamination, as well as transfer of kinetic energy to the target.

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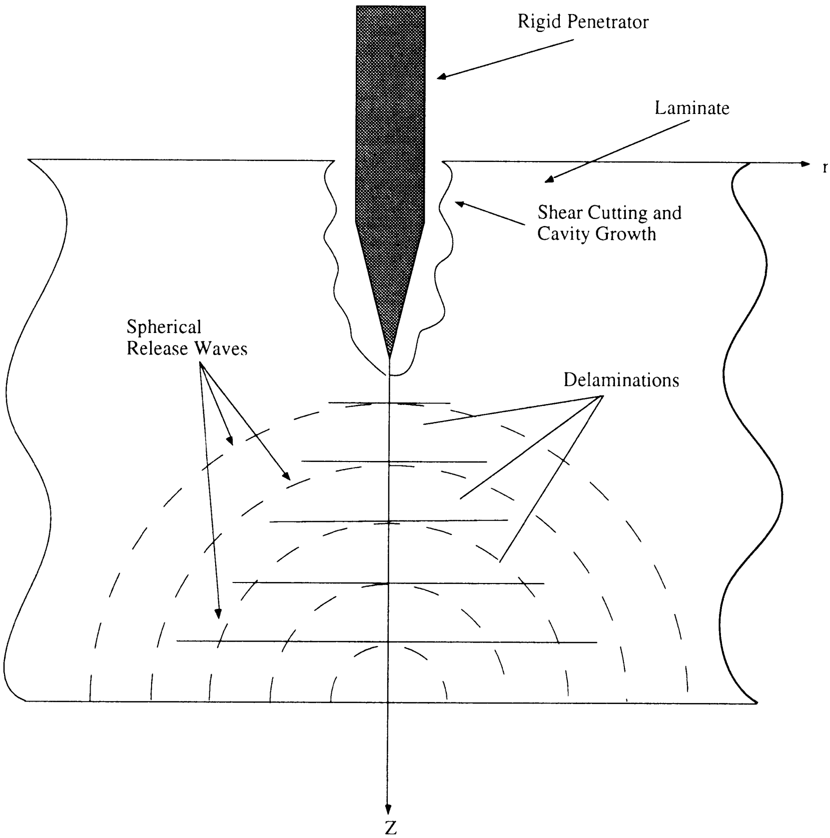

Figure. 1 A Schematic of the Delamination in a Composite Laminate Due to Penetration by a Metal Projectile [4]

In general, the failure mechanisms involve fiber breakage, matrix cracking, ply cracking, delamination, and fiber pull out (fiber debonding). Various energy dissipation mechanisms active during the high impact event is schematically shown in Fig.2. It may not be practical to describe each and every one of these failure processes. However, it is important to identify and model a few salient and dominating processes in the penetration models.

3. Modeling damage mechanisms

There is a relatively large body of work for composites under low impact loading conditions [5-8]. Because of inherent heterogeneity and anisotropy, unlike metals, behavior of composites vary with

