

NUMERICAL ANALYSIS OF PROJECTILE IMPACT
IN WOVEN TEXTILE STRUCTURES

David Roylance*

INTRODUCTION

Textile structures have been used to provide protection against ballistic threats since the Second World War, with the development then of flak jackets for aircraft crewmen. Now used widely by military and police personnel, these devices have been constructed principally of ballistic nylon or impregnated fiberglass. In recent years, however, improved devices have been developed using aramid fibers (DuPont's Kevlar 29 or 43), and these are being considered for such additional applications as aircraft engine rotor-blade burst containment. Development and design of these devices has been largely empirical, and considerable effort has been expended to develop rational analytical tools which may be used in design, or at least in improving the designer's intuition.

Although closed form-mathematical analyses can be applied to the initial ballistic response of a single fiber [1], late-time effects arise due to stress wave interactions and reflections which make such closed-form analyses intractable. In the case of woven panels, each fiber crossover acts to reflect a portion of the stress wave which is propagating outward from the impact point, so here closed-form treatments

* Associate Professor, Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139.

are completely inapplicable. The complexity of these phenomena have resulted in the development in our laboratory of a series of computer codes, and these numerical treatments have proven to be of great value in understanding the ballistic event. These codes do not involve the idealizing approximations needed in many other treatments, such as modeling the woven panel as a membrane, so that the user is able to proceed directly from fiber material properties, weave geometry, projectile velocity, etc.

NUMERICAL ANALYSIS OF TEXTILE IMPACT

The computer method used in the numerical analysis of textile impact is an outgrowth of a technique pioneered by Davids et al. [2] and applied successfully to a variety of wave propagation problems. This approach, which is similar in final form to finite-difference analysis but markedly different in derivation, was first used by Lynch [3] to analyze transverse impact of single fibers and later extended by Roylance et al. to the study of viscoelastic fiber impact [4] and impact of woven textile panels [5]. Referring to Fig. 1, the woven panel is first idealized as an assemblage of pin-jointed, flexible fiber elements, each having a mass which makes the areal density of the idealized mesh equal to that of the panel being simulated. The initial projectile velocity is imposed on the node at the impact point, which causes a strain to develop in the adjacent elements. The tension resulting from this strain is computed from the constitutive law, and

this tension is used to calculate an acceleration in the neighboring elements. The computer proceeds outward from the impact point in this manner, using a momentum-impulse balance, a strain-displacement condition, and a constitutive equation to compute for each element the current values of tension, strain, velocity, position, and such ancillary but important quantities as strain energy and kinetic energy.

At the end of these calculations, a new projectile velocity is computed from the tensions acting on the projectile from the fibers, and the process is repeated for a new increment of time. In the development of such codes, due attention must be given to matters of efficiency, stability, and accuracy. As now developed, the fabric code produces data in excellent agreement with experiments, and does so at reasonable cost (approximately \$15 for a typical impact event simulation, using MIT's IBM 370/168 system).

MATERIAL PROPERTIES

The numerical algorithm is finally terminated by simulated rupture of the fibers. Since the strain and tension histories are computed for each element in the mesh, a variety of failure criteria may be easily incorporated. The use of Eyring-type rate process fracture criteria [6] are particularly attractive, since they are computationally convenient and still provide good simulation of time and temperature effects. A simple but very useful such criterion is that due to Zhurkov, who states that

the lifetime τ of a solid subjected to a constant stress σ is:

$$\tau = \tau_0 \exp\left(\frac{U - \gamma\sigma}{kT}\right)$$

where k is Boltzman's constant and T is the absolute temperature. τ_0 , U and γ are material constants related to the dissociation kinetics of the atomic bonds and the internal defect structure of the material. For time-varying stresses and/or temperatures, one may assume superposibility and write Zhurkov's equation in the form

$$\int_0^{\tau} \frac{dt}{\tau_0 \exp\left\{\frac{[U - \gamma\sigma(t)]}{kT(t)}\right\}} = 1$$

In our numerical treatment, the current value of the above integral is computed at each node. The time and location of rupture is determined when the integral value reaches unity at any node.

