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# Application of an Analytical Model for Ballistic Penetration to Composite Targets

by S. R. Bodner  
and A. M. Rajendran

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## Application of an Analytical Model for Ballistic Penetration to Composite Targets

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## Abstract

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This report presents the procedures developed for adopting a two-dimensional (2-D) analytical model of ballistic penetration and perforation in isotropic targets to target plates of composite materials (e.g., glass [fiber] reinforced plastics [GRP]). The depths of penetration in S-2 glass fiber/polyester matrix composite laminates were calculated using this analytical model and compared with the measured data. The initial formulation is based on blunt-nosed rigid projectiles and normal impact velocities up to about 1 km/s. Some preliminary results are described, and directions for further investigations are indicated. This report also briefly reviews penetration mechanisms in GRP laminates and some experiments and analytical/computational modeling efforts by other investigators.

## **Acknowledgments**

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# 1. Introduction

Glass (fiber) reinforced plastic (GRP) composites are becoming increasingly popular in various industrial and military applications due to their particular physical and mechanical properties and tailorability to suit the requirements of specific applications. Composite materials offer a host of material variables that can be incorporated into the design of armor, and the designer is often faced with the challenge of designing the most optimum laminate configuration for the specific armor application. However, to determine the most optimum configuration from the multitude of possible combinations by experiments alone is prohibitively expensive and time-consuming. Thus, it is extremely important to develop analytical or numerical models to accurately predict the response of these composite armors under projectile impact and penetration.

Until now, the bulk of the work on modeling has focused on developing empirical models for engineering purposes. A large number of experiments have been conducted to establish a database of failure/no-failure conditions. Many experimental parameters (e.g., impact velocity, laminate thickness, ply arrangement, angle of impact, and projectile mass) were varied from experiment to experiment. Data from the penetration experiments were employed in the empirical modeling. Unfortunately, these empirical models cannot be used as predictive tools outside the tested velocity regimes and geometric configurations.

A two-dimensional (2-D) analytical model for penetration and perforation of homogeneous, isotropic target plates by rigid penetrators was developed by Ravid and Bodner (1983). That model is applicable for rigid penetrators and is completely self-contained, in that no empirical factors are required, and standard mechanical properties are utilized. The model involves five interconnected stages of the penetration and perforation process; where each is characterized by distinct geometrical features. Attention was given to the details of the failure mechanisms at the perforation condition.

There is considerable interest in developing a corresponding analytical model for targets composed of composite materials, such as glass fiber filaments or woven cloth in a polymer matrix, such as epoxy or polyester. The present report explores the possibility of adopting the dynamic plasticity model of Ravid and Bodner (1983) to analyze the penetration and perforation of rigid projectiles in targets of composite materials. In addition, this report presents a brief review of analytical/computational models that have been proposed to describe the penetration process in composite laminates and discusses the need for high strain rate characterization of polymeric composite materials.

Despite the basic anisotropy of the composite targets and that some of the mechanisms of penetration and failure differ from those of isotropic plates, it seems that the overall penetration patterns are similar for the two cases. Shortly after impact and a shock phase, which can probably be ignored for moderate impact velocities, except for the possibility of generating damage, there will be an initial stage of penetration in which target material forward of the projectile will be displaced and moved toward the impact surface. A zone of nonelastically deformed material (a plastic flow field in the case of metallic targets) will surround the projectile radially and longitudinally. When the front of that zone reaches the rear surface, the motion of the displaced target material will change direction and move forward to form a bulge on that surface. For metallic targets at that stage, a truncated conical or a cylindrical-like section of target material (i.e., a plug) generally forms forward of the projectile. Failure of material in the region between the projectile and the outer target surface will then lead to perforation of the target by plugging or tensile instability.

A complete qualitative description of the penetration and perforation process in laminated plates is given by Reid et al. (1995), who refer to unpublished reports by Greaves (1995) where the phases are considered: "Phase 1 involves compression, shear, indentation, and expulsion of debris. In phase 2 formation of a cone of delaminations, fiber stretching and fractures occur and the projectile exits from the back face."

For isotropic metallic target plates and not too high impact velocities, the resistance to penetration is due to inelastic deformation and inertial effects, and the same seems to be true for

composite plates. Delamination damage of the composite plates resulting from initial stress waves and the displacement of target material will also occur, but is not considered to be a major dissipation mechanism during the initial stage of ballistic penetration. It could, however, influence the effective strength of the target and would be an important factor in the residual strength of the perforated plate. Whether shock waves generated at initial impact are a significant factor for blunt-ended projectiles is uncertain. Shock wave effects generally can be ignored for metallic projectiles and targets when the impact velocity is less than 1,000 m/s. It is known that shock wave effects can be significant for ceramic targets, and their possible relevance for composite targets, such as laminated glass/epoxy, has to be examined, especially in relation to the possibility of generating damage. An analytical model for studying shock effects due to ballistic impact is described in Ravid, Bodner, and Holcman (1987) and can be exercised for a particular application.

A brief review of the main features of the dynamic plasticity penetration model of Ravid and Bodner (1983) is given in section 3, and the directions suggested for modification of the analytical model for application to composite targets are described. The overall objective is to formulate a fully contained 2-D analytical model for ballistic penetration and perforation of composite target plates normally impacted by rigid projectiles.

## **2. Background**

This section provides a brief background on: (1) penetration mechanisms into composite targets, (2) related experiments, and (3) a review of analytical modeling efforts. Most of the penetration tests are traditionally performed at industries and Army laboratories, and the results are usually published as internal documents or in conference proceedings or government reports. The review provided here is mainly to serve as background material for our analytical model development effort and is not intended to be comprehensive.

