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13. ABSTRACT *(Maximum 200 words)*

Ballistic impact of thick-section composites is an extremely complex technical problem. In this research project we have introduced a new approach in using the quasi-static punch curve to describe the mechanics of penetration. Using this punch curve, we are able to capture the mechanical characteristics of penetration and avoid modeling the untractable damage progression in the target during penetration.

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HIGH VELOCITY IMPACT AND PENETRATION OF THICK COMPOSITE LAMINATES

A final report

by

C. T. Sun

October 1994

submitted to
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A. Statement of the Problem Studied

Thick-section composite laminates have light weight and excellent structural properties for applications in armor vehicle constructions. For such applications, their capability to resist ballistic impact must be understood. Of particular interest are the ballistic limit of a given composite and the ability to predict residual velocity of the projectile after penetration. Subsequently, one would be interested in the residual structural properties of the composite after impact.

Fiber composites are highly heterogeneous. Moreover, thick-section composite laminates may contain hundreds of composite laminae. Under ballistic impact loading, the resulting failure modes are extremely complex. The factors that can affect the failure modes include the shape, mass and rigidity of the projectile, the composite system, the thickness and lateral dimension of the target, and the impact velocity. It is conceivable that an accurate detailed modeling of damage progression during ballistic impact would be a formidable task.

A direct modeling of the dynamic penetration process would also require new constitutive models for the composite that take into account the strain rate effect. Since fiber composites are brittle as compared with metals in the penetration process, thousands of cracks (rather than plastic deformation) would occur. These cracks are almost untractable.

The main objective of this investigation was to find new approaches that would allow us to circumvent the aforementioned difficulties in predicting the ballistic limit and residual velocity for a given composite laminate.

B. Summary of the Most Important Results

B.1 Static punch curve

To avoid modeling the detailed damage progression but still capture the effect of various failure modes during penetration, a new approach was proposed. A quasi-static punch test was performed on the composite target with a punch that has the shape and rigidity of the projectile. From this punch test, a load-deflection curve (the punch curve) was generated. This punch curve reflects the damage progression and stiffness degradation of the composite target during the penetration. This punch curve can be considered as the "structural constitutive model" that displays the highly nonlinear behavior of the composite target in the entire penetration process.

Figure 1 shows typical punch curves for the $([0/90/\pm45]_S)_2$ graphite/epoxy laminate punched with a blunt-ended steel penetrator. In the figure are results for two tests. It is evident that the punch curve is quite reproducible. For this laminate the punch curve indicates two major drops in punch force, as indicated by check points A and C.

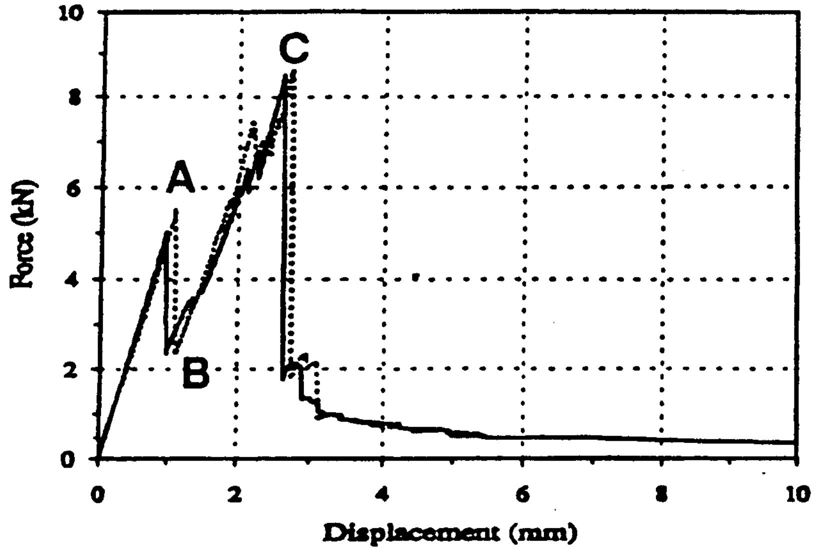

Figure 1 Quasi-Static punch curve for a $([0/90/\pm45]_s)_2$ graphite/epoxy laminate with a blunt punch

Examination using acoustic microscopy revealed substantial delamination after check point A. Thus, check point A indicates the onset of delamination. The big drop in punch force at checkpoint C represents the formation of the shear plug. The long tail after that was the friction between the punches and the composite.