In the course of the iterative calculations, a constitutive material law must be evoked at each element in order to compute the element tension from its strain (or strain history). One would expect that a model incorporating viscoelastic effects would be necessary for proper simulation of polymeric structures and in fact, there is considerable evidence that relaxation does indeed occur in the ballistic time frame [8]. This is expected in light of the dynamic mechanical spectrum of nylon, in which

a beta relaxation is observed having an apparent activation energy of ~ 14 kcal/mole [9]; this relaxation is calculated to occur in approximately five microseconds at room temperature.

A general viscoelastic model well suited for computing tensions from prescribed strains is the Wiechert model, depicted schematically in Fig. 2. This model takes the polymer response to be that of the shown array of Newtonian dashpots and Hookean springs. The differential tension-strain law for the j th arm of the model is

$$\dot{\epsilon} = \frac{1}{k_j} \dot{\sigma}_j + \frac{1}{\eta_j} \sigma_j$$

where the dots indicate time differentiation, σ is the tensile stress and ϵ is the strain. Casting this equation in finite difference form relative to a discrete time increment Δt and solving:

$$\sigma_j^t = \frac{1}{[1 + (\Delta t / \tau_j)]} [k_j (\epsilon^t - \epsilon^{t-1}) + \sigma_j^{t-1}]$$

where the superscripts t and $t-1$ indicate values at the current and previous times respectively, $\tau = \eta_j / k_j$ is a characteristic relaxation time for the j^{th} arm. The total tension at time t is the sum of all the σ_j plus the tension in the equilibrium spring k_e :

$$\sigma^t = k_e \epsilon^t + \sum_j \frac{k_j (\epsilon^t - \epsilon^{t-1}) + \sigma_j^{t-1}}{1 + (\Delta t / \tau_j)}$$

This tension-strain calculation is performed at each element node. In addition to storing all the k_j and τ_j , the computer must also store the previous strain and tension values at each node.

Finally, it should be noted that the above models for dynamic fracture and viscoelastic constitutive response may not be applicable to some materials. The modification or replacement of these models is very convenient in the computer code, since they exist as separate subroutines. The easy implementation of various material response models is one of the strongest advantages to this numerical treatment of impact.

RESULTS

The Fabric code has been used to perform computer experiments aimed at elucidating the influence of various material properties on the impact resistance of woven panels. The objective of this work has been to provide a tool for the designer of personnel armor devices, and to enhance his intuition as to the physics of the impact event. Certain related phenomena have also been explored, including the influence of nonlinear viscoelastic response and the role of backup layers in reducing dynamic deformation and blunt trauma. Certain findings from these studies will be described briefly here in order to illustrate the utility of the method.

Assessment of accuracy of the numerical analysis is somewhat problematical, as no closed-form mathematical analyses are available against which to check the code results. Certain experimental observations are available, however, one of which is shown in Fig. 3. This figure is a plot of residual projectile velocity after penetration of a Kevlar panel, as a function of initial velocity. The good agreement of the predicted and observed

results is especially satisfying, since it provides some assurance that both the transient response and the final fracture processes are being modeled reasonably. It might also be mentioned that this particular plot is one which plays an important role in the design process, so that the ability to generate it numerically without prior ballistic data or any idealizing assumptions is of considerable practical importance.

Figure 4 presents the results of a series of computer experiments in which the response of various ballistic candidate materials is compared. The principal parameters of interest here are the dynamic modulus of the material and its dynamic breaking strain. It is seen clearly that the energy absorption rate of a given fabric rises monotonically with the modulus, increasing in the order of nylon, Kevlar 29, Kevlar 49, and graphite. However, Kevlar 29 demonstrates the best balance of high modulus and reasonable breaking strain, with the result that it is the superior ballistic material. It should be mentioned that Kevlar 49 is not found experimentally to be as deficient as this figure would predict, indicating that an improved model of fracture for this material is needed.

CONCLUSIONS

Although the numerical method described above was developed for use in design and analysis of ballistic protection devices for personnel armor, its potential for use in a similar role in rotor blade burst containment at high velocity is obvious.

The speed range for which the code is well suited is that for which wave propagation effects become important: approximately 200 m/sec and above. The code is applicable at lower impact speeds, but would not be cost effective in comparison with structural dynamics approaches.