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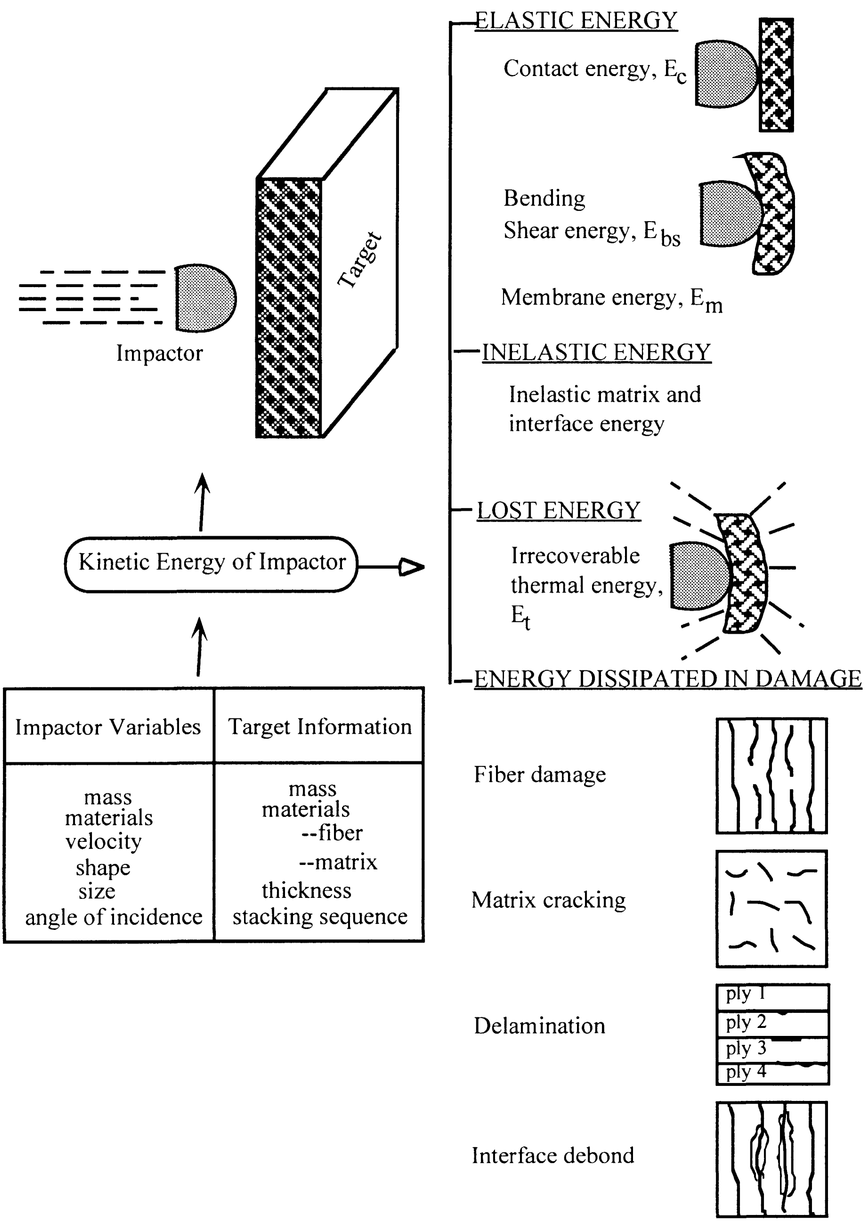

Figure 2 : Schematic of energy balance approach in high impact event

geometry (thickness, fiber orientation, ply sequence), and constituent material (matrix, fiber, interface) properties. Also extension of low velocity (drop weight) results in composites to high velocity (ballistic penetration) needs a careful study. In the former the damage is barely visible whereas in the latter, much higher energy is encountered triggering a new sequence of failure modes. In low velocity impact the predominant failure modes are delamination and matrix cracking; in high velocity impact, failure is dominated by fiber fracture, pull out and matrix shear failure [7].

3.1 Fiber Breakage

A statistical method commonly used to determine the strength of a brittle fiber is the Weibull [9] model. In this model, it is assumed that the fiber material is isotropic and statistically homogeneous [10]. This method has been widely used to model the fiber failure in polymer matrix composites [11-15]. In the case of woven or braided composites, the strength or fracture toughness of the fiber bundle is the most important quantity for analysis, rather than the strength of a single fiber.

The strength theory of bundles is derived from the statistical theory for the strength of a single fiber [16]. Coleman [17] examined the strength of long fibers taken from a common source (e.g. a spool of fiber). He showed that $P(\sigma_f)$, the cumulative strength distribution function, has the form of a Weibull distribution (σ_f is the failure stress of a fiber). Given a fiber divided into a number of elements or links, the probability that a fiber link has a strength greater than σ_f is $1-P(\sigma_f)$, and the probability that all links do not fail at σ_f is $[1-P(\sigma_f)]^N$. Therefore, the probability that at least one link out of 'N' links breaks is:

$$P_f(\sigma_f) = 1 - [1 - P_f(\sigma_f)]^N \qquad (1)$$

For long fibers, (as N $\rightarrow \infty$), the cumulative probability of failure is given by:

$$P_f(\sigma_f) = 1 - e^{\left[-L\left(\frac{\sigma_f}{\sigma_0}\right)^m\right]} \qquad (2)$$

where P_f is the probability of failure of a fiber at a stress level equal to or less than σ_f, σ_0 is the Weibull scale parameter for the unit fiber length ratio, 'm' is the Weibull shape parameter and 'L' is the length ratio with respect to a reference length (the fiber length at which σ_0 and 'm' are determined). The Weibull scale and shape parameters for a fiber material are determined from several experiments [16].

3.2 Interface Debonding

Fiber-matrix interface plays a very critical role in determining the damage process in composites. Interface models can be broadly classified into two categories, namely interphase layer models and spring layer model. The interface layer model Robertso [18] considers an interface layer between the fiber and matrix of specified thickness and thermomechanical properties different from those of the fiber and the matrix. Interface layer models in general require too many parameters for completely describing the interphase. Also it is not possible to determine these parameters through simple testing procedures.

