Impact Performance of Laminates Made of Syntactic Foam and Glass Fiber Reinforced Epoxy as Protective Materials

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ABSTRACT: Impact performance of two-dimensional quasi-isotropic laminates subjected to impact loading with flat-ended impactors has been studied in terms of impact stress, strain rate, and volume fraction of laminae. A simple model was formulated to predict impact stress within an elastic limit as a function of volume fractions of laminae. Individual impact parameters for syntactic foam and fiber-reinforced epoxy were experimentally obtained at impact energy levels of 0.54 and 0.87 Joule, and used to predict impact stress of the laminates made of the same materials. A reasonable agreement between predictions and experimental results were found. © 2003 Wiley Periodicals, Inc. J Appl Polym Sci 89: 2306–2310, 2003

Key words: impact; protection; strain rate; volume fraction; laminate

INTRODUCTION

Such factors affecting impact performance during collision as impact force, impact stress, impact energy, impact speed, impact duration, and material properties are interrelated.[1–6] The prediction of impact force and impact stress transmitted through protective materials are important for determining shape and dimensions in the design process of protective devices such as protective helmets and mouthguards for a given set of impact conditions.

When laminates are used as protective materials, their impact performance depends on how laminae of different properties are combined.[1,6] Kim and Mathieu[1] discussed two parameters, i.e., force and stress distribution in laminates, and it was suggested that the maximum protection can be achieved by optimizing the two parameters. Additional considerations to the two parameters may include the strain rate sensitivity of the laminate. Most polymer-based laminates are time-dependent and their time-dependent properties depend on the volume fractions of constituent laminae. Kim and Shafig[7,8] studied the impact force transmitted through viscoelastic monolayer subjected to drop-weight impact loading by varying specimen thickness. The present article extends this study to further develop insight into the effect of volume fractions of laminae in laminates on impact force/stress.

FORMULATION FOR IMPACT FORCE OF LAMINATES SUBJECTED TO STRAIN RATE VARIATION DUE TO VARIATION OF VOLUME FRACTION OF LAMINAE

When a flat-ended impactor collides with a monolayer specimen, the strain rate depends generally on the thickness of specimen for a given diameter and the compressive elastic modulus (E_c) is given by[8]

$$E_c = E_0 h^{-n'} \tag{1}$$

where E_0 is a constant, h is the thickness of the test specimen and $-n' = d(\ln Ec)/d(\ln h)$. Also, impact force F is given by[8]

$$F = h^n \, c \sqrt{\Lambda} \tag{2}$$

where Λ is the elastic strain energy ($\approx$ impact energy), $c = d\sqrt{\pi E_0/2}$ and $n = -(n' + 1)/2$. Equations (1) and (2) are based on an assumption[8] that

$$t = Ah \tag{3}$$

where t is the contact time during impact and A is a constant. For further development, eq. (3) can be replaced with

$$t = Ah^{\alpha} \tag{4}$$

where α is a constant, for generalization without affecting the resulting forms of other equations.

When a laminate consisting of two different sets of properties due to two different laminae is considered

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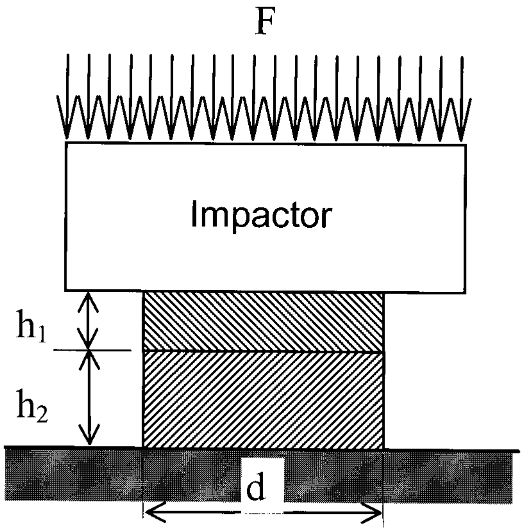

Figure 1 Impact loading configuration for laminates of various volume fractions.

as shown in Figure 1, its compressive modulus (E_c) can be found using the rule of mixtures[9]

$$\frac{1}{E_c} = \frac{v_1}{E_1} + \frac{v_2}{E_2} \tag{5}$$

to be

$$\frac{1}{E_c} = \frac{v_1 E_{02} h_2^{-n_2'} + v_2 E_{01} h_1^{-n_1'}}{E_{01} E_{02} h_1^{-n_1'} h_2^{-n_2'}} \tag{6}$$

where subscripts 1 and 2 indicate individual laminae, v is the volume fraction, and $E_0 = 2c^2/\pi d^2$.

