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Amplification of Air Shock Waves by Textile Materials

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The peak reflected pressure measured under a flexible and porous textile material exposed to air shock waves may increase by an order of magnitude over the case where no material is present. This peak pressure amplification is a result of the development of shock waves in the two phase (solid/air) material as a result of the low equilibrium sound speed in porous materials and the increase in density of the materials during the transit of the shock wave. This peak pressure amplification may increase the lung injury severity for humans with layered textile materials covering their torso who are exposed to strong air shock waves.

The dynamics of shock wave propagation and reflection in flexible and porous textile materials were studied both analytically and experimentally by using an air driven shock tube. A numerical model of the human chest-lung system was adapted for evaluating the effects of different textile materials covering the human chest. Experimental shock tube results were input to the computer model of the human chest to allow a comparison between the different textile materials.

1. INTRODUCTION

There is evidence that soldiers wearing fibrous body armor are more vulnerable to injury from blast waves than personnel not wearing the armor [1]. Fibrous body armor materials, such as Kevlar®, apparently cause the blast wave to couple more efficiently with the soldier's chest-lung system, thus increasing the risk of lung injury. This 'blast amplification' effect is likely to be a consequence of the layered construction and fiber properties of the present body armor. It's important to determine what factors influence the manner in which body armor materials transform blast wave loads on the human body. The specific objective of this study is to determine how air shock waves interact with and are transformed by a wide range of compressible textile layers of interest to the US Army for ballistic, chemical and environmental protection. The approach relies both on shock tube experiments and a numerical model of the human chest-lung system.

Fibrous body armor is designed to protect soldiers from the most common battlefield threat — fragmenting munitions. The current US body-armor vest, part of the Personnel Armor System, Ground Troops (PASGT), is constructed of 13 layers of Kevlar 29 cloth sandwiched between an inner and outer nylon shell fabric. The PASGT vest provides a high level of ballistic protection without greatly hindering the soldier's mobility and effectiveness. However, the PASGT vest was not designed to protect against blast effects.

Some battlefield threats to the soldier do involve a direct blast. Aside from conventional bomb blasts, the increased presence of fuel-air explosives on the modern battlefield constitutes a threat which may become more important in the future [2,3]. There has also been some concern that repeated exposure of personnel to high intensity gun muzzle blast waves could produce cumulative-damage injuries to artillery gun operators. Operators wearing the PASGT vest might be even more vulnerable to cumulative-damage effects if their body armor amplifies the blast wave. Finally, tank crews are usually well protected from fragments but may be exposed to blast waves in certain situations. Blast waves can diffract into a crew compartment through open hatches and can be intensified through reflection off walls and floors [4]. Crew members exposed to such complex shock waves could thus also be vulnerable to body armor blast wave amplification. If the PASGT vest increases the risk of blast injury, then the magnitude of the increased risk for these various cases needs to be known.

Blast intensity is usually reported in terms of overpressure, which refers to the pressure above atmospheric pressure (usually assumed to be 101 kPa). Blast overpressure damages the body most where large density differences are present. Disregarding the eardrums, the lungs and the intestines are the vital organs most susceptible to blast overpressure [5]. The chest wall is rapidly compressed during the passage of a blast wave. The sudden acceleration, deceleration, and oscillations due to chest wall compression, combined with direct shock wave transmission, reflection, and focusing in the body tissues, are the causes of blast tissue injury. Peak overpressures of 70 to 150kPa can cause lung damage if the shock wave's positive phase lasts 5 milliseconds or more. The human body is better able to cope with shock waves of shorter duration, so that the threshold of lung damage rises to 350 kPa overpressure for shock waves with a positive phase of 1 millisecond [6].

People can be protected from blast effects if they are behind rigid walls, within enclosures, or wearing rigid vests enclosing the chest [7]. Soft materials do not have a similar protective effect. Intuitively, one would assume that foam rubber would cushion a blast wave and reduce blast injuries. On the contrary, workers in Sweden found that layers of sponge rubber covering rabbits and anthropometric mannikins significantly increased blast-wave effects over the unprotected condition [8]. Soft materials do not offer much protection from blast and often seem to increase the damage.

The Walter Reed Army Institute of Research (WRAIR) clearly demonstrated the blast-enhancing qualities of ballistic vests in work conducted over the past few years [1,9]. These studies indicate that the PASGT vest reduces by 25% the blast overpressure necessary to cause a given level of mortality.

