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Compressive evaluation of homogeneous and graded epoxy–glass particulate composites

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ABSTRACT

The propagation of stress waves in epoxy–glass particulate composites and graded materials was studied experimentally. Materials tested in this study consisted of an epoxy matrix with various concentrations of spherical glass particles having a mean diameter of 42 μm. Plate impact experiments were performed using a gas gun. Embedded within the specimens were manganin stress gauges used to record propagating compressive longitudinal stress waves through the material. High strain rate experiments using a Split Hopkinson Pressure Bar (SHPB) apparatus were also performed to evaluate the dynamic strength of the specimens, while quasi-static compression tests were undertaken to characterize their quasi-static behavior. Ultrasonic wave speed measurements were carried-out in order to obtain additional material properties and characterize the gradation in functionally graded materials (FGM). It was found that low volume fractions of particles are detrimental to the performance of the material under impact loading, while concentrations in the range of about 30 to 45% by volume exhibit characteristics of higher degrees of scattering. This suggests that materials in this latter range would be more effective in the thwarting of destructive shock waves than the homogeneous matrix material. Impact testing of FGM specimens suggests that impact loading on the stiff (high volume fraction) face results in much higher levels of scattering. Therefore, such materials would be effective for use in light weight armor or as shielding materials due to their effective attenuation of mechanical impulses.

1. Introduction

The study of the damage behavior of particulate composites has traditionally focussed on quasi-static loading. For example, Bazhenov [1] explored the quasi-static response of regular arrays of rigid particles in an elasto-plastic matrix, in which damage failure was related to particle/matrix debonding. That work revealed that the deformation behavior of the composite depended on the relation between the matrix strength and yield stress. Numerically, Garishin and Moshev [2,3] explored the quasi-static response of high volume fraction particulate composites, using a discrete structural model.

Early dynamic research includes Herrmann's description of the Hugoniot curve in a ductile powder composite of porous aluminum and iron [4]. This was followed by the formulation of a stress wave propagation model in composite materials. In that work, Barker idealized composites as consisting of a system of periodically alternating materials, where the interaction between the successive layers of the resulting complex laminate would represent the scattering effect thought to be present within more general composites [5]. A similar approach was adopted by Oved et al. [6]. This simplistic, but appealing model was preserved as an experimentally ideal set up by Zhuang et al. [7], who, with the aid of internally positioned gauges, tracked a propagating shock wave at two discrete points located at the interfaces between alternating layers of aluminum and polycarbonate. Related experiments on laminated and fibrous composites include the works of Richardson and Wisheart [8], Cantwell and Morton [9], Aslan et al. [10], and Hebert et al. [11].

The bulk of the experimental work dedicated to particulate composites has focussed mainly on their fracture properties [12–16]. However, few attempts have been made to quantify the amplitude of compressive wave propagation in heterogeneous material, and much remains to be clarified concerning that process. In the above-quoted works, the phenomenon of geometric dispersion of elastic waves has received limited attention. The idea of geometric dispersion has guided this study into investigating the basic physical principles governing the propagation of elastic longitudinal stress waves in non-homogeneous particulate composites and graded materials. In particular, emphasis is placed on distinguishing material characteristics that can inherently thwart the evolution of a destructive shock wave. One of the primary mechanisms thought to impede of stress wave propagation is the phenomenon of scattering. Despite numerous analytical studies, the exact mechanism of scattering is not fully understood. Further, there is a lack of experimental data concerning particulate graded materials. This study is an experimental investigation of the propagation of stress waves in various

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concentrations of epoxy-glass particle composites and graded materials. In addition to impact experiments, both high strain rate and quasi-static compression experiments were performed in order to fully characterize the properties of the materials involved. Ultrasonic wave speed measurements were also performed and analyzed to obtain additional information on the inherent properties of the materials.

The use of projectile impact conducted in order to investigate the propagation of stress waves through a material has been used extensively in previous studies [17–20]. The components necessary to perform impact experiments and gather data, such as gas guns, stress gauges, piezoresistive pulse power supplies, and velocity–interferometry systems have been well documented and are readily available. The data analyses performed for such experiments have been presented based on wave propagation theory and experimental correlations in [21–27]. The majority of experimental results obtained in the present study rely on data gathered from projectile impact, using stress gauge data to characterize the evolution of stress waves in the material. Additional relevant characteristic material data were obtained by means of Split Hopkinson Pressure Bars (SHPB) and ultrasonic pulser/receivers, resulting respectively in measurements of dynamic material strength at various strain rates, and longitudinal wave speed within the material [28–32]. The following sections present the procedures used to prepare the materials used in the study and a description of the experimental methods. The Experimental results section presents the relevant data gathered, which is followed by an associated discussion and some concluding remarks.

