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SHOCK RESPONSE AND FINITE ELEMENT MODELING OF NANOCLAY AND GRAPHITE PLATELET REINFORCED VINYL ESTER NANOCOMPOSITES

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ABSTRACT

The shock response of Derakane 411-350 vinyl ester thermoset beam specimens with 1.25 and 2.5 wt. percent randomly distributed exfoliated graphite nanoplatelets and Cloisite 30B nanoclay were investigated. Shock tube apparatus was used to study the material response at a peak pressure of 70 psi (482.6 kPa), and approximate strain rate of 1000 per second; and 120 psi (827.4 kPa), and approximate strain rate of 1400 per second. Shock tube experiments were also modeled using the explicit finite element program, ANSYS LS-DYNA.

The energy absorption improved by about 150 percent with increasing nano reinforcement, for shock tests conducted at 120 psi peak pressure. A close agreement was observed between experimental data and finite element modeling of the shock response.

INTRODUCTION

Nanocomposites are often touted as the material of the 21st century finding applications in almost all industries including automobiles, electronics, space, chemicals, sensors, storage systems, health care, and structural applications among others. These new class of composites are increasingly being studied for their application in structures such as spacecrafts, airplanes, warships etc. which requires high stiffness-to-weight ratio along with high damping. Nanoclay [1-4] and graphite platelets [5-9] are some of the nano scale inclusions proposed as filler materials showing promise for structural applications, and have been investigated in this work for naval ships and homeland security applications.

The objective of this work is to study the shock response of nanoclay/ vinyl ester; and graphite platelet/ vinyl ester nanocomposites with 1.25 and 2.5 wt. percent reinforcement in comparison with the pure polymer. These nanocomposites are planned to be used as face plates of sandwich composite structure with fire-resistant foam layered in between to further enhance the energy absorption along with optimal flexural rigidity, vibration, damping and reduced flammability. These new materials are being developed to make structures blast/shock/impact resistant with reduced weight for naval ships and homeland security applications.

SHOCK TESTS

A simple shock tube consists of two halves isolated from each other by a diaphragm with high gas pressure on the driver side of the shock tube [10-11]. Diaphragm is controlled to burst at the required pressure difference which develops a shock wave. This shock wave propagates into the test section (low pressure or driven section) of the tube. At the same time, an expansion wave develops and propagates in the driver side of the tube. If a test specimen is kept in the driven section (low pressure region) of the shock tube, the specimen undergoes this shock which simulates the rush of gas after an explosion. The shock tube test facility at University of Rhode Island was utilized in the current study.

Shock tube tests were conducted on plates of dimension 254 mm x 101.6 mm x 9.9 mm (10” x 4” x .39”). One panel from each configuration was subjected to 70 psi (482.3 kPa) and another at 120 psi (827.4 kPa) peak pressure. It is to be noted that pure vinyl ester specimen was first impacted with 70 psi (482.3 kPa) peak pressure and then with 120 psi (827.4 kPa) peak pressure. It was reported that samples subjected to 70 psi (482.3 kPa) peak pressure did not fracture. However, post impact samples received show hairline fractures for 1.25 and 2.5 wt percent graphite platelet samples subjected to 70 psi peak pressure. All the samples subjected to 120 psi (827.4 kPa) peak pressure fragmented into pieces.

The nanocomposite panels were held under simply supported conditions so as to minimize damage due to gripping and clamping. The span of the simply supported plate was 152 mm (6”) and the overhangs measured 50.8 mm (2”) along each end. The center of the specimen was kept in line with the center of the shock tube. The ratio of the loading diameter to the span was 0.5. The specimens were blast loaded from the exit of the shock tube on the face opposite to the supports [11].

Dynamic pressure sensor (PCB Piezotronics A123) mounted near the exit of the shock wave measures the shock pressure and reflected pressure history. Shock velocities are measured using break circuits and adequate calibration data is also available for the same. The shock wave velocities for the experiments conducted in this study were 500 m/s for a peak pressure of 70 psi (482.3 kPa) and 600 m/s with a peak pressure of about 120 psi (827.4 kPa). Images of the specimens loaded by the shock wave were captured in real time intervals of 100-150 microseconds [11] by using a high-speed IMACON 2000 camera.