2. BACKGROUND

The interaction of an air shock wave with a porous and compressible textile layer is shown schematically in Fig. 1.

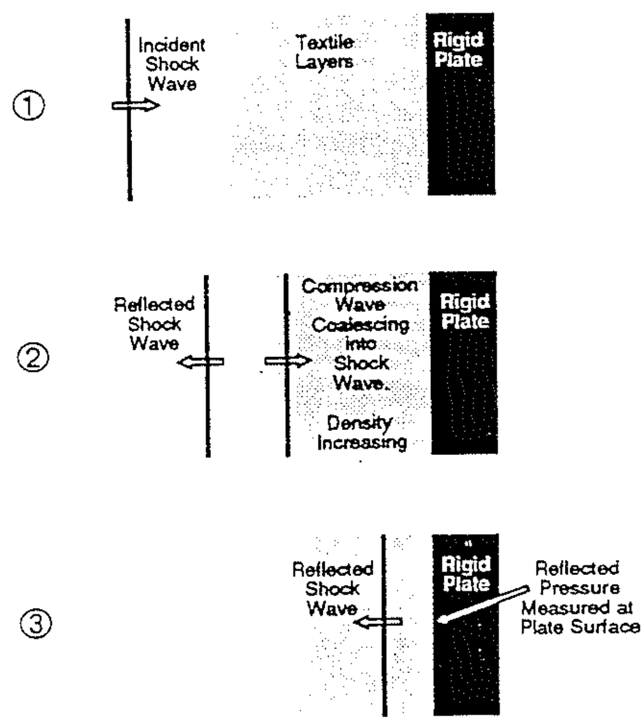

Fig. 1 Shock wave interaction with a supported textile layer

Initially, part of the shock wave is reflected from the surface of the textile layer, and part is transmitted into the material. The compression wave transmitted into the material may remain as a simple compression wave, or it may coalesce into a shock wave. As discussed by Mazor *et al.* [10] and Nowinski [11], the criterion for whether the compression wave coalesces into a shock wave is the situation where the equilibrium sound velocity in the material changes so that later compression pulses can catch up with and reinforce the initial compression wave. This criterion will be discussed later in the context of porous and compressible materials. After the shock wave reaches the rigid backing, a part is again reflected back into the material, and a part is transmitted into the rigid plate. The peak reflected pressure measured at the plate is a measure of the amplification of the peak pressure due to the transformation of the shock wave by the textile material.

The shock wave transmission and the reflection process is greatly influenced by the equilibrium sound speed in the material. Sound speed in solid materials is determined by [12] $c = \sqrt{E/\varrho}$, where the equilibrium sound speed c is determined by the modulus E and the density ϱ.

This is not the case for porous and compressible materials. Research on shock wave transmission through porous materials has shown that the equilibrium sound speed in two-phase mixtures is lower than the equilibrium sound speed of either phase alone [13]. The equilibrium sound speed c for a two-phase mixture consisting of air and a polymeric material is given by [14]:

$$c^2 = \Gamma c_a^2 \Big/ \gamma(1+\eta)(1-\varepsilon_0)^2 \qquad (1)$$

$$\Gamma = \gamma(1+\eta\varphi)/(1+\gamma\eta\varphi) \qquad (2)$$

Γ is the adiabatic exponent for the textile/air mixture, c_a is the velocity of sound in air (330 m/s), γ is the air adiabatic exponent, η is the mass ratio of polymer to air in the sample, ε_0 is the polymer volume fraction in the material, and φ is the ratio of the specific heat of the solid polymer to the specific heat of air. If we assume that Γ is equal to γ (neglect heat transfer between the two phases), we may write the equilibrium sound speed in the material as a function of the measured apparent bulk density of the textile material ϱ_b, the true solid density of the polymer ϱ_s, and the density of air ϱ_a (1.2 kg/m^3)

$$c^2 = c_a^2 \Big/ \left[1+\left\{(\varrho_b/\varrho_a)/(1-\varrho_b/\varrho_s)\right\}\right]\left(1-(\varrho_b/\varrho_s)\right)^2 \qquad (3)$$

The solid densities for the polymers used in the experimental shock tube study ranged from 970 kg/m^3 for Spectra® (polyethylene) to 1400 kg/m^3 for Kevlar. The plot of equilibrium sound speed as a function of apparent bulk density for a porous material comprised of a solid polymer material and air is shown in Fig. 2, using the solid density of Kevlar as an example. The corresponding curves for materials with lower solid densities would be shifted slightly upward and to the left from the curve for Kevlar.