2. Materials

The specimens used in this study were fabricated with an epoxy thermoset matrix mixture. Different variations of these materials were created, ranging from an indigenous material (no added particulates) to mixtures that included glass particles, and functionally graded materials. The following is an overview of the methods used to prepare and cast each specific type of material.

2.1. Preparation of virgin epoxy

The epoxy used in all the castings is an Epo-Thin™ resin and hardener, manufactured by Buehler, Ltd. It is a low-viscosity thermoset with a nominal curing time of 18 h at room temperature. The resin is a bisphenol-A type epoxy resin. The hardener's primary ingredient is a polyoxyalkylamine blend. The density of the mixed epoxy is given by the manufacturer as 1147 kg/m^3 and was also confirmed experimentally.

2.2. Preparation of homogeneous particulate materials

The procedure used for producing castings containing micro-scale glass particles was identical to that used for the virgin epoxy specimens. Spherical soda-lime glass beads, manufactured by the Mo-Sci Corporation, were used. The primary ingredient of these particles is silica (SiO_2), with a concentration of 72.5% by weight. The specific gravity of the particles is given by the manufacturer as 2.5, and the mean diameter as 42 μm. The nature of this study called for various concentrations of these particles to be mixed with the epoxy prior to casting. The concentrations used for casting were chosen incrementally to be 2, 10, 20, 30, and 40 g of glass per 17 g of epoxy (17 g was the nominal weight of epoxy used to fill a single casting cup, composed of 12.5 g of resin and 4.5 g of hardener). Knowing the densities of the glass particles and the epoxy, it is straightforward to obtain the volume fractions for each respective concentration. These were approximately 5, 21, 35, 45, and 52%, respectively.

2.3. Preparation of functionally graded specimens

Functionally graded material (FGM) castings were produced by combining virgin epoxy with glass particles. This consisted of 12.1 g of resin, 4.3 g of hardener, and 38.6 g of glass particles. In the absence of further mixing, the glass particles, which were initially uniformly distributed in the epoxy, gradually settled toward the bottom of the mold, concurrently with the hardening processed triggered by the thermosetting reaction. As a result, the bulk of the glass particles settled at the bottom due to gravity. However, a substantial number of particles remained suspended at various intermediate heights, resulting in specimens exhibiting smooth property gradations with vertical distance. More details on the gradation of these specimens can be found in the Experimental results section, which presents data from ultrasonic measurements.

2.4. Predicted and measured specimen densities

The theoretical density of each glass–epoxy composite specimen was evaluated using the rule of mixtures. The given specific gravity of the glass particles was 2.5. The density of the epoxy was given by the manufacturer as 1147 kg/m^3. The rule of mixtures, as it applies to the current specimens, can be formulated as:

$$\rho_{mix} = \left(\rho_{glass}\right)\left(V_{f-glass}\right) + \left(\rho_{epoxy}\right)\left(1 - V_{f-glass}\right), \tag{1}$$

where $V_{f\text{-}glass}$ is the volume fraction of glass, and ρ_{mix}, ρ_{glass} and ρ_{epoxy} are the densities of the composite mixture, the glass particles, and the epoxy matrix, respectively. For each volume fraction, individual specimens were weighed, their volume measured, and the associated measured density was obtained. Differences between theoretical and measured densities increased with increasing volume fractions of the glass particles in the matrix. The presence of air voids is noted to be exacerbated by the accumulation of glass beads in the castings, and was identified as a primary contributor to this variance. The weight and density of the constituents, and the measured and theoretical volumes of the composites were used to approximate the volume of air in each specimen. This volume of air was then divided by the measured volume to calculate the percentage of air by volume in each specimen. Table 1 summarizes these evaluations and shows that the maximum air volume fraction is 4.1% for the specimens measured.

3. Methods of evaluation

3.1. Impact testing

The primary focus of this study was to investigate the behavior of cast epoxy materials subjected to impact loading. Following methods established by other researchers [1,2,4,17–20], an experimental procedure and setup were designed, which is shown in Fig. 1. To achieve planar plate impact, a 19 mm (0.75 in.) diameter polycarbonate impactor was machined to a thickness of 3.18 mm (0.125 in.). In order to accelerate the impactor to the desired impact speeds of approximately 300 m/s, a single stage helium-powered gas gun with a 2.1 m (7.0 ft) long, 2.54 cm (1.00 in.) diameter barrel was used. The impactor was appended to the front face of a 2.53 cm (0.995 in.) diameter, 2.54 long

Table 1
Density and air void data for epoxy–glass specimens.

Specimen	V_f glass (%)	Theoretical density (kg/m^3)	Measured density (kg/m^3)	Volume of air (cc)	Percent air by volume
0 g	0	1147	1160	0	0
2 g	5	1216	1204	0.0608	1.003
10 g	21	1435	1420	0.0607	1.014
20 g	35	1621	1591	0.1114	1.846
30 g	45	1752	1713	0.1354	2.251
40 g	52	1849	1773	0.2475	4.101