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PUNCH-SHEAR CHARACTERISTICS OF NANOCLAY AND GRAPHITE PLATELET REINFORCED VINYL ESTER PLATES, LAMINATED FACE SHEETS AND SANDWICH COMPOSITES UNDER LOW VELOCITY IMPACT

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ABSTRACT

This work describes the punch-shear response of nanoparticle reinforced vinyl ester plates, laminated face sheets and sandwich composites using Dynatup 8250 drop-weight impact test instrument according to the ASTM D3763 Standard. Tests were performed on 4”× 4” square plate specimens with fixed circular boundary condition, impacted by a hemispherical-head plunger with added mass. The impact load, displacement, energy plots and visual inspection of the post damaged specimens depicted the punch-shear characteristics of these composites.

Test results show more than 10% improvement in impact energy absorption with addition of 2.5 wt. pct. graphite platelets to pure vinyl ester. Maximum improvement in energy absorption (about 40%) was observed with Owens Corning HP ShieldStrand® glass fabric face sheets compared to the E-glass/vinyl ester. In another set of experiments with fly-ash based EcoCore® sandwiched in between E-glass/vinyl ester face sheets showed approximately 85% more energy absorption than with Tycor®, Balsa wood and PVC foam cores.

INTRODUCTION

Focus of the research is on developing stronger, safer and more cost-effective structures for the new generation naval ships; especially nanoparticle reinforced glass/carbon polymeric based composites and structural foams for blast/shock/impact mitigation. This paper describes the punch-shear response of nanoparticle reinforced vinyl ester plates, laminated face sheets and sandwich composites using Dynatup 8250 drop-weight impact test system according to ASTM D3763 Standard [1]. Low-velocity tests were performed on 4” × 4” square plate specimens with fixed circular boundary condition and impacted by a hemispherical-head plunger with added mass. The impact load, displacement, energy plots and visual inspection of the post damaged specimens depicted the failure characteristics and punch shear response of these composites [2].

MATERIAL DESCRIPTION

510A-40 brominated vinyl ester nanoparticle reinforced composite plates

Five different Derakane 510A-40 vinyl ester thermoset nanocomposites, reinforced with 1.25 and 2.5 wt. percent Cloisite 30B nanoclay and exfoliated graphite (xGnP) nanoplatelets, were manufactured at Michigan State University - Composite Materials and Structures Center.

Laminated woven fabric composite face sheets

Four different woven fiber fabric laminated composite face sheets were fabricated with Dow Derakane 510A-40 brominated vinyl ester resin by the VARTM process at the University of Alabama - Birmingham. The base specimen is a five-ply E-glass woven fabric with laminate schedule [(0/90)/(+45/-45)/(90/0)/(-45/+45)/(0/90)]. The second face sheet was prepared with same laminate configuration, but with 2.0 wt. pct. xGnP-15 exfoliated graphite platelets pre-mixed in the vinyl ester resin before fabrication. The third face sheet was made with five-layers of Owens Corning high performance HP ShieldStrand® glass fabric with similar laminate schedule and resin. The fourth face sheet was made with only three plies of FOE treated T-700 carbon fabric [(0/90)/(+45/-45)/(0/90)] laminate schedule in same matrix. Here the number of plies was reduced from five to three to keep stiffness of this carbon fabric laminate consistent with the other glass fabric face sheets.

Sandwich composites made with five-ply E-glass face sheets and light-weight cores

Six different kind of sandwich composites fabricated with 2” thick Tycor® (an engineered 3-D fiber reinforced damage tolerant core from WebCore Technologies), poly-vinyl chloride (PVC) foam, balsa-wood and three types of fire-resistant EcoCore®(fly-ash based core material mixed with chopped JM3 and OC2 glass-fibers) sandwiched in between the five-ply E-glass/vinyl ester face sheets were fabricated at University of Alabama – Birmingham. The impact test specimens were cut in size of 4”x 4” (101.6mm x 101.6mm) each using bench saw from individual fabricated panels.