Certain alterations in coding would be required in treating burst containment problems. First, one would relax the present restriction to zero-obliquity impact. Such impacts are used as worst-case events in personnel armor, but a more general treatment would be needed for burst containment analysis. A loss of symmetry would result, accompanied by proportionally greater computation time, but the principles of analysis would be unchanged. Another coding alteration would involve the projectile size, and a provision for larger projectiles would be incorporated without major difficulty. Motion of the impacting fragment would likely be followed by an incremental rigid-body motion scheme.

It is this author's hope that the community concerned with hardening against rotor bursts will agree that the method described here would constitute a valuable addition to the techniques presently available or under development. The implementation and verification of the method for this type of problem would not be an overly large task.

REFERENCES

1. D. Roylance, Tex. Res. J., in press.
2. P. Mehta and N. Davids, AIAA J. 4, 112 (1966).

3. F. Lynch, TR70-16, Army Materials and Mechanics Research Center (1970).
4. D. Roylance, J. Appl. Mech., 40, 143 (1973)
5. D. Roylance et al., Tex. Res. J., 43, 34 (1973).
6. A. Krausz and H. Eyring, Deformation Kinetics, Wiley, 1975.
7. S. Zhurkov, Int. J. Fracture Mech., 1, 311 (1965).
8. J. Smith et al., Tex. Res. J., 35, 743 (1965).
9. N. McCrum et al., Anelastic and Dielectric Effects in Polymeric Solids, Wiley, 1967.

