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A HIGH VELOCITY IMPACT PENETRATION MODEL FOR THICK FIBER-REINFORCED COMPOSITES

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ABSTRACT

A model for numerical simulation of high velocity impact penetration of thick fiber-reinforced composites is proposed. The model is developed based on phenomenological observation from numerous ballistic impact tests. It was concluded that the deceleration of the projectile is caused by three major energy absorption mechanisms, each of which represents one of the three stages of the penetration process in sequence: (i) punching; (ii) fiber breaking; and (iii) delamination. The current model utilizes a continuum approach based on the framework of damage mechanics. It includes the basic orthotropic constitutive behavior. The three major failure mechanisms are modeled by three independent failure criteria. Damage of materials is progressed using a degradation model of the failure of the composites. The model has been incorporated into a two-dimensional nonlinear transient dynamic finite element program - DYNA2D. A one-way erosion algorithm with which composites can be eroded upon the occurrence of certain failures has been incorporated into the code. Numerical simulations have been performed and results showed good correlation with ballistic tests.

INTRODUCTION

Composites have proven superior to monolithic materials, providing an additional dimension to design, because of their specific stiffness and strength, and their tailorability to bear loads and withstand various severe environments. As a result, there has been increased use of advanced fiber-reinforced composite materials in various military applications. A potential application of these materials is in the design of ammunition protection systems against such threats as high velocity fragment impacts and explosive loads.

During the past two decades there has been steady progress in analyzing the response and behavior of composites subjected to static and quasi-static loadings. However, the amount of work that has been devoted to the dynamic response of composite structures in the structural dynamic regimes and low velocity impact problems is limited [1]. Moon's work in 1972 [2], 1976 [3], 1977 [4], Sun's work in 1975 [5], 1976 [6] and Greszczuk's work in 1975 [7] represent some of the earliest contributions in the impact dynamic regimes but again, these are restricted only to relatively low velocity impact problems. Little theoretical and computational research has been performed in the area of response of structures to high velocity impact penetration or explosive loading.

As a manufacturer of various defense equipments, FMC has particular interest in using fiber-reinforced composites for equipments, and therefore is continuously performing research in advanced materials such as fiber-reinforced composites. Potential applications of these materials lie in the design of protective structures for ammunition systems and armor vehicle hulls. The major reason for the selection of composites is its light-weight, high strength, tailorability and damage tolerance. In both applications, thick composites are usually required and the ballistic performance of these composites is a major design consideration. It has, therefore, prompted the need for developing an adequate model which can predict the ballistic performance of composites.

Numerous ballistic impact tests were performed on S-2 glass/polyester [8]. Observation of test panels after impact suggests that the penetration process is basically broken down into three sequential stages: (i) punching; (ii) fiber breaking; and (iii) delamination. Each stage of the process is characterized by a specific failure mechanism which absorbs a certain proportion of energy and is responsible for the deceleration of the projectile.

Our objective at this point was to develop a reasonable model that can be incorporated into a hydrocode and used in large scale simulations for predicting the ballistic performance of the composites. This report documents the effort we have undergone for the development of a two-dimensional progressive damage composite model that can be applied to simulate the high velocity impact penetration of composites. It consists of four parts and is organized as follows. The first part summarizes the phenomenological results obtained from the ballistic tests. The second part explains the formulation of the basic model. The third part discusses the implementation of the model into the hydrocode. The fourth part illustrates the performance of the model and compares the results with actual experimental data.

PHENOMENOLOGICAL RESULTS

Testing

Ballistic tests were performed for various woven roving polymeric composites at velocities above 2,000 f/s. Single composite panels were tested. Fibers used in the fabrication of the laminated panels include S-2 glass. Thickness of the test panels is in the neighborhood of 1.7". A steel witness plate was placed at the back of the target to catch the projectile. Two types of projectiles were used in the tests; a Fragment-Simulating Projectile (FSP) and an Armor Piercing (AP) round. In this work, the discussion is confined only to FSP. For partially perforated panels, the penetration depth and damage zone were measured. For completely perforated panels, the residual velocity was measured.