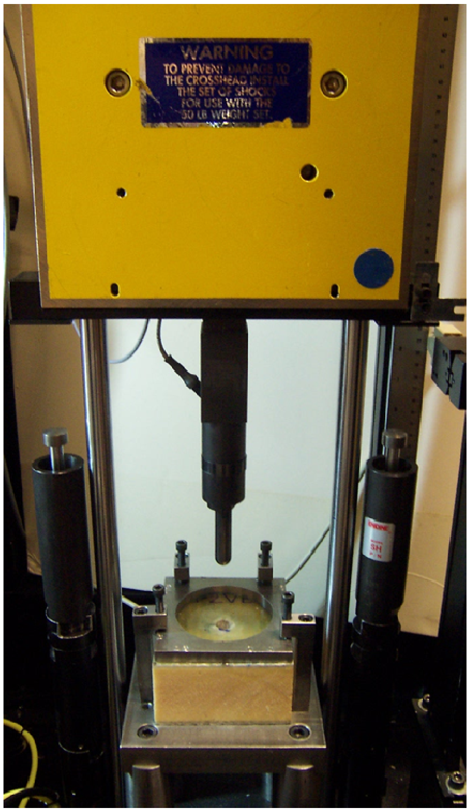


Figure 1. Low velocity impact test system

LOW-VELOCITY IMPACT TESTS

The experiments were performed using Dynatup 8250 drop weight impact test system [Figure 1], according to the ASTM D3763 Standard. Specimen clamp assembly consists of parallel rigid steel plates with a 3” (76.2 mm) diameter hole in the center of each. Sufficient clamping force was applied to prevent slippage of the specimen during impact. Plunger assembly consists of a ½” (12.70mm) diameter steel rod of 2” (50.8mm) length with a hemispherical end of the same diameter positioned perpendicular to, and centered on, the clamp hole. Dynatup Impulse^{TM} data acquisition systems are equipped with load and velocity transducers to provide data collection, analysis and reporting. Using an instrumented tup, the data acquisition hardware captures instantaneous load signals and transfers to the impulse software for further data processing. The velocity at impact is measured just prior to impact using a photoelectric-diode and flag system.

EXPERIMENTAL PROCEDURE

Three samples from each type of nanoparticle reinforced vinyl ester plates, laminated face sheets and sandwich composites were tested under low-velocity impact and the average data considered for this investigation. Impact drop weight and height were determined such that velocity slowdown is less than 20% during the impact event as well as the applied impact energy was at least three times the energy absorbed by the specimen at peak load [1]. This configuration provided about 38 J of impact energy and 3.6 m/s impact velocity for the nanoparticle reinforced vinyl ester plates and about 185 J impact energy and 4 m/s impact velocity for the laminated face sheets and sandwich composites. A steel plunger with hemispherical end (0.5” dia. × 2” long) was used for penetrating the specimens with the required impact energy and velocity.

VISUAL INSPECTION

510A-40 brominated vinyl ester nanoparticle reinforced composite plates

The visual inspection of the specimen illustrates that the radial growth of damage centering impact point is less for pure vinyl ester [Figure 2.(i)] than its nano-composites. Nanoclay reinforced composites are damaged equally on both faces [Figures 2.(ii) and 2.(iii)], whereas graphite platelet reinforced composites showed more damage on the rear than impact side [Figures 2.(iv) and 2.(v)]. In some cases of graphite platelet reinforced nanocomposites, fracture propagates very less on impact side. Penetration of plunger through the specimen required some more load due to the shearing friction between plunger wall and the inner surface of the punch through hole, which resulted to additional energy absorption.

Laminated woven fabric composite face sheets

Visual inspection of these specimens confirms that the radial growth of delamination was less for E-glass/vinyl ester face sheet [Figure 3.(i.b)] than HP- glass/vinyl ester face sheet [Figure 3.(iii.b)] and occurred at reverse side for both sheets. Due to opacity of E-glass/xGnP-vinyl ester and T-700 Carbon/vinyl ester face sheets, the occurrence of delamination was not visible [Figures 3.(ii) and 3.(iv)]. In case of T-700 Carbon/vinyl ester face sheets, carbon fiber strands were peeled off partially from back side [Figure 3(iv.b)]. The shredded fibers due to plunger penetration were clogged in the puncture hole.

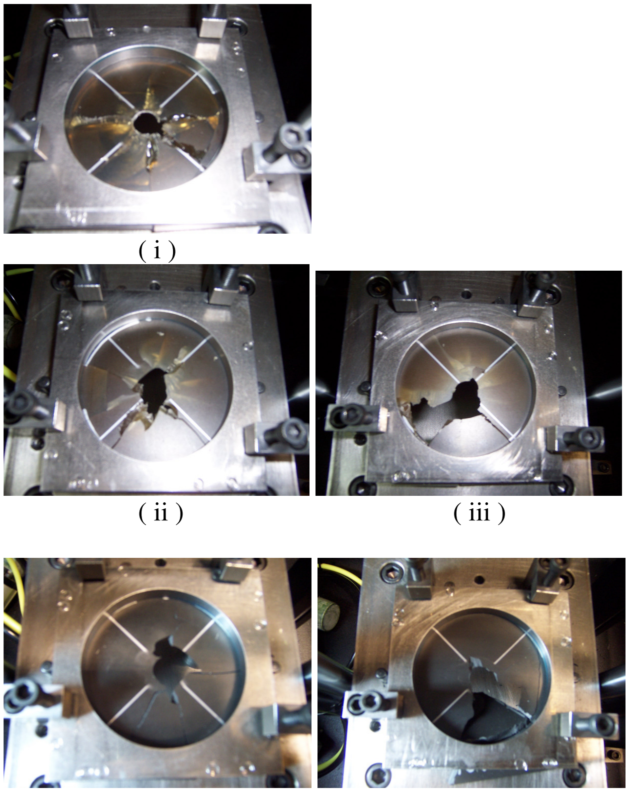

(i)
(ii) (iii)
(iv) (v)

Figure 2. 510A-40 brominated vinyl ester nanoparticle reinforced composite plates after impact
(i) Pure vinyl ester, (ii) 1.25 wt.pct. Nanoclay, (iii) 2.5 wt.pct. Nanoclay, (iv) 1.25 wt.pct. Graphite, (v) 2.5 wt.pct. Graphite.