The spring layer model [19] considers a very thin interfacial zone of unspecified thickness between the fiber and matrix. At the interface I between phases 1 and 2, the usual condition of the continuity of the traction vector must be satisfied

$$\left[\sigma_{ij} n_j\right]_I = 0, \tag{3}$$

where n is the normal vector to I, and σ is the stress.

3.3 Matrix Microcracking

The goals for a successful micromechanics based damage is in predicting microcrack initiation and the increase in density of microcracks. When microcracks form in an undamaged composite, the stresses change. In general all stress components become non-zero. Garrett and Bailey [8] assume that the x-direction stress in the 90° plies becomes equal to the transverse strength of the unidirectional material. The theory simply states that microcracking initiates when

$$\sigma_{xo}^{(1)} = \sigma_T, \tag{4}$$

where σ_T is the transverse tensile strength of a unidirectional laminate. The strain to initiate microcracking is then

$$\varepsilon_{init} = \frac{\sigma_T - k_{th}^{(1)} T}{E_o^c k_m^{(1)}} \tag{5}$$

where E_o^c is the longitudinal modulus of the undamaged laminate, $k_m^{(1)}$ and $k_{th}^{(1)}$ are mechanical load and thermal stress constants for ply group 1. This analysis is a first-ply failure model derived using a maximum stress failure criterion. Although simple in concept, the strength model or first-ply theory is in poor agreement with experimental observations.

The failure of strength-based models led Parvizi et al. [20] to propose an energy criterion. They postulate that the first microcrack forms when the energy released due to the formation of that microcrack exceeds some critical value. By the energy criterion, the first microcrack forms when $G_m \geq G_{mc}$, here G_m is the energy release rate associated with the formation a complete microcrack and G_{mc} is the microcracking fracture toughness of the composite material system. This prediction is in better agreement with experimental observation than any strength model because it correctly predicts that the strain to initiate microcracking increases significantly as the thickness of the 90° plies decreases [6]. The energy criterion appears to capture most features of the experimental observations and to be a significant improvement over strength theories.

Liu and Nairn [21] proposed an energy failure criteria which using total microcrack energy release rate to predict microcrack density as a function of applied load. The final expression of energy release rate, G_m is:

$$G_m = [\sigma_{xo}^{(1)}]^2 C_3 t_1 Y(D) \qquad (6)$$

where C_i are materials constants related to elastic constants, $\sigma_{xo}^{(1)}$ is the initial x-axis stress in ply group 1, t_1 is the total thickness of ply group 1, and *Y(D)* is a function that depends on the microcrack density, r by following approximation:

$$Y(D) = 2\chi(f\langle\rho\rangle/2) - \chi(f\langle\rho\rangle) \qquad (7)$$

3.4 Damage Due to Delamination

Laminated continuous fiber composites are observed to develop substantial load-induced delamination at the ply level prior to failure. Allen [22] developed an approach to model damage evolution in a

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laminated structural component for any loading history, given only a set of input data which does not depend on the stacking sequence.

Furthermore, the structure is modeled as a simply connected domain, with the effects of microcracking reflected by a set of internal state variables. The approach constructs a nonlinear damage-dependent lamination theory which can be implemented in any computational structural algorithm.

The key of the model is the damage-dependent lamination theory which models the effects of interply delaminations. Unlike the ply level model for matrix cracking, statistical homogeneity cannot be assumed for delaminations. The damage is therefore accounted for via area averaging in the laminate plane, accompanied by a kinematic assumption through the thickness. Because the lamination theory is damage dependent, it produces stress redistribution as damage develops for a given load history. This predicted stress redistribution in turn affects the evolution of damage, thus producing a damage evolution model which can be used for any stacking sequence regardless of the load history applied to the component.

4. Modeling the high impact event

Modeling the penetration of a metal projectile into a composite laminate at high velocity impact is extremely complex. Both the geometric and material responses are three dimensional and usually a two dimensional axisymmetric idealization is not possible. Computational methods demand extensive computing resources, in terms of memory and CPU time. Several complications arise in the penetration modeling of a composite target. A major simplification in the penetration modeling of a homogeneous, isotropic target is done by invoking axisymmetry and further simplification is done assuming cylindrical cavity expansion, which reduces the problem to a one-dimensional problem. Such simplification is generally not possible in the case of composite targets; for special cases e.g., quasi-isotropic laminates whose in-plane properties are isotropic, one can assume "restricted axisymmetry". A substantial simplification in the model can be realized by invoking a “plane strain" assumption, where the composite laminate target is idealized as a stack of thin, independent layers (plies) which are normal to the penetration direction. Incidentally, this same kinematic assumption has also been used in the penetration modeling of metal targets [23].