**2.1 Penetration Mechanisms.** The mechanics of projectile penetration in fiber-reinforced composite targets is still not fully understood; however, several experimental investigations have

been undertaken to document the dominant failure mechanisms in composite targets (e.g., Bless et al. 1987). Bless et al. (1991) summarized various penetration mechanisms that develop in graphite/epoxy and S-2 glass/phenolic composites. The penetration and perforation process can be divided into three stages: impact, entry, and exit. In the impact phase, shock waves and elastic waves are generated in both the projectile and target. The maximum intensity of the shock wave depends on the impact velocity and the shock impedance of the target and projectile. Both waves could cause delamination of composite targets, possibly through spall-type failure. In the entry phase, the target material suffers mostly compressive failure in the contact region. The fibers and matrix fail around the penetration cavity.

The dominant failure mechanisms during the entry phase seem to be cutting of fibers due to shear and cavity expansion, which refer to the radial expansion of the target material away from the path of the projectile. This radial expansion is usually accompanied by local buckling of the fibers and microcracking of the matrix (epoxy) material. The fibers may undergo single shearing, where the fibers are cut only once, and the loose ends are left in the wake of the projectile; double shearing, where the fibers are cut twice and ejected from the penetration cavity; as well as kinking, due to compressive stresses during cavity expansion. The matrix suffers mostly compressive and shear failure during this stage.

In the exit phase, a transition from compressive failure to tensile or shear failure seems to occur, usually accompanied by extensive delamination. The time-dependent delamination process is initiated during the earlier time of the impact phase. However, the delamination growth (propagation) will continue until the arrival of the projectile near the delaminated areas. The plies are pushed ahead of the projectile, and tensile failure of fibers may occur away from the projectile nose. Fiber pullout may also occur in this stage. In the final exit mode, projectile energy is absorbed due to fiber failure, fiber pullout and delamination, as well as transfer of kinetic energy to the target. There is often extensive delamination accompanying fiber stretching. In general, the failure mechanisms involve fiber breakage, matrix cracking, ply cracking, delamination, and fiber pullout. It may not be practical to describe each and every one of these exit failure processes.

**2.2. Experiments.** For accurate modeling, the laminate strength variation, with respect to strain rate, has to be determined from high strain rate and shock-loading experiments. For this purpose, two experimental configurations are often considered: split Hopkinson bar (SHB) and plate impact tests. The SHB tests generate strength vs. strain rate data at strain rates above 200/s. The plate impact tests provide spall (dynamic tensile failure) strength and compressive strength at very high strain rates. Compressive strength at high strain rate is often calculated from the stress-gauge-measured steady-state value of the Hugoniot elastic limit (HEL), the stress amplitude at which inelastic deformation begins. Typically, one can identify the arrivals associated with the acoustic velocity, the compressive failure of the matrix, and the compressive failure of the fibers.

Chou and Deluca (1993) documented and summarized the results from high strain rate, as well as ballistic tests on GRP materials. There are only a few references in the open literature that involve studies on projectile penetration into composite armors (e.g., Bless, Krolak, and Askin 1985; Bless, Hartman, and Hanchak 1985). There are several material and impact parameters that can affect the penetration mechanisms, and one can systematically evaluate the effect of each parameter while keeping the other parameters constant. The key material parameters are the fiber, matrix, sizing, and lay-up, while the key impact parameters are impact velocity, projectile mass and nose shape, and the ratio of the target thickness to the projectile diameter. Presently, various types of fibers are available (e.g., graphite, glass, kevlar, spectra, etc.) that can be combined with suitable matrices (e.g., epoxies, phenolic, thermoplastics, etc.) to design laminates for practical applications.

**2.3 Some Analytical Modeling Efforts.** Modeling the penetration of a metal projectile into a composite laminate at high-velocity impact is extremely complex. Both the geometric and material responses are three-dimensional (3-D) and usually a 2-D axisymmetric idealization is not possible. Computational methods demand extensive computing resources, in terms of memory and CPU (central processing unit) time. While the advent of increased computing capabilities makes a computational approach feasible, there is a real need for analytical modeling. By invoking appropriate simplifying assumptions, mathematical complication can be minimized in the analytical modeling efforts. It would be useful if the penetration models developed for metal

targets could be adopted to describe penetration into composites. A major simplification in the penetration modeling of a homogeneous, isotropic target is achieved by invoking axisymmetry, and further simplification is obtained by assuming cylindrical cavity expansion, which reduces the problem to a one-dimensional (1-D) one. Such simplifications are generally not possible in the case of composite targets, but for quasi-isotropic laminates whose in-plane properties are isotropic, "restricted axisymmetry" can be assumed. A substantial simplification in the model can be realized by invoking a "plane strain" assumption, where the composite laminate target is idealized as a stack of thin, independent layers (plies), which are normal to the penetration direction. Incidentally, this same kinematic assumption has also been used in the penetration modeling of metal targets (e.g., Luk and Forrester 1987).