Strain Rate Approximation

For viscoelastic materials, the rate of loading is an important characteristic since energy absorbed before failure may vary for different strain rates. Viscoelastic materials typically become stiff at high strain rates with a reduction in strength and vice versa. An approximation of the transient strain rate under shock tube testing has been obtained using the bending moment equation under quasi-static load conditions.

Transient load data was obtained from pressure profile curve by multiplying it with the effective area of the driven section (3” Diameter) as shown in Figure 1. The transient shock load in this test was applied on a circular region which was approximated as a rectangular zone along the beam width as shown in Figure 2.

The quasi-static bending moment equation was used for computing the flexural stress (σ):

$$\sigma = \frac{M \cdot y}{I} \tag{1}$$

Transient bending strain, ε(t) as a function of the instantaneous transient load, is obtained from:

$$\varepsilon(t) = \frac{\sigma(t)}{E} \tag{2}$$

For the case of impact loading, the transient bending moment, *M*(t), was computed from transient load, *P*(t), obtained from the impact machine at each time step, t. Boundary conditions are approximated as a simply-supported beam. Substituting value of σ from Equation (1), to obtain the, ε at each time step, t.

$$\varepsilon(t) = \frac{M(t) \cdot y}{E \cdot I} \tag{3}$$

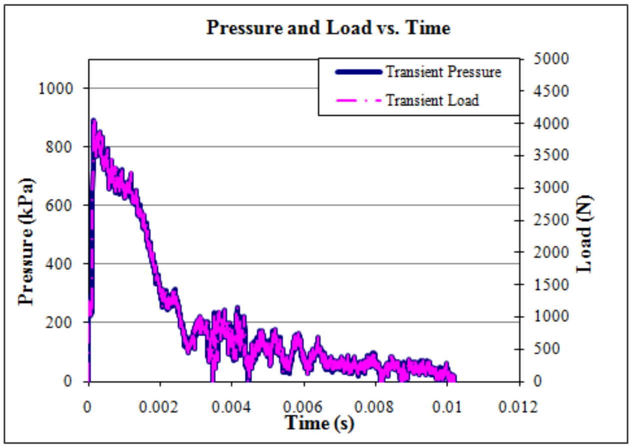

Figure 1. Pressure and load vs. time for pure vinyl ester specimen obtained from shock tube test

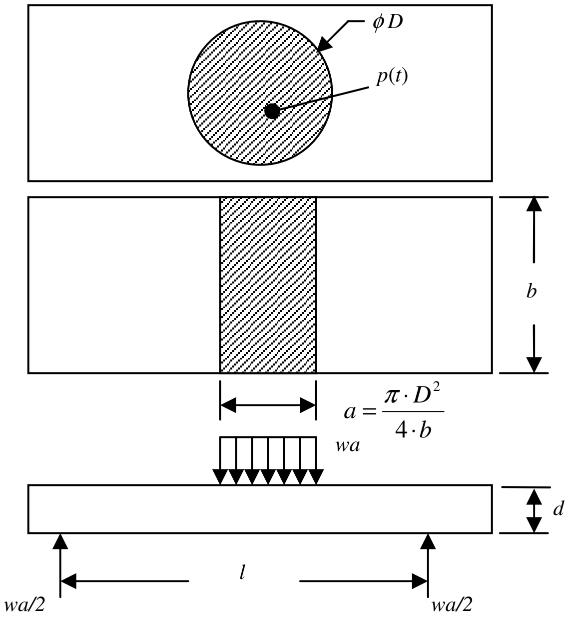

Figure 2. Boundary condition for Shock Test

Maximum bending moment at the center is given by:

$$\begin{aligned} M(t) &= \frac{1}{8} wa \cdot (2l - a) \\ &= \frac{1}{8}\left(p(t) \cdot b\right) \cdot \left(\frac{\pi \cdot D^2}{4b}\right) \cdot (2l - a) \\ M(t) &= \frac{1}{8} p(t) \cdot (2l - a) \end{aligned} \tag{4}$$

where $p(t)$ = Transient pressure
and $P(t)$ = Transient load

The area moment of inertia for rectangular beam specimen is given by:

$$I=\frac{b\cdot d^3}{12} \tag{5}$$

With the maximum flexural stress occurring at the outermost bottom layer of the specimen:

$$y=\frac{d}{2} \tag{6}$$

Substituting value of *M*(*t*), *I*, and *y* from equation (4), (5), (6) respectively in equation (3) gives:

$$\varepsilon(t)=\frac{\frac{1}{8}P(t)\cdot(2l-a)\cdot\frac{d}{2}}{E\cdot\frac{bd^3}{12}}=\frac{3}{4}\left(\frac{P(t)\cdot(2l-a)}{E\cdot b\cdot d^2}\right) \tag{7}$$

or

$$\varepsilon(t)=K\cdot P(t) \tag{8}$$

where

$$K=\frac{3}{4}\left(\frac{(2l-a)}{E\cdot b\cdot d^2}\right) \tag{9}$$

K will be a constant based on the experimental set-up and type of material tested. The transient strain computed as a function of the transient load using equation (8) is plotted with time on the x-axis. A typical graph of transient strain versus time (and load versus time) for a 2.5 wt. percent graphite platelet/vinyl ester is shown in Figure 3.

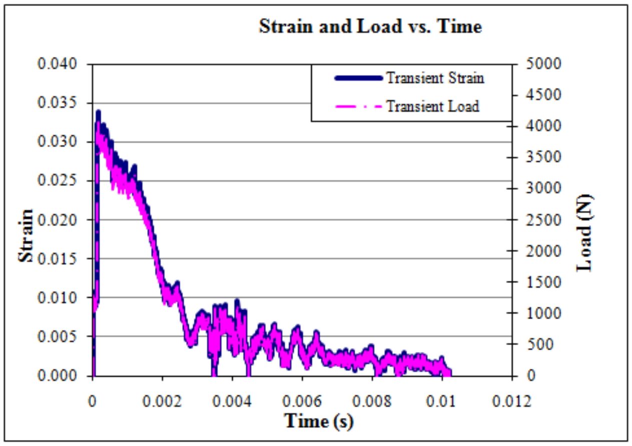

Figure 3. Strain and load vs. time for pure vinyl ester specimen obtained from shock tube test

Strain rate was then computed based on the initial slope. A typical graph for the slope of strain curve from shock tube for a peak pressure of 120 psi for pure vinyl ester is shown in Figure 4 with a linear fit line in the initial portion. An approximate strain rate of 1000 per second and 1400 per second respectively for the 70 psi and 120 psi peak pressure was computed for the shock tube tests.

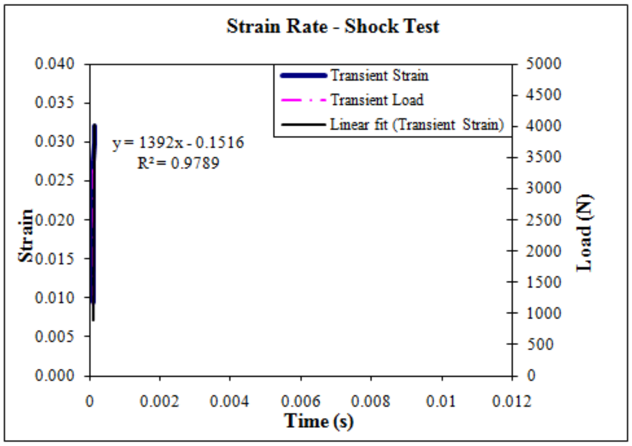

Figure 4. Strain rate for pure vinyl ester specimen for a shock tube test with a peak pressure of 120 psi

Analysis of Shock Tube Test Data

The pressure profile curve, real time images, post-impact visual examination and deflection data of vinyl ester nanocomposites were reported by the University of Rhode Island [11]. No failure was reported in the vinyl ester specimens subjected to 70 psi peak pressure, while specimens subjected to 120 psi peak pressure were shattered in pieces.

