MODELING LAYERED COMPOSITE MATERIALS USING MPM IN AN EULERIAN SHOCK PHYSICS CODE

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Keywords: Shock, Anisotropic, Composite, MPM (Material Point Method)

Abstract
The work presented in this paper summarizes a new technique for initializing layered composite materials for use with the Material Point Method (MPM) within an Eulerian shock physics hydrocode. The Material Point Method (MPM) within a shock physics hydrocode permits simulating material strength and failure using Lagrangian numerical methods while still allowing shock waves through the materials. This technique uses marker particles and a background grid to update the marker particle state. Since the marker particle is Lagrangian, the advection process does not adversely affect the state of the material. The marker particle is inserted into the grid at the material mass centroid of an arbitrary polyhedron where the density is held constant for each cell within the grid. In the case of a composite material, the mass centroid corresponds to a single lamina. Lamination and material information are input by the user and used to initialize the marker particle at the beginning of the analysis. The technique described herein increases the accuracy and robustness while decreasing memory requirements.

1. Introduction

The lightweight and high strength qualities of fiber-reinforced composite materials make them desirable in many structural applications. Modeling these complex materials in an Eulerian shock hydrocode has many challenges. Two of the main challenges are the advection of the material state and initialization of the anisotropic layered materials. Typically, in Eulerian shock hydrocodes, advecting the state of the material has shown to produce errors in the material state. For example, material healing or numerical fracture may happen solely from the advection process. In Figure 1, a material at an arbitrary cycle has a state variable with values 1 and 0 in two separate cells as shown. If the material moves half the width of a cell during a single cycle, the new cell properties are volume fraction weighted based on the amount of each material in the cell as described in Equation 1.

$$\text{State}_{\text{new}} = \frac{\emptyset_{\text{left}}\text{State}_{\text{left\_old}} + \emptyset_{\text{right}}\text{State}_{\text{right\_old}}}{\emptyset_{\text{left}} + \emptyset_{\text{right}}} \tag{1}$$
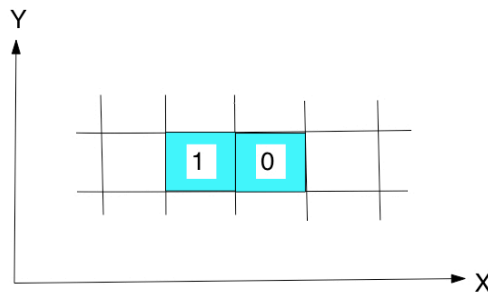
Figure 1. Initial state of material at an arbitrary cycle

From Equation 1, the new state becomes a mixture of the left and right states based on the volume fraction of the left and right cells, ϕ. In this example, the material moved half a cell width, therefore $\phi = 0.5$ for both the left and right cells. When determining the new state, the state variable value becomes 0.5 by simple rigid body movement through the grid, see Figure 2. These types of advection techniques may adversely affect the material response, so a Lagrangian technique is desired to remove advection error for increased accuracy in predicting material strength and failure.
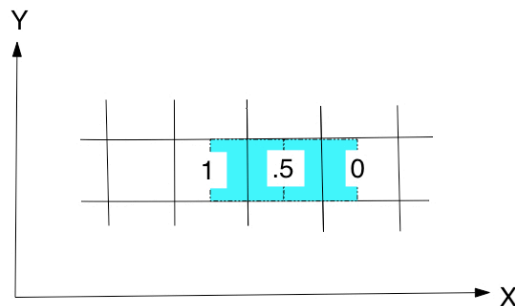

Figure 2. Final state of material at an arbitrary cycle after advection

Although the use of the Material Point Method (MPM) in finite volume shock hydrocodes has been previously developed [1], it has not been used to represent layered composite materials within a shock hydrocode. The MPM method utilizes marker points to track the state of the material within a finite-volume Eulerian grid. The strength and failure response of the material is tracked using a Lagrangian method, where the identity of the marker particle is retained during advection (Figure 3) and the stress acceleration is computed from the individual marker particles.
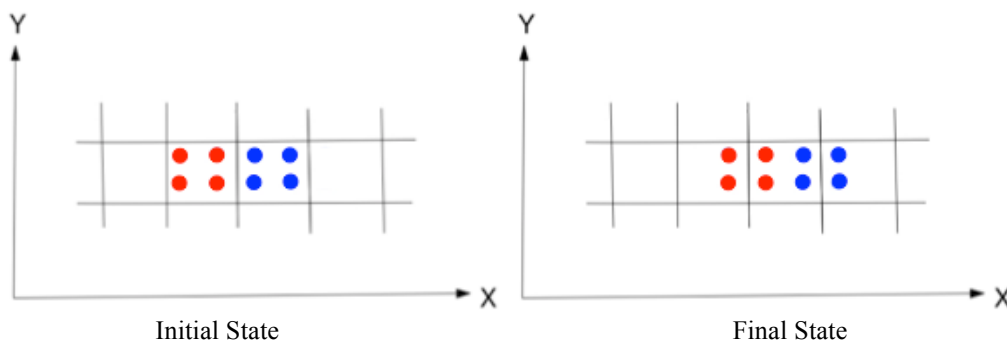

