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A new concept of shock mitigation by impedance-graded materials

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ABSTRACT

Over the last several decades, homogenous single-layer armor has been replaced by multi-layer integral armor to improve ballistic penetration resistance. This has led to better attenuation of shock wave energy by multiple interface reflections and transmissions. Efforts have been reported to improve the penetration resistance by providing higher energy dissipation at higher levels of impedance mismatch. However, high stress concentrations and stress reversals have made these interfaces the primary sources of failure. This paper discusses a concept for a new class of blast and penetration resistant (BPRM) materials which are layer-less but designed to have a continuous gradient of impedance that can dissipate the shock energy without material failure. In a simplistic approach by applying the classical theory of uniaxial stress propagation, it has been shown that attenuation of the stress wave energy would be possible by controlling the impedance distribution within the body of such a material. The development of such material to resist blast or impact will overcome the current common difficulty of interfacial delamination failure in any protective barrier system or armors.

1. Introduction

An impinging shock on a structural panel produces high pressures followed by unloading at free surfaces. The resulting tensile states produced through interactions usually cause structural failure and production of diverging debris. For thick panels the shock-wave propagation and attenuation are a function of the material's characteristics. At velocities higher than 7 km/s, the thermodynamic influences predominate, and melting and vaporization accompany the material's destruction, whereas at lower velocities if the shock is not attenuated, extensive structural destruction results from scabbing and fragmentation. Shock attenuation techniques by impedance-mismatched multilayering of materials commonly adapted for integral armor has proven to be generally effective. Efforts have been reported to improve the penetration resistance by providing higher-energy dissipation by higher levels of impedance mismatch. Ghiorse et al. [5] and others [3,4] used materials of various impedances to reduce spalling and achieve high V50 ballistic results. However, high stress concentrations and stress reversals have made these interfaces the primary sources of failure. The question arises why a layer-less material cannot be created in which the shock wave will be continuously attenuated until it becomes harmless to the structure. Interestingly, energy attenuation by internal wave interaction in continuous but graded material systems is common in nature. We can look for its proof in wave energy attenuation in the atmosphere and ocean water density gradation [1]. However, the development of such an innovative material faces a few problems. First, it requires a thorough understanding of the shock attenuation process in the nanoscale and microscale layers of the material. Second, it requires knowledge of the material's thermodynamic and microstructural transformation mechanism under high strain rate. Third, a verifiable model must be developed for the shock wave attenuation in the continuous-impedance-graded hypothetical material. Our investigation focuses on a layer-less but continuous-impedance-graded material system that can dissipate the same shock energy without material failure. In this paper we will discuss the very basic mechanics of stress wave attenuation as it propagates through a series of materials of different impedances. We will also look into the energy attenuation as a result of change of impedance at each stage.

2. Research background and approach

Continuous shock attenuation by design is a new concept now possible to comprehend because of the quantum jump in material technology at the nanoscale and microscale levels and the availability of high-performance computational facilities for model developments that can relate the micro- and nano-structural behavior to the macroscale performance. While the devastations of blast effects are observed in the macroscale level, one must understand that the shockwave front presented to the material in the first few nanoseconds triggers set conditions through the first

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few layers of nanoparticles for the progressive response. The response may range from thermodynamic transformation to elastic deformation. The theory of continuous attenuation of the shock will be tested in a continuous-impedance-graded designed material. However, to keep the problem simple at the initial stages of this investigation and to make the hypothesis amenable to experimental verification, analysis will be made for the stress wave propagation through a multiple-impedance bar made of short lengths of smaller bars of several materials with highly differing impedances (Fig. 1). We will use the one-dimensional stress wave propagation to detect the time required for the passage of the stress wave through each bar and energy partitioning at each interface. Experimental work will be performed using the ERDC–CRREL type Hopkinson pressure bar system, which can produce a sustained pressure wave of 10–10^2 μs (Fig. 2). With thermo-optical devices this shock bar can produce shocks in the nanosecond range.