Recently Lu and Vaziri (1994) presented an extensive review on constitutive and failure models for numerical analysis of the impact response of composite materials. In this report, they have cited the various papers that describe damage initiation and effects of damage on stiffness reduction. Several analytical approaches to modeling damage in composite laminates were also cited. Most of these studies were performed under either quasi-static loading or low-velocity impact conditions. For very high-velocity impact situations, the pressure in the region surrounding the penetrator is extremely high and greatly exceeds the strength of the target material. Typically, hydrodynamic theory is used in such cases to predict the depth of penetration and the deceleration of the penetrator. The basic hydrodynamic equations, developed mainly for elastic-plastic metallic targets, can be directly applied to composite targets; however, several fundamental issues need to be addressed. For instance, the pressure,  $R_t$  (Tate's model parameter [1967]), required for target material to undergo inelastic deformation, is generally a function of the impact velocity, depth of penetration, and a host of other factors, although some approximate results can be obtained by treating  $R_t$  as a material constant. Whether such an approach can be successful for composites is still an open question. Also,  $R_t$  has to be described from a physical standpoint based on a mechanistic model.

Pierson et al. (1993) developed an engineering approach to predict the dynamic penetration process of a rigid projectile into carbon fiber-reinforced plastic (CFRP). To describe the penetration force vs. time for a flat impactor into CFRP, the 1-D Averbuch-Bodner model

(1974) was employed. The force vs. time history predicted by that model did not match well with the measurements, although the peak resistance force was reasonably well indicated. In the same paper, Pierson et al. (1993) extended the use of this model to describe the response of CFRP to conical projectile penetration with reasonable success. The predicted force vs. time history matched the experimental data.

Lee and Sun (1992) developed a model to predict the penetration process for composite laminates impacted by a blunt projectile. Under this study, a series of static punch tests was performed to study the mechanism of penetration. The test results showed that delamination and plugging were the primary failure mechanisms in the laminates, due to static penetration by a blunt projectile. This approach requires finite element modeling of the test configuration. The static penetration model is used to guide the simulation of the dynamic test. The ballistic limits of graphite/epoxy laminates were reasonably well predicted.

Using Whitney-Pagano (1970) laminated plate theory, Zhu, Goldsmith, and Dharan (1992a, 1992b) developed an analytical model suitable to predict the ballistic limits of laminates. The deformation and failure modes include: (1) a spherical bulging (as in the Ravid-Bodner [1983] model), (2) delamination, and (3) fiber extension (to predict fiber breakage). Matrix cracking was neglected in this model. The penetration stages consisted of indentation, perforation, and exit of the projectile. A finite difference computer program solving the governing equations of Whitney and Pagano (1970), in conjunction with the various failure criteria, was developed, and the ballistic limit of a Kevlar/polyester laminate was successfully predicted.

**2.4 Computational Modeling.** At present, the use of shock wave propagation-based finite element/difference "hydrocodes" to analyze projectile penetration into composite targets is restricted, due to the nonavailability of constitutive and failure models in these codes. Among the various general purpose 3-D codes, the DYNA3D code (Hallquist 1988) has an orthotropic material model with a damage description capability. Lu and Vaziri (1994) have cited a few limited attempts by various researchers to describe the response of composite materials to impact and penetration. Unfortunately those works failed to use an accurate equation of state (EOS) to account for the effects of anisotropy and were limited to quasi-isotropic or transversely

isotropic stress states and low-velocity regimes. Anderson et al. (1994) presented a detailed description of an elastic-plastic orthotropic model; this model has been implemented in the EPIC code (Johnson et al. 1994). Recently, Rajendran, Grove, and Anderson (1997) performed plate impact simulations to evaluate the model's ability to describe shock wave propagation in GRP materials.

### 3. Dynamic Plasticity Penetration Model

Here, the Ravid-Bodner model (1983) is adopted to predict the depths of penetration (DOP) in thick S2-glass fiber/polyester laminates due to a rigid steel projectile with a blunt nose. A full description of the original model and its modification to composite targets is given in the following sections.

**3.1 The Analytical Approach.** The basic approach of the dynamic plasticity analytical model of Ravid and Bodner (1983) is to enforce overall work-rate balance of the components of the system. That is equivalent to overall momentum balance, but does not require the detailed calculation of the specific forces acting on the projectile and is also amenable to approximation techniques. In particular, the inertial work rate of the projectile is taken to be equal to the work rates due to dissipation and the inertia of target material during the process. To calculate those work rates, the inelastic region is divided into convenient zones, and a deformation velocity field is assumed for each zone that has to meet the conditions of incompressibility, mass conservation, and velocity continuity normal to all boundaries of the zones and interfaces. Wave propagation and elastic effects are ignored, and the material is assumed to be viscoplastic, in that the flow stress is a function of plastic strain rate.

A sequence of five stages of the penetration and perforation process is identified, each of which is characterized by a particular deformation pattern (Figure 1 of Ravid and Bodner [1983] reproduced here as Figure 1). The first stage involves inelastic deformation zones surrounding the projectile radially and longitudinally within an overall cylindrical boundary (Figure 2 of Ravid and Bodner [1983] reproduced here as Figure 2).