Initial State   Final State

Figure 3. Material advection at an arbitrary cycle using MPM

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Using marker particles to represent composites leads to the challenge of how to initialize a marker particle in order to accurately represent the directionality of the composite lamina within the finite-volume grid.

2. Procedure

A significant challenge exists with inserting markers that represent composite layers into the finite-volume grid with the correct initial orientation when the general case is considered where a layer may cross a computational cell at any orientation. Previous work describes a user-defined process for inserting layered composite materials into a finite volume grid using multiple coordinate systems, [2]. The previous work also developed a method for advecting layered composites and preserving the original material orientation. However, because of the Eulerian nature of the numerical method, this does not preserve the state of the material during the advection process. In what follows, we describe the implementation of the previous layering method for use with the MPM.

The first step is to gather the user input data that sets a user-defined coordinate system within the global coordinate system. The user-defined coordinate system within the computational grid is defined using three points in space: the origin, a point defining the 3-axis and a point defining the 1-3 plane. Figure 4 illustrates the user defined coordinate system and its defining components. It is noted that the origin for this method is always placed at the base of the object to be inserted into the grid.
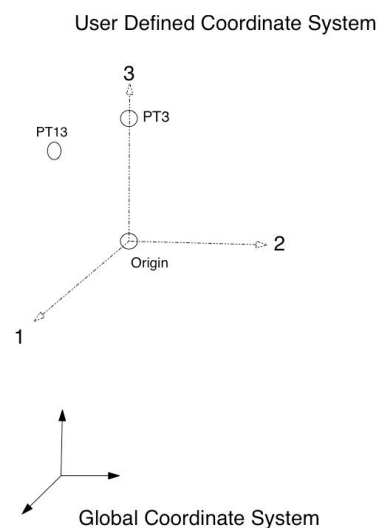

Figure 4. User-defined coordinate system relative to the global coordinate system

In addition to the user-defined coordinate system, the number of material layers, layer orientation, and thickness of each layer must also be defined. The layer orientation is used to initialize a material direction vector for each marker particle. The layer orientation describes the material rotation from the global coordinate system into a local coordinate system for performing physics computations such as the stress response to a given strain or strain-rate field. The user inputs the layer's orientation by a combination of two rotations relative to the user-defined coordinate system. Specifically, the user specifies the axes and the rotation

desired about these axes. Using Figure 5 as an example, the first rotation is from the unprimed to the primed axes, and the second rotation if from the primed to the double primed axes.
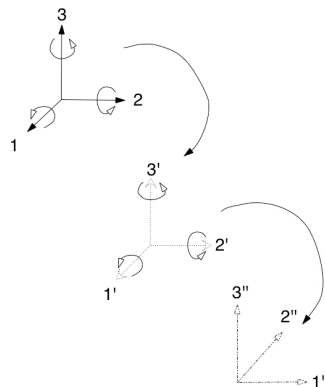

Figure 5. Layer orientation based on the user-defined coordinate system

Next, knowing the object location and orientation within the grid, the marker particle location and mass is set. Since a given layer may intersect a cell at any arbitrary location and orientation, a generalized method for computing the marker mass and location is needed. For example, in Figure 6 a single layer (shaded region) cuts a cell at an arbitrary location, creating a polyhedron and vertices at the cell boundary intersection.
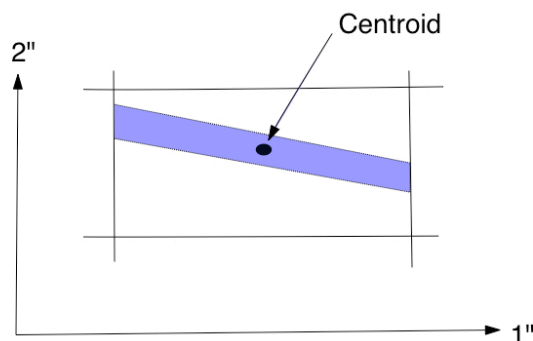

Figure 6. Finite volume cell intersected by a composite layer

Using the polyhedron representing the lamina, a volume is computed and the initial density is used to compute the marker mass. It is assumed that the density is constant within the cell and the polyhedron contained within the cell. To compute the centroid, the vertices of the polyhedron are used. The computed centroid becomes the global location of the marker particle. Therefore, using the mass and centroid of the polyhedron a marker is inserted into the grid representing the layer and orientation it defines.