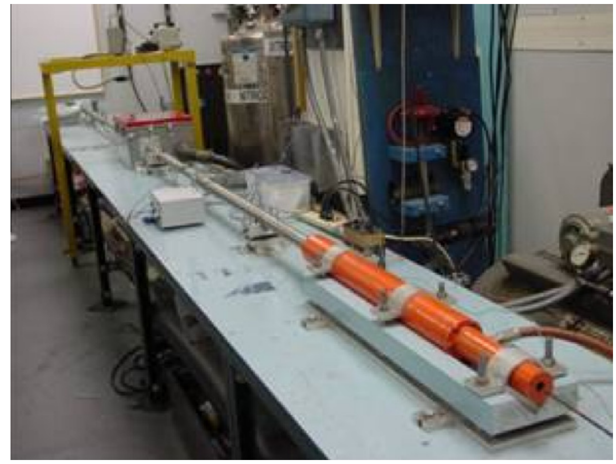

Fig. 2. Basic Hopkinson bar system.

3. Stress wave propagation

For small deformations in elastic solids, the stress–strain relationship is expressed as:

$$\sigma = E\frac{\partial u}{\partial x}, \tag{1}$$

where σ is the stress, u is the deformation, and E is the modulus of elasticity, which is independent of loading. The equations of wave propagation are derived by a combination of three-dimensional stress–strain relations, compatibility conditions, and the equations of motion; the combination is so complicated that it virtually prevents an analysis of impact problem by this means. Consequently, less rigorous theories have been postulated that attempt to retain the major ingredients of the "exact" treatment while simplifying the mathematical solutions.

The simplest form of approximate wave propagation theory is the one-dimensional wave propagation theory. It provides a good description of the major features of the stress and strain histories that can be most accurately observed in experiments of linear impacts of bars.

The one-dimensional equation for longitudinal motion is derived from a force balance across an element ∂x, such as shown in Fig. 3.

It is assumed that the plane cross section remains plane, that the stress distribution is uniform across the section, and that the radial inertia may be neglected.

From consideration of Eq. (1), the differential force dF across the element dx of the cross-sectional area A is given by

$$dF = A\frac{\left(E\frac{\partial u}{\partial x}\right)}{dx}du = AE\frac{\partial^2 u}{\partial x^2}. \tag{2}$$

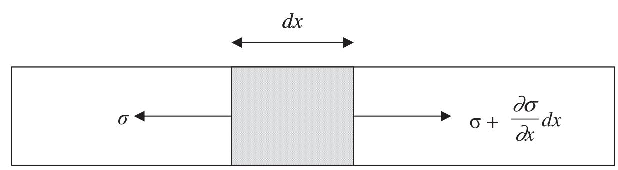

Fig. 3. Stresses acting on a one-dimensional element.

Again, from the equation of motion, denoting the time by t and assuming ρ as the mass density of the material, the differential force dF across the same element is given by

$$\partial F = \rho A\frac{\partial^2 u}{\partial t^2}. \tag{3}$$

Now, comparing Eqs. (2) and (3), we have

$$\frac{\partial^2 u}{\partial t^2} = c^2\frac{\partial^2 u}{\partial x^2}, \tag{4}$$

where c is the longitudinal wave velocity in the material, defined as:

$$c = \sqrt{\frac{E}{\rho}}. \tag{5}$$

Eq. (4) represents a non-dispersive wave, and its solution is given by

$$u = f(x - ct) + g(x + ct) \tag{6}$$

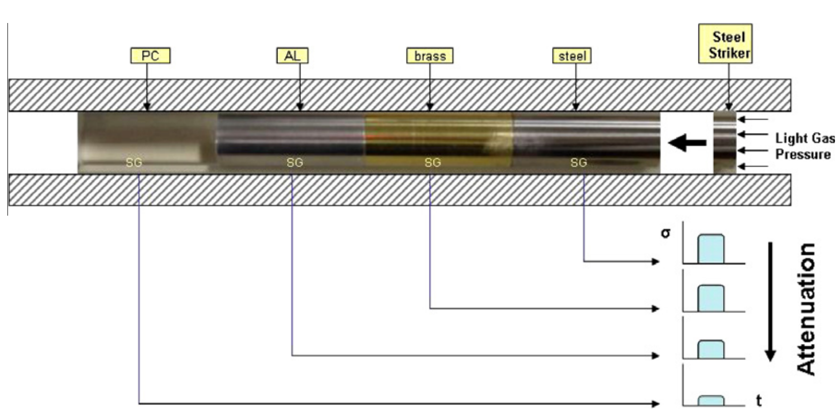

Fig. 1. Multiple-impedance pressure bar.

