Enhancement in ballistic performance of composite hard armor through carbon nanotubes

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(Received 20 August 2013; final version received 25 November 2013)

The use of carbon nanotubes in composite hard armor is discussed in this study. The processing techniques to make various armor composite panels consisting of Kevlar®29 woven fabric in an epoxy matrix and the subsequent V50 test results for both 44 caliber soft-point rounds and 30 caliber FSP (fragment simulated projectile) threats are presented. A 6.5% improvement in the V50 test results was found for a combination of 1.65 wt% loading of carbon nanotubes and 1.65 wt% loading of milled fibers. The failure mechanism of carbon nanotubes during the ballistic event is discussed through scanning electron microscope images of the panels after the failure. Raman Spectroscopy was also utilized to evaluate the residual strain in the Kevlar®29 fibers post shoot. The Raman Spectroscopy shows a Raman shift of 25 cm\(^{-1}\) for the Kevlar®29 fiber utilized in the composite panel that had an enhancement in the V50 performance by using milled fiber and multi-walled carbon nanotubes. Evaluating both scenarios where an improvement was made and other panels without any improvement allows for understanding of how loading levels and synergistic effects between carbon nanotubes and milled fibers can further enhance ballistic performance.

**Keywords:** carbon nanotubes; ballistic composites; composite armor; nanocomposite materials

1. Introduction

Composite armor has been widely used in both civilian and military applications in order to achieve high levels of ballistic protection while minimizing the amount of weight required. There is a wide range of fibers and resins employed in order to optimize against particular threat levels and maintain flame, smoke and toxicity standards. Because the C–C bond in graphite is the strongest bond in nature [1], carbon nanotubes theoretically have the capacity to drastically improve energy absorption in ballistic events. Carbon nanotubes have been shown to elastically sustain loads at large deflection angles. With this capability and measured tensile strength of 0.15 TPa and Young’s modulus of 0.9 TPa [2], their energy absorption capabilities could be drastically superior to conventional fibers or high strength steels.

The energy absorption in ballistic events for composite hard armor applications is largely through crack propagation during the delamination of plies. The fracture of thermosetting resin involves a multi-scale event from the microscopic interaction of multi-walled carbon nanotubes (MWCNTs), through ‘sword-in-sheath’ type fracture...
mechanism, or their interaction with the resin matrix through their surface bonding. The crack propagation can be mitigated through the placement of MWCNTs in the matrix. Because of this complex interaction, the theoretical strength and resiliency of MWCNTs can have an impact on the energy absorption of laminates, but is limited by the bonding strength between the resin and MWCNT. Assuming that the bonding strength is not negligible, the fracture toughness of the brittle epoxy polymer matrix will increase with the addition of MWCNTs, acting as aggregate to improve the critical stress intensity factor, $K_C$. The proper loading of MWCNTs, in addition to other larger particles such as milled fiber, will result in higher fracture toughness in the epoxy polymer matrix.

Due to the failure mechanism of the crack propagation between plies in composite armor panels, certain physical characteristics of laminates can have an influence on ballistic performance. One of these physical characteristics is interlaminar fracture toughness. There are multiple techniques that have been utilized to improve the interlaminar fracture toughness. Through-thickness reinforcement or ‘z-pins’ have been shown to improve delamination properties; however, experiments and numerical simulations show that the ‘z-pins’ can decrease the tensile strength of the composite by 27%, and the compressive strength by 30% [3]. However, Blanco et al. [4] have shown analytically that Mode I interlaminar toughness can increase through the use of aligned carbon nanotubes. It has also experimentally been shown to improve out-of-plane mechanical properties without detriment to the in-plane properties. While they successfully enhanced the interlaminar shear strength by approximately 30% [5], it has required special processing whether through chemical vapor deposition (CVD) or electrophoresis.

Extensive research has been conducted to increase interlaminar shear strength properties through an introduction of nano-sized particles onto the fiber or filament prior to the addition of the resin matrix. Typical methods include growing carbon nanotubes on the surface of the filaments [6] and growing carbon nanotubes on the surface of the tows [7]. The use of nano-thickness paper between plies of laminates, or interleaving has been investigated to improve damage tolerance for low velocity impact. Polymer nano fabric interleaving has been found to increase the threshold impact force by 60%, and reduce impact damage growth rate from 0.115 to 0.105 mm² N⁻¹ with impact force [8]. An introduction of carbon nanotube array at the surface of the fabric reinforcement has been shown to improve interlaminar properties to help with delamination issues in composite laminates [9].