In Figure 7, a typical solid object, which incorporates four layers is shown. Figure 8 shows the same object with an MPM representation or multiple marker particles inserted based on the layer location. In Figure 8, one marker particle is used per layer as an example, but inserting multiple marker particles per layer in a given cell is possible by subdividing the cell

into smaller volumes and repeating the above process. The number of cell subdivisions is controlled by the user input.
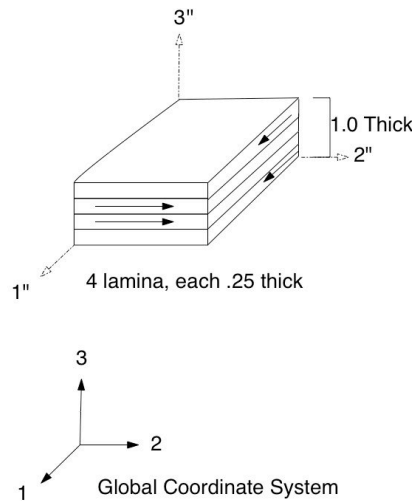
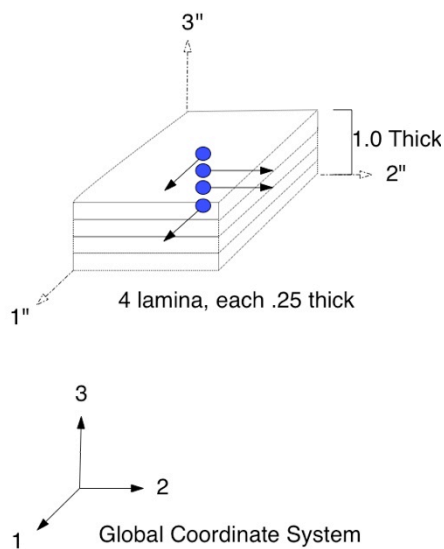**Figure 7.** Original object insertion for a layered composite object

Figure 8. Marker particle object insertion for a layered composite object

3 Examples

To demonstrate the initialization of the marker particle fields for layered composite materials, two examples are provided. The first example is a four-lamina oblique plate, with a [0/90/90/0] layup being impacted by a steel flyer. The plate (blue) and impactor (red) are shown in Figure 9 and a close-up view showing the orientation vectors plotted by layer with the marker particles is given in Figure 10. For this example, one can see that the 0° lamina is oriented along the x-axis of the plate or at a 45° angle of obliquity to the global coordinate
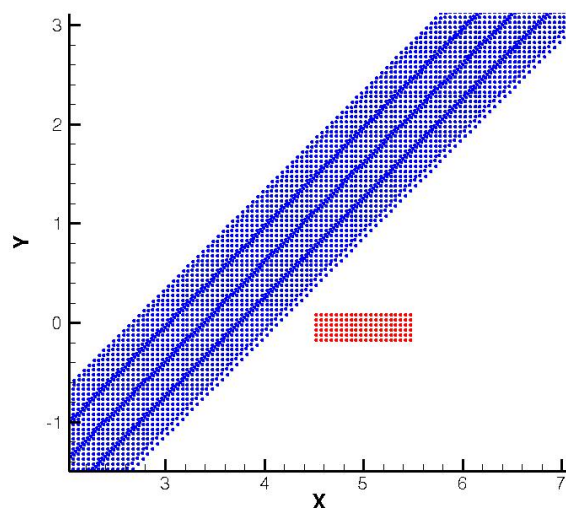
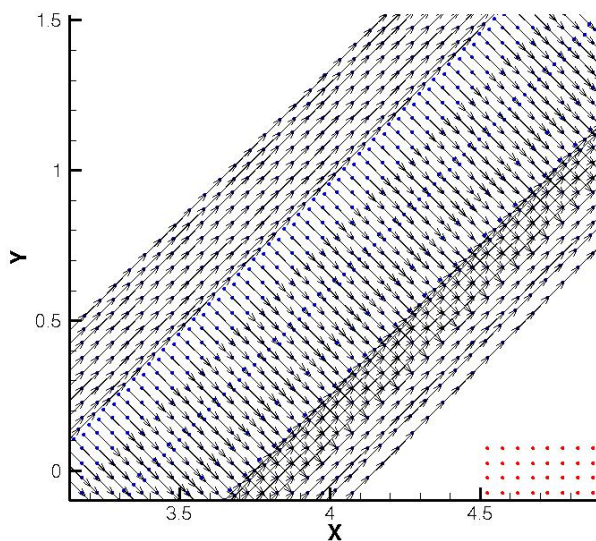**Figure 9.** 2D composite example showing oblique composite plate impact