Fig. 2 shows that textiles and polymeric foam occupy the minimum velocity range for most materials, due to their low apparent bulk density. Equilibrium sound velocities of these materials are in the range of 30 to 80 m/s. We can see that any changes in density due to sample compression could have an influence on the shock transmission properties of these materials. Since the equilibrium sound speeds are so low, it is possible to have a shock wave in the material even when the material shock velocity is much less than the sound speed in air.

3. EXPERIMENTAL METHODS

3.1 Shock Tube Experiments

Textile materials were tested in the 0.3m-diameter shock tube at Walter Reed Army Institute of Research (WRAIR). Shocks of known strength were created in the test section of the

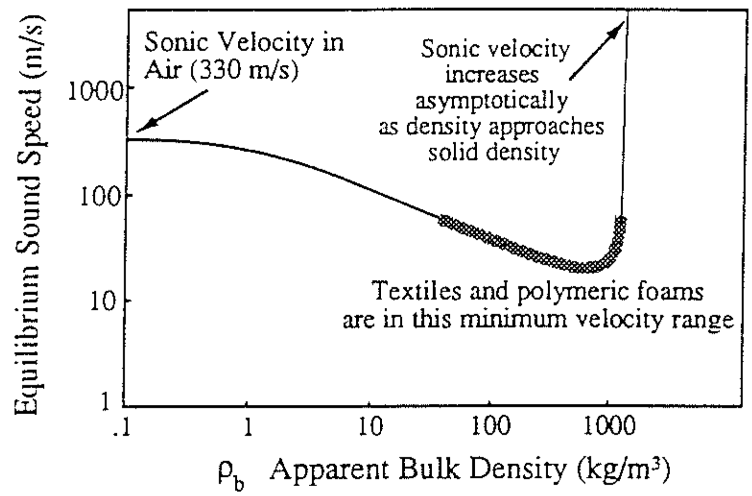

Fig. 2 Equilibrium sound speed in porous compressible materials

shock tube by increasing the pressure in the driver section until a Mylar® diaphragm ruptured; diaphragms of various thickness allowed different shock strengths. The long test section of the shock tube assured uniformity of the shock front at the end of the tube. A piezoelectric pressure transducer allowed the side-on shock wave profile near the exit to be recorded. Fabric test samples were mounted at the exit of the shock tube. Two pressure transducers were mounted side-by-side across the shock tube exit. The fabric sample only covered one of these transducers. This allowed the shock wave load on the bare plate to be recorded at the same time as the shock wave load under the plate covered by the fabric sample. Since these two pressure transducers were mounted face-on to the shock wave, they recorded the reflected shock pressure at the plate surface, rather than the side-on pressures recorded by the transducer inside the tube.

For air shock waves of known strength, the relationships between the measured side-on pressure, the reflected pressure at a rigid plate, and the shock wave velocities in air are given by [12]:

$$p_r = 2p_{s0} + (\gamma + 1)p_{s0}^2 \Big/ \{(\gamma - 1)p_{s0} + 2\gamma p_0\} + p_0 \tag{4}$$

$$M_a = u_a \Big/ c_a = \sqrt{1 + \{(\gamma + 1)/2\gamma\}(p_{s0}/p_0)} \tag{5}$$

where p_r is the reflected peak pressure, p_{s0} is the measured side-on overpressure, p_0 is the ambient pressure, γ is the specific heat ratio of the fluid medium ($\gamma = 1.4$ for air), M_a is the Mach number, c_a is sound velocity in air, and u_a is the shock wave velocity.

3.2 Test Conditions and Materials

Four side-on shock/blast levels of 55 kPa, 140 kPa, and 170 kPa were used to load the textile samples. The positive phase duration of each shock wave was about 5 milliseconds. For positive phase durations of 5 milliseconds, the threshold of lung damage is 140 kPa overpressure, so the test conditions spanned the human injury threshold level.

Test conditions also included varying the number of fabric layers for the textile materials. Fabric stacks of 4, 8, 12, 16, and 20 layers were tested at each of the four blast levels. Ballistic protection vests usually contain 10 to 20 layers, so it's important to determine if the number of layers influences the shock wave transmission process.