Figure 2 shows the punch curve for a 48 ply $[(0/90/\pm45)_S]_6$ graphite/epoxy laminate. There are a number of sharp drops in the punch curve indicating onset and progression of delamination.

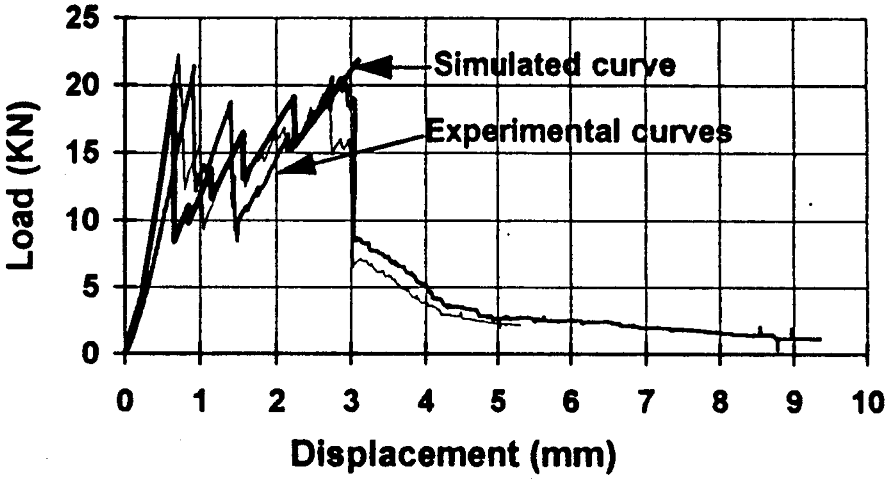

Figure 2 Quasi-static punch curve for a 48 ply $([0/90/\pm45]_s)_6$ graphite/epoxy laminate

Figure 3 shows the punch curve for an S2 glass woven fabric/polyester composite 0.3 inch thick. The penetrator was conical in shape with a rounded tip. Point A indicates onset of matrix cracks and local delamination in the laminate. Point B signifies fiber breakage under the puncher. Point C represents the final stage of fiber breakage and the beginning of massive delamination at the bottom portion of the laminate. From Point D on, the punch curve represents frictional resistance of the punched laminate to the puncher.

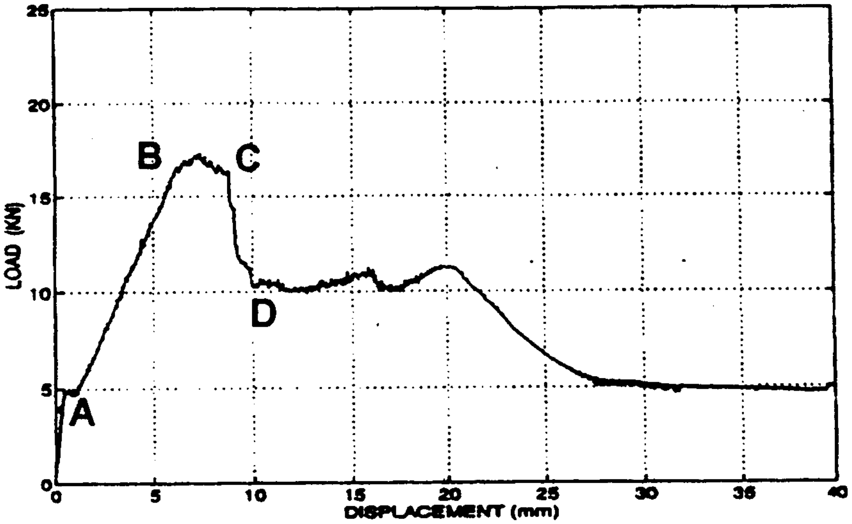

Figure 3 Punch curve for an S2 glass woven fabric/polyester composite 0.3 inch thick