Figure 10. 2D composite example showing marker particles with the layer orientation vectors
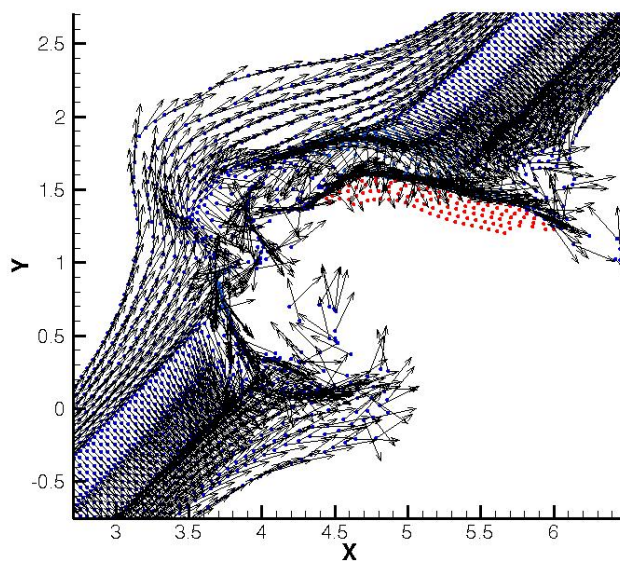

Figure 11. 2D composite example showing the post impact response of the composite plate

system. Figure 11 shows a post impact picture of the composite where the orientation vector rotations from the impact and damage can be seen. The second example shown in Figure 12 is a [0/90/90/0] layered composite plate being impacted by a copper sphere. In Figure 12, the plate is represented by the red markers and the copper impactor is represented by the blue markers. Additionally, due to symmetry only ¼ of the problem is modeled. Again, the 0° lamina of the composite plate is oriented along the x-axis. Figure 13 shows a close-up of the orientation vectors plotted by layer with the marker particles and Figure 14 shows a post impact response of the material vectors. The results show proper insertion of the marker
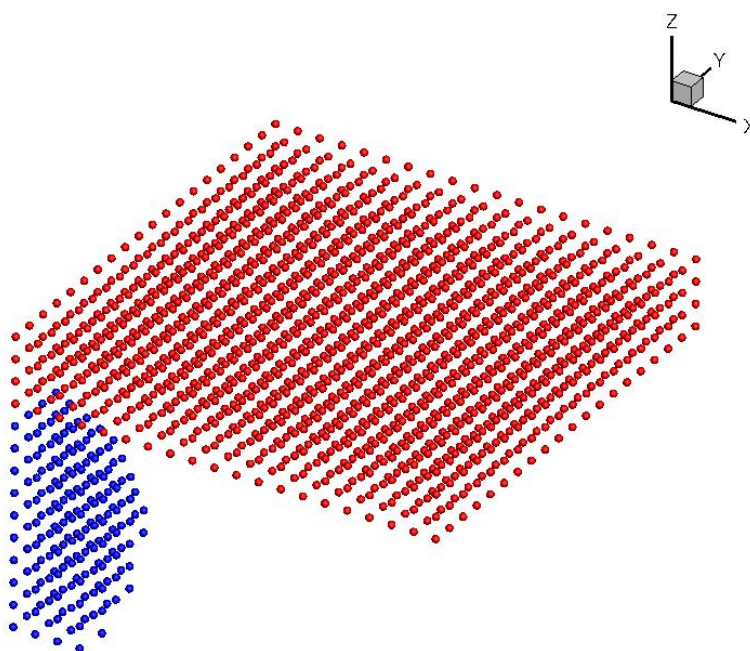