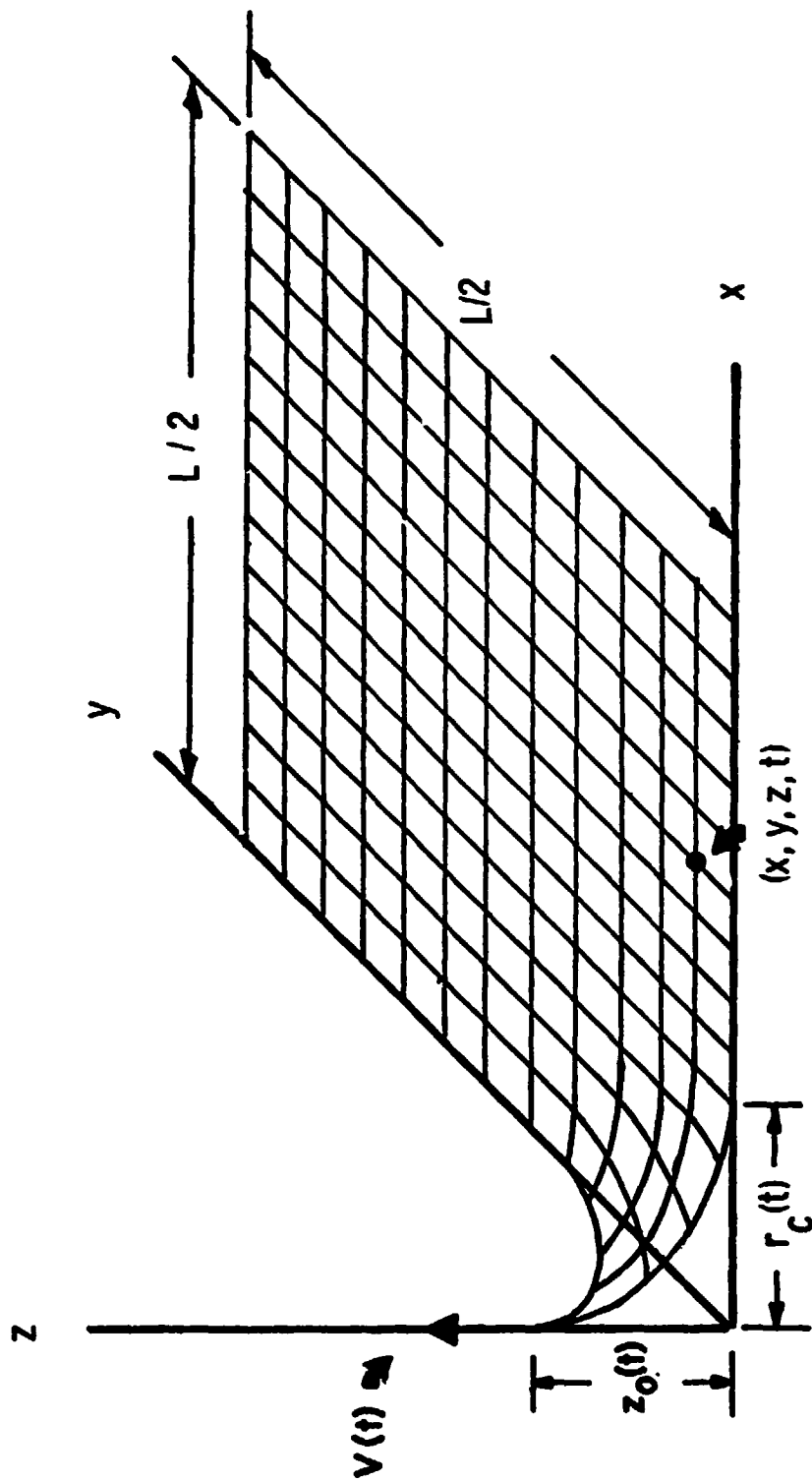
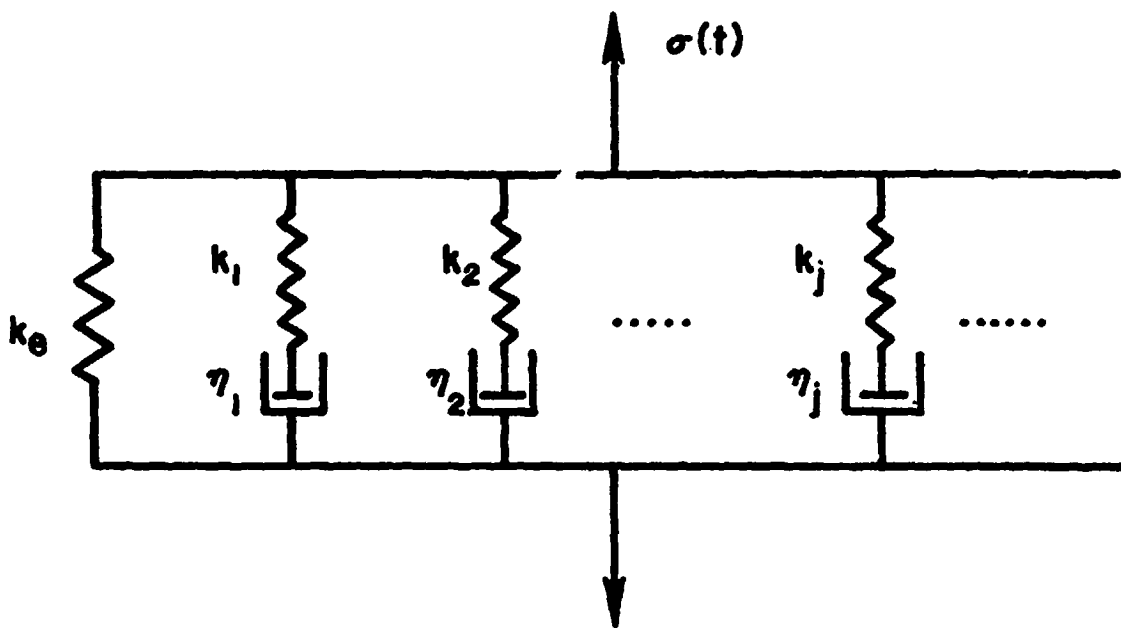


FIG. 1 DISCRETE-ELEMENT MESH USED IN NUMERICAL ANALYSIS OF IMPACT UPON WOVEN TEXTILE PANELS

WIECHERT MODEL



$$\sigma(t) = \left\{ k_0 + \sum^n \frac{k_j D}{D + \frac{1}{\tau_j}} \right\} \epsilon(t)$$

$$(D \equiv \partial/\partial t, \tau_j = \eta_j/k_j)$$

$$\sigma^t = k_0 \epsilon^t + \sum^n \frac{k_j (\epsilon^t - \epsilon^{t-1}) + \sigma^{t-1}}{1 + (\Delta t/\tau_j)}$$