The punch curve captures all the damage events that have taken place during penetration in a quasi-static manner. The area under the curve is the energy dissipated during penetration. In using the punch curve to model dynamic penetration in ballistic impact, the strain rate effect on the punch curve must be assessed. This is similar to extending a static constitutive model to a strain rate-dependent constitutive model.

B.2 Simple energy models

From the punch curve, the energy dissipated during the quasi-static penetration is equal to the area under the curve. This quasi-static penetration energy can be used as a first approximation in estimating the ballistic limit and residual velocity. From the energy consideration that the incident kinetic energy of the projectile is equal to the penetration energy plus the residual kinetic energy of the projectile, the residual velocity of the projectile can be obtained as

$$v_r = \sqrt{v_o^2 - \frac{2}{m} E_{SP}}$$

where m and v_0 are the mass and approach velocity of the projectile, respectively, and E_{SP} is the quasi-static penetration energy. For graphite/epoxy composite laminates impacted with a blunt-ended projectile, the predicted residual velocities are higher than the experimental data, as shown in Figs. 4 and 5. This implies that there is a difference between the static penetration energy and the dynamic penetration energy.

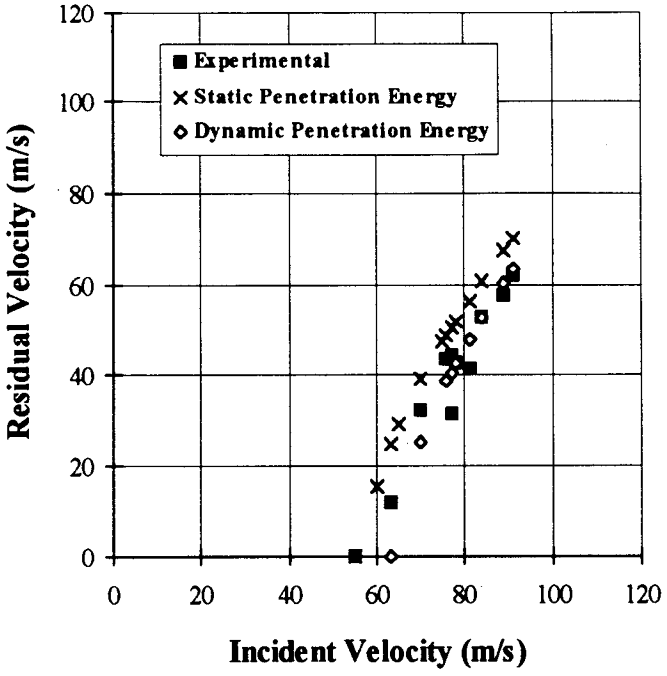

Figure 4 Residual velocities for a 32 ply ($([0/90/\pm45]_S)_4$) graphite/epoxy laminate

