Lightweight nanocomposite hierarchical structures for blast mitigation

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An energy-absorption approach to the design of protective panels produces polymeric materials that can withstand fire, smoke, and toxicity.

Recent security infringement events and current trends have stimulated the homeland security, defense, and aerospace industries to increase their interest and activity in the areas of blast- and ballistic-impact mitigation. Such events are energy intensive, and their effects are compounded by fire, smoke, and toxicity. Blast and ballistic impacts tend to have dynamic loads that overwhelm the static load resistance of most typical materials, hence the use of multilayered, sandwich-type structures is preferred.

At Pittsburgh State University’s Center for Nanocomposites and Multifunctional Materials (CNCMM), our design and research efforts center on developing new, lightweight materials and structures with high resistance to dynamic loads. This is achieved by using nanoparticles and microspheres (see Figure 1) in the formulation of nanocomposites and ‘syntactic’ foams, as well as of hierarchical structures (structures within structures).

The presence of nanoparticles in a polymer matrix typically confers enhanced stiffness and the ability to absorb energy but decreases energy dissipation. However, in three-component systems—such as the matrix-filler/reinforcement-nanoparticle one we have developed—both energy absorption and dissipation are enhanced. A 3D glass fabric is the material of choice for the outermost layer(s) of the sandwich design. This particular approach gives slightly lower stiffness and strength than facesheets reinforced by roving oriented at different angles, but has much higher shrapnel penetration resistance. The core is made of honeycomb filled with nanocomposite-syntactic foam. Such a lightweight compliant core and facesheets provide deceleration of the blast wave as it interacts with the structure, and helps to reduce overpressure (peak static pressure). Indeed, good technical design requires that overpressure levels remain below the static load capacity of the panel (see Figure 2).

Figure 1. Nanoparticles (silicon carbide, nanoclay, carbon nanofiber, and nanographene) used in CNCMM’s design and creation of nanocomposite hierarchical structures.

Figure 2. Schematic representation of the hierarchical structure with fiber-reinforced, nanocomposite-impregnated 3D fabric facesheets (dark gray), and a nanocomposite-syntactic foam-filled honeycomb core (white).
Figure 3. A VibraCell sonicator used for nanoparticle infusion of the polymer matrix and nanocomposite formulation.

Compression molding and vacuum-infusion molding are the preferred processes for fabricating our hierarchical structures (see Figure 3). The molds are typically made of stainless steel. The structures are currently being produced as 12×12in and 24×24in panels, which are cured at room temperature for 24h. Post-curing is carried out at 93°C for 3.5h. Samples are characterized for structural integrity, energy absorption, fracture toughness, impact, strain, and flammability resistance using a Universal Testing Machine and an FTT cone calorimeter.

At CNCMM, we have determined that higher sonication or nanoparticle-matrix infusion temperatures and times and higher mold temperatures are opportunities for innovation in the blast-resistance panel-processing window. Our work also demonstrates that nanocomposite hierarchical materials can achieve synergy in both energy absorption and dissipation. Of note, in terms of the system’s cost-effectiveness, vinyl ester resin can be formulated as a viable alternative to traditional matrices such as epoxy and polyurethane.

DMTA (dynamic mechanical thermal analysis) data indicate that the maximal tangent of the angle of mechanical losses and the glass transition temperature increase with the volume concentration of nanoparticles for three-component systems such as vinyl ester-silicon carbide (SiC) nanocomposite-impregnated 3D fabric. This effect is not observed for the two-component system, vinyl ester-SiC nanocomposite. This finding suggests a synergy with hierarchical design that is also present in the flammability resistance properties, as is evident in the decrease in the peak heat release rate value of the panel sample compared with the foam-filled core. Also, fiberglass fabric/phenolic-type honeycomb exhibits better flammability resistance than does the carbon fabric/phenolic type. With respect to processing and energy absorption properties, compression fabrication has a slight edge over vacuum infusion, and the 90° fiber orientation yields the best overall performance result.

In summary, we have shown that nanocomposite hierarchical materials have properties and characteristics—particularly with respect to energy absorption and dissipation—that make them suitable for blast mitigation. Moreover, vinyl ester resin is a viable alternative matrix in nanocomposite hierarchicals for the applications described here. Our current efforts are focused on real-time, blast- and ballistic-impact testing of fabricated panels. We are collaborating with Day and Zimmermann Corp. to implement this portion of our research. Other potential applications of CNCMM’s nanocomposite hierarchical structures include cryogenic storage tanks (e.g., helium, hydrogen), storm-proof structures, and sympathetic detonation mitigation (insensitive munitions).

This work is supported by the Office of Naval Research Solid Mechanics Program (grant N00014-05-1-0532). Support of the Pittsburg State University administration for CNCMM is greatly appreciated, as are the efforts of CNCMM’s staff, students, and principal investigators.

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References

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