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Impact mitigation in layered polymeric structures

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Impact mitigation in layered polymeric structures is studied to quantify the importance of impact impedance mismatch and energy dissipation modes on the overall transmission of a pressure wave. Internal reflection within the laminate structure is enhanced by optimizing the impedance between the laminate layers creating a virtual echo chamber for the impact wave. The high internal reflection potential of the structure enhances the residence of the energy within an energy dissipating viscoelastic layer. All the laminates of this research are composed of commonly available polymeric materials. A novel approach to measurement employs a Newton's cradle to correctly and accurately account for all input and output energies. As much as 90% of the theoretical transferrable energy can be dissipated by this mechanism. Statistical analysis of transmission and dissipation data shows that dissipative modes are of primary importance for mitigating impact forces, while other factors are of secondary importance. The most significant model is obtained when both dissipation and impedance are accounted for. The effect of increasing internal reflection within the dissipative structure results in the most significant variable for energy dissipation and transmission being the dissipative potential of a viscoelastic layer as determined from its tan-δ envelope. A dynamic finite element analysis technique has also been developed that models the time evolution of energy within the laminate structure following an idealized impact, and verifies the experimental results.

1. Introduction

Protective packaging is a material concept that extends across numerous everyday experiences. From egg cartons to sports equipment, it is necessary that a minimum amount of impact mitigation is employed to protect sensitive contents [1]. In spite of the criticality of protective packaging's function, there is little argument that most packaging does not fulfill its function except in low impact situations [2–4]. Much of this is due to sacrifice in design which not only must protect contents, but must do so at a given cost, a given weight, a given form factor, and even a given aesthetic [5,6]. Many materials are used in this function, from soft foams, to very hard metals and carbon fiber composites. In addition there has been innovation around the use of bioinspired structures and complex laminates [7–9]. In many cases the proposed solution is to provide a mechanism to deflect or dissipate impacting energy. Deflection mechanisms can employ hard interfaces to provide a reflecting surface based solely on an impact impedance mismatch model [10]. Alternatively a mechanism can use destructive absorption or dissipation mechanisms such as observed in tank ceramic tiles to absorb energy [11]. Additionally, the use of water bladder designs [12], and beam buckling elements [13] for example, have been proposed to dissipate energy. However, in each case the impact rate as well as intensity must be considered in designing an effective protective package [14]. If the energy dissipating mechanism of the design is not compatible with the rate of energy deposition into the protective structure, it will be ineffective [15,16]. In fact, many destructive impacts occur with a pressure wave delivered in tens of kHz rate, but then is propagated through the protective package at the speed of sound in that material imputing a rate in the MHz range. If the packaging has no dissipating mechanism the impact wave may be spread out over time somewhat, but the total energy delivered to the object to be protected may be nearly conserved. A mechanism which spreads out the impact wave will reduce the peak energy delivered to the protected object, however; it is an area of active study to determine if this is adequate in all cases for protection [17,18].

In this article we present data on a 3 (or more) layer polymer laminate that creates an improved dissipating structure capable of creating an echo chamber in the middle of which is a dissipating

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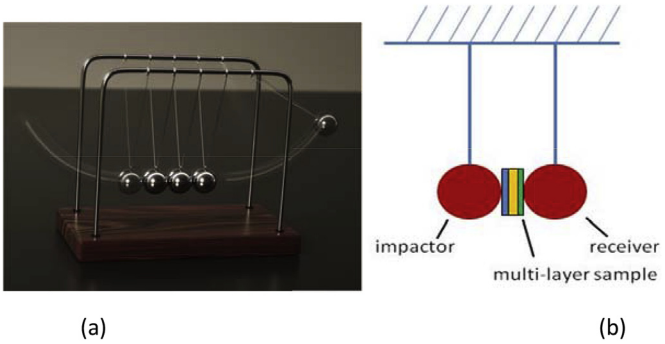
viscoelastic medium. Multiple reflections through the viscoelastic medium allows impact energy to be progressively degraded with each pass. Data was obtained using relatively low energy impact experiments employing a simple measurement and accurately accounts for all energy inputs and outputs. Results show all of the delivered energy can be accounted for by transmission, impact impedance by reflection, and energy dissipation in the viscoelastic medium. While dissipative factors are of primary influence in minimizing energy transmission, neglect of reflection does not provide as statistically satisfactory an account for the total evolution of energy following impact. Our results show that energy transmitted to a receiving body can be reduced by an order of magnitude using designed (but not exotic) laminate structures. In addition we present a dynamic finite element analysis method that allows one to optimally design a laminate structure based on the details of package construction and impact parameters.