For a circular plate, impact force according to the energy conservation principle is given by[10]

$$F = d\sqrt{\frac{\pi E_c \Lambda}{2h}} \tag{7}$$

where d is the diameter, F is the impact force, and Λ is the elastic strain energy ($\approx$ impact energy) as already noted. Combining eqs. (6) and (7) yields

$$F = d\sqrt{\frac{\pi \Lambda E_{01} E_{02} h_1^{-n_1'} h_2^{-n_2'}}{2h(v_1 E_{02} h_2^{-n_2'} + v_2 E_{01} h_1^{-n_1'})}} \tag{8}$$

This equation accounts for the impact force transmitted through a laminate consisting of two laminae with two different sets of properties.

EXPERIMENTAL

Constituent materials

A batch of hollow microspheres used was 3*M* Scotchlite Glass Bubbles K1. A size distribution of microspheres was obtained using a Malvern 2600C laser particle size analyzer and is shown in Figure 2. Densities were measured using an air comparison pycnometer (Beckman 930) and an average of three measurements was found to be 0.128 g/cc for microspheres.

Fibers used for manufacturing fiber-reinforced composites were E-glass (FGI MU 4500A), which were in a form of unidirectional dominated fabric in which 6% fibers are floated in the weft direction with a spacing of approximately of 1 cm, and these fibers in both weft and warp directions were stitched with an inorganic material to form the fabric.

A resin system used for both syntactic foam and fiber-reinforced composites consisted of West System products , epoxy 105 (a blend of bisphenol A and bisphenol F), and Slow Hardner 206 (a blend of aliphatic amines and aliphatic amine adducts based on diethylene triamine and triethylenetetramine). A mixture ratio of resin to hardener was 5 to 1 by volume. An average of five measurements for the mixture density was found to be 1.108 g/cc.

Specimen preparation

Syntactic foam

Syntactic foam was manufactured using the compaction method.[3,5] Steel molds were used for manufacturing syntactic foam specimens for both compressive properties and impact performance. Each mold with a cylindrical cavity of $\phi 28 \times 90$ mm was cleaned using acetone and followed by spraying release agent (Acheson) onto them before molding. The resin system placed in a mixing pot was stirred gently for about 2–5 min and then predetermined amounts of microspheres were progressively added while stirring. The mixture for syntactic foam was poured into the mold and subsequently a pressure of 87.62 kPa was applied for compaction. The mixture was left for at least 12 h for curing before cutting into mechanical test specimens with a foam density of 0.40. A scanning electron microscope image of fracture surface of the cured foam is shown in Figure 3 for microstructure. Volume fractions of microspheres, resin, and air voids

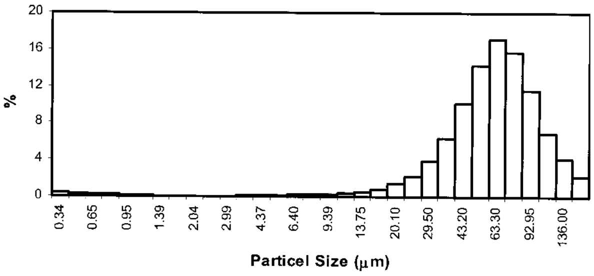

Figure 2 Size distribution of microspheres used.

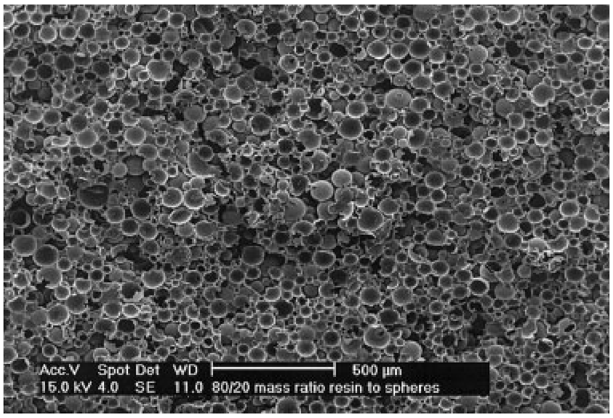

Figure 3 SEM image of fracture surface of manufactured syntactic foam made of hollow microspheres and epoxy resin.

were found to be 0.63, 0.29, and 0.088, respectively, using

$$v_r = \frac{\rho_f - \rho_p(1 - v_{\text{avoid}})}{\rho_r - \rho_p} \tag{9}$$

$$v_{\text{avoid}} = 1 - \rho_f\left(\frac{m_p}{\rho_p} + \frac{m_r}{\rho_r}\right) \tag{10}$$

$$v_p = 1 - v_r - v_{\text{avoid}} \tag{11}$$

where v is the volume fraction, ρ is the density, and subscripts f, p, r, and "avoid" denote, respectively, foam, microsphere, resin, and air void.