Results

Figure 1 shows the sectional view of a 1.74-inch thick GRP panel struck by a 20-mm FSP at just above V_{50}. Examination of the post-test appearance of these panels clearly reveals the cavities as shown in Figure 1. Three major failure modes can be identified: punching shear, tensile and delamination failure, each of which represents in succession a stage in the penetration process. The relative thickness of each stage depends on the overall laminate thickness. The amount of failure in each mechanism represents its share of energy absorption and is responsible for the deceleration of the projectile.

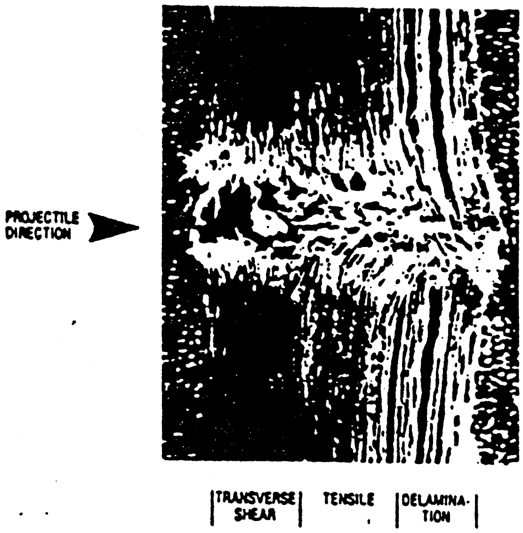

Figure 1 Failure Modes in Ballistically Penetrated GRP Laminates for an Impact Velocity at just above V_{50}

THEORETICAL MODEL

Approach

A key element in this development was in identifying and quantifying the different failure modes as the projectile penetrates the composites. A schematic of these processes is shown in Figure 2. This represents the major failure modes which were noted also in [9]. The initial penetration zone is dominated by transverse shear failure, followed by ply tensile failure and then delamination. Each mode of failure absorbs a percentage of the projectile's kinetic energy and is responsible for the deceleration of the projectile. Therefore, any analytical tool must model these major failure modes and have the flexibility to accept other failure mechanisms as they are identified.

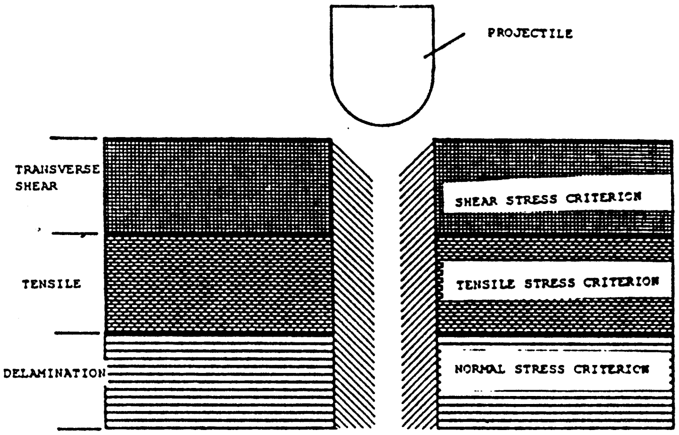

Figure 2 Schematic of Failure Modes at Different Depths of the Ballistic Laminate for Impact Velocity just above V_{50}

Upon understanding the major failure modes occurring during the penetration process, our effort was to direct towards the development of a model that can be used to predict the ballistic performance of thick fiber-reinforced composites. The penetration phenomena occurring during high velocity impacts of thick fiber-reinforced composites are believed to be very complicated. At this stage of the development effort, it is best to confine the penetration of composites to a two-dimensional problem and to treat the failure issue in as simple a manner as possible for several reasons. First, there is a large number of unknowns, and choosing a more complex theory could have the effect of obscuring the primary failure mechanisms. Secondly, a more complex theory can most likely be formulated later if these simple theories have shown reasonable results. So at this point, only the macro behavior is considered representing the three major failure modes described earlier. It is believed that micro damage and failure will not be a significant part of the energy absorption particularly for high velocity penetration of composites.