FIG. 2 SCHEMATIC ILLUSTRATION OF WIECHERT VISCOELASTIC CONSTITUTIVE RELATION, USING SPRING-DASHPOT ANALOGIES

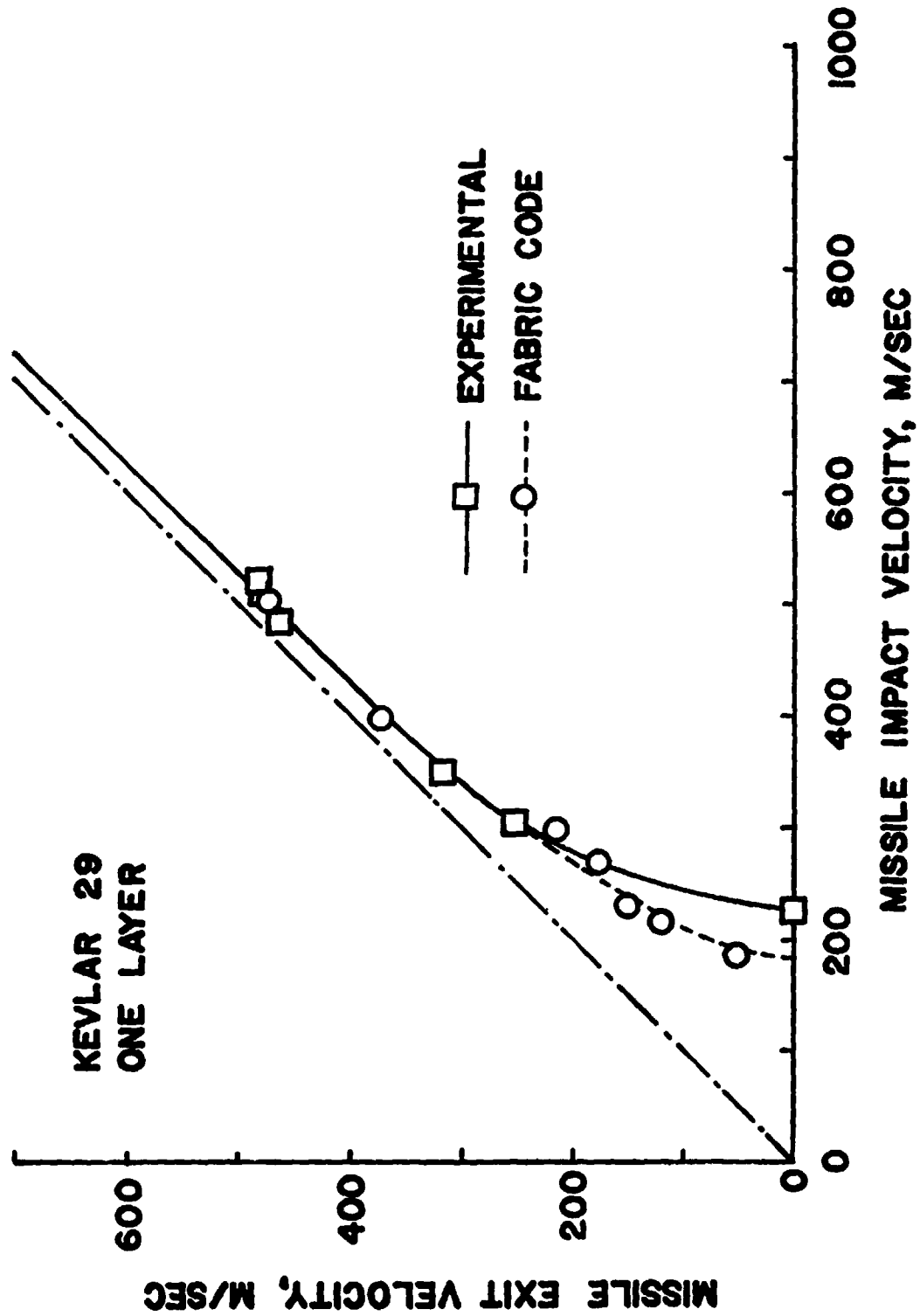


FIG. 3 V_s - V_r CURVE FOR A 2 x 2 BASKETWEAVE PANEL, WITH AREAL DENSITY OF 0.421 kg/m² AND PROJECTILE MASS OF 1.10 gms.