The foam was cut into cylindrical specimens of 12 mm in diameter. The thickness of the specimens was 10 mm for compressive testing but varied from 4 to 20 mm for impact testing.

Fiber-reinforced laminates (FRL)

A two-dimensional quasi-isotropic laminate consisting of five plies, $[0/36/72/108/144]_T$, was manufactured using an aluminum mold (with a cavity depth of 3 mm). The five plies of glass fiber fabric were laid up one by one over resin partially contained in an open cavity of lower part of the mold, and then resin was added on the top of the fabric for manual rolling to increase wetting and followed by covering up with the upper mold. A molded panel gave a glass fiber volume fraction of 0.51. The laminate was cut into circular specimens of 12 mm in diameter and then some of these specimens were glued together by placing one on top of another to produce specimens with various thicknesses. Some damage in a form of whitening 0.5 to 1 mm wide along the edge of each specimen was observed after cutting. The compressive test specimens were 4 mm thick. Specimen thickness for impact tests was varied from 4 to 20 mm while diameter was kept constant.

Foam/FRL laminates

Foam and FRL were laminated to make cylindrical specimens with various volume fractions of foam and FRL but constant diameter and thickness ($\phi 12 \times 16$ mm). The values of h_1, h_2, v_1, and v_2 used with eq. (8) are listed in Table I.

Mechanical testing

Compressive tests were conducted on a universal testing machine (Shimadzu 5000) at a crosshead speed of 1 mm/min to obtain mainly elastic moduli of manufactured foam and FRL. Each compressive specimen was placed between platens of 22 mm in diameter attached to a compression cage with an extensometer. To minimize friction between specimen surface and platen surface, the surfaces were greased with Shell Retinex A.

Drop weight impact test setup consisted of a flat-ended impactor, an electromagnet for the impactor release mechanism, a load cell with a capacity of 10 kN, and a computer with software for data logging (DocuWave, Version 1.10, Tektronix, Inc.). This setup produces data for impact force vs time as output. More details for the test setup is found elsewhere.[5] The impact tests were conducted on three different types of specimens, i.e., foam, FRL, and foam/FRL laminate. An impact height of 400 mm was used for all specimens to maintain a constant impact speed, but impactor mass was varied.

RESULTS AND DISCUSSION

Typical stress–strain curves obtained from compressive testing are shown in Figures 4 and 5, respectively, for foam and FRL. Good degrees of linearity exhibit up to 13 and 40 MPa for foam and FRL, respectively. Averages of 287 and 1318 MPa for compressive elastic moduli for foam and FRL, respectively, were obtained each from five specimens.

To confirm the generalized assumption eq. (4), contact time, which is the duration between initial zero

TABLE I
Values Used with Eq. (8)

h_1 (mm) foam	h_2 (mm) FRL	v_1 (mm) foam	v_2 (mm) FRL
0	16	0	1
4	12	0.25	0.75
8	8	0.5	0.5
12	4	0.75	0.25
16	0	1	0

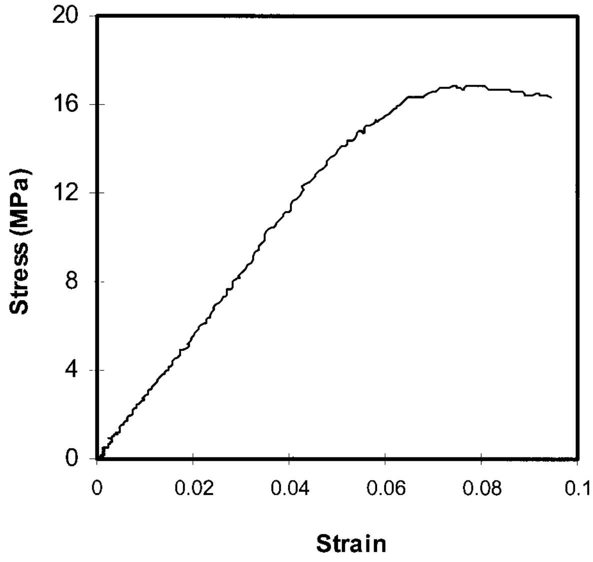

Figure 4 A typical compressive stress–strain curve of syntactic foam.

force and peak force during impact, was measured as a function of specimen thickness and is shown in Figure 6. The generalized assumption eq. (4) appears to represent trends of the four different cases reasonably. Obtained values for constants A and α in eq. (4) are listed in Table II.