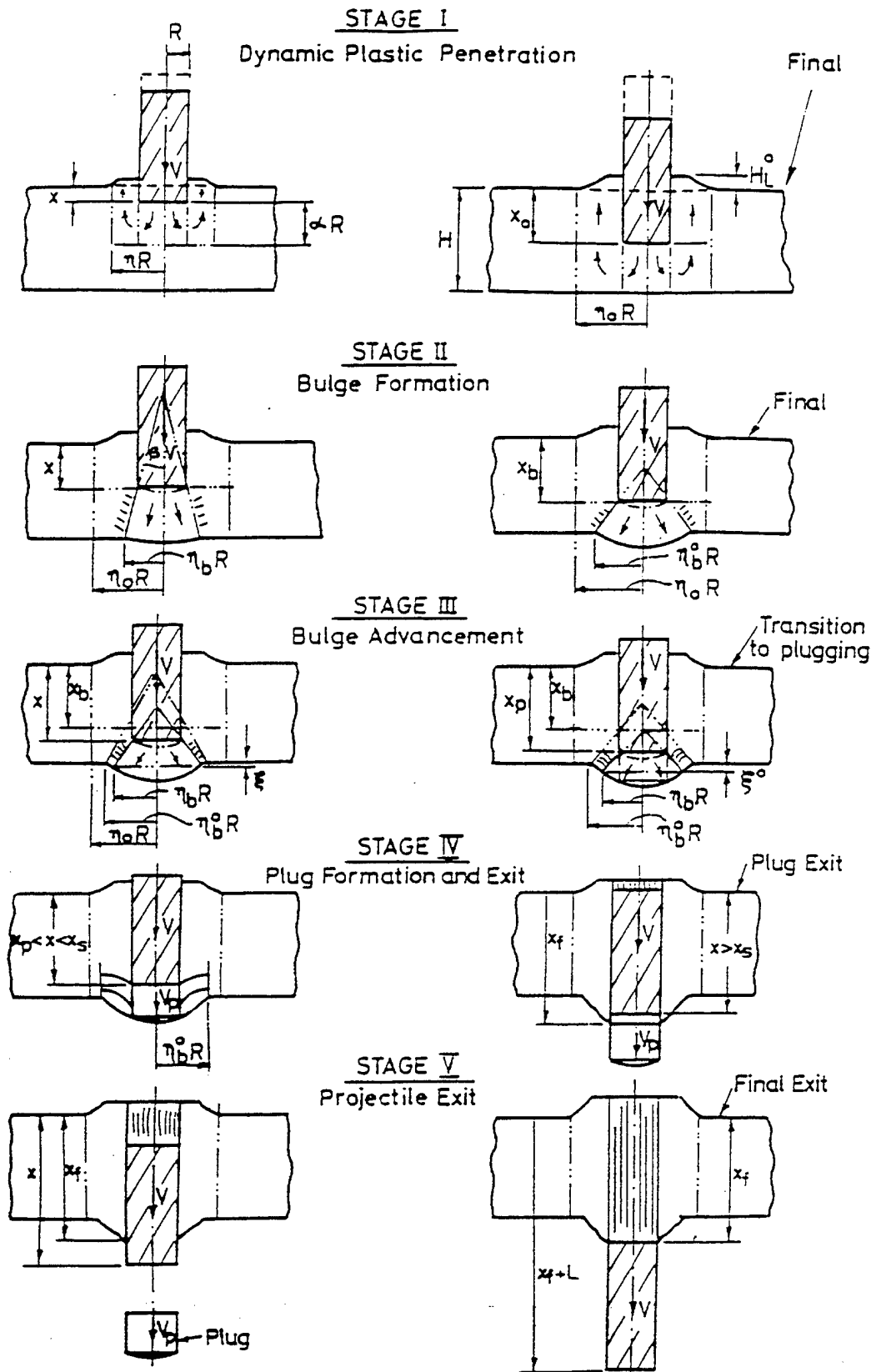


Figure 1. Schematic of 5-Stage Sequence of Deformation Mechanisms for Perforation Process.

