Effect of Fiber Volume Fraction on Composite Response under Ballistic Impact Load

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1 Introduction

Fiber volume fraction is the ratio which decides on the amount of fiber material and resin presence in the manufacturing of composites. Hence, this ratio plays a significant role in the determining the elastic properties of the material. It is necessary to have the right amount of mix as a minor change in the properties can bring about a catastrophic failure. In the present study, we strive to investigate the variation in the elastic parameters of the material. The study investigates the effect by simulating a ballistic impact load over a lamina with varying fiber volume fraction. The elastic parameters are calculated using the rules of mixture and are then used to determine the response of lamina subjected to ballistic impact. In order to observe the response of lamina, a progressive failure damage model in consideration with a string of failure criteria is implemented while considering fiber and matrix damage that are associated with various modes of failure which occur during the course of damage based on the continuum damage mechanics (CDM) model. A commercial FE code ABAQUS is used to formulate a subroutine VUMAT and simulate the phenomenon of penetration. The present study investigates the effect of fiber volume fraction on the strength of composite materials. A lamina is subjected to impact by a .22 caliber projectile while varying its volume fraction with help of a Python interface. The damage pattern of lamina are studied to determine the effect of volume fraction.

2 Damage modeling

A two dimensional progressive damage model suggested by Matzenmiller et. al.[1] is implemented using VUMAT to model the response of composite lamina. The damage model has two phases, namely damage initiation which occurs when any of failure criteria is satisfied, and damage evolution under which the elastic properties of the lamina deteriorates and ultimately becomes 0 when the material fails. The change in the magnitude of elastic properties results in variation in stresses. The 5 failure modes associated with the composites used are 1 fiber shear punch, as the fiber tends to distort and in turn giving rise to cracks on the inner surface. Fiber shear punch is a modeified Hashin[2] criteria for fiber failure. The criteria are introduced for a unidirectional layer as a quadratic equation In axial direction,

$$\frac{S_{11}}{F_{1T}} = {r_1}^2 \tag{1a}$$

and in the transverse direction,

$$\frac{S_{22}}{F_{2T}} = {r_2}^2 \tag{1b}$$

where, r_1 and r_2 are the damage thresholds, F_{1T} and F_{2T} are strengths in direction 1 (along the fiber), direction 2 (normal) and S_{ij} are stresses in such that $i = j$ are normal stresses and $i \neq j$ are shear stresses. 2 fiber failure in compression because of the tendency of fiber to have high compressive stress in the vicinity of point of impact. The compressive fiber failure can be written as

$$\frac{S_{11}}{F_{1C}} = {r_3}^2 \tag{2a}$$

$$\frac{S_{22}}{F_{2C}} = {r_4}^2 \tag{2b}$$

where, r_3 and r_4 are the damage thresholds, F_{1C} and F_{2C} are compressive strengths in direction 1 (along the fiber), direction 2 (normal) and S_{ij} are stresses. 3 The fibers will end up as a loose bundle upon the failure of matrix material and hence an in-plane matrix criteria in used to identify such instances. Mathematically,

$$\frac{S_{12}}{F_{12}} = {r_5}^2 \tag{3}$$

where, r_5 is the damage threshold, F_{12} is shear strength and S_{12} is shear stress. Each failure mode corresponds to a damage variable which in turn records and evaluates the damage evolution by the means of damage growth function given as -

$$d_j = 1 + \exp^{\frac{1-{r_i}^m}{m}}, r_j > 1 \tag{4}$$

where m is the material softening parameter that regulates the softening response of laminated composites. Higher the value of m, the laminate will be more brittle in nature and lower values makes it ductile[3, 4]. Damage threshold r_i are initially set near to 1, which makes the damage variable 0. But, once the damage initiates, the value of damage thresholds rises until the damage variable reaches to 1. The value of damage variable 1 causes the elastic parameters of material degrades to 0. The damage variable is employed in stress-strain relation to evaluate the values of stresses. Stresses $[S]$ are computed using the expression[5]

$$[S] = [C_d][\epsilon] \tag{5}$$

where $[C_d]$ is stiffness matrix that is derived by inverting the compliance matrix $[S_d]$

$$[S_d] = \begin{bmatrix} \frac{1}{(1-d_1)E_{11}} & \frac{-\nu_{21}}{E_{22}} & 0 \\ \frac{-\nu_{12}}{E_{11}} & \frac{1}{(1-d_2)E_{22}} & 0 \\ 0 & 0 & \frac{1}{(1-d_3)G_{12}} \end{bmatrix} \tag{6}$$

where d_j are damage variables used to store values of coefficient of stiffness blackuction.

3 Fiber volume fraction

The fiber volume fraction is said to have an important role in composite engineering as the material parameters of laminates depends on the composition of fiber and matrix. The ratio is calculated by analyzing the organization of fibers and resins. There are often voids in the material during manufacturing and the same must be accounted for. Too much fiber volume decreases the strength of composite due to the lack of space for matrix to hold it together. And the same can be said if the matrix volume is high which then lacks enough reinforcement. The present study hence investigates the effect of impact response over a range of fiber volume fraction for impact analysis on composites.

There are several methods to calculate the elastic properties of composite lamina using volume fraction. Sudheer M et. al. [6] investigated the variation in the results from rule of mixture, Halpin-Tsai, Nielsen and Chamis elastic models along with analytical and FE pblackicted solutions. Mendoza Jasso et. al.[7] studied the effect of volume fraction on failure initiation in a holed plate subjected to tensile loading. You et. al. [8] studied the factor influencing the strength of GFRP rebar material and increased it using fiber volume fraction. Young et. al. [8] optimized the fiber volume fraction without changing the cross-section of rebars hence enhancing the tensile properties. The spaces between fibres were removed by filling it and making a compact core by tightly surface wrapping them. Other previous works[9, 6] used various mathematical expressions to pblackict the elastic constants such as stiffness and strength of composite material. Rule of mixture is applied in the present study to investigate the effect of volume fraction.