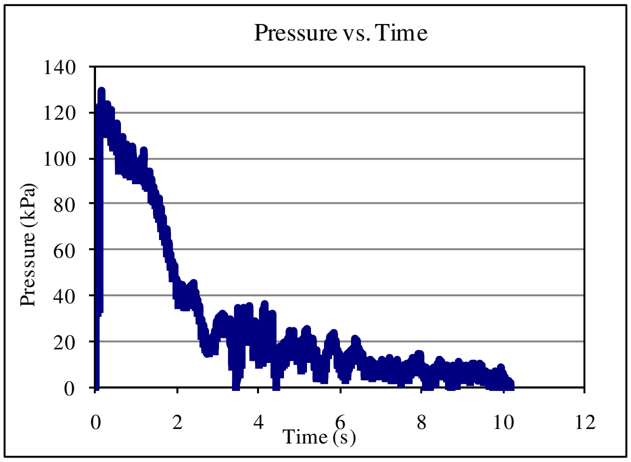

Figure 5. Pressure profile for pure vinyl ester subjected to 120 psi peak pressure [11]

The typical pressure profile curve, real time images and the post-impact images for pure vinyl ester specimen subjected to 120 psi peak pressure is shown in Figures 5 to 7 and the response deflection versus time graph is shown in Figures 8 and 9. It is to be noted that in the case of pure vinyl ester, the same specimen was used for both 70 psi and 120 psi peak pressure.

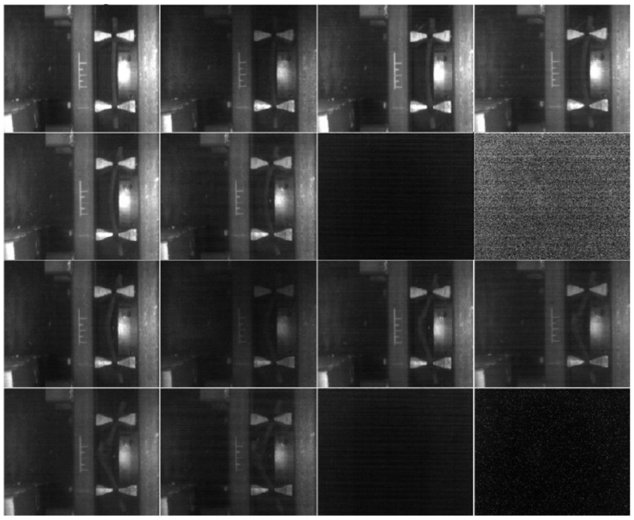

Figure 6. Post impact image of 2.5% graphite platelet/vinyl ester subjected to 120 psi peak pressure in shock tube [11]

Figure 7. Real time image of 2.5% graphite platelet/vinyl ester specimen subjected to 120 psi peak pressure in shock tube [11]

In order to analyze the material response to shock loading, quasi-static approach was adopted. In the quasi-static method, energy absorbed by each specimen is obtained by correlating the mid-span deflection with the pressure in terms of transient load. Pressure at respective time intervals was converted to transient load exerted on the specimen by multiplying it with the effective cross-sectional area of the driven section (3" Diameter). Transient load thus obtained was plotted against respective mid-span deflection. Energy absorbed was then computed with numerical integration up to the point of maximum deflection (failure). For this numerical integration, DPlot software [12] was used which employs trapezoidal rule to do the integration.