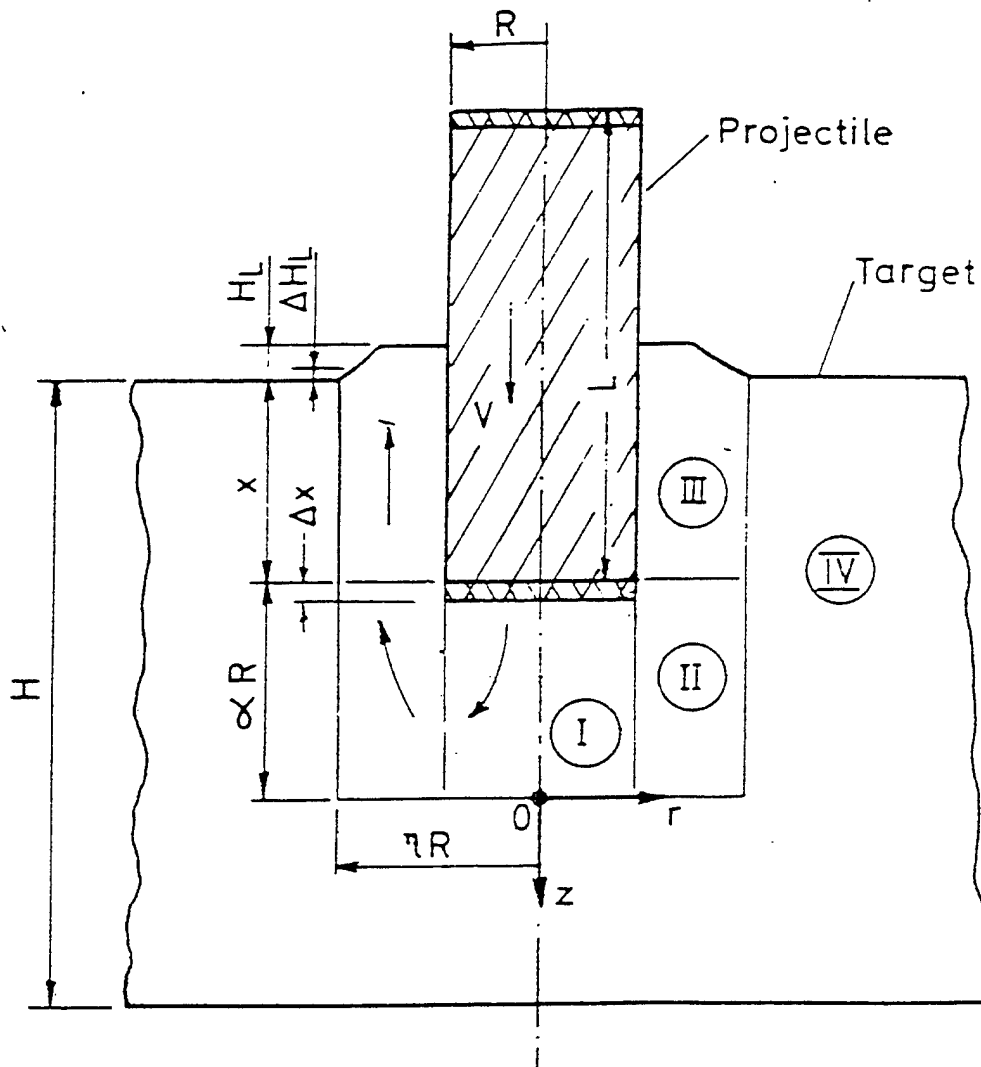


Figure 2. Plastic Flow Field for Stage 1 of Perforation Process - Dynamic Plastic Deformation.

The primary deformation mechanisms are cavity expansion in the radial direction and compression forward of the projectile. Material displaced by the projectile moves to the impact surface to form an entry lip. The deformation velocity field assumed by Ravid and Bodner (1983) is given here as Table 1.

**Table 1. Particle Velocities and Strain Rates for Each Zone of the Plastic Flow Field Assumed During Stage 1 of the Penetration Process**

Zone Notation (Figure 2)	Velocity Field: $v_i$			Strain Rate Field : $\dot{\epsilon}_{ij}$			
	$v_r$	$v_\theta$	$v_z$	$\dot{\epsilon}_{rr}$	$\dot{\epsilon}_{\theta\theta}$	$\dot{\epsilon}_{zz}$	$\dot{\epsilon}_{ij}$ for $i = j$
I	$\frac{vr}{2\alpha R}$	0	$-\frac{vz}{\alpha R}$	$\frac{v}{2\alpha R}$	$\frac{v}{2\alpha R}$	$-\frac{v}{\alpha R}$	0
II	$\frac{v(\eta^2 R^2 - r^2)}{2\alpha R r (\eta^2 - 1)}$	0	$\frac{vz}{\alpha R (\eta^2 - 1)}$	$\frac{-v(\eta^2 R^2 + r^2)}{2\alpha R r^2 (\eta^2 - 1)}$	$\frac{v(\eta^2 R^2 - r^2)}{2\alpha R r^2 (\eta^2 - 1)}$	$\frac{v}{\alpha R (\eta^2 - 1)}$	0
III	0	0	$\frac{-v}{(\eta^2 - 1)}$	0	0	0	0
IV	0	0	0	0	0	0	0

The dissipation terms for stage 1 are due to straining over the volume of the inelastic deformation zone, shear straining on the boundaries of subzones, and friction on the projectile/target interfaces. Inertial effects in the target are due to convective and local acceleration of target material. The dimensions of the overall cylindrical boundary of the inelastic zone,  $\alpha R$  and  $\eta R$  (Figure 2), are determined by minimizing (at each increment of projectile displacement [or time]) the sum of the dissipative work rates of the target that includes the term due to convective acceleration of the target material. However, the summation does not include the term due to the local acceleration of target material that acts as an effective mass contribution to the projectile inertial term. The governing variational theorem for the minimization procedure has been proven in the appendix to Ravid, Bodner, and Holcman (1994b).

The first stage of penetration is completed when the front of the plastic flow zone reaches the rear surface. Subsequent to that condition, stage 2, material displaced by the projectile moves forward to form a bulge. A spherical bulge and a radial flow field forward of the projectile are assumed, as shown in Figure 1. The geometry is fully determined by mass conservation; so, a minimization procedure is not required for this and subsequent stages. At a certain condition of deformation, the spherical bulge shape ceases to operate and a change in deformation mechanism is required. A bulge advancement mode is introduced as stage 3, in which further displaced target material translates the original shape longitudinally to form a new spherical surface with a smaller radial extent as shown in Figure 1. Again, the geometry is fully determined by mass conservation.

Simultaneous with stages 2 and 3, a number of deformation modes are considered that could lead to failure. These include plug formation within the bulge region (stage 4) and the development of large shear strains along the truncated conical segment of the flow zone, which could be due to adiabatic shear band formation. In these cases, failure would be generated by the maximum shear strain reaching a limiting value. For very ductile target materials, tensile failure of the spherical cap along its periphery could occur. Plug ejection by any of the various possibilities followed by projectile exit is considered to be stage 5, which completes the process. It is noted that possible failure modes leading to perforation are not considered during stage 1 of the penetration process.

The penetration analysis of Ravid and Bodner (1983) was developed for a blunt nosed projectile. Since the original formulation was developed, a number of improvements have been incorporated into the analytical model. These are the consideration of conical, hemispherical, and ogival nose shapes, applicability of the model for all projectile length to diameter ( $L/D$ ) ratios (previously, there were some limitations for small  $L/D$  ratios), consideration in stage 1 of possible movement of displaced target material into the cavity for deep penetrations, and thermo-mechanical coupling. These modifications have been published in Ravid, Bodner, and Holzman (1994a).