In terms of geometry, it is assumed the problem is axisymmetric in nature. This means the sub-laminate lay-up is quasi-isotropic. This is consistent with the axisymmetric finite element formulation and does not violate the physical construction of the ballistic armor since the composite construction used is, in general, $[0/90,\pm45,0/90]_{2n}$ for structural design reason. However, if the ±45 plies are not a structural requirement, it may prove more advantageous from the ballistic standpoint to use just woven (0/90) cross-plies.

Constitutive model

The constitutive relationship for the two-dimensional axisymmetric model is governed by equation (1) and is based on the material reference coordinate system a-b-c.

$$\begin{Bmatrix} \varepsilon_{aa} \\ \varepsilon_{bb} \\ \varepsilon_{cc} \\ \gamma_{ab} \end{Bmatrix} = \begin{bmatrix} 1/E_{aa} & -\nu_{ba}/E_{bb} & -\nu_{ca}/E_{cc} & 0. \\ -\nu_{ab}/E_{aa} & 1/E_{bb} & -\nu_{cb}/E_{cc} & 0. \\ -\nu_{ac}/E_{aa} & -\nu_{bc}/E_{bb} & 1/E_{cc} & 0. \\ 0. & 0. & 0. & 1/G_{ab} \end{bmatrix} \begin{Bmatrix} \sigma_{aa} \\ \sigma_{bb} \\ \sigma_{cc} \\ \sigma_{ab} \end{Bmatrix} \tag{1}$$

The orientation of this material reference coordinate system relative to the element coordinate system or the global coordinate system may be defined by the user. The value of this orientation is used to set up the initial configuration for the material transformation. During penetration, large deformation will occur in the model and the material orientations of all the elements in the model are updated. The value of the orientation parameter is calculated for each element and stored as a history parameter for each element. Transformation operation is performed based on this orientation parameter in calculating the stresses and strains.

Cauchy stresses are calculated for each element in each cycle (time step). The directions of these stresses are transformed to the material coordinates before determining failure. This is required because the strengths of the composites are usually characterized with respect to the material coordinate system.

Equation of State

During high velocity impacts, shock waves are produced in the composites. A great deal of attention have been received in this topic. The behavior of solids subjected to high pressure can be described by an equation of state. Numerous equations of state have been developed for various homogeneous materials. To the authors' knowledge, there are few proven equations of state for fiber-reinforced composites at this time.

Munson and Schuler [10,11] developed a model for laminated composites using a mechanical rule of mixture. In their model the thermodynamics was neglected, the constitutive relations for each constituent in the composites was assumed $p_n = p_n(\rho_n)$ where p_n is the pressure of the n-th constituent at any position x and it is assumed equal for all the constituents. Tsou and Chou [12] used a similar model but included the thermodynamics in the analysis. Recently, O'Donoghue and Anderson [13] has formulated a mixture theory capable of modeling fiber-reinforced composites. It however, remains to be validated.

Before any equation of state has been proven valid, at this point, a linear relationship between the pressure and the natural logarithm of the relative volume was adopted, given by Equation (2):

$$P = K * \mathrm{Log}\ (\ V\ /\ V_o\ ) \tag{2}$$

where p is the pressure, K is the bulk modulus, V and V_o are the instantaneous and initial volume respectively, and the term (V / V_o) is the relative volume.

Failure criteria

The dominating failure modes during a high velocity penetration of thick composites are illustrated schematically in Figure 2. At this stage, three independent failure criteria have been formulated for punching shear failure, inplane tensile failure and delamination, and they are governed by the following simplified expressions:

(i) Punching shear failure

Failure occurs when the following is met:

$(\sigma_{ab})^2 \geq (S_{rz})^2$

where σ_{ab} is the transverse shear stress and S_{rz} is the punching shear ply strength

(ii) Inplane tensile failure

Failure occurs when the following is met:

$(\sigma_{aa})_t \geq (S_{rr})_t$

where $(\sigma_{aa})_t$ is the longitudinal tensile stress and $(S_{rr})_t$ is longitudinal tensile ply strength

(iii) Delamination

Delamination occurs when the following is met:

$(\sigma_{bb})_t \geq (S_{zz})_t$

where $(\sigma_{bb})_t$ is the transverse tensile stress and $(S_{zz})_t$ is the transverse delamination strength

The above criteria are the simplified versions of more general orthotropic failure criteria such as those formulated by Norris [14] and Tsai-Wu [15]. In this work our philosophy was to address the failure issue using as simple a criterion as possible for each failure mode to capture the basic important phenomenon. Higher order failure criteria will be developed once the model is proven valid.