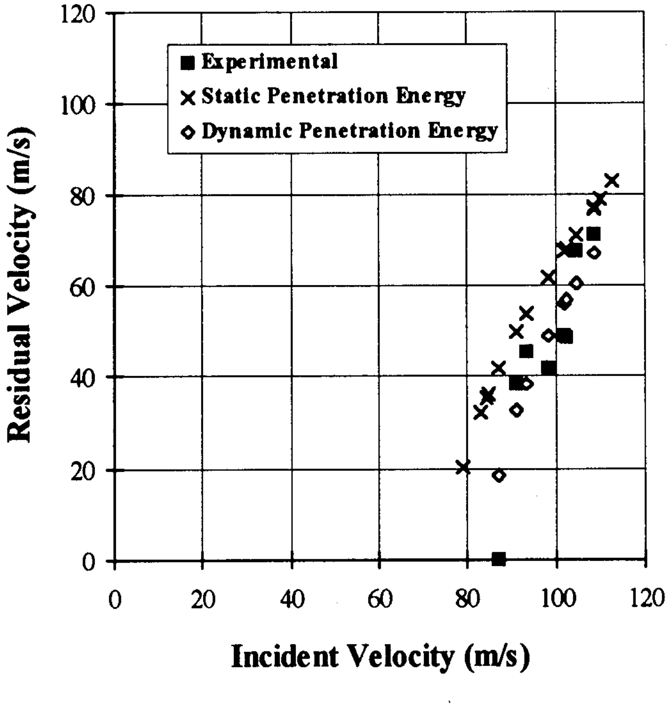

Figure 5 Residual velocities for a 48 ply ($([0/90/\pm45]_S)_6$) graphite/epoxy laminate

It is conceivable that the dynamic penetration energy E_{DP} is dependent on the impact velocity v_o. For the range of impact velocities in our tests, we assume that E_{DP} is constant, which can be calculated using the energy balance equation,

$$E_{DP} = \frac{1}{2} m(v_o^2 - v_r^2)$$

If E_{DP} is truly constant, then it can be determined by an impact test of a single impact velocity. Using a constant E_{DP} obtained based on the experimental data, the residual velocity can be calculated. The results are also shown in Figs. 4 and 5. These predictions agree very well with the experimental data.

B.3 Dynamic response Model

The use of dynamic penetration energy described above needs data from a few dynamic penetration tests to provide a good estimate of the dynamic pentration energy E_{DP}. These dynamic penetration tests have to be performed for each projectile-target combination to estimate the value of E_{DP} for that combination. It is also unclear if the value of the dynamic penetration energy will remain a constant for a larger range of incident velocities. Thus, there exists a need to model the dynamic response of the target in order to accurately estimate the energy consumed during dynamic penetration. A dynamic model would also provide an insight into the various damage mechanisms that occur during the penetration process. This model should be able to predict the dynamic response of the targets of different sizes during penetration by different types of projectiles and at different ranges of incident velocities, without performing any dynamic penetration tests. For this purpose, a ring element was formulated to model the static and dynamic response of the target plate. This element can be used to perform an axisymmetric analysis of penetration under static and impact loading. This element has 2 nodes along the centerline of the plate with 2 degrees of freedom, transverse deflection and rotation, per node as shown in Fig. 6.

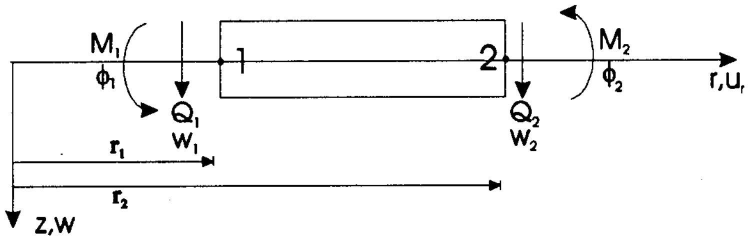

Figure 6 The ring element with the nodal degrees of freedom and the generalized nodal forces

The displacements were assumed to be of the form

$$w = a_0\left(\frac{D}{K}\ln(r) - \frac{r^2(1-\ln(r))}{4}\right) - a_1\frac{r^2}{4} - a_2\ln(r) + a_3\,,$$

and
$$\phi = a_0\left(\frac{r\ln(r)}{2} - \frac{r}{4}\right) - a_1\frac{r}{2} + \frac{a_2}{r},$$

where $D = \dfrac{E_{rr}h^3}{12\left(1-\nu_r^{\,2}\right)}$ is the bending stiffness, $K = kG_{rz}h$ is the transverse shear rigidity, and h is the thickness of the specimen. These shape functions were chosen to reproduce in an exact fashion the deflection of a plate that includes transverse shear deformation. The 4 x 4 stiffness matrix for the element was obtained as

