Simulation of Composite Material Response Under Dynamic Compressive Loading

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ABSTRACT

Realistic computer prediction of high-velocity impact and penetration events involving composite materials requires a knowledge of the material behavior under large compressive stresses at high rates of deformation. As an aid to the development of constitutive models for composites under these conditions, methods for numerical simulation of the material response at the microstructural level are being developed. At present, the study is confined to glass fiber/epoxy composites. The technique uses a numerical model of a representative sample of the microstructure with randomly distributed fibers. By subjecting the boundary of this numerical sample to prescribed loading histories, a statistical interpretation allows prediction of the global material response. Because the events at the microstructural scale involve locally large deformation, and because of the constantly changing picture with regard to contact between the fibers, the Eulerian code CTH is used for these calculations. Certain aspects of material failure can also be investigated using this approach. The method allows the mechanical behavior of composite materials to be studied with fewer assumptions about constituent behavior and morphology than are typically required in analytical efforts.

Introduction

A goal in the emerging field of the computational mechanics of materials is the reliable prediction of the macroscopic mechanical properties of a material on the basis of numerical simulation at the microscale level. In this paper we describe our efforts at the numerical microscale modeling of glass reinforced epoxy composites in the regime of large pressure and large shear strains. The objective of this effort is to supply information, based on numerical experimentation, helpful in the development of macroscopic models for the constitutive response and failure behavior of the material.

Numerical micromechanical modeling of composites has a long history. It has been used largely to guide and help to validate various analytical modeling efforts (see, for example, Dvorak, 1991). Micromechanical finite element analysis has also been used more directly in attempts to characterize the stiffness and strength of composites (see, for example, Adams and Crane, 1984). Most previous work on unidirectional composites has concerned a small number of fibers in simple geometries. In the present work, we employ an Eulerian finite difference code, rather than a Lagrangian finite element code, to help come to grips with the difficulties in modeling more complex structures and geometries. Although the work presented here concerns only plane strain deformations of unidirectional composites, we believe that the methods being developed will be readily extendable to three dimensions and to different types of composites.
The class of applications of interest here is the perforation of composite plates by metal fragments moving at velocities on the order of 1.0 km/s. This type of problem is of current interest in the defense community, because certain armored vehicle hulls are being made from glass-reinforced plastic (GRP) panels. Although GRP is not currently regarded by armor designers as suitable for the armor itself for land vehicles, there is still a strong motivation to use composite structural materials which provide the maximum obtainable resistance to perforation by the small fragments which might occur in behind-armor debris.

It would be a great asset to designers of these vehicles to be able to predict resistance to fragment perforation solely on the basis of analysis of the composition and microstructural morphology of the composite. One important analytical method available for investigating this type of perforation problem is computer simulation using wavecodes, and these wavecodes are totally dependent on the accuracy of the constitutive models that they incorporate. Therefore, for purposes of modeling the penetration process at the macroscopic scale, it is important to have constitutive models that are well-founded and accurate over the regimes of stress and deformation anticipated in these problems.

To help characterize this stress and deformation regime, we now briefly discuss a representative problem involving the penetration of a fairly typical armor material, 5083-H131 aluminum, by a projectile composed of a hard, dense tungsten alloy typical of materials used in anti-armor munitions (Figure 1). Simulation of this event was carried out using CTH (McGlaun, Thompson, and Elrick, 1990), an Eulerian wavecode in wide use in the armor/anti-armor community in the United States. The hydrostatic pressure and von Mises equivalent stress predicted at the point labeled A in Figure 1 are shown in Figure 2. The pressures at this point are evidently on the order of 1.0 GPa. The shear stresses are limited by the flow stress for this particular aluminum alloy, which is about 0.25 GPa. At this same point, the equivalent plastic strain reaches a maximum value of 0.65, and the maximum equivalent plastic strain rate is about $10^5$ s$^{-1}$. Of course, these values will not translate directly to GRP target material, but they at least provide some indication of the conditions we need to investigate.

![Figure 1. Tungsten alloy rod impacting an aluminum half-space.](image)

The immediate objective of the present work, then, is to predict the constitutive response and failure behavior of fiberglass materials in the pressure range of about 1.0 GPa, strains of up to about
Figure 2. Pressure and von Mises equivalent stress as a function of time at point A, illustrating a typical stress path in a target material.

