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Meso-scale modeling of hypervelocity impact damage in composite laminates

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ABSTRACT

Objectives: This paper presents an approach to numerical modeling of hypervelocity impact on carbon fiber reinforced plastics (CFRP).

Methods: The approach is based on the detailed meso-scale representation of a composite laminate. Material models suitable for explicit modeling of laminate structure, including fiber-reinforced layers and resin-rich regions, are described. Two numerical impact tests with significantly different impact energies were conducted on thermoplastic AS4/PEEK materials with quasi-isotropic layups. Simulations employed both SPH and Finite element methods.

Results: Results of simulations are verified against experimental data available from the literature and demonstrate good correlation with the experiments.

Conclusions: Developed modeling approach can be used in simulations where post-impact damage progression in composite material is of the main focus.

1. Introduction

Composite materials are being used extensively for space applications. During operation they can be subjected to hypervelocity impacts (HVI) of orbital debris at an average velocity of 11 km/s. A number of experimental programs have been conducted over the last 25 years to study the behavior of composites under HVI [1–9]. However, due to limitation on the projectile speed which can be achieved using the existing laboratory equipment (typically, no higher than 8 km/s) and extreme expensiveness of the physical experiments, modeling became an important tool for study of hypervelocity impacts.

Most papers related to modeling of HVI on fiber-reinforced plastics deal with particular type of application, such as spacecraft shielding (e.g., [10,11]). Composite materials in those works are represented as macroscopically homogeneous orthotropic media (referred as macro-scale or "homogenized laminate" approach in the following). This technique allows simulating adequately main HVI phenomena accompanied the shielding systems perforation and calculating the overall size of the impact hole or crater in composite. However, in order to obtain more detailed information about local damage and its progression in a composite, models of higher resolution are needed. It is especially the case for spacecraft load-bearing structural members (e.g., composite truss tubes) and pressurized components of onboard systems (e.g., composite pressure vessels) where the impact damage formation is governed by superposition of impact and quasi-static loading. Here mechanisms of post-impact fracture progression and possible failure of impact-damaged composite structure is of the main interest rather than just evaluation of the size of a perforation hole. Thus, higher level of detail is required for modeling of impact on such components.

Moreover, it was found in Ref. [12] that for filament-wound composites delamination propagation may be restrained by interweaving of filament bands and depends on the filament winding pattern used. Then adequate capturing of material damage and fracture requires explicit representation of complex winding patterns in numerical model. Macro-scale approach cannot be utilized in this case and, thus, is not applicable for simulating HVI-induced damage in general type of continuous fiber/polymer matrix composites.

In this paper we present more general approach based on meso-scale representation of composite laminates, including modeling of individual plies and resin-rich regions between them. This technique can be classified under "continuum approach" in damage mechanics (e.g., [13]). Although we do not deal directly with filament-wound composites in the current paper, the technique we describe here can also be applied to this type of materials with no additional modifications required.

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Our modeling approach is presented in Section 2 of the current paper. It is then used to simulate damage produced by aluminum projectiles in AS4/PEEK laminates under conditions similar to those used in experiments conducted at the University of Kent at Canterbury (UKC data) and NASA Johnson Space Center (JSC data) and reported in Refs. [5] and [7]. Two HVI tests used for simulations were chosen to represent impacts with different kinetic energies. Results of simulations compared with the experimental data in terms of predicted and measured delamination area. ANSYS AUTODYN-3D hydrocode was used for all simulations presented in this paper.

2. Modeling approach

Fracture of a composite includes both intralaminar and interlaminar mechanisms. In the former case, it is confined to anisotropic linearly elastic fiber-reinforced layers of a laminate and is brittle in nature for the most of existing CFRP systems. Mechanisms of intra-ply damage include fiber breakage and matrix cracking along fibers. Interlaminar fracture or delamination is attributed to relatively tough isotropic polymer matrix concentrated in the resin-rich regions (RRR) between each pair of fiber-reinforced layers. Deformation in these regions prior to failure initiation is determined by the properties of the polymer resin. Subsequent damage and fracture may be either due to deformation of the matrix within RRR (cohesive fracture), or due to debonding on the interface between resin-rich region and fibers adjacent to it (adhesive fracture) [14]. To reproduce the above mentioned fracture mechanisms more precisely, each composite laminate in our simulations has been represented as a structure consisting of alternating fiber-reinforced and finite-thickness resin-rich layers. By doing that, we uncouple the description of behavior of two physically different components of a laminate and employ more suitable material models for each of them. This introduces higher level of realism in modeling compared to the case of macro-scale representation.