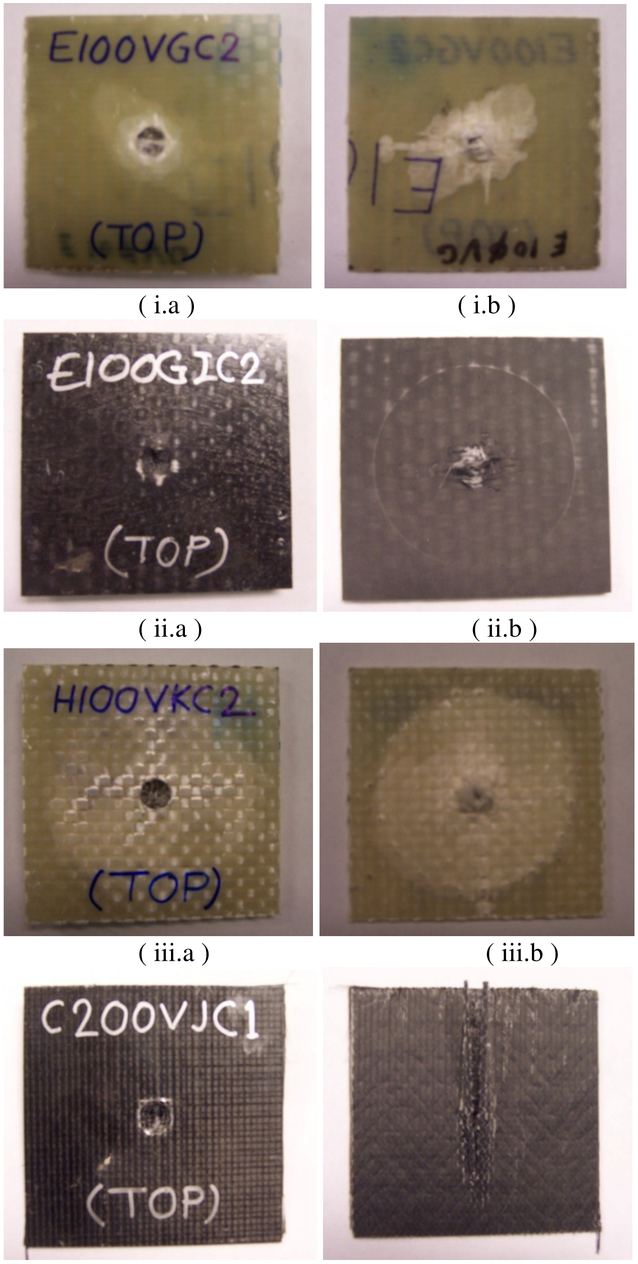
Sandwich composites made with five-ply E-glass face sheets and light-weight cores

The visual inspection of the specimen depicts that the radial growth of delamination is least in tough core, whereas more in case of softer cores. E-glass/Tycor sandwich [Figures 4.(i.a) to 4.(i.c)] shows three different modes of failure due to impact on web-intersection, web-line and direct foam zones respectively. It can be observed that the softest foam-zone showed maximum delamination whereas the web-intersection allowed least delamination. Fly-ash based EcoCore is the toughest and has highest density among all. It showed less delamination as well as less depth of penetration [Figures 4.(iv) to 4.(vi)]. PVC and Balsa cores showed average performance with respect to delamination and puncture [Figures 4.(ii) and 4.(iii)].

Cross section microscopy of laminated face sheets and sandwich composites is ongoing for determining the energy absorption mechanisms.

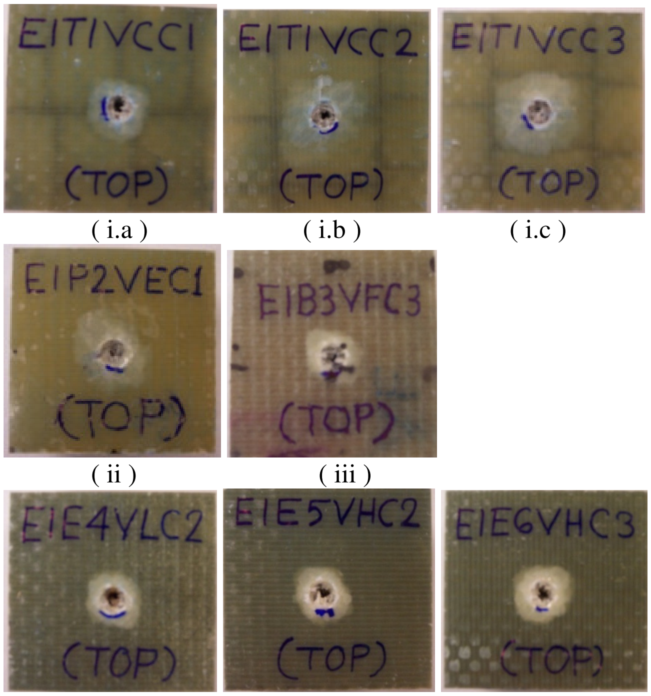
RESULTS AND DISCUSSION

The Dynatup impulse data acquisition software provided instantaneous impact point displacement and applied load data. The load versus deflection data were plotted up to failure point for each tested sample. Corresponding cumulative energy absorption data were generated using Trapezoidal numerical integration method (Equation 1). In case of laminated woven fabric composite face sheets, absorbed energy was normalized-to-thickness (NTT) to eliminate the effects of specimen thickness variations and plotted accordingly.