1.0, and strain rates of about $10^5$ s$^{-1}$. This regime is inaccessible using most readily available experimental techniques for the evaluation of mechanical properties of materials. Therefore it is a good candidate for the use of numerical simulation at the microstructural level to help predict these mechanical properties.

It should be kept in mind that several failure mechanisms are involved in the perforation of GRP plates (Bless, Hartman, Azzi, Benyami, and Jurick, 1991), and it is not expected that the two-dimensional analysis presented here will be sufficient to allow simulation of the entire process. We take the approach of starting with a simple case, which is the plane strain deformation of a cross-section of a GRP with unidirectional reinforcement. Once the general approach is developed and validated experimentally, more complex materials and deformations will be analyzed.

The present work deals primarily with efforts to carry out physically legitimate simulations of how GRP deforms micromechanically and some qualitative results of these calculations. However, parallel efforts underway include the development of macroscopic constitutive and failure models which make use of the micromechanical results. Also, an experimental effort is underway to provide mechanical property data on the constituent materials, and also to provide data by which the calculated response of the composite may be validated.

**Method**

Our present method of analysis uses the CTH code mentioned above as a tool for investigating the microscopic, rather than the macroscopic, response of the composite material. At present, our capabilities are limited to the rather restrictive case of plane strain deformations of a unidirectional
GRP. However, the eventual aim is to include fully three-dimensional deformations, as well as more general materials.

Figure 3 shows a CTH model of a sample cross-section of a GRP material with unidirectional reinforcement. The matrix material is Epon 828 epoxy, and the fiber material is S-2 glass. The region surrounding the composite is a fictitious material called the “frame,” which is subjected to a time-dependent homogeneous deformation. The effect is to prescribe the deformation at the boundary of the elliptical sample.

We generally use an elliptical sample because we have found that this shape tends to minimize the undesired effects of waves propagating inward from the boundary. The macroscopic deformation of the sample is controlled by the time-dependent but homogeneous deformation of the frame. As the frame changes its rate of deformation, it causes stress waves to move into the sample region. If the boundary were circular, these waves would converge at a singular point in the center of the sample, which might cause problems in a simulation. A rectangular sample has been found to cause problems near the corners, where stress singularities are created inappropriately. An elliptical sample avoids these problems.

The fiber locations are generated randomly. A random number generator provides an initial guess for the set of fiber center coordinates. If left unchanged, some of these center locations would correspond to fibers that overlap. Therefore, an iterative relaxation algorithm is applied to the fiber locations. This algorithm causes the fibers to separate from each other slightly at each step of the iteration until they do not overlap. When none of the fibers overlap, the algorithm stops. This approach allows some of the fibers to barely touch, as they would in a real composite. We believe that the approach of random generation of the fiber locations gives greater realism than the
assumption of a periodic structure, e.g., a hexagonal or square arrangement of fibers. A demonstration of the importance of randomness is provided below.

As the sample deforms, various averaged quantities are computed within the sample. These include the Cauchy stress tensor $\sigma$ in each constituent and in the composite, the volume fractions of the constituents, the Eulerian velocity gradient tensor $L$, the deformation gradient tensor $F$, and the equivalent plastic strain. To minimize the effects of proximity of the prescribed-displacement boundary on these averaged quantities, we perform the averaging only within a subregion of the elliptical sample sufficiently far from the boundary of the sample so that these “edge effects” may be neglected.

CTH is an Eulerian code, which means that the numerical mesh is fixed in space, while the material flows between the cells. This general approach has been fairly standard in computational fluid dynamics for some time. However, the ability to model solids in an Eulerian code is a relatively recent development. The Eulerian approach for solids has its greatest benefit in problems involving very large deformations. The reason is that because the mesh is fixed, there is never any problem with mesh distortion, which can cause problems in a Lagrangian code. The main disadvantage of the Eulerian approach is the difficulty in treating mixed cells, i.e., cells containing more than one material or cells partially containing void. Mixed cells cause problems primarily because a homogeneous flow code (one velocity field for all materials present in the simulation) like CTH cannot distinguish between the different motions of different materials within a cell. Similarly, the code averages the constitutive properties of different materials within a mixed cell. Therefore many difficulties occur along the interfaces between solid materials and at free surfaces.