Experimental results for impact stress obtained as a function of specimen thickness at two different impact energy levels of 0.54 and 0.87 J for individual foam and FRL are given in Figure 7. Maxima of impact stress for both foam and FRL can be seen to be 18 and 74 MPa, respectively, which are not significantly higher than respectively 16 and 60 MPa, which are limits of reasonable linearity as shown in static stress–strain curves (see Figs. 4 and 5). Judging from that the limits of linearity under high strain rate loading is higher than that of low strain rate loading; the maxima appear to be within reasonable linear limits. Significant differences between FRL and foam in impact stress response can be seen in Figure 7. Foam appears to be relatively insensitive to both impact energy and specimen thickness, whereas FRL appears to be significantly affected by both impact energy and specimen thickness. The sensitivities to impact energy and thickness are reflected in values of c and n of eq. (2). The values of n and c obtained are listed in Table III. Standard errors of fit for data into eq. (2) were found to be 3.95, 2.93, 1.47, and 1.81, respectively, for 0.87 J(FRL), 0.54 J(FRL), 0.87 J(Foam), and 0.54 J(Foam).

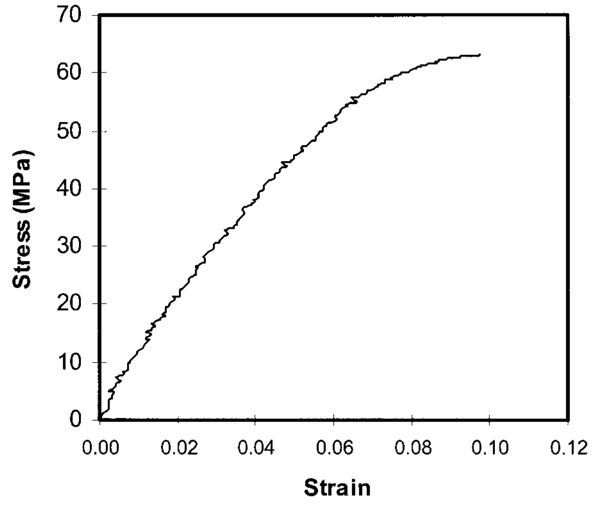

Figure 5 A typical compressive stress–strain curve for FRL.

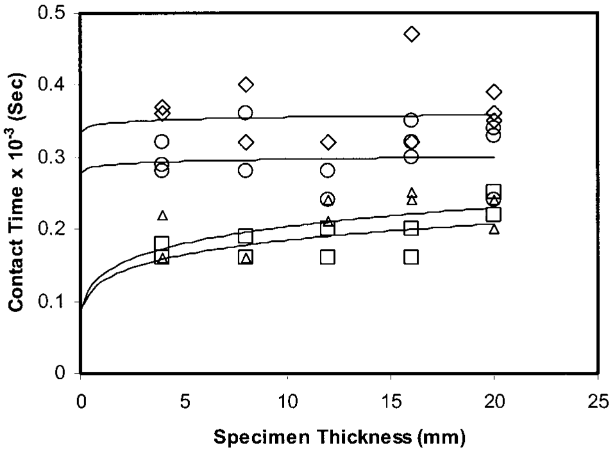

Figure 6 Contact time measured as a function of specimen thickness for individual foam and FRL at different impact energy levels: (□) FRL, 0.87 J; (△) FRL, 0.54 J; (○) foam, 0.87 J; and (◇) foam, 0.54 J. The solid lines are best fit to data points, drawn on the basis of eq. (4).