Ten fabric materials were tested in the shock tube. Three types of Kevlar 29 and Kevlar 49 fabrics were tested. These Kevlar fabrics included the material used in the PASGT vest [16]. Other test fabrics included three types of Spectra high-strength polyethylene fabric, Nomex® triaxial weave cloth, ballistic nylon cloth [17], cotton/nylon Battle Dress Uniform (BDU) fabric [18], and one type of polyurethane foam. Material properties are given in Table I. Apparent bulk densities were measured at a pressure of 0.14 kPa.

Table I
Material Properties

Material Composition	ρ_s, Solid Density (kg/m³)	ρ_b, Apparent Bulk Density (kg/m³)
Polyurethane Foam	1000	74
Spectra A	970	261
Spectra B	970	420
Spectra C	970	393
Cotton/Nylon	1300	398
Nomex	1380	426
Ballistic Nylon	1140	655
Kevlar A (PASGT)	1440	740
Kevlar B	1440	412
Kevlar C	1440	715

An example of a typical shock tube test result on a fabric sample is shown in Fig. 3. The output from both the bare plate transducer and the transducer under a fabric sample are shown.

The parameters of most interest for these pressure-time traces are the peak reflected overpressures, and the reflected impulse, I_r. I_r is defined as the integral of the positive reflected blast overpressure curve, $p_r(t)$:

$$I_r = \int_{t_0}^{t_0+t_d} p_r(t)\mathrm{d}t \tag{6}$$

where t_0 is the initial arrival time of the shock front and t_d is the positive pulse duration.

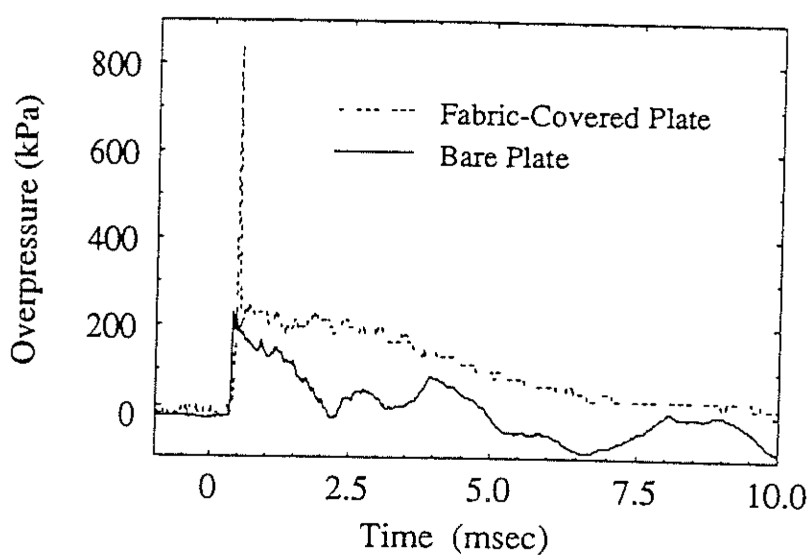

Fig. 3 Face-on pressure-time profiles for one transducer mounted under a fabric sample and the other mounted on a bare plate

We may define a peak pressure ratio as: $\delta = (p_{rm}/p_r)$; where p_{rm} is the measured reflected pressure under the test sample, and p_r is the reflected pressure at the bare plate.

We may also experimentally measure the average shock wave speed through the material (u) by comparing the difference in arrival times (Δt) between the air shock wave (velocity u_a) and the material shock wave passing through a given thickness Δx : $u = \Delta x/[(\Delta x/u_a) - \Delta t]$; this gives the average Mach number in the material $M = u/c$.

4. EXPERIMENTAL RESULTS

Measured shock properties such as reflected peak pressure, transmitted impulse, and material shock wave speed, were clearly related to material variables and properties such as areal density, number of layers, bulk density, thickness, etc. In the following paragraphs we present results for the single blast level of 85 kPa. In general, most shock properties correlated well with the material bulk density. The measured shock wave speed in the materials remained well below the shock velocity in air, but above the calculated sound speed for each material, so that the Mach numbers in the materials ranged from around 1 to about 4.