In spite of these difficulties, there are many cases in which an Eulerian code is the method of choice. One such situation is the present case of microscale modeling of a composite, because of the constantly changing picture regarding contact between the fibers and the possible creation of void due to damage within the matrix material. Simulation of large strains of the sample shown in Figure 3 would present serious difficulties for a Lagrangian code.

The greatest challenge in carrying out simulations of this kind is to build in accurate representations of the physics at the microstructural level.

The simulation can operate in either of two modes:

- Prescribed deformation mode: the deformation gradient tensor in the frame is a given piecewise linear function of time.
- Prescribed stress mode: the in-plane components of the average Cauchy stress in the sample are given piecewise linear functions of time.

In the prescribed stress mode, the homogeneous deformation in the frame is dynamically adjusted according to the difference between the prescribed stress and the actual stress in the sample. For example, if the prescribed stress at some time is greater than the actual sample pressure, then the frame will increase its rate of contraction, leading to an increase in the sample pressure.

We now present some computational results which show how the method described above yields results useful in the development of macroscopic constitutive models.
Random structure vs. periodic structure

We compare the microscale deformation predicted for identical loading paths for two different microstructures: (1) random placement of the fibers, and (2) hexagonal placement of the fibers. The initial volume fractions of the fibers are nearly identical between the two cases, 72.75% for the random placement and 72.86% for the hexagonal placement. The loading path consists of isotropic compression in the plane to a pressure of 0.5 GPa, followed by shear loading determined by a ramp function of time. This loading path is illustrated in Figure 4.

![Figure 4. Loading history.](image)

The fibers are modeled as elastic-perfectly plastic with yield stress 4.0 GPa, Young’s modulus 60.5 GPa, and Poisson ratio 0.2. The matrix is modeled as elastic-perfectly plastic with yield stress 0.1 GPa, Young’s modulus 7.28 GPa, and Poisson ratio 0.3. In both materials, failure is assumed to occur when the equivalent plastic strain reaches 0.05. After failure, the material cannot sustain shear stress or tensile pressure.

Figure 5 shows the predicted distributions of von Mises equivalent stress \( \tau \) in the two materials when the deformation has progressed to the point that \( F_{12} = F_{21} = 0.02 \) in both cases. (These do not correspond to identical times.) The darker the shading, the larger the value of \( \tau \). It is evident from the figure that in the random case, the fibers tend to stack up against each other in such a way that contact forces between them sustain most of the shear stress. On the other hand, in the hexagonal case, the fibers are not yet in contact with each other, so there are no such contact forces.

This qualitative difference in how the two configurations sustain shear loads has a large effect on the predicted stress-strain curves. Figure 6 shows the average values of \( \sigma_{12} (=\sigma_{21}) \) as a function of \( F_{12} (=F_{21}) \) for the two composites.

Failure of the composite is reflected in the calculations by a rapid increase in strain rate as load is increased slowly. It is interesting to compare the failure mechanisms at work in the random and hexagonal cases. In the random case, failure occurs due to the onset of fiber slip, in which the fibers
start to slide past each other. In the hexagonal case, an earlier failure mechanism occurs. Because none of the fibers are initially in contact with each other, the ability of the material to sustain shear stress is limited by the strength of the matrix material which totally surrounds each fiber. When this matrix material starts to fail, a sudden increase in the velocity gradient tensor component \( L_{12} \) occurs (Figure 7). The fibers then readjust themselves so that they start to come into contact with each other, and contact forces develop. The load can then increase until fiber slip starts to occur.
The matrix failure mechanism is not as important in the random case, because the shear loads tend to be sustained by contact forces from the beginning.

Many micromechanical studies of composite materials in the literature have assumed a periodic structure. The present analysis suggests that some important features of composite material response may be overlooked when the random nature of the microstructure is neglected. This observation has also been made in the context of the elastic properties of unidirectional composites (Adams and Tsai, 1969).