Recently Lu and Vaziri [24] presented an extensive review report on constitutive and failure models for numerical analysis of the impact response of composite materials. In this report, they have cited the various papers that describe damage initiation and effects of damage on stiffness reduction. Several analytical approaches to modeling damage in composite laminates were also cited. Most of these studies were performed under either quasi-static loading or low velocity impact conditions. For very high velocity impact situations, the pressure in the region surrounding the penetrator is extremely high and greatly exceeds the strength of the target material. Typically, hydrodynamic theory is used in such cases to predict the depth of penetration and the deceleration of the penetrator. The basic hydrodynamic equations, developed mainly for elastic-plastic metallic targets, can be directly applied to composite targets; however, several fundamental issues need to be addressed.

Pierson, Delfosse, Vaziri, and Poursartip [25] developed an engineering approach to predict the dynamic penetration process of a rigid projectile into carbon fiber reinforced plastic (CFRP). To describe the penetration force vs. time for a flat impactor into CFRP, the Awerbuch-Bodner model [26] was employed. The model-predicted force-time history did not match well with the measurements. In the same paper, Pierson, Delfosse, Vaziri, and Poursartip [25] extended the use of this model to describe the response of CFRP to a conical projectile penetration with reasonable success. The model-predicted force vs. time matched the experimental data.

Lee and Sun [27] developed a model to predict the penetration process for composite laminates impacted by a blunt projectile. Under this study, a series of static punch tests was performed to study the mechanism of penetration. The test results showed that the delamination and plugging were the primary failure mechanisms in the laminates due to static penetration of a blunt projectile. This approach requires finite element modeling of the test configuration. The static penetration model is used to guide the simulation of the dynamic test. They predicted the ballistic limits of graphite/epoxy laminates reasonably well.

Using Whitney-Pagano [28] laminated plate theory, Zhu, Goldsmith, and Dharan [29, 30] developed an analytical model suitable to predict the ballistic limits of laminates. The deformation and failure modes include: 1) a spherical bulging (as in the Awerbuch-Bodner model), 2) delamination, and 3) fiber extension (to predict fiber breakage). Matrix cracking was neglected in this model. The penetration stages consisted of indentation, perforation, and exit of the projectile. A finite difference computer program solving the governing equations of Whitney-Pagano in conjunction with the various failure criteria was developed and the ballistic limit of a Kevlar/polyester laminate was successfully predicted.

Recently Bodner and Rajendran [31] adopted the Ravid-Bodner model [32] to predict the depths of penetration (DOP) in thick S2-glass fiber/polyester laminates due to a rigid steel projectile with a blunt nose. The directional properties were introduced into the model during different stages of the penetration process. Since the model is a two-dimensional isotropic model, it was necessary to introduce a pseudo-strength which was assumed to be the average of the in-plane and transverse strengths of the laminates. The measured strengths were employed in the analysis to predict the DOP in the laminates.

Among the various general purpose three dimensional codes, the DYNA3D code [33] has an orthotropic material model with a damage description capability. We are unable to cite any publication that describes a detailed penetration calculation using a fully orthotropic or even a 2D transversely isotropic material model in a hydrocode. The stress calculations are erroneous when metal based equations of state are employed since they are incapable of describing the shock attenuation characteristics of polymeric composites. Anderson, Cox, Johnson, Maudlin [34] presented a detailed description of an elastic-plastic orthotropic model; this model has been implemented in the EPIC code [35].

5. Summary

Fiber reinforced composites while providing distinct advantages over monolithic materials for lightweight armor applications, pose a great challenge in the design of an optimum configurations. Through computational design analyses, it is possible to exploit the full potential of composite capabilities. However, there is an urgent need for accurate descriptions of the effects of the various damage processes on the degradation of stiffness and strength through micromechanistic damage based constitutive models. Unlike metals, the behavior of composite laminates varies with geometry (thickness, fiber orientation, number of plies, etc.) and this geometry-influenced material property variation adds to the complexity of modeling the material behavior of composite laminates. Since composite materials exhibit anisotropic behavior, most simplified analyses consider composite laminates only with some material symmetry, such as quasi-isotropic, transversely isotropic, etc. An extensive three dimensional finite element analysis under shock and high velocity impact loading conditions

Transactions on the Built Environment vol 32, © 1998 WIT Press, www.witpress.com, ISSN 1743-3509

has not been considered until recently; however with the advent of increased computer capabilities, this approach is now feasible.

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