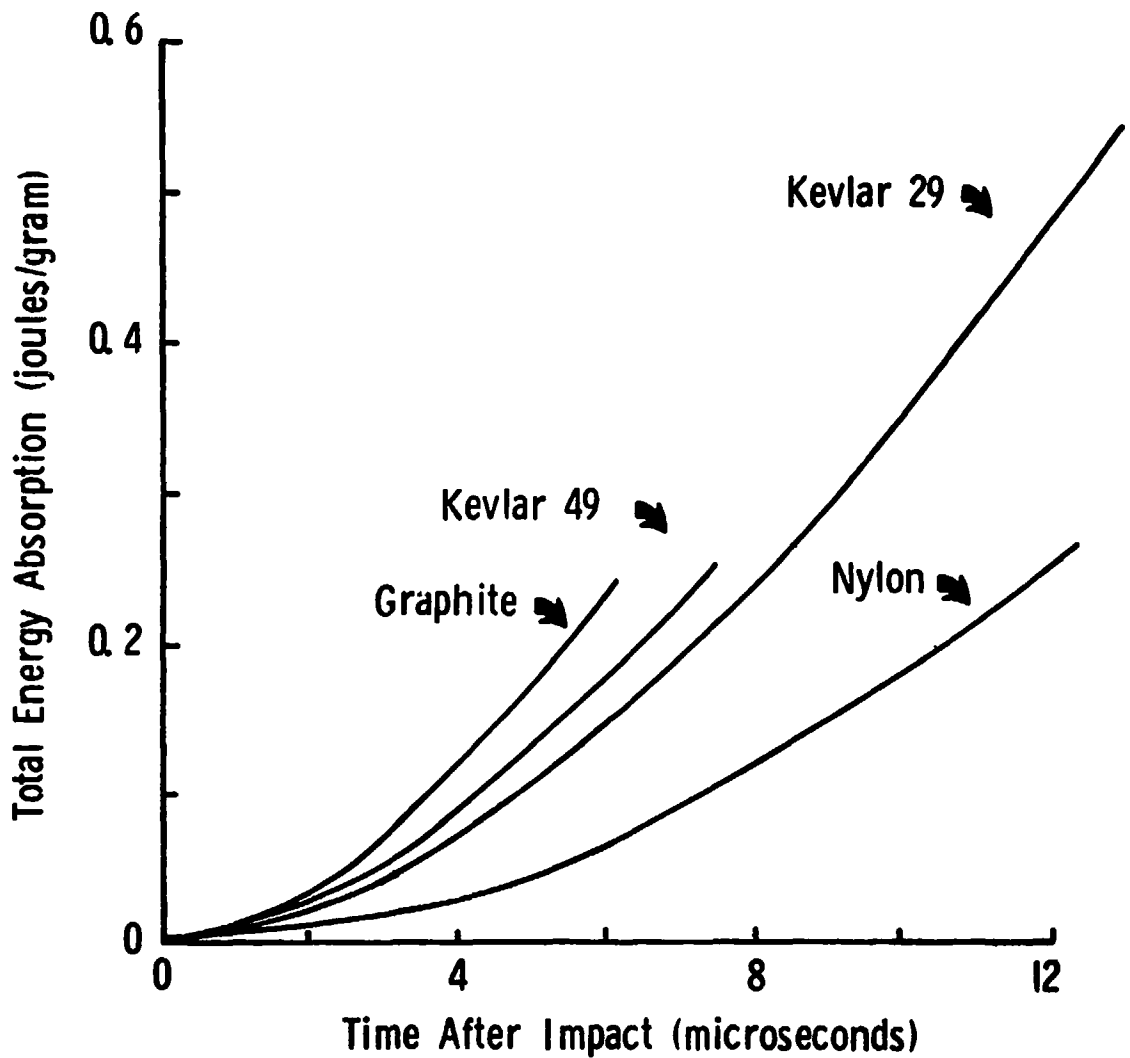


FIG. 4 COMPARISON OF BALLISTIC ENERGY ABSORPTION FOR VARIOUS CANDIDATE FABRICS; FABRIC WEIGHTS AND MISSILE MASS AS IN FIG. 3

DISCUSSION

D. Oplinger, AMMRC

Is the code capable of handling multiple-layer fabrics?

D. Roylance, MIT

As presently configured, the code simulates multiple layers only in that it uses a numerical mesh of weight equal to the fabric being simulated. Such an approach obviously misses any layer-layer interactions which might be present, but comparisons with limited experimental results using multiple-layer targets have been very promising.