The basic assumption currently used is that the composites behave elastically to failure for each mode of deformation. This is believed reasonable as most fiber-reinforced composites do exhibit this behavior closely, especially at high rate of loading [16]. However, in some materials, nonlinear shear deformation may occur and this will be developed in the future. Another important enhancement is the distinction between tensile and compressive stresses when a higher order failure theory is implemented. Such feature is important for a general impact model instead of just a high velocity penetration model.

Degradation model

The above criteria describe the three major failure modes of material during the penetration process. When failure occurs, materials will lose their load carrying capacity in certain modes of deformation. To accommodate that, the properties of the composites and the stresses are modified. The type of changes made depends on the type of failure that the composites experience. The following degradation model is formulated for the three failure mechanisms:

(i) When punching shear failure occurs, the following is invoked:

$$S_o = \begin{bmatrix} 1/E_{aa} & -\nu_{ba}/E_{bb} & -\nu_{ca}/E_{cc} & 0. \\ -\nu_{ab}/E_{aa} & 1/E_{bb} & -\nu_{cb}/E_{cc} & 0. \\ -\nu_{ac}/E_{aa} & -\nu_{bc}/E_{bb} & 1/E_{cc} & 0. \\ 0. & 0. & 0. & 1/G_{ab} \end{bmatrix}$$

$$\downarrow$$

$$S_d = \begin{bmatrix} 0. & 0. & 0. & 0. \\ 0. & 1/E_{bb} & 0. & 0. \\ 0. & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. \end{bmatrix}$$

and

$$\sigma_o = \begin{Bmatrix} \sigma_{aa} \\ \sigma_{bb} \\ \sigma_{cc} \\ \sigma_{ab} \end{Bmatrix} \longrightarrow \sigma_d = \begin{Bmatrix} 0. \\ \sigma_{bb} \\ 0. \\ 0. \end{Bmatrix}$$

where S_o and S_d are the undamaged and damaged compliance matrices respectively, and σ_o and σ_d are the stress components of the original and damaged states respectively.

(ii) When inplane tensile failure occurs, the following is invoked:

$$S_o = \begin{bmatrix} 1/E_{aa} & -\nu_{ba}/E_{bb} & -\nu_{ca}/E_{cc} & 0. \\ -\nu_{ab}/E_{aa} & 1/E_{bb} & -\nu_{cb}/E_{cc} & 0. \\ -\nu_{ac}/E_{aa} & -\nu_{bc}/E_{bb} & 1/E_{cc} & 0. \\ 0. & 0. & 0. & 1/G_{ab} \end{bmatrix}$$

$$\downarrow$$

$$S_d = \begin{bmatrix} 0. & 0. & 0. & 0. \\ 0. & 1/E_{bb} & 0. & 0. \\ 0. & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. \end{bmatrix}$$

and

$$\sigma_o = \begin{Bmatrix} \sigma_{aa} \\ \sigma_{bb} \\ \sigma_{cc} \\ \sigma_{ab} \end{Bmatrix} \longrightarrow \sigma_d = \begin{Bmatrix} 0. \\ \sigma_{bb} \\ 0. \\ 0. \end{Bmatrix}$$

where S_o and S_d are the undamaged and damaged compliance matrices respectively, and σ_o and σ_d are the stress components of the original and damaged states respectively.