Nanoparticles have been utilized in resin matrices to enhance electrical, thermal and mechanical properties with success [10,11]. Most of the work focused on the use with epoxy based resins, due to its popularity in the industry. Yasmin et al. [11] obtained a 60% increase in elastic modulus with decrease in tensile strength for the addition of nanoclay. Liu et al. [12] added nanoclay into the bisphenol A side of the epoxy mixture, and had an increase in elastic modulus, decrease in glass transition temperature and about an 80% increase of stress intensity factor. They also found an increase of impact strength (Charpy impact tests) from 32.1 to 38.1 kJ m⁻² with 3 wt% of nanoclay. Zhao and Hoa [13] looked thoroughly at the effect of particle dispersion, size and volume fraction on the effect of toughness in epoxy resin. They found particle size in the resin system can be reduced to lessen stress concentration, up to a particular limit. 2D/3D analytical cell models of fracture were proposed to give correlation of parameters to toughness. They found that the addition of 5% volume fraction of spherical silicate can improve the toughness of epoxy up to 18 times. They also theorized that for particles of larger aspect ratios, the improvements can be more. Particle volume fraction $V_p$ has an inverse relation to the
possible maximum energy release (PMER); however, increasing $V_p$ beyond a specified limit does not enhance the PMER significantly.

While all of the afore mentioned research pertains to improving specific mechanical properties that could theoretically have an improvement in ballistic performance, there has been minimal research pertaining to ballistic testing of composite armor panels utilizing nanoparticles. Ma et al. [14] showed better impact resistance and a 43% reduction in deflection on composite armor panels utilizing 5% nanoclay in an epoxy matrix. Grujicic et al. [15] have published extensive research on the development of a material model and transient nonlinear dynamic simulation for modeling MWCNTs in composite armor. The effect of functionalization of the MWCNTs on atomic level mechanical properties were investigated through the use of molecular mechanics calculations [16] with subsequent scale up to macroscopic mechanical properties [17]. Further research in computer simulation showed that a 6% improvement in V50 ballistic performance with 30 caliber fragment simulated projectiles can theoretically be obtained with the addition of either 30% by volume MWCNT mat or 0.498% by volume MWCNT doped matrix [18]. Continued use of these models to optimize performance through variance of the location and thickness of the carbon nanotube reinforced composite mats concluded that both the position and thickness of the mats affect the ballistic performance of the armor [15]. Additional finite element simulation revealed that the mode of nanotube deformation has an impact in the effectiveness of MWCNT based mats on the strike face of composite armor [19].

In this study, composite armor panels were fabricated by utilizing both the interleaving of nanoparticle based paper and the dispersion of MWCNTs in epoxy matrix. These techniques were subsequently evaluated for ballistic performance as measured by V50 ballistic limit as defined per MIL-STD-662 F [20].

The objective of this research is to determine the effectiveness of the use of MWCNTs for improvement of ballistic performance in composite armor panels. The ballistic performance improvements of the MWCNTs are also considered when used in combination with micro-sized milled fibers.

A secondary objective is to look for a correlation between the Raman shift due to residual axial strain in Kevlar®29 used in these composite armor panels and the ballistic performance of the panels.

The organization of this paper is as follows. Section 2 is an overview of the various materials, the processing techniques for fabrication of the panels and the test methods used for evaluation. The main results from these tests are presented in Section 3, while the key conclusions are stated in Section 4.

2. Experimentation

2.1. Materials

MWCNTs supplied by Arkema were utilized throughout the experimentation, whether impregnated as paper or dispersed in the resin matrix. The MWCNTs have diameter up to 100 nanometers and length up to 100 microns. They have a specific gravity of 2.90 g cm$^{-3}$, and an apparent density of 0.15 g cm$^{-3}$. They have a surface area between 100 and 250 m$^2$ g$^{-1}$, and a tensile modulus on the scale of 10$^3$ GPa. In the case of the panels constructed with Kevlar®/epoxy prepreg, MWCNTs were functionalized by Zyvex Performance Materials' Kentera™ stacking technique [21].
S2 glass fiber supplied by AGY Industries (Aiken, SC, USA) was utilized for plain weaving by BGF Industries (Greensboro, NC, USA). The weaving was completed to meet the specifications as defined in MIL-DTL-64154B [22]. Kevlar®29 fiber was provided by DuPont industries in Richmond, VA, USA. It is a 3000 denier fiber woven by BGF industries into a 17 × 17 pick count plain weave of 14 oz yd$^{-2}$ as defined in MIL-DTL-62474F [23]. Milled E-glass fibers are ground particulates from fiberglass. In this study, an unsized E-glass milled fiber has an average fiber diameter of 10 μm, average length of ~50 μm and a nominal bulk density of 0.525 (g cm$^{-3}$).