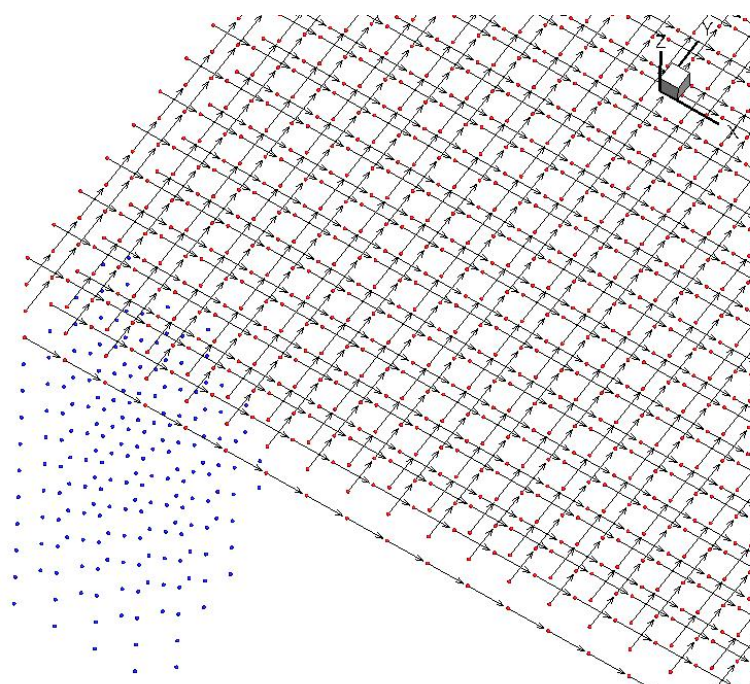**Figure 12.** 3D composite example showing composite plate impact

Figure 13. 3D composite example showing marker particles with the layer orientation vectors
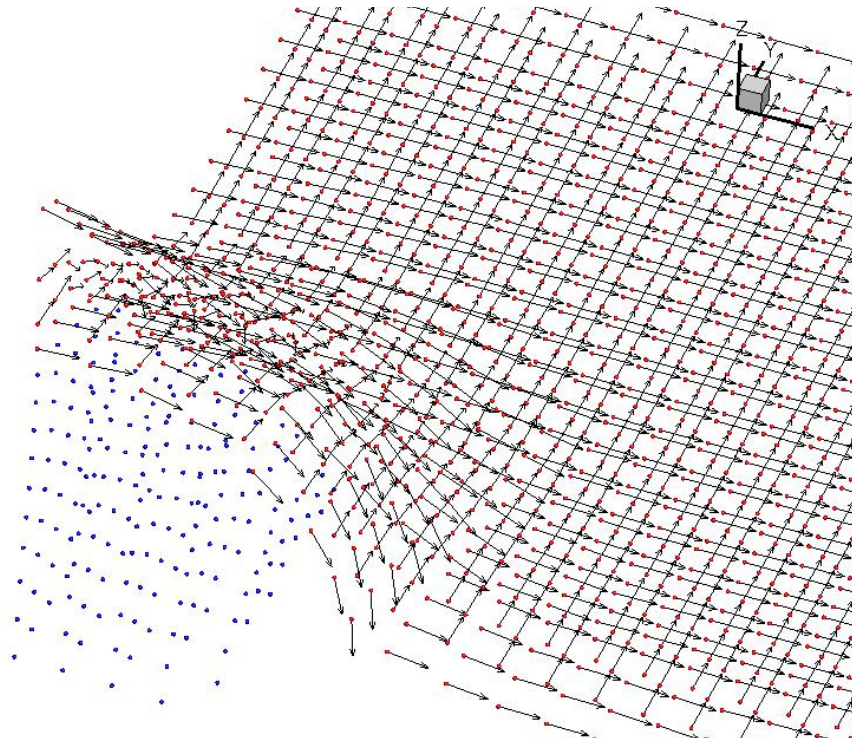
Figure 14. 3D composite example showing the post impact response of the composite plate

particle fields to represent the composite lamina geometry and tracking of the deformation field due to impact.

4 Conclusions

A new technique for initializing marker particles to represent composite materials has been developed for use in a shock physics hydrocode. This technique allows for the use of a hybrid numerical technique that utilizes a Lagrangian particle numerical method, such as MPM, within a finite volume shock physics hydrocode. The method as described, initializes the mass and centroid of the marker particle based on a constant density in a given cell. The technique is shown to be useful for predicting composite materials response when subjected to shock and/or high rate deformation.

5 Acknowledgements

References

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