(i.a) (i.b)
(ii.a) (ii.b)
(iii.a) (iii.b)
(iv.a) (iv.b)

Figure 3. Laminated woven fabric composite face sheets after impact [(a) impact side and (b) reverse side] (i) E-glass, (ii) E-glass/xGnP-15, (iii) HP-glass, (iv) T-700 Carbon.



(i.a) (i.b) (i.c)

(ii) (iii)

(iv) (v) (vi)

Figure 4. Sandwich composites made with five-ply E-glass face sheets and light-weight cores after impact (i) E-glass/Tycor [impacted at (a) web-intersection, (b) web-line and (c) foam-region], (ii) E-glass/PVC, (iii) E-glass/Balsa, (iv) E-glass/EcoCore 0.0wt.pct., (v) E-glass/EcoCore 4.5wt.pct. JM3 and (vi) E-glass/EcoCore 4.5wt.pct. OC2

$$E(1) = E(-1) + 0.5 \times [L(1) + L(-1)] \times [D(1) - D(-1)] \quad \ldots (1)$$

Where,
E(1) = Energy absorbed up to the current displacement data point,
E(-1) = Energy absorbed up to the immediate former displacement data point,
L(1) = Required load for the current displacement data point,
L(-1) = Required load for the immediate former displacement data point,
D(1) = Current displacement data point, and
D(-1) = Immediate former displacement data point

Figures 6, 11, 16 show the superimposed load response and Figures 7, 12, 17 show energy response with respect to tup deflection. Load versus deflection plot shows two distinct phases of failure propagation for complete puncture [2]. These two phases are damage initiation and puncture propagation.

Damage initiation phase

The first phase, named as damage initiation phase, is observed from the moment of impact to the point of peak load, where the damage initiates with almost uniform deflection with some initial fracture peaks [Figure 5].

Pure vinyl ester and nanoclay reinforced vinyl ester show stiff but linear load-deflection response at this stage. A little change of slope explains fracture initiations and plastic flow [Figure 6]. Graphite platelet reinforced vinyl ester has distinctive multi-peak load fluctuations at this phase. This response showed large fracture generation at the rear side of the specimen. Energy absorption is carried out mainly at this phase [Figure 8].

All laminated face sheets showed a smooth elastic deformation with close stiffness [Figure 11]. E-glass/vinyl ester face sheet showed marginally higher stiffness than that of the other configurations. HP-glass/vinyl ester face sheet sustained maximum peak load among all. E-glass/vinyl ester and T-700 Carbon/vinyl ester face sheets took more or less same amount of load before puncture. E-glass/xGnP-vinyl ester composite took least load in this phase. However, this face sheet fairly deflected during the damage initiation phase and hence absorbed maximum energy up to peak load same as HP-glass/vinyl ester face sheet; whereas T-700 Carbon/vinyl ester absorbed least energy [Figure 13].

The sandwich composites show five clear peaks indicating failure of each fiber lamina of the impact side face sheets up to peak load [Figure 16]. PVC sandwich fails at minimum peak load. All other sandwiches took approximately same amount of load at this phase. Energy absorption remained less for all sandwiches [Figure 18].

Puncture propagation phase

At the point of peak load, puncture is initiated and accomplished by rapid load-reduction. This phase can be identified as puncture propagation phase [Figure 5].

Vinyl ester nanocomposite plates showed sharp and smooth load-reduction. Comparatively harder and brittle graphite platelet reinforced nanocomposites absorbed less energy in this phase. Puncture propagation phase absorbed less energy due to short duration and material fragmentation occurred severely with some hinging effects [Figure 6 and 9].

Some prominent hinging effects of attached fiber fragments with the surface of the plunger are observed in case of all laminated face sheets. Only E-glass/xGnP vinyl ester composite showed comparatively smooth puncture propagation [Figure 11]. HP-glass/vinyl ester composite face sheet provided lot of resistance after peak load and continued to cause delaminations. Hence the load-deflection plot shows a distinctive wavy plateau region at peak load. HP-glass/vinyl ester face sheet absorbed 60% more energy than E-glass/vinyl ester face sheet during the puncture propagation phase. E-glass/xGnP-vinyl ester and

T-700 Carbon/vinyl ester showed comparative less energy absorption [Figure 14].

In case of sandwich composites load reduction is very less and slow. Plunger could not penetrate the 2.25” thick sandwich specimen deeper than 0.6” (15 mm). Lot of hinges [Figure 16] depicts uneven resistance due to ripped fiber and core materials which influenced significant energy absorption after peak load. EcoCore showed the best energy absorption in this phase [Figure 19].