**3.2 Modification for Composite Targets.** The governing material properties for stage 1 of the isotropic dynamic plasticity penetration model are the compressive flow stress  $\sigma_y$  for straining over the volume of the plastic flow region, and the shear stress  $\tau_y$  due to shear straining at velocity discontinuities tangential to the subzone boundaries. In the case of isotropic materials, these can be related by  $\sqrt{3}\tau_y = \sigma_y$ , according to the von Mises criterion. The flow stresses are taken to be linear functions of the logarithm of strain rate averaged over the respective regions. For application of the model to composite materials, a reasonable value for the shear flow stress  $\tau_y$  would be that of the matrix material. The term  $\tau_y$  should therefore be determined independently of  $\sigma_y$  as a directly measured quantity or approximated by the matrix flow stress in shear.

Since the composite can be considered to have local orthotropic symmetry with orthogonal coordinate axes 1, 2, 3, the generalization of the von Mises isotropic yield function is given by Spencer (1991),

$$\frac{(\sigma_{11} - \sigma_{22})(\sigma_{11} - \sigma_{33})}{Y_1^2} + \frac{(\sigma_{22} - \sigma_{33})(\sigma_{22} - \sigma_{11})}{Y_2^2} + \frac{(\sigma_{33} - \sigma_{11})(\sigma_{33} - \sigma_{22})}{Y_3^2} + \frac{\sigma_{23}^2}{K_1^2} + \frac{\sigma_{31}^2}{K_2^2} + \frac{\sigma_{12}^2}{K_3^2} = 1 \quad (1)$$

In equation (1),  $Y_1, Y_2, Y_3$  could be interpreted as yield stresses for uniaxial compression (or tension, depending on the situation) in the  $x_1, x_2, x_3$  directions, respectively. For composites, the yield values in compression are generally not the same as to those in tension.  $K_1$  is the shear yield stress in the  $x_3$  direction on the plane  $x_2 = \text{constant}$  and  $K_2$  and  $K_3$  have analogous interpretations. For the present application of a laminated plate, it would be reasonable to set  $\tau_y = K_1 = K_2 = K_3$ , and  $Y_1 = Y_2$  where the  $x_1, x_2$  axes are in the plane of the plate and the  $x_3$  direction normal to it.

Another essential change in the calculation procedure would be that the work rate due to dissipation over the effected volume should separately consider the work rates due to the stress

components in the plane of the plate,  $\sigma_{rr}$  and  $\sigma_{\theta\theta}$  (using cylindrical coordinates), and to the normal (i.e., longitudinal) stress  $\sigma_{zz}$ . In the case of stage 1 of the analytical model (i.e., prior to rear surface bulging), the coordinates that represent the strain rate field correspond to the principal axes of the material so that obtaining the expression for the dissipation is fairly direct. The in-plane stress components would have the material "flow" stress value  $Y_1(=Y_2)$  while the normal (transverse) stress would correspond to  $Y_3$ . The expression for the work rate in a volume zone  $V_n$  would then be,

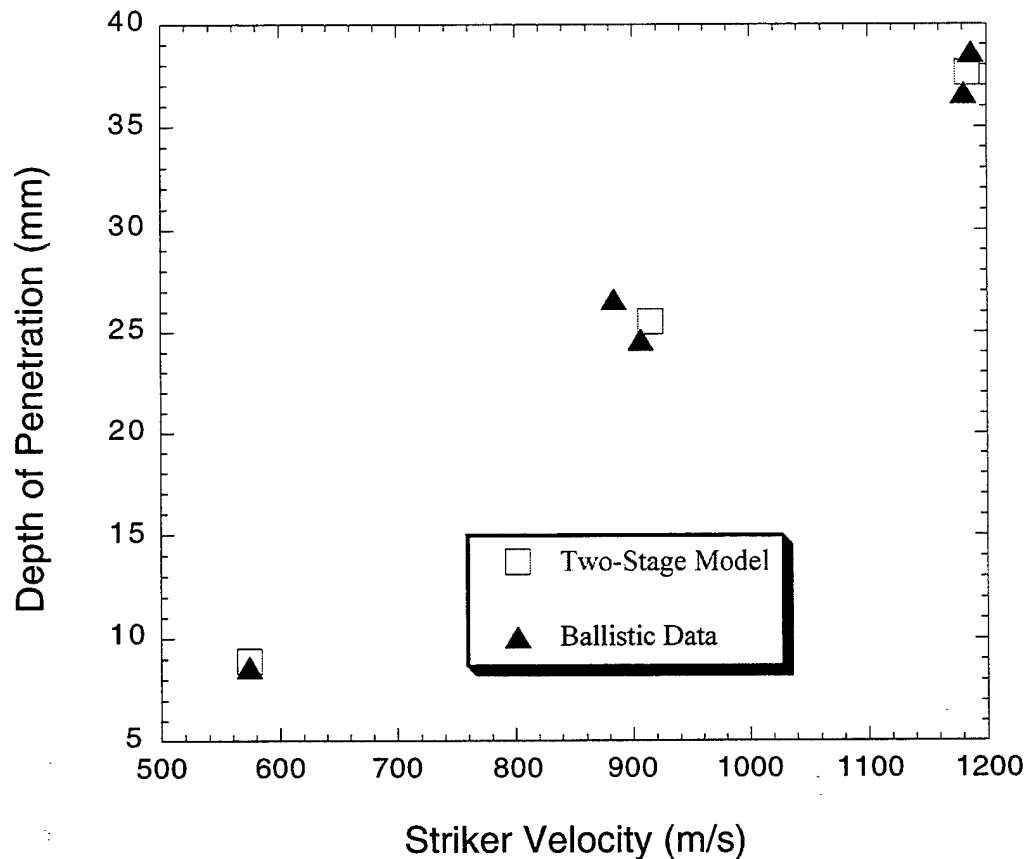
$$\dot{W}_V^n = \int_{V_n} \sigma_{ij} \dot{\epsilon}_{ij} dV = \left\{ Y_1 \left[ (\dot{\epsilon}_{rr})^{avg} + (\dot{\epsilon}_{\theta\theta})^{avg} \right] + Y_3 (\dot{\epsilon}_{zz})^{avg} \right\} V_n , \quad (2)$$