(iii) When delamination occurs, the following is invoked:

$$S_o = \begin{bmatrix} 1/E_{aa} & -\nu_{ba}/E_{bb} & -\nu_{ca}/E_{cc} & 0. \\ -\nu_{ab}/E_{aa} & 1/E_{bb} & -\nu_{cb}/E_{cc} & 0. \\ -\nu_{ac}/E_{aa} & -\nu_{bc}/E_{bb} & 1/E_{cc} & 0. \\ 0. & 0. & 0. & 1/G_{ab} \end{bmatrix}$$

$$\downarrow$$

$$S_d = \begin{bmatrix} 1/E_{aa} & 0. & -\nu_{ca}/E_{cc} & 0. \\ 0. & 0. & 0. & 0. \\ -\nu_{ac}/E_{aa} & 0. & 1/E_{cc} & 0. \\ 0. & 0. & 0. & 0. \end{bmatrix}$$

and

$$\sigma_o = \begin{Bmatrix} \sigma_{aa} \\ \sigma_{bb} \\ \sigma_{cc} \\ \sigma_{ab} \end{Bmatrix} \longrightarrow \sigma_d = \begin{Bmatrix} \sigma_{aa} \\ 0. \\ \sigma_{cc} \\ 0. \end{Bmatrix}$$

where S_o and S_d are the undamaged and damaged compliance matrices respectively, and σ_o and σ_d are the stress components of the original and damaged states respectively.

COMPUTER IMPLEMENTATION

Basic Algorithm

Included as history variables are the Cauchy stresses, an angle to define the material directions, and three failure parameters that indicate punching shear failure, inplane fiber breakage, and delamination. The following summarizes the steps that are taken to update the Cauchy stress state from time n to time n+1:

i. Check values of the parameter for punching shear, fiber breakage and delamination failures, set their values to 1.0 if they exceed 0.51. If not, set their values to 0..

ii. Compute the angle between element side 1-2 and the material a-axis at time n since the stored angle refers to the geometry at time n.

iii. Update stored angle to time n+1.

iv. Transform Cauchy stresses and strain rates into the local coordinate system of the material.

v. Compute the constitutive matrix by setting the material constants to either their values or zero as a function of material failure.

vi. Compute trial stress state in material coordinates.

vii. Check for various failures and modify stresses and the constitutive matrix.
viii. Transform the remaining trial stresses back to the global coordinate system.
ix. Compute pressure, p, for material under compression.

Numerical implementation

The above algorithm has been implemented into a two-dimensional axisymmetric nonlinear transient dynamic finite element program - DYNA2D. It is incorporated as an individual material subroutine. During the implementation of the algorithm and testing of the model, several problems were encountered. At the beginning, no transition to failure is made, i.e. if the failure criterion is met then the failure is instantaneous. Numerical instability has been observed in many instances. A transition to failure scheme in which failure was assumed to occur during a finite time was adopted [17]. The numerical instability problem was resolved. Since some composites exhibit high strain rate sensitivity in both strength and modulus, a feature in which the strength for each mode of failure can be defined as a function of strain rate has been incorporated. The issue of rate dependency of moduli will be addressed in the future.

On simulating partial perforation and complete penetration problems, the solution time becomes excessive. This is caused by the reduction of time-step size as the elements in front of the projectile become distorted. Most hydrocodes have an automated scheme based on the wave property and the size of the controlled element for calculating the time-step size. As the element becomes distorted, the time-step size will reduce and therefore, solution progresses very slowly towards the end of the penetration process. A one-way erosion algorithm, with which composites can be eroded upon failure of the material under certain failure modes, has been developed and incorporated into the finite element program. Such erosion algorithm has facilitated the solution process of the penetration simulation.

VALIDATION

Previously conducted ballistic tests were selected to validate the proposed model. Selected tests include both partial perforation and complete penetration cases. Analyses were performed to simulate these ballistic tests and results were compared to tests in terms of penetration depth for partial perforation, residual velocity for complete penetration, deformation pattern, failure mechanisms and the extent of each failure mechanism. Four ballistic tests were used for the validation.