The general trend for all the materials tested is illustrated in Fig. 4 for the blast level of 85 kPa. There is a generally decreasing peak shock amplification with an increase in material apparent bulk density, when averaged over the peak pressure measured for each layer. This average obscures some interesting trends for the particular materials. Some materials exhibited an increase in peak reflected pressure amplification as more layers were added (Fig. 5a), while some materials showed a decrease with added layers (Fig. 5b). An explanation is provided by Equation (3); materials which showed an increase in amplification with added layers were below the apparent bulk density for their calculated theoretical minimum sound velocity. This implies that the shock wave was slowing down as the material compressed, which allowed more compression waves to add to the shock wave strength, thereby increasing the peak pressure. Materials which showed a decrease in shock pressure with additional layers were beyond the minimum sound velocity, so that the shock wave speeded up as the sample was compressed, and later compression waves could not contribute to the shock wave strength.

The implication is that for a given material, the peak reflected pressure amplification may be reduced by decreasing the air volume within the fabric by precompression, thus

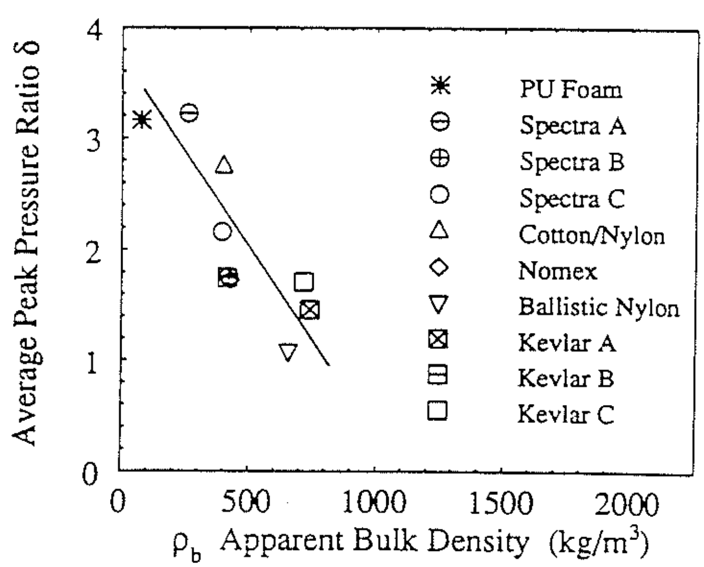

Fig. 4 Influence of material apparent bulk density on average peak pressure ratio for all materials

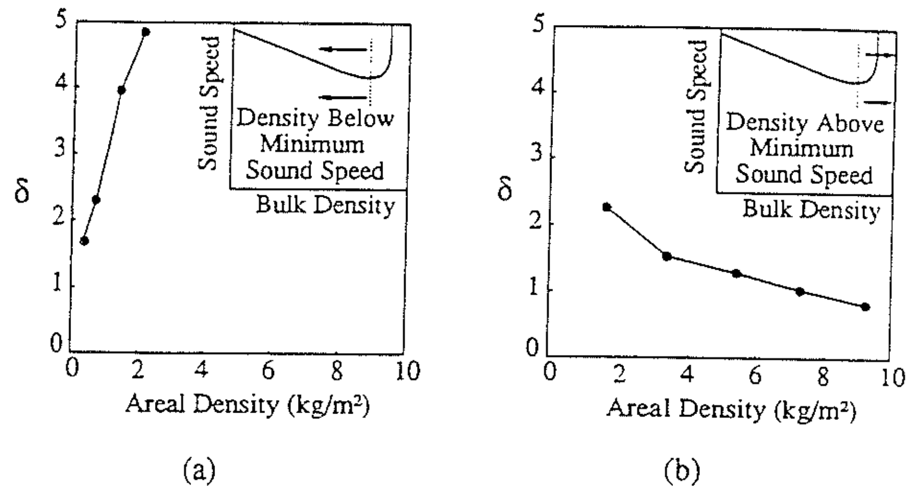

Fig. 5 (a) Materials below apparent density for minimum sonic velocity show increasing amplification factors with more layers, example shown is Spectra A, (b) Materials above apparent bulk density for minimum sonic velocity show decreasing amplification factor with more layers, example shown is Kevlar A

increasing the apparent bulk density. One of the Spectra fabrics was retested while precompressed by means of a gauze net tightly holding it down in place. The thickness of these precompressed samples was not measured, so the actual density values are not available. The test results showed a great reduction or elimination of the shock wave peak pressure reflection for the precompressed samples, while the transmitted impulse remained the same, implying that the density had increased enough to prevent the formation of a shock wave in the material. An example is shown in Fig. 6.