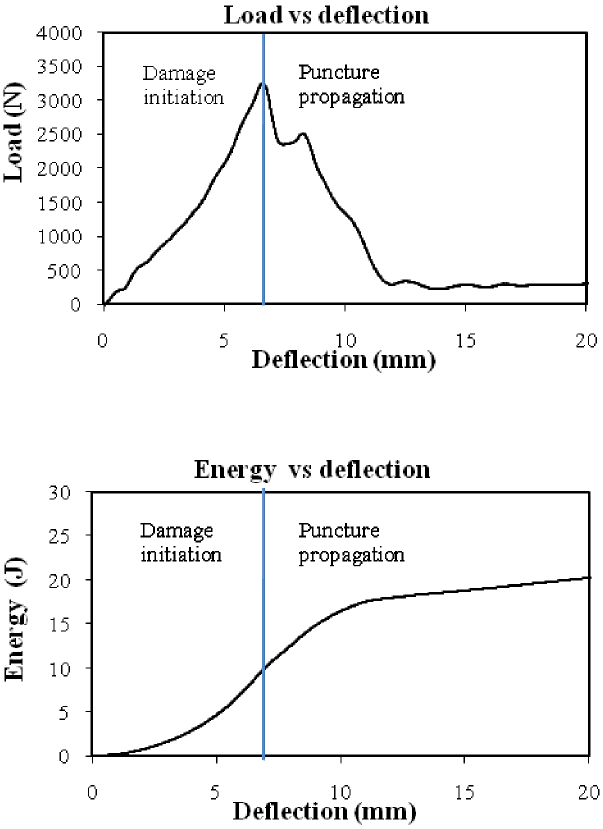


Figure 5. Punch-shear failure phases in puncture-deflection frame [Ref. 2]

Total Energy absorption

The total energy absorption was calculated as the sum of the energy absorbed for damage initiation and puncture propagation phases up to complete failure of the specimen.

Table 1 and bar charts [Figures 8-10, 13-15 and 18-20] of energy absorption at damage initiation and puncture propagation phases as well as the total energy absorption are provided for comparative investigation of the punch shear response of all types of vinyl ester nanocomposites, laminated face sheets and sandwich composites under low-velocity impact.

Table 1. Energy absorption of composite samples

Impact energy = 38 J			
Impact velocity = 3.6 m/s			
510A-40 brominated vinyl ester nanoparticle reinforced composite plates	**Energy absorption (J)**		
	Damage Initiation	**Puncture propagation**	**Total**
Pure vinyl ester	9.05	6.22	15.27
1.25 wt.pct. Nanoclay	6.63	7.09	13.72
2.5 wt.pct. Nanoclay	5.65	7.78	13.42
1.25 wt.pct. Graphite	11.56	2.88	14.43
2.5 wt.pct. Graphite	13.65	3.26	16.90
Impact energy = 185 J			
Impact velocity = 4 m/s			
Laminated woven fabric composite face sheets	**Energy absorption (NTT) (J)**		
	Damage Initiation	**Puncture propagation**	**Total**
E-glass	9.14	9.98	19.12
E-glass/xGnP-15	12.81	8.35	21.16
HP-glass	12.13	16.00	28.13
T-700 Carbon	5.45	7.53	12.98
Impact energy = 185 J			
Impact velocity = 4 m/s			
Sandwich composites made with five-ply E-glass face sheets and light-weight cores	**Energy absorption (J)**		
	Damage Initiation	**Puncture propagation**	**Total**
E-glass/ Tycor	32.70	54.30	87.00
E-glass/ PVC	29.22	52.28	81.50
E-glass/ Balsa	24.61	63.87	88.48
E-glass/EcoCore 0 wt.pct.	47.80	113.00	160.80
E-glass/EcoCore 4.5 wt.pct. JM3	34.65	121.10	155.75
E-glass/EcoCore 4.5 wt.pct. OC2	23.89	130.40	154.29

Nanoparticle reinforced vinyl ester plates

The first set of experiments on nanoparticle reinforced vinyl ester plates showed more than 10% improvement in impact energy absorption with the addition of 2.5 wt. pct. graphite platelets to pure vinyl ester. However, the nanoclay and 1.25 wt. pct. graphite platelet reinforcements showed a detrimental effect [Figure 10].

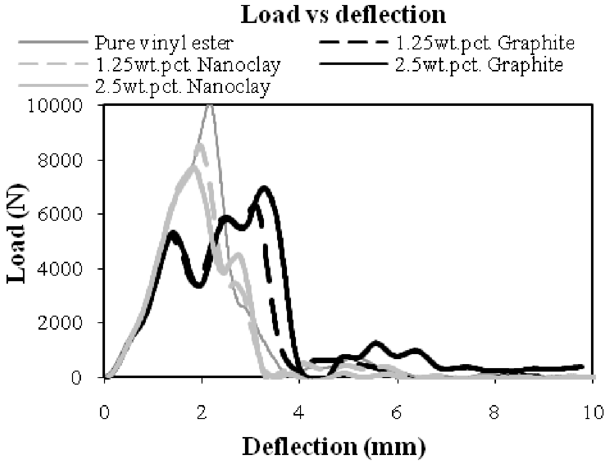


Figure 6. Load-deflection response of vinyl ester nanocomposites

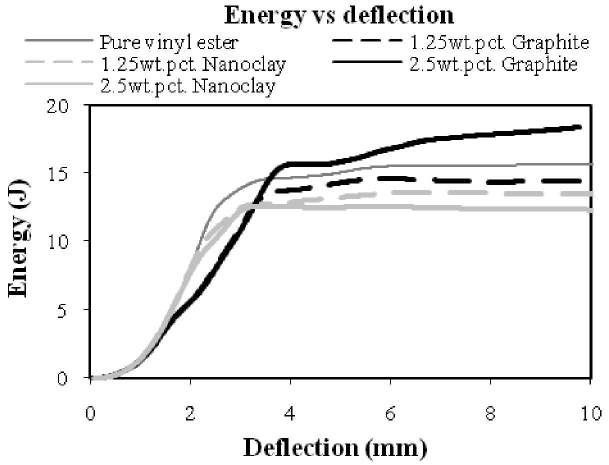


Figure 7. Energy-deflection response of vinyl ester nanocomposites

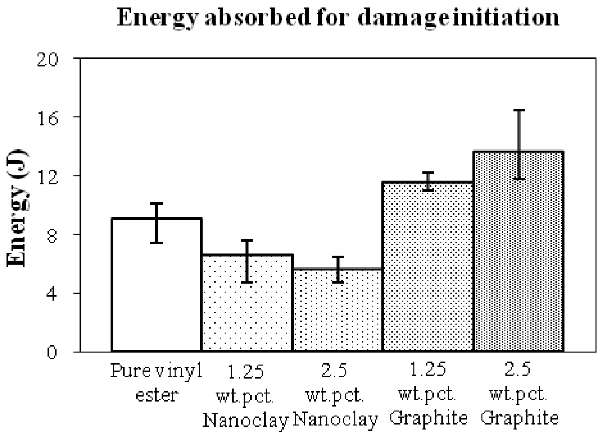


Figure 8. Energy absorbed for damage initiation (up to max. load) of vinyl ester nanocompsites

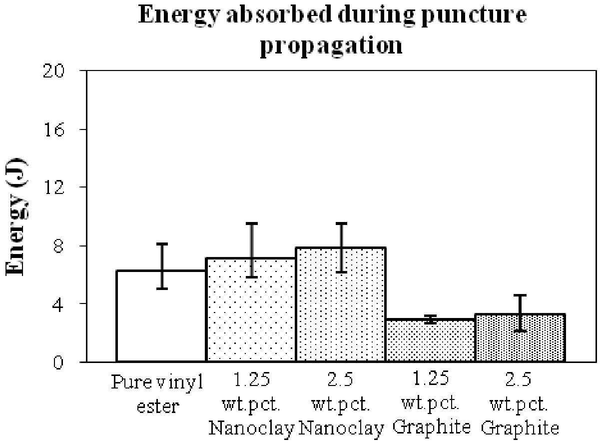


Figure 9. Energy absorbed during puncture propagation (from max. load to zero load) of vinyl ester nanocompsites

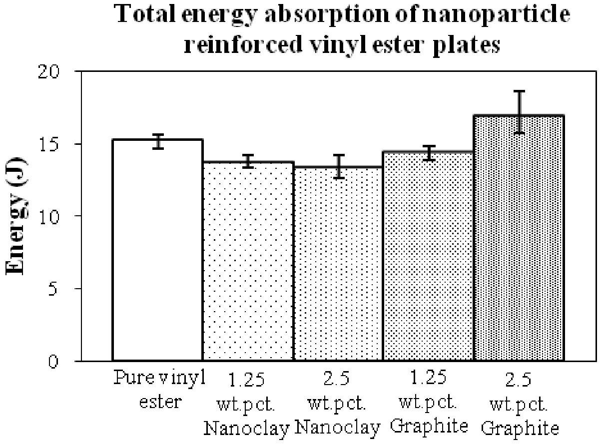


Figure 10. Total absorbed energy during punch-shear test of vinyl ester nanocompsites

Laminated woven fabric composite face sheet

The second set of experiments on laminated composite face sheets showed thickness dependent punch-shear response. In this case the absorbed energy was normalized-to-thickness (NTT) to eliminate the effects of specimen thickness variations. Addition of graphite platelets in vinyl ester matrix showed approx. 10% better energy absorption than reference E-glass face sheet; whereas the FOE treated T-700 carbon fabric displayed lowest energy absorption. Maximum improvement (about 40%) in energy absorption was observed with Owens Corning HP ShieldStrand® glass fabric face sheets compared to the E-glass/vinyl ester [Figure 15].

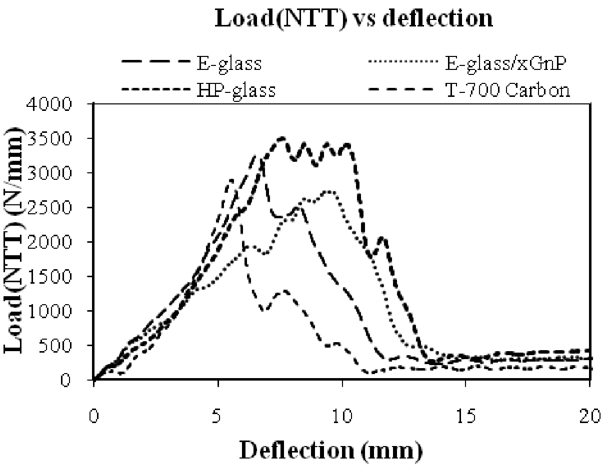


Figure 11. Load(NTT)-deflection response of laminated face sheets

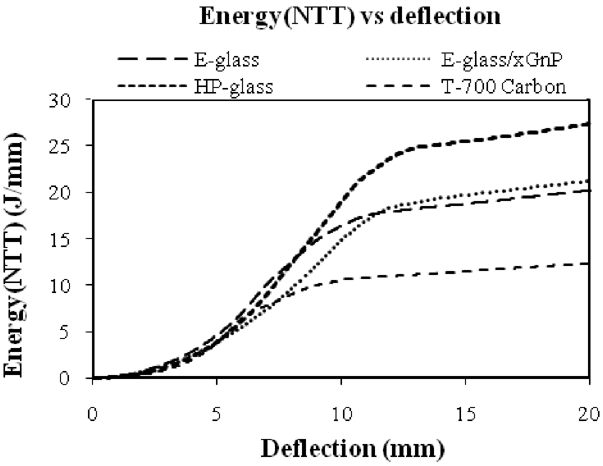


Figure 12. Energy(NTT)-deflection response of laminated face sheets

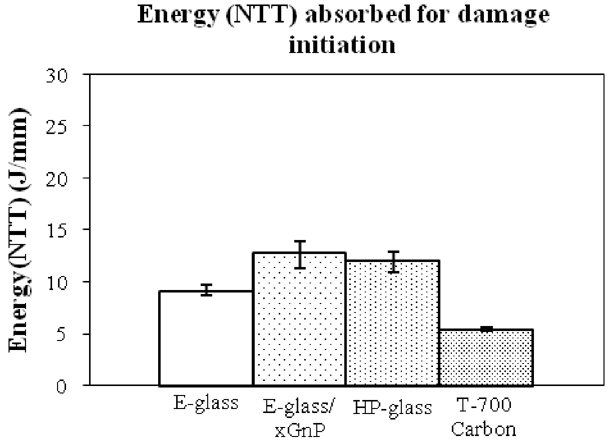


Figure 13. Energy (NTT) absorbed for damage initiation (up to max. load) of laminated face sheets

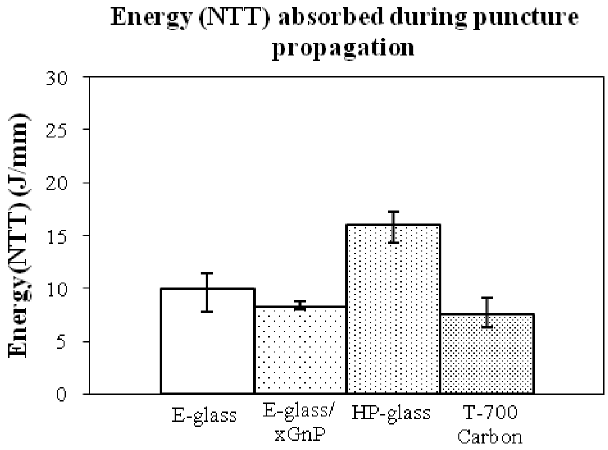


Figure 14. Energy (NTT) absorbed during puncture propagation (from max. load up to 20 mm deflection) of laminated face sheets

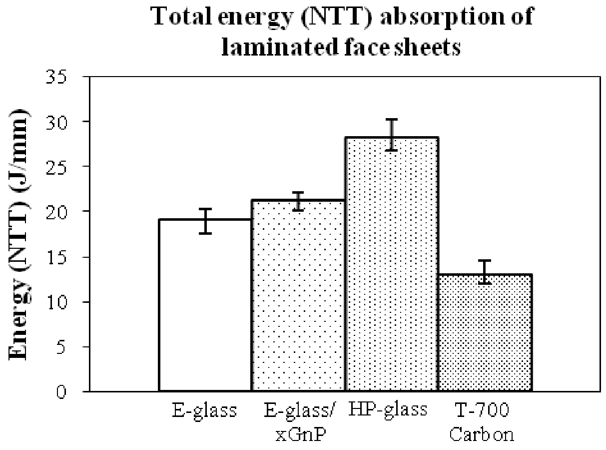


Figure 15. Total energy (NTT) absorbed for punch-shear test of laminated face sheets

Sandwich composites made with five-ply E-glass face sheets and light-weight cores

The third set of low-velocity punch-shear tests showed that PVC and Balsa sandwiches absorbed more or less same energy. The Tycor® sandwich composite has glass fiber webs embedded in the foam core. The punch-shear energy absorption at the intersection of the webs was observed to be double of that at foam-region. The response at web line was an average of that at other two locations. Spatial non-uniformity of the core resulted in larger data scatter, with the average response of Tycor® sandwich composite similar to that of PVC foam and balsa wood sandwich composites. EcoCore® sandwich composites absorbed approximately 85% more energy than Tycor, PVC and Balsa sandwiches. The higher density of EcoCore® core provided significant resistance to plunger penetration during impact which resulted in higher energy absorption than other sandwich composites made with light-weight and softer core [Figure 20].

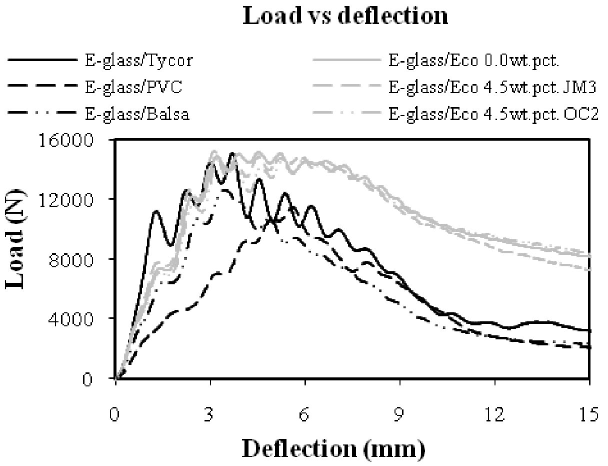


Figure 16. Load-deflection response of sandwich composites

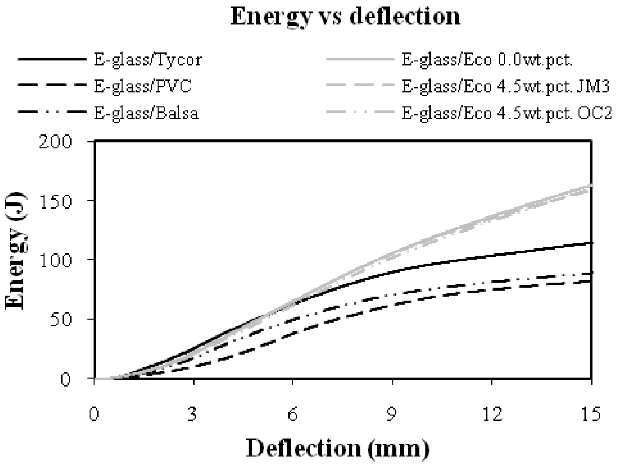


Figure 17. Energy-deflection response of sandwich composites

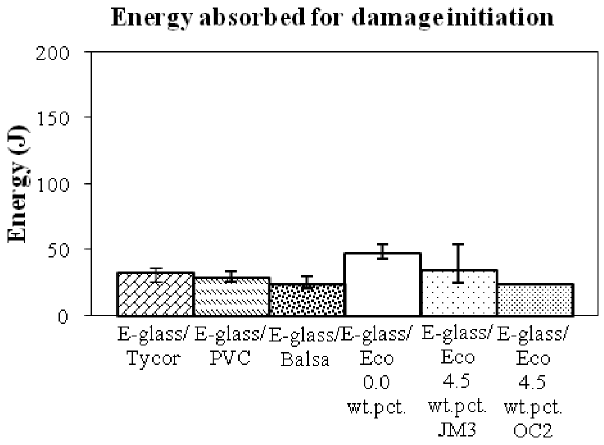


Figure 18. Energy absorbed for damage initiation (up to max. load) of sandwich composites

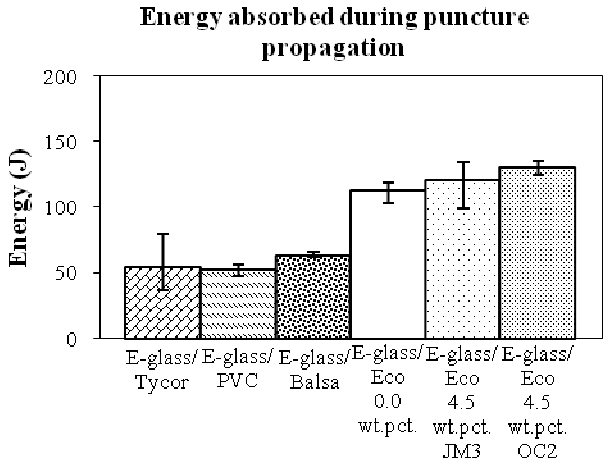


Figure 19. Energy absorbed during puncture propagation (from max. load up to 15 mm deflection) of sandwich composites

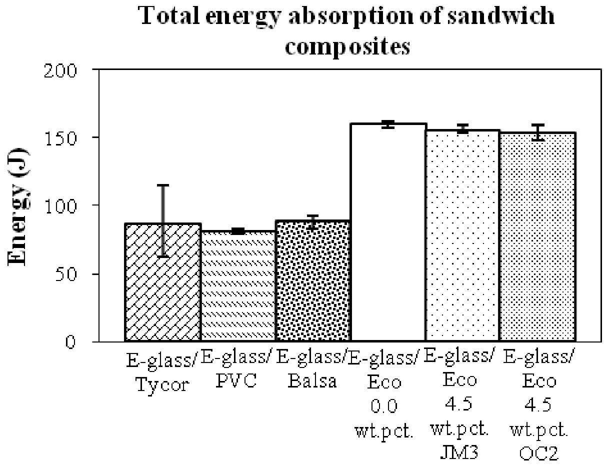


Figure 20. Total energy absorbed during punch-shear test of sandwich composites

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