which defines two superimposed waves traveling in the positive and negative directions.

The longitudinal strain ε from the above can be expressed as:

$$\varepsilon = \frac{du}{dx} = f'(x - ct) + g'(x + ct), \tag{7}$$

and the corresponding longitudinal stress σ as:

$$\sigma = \varepsilon E = E[f'(x - ct) + g'(x + ct)]. \tag{8}$$

The particle velocity derived from Eq. (6) is given by

$$v = \frac{du}{dt} = c[-f'(x - ct) + g'(x + ct)]. \tag{9}$$

Considering the wave that will travel only in the positive direction,

$$\sigma = E\varepsilon = Eg'(x + ct) = \frac{Ev}{c}. \tag{10}$$

Using Eq. (5) and eliminating E, Eq. (10) can be rewritten as:

$$\sigma = \rho c v. \tag{11}$$

Note that in Eq. (11), ρ and c are the material characteristics, and for a given material their values are constant. Their product, ρc, is termed the *impedance* of the material. This is a very important parameter of the material, as it controls the wave transmission characteristics from one material to the other.

4. Wave transmission through impedance discontinuity

Fig. 4 represents the junction of two materials of uniform diameter. Assuming that the stresses are at all times uniformly distributed over the cross sections, we may consider that this wave is wiped out as it crosses the interface, but the pressure it exerts on the second material (material 2) starts two new waves, one we call the "transmitted" wave moving to the right and the other the "reflected" wave moving to the left. A consideration of equilibrium of forces at the interface results in

$$F_i + F_r = F_t, \tag{12}$$

where F represents the force, and the subscripts i, r, and t denote incident, reflected, and transmitted parameters. If v represents the particle velocity, then it can be shown that

$$v_t = v_i - v_r. \tag{13}$$

Using Eq. (11) and considering that $F = A\sigma$ and impedance $Z = \rho c$, we have

$$\sigma_t = T_1\sigma_i \quad \text{and} \quad \sigma_r = R_1\sigma_i \tag{14}$$

where $T_1 = \frac{2Z_2}{Z_1+Z_2}$ and $R_1 = \frac{Z_2-Z_1}{Z_1+Z_2}$.

The energy W in the stress wave is given by

$$W = \frac{A}{\rho c}\int \sigma^2 dt. \tag{15}$$

It is obvious from Eq. (14) that the impedance Z controls the amplitude of the stress wave after reflection and transmissions through the interface. Thus, the energy of the wave too can be controlled by the impedance values of the bar. Our aim in this investigation is to design the impedance distribution through the stress wave propagation path such that maximum attenuation is possible. Fig. 5 gives a schematic of the wave transmission through the multiple-impedance pressure bars. Note that because of the different velocities of the wave through different materials, tracking the stresses at a given point soon becomes arduous and computational aid becomes essential. Moreover, the stress wave itself is not uniform. Fig. 6a gives the typical stress waveform generated from an impact. For a numerical treatment of the problem, the wave needs to be divided into discrete elements, each of rectangular shape, as shown in Fig. 6b and c. Each of these discrete rectangular waves can be treated separately in propagation, tracked computationally, and finally synthesized to give the final wave form. The method has been discussed in detail by Dutta [2].