2. Experimental

All foams and elastomers were provided by Dow Chemical Polyurethane Research and Development (Freeport, TX). Polycarbonate and ABS sheet were purchased from McMaster-Carr Co. (Elmhurst IL). A commercial child's baseball batting helmet (Easton Z5) was purchased from a local sporting goods store and the foams utilized as components for test and as a benchmark. The Newton's Cradle was purchased from Amazon.com, Inc and modified to meet the test requirements. The position of the spheres in the NC before and after impacts were recorded using an AIA motion picture camera mated to a desk-top computer and analyzed for impact parameters using a verticule, accurately measured using frame-by-frame analysis. Precision of measurements was better than ±5%.

The novel experiments of this article are focused on a physically correct screening approach for gathering data and additionally, choice of materials for testing our hypotheses. The experiments were designed with the purpose of accurately reflecting the dynamics of head-to-head collisions, presenting the ability to accurately account for the energy balance of such impacts. Our experimental approach employed a modified Newton's cradle (NC) [19]. A NC is a device that demonstrates conservation of momentum and energy via a series of swinging spheres. An example of a NC and schematics of our modification arranged for testing an energy dissipating laminate are presented in Fig. 1 (a) and Fig. 1 (b), respectively.

The modified NC is characterized by spheres, each of approximately 0.23 kg and 225 mm swing length. In the NC modification only two adjacent spheres are employed to create the colliding masses as in a typical head-to-head impact. One of the spheres is referred to as the “impactor” and is responsible for introducing energy into the system. The other sphere is referred to as the “receiver”. Interposing between these masses in our experiments is a 25 mm-diameter disk (about 5 g) composed of one or more layers of plastic material to be tested for impact dissipation. Adhesive tape is used for holding the laminate sample to the receiver sphere. The center-of-mass of the receiver/laminate is assumed to be essentially the same as that of the receiver sphere itself, owing to the small mass of the laminate. The mass of the laminate is small relative to the spheres and its contribution to the energy balance (apart from dissipative processes) has been neglected herein. In this particular incarnation the impact energy of this test is about 0.1 J. However, scaling to higher energies is a simple matter of increasing mass and swing length. After the video camera records the test, energies can be simply calculated as potential gravitational energies from the maximum heights of the spheres before and after the impact. The experimental procedure is illustrated by Fig. 2.



(a) (b)

Fig. 1. Newton's cradle as commonly encountered and as employed for the experiments in this article. The laminate structure is adhered to the receiver with adhesive tape.

In step A the impactor is lifted to a fixed height where the total energy of the system is solely the gravitational potential energy of the impactor calculated from the mass and vertical height from the equilibrium position. In Step B the impactor has been released. At the moment just prior to impact, all the potential energy in Step A has been transformed into kinetic energy within the impactor. With impact, part of the energy is transferred to the receiver, and part is reflected/dissipated by the laminate sample. As shown in Step C, part of the energy remains with the impactor, and both spheres move in the swing direction reaching a final height dictated by the mechanics and dynamics of the entire system. At the position of maximum height after impact (defining StepC), all of the energy in the system is again in the form of gravitational potential energy. From this state we can evaluate 1) the total energy of the system after impact, 2) the total energy dissipated by the laminate structure, and 3) the energy transmitted to the receiver. Additional impacts that occur after the impactor and receiver have reached their maximum heights following the first impact are outside the analysis interval represented in Fig. 2 and therefore do not influence the results.

For each test two outputs were computed, and derivation of all subsequent energy balance equations can be found in supplemental on-line information. One is the percentage energy dissipated calculated from the total energy of the system before and after impact as:

$$\%Energy_{Dissipated} = \frac{Energy_{StepA} - Energy_{StepC}}{Energy_{StepA}\Big/2} \tag{1}$$

The second is the percentage of energy transmitted to the receiver calculated as:

$$\%Energy_{Transfered} = \frac{Energy_{StepC\_receiver} - Energy_{StepA}\Big/4}{3Energy_{StepA}\Big/4} \tag{2}$$

In Equations (1) and (2) $Energy_{StepA}$ is the energy of the system before the impact (i.e. gravitational potential energy of impactor at Step A in Fig. 2), $Energy_{StepC}$ is the energy of the system after the impact (i.e. gravitational potential energy of impactor and receiver at Step C in Fig. 2) and $Energy_{StepC\_receiver}$ is the gravitational potential energy of receiver at Step C in Fig. 2. The numerical terms multiplying the *Energy* parameters are used for normalizing the results between the two extreme cases of (1) pure elastic impact, and (2) completely inelastic impact. In case of a pure elastic impact the amount of dissipated energy is null and the energy is completely transmitted. On the other extreme, there is the completely inelastic impact, where upon impact the two spheres