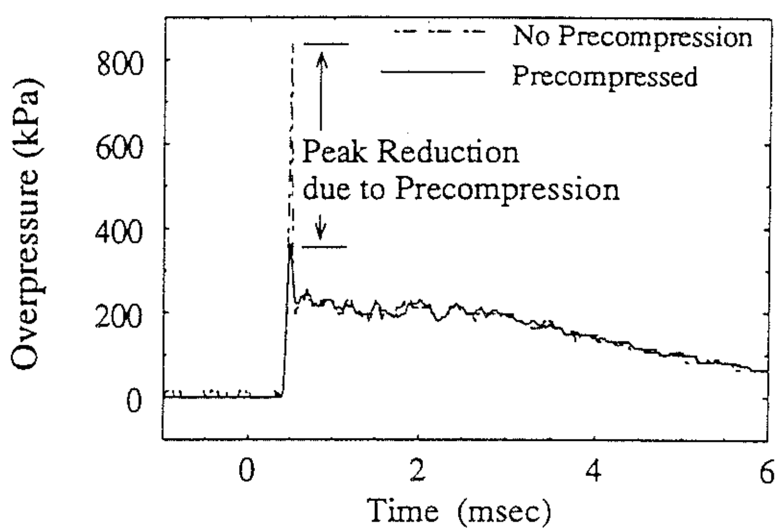

Fig. 6 Precompression to higher bulk density reduces or eliminates peak pressure amplification. Total reflected impulse does not change

5. INTERACTION OF TRANSMITTED SHOCK WAVES WITH THE HUMAN BODY

It is not clear whether the transmitted peak pressure or the transmitted impulse is more important as a injury mechanism for the human chest-lung system. We can think of these as two possible separate modes.

Mode I lung injuries are due to the high velocity stress waves transmitted through the body tissues. These stress waves are a direct result of the very high peak reflected pressures at the body surface. It is unlikely that true shock waves develop in the denser body tissues such as muscle and bone since their equilibrium sound speeds are very high. Lung damage is thus caused by the disruptive stresses present when the compression waves encounter large density differences in body tissues. It is even possible that a shock wave may redevelop in the two-phase porous parenchymal structure of the lung, just as shock waves develop in the textile materials. The experimental shock tube results are directly applicable to this mode of lung injury, and we could say in general that reducing a material's apparent bulk density would increase the potential for lung injury.

Mode II lung injuries are due to the gross inward deformation of the chest wall, and injuries are related to the pressure increase within the lungs. In this case, the transmitted impulse under the textile layers is the most important parameter, and the peak shock pressure would have very little effect on lung injury. For this injury mode, we must use a lumped-parameter chest model to determine the response of the human chest-lung system to the loading functions measured experimentally in the shock tube tests. This model was developed by the Lovelace Foundation [19]; a more complete description of the model, as well as a listing of the computer program, may be found in Reference [20]. The lung is a gas-filled chamber connected to the outside atmosphere by an orifice which simulates the throat passage. A movable chest wall mass acts as a piston, which compresses the gas in the lung cavity when acted upon by a force. The elastic resistance and viscous damping of the chest tissues are provided by the spring and dashpot connected to the chest wall mass. Additional compression resistance is provided by the gas in the lung cavity. The constants in the system of equations which make up the model were obtained through extensive animal experimentation on many different sizes of mammals and extrapolated to humans. The model allows the chest wall displacement, internal lung pressure, and the internal lung volume to be determined over time in response to an external load on the chest.