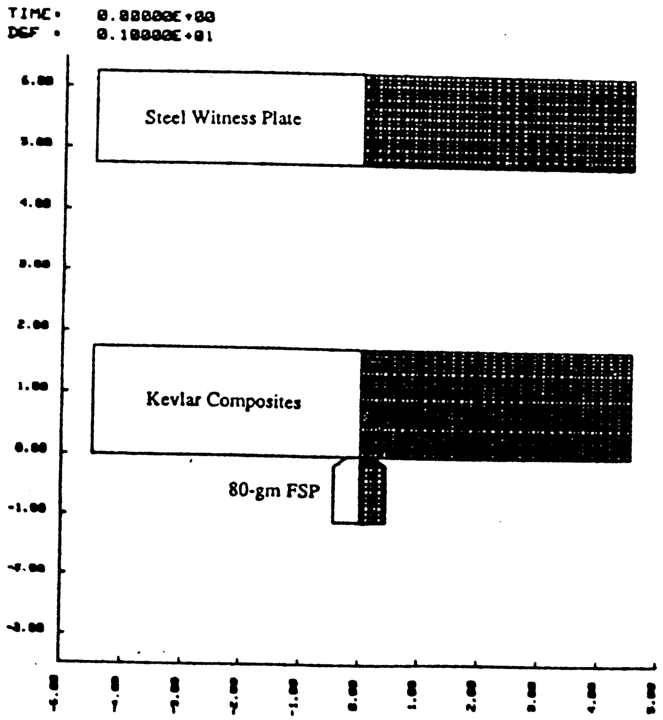

Figure 3 Finite Element Model of a FSP Impacting a Kevlar Panel

The first model involves an 80-gram FSP impacting a 1.75-inch Kevlar-49 Polyester composite panel at a velocity of 5,699 ft/sec. A 1.5-inch 4340 steel witness plate was placed behind the composite panel to stop the penetrated projectile. Figure 3 shows the finite element model. The penetration model predicted that the projectile would penetrate to a depth of 0.6 inch compared to that of 0.63 inch measured in the ballistic test. Figures 4-7 show a sequence of the simulation results. Extensive delamination was predicted as shown in Figure 8 and this resembles that found in the tested panel. The second model involves the same FSP impacting a 1.75-inch Kevlar-49 Polyester composite panel at a velocity of 5,893 ft/sec and then a 1.5-inch S-2 Glass Polyester composite panel. Our model predicted a complete perforation of both panels and the calculated residual velocity was 2,375 ft/sec compared to 2,740 ft/sec measured in the test. The third model involves the same FSP impacting a 1.75-inch Kevlar-49 Polyester composite panel at a velocity of 6,135 ft/sec and then a 1.588-inch Kevlar-49 Polyester composite panel. Our model predicted a complete perforation of both panels and the calculated residual velocity was 2,600 ft/sec compared to 2,949 ft/sec measured in the test. In these three models, the extent of failure predicted in the simulations closely resembled that of the tested panels.

The fourth model involves a 20-mm FSP impacting a 1.74-inch S-2 Glass-reinforced Polyester composite panel at a velocity of 2,351 ft/sec. Ballistic test shows partial perforation of the projectile in the panel with extensive delamination both in the front and the back sides. Simulation using the proposed model predicted partial penetration with a penetration depth which is approximately the same as that measured in the test. However, some discrepancy was found in the extent of the delamination on the both the entry and