where the symbol  $(\dot{\epsilon}_{ij})^{avg}$  indicates an average value of the strain rate component in the zone. Ravid and Bodner (1983) provided expressions for the strain rate components for stage 1 as given in Table 1. The sum of the components is zero due to plastic incompressibility. Since the flow stress is a function of strain rate, the values  $Y_1$ ,  $Y_3$ , and  $\tau_y$  should depend on associated average strain rates over the zone of interest.

Stages 2 and 3 of the penetration process involve inelastic flow fields with geometries that are complicated with respect to the material coordinates of the orthotropic target plate. In these stages, the shear effect is relatively more important so that some average value for the direct flow stress of the material may be adequate. Also, the failure strain for some composites such as glass fibers in polyester, is usually not large so that stage 1 can constitute the major resistance to ballistic perforation of such materials. With such an approximation, modification of the computer program developed for the analysis of Ravid and Bodner (1983) to apply to orthotropic target plates is reasonably straightforward insofar as other effects (e.g., damage due to stress waves) are not present. Prior to operating the fully modified program, some exercises were performed using a reasonably realistic value for  $\tau_y$  and an overall average value for  $\sigma_Y$  in a program that only modified the shear flow stress from the isotropic case. The relevant material properties and dimensions for the reference tests are given in the appendix.

The first exercise (series 1) was the penetration of a blunt-nosed projectile of 12.7-mm diameter and 13.4-gm mass penetrating a 43.2-mm-thick laminated target plate at impact velocities ranging from 610 to 1220 m/s. The plate was constructed of layers of woven fiberglass with a polyester matrix. For this exercise, a simple average of  $Y_1$  (230 MPa) and  $Y_3$  (670 MPa) was used for  $\sigma_Y$ , namely 450 MPa, and  $\tau_y$  was reduced from  $\sigma_Y / \sqrt{3}$  by the factor 0.22, which corresponded to  $\tau_y = 57$  MPa. The strain to failure of the composite target was 7%, but this property is not utilized if material failure leading to perforation does not occur.

Six ballistic tests (two each at about 610, 915, and 1220 m/s) were run for this projectile, and the penetration depths were measured; there were no perforations for these tests. The test results and the predictions of the calculations are shown in Figure 3.



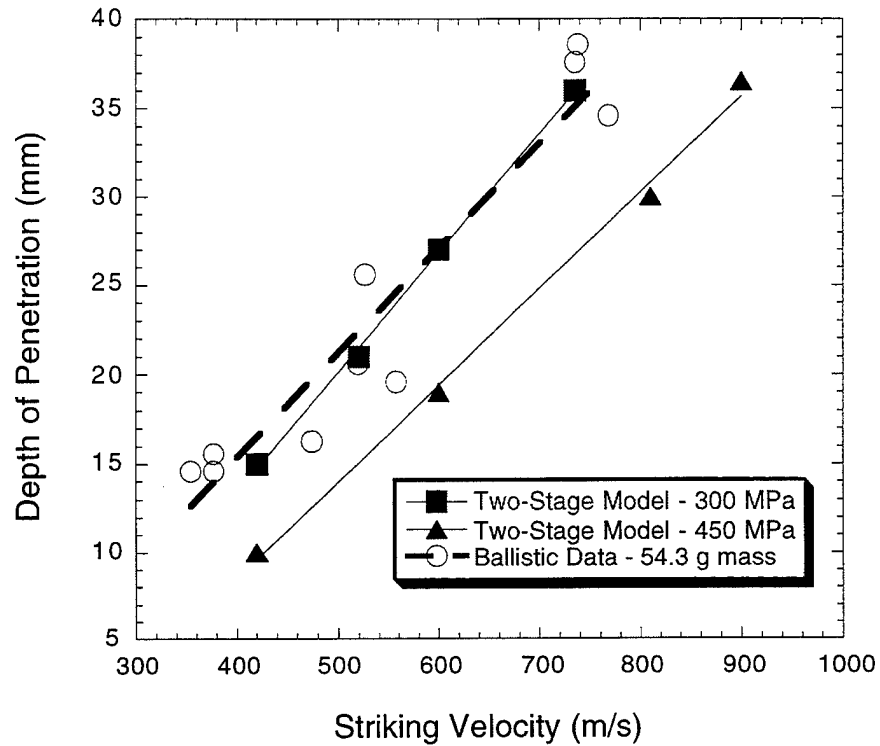
**Figure 3.** A Comparison Between the DOP Obtained From the 2-Stage Penetration Model and Ballistic Tests for a 13.4-gm Mass and 12.7-mm-Diameter Steel Projectile Penetration Into a 43-mm-Thick GRP Laminate.