$$\begin{Bmatrix} Q_1 \\ M_1 \\ Q_2 \\ M_2 \end{Bmatrix} = \begin{bmatrix} K_{11} & K_{12} & K_{13} & K_{14} \\ K_{21} & K_{22} & K_{23} & K_{24} \\ K_{31} & K_{32} & K_{33} & K_{34} \\ K_{41} & K_{42} & K_{43} & K_{44} \end{bmatrix} \begin{Bmatrix} w_1 \\ \phi_1 \\ w_2 \\ \phi_1 \end{Bmatrix}$$

where the stiffnesses K_{ij} were explicitly obtained in terms of D, K and the nodal positions.

The contact between the projectile and the specimen was modeled using contact springs between the single node representing the projectile and the elements of the specimen which overlap in diameter with the projectile.

In this study, a serious effort was made to determine the parameter that governs the penetration behavior of blunt projectiles in thick composite laminates. Since most of the contact occurs along a ring at the periphery of contact and the shear plug forms along contact, this parameter would be defined along this periphery of the shear plug. The shear force at the plug periphery decreases when damage occurs in the specimen and increases on further deflection, and thus this fluctuating quantity is not a good parameter to use as the criterion. The transverse shear strain at the plug periphery, on the other hand, increases on initiation of damage since the transverse shear modulus is taken to degrade at damage initiation. Thus, the more stable variation of the shear strain at the plug point during the penetration process makes this a good parameter to be used as the criterion for predicting damage initiation and propagation.

Analyses were performed on 32 ply, 48 ply, and 64 ply laminate cases for different target sizes and the two different projectiles. The plots of residual velocities versus incident velocities show that the present model is very effective in predicting the residual velocities for a range of thickness and size of targets at different velocities as shown in Figs. 7 and 8. However, for projectiles of smaller masses with higher impact velocities, the present dynamic model seems to have overpredicted the residual velocity. One possible reason could be that the transverse shear strain at failure might be strain rate dependent.

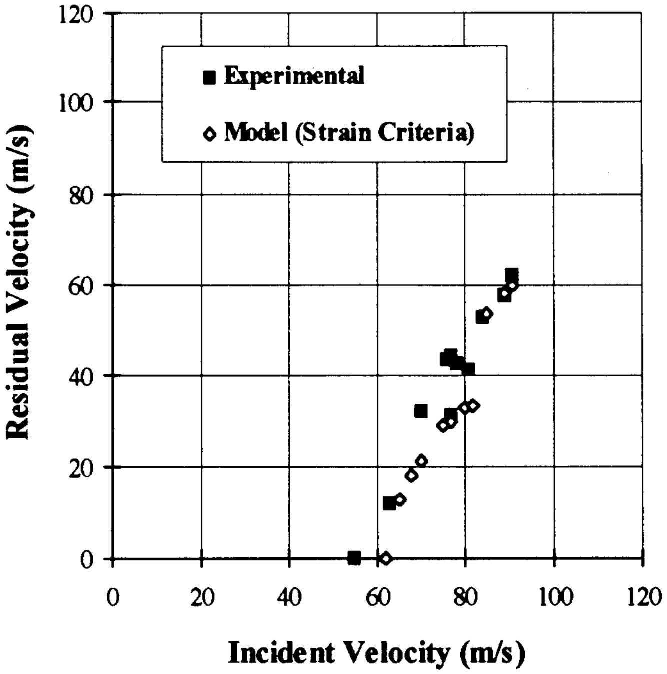

Figure 7 Residual velocities for a 32 ply ($[0/90/\pm45]_s)_4$ graphite/epoxy laminate