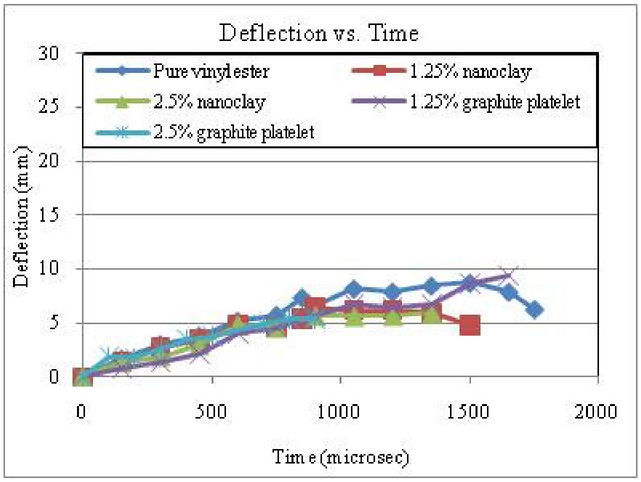

Figure 8. Mid-point deflection vs. time obtained from high speed images for vinly ester panels with and without nano reinforcement at 70 psi peak pressure

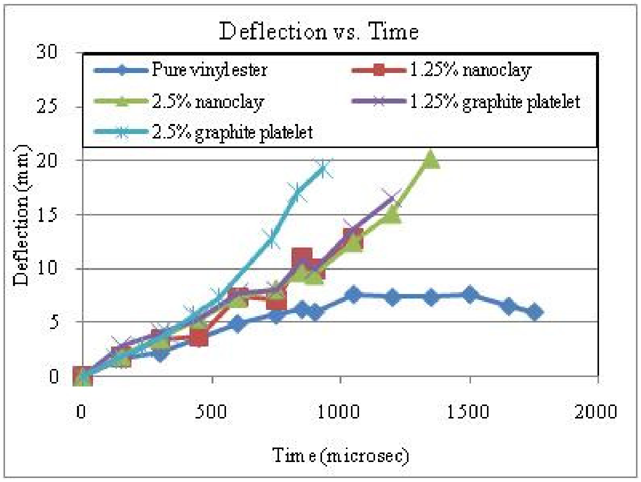

Figure 9. Mid-point deflection vs. time obtained from high speed images for vinly ester panels with and without nano reinforcement at 120 psi peak pressure

Finite Element Analysis of Shock Tube Test

Finite element modeling using ANSYS LS-DYNA of vinyl ester nanocomposite beam specimens subjected to shock loading was attempted. ANSYS LS-DYNA has the advantage of having explicit finite element program which provides faster solutions for large deformation and multiple nonlinearities problems [13].

The material to be analyzed is approximated to be randomly distributed nanoparticles in an isotropic matrix and the structure is supposed to have large deformations and complex loading through the thickness. Solid 168, a higher order 3D, 10 node tetrahedral structural solid, explicit dynamic element was used for modeling. The element is defined by ten nodes each having three degree of freedom at each node for translation motion in x, y, and z direction. No real constants need to be defined for this element as everything is defined in the material geometry.

Standard piecewise material model was used for defining the material properties. This model provides a multi-linear elastic-plastic material option that allows input of stress-strain curve at different strain rates and effective failure plastic strain can be defined for defining failure point [13]. This material model required true stress-true plastic strain curve, density, and effective failure plastic strain as input. Engineering stress-strain and failure strain was obtained from quasi-static test and was converted to true stress-true plastic strain for input in the material model [14]. It is to be noted that the quasi-static test were conducted on nanocomposites produced using brominated 510A-40 vinyl ester resin as opposed to the non-brominated Derakane 411-350 vinyl ester resin used for shock tube experiments. Density of non-brominated Derakane 411-350 vinyl ester resin nanocomposites was used in finite element modeling [14].

Model of the structure was created using appropriate key points exactly in the same way as in shock tube experimental setup. A dense meshing in the loading area and a coarse meshing in outer area was employed. A total of 51786 elements with 76596 nodes were created.

Proper restraints were then assigned to define the boundary condition to match the experimental set-up as shown in Figure 10. As the test specimen was simply supported at a span of 150 mm (6”) with an overhang of 50 mm (2”) at both ends, the respective lines in the model were restrained to move in z-direction. To avoid twisting of the specimen, node at the center of the specimen and center of the left support were restrained to move in x and y direction.