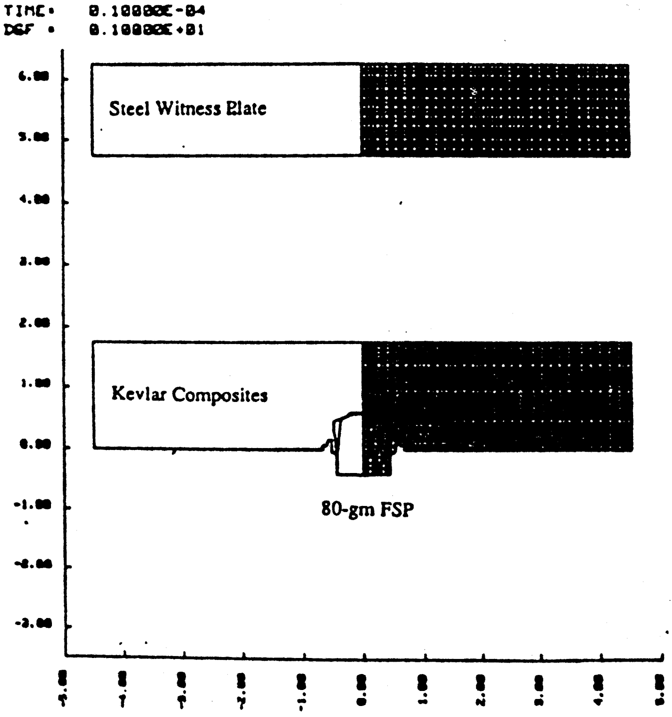

Figure 4 Impact Behavior of Kevlar Panel after 10 micro-seconds

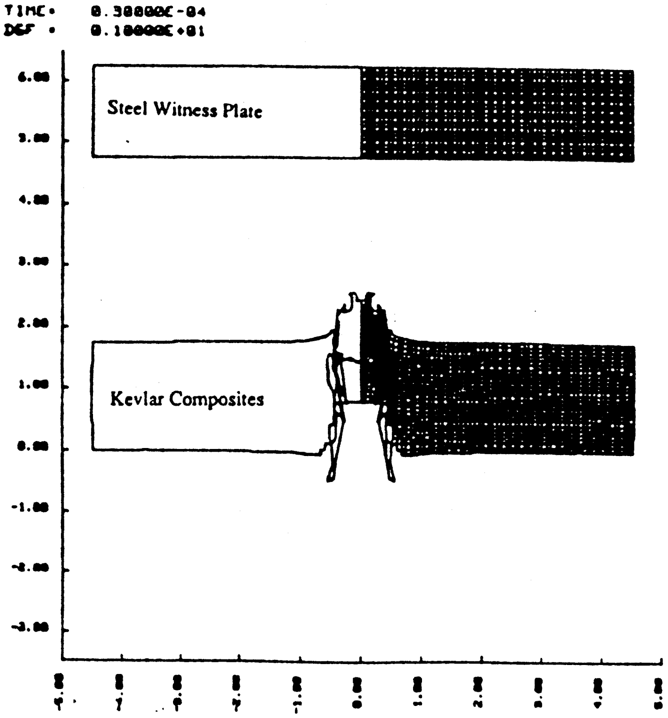

Figure 5 Impact Behavior of Kevlar Panel after 30 micro-seconds

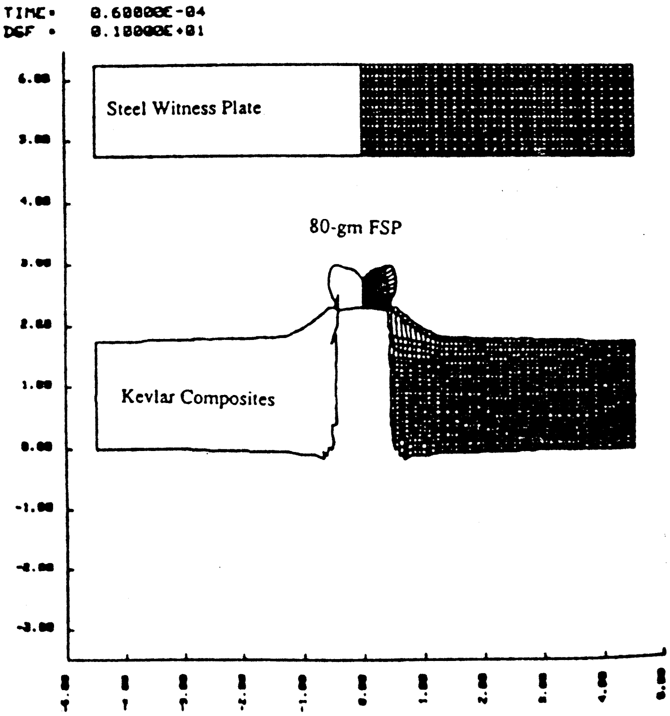

Figure 6 FSP exiting the Kevlar Panel after Complete Penetration

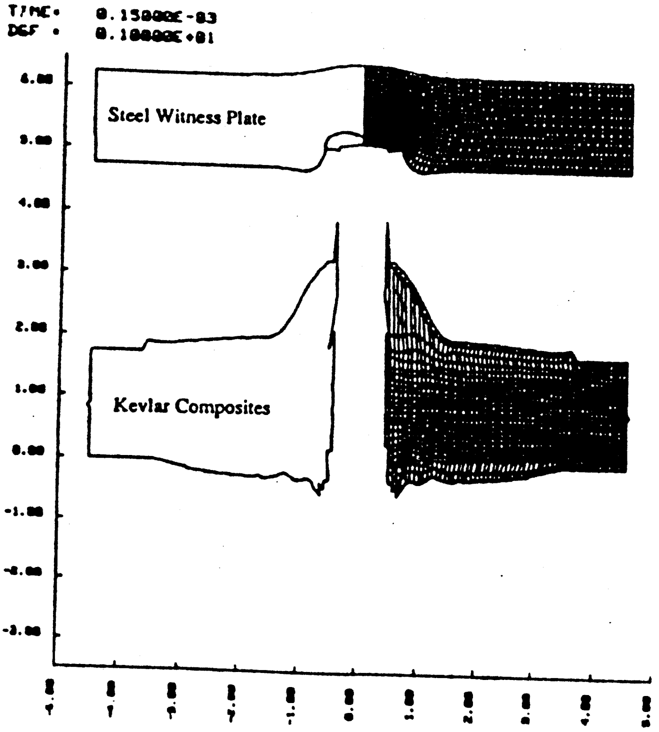

Figure 7 FSP Perforated the Steel Witness Plate

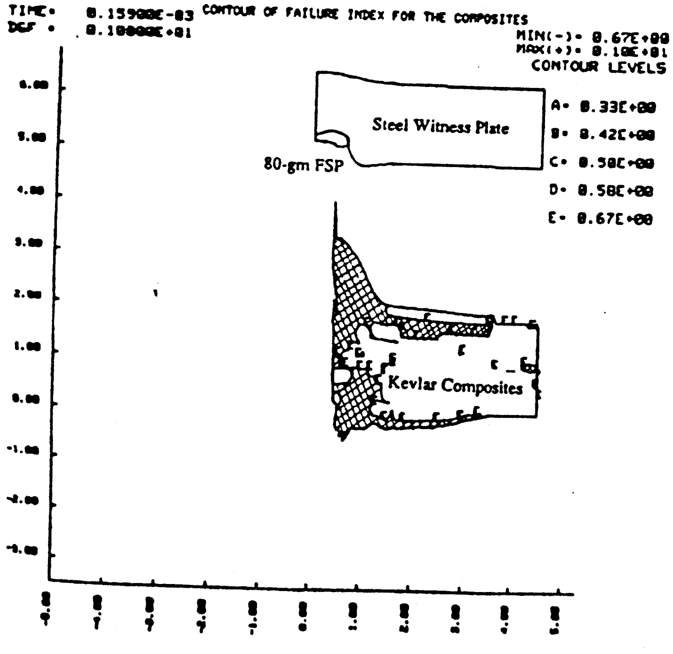

Figure 8 Delaminated Region in the Penetrated Kevlar Panel

exit faces of the panel. The model gave a smaller area of delamination. This is a short-coming of the current model in which micromechanics aspects of the failure behavior cannot be isolated. In this particular material, the composite system was tailored such that mismatch was produced between the fiber and the matrix. Such a mismatch may promote propagation of delamination at low energy impact (particularly when the projectile has decelerated to a low speed) instead of punching through. Refinement of the current model is required to provide a better estimate of the delamination behavior. However, it is believed the energy associated with the propagating delamination is a minimum in this case and therefore has little effect in the prediction of the ballistic performance of current systems.

CONCLUSION

In summary, a first-cut model for predicting the high velocity penetration of thick fiber-reinforced composites was developed. The model has been incorporated into a nonlinear transient finite element program - DYNA2D. A one-way erosion algorithm with which composites can be eroded upon certain combination of failure modes was developed and included in the code. Good correlation was found between the model and ballistic tests. The current model is restricted to 2-D axisymmetric geometry and is valid for quasi-isotropic laminates. Though it is adequate for the composites being considered at the present time, improvements can be made for a more general composite construction. Currently research is continuing on a refined constitutive model in which certain micromechanics aspects of the failure process, and rate dependent effects on both the stiffness and the strength of composites can be addressed. Future development will be directed towards other dissipation mechanisms, higher-order equation of state and failure criteria, and a three-dimensional generalization of the model.

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