Longitudinal properties [6] ,

$$E_1 = V_f E_f + (1 - V_f)(E_m) \tag{7a}$$

$$\nu_1 = V_f \nu_f + (1 - V_f)(\nu_m) \tag{7b}$$

Transverse properties [6] ,

$$\frac{E_{11} E_m}{V_f E_f + V_m E_m} \tag{8a}$$

$$\frac{\nu_{12} E_2}{E_1} \tag{8b}$$

Shear properties

$$\frac{G_{12}}{V_f G_f + V_m G_m} \tag{9}$$

where, Youngs modulus of the matrix and fiber are taken as E_m and E_f. Poissons ratio are taken as ν_m and ν_f respectively. Elastic properties of lamina are E_{11}, E_{22} and G_{12}.

4 Results and Discussion

Initially while implementing the work of Sudheer M. et. al. [6], change in Youngs modulus and Shear modulus is obtained with variation in fiber volume fraction. The Youngs modulus, E_1 is plotted in Fig. 1. It can be observed that the E1 varies linearly with respect to change in volume fraction. Similar observation can be made for Poison ratio P_{12} and P_{21} are plotted in Fig. 1.

All analysis were executed by considering a target lamina of diameter 25.4 * 254 mm and width 0.272 mm. A .22 caliber projectile of diameter .22 inch with a rigid mass of 3.14 g is impacted on the target with varying volume

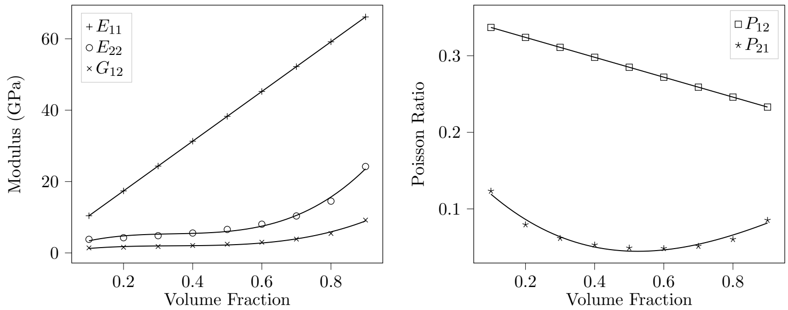

Figure 1: Variation in modulus E_1, E_2 and G_{12} with respect to volume fraction

fraction of composite plates from 0.1 to 0.9 and at velocity 100 m/s. The plate is fixed on both sides, and the projectile is moving in the z-direction. It is discretized using eight node linear brick element with blackuced integration (C3D8R) whereas, R3D4 is used for the projectile, both having mesh size of 0.2 mm x 0.2 mm. A total of 40005 and 840 elements are generated in disc and projectile respectively. A general contact algorithm is used to formulate contact between disc and projectile with a penalty contact of friction coefficient 0.3. It is observed that the volume fraction of 0.5 and 0.75 absorbs the most energy.

It is observed that volume fraction 0.5 and 0.75 exhibits more elastic response to the projectile and hence are able to absorb relatively more energy. The laminae with volume fraction 0.5 and 0.75 have more elastic response and hence more deflection.

It is observed that though the magnitude of moduli is increasing but as the fiber volume fraction increases, it makes the lamina act like a loose bundle of fibers and hence not able to absorb enough energy from projectile. The volume fraction in the range 0.5 to 0.75 is resulting in the lower value of residual velocity which means the lamina of volume fraction 0.5 to 0.75 are absorbing more energy than the rest and hence is the range from which the values of 0.5 to 0.75.

5 Conclusion

The effect of fiber volume fraction in behaviour of composite lamina subjected to ballistic impact loading is investigated in present work. The conjunction of Python, ABAQUS and FORTRAN is addressed to perform automation. An interface, developed using Python, is capable to interact with ABAQUS, to modify the material parameters. The material parameters are

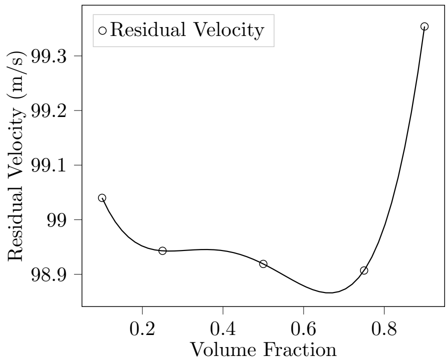

Figure 2: Variation in residual velocity due to change in volume fraction

calculated using the rule of mixture by numpy module in Python and are then forwarded to ABAQUS Material library where it gets modified. The ABAQUS then runs the analysis for that particular set of material parameters and returns again to fetch the new set of parameters. The results shows there is a variation in behaviour of lamina with different volume fractions. The variation in fiber volume fraction is calculated using the rule of mixture formula a nd fed into the python interface.

- The residual velocity is plotted to study the response of lamina.
- The lamina with fiber volume fraction of around 0.1 is said to have a low amount of fibers but high matrix material resulting in less absorption of energy.
- The lamina with fiber volume fraction of 0.9 acts like a loose bundle of fibers due to inability of matrix to hold it together.
- The lamina with fiber volume fraction of 0.5 to 0.75 is shown to have the maximum absorption of energy. Hence, the ideal value of fiber volume fraction lies in the region which is also in agreement with suggestion from Gibson et. al.[10].

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