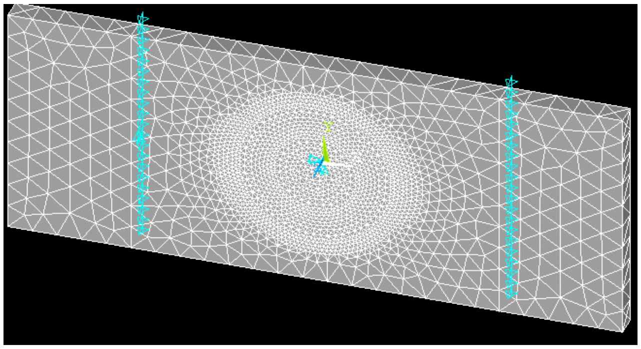

Figure 10. Finite element model of beam specimen for shock response characterization with boundary condition

Load applied in the experiments was by the shock coming out of a tubular section. This load was approximated to be equally distributed in the circular region of the same area. Due to the inherent problem with 3D Tet-Solid 168 element on applying uniformly distributed load [15], a nodal load was applied instead on all the nodes of the circular region. It was assumed that all the nodes are equidistant in the loading area. Load on the nodes on periphery of the circle (external nodes) was half in magnitude to that of load on nodes inside the circular region (internal nodes).

Solution was then obtained for transient analysis using explicit dynamics method. Time at the end of the load step was defined to be the time at which maximum deflection was observed in the experiments. Deformed view of the structure due to the applied load was captured and mid-point deflection was obtained to compare with the experimental results.

EXPERIMENTAL RESULTS

The energy absorbed by vinyl ester nanocomposites obtained from numerical integration of the load vs. mid-point deflection is tabulated in Table 1, and the trend shown in Figure 11. It is to be noted that specimens subjected to 70 psi peak pressure did not fail while all other specimens fragmented into pieces. Further, in case of pure vinyl ester the same specimen was used for both 70 psi as well as 120 psi peak pressure.

Table 1. Energy absorption for nanoclay and graphite platelet/ vinyl ester nanocomposites for peak pressure of 70 psi and 120 psi

Specimen	Energy absorption (J)	
	70 psi	120 psi
Pure vinyl ester	16.95	22.94
1.25% nanoclay/ VE	12.54	39.33
2.5% nanoclay/VE	11.34	45.50
1.25% graphite platelet/VE	19.43	45.53
2.5% graphite platelet/VE	9.58	62.81

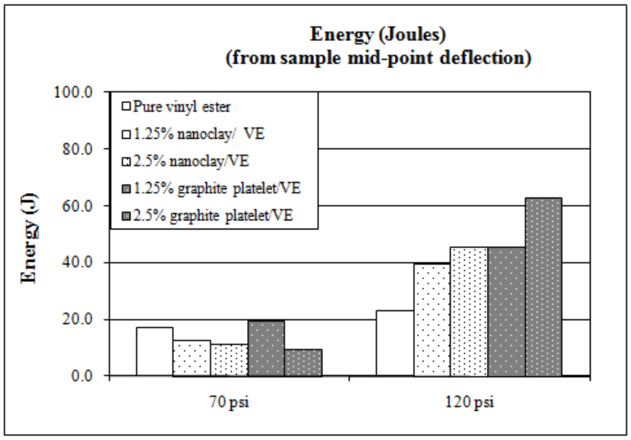

Figure 11. Energy absorption for nanoclay and graphite platelet/ vinyl ester nanocomposites for peak pressure of 70 psi and 120 psi

It was concluded that the energy absorption characteristics of vinyl ester specimens that did not fail when subjected to 70 psi peak pressure was not an appropriate measure of total energy absorption as high stiffness of material can lead to lower deflection which in turn may show lesser energy absorption. The trend of energy absorbed for the 120 psi peak pressure (where samples fragmented into pieces) is shown to be increasing with increasing reinforcement, with 2.5 wt. percent graphite platelet showing maximum improvement.