**Effect of pressure on strength**

The apparent importance of contact forces between the fibers in the case of the randomly generated composite structure discussed above suggests that there may be certain similarities between this type of composite and frictional materials, such as soils. The characteristic feature of the macroscopic response of frictional materials is the dependence of their strength on hydrostatic pressure. Therefore, we now use the microscale modeling approach to investigate the influence of pressure on the ability of a composite to sustain shear forces.

Four cases were simulated for the same material using identical numerical samples. The fiber volume fraction was 72.7%. The matrix material had a constant flow stress of 0.1 GPa, and the fiber material had a constant flow stress of 4.0 GPa. Both materials had a shear strain to failure of 0.05.

In each of the four cases, the sample was compressed by isotropic contraction of the frame to a different value of pressure. The pressure values were 1, 0.5, 0.1, and 0 GPa. Following this...
compression, and while holding the pressure fixed, the samples were subjected to identical shear stresses which increased linearly with time. Thus, the loading histories were as shown in Figure 4, but with different final pressures.

Figure 8 shows stress-strain curves for the shear portion of the loading for each of the four values of pressure. For each of the four values of pressure, Figure 9 shows the "ultimate shear stress," which we define to be the maximum value of $\sigma_{12}$ attained during loading. Evidently, there is a fairly strong predicted dependence of this ultimate stress on pressure.

![Figure 8. Computed stress-strain curves in shear for four values of pressure.](image)

**Effect of bond properties on strength**

It is well known that the nature of the bond between fiber and matrix materials has an important effect on the mechanical properties of composites. We now present microscale simulations aimed at reproducing this effect. We consider two cases: (1) "compatible" bonding, in which the two constituents are rigidly bonded, and (2) "incompatible" bonding, in which the interface has no adhesion and no friction.

Figure 10 shows a stress-strain curve in shear for the two materials at a pressure of 0.5 GPa. Evidently the composite with the compatible materials has higher strength but lower ductility (as indicated by the lower strain at failure). Figure 11 shows the fraction of matrix material that has failed as a function of time for each material. (Failure occurs at an equivalent plastic strain of 0.05.) Note the far slower development of failure for the incompatible case.

![Figure 10. Stress-strain curve in shear for compatible and incompatible bonding.](image)
Figure 10. Stress-strain curves in shear for composites with different bond properties at 0.5 GPa pressure.

Figure 9. Dependence of the strength of a composite in shear on the hydrostatic pressure.
The experimental ballistic data of Bless, Hartman, and Hanchak (1985) and Vasudev and Mehlman (1987) show that composites with incompatible bonding have ballistic performance superior to that of the same materials with compatible bonding. This is consistent with the calculated result that failure occurs later in the incompatible material than in the compatible material. This result will probably continue to hold in three dimensions as well as in the two-dimensional case shown here. It is possible that this lower susceptibility to damage outweighs the predicted lower strength of the incompatible material. Also, when fiber stretching is included in the model (in three dimensions), the conclusion regarding lower strength of the incompatible material may change.

**Discussion**

In spite of the many simplifying assumptions used in the analysis discussed above, the simulations provide insight into how composite materials sustain loads, deform, and fail. We are continuing to refine the modeling techniques and to identify the best way to use the micromechanical capabilities to provide macroscopic constitutive models.

The most troublesome issue in the micromechanical modeling has been the treatment of the points of contact between fibers. The implementation of an accurate treatment of these points is a difficult problem in any code, either Eulerian or Lagrangian. It is probable that some special technique, analogous to singular elements in a finite element code, will need to be developed in order to treat this contact problem accurately.

We would also like to be able to include a better model for the failure of interfaces between constituents. A numerical technique we are developing permits the representation of the initiation
and growth of individual cracks in a continuum. This technique holds promise for the simulation of interfacial cracking in a composite and other modes of failure.

An experimental program is underway to provide data about the constituent responses and to enable us to validate the data generated by the simulations. The experimental methods include standard quasi-static tests, split Hopkinson bar tests, and planar impact tests using a gas gun. This set of tests will provide constitutive data over a wide range of stresses and loading rates.

Another aspect of the present project is the use of microscale simulations to model the propagation of shock waves through a microstructure. This type of analysis, although in its early stages, has given insight into the shock wave spreading which occurs because of geometrical dispersion due to material inhomogeneity.

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References


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