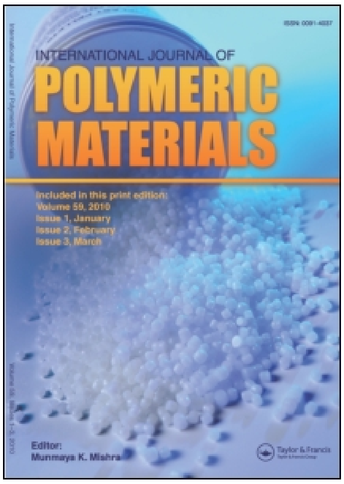

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Dynamics of an Explosion Blast-proof Aircraft Luggage Container. Part I—Deformation Rates

D. C. Prevorsek[a]; H. B. Chin[a]; Y. D. Kwon[a]; S. E. Sund[a]; D. Hsieh[a]
[a] Corporate Technology Center, Allied Signal Inc., Morristown, N.J.

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Dynamics of an Explosion Blast-proof Aircraft Luggage Container. Part I—Deformation Rates

D. C. PREVORSEK, H. B. CHIN, Y. D. KWON, S. E. SUND, and D. HSIEH
Corporate Technology Center, AlliedSignal Inc., P.O. Box 1021, Morristown, N.J. 07962-1021

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The mechanical properties of ultra-strong polyethylene fibers of Spectra type exhibit very large strain-rate effects. The modulus and strength of these fibers increases with increasing strain-rate. In ballistic impacts involving high deformation rates, the performance of Spectra fiber composites is, therefore, markedly better than predicted on the basis of data obtained at low deformation rate standard testing procedures. To prevent aircraft disasters caused by explosions in the luggage compartments, the Federal Aviation Agency initiated a program to develop an explosion blast-proof luggage container. Based on previous work, Spectra fibers produced by AlliedSignal were an obvious choice for this application. The scope of the present study was to determine the deformation rates in a fiber reinforced composite wall of an aircraft luggage container. The simulated blast corresponded to the explosion of a typical terrorist device.

KEY WORDS Polyethylene, ultra-strong fibers, Spectra, deformation rates, explosion blast.

INTRODUCTION

One of the problems in the design of an explosion blast-proof enclosure is the use of proper engineering moduli (E_{ij}) of the material constituting the walls of the container. This issue is particularly critical in cases where the walls of the enclosure contain materials exhibiting large strain-rate effects and hence the typical data base developed on the basis of standard testing methods is not applicable. Because of its unmatched damage tolerance and energy absorption potential, Spectra fiber composite is an outstanding candidate for aircraft hardening, provided the use temperatures allow the use of ultra-strong polyethylene fibers. An application where these conditions are met is the explosion blast-proof luggage container.

Strain rate dependence of the mechanical properties of Spectra fibers is well documented.[1] These fibers get stronger and stiffer with increasing rates of deformation and the effects greatly exceed those observed with other reinforcing fibers. Therefore, it is essential that in the analysis of wall deformation and penetration, the mechanical properties of the fibers and composite correspond to those of deformation rates experienced by the material. It will be shown that the deformation rates are time- as well position-dependent. This leads to property gradients in the material that increase with the increasing amount of explosive and decreasing distance between the explosive and the wall of the container.

A calculation procedure has been developed to treat such cases. In this study we review the first step in this procedure, the estimates of the rate of deformations in the confining wall adjacent to the explosive.

With the deformation rates in the container wall established, we were able to estimate the deformations caused by bomb blast. This in turn allowed us to estimate the relative weights of the containers made of Kevlar fabric, Spectra fabric and SpectraShield, giving equal containment potential against the blast of explosion.

We plan to experimentally verify these calculations and present the data to the Federal Aviation Agency (FAA), the potential users, designers and fabricators of the aircraft luggage containers, etc.

STRAIN RATE EFFECTS IN SPECTRA COMPOSITES

Effects of strain rate on the mechanical properties of Spectra fibers were studied extensively theoretically and experimentally.[2] The experimental data show that both strength and modulus increase as the strain rate increases and that at ballistic rates of deformations the modulus is about three times that at deformation rates of standard laboratory testing.

Much less is currently known about the strength at ballistic deformation rates. Based on the available data, we currently assume that the strength increase resulting from the increase in the deformation rate from 10^1 to 10^5 is about 40%.

Another approach to study the deformation rate dependence of Spectra fiber properties is by analyzing the deformations on ballistic impact. These calculations have also been made. Using the high speed camera to record the deformation of flat plates during impact and by matching the observed deformations we obtained sets of properties listed in Table I. With these data it is now possible to predict the responses of Spectra panels subjected to impacts of various projectiles or shock waves generated by explosions.

The stress-strain behavior of Spectra® composites can be represented using effective properties by

$$\sigma_{ij} = C_{ik}\varepsilon_{kj} \tag{1}$$

TABLE I

Effective engineering moduli of uniaxial Spectra composite (unit: GPa)

Strain Rate (min^{-1})	10	500	1000	5000	10,000
Spectra 1000 fiber E_{xx}	101	130	145	221	268
Spectra unidirectional composite (fiber 70% by wt/Kraton D1107)					
E_{xx}	70	91	101	154	188
E_{yy}	6.1	6.4	6.5	6.8	6.9
E_{zz}	6.1	6.4	6.5	6.8	6.9
G_{xy}	3.7	3.8	3.9	4.0	4.0

where σ_{ij} is the effective stress tensor, C_{ij} the effective moduli and ε_{ij} the strain tensor. Note that the Spectra® composites used in this study are orthotropic materials.

The effective elastic moduli can be predicted from the properties of its constituent components using micromechanics. Micromechanics will give the properties of unidirectional composite and the lamination theory will give the effective properties of multi-directional composites. Among the proposed micromechanics models of composite materials the Halpin-Tsai model[3] gives composite properties which are in reasonably good agreement with experimental data.

Halpin and Tsai proposed the following semiempirical model which is simple but widely applicable:

$$Q_c = \frac{Q_m(1 + \xi\chi v_f)}{1 - \chi v_f} \tag{2}$$

in which

$$\chi = \frac{Q_f - Q_m}{Q_f + \xi Q_m} \tag{3}$$

where Q represents the elastic moduli and v is the volume fraction. ξ is regarded as the reinforcing factor which can be estimated from the geometrical structure of the composite or determined empirically. The subscripts c, m and f denote the composite, matrix and fiber, respectively. Note that the Halpin-Tsai equation reduces to the longitudinal rule of mixtures (Voigt form) as $\xi \to \infty$. The equation reduces to the transverse rule of mixtures (Reuss form) as $\xi \to 0$. For most cases, the properties predicted by this model are quite accurate with proper choice of ξ value. In Table I, the predicted properties of the Spectra® composite by this model are given.

From these composite properties, three dimensional anisotropic moduli of Spectra® composite are obtained using the lamination theory. The constitutive relations of laminates can be expressed by

$$N_i = A_{ij}\varepsilon_j + B_{ij}\kappa_j \tag{4}$$

where

$$N_i = \frac{1}{h}\int_{-h/2}^{h/2} \sigma_i \, dz \tag{5}$$

$$A_{ij} = \frac{1}{h}\int_{-h/2}^{h/2} Q_{ij} \, dz \tag{6}$$

$$B_{ij} = \frac{1}{h}\int_{-h/2}^{h/2} Q_{ij} z \, dz \tag{7}$$

where σ_i and ε_i denote the stress and strain of *i*th ply and mid-plane strains, respectively, and κ_j denote the curvatures of the plate. h is the thickness and z is the coordinate in the thickness direction. Q_{ij} is the elastic moduli of individual plies obtained by using micromechanics, thus A_{ij} are the effective moduli of a multidirectional laminate. B_{ij} are called coupling stiffnesses and vanish for symmetric laminates, resulting in uncoupling of bending and stretching.

The effective engineering moduli (E_{ij} and G_{ij}) and Poisson's ratios (ν_{ij}) of a multidirectional laminate can be obtained from the above effective moduli (Eq. 6), i.e.,

$$E_{ii} = \frac{1}{a_{ii}}, \quad i = 1, 2, 3 \tag{8}$$

$$G_{12} = \frac{1}{a_{66}}, \quad G_{23} = \frac{1}{a_{44}}, \quad G_{13} = \frac{1}{a_{55}} \tag{9}$$

$$\nu_{12} = -\frac{a_{12}}{a_{11}}, \quad \nu_{23} = -\frac{a_{23}}{a_{22}}, \quad \nu_{13} = -\frac{a_{13}}{a_{11}} \tag{10}$$

where a_{ij} is the inverse matrix of the stiffness matrix A_{ij}, i.e.,

$$a_{ij} = A_{ij}^{-1} \tag{11}$$

These effective engineering moduli are used for analyzing the behavior of laminated composite. Table II gives the engineering moduli of Spectra® composites.

RATE OF DEFORMATIONS IN THE COMPOSITE PANEL EXPOSED TO THE EXPLOSION

To determine the deformation rates in the walls surrounding an explosive center we make use of the data in Figure 1[4] where the shock front velocity "u" in ft/ms is plotted against scaled distance Z given by:

$$Z = R/W^{1/3} \tag{12}$$

TABLE II

Effective engineering moduli and Poisson's ratio of [0/90] Spectra composite (unit GPa)

Strain Rate (min^{-1})	10	500	1000	5000	10,000
E_{xx}	38	49	54	81	98
E_{yy}	38	49	54	81	98
E_{zz}	6.3	6.6	6.7	7.0	7.1
G_{xy}	3.7	3.8	3.9	4.0	4.0
G_{yz}	3.7	3.8	3.9	4.0	4.0
G_{zx}	3.7	3.8	3.9	4.0	4.0
Poisson's Ratio					
ν_{xy}	0.058	0.048	0.045	0.032	0.028
ν_{yz}	0.3	0.3	0.3	0.3	0.3
ν_{xz}	0.3	0.3	0.3	0.3	0.3

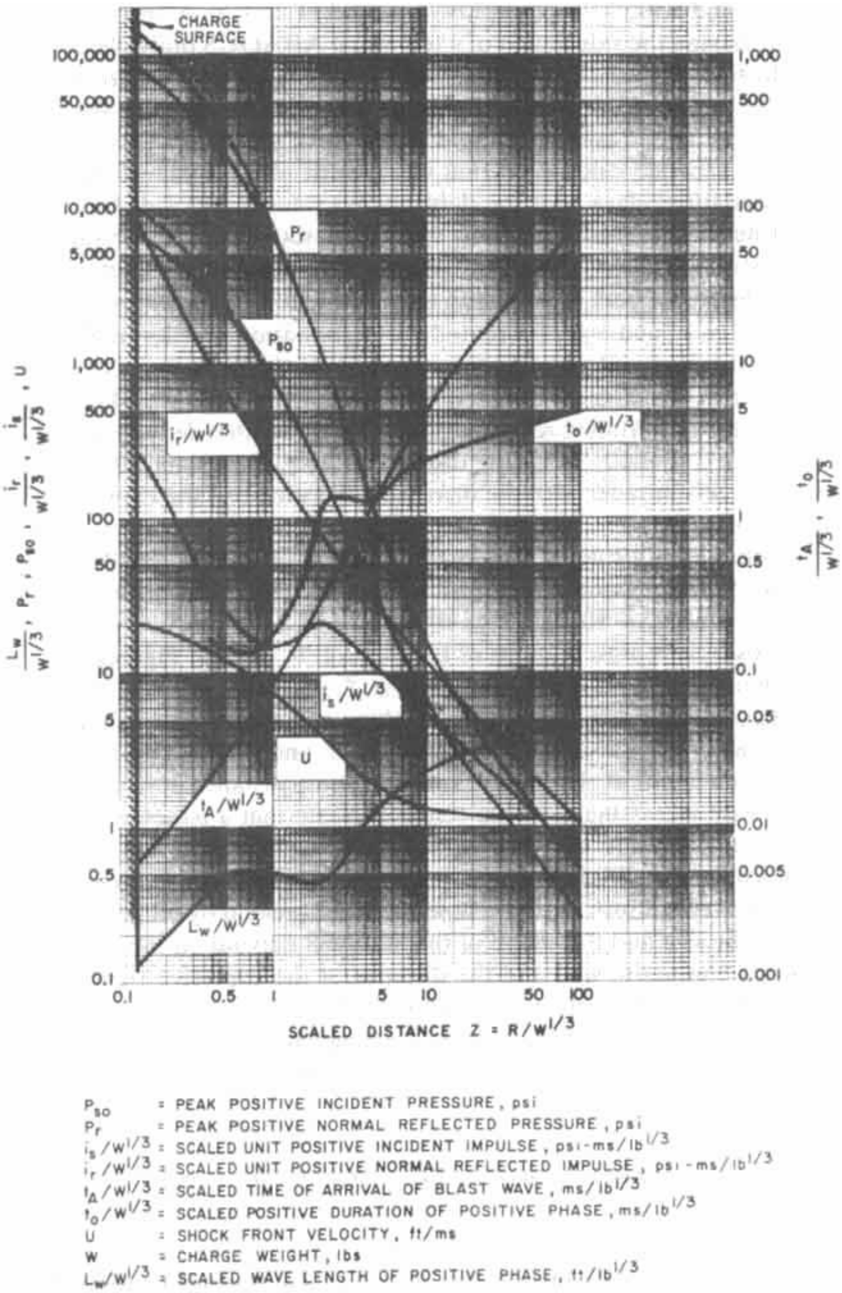


FIGURE 1 Positive phase shock wave parameters for a spherical TNT explosion in free air at sea level (from Reference 4).

where W = weight of explosive in lbs and R is the distance between the explosive and the wall in feet.

The calculations were carried out for a Spectra Shield panel having a thickness of 0.2 inches and with 2 lbs of explosive placed at 2, 4, 6, 8 and 10 inches from square plate having the side length of 4 feet using ABAQUS finite element analysis routine.[5] In the Phase I of our calculations described here, we were concerned only with the order of magnitude of strain rate immediately after the blast front reaches the wall of the container. With these data, we will carry out in the next phase a more accurate calculation that will include also the failure criteria.

These calculations show that the deformation rates in the wall may exceed 10^4 min^{-1} and hence the tensile modulus of Spectra should fall in the range of 3000 g/d and the strength close to 50 g/d. Under these conditions, the energy absorption potential of Spectra fibers is estimated to be about 3.5 times that of aramid fiber.

In Figures 2 a, b, and c are presented the deformation profiles in Z direction of the panel in the plane intersecting the epicenter of the explosion. The variable is the distance z in the Z direction from the panel. The time $t = 0$ is the time at which the shock wave front reaches the panel. The presented deflections correspond to the time of $t = 4 \times 10^{-6}$ s for the distances $z = 1$, 3 and 6 inches. As expected, the deflection gets broader with the increasing distance z of the explosive from the wall of the container.

The representation of deflection as the function of time at equal distance z of the explosive from the panel are shown in Figures 2 d, e, f and g for the respective times of 4×10^{-6}, 8×10^{-6}, 1.2×10^{-5} and 1.6×10^{-5} s.

The stereoscopic representations of Figures 2 a, b, c are in Figures 3 a, b, c and those of Figures 2 d, e, f, g in Figures 3 d, e, f, g.

The plots of fiber strain for the three values of z used in the calculations with time as parameter are presented in Figures 4 a, b, and c. These data show that the maximum strain is not at the epicenter but at some distance Y from it. Note that Y increases with increasing z. These results indicate that a puncture of the wall as the result of an explosion will take place only if the explosive is very close to the wall of the container. When this distance is increased above 2–3 cm, one would expect that in very uniform sample a hole would be created by blowing off a section of the wall. The size and the shape of this wall will depend on the structure (fiber lay-up) of the composite wall and the distance of the explosive from the wall. In explosive technology this effect is sometimes referred to as holing.

The characteristic shape of the hole in the panel created by the blast is presented more accurately by the plot of von Mises failure stress, σ, where

$$\sigma = \frac{1}{\sqrt{2}} [(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]^{1/2} \tag{13}$$

for the three cases of z (see Figures 5 a, b, and c) and times (Figures 5 d, e, f, g).

With these data it is now possible to determine the strain rates at the moment the explosion blast reaches the wall of the container. To estimate these deformation rates we selected a time of 4 microseconds. The corresponding fiber deformation rates are presented in Table III.

These calculations show that the deformation rate in the wall in an actual situation can exceed 10^4 min^{-1} and hence the modulus of Spectra fiber should fall in the

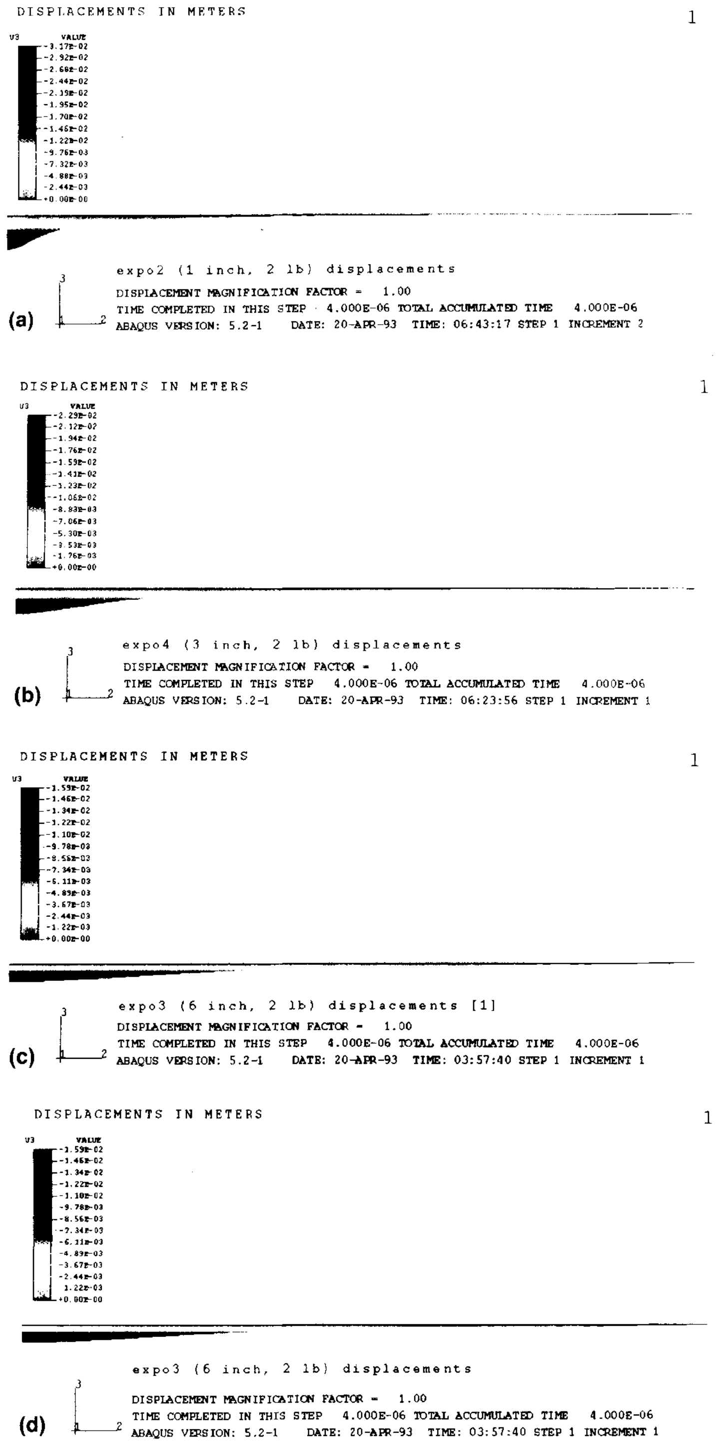


FIGURE 2 (*continued*)

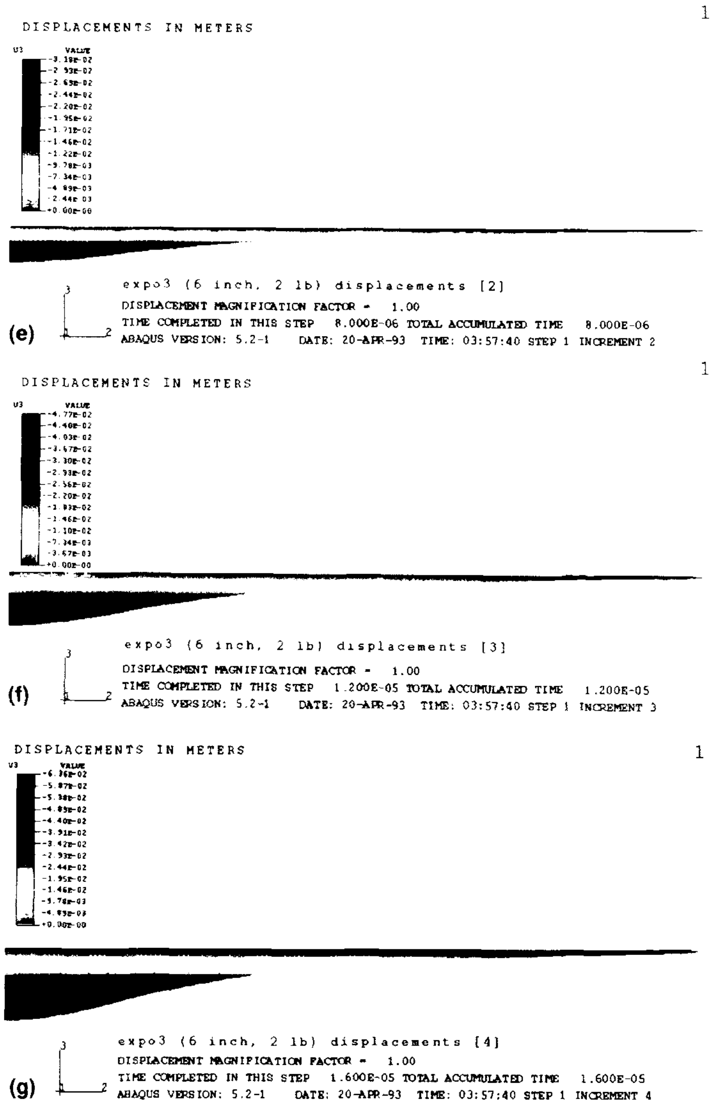


FIGURE 2 Deformation profile in Z direction of the Spectra composite panel at the explosion (m: mass of explosive, lbs, d: distance of the explosive from the panel, inch, t = time, microseconds). (a) $m = 2$, $d = 1$, $t = 4$; (b) $m = 2$, $d = 3$, $t = 4$; (c) $m = 2$, $d = 6$, $t = 4$; (d) $m = 2$, $d = 6$, $t = 4$; (e) $m = 2$, $d = 6$, $t = 8$; (f) $m = 2$, $d = 6$, $t = 12$; (g) $m = 2$, $d = 6$, $t = 16$.

range of 3000 g/d and the strength close to 50 g/d. Under these conditions, the energy absorption potential P of Spectra fibers is given by

$$P = k.\ J.\ C. = k.\ J.\ E/\rho \tag{14}$$

where

J = energy to break the fiber in tension

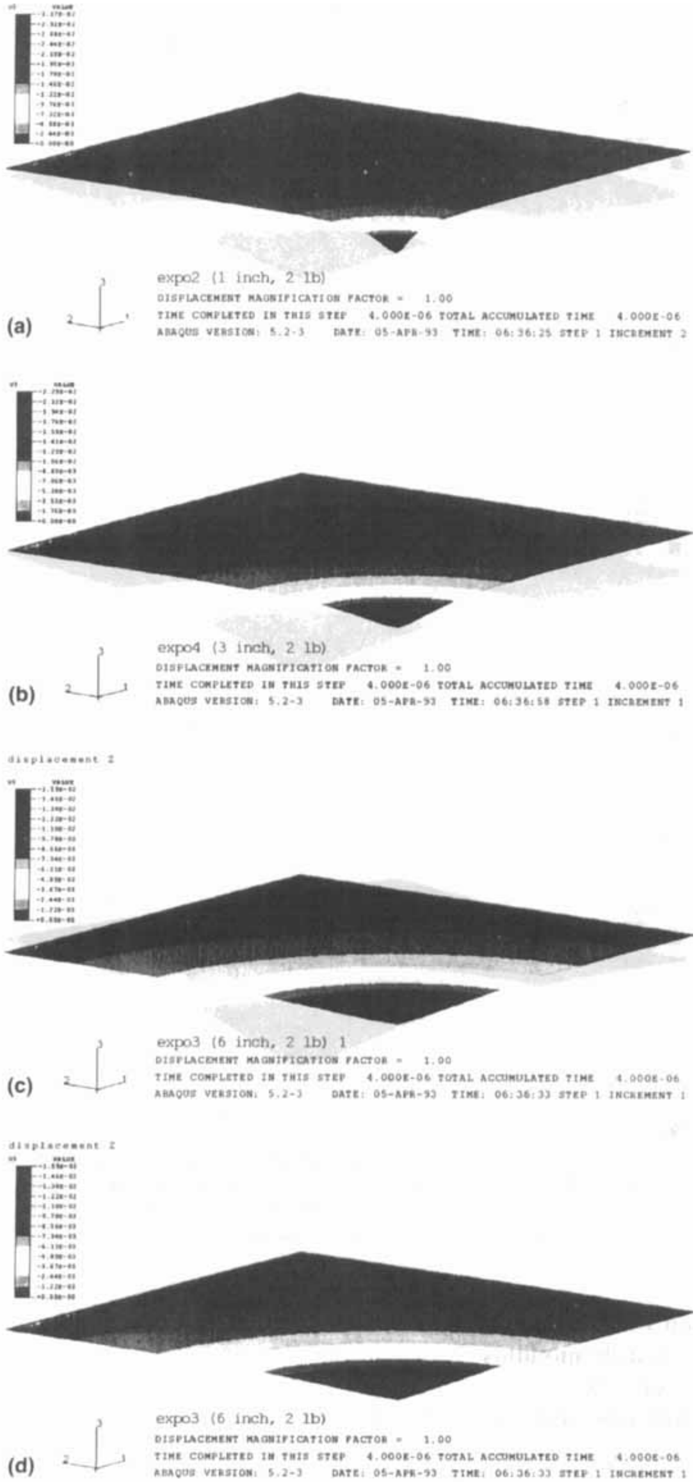
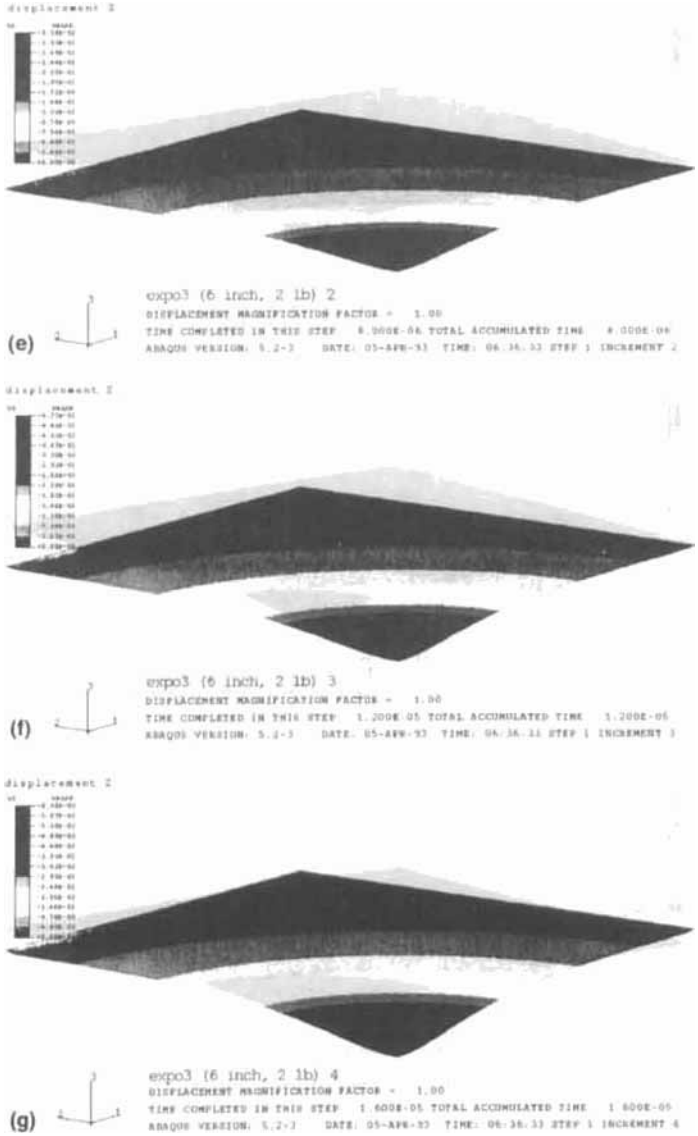


FIGURE 3 (*continued*)



F RE 3 Stereoscopic representation of the deformation of Spectra composite panel at the explosion (m: mass of explosive, lbs, d: distance of the explosive from the panel, inch, t = time, microseconds). (a) $m = 2$, $d = 1$, $t = 4$; (b) $m = 2$, $d = 3$, $t = 4$; (c) $m = 2$, $d = 6$, $t = 4$; (d) $m = 2$, $d = 6$, $t = 4$; (e) $m = 2$, $d = 6$, $t = 8$; (f) $m = 2$, $d = 6$, $t = 12$; (g) $m = 2$, $d = 6$, $t = 16$.

C = strain wave propagation velocity
E = fiber tensile modulus
ρ = fiber density
k = a proportionality constant ≤ 1

reaches values that are about 3.5 times those of Kevlar.

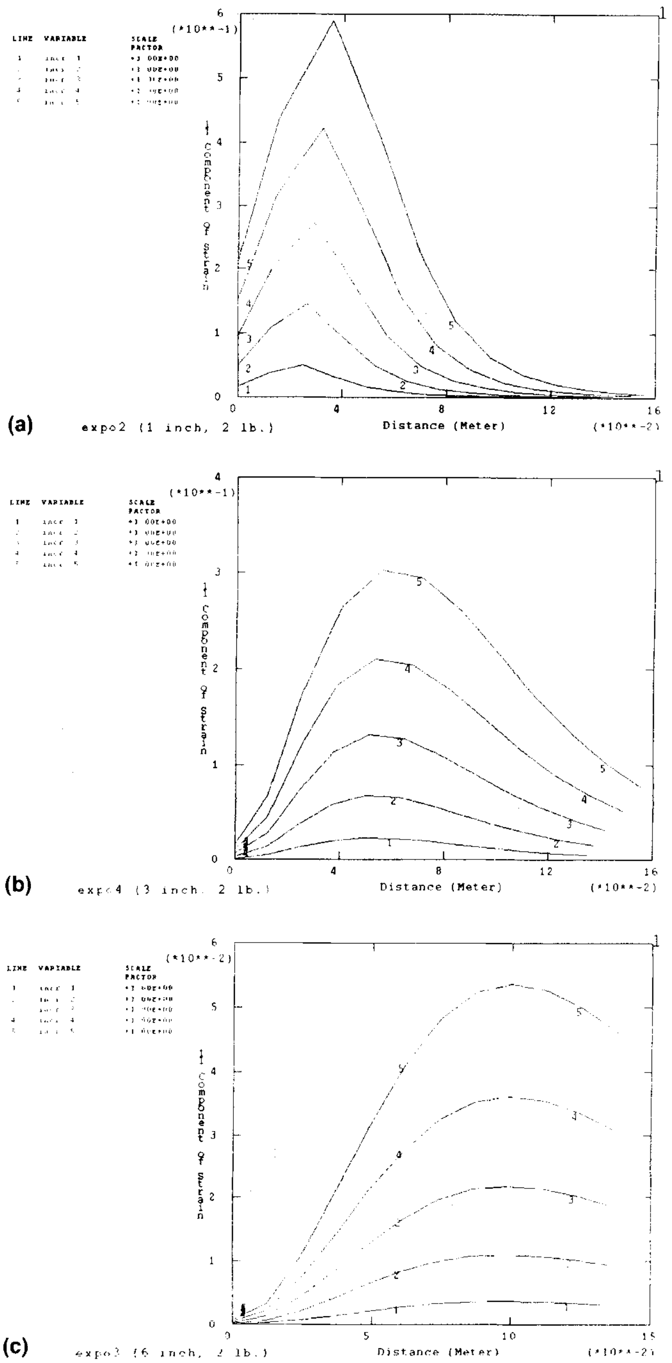


FIGURE 4 Strain in the Spectra fiber as the functions of time and position after the explosion (m: mass of explosive, lbs, d: distance of the explosive from the panel, inch, t = time, microseconds). (a) $m = 2, d = 1, t = 1$–5; (b) $m = 2, d = 3, t = 1$–5; (c) $m = 2, d = 6, t = 1$–5.

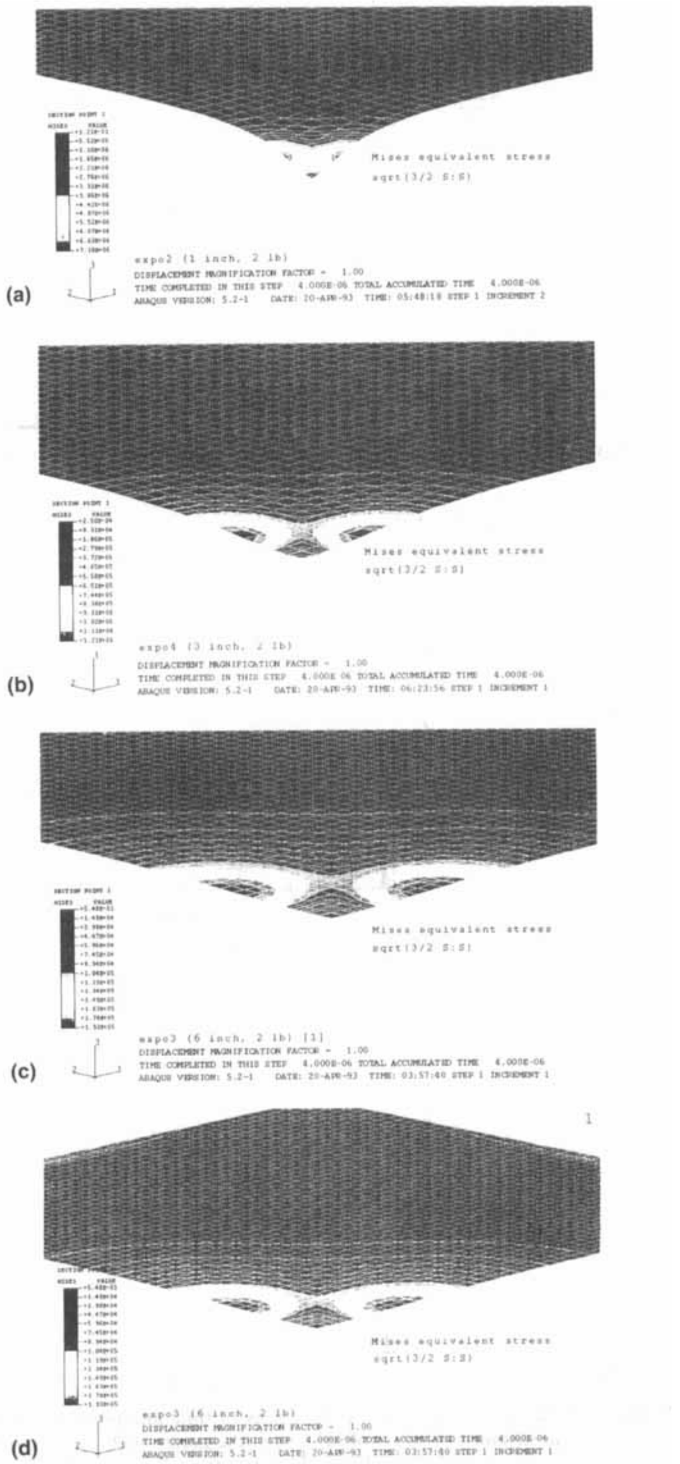


FIGURE 5 (*continued*)

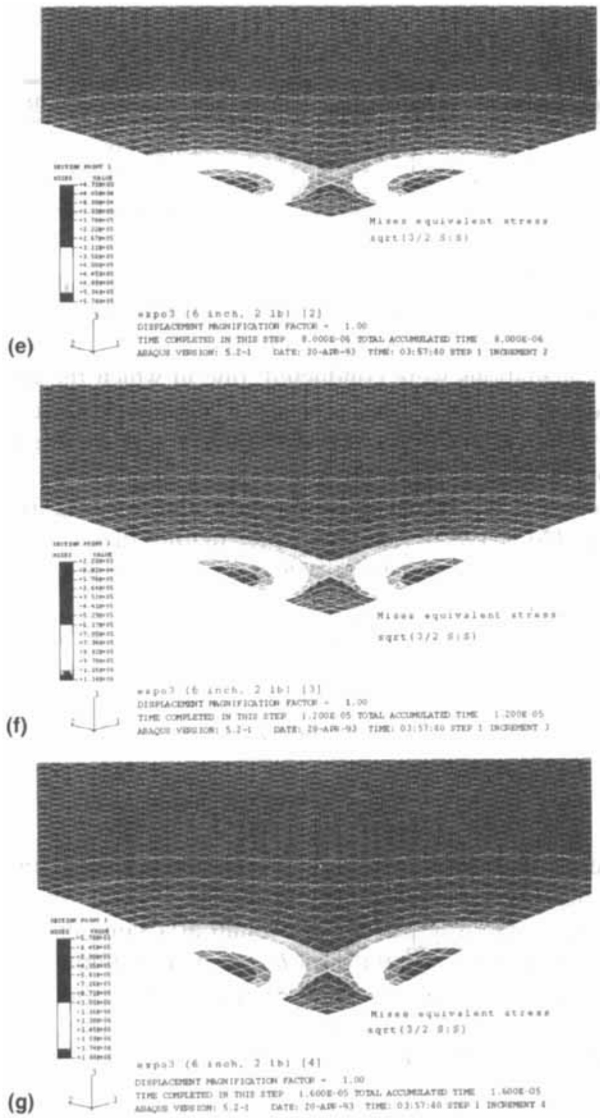


FIGURE 5 von Mises equivalent stress (m: mass of explosive, lbs, d: distance of the explosive from the panel, inch, t = time, microseconds). (a) $m = 2$, $d = 1$, $t = 4$; (b) $m = 2$, $d = 3$, $t = 4$; (c) $m = 2$, $d = 6$, $t = 4$; (d) $m = 2$, $d = 6$, $t = 4$; (e) $m = 2$, $d = 6$, $t = 8$; (f) $m = 2$, $d = 6$, $t = 12$; (g) $m = 2$, $d = 6$, $t = 16$.

The meaning of the proportionality constant is that under the blast the fibers may break through other less energy consuming mechanisms such as shear.

ESTIMATES OF THE AMOUNT OF EXPLOSIVE WHICH SPECTRA AND ARAMID CONTAINERS COULD CONTAIN

With the Spectra/aramid energy absorption ratio of 3.5 determined, we can use the data published in Reference 5 ("Structures to Resist the Effects of Accidental

TABLE III

Fiber deformation rates in the wall a Spectra container

Distance from the wall	Time	Fiber Deformation Rate
1"	4×10^{-6}S	54×10^3 sec^{-1}
3"	4×10^{-6}S	8×10^3 sec^{-1}
6"	4×10^{-6}S	1.4×10^3 sec^{-1}

Explosions," Army TM 5-1300) to estimate the weight ratio of the explosive that could be confined by two containers of equal weight but one constructed with Spectra 1000 and the other with Kevlar 29 fibers.

Two types of calculations were conducted: one in which the energy absorption potential of fibers is related to the velocity of the shock wave (i.e. the kinetic energy) and the other where the peak reflected pressure on the wall is related to the energy absorption potential of the composite wall.

In this consideration, we use the plot shown in Figure 1 (Figure 2-7 of the army technical manual TM 5-1300 (Reference 5)); in this figure, the peak reflected pressure Pr (psi) and the shock front velocity U (ft/ms) are plotted against the scaled distance $Z = R/W^{1/3}$ (ft/lb$^{1/3}$).

In the range of $Z = 0.1-1$, a numerical regression gives an approximate relation of

$$Pr = 7000/Z^{1.225} \tag{15}$$

$$U = 5.6/Z^{0.648} \tag{16}$$

Now, suppose we have two composite panels and one of them can absorb 3.5 times as much energy as the other. How does this affect the charge weight of explosive which the composite panel can contain at a same distance?

Applying the definition of Z in terms of R and W in combination with Equations (15) and (16) and assuming that the ratio of energy absorption can be equated to the ratio of Pr or U^2, we can derive the following equations relating the energy absorption capability P to W for the two composite panels 1 and 2.

$$P_2/P_1 = Pr_2/Pr_1 = (W_2/W_1)^{0.4083} \tag{17}$$

or

$$P_2/P_1 = (U_2/U_1)^2 = (W_2/W_1)^{0.432} \tag{18}$$

When the ratio of P between two composite panels is, for example, 3.5 as in the case of Spectra composite panel vs aramid composite panel, the ratio of W from Equations (17) or (18) comes out to be about 18–21.

Even among the Spectra composites themselves, the energy absorption potential varies substantially depending on how the composite is constructed. For example, the Spectra composite panel made by laminating (0/90 deg.) unidirectional prepreg layers (trade name of this is SpectraShield) shows about 40% greater energy absorption potential than the Spectra composite made from the fabrics of Spectra fiber. In this case, applying the Equations (17) and (18) again, one finds that the luggage container made of SpectraShield composite would withstand the explosion blast from a bomb which is 2.3 times heavier than the bomb which the luggage container of same weight but made of Spectra fabric composite would withstand.

Since the above calculations assume that, in the process of container failure caused by the blast, all fibers are broken in tension, the above estimates represent the upper limit in the relative performances of Spectra vs aramid. Although we believe that this assumption is justified for the conditions under which the blast experiments for FAA are currently carried out, we also carried out the calculations in which we assumed that the energy to break Spectra fibers is only 2 times that of aramid, to simulate the conditions under which a substantial fraction of fibers failed in shear. These calculations yielded a W_2/W_1 ratio of 5.5 for the Spectra composite and aramid composite containers of equal weight. This further increased our interest in the experimental verification of these calculations.

Since these calculations predict that Spectra containers could confine about 5–20 times greater quantities of the explosive than an aramid containers of comparable weight, it is imperative that these predictions be verified although this may be costly.

SUMMARY AND CONCLUSIONS

The calculations presented above show that the deformation rates which a luggage container wall will experience during an explosion are about five orders of magnitude higher than that of standard laboratory testing. Therefore, the properties of Spectra composites reported in the Spectra promotional literature cannot be used for this purpose. Sets of properties as function of deformation rates have been obtained for use in the design consideration of explosion blast-proof luggage containers.

With these data, it was possible to estimate the weight ratio of Spectra/aramid containers that would contain an equal amount of explosive. These calculations showed such a large performance advantage of Spectra over aramid (5–20) that it is imperative that these predictions be verified by experiments.

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