Figures 12 and 13 show the deformation of pure vinyl ester nanocomposites subjected to 70 psi and 120 psi peak pressure obtained from finite element modeling. Figures 14 and 15 show the deflection with respect to time obtained from finite element model and comparison with the experimental results.

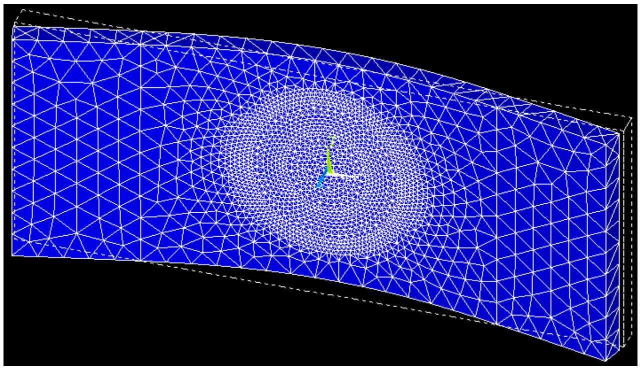

Figure 12. Deformation of pure vinyl ester subjected to 70 psi peak pressure from FEA

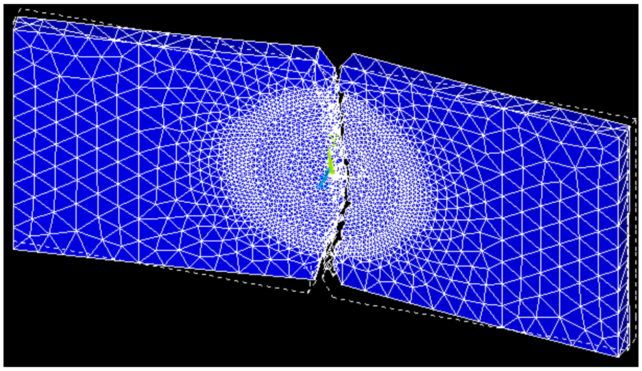

Figure 13. Deformation of pure vinyl ester subjected to 120 psi peak pressure from FEA

For 70 psi peak pressure experiments, it is observed that the FEA model of graphite platelet reinforcement showed failure occurring contrary to the experimental tests conducted and reported by University of Rhode Island [11]. The experimental deflections and those obtained from finite element model are observed to be close. Further, the post-impact samples of graphite platelet received from University of Rhode Island did show some hairline fracture.

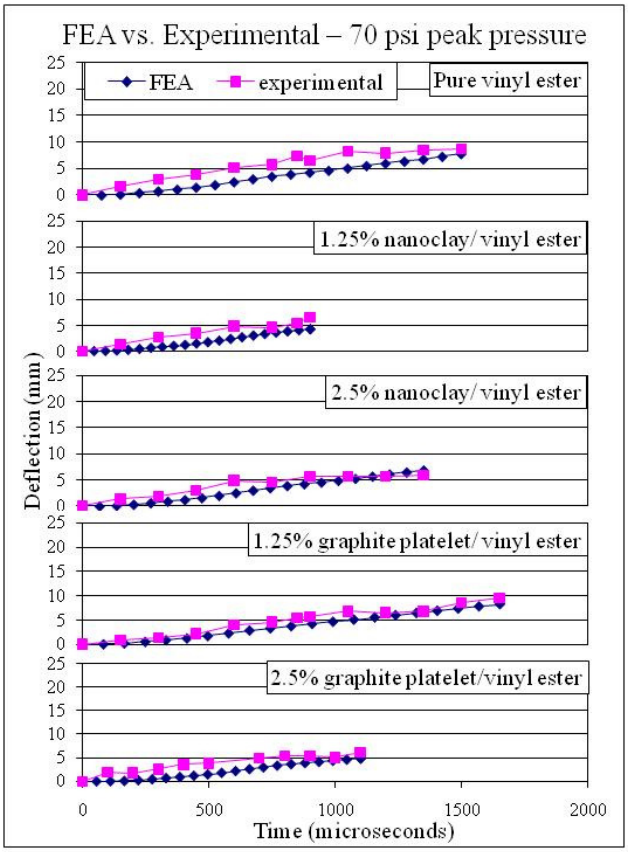

Figure 14. Deflection vs. time obtained from finite element model and shock tube experiments for nanoclay and graphite platelet/ vinyl ester subject to 70 psi peak pressure