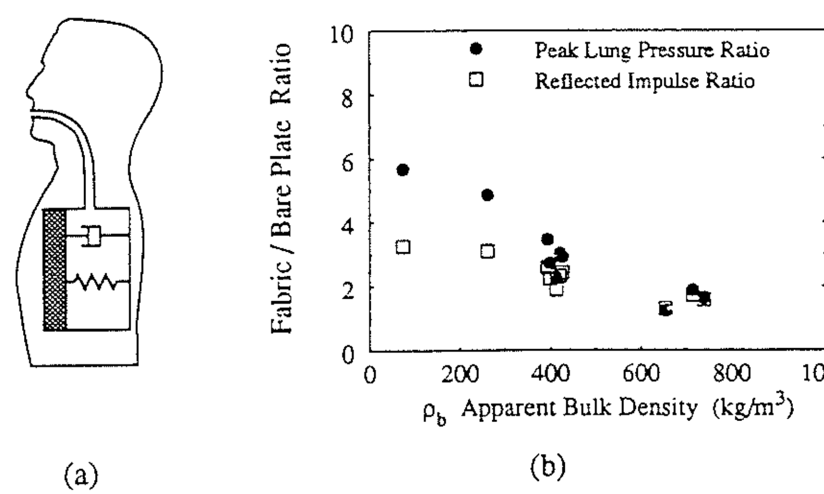

Fig. 7 (a) Schematic of lumped-parameter chest-lung model, (b) Average reflected impulse ratio (fabric/bare plate) and average peak lung pressure amplification caused by the presence of textile layers covering the chest

The Mode II lung model may also be used to provide an estimate of the actual increase in lung pressure due to fabric layers over the chest. Since each blast test in the shock tube used two face-on transducers — one covered with fabric and the other bare — the lung model can be used to directly compare the two cases. The lung model was used to calculate the peak internal lung pressure from both the bare plate pressure trace and the pressure trace under the fabric sample. The peak lung pressure amplification is then defined as the peak lung pressure for the fabric-covered plate divided by the peak lung pressure for the bare plate. The results for the case of a 85 kPa overpressure blast are shown in Fig. 7 for all the materials again as a function of apparent bulk density. Also shown in Fig. 7 is the reflected impulse ratio, defined as the reflected impulse measured under the fabric divided by the reflected impulse measured at the surface of the bare plate.

Fig. 7 shows that maximum lung pressures also occur for textile materials with lower apparent bulk densities. The calculated peak lung pressure is mainly determined by the reflected impulse ratio, with the two highest lung pressures caused by the polyurethane foam and the Spectra fabrics. Just as for the reflected peak pressure measurements, these numerical modeling results also point to materials with low apparent bulk densities (or low solid mass fractions) as having a higher potential for increasing human lung injury during exposure to air shock waves.

6. CONCLUSIONS

Compressible and porous textile materials have the tendency to amplify the reflected peak pressure of air shock waves. The degree of amplification is related to the apparent bulk density of these materials, with materials of low bulk density (low solid mass fraction) having the greatest tendency to produce very high shock pressures. The peak pressure amplification is related to the low equilibrium sound speed in two-phase mixtures of solids or liquids and gases, and also to the fact that these materials compress under pressure loading, which can intensify the shock wave in the material.

Reflected pressure amplification may be reduced by eliminating some of the free air volume within the textile layers, forcing it to behave more like a solid material, which prevents coalescence of compression waves into a shock wave within the material. This approach may not be practical for ballistic protective textile materials, which are most effective when fabric layers are able to deform freely under fragment impact. Another approach, not pursued in this study, is to add a rigid high density material on the outer surface of the compressible and porous layer to reflect more of the incident shock wave. This approach was shown to reduce blast injuries for two types of polymeric foams [21]. Since many future personnel armor systems may incorporate rigid ceramic or composite elements to improve protection against high-velocity bullets, this would also mitigate some of the blast-enhancing qualities of present soft body armor systems.

Numerical modeling of the effect of the transmitted reflected impulse under the fabric upon internal lung pressure also indicates that low-density materials have the highest potential for increased lung injuries. Because this modeling is most affected by the measured impulse, which depends in the shape of the transformed pressure pulse under the fabric, this is a separate injury mechanism from the peak pressure amplification which would tend to cause lung injuries by direct stress wave effects.

It was not possible from the experimental and modeling results to determine which injury mode, gross chest wall deformation and lung pressure increase (Mode II), or direct stress wave transmission (Mode I), is the mechanism of lung injury. This is more appropriately determined with physiological measurements, which have been pursued at Walter Reed Army Institute of Research. Our results do suggest that it should be possible to distinguish between the two modes of injury by testing the same material both in the compressed and uncompressed state, since compression greatly reduces the reflected peak pressure, yet has little effect on the measured total impulse.

Past research, which focused exclusively on the material properties of the Kevlar PASGT vest, indicated that Kevlar seemed to increase lung injuries more than other materials.

Experimental results on ten materials presented in this paper suggest that, by virtue of its high solid density, and corresponding high bulk density of woven fabric layers, Kevlar actually has the lowest potential of those fabrics tested to amplify air shock waves and intensify lung injuries.

ACKNOWLEDGEMENTS

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