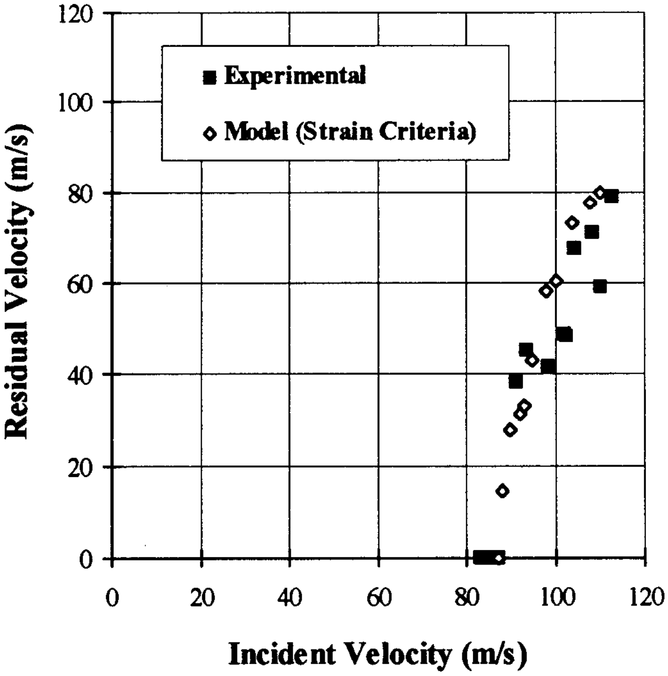

Figure 8 Residual velocities for a 48 ply ($[0/90/\pm45]_s)_6$ graphite/epoxy laminate

In conclusion, ballistic impact of thick-section composites is an extremely complex technical problem. In this research project we have introduced a new approach in using the quasi-static punch curve to describe the mechanics of penetration. Using this punch curve, we are able to capture the mechanical characteristics of penetration and avoid modeling the untractable damage progression in the target during penetration.

C. List of Publications

Journals

- S-W. R. Lee and C. T. Sun, "A Quasi-Static Penetration Model for Composite Laminates," *Journal of Composite Materials*, Vol. 27, No. 3, 1993, pp. 251-271.
- S-W. R. Lee and C. T. Sun, "Dynamic Penetration of Graphite/Epoxy Laminates Impacted by a Blunt-Ended Projectile," *Composites Science and Technology*, Vol. 49, 1993, pp. 369-380.
- C. A. Weeks and C. T. Sun, "Multi-Core Composite Laminates," *Journal of Advanced Materials*, Vol. 25, No. 3, April 1994, pp. 28-37.
- S-W. R. Lee and C. T. Sun, "On the Apparent Bending Isotropy in Clamped Elliptic Composite Laminates," accepted for publication in the *Journal of Composite Materials.*

Conferences

- S-W. R. Lee and C. T. Sun, "Ballistic Limit Prediction of Composite Laminates by a Quasi-Static Penetration Model," *24th International SAMPE Technical Conference*, Toronto, Canada, October 20-22, 1992.
- C. A. Weeks and C. T. Sun, "Design and Characterization of Multi-Core Composite Laminates," *Proceedings of the 38th International SAMPE Symposium and Exhibition, Advanced Materials: Performance Through Technology Insertion*, Anaheim, California, May 10-13, 1993, pp. 1736-1750.
- C. T. Sun and S. V. Potti, “High Velocity Impact and Penetration of Composite Laminates, *Proceedings of ICCM-9, Ninth International Conference on Composite Materials*, Madrid, Spain 12-16 July 1993, Vol. 4, pp. 157-165.
- C. T. Sun and S. V. Potti, Abstract only, "Dynamic Impact and Penetration of Thick composite Laminates," *Presentation at the Army Symposium on Solid Mechanics*, Plymouth, Massachusetts, 17-19 August 1993.
- S-W. R. Lee and C. T. Sun, "Bending Characteristics of Clamped Elliptic Symmetric Composite Laminates," *Proceedings American Society for Composites, 8th Technical Conference on Composite Materials*, Cleveland, Ohio, October 19-21, 1993, pp. 1087-1096.

D. List of Participating Scientific Personnel

S-W. R. Lee	(Ph.D., August 1992)
C. W. Weeks	(M.S., August 1992)
S. V. Potti	(Ph.D. Candidate)
S. V. Thiruppukuzhi	(Ph.D. Candidate)