For 120 psi peak pressure experiments, it is observed that the 2.5 wt. percent nanoclay reinforced vinyl ester does not show failure in the FEA model as opposed to the experimental tests conducted and reported by University of Rhode Island [11]. A larger variation between the experimental and finite element model deflections is observed for 2.5 wt. percent reinforcement of nanoclay and graphite platelet as shown in Figure 15. It is suspected that the pressure profile curve recorded for these cases are erroneous. It is also noted that brominated 510A-40 vinyl ester resin was used for defining the material model in finite element analysis instead of the non-brominated derakane 411-350 vinyl ester resin which was actually tested in shock tube. This might also be the reason for discrepancy as 2.5 wt. percent reinforcement of nanoclay and graphite platelet are showing inferior properties with brominated 510A-40 vinyl ester resin. Variation in deflection of pure vinyl ester is also attributed to the reuse of same sample that was used for 70 psi peak pressure testing in the subsequent 120 psi peak pressure testing.

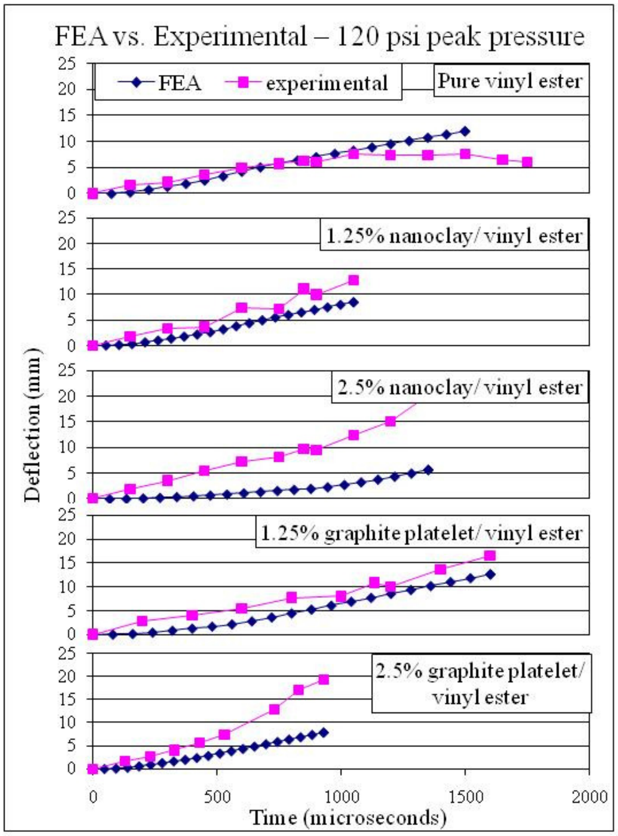

Figure 15. Deflection vs. time obtained from finite element model and shock tube experiments for nanoclay and graphite platelet/ vinyl ester subject to 120 psi peak pressure

CONCLUSION

Energy absorption under shock testing is shown to be increasing for nanoclay and graphite platelet reinforced vinyl ester nanocomposites tested at a strain rate of 1400 per second (120 psi peak pressure). Graphite platelet reinforced vinyl ester nanocomposites also showed very good improvement in material response under shock testing obtained using dynamic approach.

For most of the cases, a good agreement with experimental deflection-time obtained from shock tube tests and finite element model was observed. Discrepancies in the results are attributed to the brominated 510A-40 vinyl ester resin used to define the material model, instead of derakane 411-350 vinyl ester resin which was actually used in the specimens that were subjected to shock tube testing. Shock tube experiments on brominated 510A-40 vinyl ester resin nanocomposites are underway to resolve these discrepancies.

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