To be suitable for hypervelocity impact simulations, in general, materials being modeled has to be characterized in terms of 1) stress-strain relations; 2) equation of state (EOS); 3) failure initiation criteria; 4) post-failure response model. Two next sub-sections describe material models employed in our study to simulate behavior of fiber-reinforced layers (Section 2.1) and interlaminar regions (Section 2.2).

2.1. Modeling of fiber-reinforced layers

Each layer in our study was considered as a homogeneous orthotropic material. In this case, incremental stress-incremental strain relations can be represented as follows:

$$\begin{bmatrix} \Delta\sigma_{11} \\ \Delta\sigma_{22} \\ \Delta\sigma_{33} \\ \Delta\sigma_{23} \\ \Delta\sigma_{31} \\ \Delta\sigma_{12} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{21} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{31} & C_{32} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix} \cdot \begin{bmatrix} \Delta\varepsilon_{11} \\ \Delta\varepsilon_{22} \\ \Delta\varepsilon_{33} \\ \Delta\varepsilon_{23} \\ \Delta\varepsilon_{31} \\ \Delta\varepsilon_{12} \end{bmatrix} \tag{1}$$

Important aspect of the hypervelocity impact physics is the propagation of shock waves through the interacting materials. As, in general, response of composites to shock loading is nonlinear, incremental stress-incremental strain relationships described by equation (1) should be modified. The aim of such modification is to separate volumetric response of the composite from its ability to carry shear stresses and to describe the former in terms of nonlinear equation of state (EOS). In this part, we employed in our study constitutive model available in AUTODYN [15]. According to this model, strain increments ($\Delta\varepsilon_{ij}$) in equation (1) can be split into their average ($\Delta\varepsilon_{ave}$) and deviatoric ($\Delta\varepsilon_{ij}^d$) components in the following manner:

$$\Delta\varepsilon_{ij} = \Delta\varepsilon_{ij}^d + \Delta\varepsilon_{ave} \tag{2}$$

Defining the average strain increment as a third of the trace of the strain tensor

$$\Delta\varepsilon_{ave} = \frac{1}{3}(\Delta\varepsilon_{11} + \Delta\varepsilon_{22} + \Delta\varepsilon_{33}), \tag{3}$$

and approximating, for small strain increments, the volumetric strain increment as

$$\Delta\varepsilon_{vol} \approx \Delta\varepsilon_{11} + \Delta\varepsilon_{22} + \Delta\varepsilon_{33}, \tag{4}$$

the total strain increments can be expressed in terms of the volumetric and deviatoric strain increments, which results in the following orthotropic constitutive relation:

$$\begin{bmatrix} \Delta\sigma_{11} \\ \Delta\sigma_{22} \\ \Delta\sigma_{33} \\ \Delta\sigma_{23} \\ \Delta\sigma_{31} \\ \Delta\sigma_{12} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{21} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{31} & C_{32} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix} \cdot \begin{bmatrix} \Delta\varepsilon_{11}^d + \frac{1}{3}\Delta\varepsilon_{vol} \\ \Delta\varepsilon_{22}^d + \frac{1}{3}\Delta\varepsilon_{vol} \\ \Delta\varepsilon_{33}^d + \frac{1}{3}\Delta\varepsilon_{vol} \\ \Delta\varepsilon_{23} \\ \Delta\varepsilon_{31} \\ \Delta\varepsilon_{12} \end{bmatrix}, \tag{5}$$

Defining pressure increment as one third of the trace of the stress increment tensor

$$\Delta p = -\frac{1}{3}(\Delta\sigma_{11} + \Delta\sigma_{22} + \Delta\sigma_{33}), \tag{6}$$

and substituting $\Delta\sigma_{ii}$ in (6) from (5), yields:

$$\begin{aligned} \Delta p = {} & -\frac{1}{9}[(C_{11} + C_{22} + C_{33} + 2(C_{12} + C_{23} + C_{31}))]\Delta\varepsilon_{vol} - \\ & -\frac{1}{3}[C_{11} + C_{21} + C_{31}]\Delta\varepsilon_{11}^d - \frac{1}{3}[C_{12} + C_{22} + C_{32}]\Delta\varepsilon_{22}^d - \\ & -\frac{1}{3}[C_{13} + C_{23} + C_{33}]\Delta\varepsilon_{33}^d, \end{aligned} \tag{7}$$

Here multiplier of volumetric strain increment can be recognized as “effective” bulk modulus (K') of orthotropic material (following the analogy with isotropic bulk modulus):

$$K' = -\frac{1}{9}[(C_{11} + C_{22} + C_{33} + 2(C_{12} + C_{23} + C_{31}))] \tag{8}$$

Finally, equation (7) can be modified to take into account nonlinear dependence of pressure on volumetric strain: