Blast and Impact Resistant Composite Structures for Navy Ships

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OBJECTIVE AND SCOPE OF RESEARCH

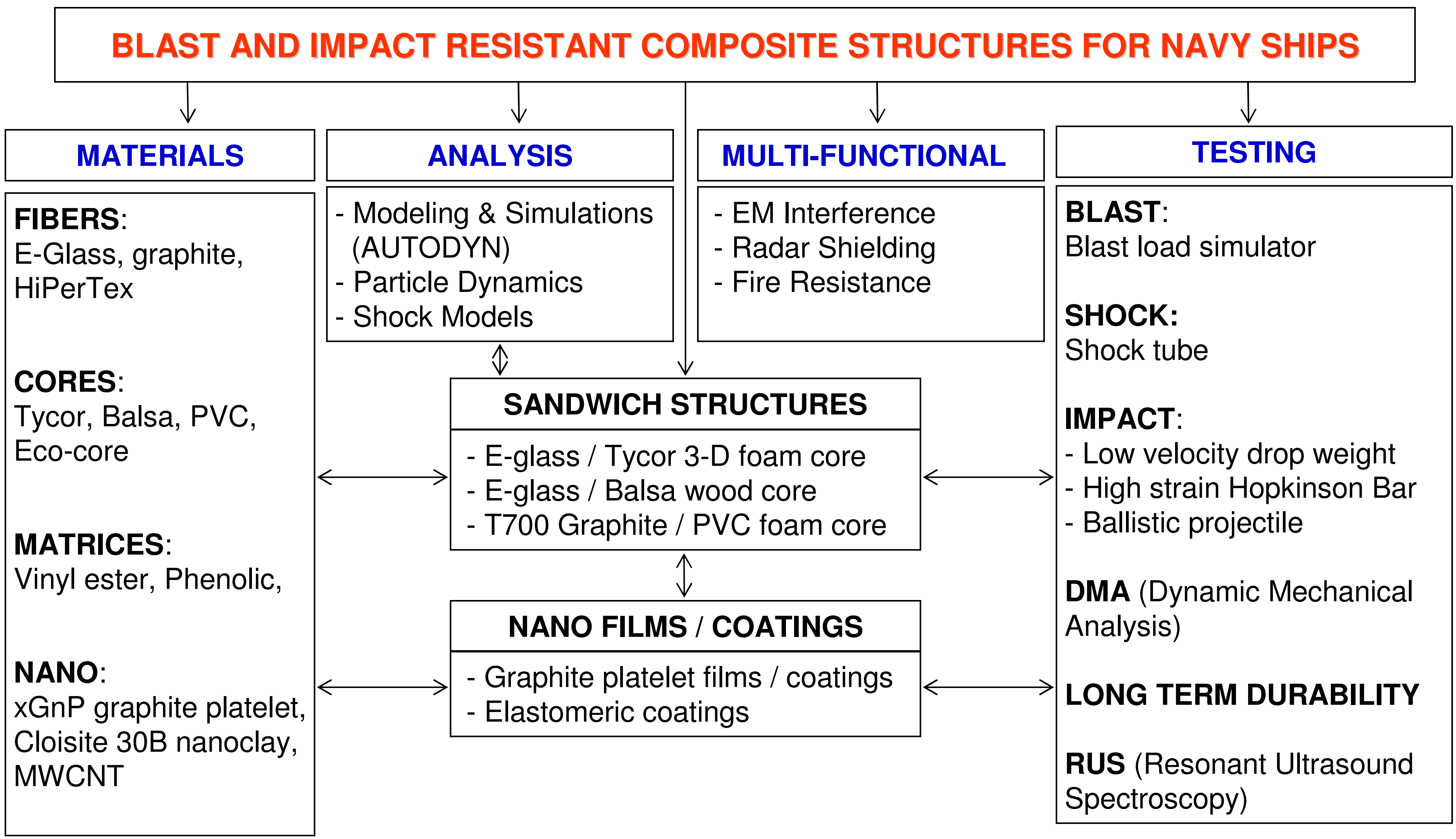
- Light weight, fast, stealthy ships are required for the US Navy littoral operations. The currently approved series of ships, the DD(X), has stringent requirements for reduced topside weight and fire/smoke toxicity.
- Need for reducing life cycle costs, and the ability to incorporate multi-functionality, including blast/shock/impact resistant features, lead towards the use of affordable composite materials and sandwich structures.

- Our research scope includes: low-cost fire-resistant exfoliated graphite nano platelet reinforced glass/carbon polymeric based composites with fly ash and 3-D fiber reinforced foams; investigating their response to low-velocity impact, ballistic, shock and blast loads; dynamic mechanical analysis for modulus, damping, creep and stress relaxation; developing constitutive models and high-performance scalable computing based modeling and simulations; accelerated testing for long-term durability; and the radar-absorbing and EM-shielding characteristics for improved stealth/safety.

RESEARCH PARTNERS

- The University of Mississippi (UM), Michigan State University (MSU), and University of New Orleans (UNO), supported by the US Army Corps Engineer Research and Development Center (ERDC) are utilizing their research strengths in modeling, analysis, fabrication and testing of affordable blast/shock/impact resistant nanoparticle reinforced composite structures for the new generation navy ships.
- University of Alabama-Birmingham (UAB) fabricated the VARTM sandwich composite panels and performed ballistic tests.
- North Carolina A&T State University (NC AT) provided their patented low-cost fire resistant fly ash based Eco-core foams.

- Northrop Grumman Ship Systems (NGSS), Gulfport, MS advised and facilitated UM on these research efforts.
- Webcore Technologies, Miamisburg, OH provided their patented TYCOR® foam cores for fabricating the blast / shock / impact resistant sandwich panels.


BLAST AND IMPACT RESISTANT COMPOSITE STRUCTURES FOR NAVY SHIPS
MATERIALS
ANALYSIS
MULTI-FUNCTIONAL
TESTING
FIBERS: E-Glass, graphite, HiPerTex
CORES: Tycor, Balsa, PVC, Eco-core
MATRICES: Vinyl ester, Phenolic,
NANO: xGnP graphite platelet, Cloisite 30B nanoclay, MWCNT
- Modeling & Simulations (AUTODYN)
- Particle Dynamics
- Shock Models
- EM Interference
- Radar Shielding
- Fire Resistance
SANDWICH STRUCTURES
- E-glass / Tycor 3-D foam core
- E-glass / Balsa wood core
- T700 Graphite / PVC foam core
NANO FILMS / COATINGS
- Graphite platelet films / coatings
- Elastomeric coatings
BLAST: Blast load simulator
SHOCK: Shock tube
IMPACT:
- Low velocity drop weight
- High strain Hopkinson Bar
- Ballistic projectile
DMA (Dynamic Mechanical Analysis)
LONG TERM DURABILITY
RUS (Resonant Ultrasound Spectroscopy)

SANDWICH COMPOSITES

- Sandwich composites with balsa and foam cores are presently being featured in a number of navy applications such as surface ship deck structures, radar masts and boat hulls. In the present work, some new and emerging cores have been explored in sandwich construction. Different core types that have been considered include:

  - Balsa wood which is a traditional core material being used in present generation ship structures. Balsa is a natural material, and is prone to local variation in properties due to cell size and cell thickness variations;

  - Polyvinyl chloride (PVC) foam core which is being used in present generation ship structures for radar mast enclosures and boat hulls;

  - Tycor (TYCOR® from Webcore Technologies), an engineered three-dimensional fiber reinforced damage tolerant core for sandwich structures, has the potential to provide improved blast and ballistic resistance. In this core, glass fiber is reinforced through the thickness of closed cell foam sheets to produce a web and truss structure;

  - Eco-core is an emerging fire resistant sandwich core. Fire damage in ship structures is of significant concern. The burn-through resistance and heat insulation characteristics of Eco-core makes it an attractive fire resistant core.

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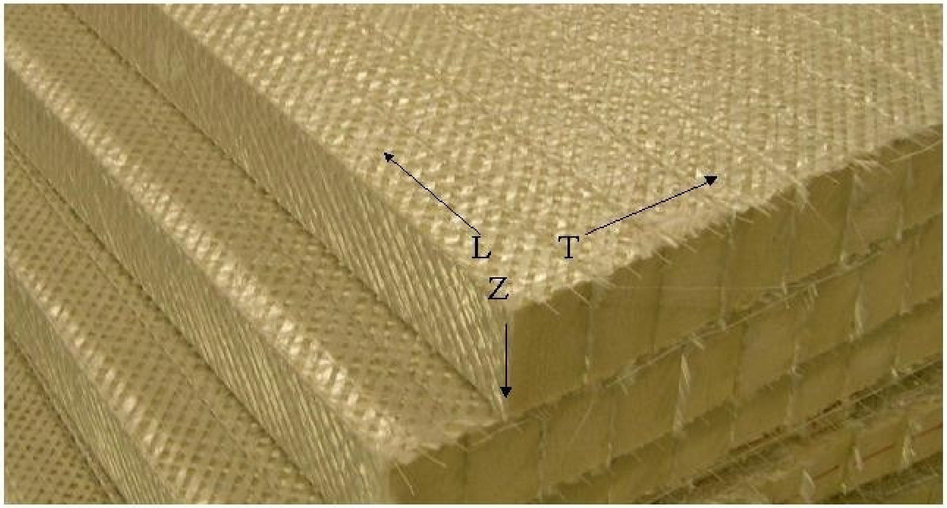
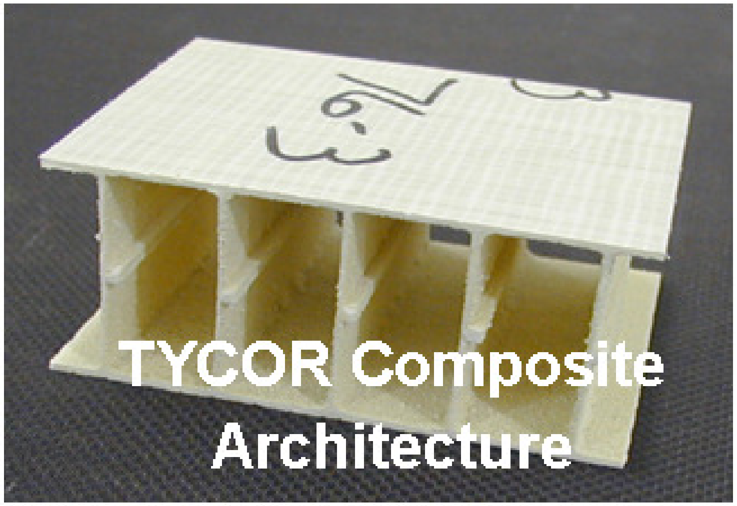


Observing the core, notice the construction. Core is made up of "sticks" bound together by a surface mesh. The length of the "sticks" is the longitudinal, or "L" direction. The through thickness is the "Z" direction. Across, or perpendicular to the "L" direction is the "T", or transverse direction.



TYCOR® 3-D STITCHED FOAM

WEBCORE TECHNOLOGIES

ECO-CORE FOAM

- Manufacturing process was scaled-up to fabricate 2 inch thick fly ash based Eco-core panels, and the processability of different chopped / milled fibers from various vendors was evaluated.
- Based on this study 4.5 wt. % of JM3 (Johns Maniville) and OC2 (Owens Corning) were chosen as reinforcement for the baseline Eco-core.
- Table lists the average compression, tension, shear, flexure and fracture properties with standard deviation based on five tested samples.

Mechanical Properties of Eco-cores

Property	Baseline	Eco-Core - JM3 4.5 wt.%	Eco-Core - OC2 4.5 wt.%
Density, g/cc	0.53 (0.02*)	0.52 (0.02)	0.52 (0.01)
Compression			
Strength, F_c, psi	3,169 (193)	2,177 (159)	2,544 (320)
Modulus, E_c, msi	0.17 (0.02)	0.16 (0.01)	0.12 (0.02)
Tension			
Strength, F_t, psi	756 (94)	881 (48)	1,152 (211)
Modulus, E_t, msi	0.38 (0.01)	0.37 (0.02)	0.40 (0.04)
Shear			
Strength, F_s, psi	740 (59)	777 (56)	678 (116)
Flexural			
Strength, F_b, psi	1,665 (129)	1,145 (191)	1,433 (136)
Modulus, E_b, msi	0.42 (0.02)	0.35 (0.03)	0.39 (0.02)
Fracture toughness, K_{Ic}, psi-in$^{1/2}$	291 (36)	419 (92)	292.5 (8)
*Standard deviation	*Note: Based on 1/2" thick panel test*		

SANDWICH COMPOSITES

- During Year-1, research focus was to design, fabricate, and test various nanoparticle reinforced and advanced composite panel configurations. E-glass/vinyl ester sandwich composite panels were designed and fabricated by the VARTM process as per Northrop Grumman Ship Building design specifications.

- The 4' x 8' x 2.32" thick sandwich panels are made up of 0.16" thick E-glass (90/0, 45/-45, 90/0, 45/-45, 90/0) face skins with Dow 510A-40 brominated vinyl ester resin and 2" thick Tycor, PVC foam and balsa cores.

- Specimens from these panels were subjected to blast, shock, impact and ballistic testing.

- From these tests, the baseline fundamental blast/shock/impact response characteristics of different material configurations were obtained.

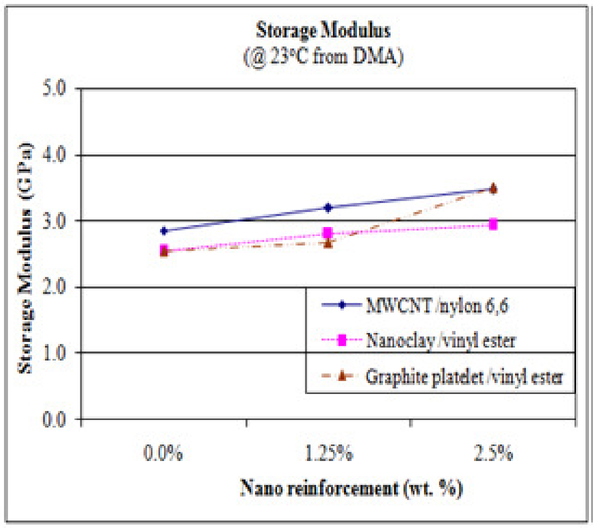
- Microstructural and computational analysis of the baseline data will shed more light on the nonlinear deformation mechanisms, damage, and failure processes at different scales.

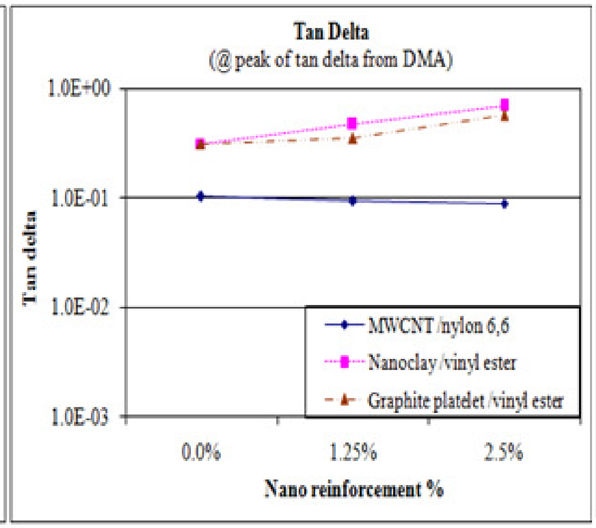
NANOREINFORCED COMPOSITES

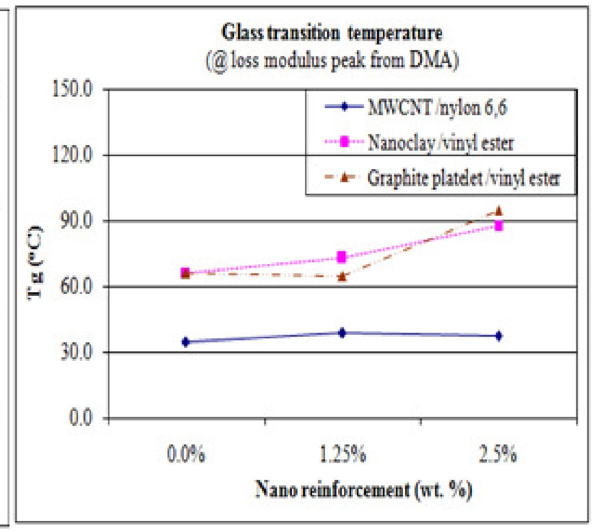
- Goal is to develop a fundamental understanding of the interaction of graphite nanoplatelets with macro reinforcing fibers and polymer matrices, and how these interactions affect the mechanical properties and durability (fire, blast and environmental) of nanoparticle modified polymer composites.
- Nanoparticles that have shown beneficial property improvement in the first year of this study are the exfoliated graphite.
- Both E-glass fibers and carbon fibers will be sized with exfoliated graphite nanoplatelets for compatibility with matrix systems in tow and woven mat form.
- 1 mil thick films containing orientated graphite nanoplatelets are being prepared for laminating into composite panels through compression molding to investigate fracture and energy absorption mechanisms and fire protection capability.
- The same material with suitable modifications will also be inserted between lamina in unidirectional composite panels to investigate their role as a composite toughening agent.

DYNAMIC MECHANICAL ANALYSIS

- *TA Instruments* Model Q800 DMA was used for characterizing the dynamic modulus, loss factor, Tg , creep and stress relaxation properties of nylon 6,6, graphite platelet and nanoclay reinforced composites.



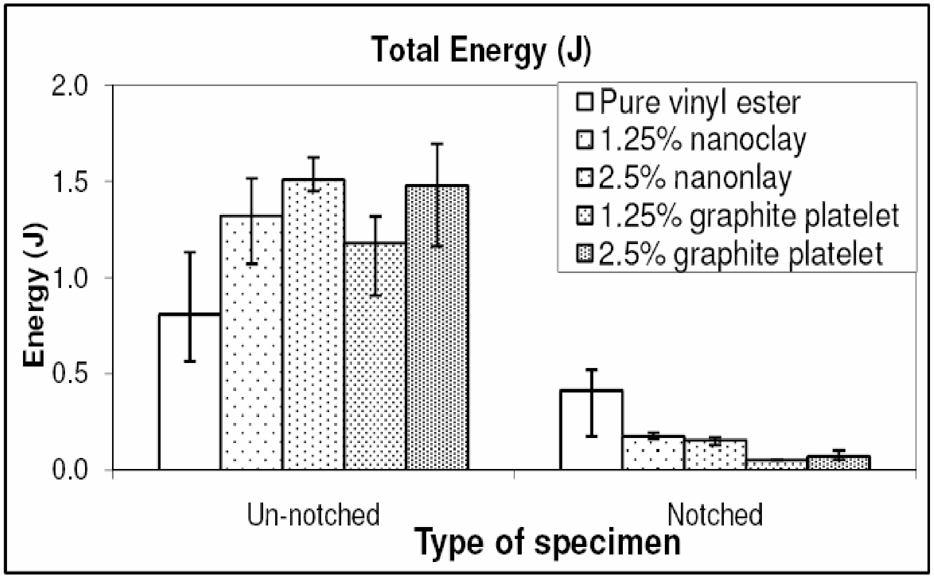




- Storage modulus of pure nylon 6,6 is greater than that of pure vinyl ester, where as the glass transition temperature and loss factor are higher for pure vinyl ester.
- Storage modulus increased with increasing reinforcement for all these nanocomposites.
- Storage modulus and glass transition temperature of 2.5 wt. percent graphite platelet reinforced vinyl ester is more than that of nanoclay reinforced vinyl ester, where as loss factor is higher for the 2.5 wt. percent nanoclay reinforced vinyl ester.

LOW-VELOCITY IMPACT RESISTANCE

- DYNATUP Model 8250 instrumented impact test system was used for evaluating the low-velocity impact resistance of graphite platelet and nanoclay reinforced composites as per ASTM D-6110-06: Standard Test method for Determining the Charpy Impact Resistance of Notched Specimens of Plastics.



- For un-notched specimens, the energy absorption of pure vinyl ester almost doubled when reinforced with 2.5 wt. percent Cloisite 30B nanoclay and exfoliated graphite nano platelets.
- However, notched specimens showed about 50% decrease in energy absorption for the 2.5 wt. percent nanoclay and a 75% decrease with 2.5 wt. percent graphite platelet reinforcements, indicating notch sensitivity.

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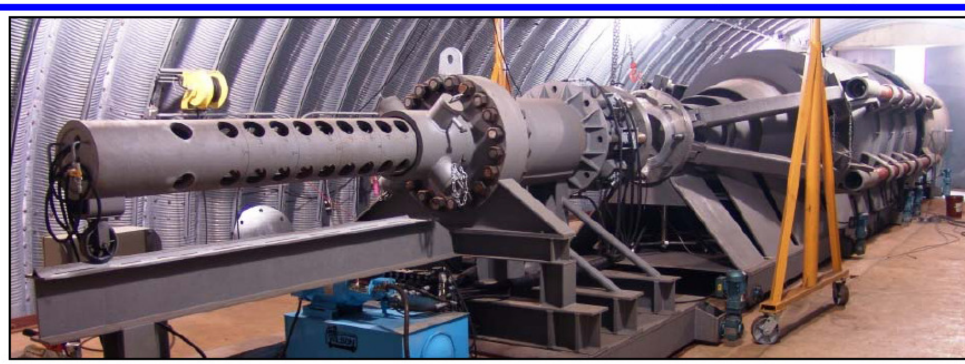
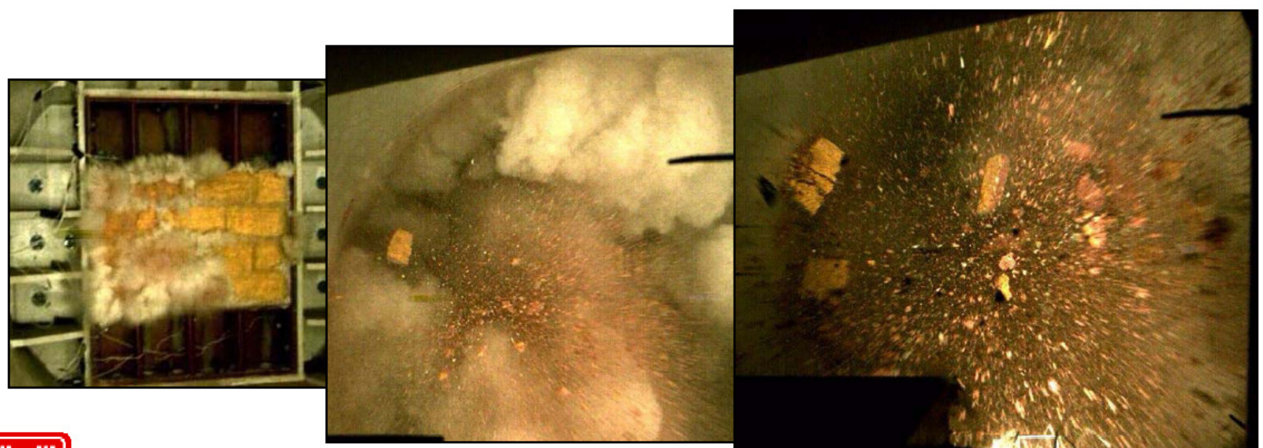
BLAST RESISTANCE OF SANDWICH COMPOSITES

- Trial blast tests, simulating an approximate threat level of about 27,000 lbs TNT at 184 feet, were conducted at the ERDC - Blast Load Simulator (BLS) facility.

Blast Load Simulator (BLS)





GSL, ERDC

Geotechnical and Structures Laboratory

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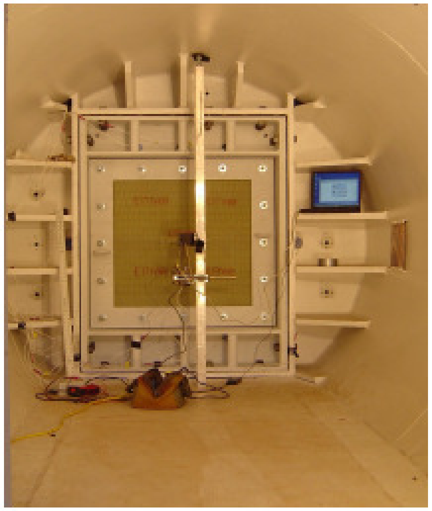
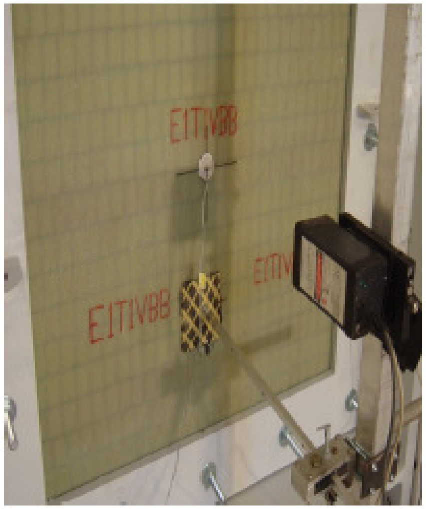
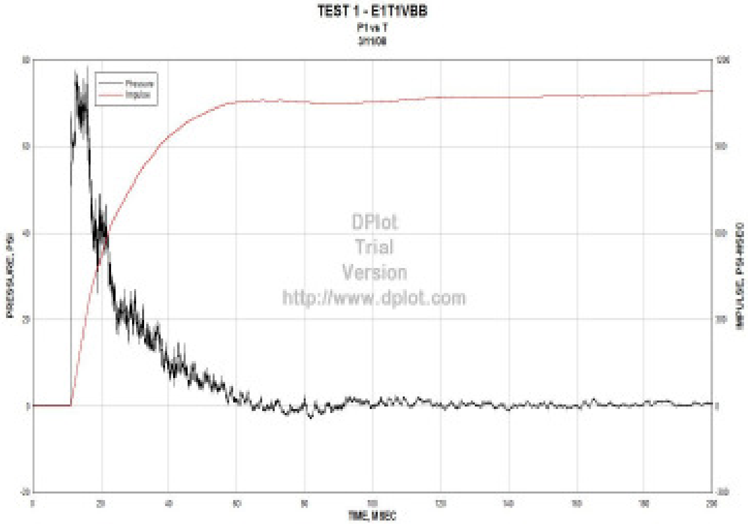
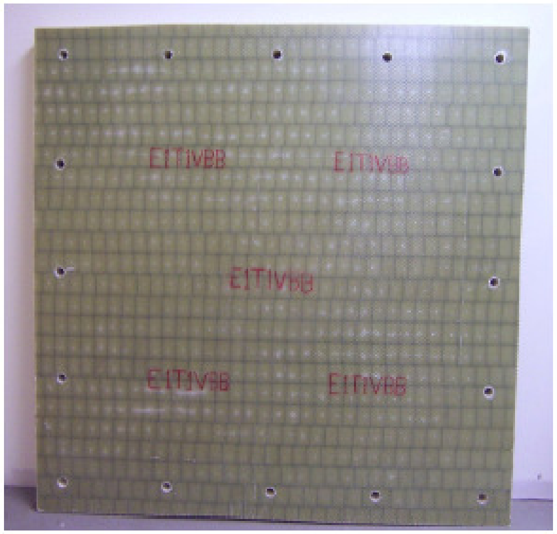
- One 4’ x 4’ E-glass/Tycor panel, with all-around bolted b.c. was subjected to about 80 psi peak pressure.



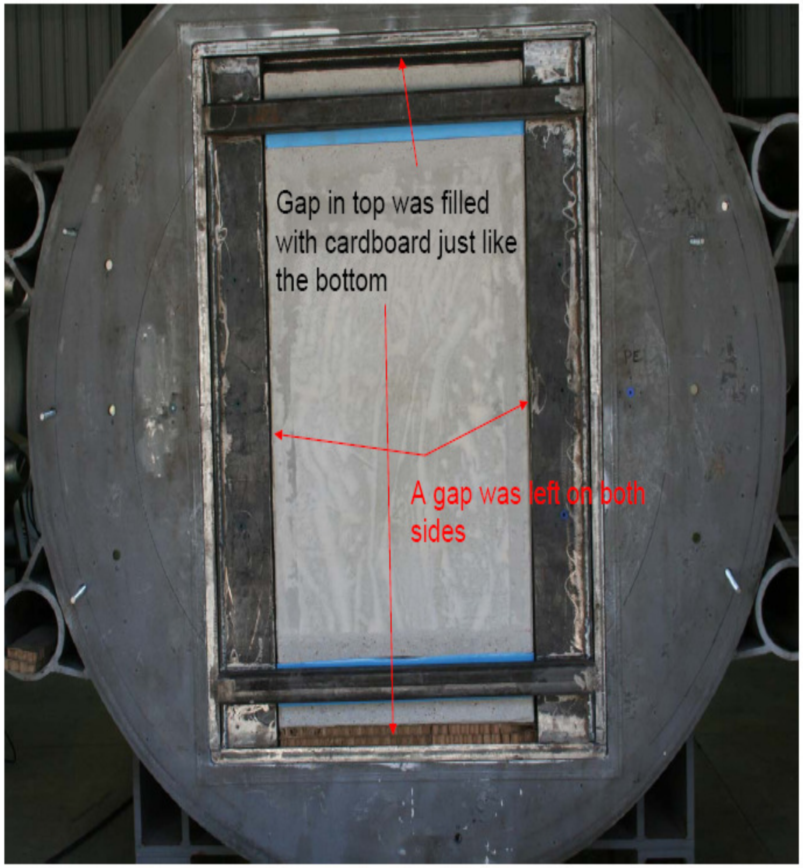




- Panel was not breached and there are no visible signs of damage.
- Foam used for filling gaps between the frame and target vessel blew out. Deflection gage disengaged and laser over heated during the experiment



- An alternate fixture for holding the panel was considered, with two-sides pinned and two-sides free, facilitating larger flexural deformation.



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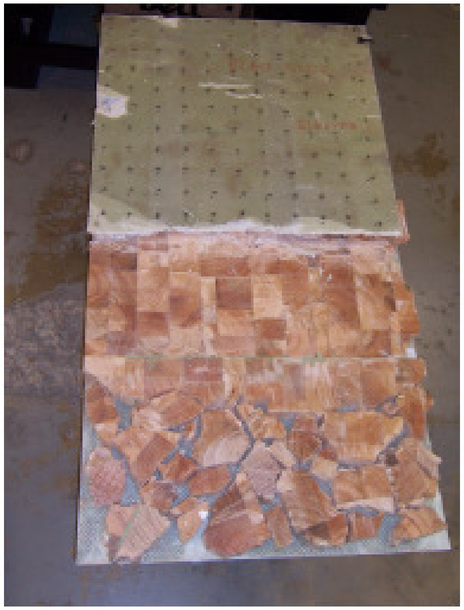
- One 64” x 34” E-glass/Balsa core panel was subjected to about 60 psi peak pressure with this alternate fixture.





  - Panel slid through the supports and was completely damaged, with E-glass face skin on blast side shearing into two halves at the middle.
  - Instrumentation, data acquisition and specimen clamping issues are being resolved for future full-scale blast experiments.

SHOCK RESPONSE OF NANREINFORCED AND SANDWICH COMPOSITES

- Shock tests were conducted (at University of Rhode Island) on nanocomposite panels of dimension 254 mm x 101.6 mm x 9.9 mm (10" x 4" x .39"). Span of the simply supported plate was 152 mm (6") and the overhangs measured 50.8 mm (2") from each end. One panel from each configuration was subjected to 70 psi (482.3 kPa) and another at 120 psi (827.4 kPa) peak pressure.
  - Panels subjected to 70 psi (482.3 kPa) peak pressure did not fracture.
  - All panels subjected to 120 psi (827.4 kPa) peak pressure shattered into pieces.
- Shock tests were also performed on E-glass/Tycor and E-glass/balsa core sandwich composite panels. Specimens were held under simply supported conditions with 203 mm (8") span and 50.8 mm (2") overhangs from each end, and subjected to peak pressure of 1200 psi (1340 m/s).

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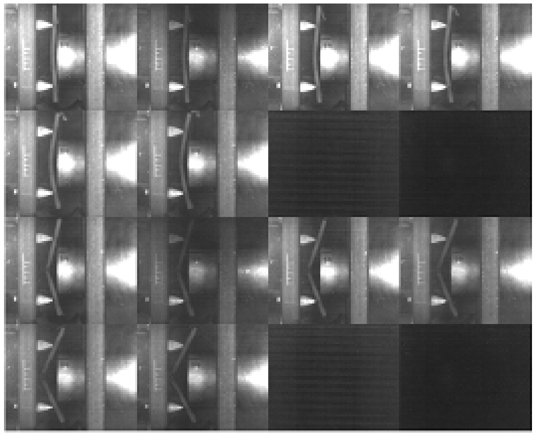
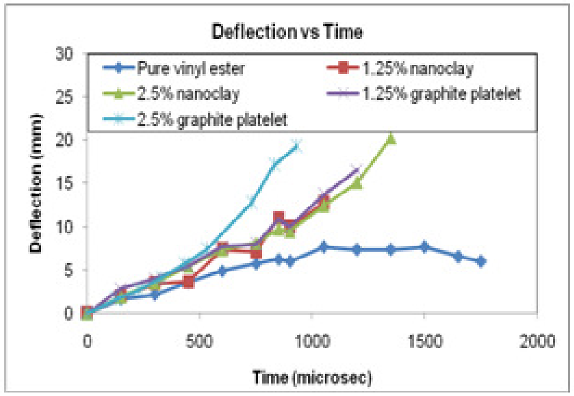
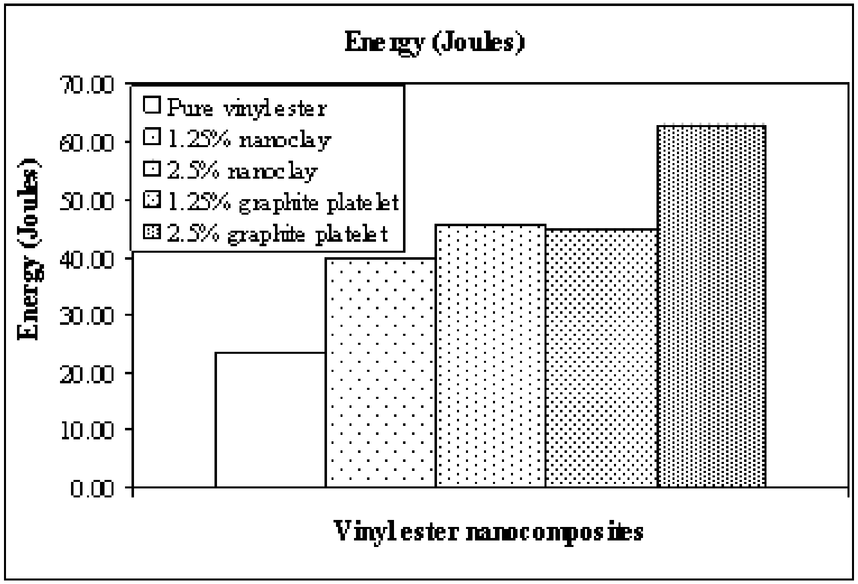


Real time image of 2.5 wt. % graphite platelet /vinyl ester specimen subjected to 120 psi peak pressure in shock tube.



Deflection vs. time from high speed images for vinyl ester nanocomposites at 120 psi peak pressure in shock tube.

Post Shock - Visual Examination



Energy absorption of pure vinyl ester and nanocomposites subjected to 120 psi (827.4 kPa) pressure in shock tube.

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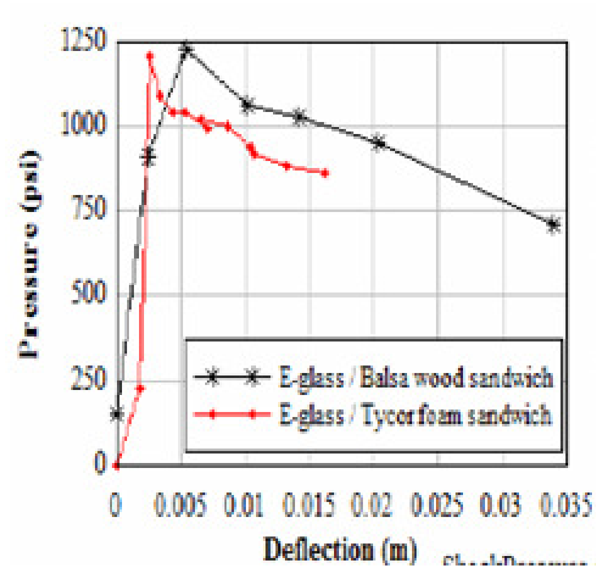
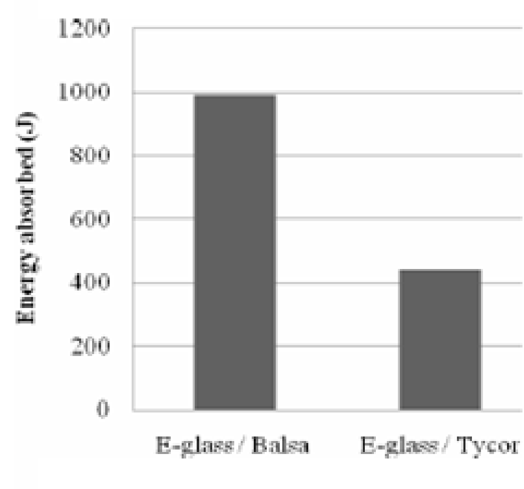
(a) (b) (c) (d)

(a) Shock face, (b) back face, and (c) left side view of E-glass/Balsa sandwich composite; and (d) the splintered balsa core pieces after shock testing at 1200 psi (1340 m/s).



(a) (b) (c) (d)

(a) Shock face, (b) back face, and (c) left side view of E-glass/Tycor sandwich composite; and (d) the splintered foam core pieces after shock testing at 1200 psi (1340 m/s).



BALLISTIC RESPONSE

- Ballistic tests compared the damage initiated by ballistic events on three sandwich structures; with equivalent E-glass face sheets but with different core materials, namely Tycor, Balsa and Foam core.

- For comparing the role of core materials, it was decided that the ballistic event should fully penetrate the structure. To this end NIJ level III was chosen as the threat level. Testing was conducted using a Universal Receiver equipped with a barrel to launch 0.30 caliber M80 ball round projectile (s).

  - Measurement of exit velocities from PVC foam and Tycor core sandwich panels was limited in most cases, due to extensive debris resulting from dislodged core particles. The exit of a large number of these particles passes through the exit chronographs causing them to default.

  - Comparing the damage zones on the back face (i.e. exit side) of panels, the PVC had very minimal damage on the exit face implying that the least amount of energy has been absorbed.

  - Balsa core engages the projectile to a higher degree and hence higher interaction between the core and the face sheets. The back face damage is larger compared to the PVC core panel.

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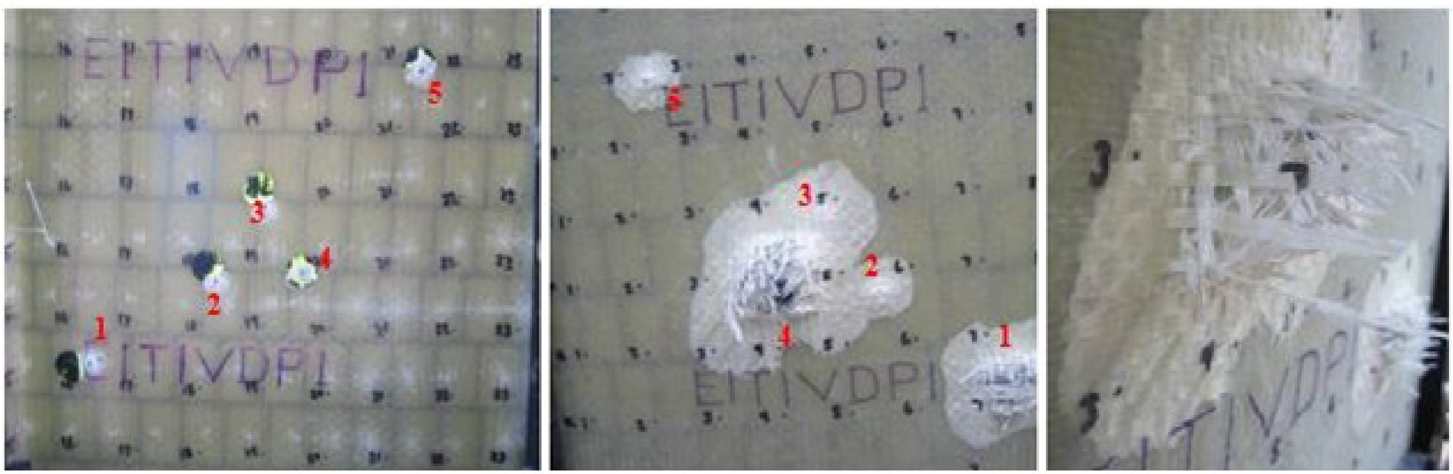
- Tycor foam core provides the most interaction, if the projectile strikes at the intersection of a web i.e. the stiffening elements of the core. The damage zone size reduces if the projectile strikes one (either x or y) element of the core. If projectile strikes between the stiffening elements of the core, the damage on the back face is very similar to the PVC foam core.



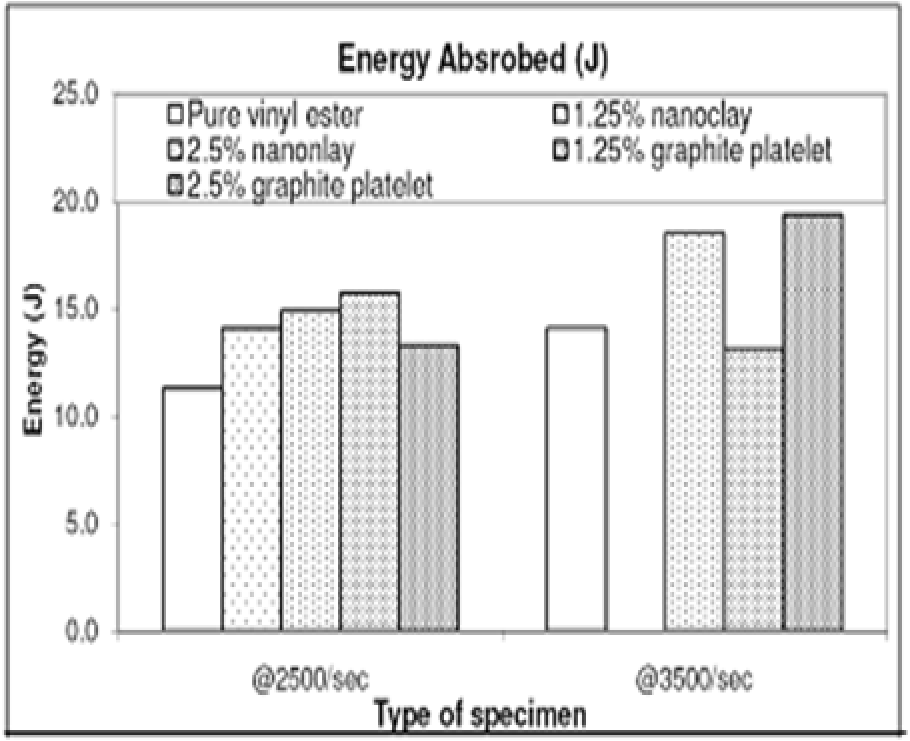
Front, back, and side views of E-glass/Tycor sandwich composite panel after projectile penetration.

  - Further evaluation of the tested panels need to be conducted for more conclusive analysis, for example tap testing, cross-section microscopy, etc.
  - Also post-mortem studies will evaluate the effects of damage interaction from multisite impacts and their effect on residual strength of the sandwich composites.

HIGH-STRAIN RATE RESPONSE

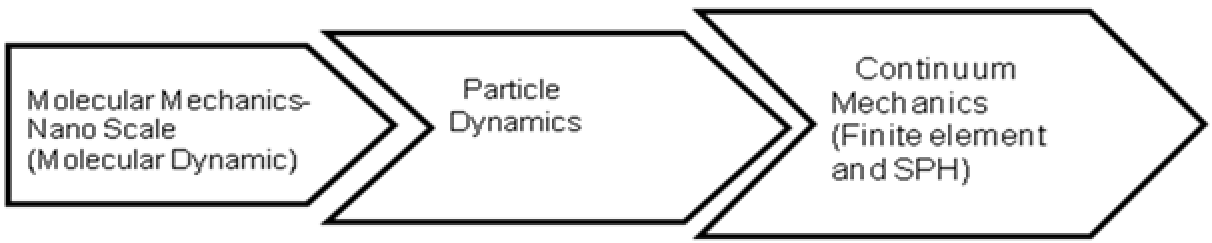
- Split-Hopkinson Pressure Bar (SHPB) tests were performed on round nanoclay and graphite platelet reinforced vinyl ester specimens, at approximate strain rates of 2500 and 3500 per second.

  - Energy absorption increased with increasing strain rate for the pure vinyl ester, and also with 2.5 wt. percent graphite platelet and nanoclay reinforcement.
  - Energy absorption showed an increase of 50% with increasing strain rate for pure vinyl ester, while it reduced by 30% with addition of 1.25 wt. percent graphite platelets.
  - 2.5 wt. percent nanoclay in vinyl ester showed a 30% increase in energy absorption for both strain rates, compared to pure vinyl ester.



CONSTITUTIVE MODELING AND SIMULATIONS

- Multiscale modeling and simulation is employed using the hierarchial approach.



- The output of one level is used as input for the next level.
  - **MOLECULAR DYNAMICS (MD)**
  - **PARTICLE DYNAMICS (PD)**
  - **CONTINUUM MODELING (AUTODYN)**

MOLECULAR DYNAMICS (MD)

- Molecular modeling is a useful tool for predicting the mechanical properties that are difficult to measure (e.g. interface properties of nano particles in a polymer matrix, dynamic properties of nano particles, thermal degradation and decomposition in fire environments).

- Bulk amorphous polymer structures were generated using commercially available Material Studio® Software by constructing polymeric chains in a periodic cell, taking in to account bond torsion probabilities and bulk packing requirements. The models are equilibrated by a series of energy minimization and molecular dynamics runs. The crystal structures for the semi-crystalline polymers are generated and the simulated bulk structures subjected to three different methods for evaluating their mechanical behavior: the static method; the fluctuation method; and the dynamic method.

- Typical results obtained for vinyl ester matrix and graphene platelets are shown. Interface and composite properties were also obtained.

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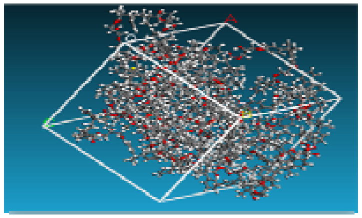
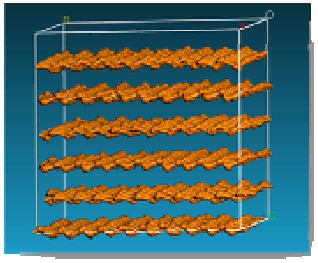
a- Matrix



10 Chain VE unit cell, 2300 atoms, Dynamic ensemble NPT, Tg 390K, Density 1.04 g/cm^3, Cut off point 9.5 Å.

Eng. Constants	6 Chains	10 Chains	12 Chains
E11 (GPa)	2.83	3.7	3.7
v12 (GPa)	.30	.31	.31
M23 (GPa)	1.08	1.407	1.407
K23 (GPa)	2.8	3.37	3.37

b- Graphene platelets



Unit cell size: 10*10 (2D)

Number of Layers: 6

Graphene Unit cell (NVT)			
Number of Super-cells	4*4		10*10
Eng. Constants	Single Layer	Double- Layer	Six Layers
E11 (GPa)	1373	31.7	30.5
E22 (GPa)	831	461.4	459
v12 (GPa)	0.30	.012	.012
M23 (GPa)	340.5	216	214.8
K23 (GPa)	624.1	248.6	247.9

Unit cells of vinyl ester and graphene platelets, and the Engineering constants obtained from MD Simulations.

PARTICLE DYNAMICS (PD)

- Particle modeling (PM), also called particle simulation, discrete modeling or quasi-molecular modeling, is a dynamic simulation method that typically uses a lattice of small (but not molecular level) particles, evolving according to laws of mechanics, as a discrete representation of fluids and/or solids.
- PD method bridges the gap between the micro-scale of molecular dynamics and the phenomenological macroscale of continuum mechanics.
- PM can handle a wide range of complex material systems, problems with complicated boundary shapes and boundary conditions, dynamic free surfaces, and fracture of solids.
- Typical results obtained using the particle modeling method on a polymeric beam specimen subjected to impact of a rigid indenter are shown.

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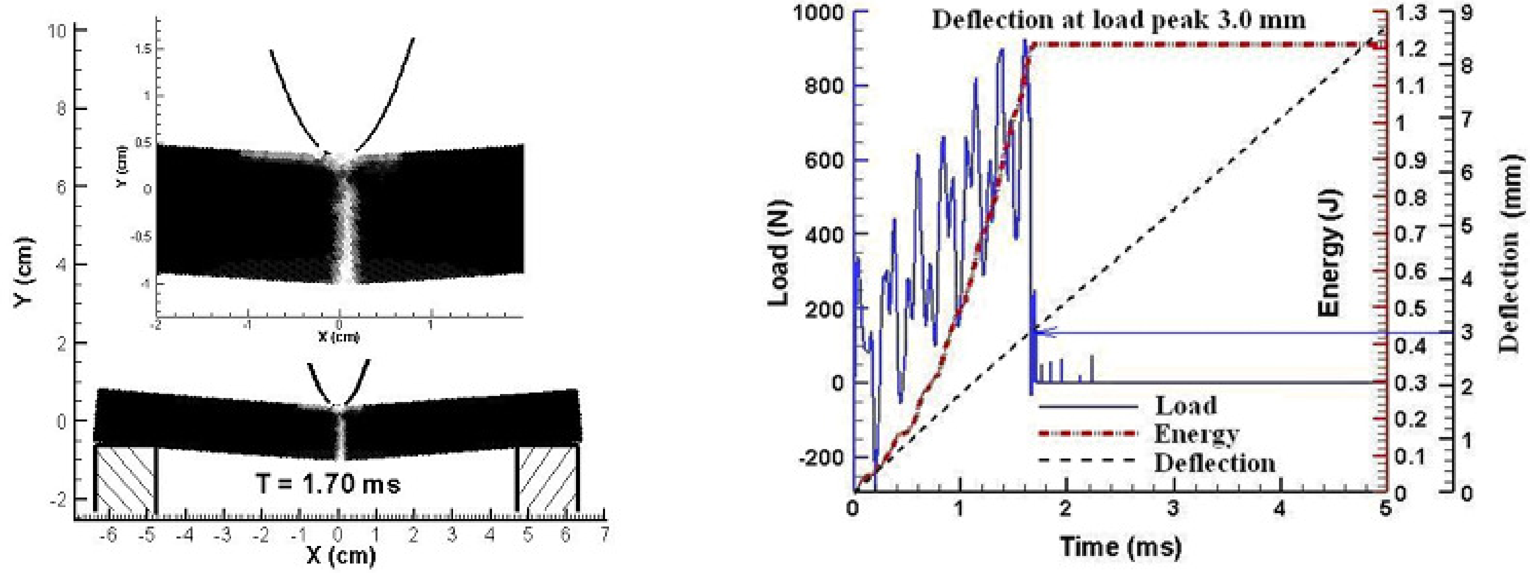

PM results of failure of a polymeric (nylon 6,6) beam subject to the impact of a rigid indenter (drop velocity of indenter ~1.87 m/s): (a) final fracture pattern; (b) load-energy-deflection versus time curves.

CONTINUUM MODELING

- Finite element analysis of fluid structure interaction (FSI) was used to study the blast resistance of sandwich composites. Commercially available hydrodynamic software AUTODYN 11.0; with either Lagrangian, Eulerian, Arbitrary Lagrangian-Eulerian (ALE) or SPH formulation, was used.

- Data is being collected to establish the Pressure-Impulse (PI) and iso-damage curves for sandwich composites made up of 0.16" thick E-glass (90/0, 45/-45, 90/0, 45/-45, 90/0) face skins and 2" thick Tycor foam and other core materials.

- Two cases of sandwich composites were simulated: (a) 36 in high x 36 in wide sandwich composite panel with all-around fixed boundary condition, and (b) 52 in high x 34 in wide sandwich composite panel simply supported at two ends and free at other two ends.

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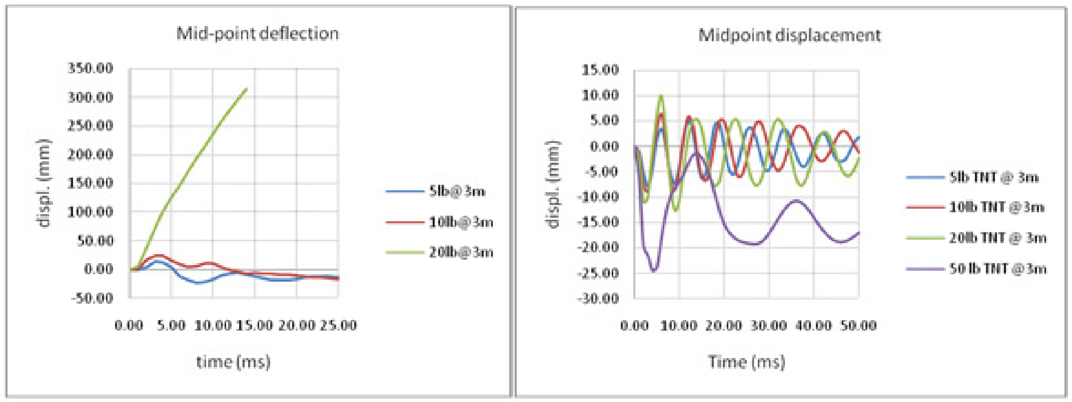
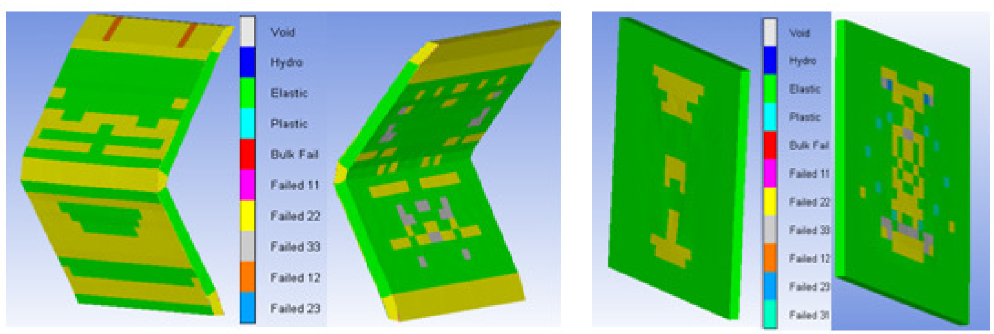


(a) (b)

Time history of midpoint displacement for sandwich composites under different blast loads with (a) simply supported on top and bottom, and (b) fixed all-around boundary conditions.



(a) (b)

AUTODYN simulation of damage region for E-glass/Tycor sandwich composite under 20lb TNT@3m with (a) simply supported on top and bottom (front face at right and back face at left), and (b) fixed all-around (front face at right and back face at left)

FIRST- PRINCIPLE SHOCK MODEL

- The response of a nanoparticle reinforced plate structure experiencing an arbitrary shock load was analyzed through modal analysis. The selected model is an Euler-Bernoulli beam with both torsional and lateral springs at its ends so that the boundary conditions are adjustable.

- Model input includes the gross properties of Young's modulus, material density, and physical geometry. The excitation force time history, or the shock pressure pulse, is discretized into sufficiently small time steps to capture the highest expected frequency content. Closed form equations have been employed to derive the eigenproblem that generates the structure's mode shapes and natural frequencies.

- Approach is to match the shock tube experiments using gross parameters of the composite materials and actual pressure pulses.

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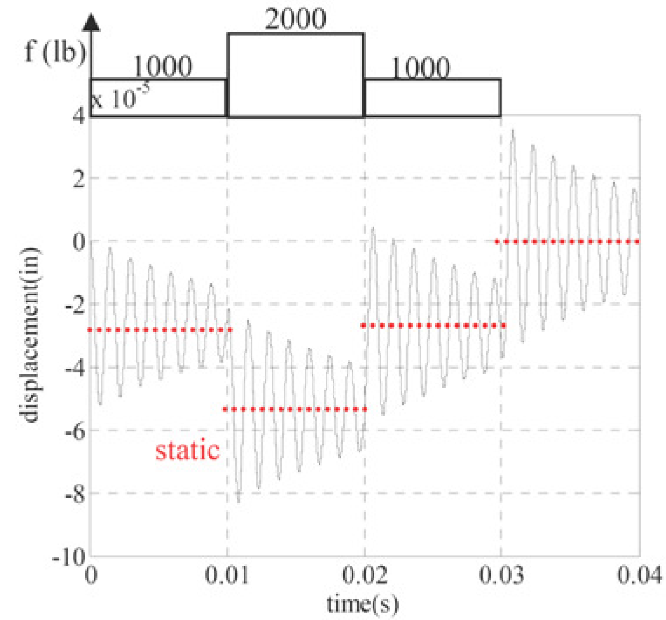
- This method captures the transient behavior, specifically at each abrupt change in force. Convergence studies will be important to ensure capture of the complex shock response.
- An additional Hertzian element is being added into this beam model to simulate any structural contact, or as a preliminary model for fluid resistance.
- Eventually the impact dynamics of a beam subjected to shock in a fluid environment will be examined. The goal is to mimic a shock load on a segment of ship hull underwater.



Centerline displacement from shock model of a sample beam subjected to three pulses (with 2% damping).

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PUBLICATIONS (ONR - supported)

CONFERENCE PRESENTATIONS

1. Hunain Alkhateb, Ahmed Al-Ostaz and P. Raju Mantena, 'Molecular Dynamic Simulations of Multi-wall Carbon Nano Tube Reinforced Nylon 6,6 Nanocomposites' Presented at MAESC 2007: Mid-South Area Engineering and Sciences Conference, Oxford, MS, May 17-18, 2007.
2. Ravi Zalani, P. Raju Mantena and Ahmed Al-Ostaz, 'Dynamic Modulus, Damping and Mode Shapes of Multi-Wall Carbon Nano Tube Reinforced Nylon 6,6 Nanocomposites' Presented at MAESC 2007: Mid-South Area Engineering and Sciences Conference, Oxford, MS, May 17-18, 2007.
3. P. Raju Mantena, Ahmed Al-Ostaz and Alexander H.D. Cheng, 'Dynamic Response and Molecular Simulations of Nano-Composites' 16th International Conference on Composite Materials, Kyoto, Japan, July 8-13, 2007.
4. Ahmad Almagableh, Swasti Gupta, P. Raju Mantena and Ahmed Al-Ostaz “Dynamic Mechanical Analysis of Graphite Platelets and Nanoclay Reinforced Vinyl ester, and MWCNT Reinforced Nylon 6,6 Nanocomposites” *Proceedings of the 2008 SAMPE Fall Technical Conference*, Memphis, TN, Sep 8-11, 2008.
5. Swasti Gupta, P. Raju Mantena and Ahmed Al-Ostaz “Effect of Strain Rates on Energy Absorption of Exfoliated Graphite Platelet and Cloisite Nanoclay Reinforced Vinyl ester Nanocomposites” *Proceedings of the American Society for Composites 23rd Technical Conference*, Memphis, TN, Sep 8-10, 2008
6. Ge Wang, Ahmed Al-Ostaz, Alexander Cheng and P. Raju Mantena “Particle Modeling for Blast Simulation” *Proceedings of the 2008 SAMPE Fall Technical Conference*, Memphis, TN, Sep 8-11, 2008.

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PUBLICATIONS (ONR - supported)

JOURNAL ARTICLES

1. P. Raju Mantena, Ahmed Al-Ostaz and Alexander H-D Cheng "Dynamic Response and Simulation of Nano-particle Enhanced Composites" *Composites Science and Technology* (in press)

2. Al-Ostaz A., Pal G., Mantena P.R. and Cheng A.H-D "Molecular Dynamics Simulation of SWCNT-Polymer Nanocomposite and its Constituents" *Journal of Materials Science*, Vol. 43, No1, pp.164-173, 2008.

3. Ge Wang, A. Al-Ostaz, A.H.-D. Cheng and P.R. Mantena (2008), "Hybrid Lattice Particle Modeling: Theoretical Considerations for a 2-D Elastic Spring Network for Dynamic Fracture Simulations", *Computational Materials Science* (in press).

4. Ge Wang, A. Al-Ostaz, A.H.-D. Cheng and P. Radziszewski (2008), "Particle modeling and its current success in the simulations of dynamic fragmentation of solids", in *Strength of Materials: New Research Trends* (Ed. Frank Columbus), Nova Science Publishers (Accepted)

FUTURE WORK

- Quantify the effect of graphene nano platelet concentration and dispersion (a) around and in between individual reinforcing fibers (intralaminar), and (b) between lamina in both unidirectional and woven fiber lamina (interlaminar).

- Accelerated tests for evaluating the long-term durability, flame retardation and microscopy quantification of failed specimens.

- Design, fabricate and evaluate the blast / shock / ballistic / impact response of T700 FOE treated carbon / vinyl ester sandwich composites with 1 to 2 inch thick Tycor, Balsa and PVC foam cores. Some panels will have graphene nano platelet dispersed resin, films or coatings.

- High-performance scalable computing based modeling and simulation of the response of composite panels to high energy blast loads, and propose optimal configurations.

- Establish a shock tube test facility with fluid-structure interaction capability, and Split-Hopkinson Pressure Bar Apparatus for the high-strain rate evaluation of materials in tension, compression and shear.

ACKNOWLEDGEMENT

- This research was funded by ONR Grant # 00014-07-1-1010, Office of Naval Research, Solid Mechanics Program (Dr. Yapa D.S. Rajapakse, Program Manager).

- Partial funding received under a subcontract from the Department of Homeland Security - sponsored Southeast Region Research Initiative (SERRI) at the Department of Energy's Oak Ridge National Laboratory is also acknowledged.

- We would like to thank Dr. Arun Shukla, University of Rhode Island for performing the shock tests, and Dr. Rob Banerjee, Webcore Technologies for providing their TYCOR® panels for this research.