It seems the agreement is very good despite the approximate nature of the reference analysis and the neglect of various mechanisms particular to composite target plates. A rationalization for the good agreement is that possible early delamination due to stress waves was not significant. Also, the use for the simple average of  $Y_1$  and  $Y_3$  implies that the factors on those strength terms in the volumetric work rate calculation were approximately the same. That is, the kinetic factors due to compression forward of the projectile and to cavity expansion in the in-plane direction were probably of similar magnitude in these cases.

In fact, a method for obtaining an average  $\sigma_Y$  for use in the subsequent penetration stages would be to weigh  $Y_1$  and  $Y_3$  by their respective kinetic factors in the expression for the volumetric dissipation rate in stage 1. It is also noted that spherical and conical-nosed projectiles would increase the relative contribution of the cavity expansion mechanism so that the average effective strength of the composite resisting penetration would be closer to the lower in-plane strength value.

A second set of tests with the same target plates as in the first series was performed with a larger projectile and impact velocities ranging from 430 to slightly over 790 m/s. This projectile was 20 mm in diameter with a mass of 54.26 g. With these conditions, the use of the simple average of  $Y_1$  (230) and  $Y_3$  (670) (namely 450 MPa) in the slightly modified analysis predicted penetration results that were lower than those of the tests (Figure 4). However, the use of a lower average strength value of 300 MPa and a shear strength of 38 MPa, based on the same factor (0.22) on the corresponding isotropic value, did lead to fairly good agreement (Figure 4).

A possible reason for the lower average strength exhibited in the second test series could be that the cavity expansion mechanism was relatively more important than that of forward compression for the larger diameter projectile. As such, the effective average strength would be dominated by the lower  $Y_1$  value. Another possible reason for the lower strength is delamination damage forward of the projectile at some distance of penetration caused by stress waves reflected from the rear surface of the plate.



**Figure 4.** A Comparison Between the DOP Obtained From the 2-Stage Penetration Model and Ballistic Tests for a 54.3-gm Mass and 12.7-mm-Diameter Steel Projectile Penetration Into a 43-mm-Thick GRP Laminate.

The duration time of the stress wave would be greater for the longer and wider projectile with a higher probability of developing damage. Determining which mechanism is the more likely cause of the exhibited lower strength level requires further investigation. Specifically, the computer program for the analytical model of Ravid and Bodner (1983) should be modified to include equation (2) for the volumetric dissipation during stage 1. The investigation of possible damage due to stress waves could utilize the shock phase analysis of Ravid, Bodner, and Holcman (1987) or a simple elastic analysis to obtain the duration time and initial amplitude of the compressive elastic pulse traveling through the thickness of the target plate.

A failure criterion may be required to determine the damage developed by the reflected tensile wave. These two sets of exercises indicate that a simple average direct strength value and a reduced shear strength can serve in a slightly modified isotropic analysis to provide approximate to good predictions for penetration in composite target plates. Numerical exercises are still to be performed with the analysis modified for fully orthotropic material strengths.

## 4. Summary

The Ravid-Bodner (1983) model for ballistic penetration into isotropic targets was modified to predict the depths of penetration into thick S2-glass fiber/polyester laminates by blunt-nosed rigid steel projectiles. The directional properties could be introduced into the model during the different stages of the penetration process. A first approximation was to introduce a pseudo strength which was taken to be the average of the in-plane and transverse strengths of the laminates. Also the shear strength term has to be modified. The experimentally determined DOP were accurately predicted by the modified Ravid-Bodner (1983) model for a steel projectile with a mass of 13 gm. For tests with a heavier 54-gm projectile, modification of the pseudostrength value would be necessary to achieve good agreement. This indicates that the relative influence of the in-plane and transverse strengths would depend on the test conditions, as expected, and the model should be modified to more properly account for the different strength factors. A suggested procedure is given in this report.

A complete mechanistic-based model to describe the penetration process in composite laminates has yet to be developed. There are several reasons for the nonavailability of fundamental models: (1) Unlike metals, the behavior of composite laminates varies with geometry (thickness, fiber orientation, number of plies, etc.) and this geometry-influenced material property variation adds to the complexity of modeling the material behavior of composite laminates. (2) Since composite materials exhibit anisotropic behavior, most simplified analyses consider composite laminates only with some material symmetry, such as quasi-isotropic, transversely isotropic, etc. (3) Impact loading induces a very complex stress state, and analysis under such loading conditions is extremely difficult. (4) Metal projectile penetration into composites involves very complex failure processes, which are poorly understood. (5) Most penetration experiments provide only failure/no-failure conditions; nonavailability of time resolved measurements and carefully recovered targets from penetration experiments make evaluation of the failure sequence mostly speculative. (6) An extensive 3-D finite element analysis under dynamic loading conditions has not been considered until recently; however, with the advent of increased computer capabilities, this approach seems to be feasible.

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**Appendix:**  
**Ballistic Tests**

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**Properties of composite target plates (fiberglass-polyester)**

density:  $1.93 \text{ g/cm}^3$  ; thickness: 43.2 mm  
in-plane compressive strength: 230 MPa  
transverse (normal) compressive strength: 670 MPa  
strain to failure: 7%  
strain rate sensitivity coefficient: 0.005 (assumed)

**Properties of projectiles (blunt nosed cylinders)**

**series 1** (impact velocities, 2000-4000 ft/s)

density:  $7.850 \text{ g/cm}^3$   
mass: 13.42 g  
diameter: 12.70 mm  
length: 13.50 mm

**series 2** (impact velocities, 1400-2600 ft/s)

density:  $7.850 \text{ g/cm}^3$   
mass: 54.26 g  
diameter: 20.0 mm  
length: 22.0 mm

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