A new material concept for protective structures based on the above theory is underway and will be validated through computer simulation and limited experimental tests. This material will incorporate a continuous-impedance-changing gradient property through its thickness, so that a shockwave within the material is modified and energy is dissipated without its failure. This

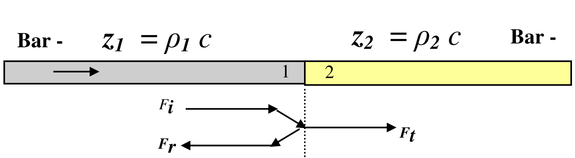

Fig. 4. Wave propagation, reflection, and transmission through an interface boundary.

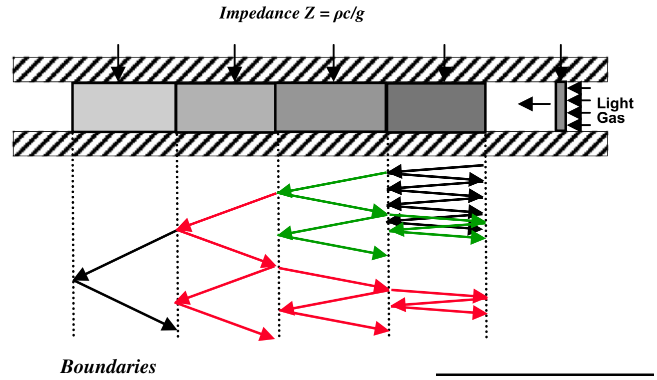

Fig. 5. Stress wave transmissions and reflections through a multilayer.

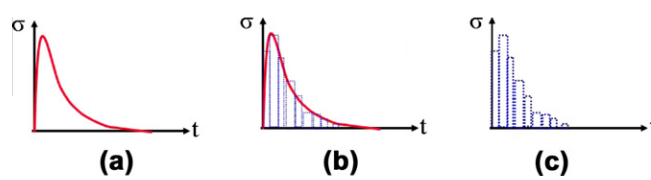

Fig. 6. Discretization of the impact-generated stress wave.

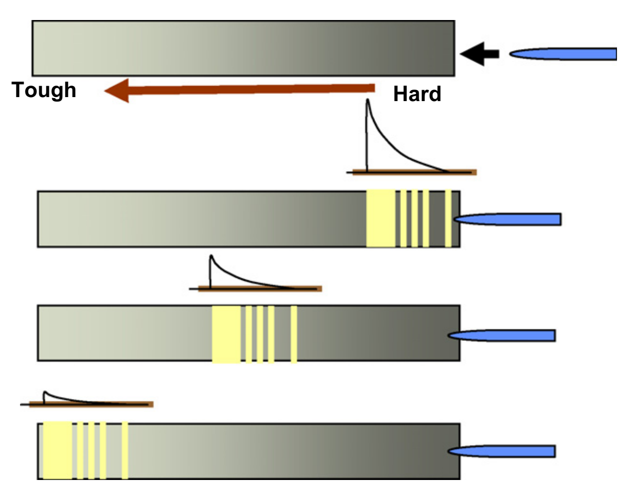

Fig. 7. Conceptual continuous-impedance-graded material.

conceptual material is shown in Fig. 7 with a superimposed stress wave propagating along its length. Because the material will have a continuous change of impedance, the damaging compression wave, which usually produces spalling or separation on the back surface or at the interface of a barrier, will be continuously modified as it propagates through the thickness. A barrier against a penetrator needs to have a hard outer surface to resist projectile or explosive impact damage, but it also needs to be tough enough to withstand the impact of crushing, and also strong enough not to spall or delaminate by the reflecting stress wave from the back surface. Composites of materials at the nanolevel, in which materials would synergistically cooperate to lend the resulting materials the desired properties, can be potentially made harder, lighter, and stronger. In this material, the graded interfaces will alleviate the stress concentrations through gradual changes in the material properties.

5. Conclusion

A concept for a new class of blast and penetration resistant (BPRM) materials has been developed. By applying the classical theory of uniaxial stress propagation, it has been shown that attenuation of the stress wave energy would be possible by controlling the impedance distribution within the body of such a material. The development of such material as armor will overcome the current common difficulty of interfacial delamination failure in composite integral armor.

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