Impact stress transmitted through each laminate as a function of volume fraction of foam is given in Figure 8. Data for 0.54 J are represented by the symbol ◆ and data for 0.87 J by the symbol □. The impact stress is initially seen to sharply decrease with a small volume fraction of foam and tends to be rapidly stabilized afterwards. This implies that, in practical applications, only a small volume of foam can be efficient for protection in the cases where a strength-dominated design is required. Predictions were made using obtained values from individual FRL and foam with eq. (8) and are given with experimental data in Figure 8. The dashed line represents for 0.54 J and the solid line for 0.87 J. Standard errors of fit

TABLE II
Constants in $t = Ah^{\alpha}$ (t in ms and h in mm)

Material	Impact energy (J)	A	α
Foam	0.87	0.288	0.0136
Foam	0.54	0.346	0.0121
FRL	0.87	0.126	0.166
FRL	0.54	0.136	0.175

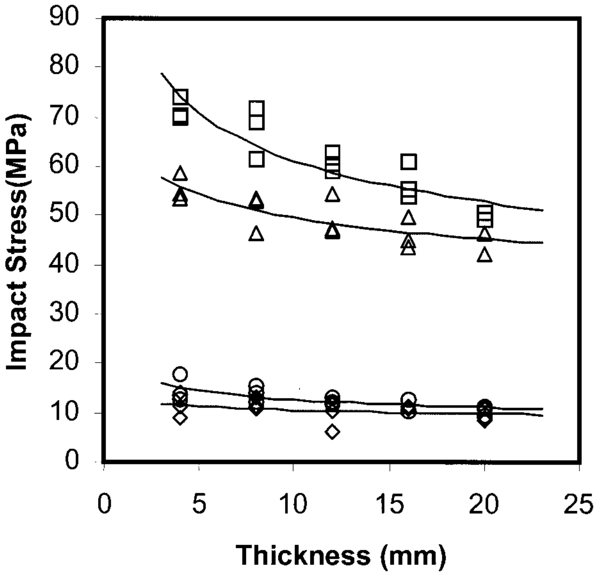

Figure 7 Impact stress measured and predicted as a function of specimen thickness: (□) FRL at an impact energy of 0.87 J; (△) FRL at an impact energy of 0.54 J; (○) foam at an impact energy of 0.87 J; and (◇) foam at an impact energy of 0.54 J. Standard errors of fit are 3.95, 2.93, 1.47, and 1.81, respectively, for 0.87 J(FRL), 0.54 J(FRL), 0.87 J(Foam), and 0.54 J(Foam).

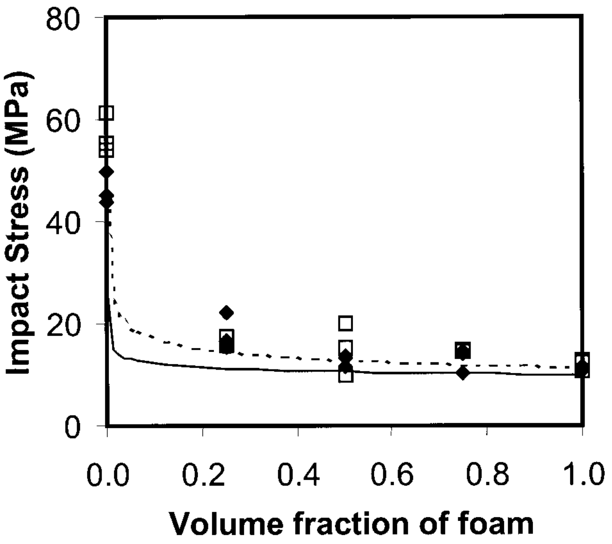

Figure 8 Impact stress vs volume fraction of foam: (◆) 0.54 Joule; (○) 0.87 Joule; (—) predicted by eq. (8) for 0.54 Joule; and (– – –) predicted by eq. (8) for 0.87 Joule. Standard errors of fit are 16.3 and 5.2 for 0.54 and 0.87 Joule, respectively.

for eq. (8) were found to be 16.3 and 5.2 for 0.54 and 0.87 J, respectively. The better fit appears to be for the higher impact energy level.

CONCLUSIONS

Impact performance of laminates has been studied using individual impact parameters of laminae to predict impact stress as a function volume fraction of laminae. A simple model representing a relationship between impact stress and volume fraction of laminae is developed, and its reasonable predictability within linear elastic limits of materials for experimental data is demonstrated.

TABLE III
Constants in $F = h^n c\sqrt{\Lambda}$ (F in N and h in mm)

Material	Impact energy (J)	n	c
Foam	0.87	−0.1931	2392
Foam	0.54	−0.1028	2036
FRL	0.87	−0.2123	12107
FRL	0.54	−0.1295	10242

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