2.2. Processing

2.2.1. Preparation of carbon nanopaper sheet for interleaving

MWCNTs from Arkema were transferred into a solvent of ethanol to form a suspension. The suspension was sonicated using a high-intensity sonicator for 20 minutes with a power of 30–50 watts. After sonication, both the suspension and probe were cooled down to room temperature. Two drops of concentrated HCl were added and the suspension was sonicated again for another 20 minutes under the same conditions. This suspension of MWCNTs was left overnight, and was capable of staying in suspension. The suspension was then filtrated through a 0.45 µm Teflon filter with the aid of vacuum to fabricate the carbon nanopaper sheets. After the filtration, a filter and heavy plate were put on top of the nanopaper sheet to allow for drying flat. The preparation was complete after the sheets were further dried through a 2 hour cycle in a 120°C vacuum oven.

2.2.2. Processing of composite laminates embedded with carbon nanopaper sheet

The panels utilizing the plain weave S2 glass and phenolic resin were prepared at Iten Industries in Ashtabula, OH, USA, and were pressed to the specifications of MIL-DTL-64154B, with the carbon nanopaper sheet placed between the first and second ply of woven S2 glass. The panel was constructed to 18″ × 18”; however, the carbon nanopaper was limited to a 12″ × 12″ size. Therefore, four plies of nanopaper were placed such that there was a 6″ overlap on the horizontal and vertical center of the panel, and a 6″ square in the center of the panel with an overlap of all four plies of the carbon nanopaper sheets. These panels were pressed to achieve an aerial density of 0.97 lb ft$^{-2}$.

2.2.3. Processing of composite laminates with MWCNTs dispersed in epoxy matrix

The panels utilizing the plain weave Kevlar®29 and epoxy resin were prepared by Zyvex Performance Materials in Columbus, OH, USA. The MWCNTs were dispersed in the epoxy resin through shear mixing, and subsequently impregnated onto the woven Kevlar®29 at either 30% or 18% resin content by weight. This material was subsequently processed in autoclave at 120 psi for an appropriate heating cycle as defined by Zyvex’s Arovex prepreg line. The panels were limited to 12″ × 12″, and two panels were constructed for each V50 ballistic test to allow for accurate values of V50 ballistic performance. A total of four baseline panels without MWCNTs and four panels enhanced with MWCNTs were produced to allow for testing with both 30 caliber fragment simulated projectiles and 44 mag soft point bullets. The loading of MWCNTs was 0.5%
for the panels without additional milled fiber, and was 1.65% for the panels made in combination with 1.65% milled fiber.

2.3. Testing and evaluation methods

2.3.1. Scanning electron microscopy

Scanning electron microscope (SEM) takes images of a sample by scanning with a high-energy beam of electrons in a raster scan pattern. A Zeiss Ultra-55 (Ziess, Oberkochen, Germany) at 5 kV was utilized for all SEM imaging in this study. Viewing of the tested panels at the nano- and micro-scale will allow for the analysis of failure mechanisms of the particle fillers during crack propagation. It will also enable the analysis of the stress transfer from the nano to micro scale.

2.3.2. Raman Spectroscopy

Raman Spectroscopy is a technique used to study vibrational, rotational and other low-frequency modes in a system [24]. It utilizes inelastic scattering or Raman scattering, of monochromatic light, from a laser. The frequency of photons in monochromatic light changes upon interaction with the sample. The photons from the laser are absorbed and subsequently reemitted by the sample. The interaction of the laser light with molecular vibrations or phonons results in a shift of the energy of the laser photons, which is then measured for information about the vibrational modes in the system. This frequency difference of the reemitted photons from its original state is called the Raman effect. Raman Spectroscopy has been shown to be capable of measuring strain on Kevlar®29 fiber through the effect of the strain on the Raman band shift [25]. Therefore, Raman Spectroscopy was utilized to measure the residual strain in the Kevlar®29 fiber after V50 ballistic testing. The Raman measurements were performed on a confocal Renishaw Ramascope using a 50× Nikon objective with 532 nm laser excitation. Control measurements were performed to ensure the effects of foreign elements from bullet and the polarization were negligible.

2.3.3. V50 ballistic limit testing

The ballistic limit, protection criteria (V50\textsubscript{BL(P)}) may be defined as the average of an equal number of the highest partial penetration velocities and the lowest complete penetration velocities which occur within a specified velocity spread. This is a standard ballistic test as defined by Military Specification MIL-DTL-662F [20]. Section 5.3.5 of this standard defines the appropriate velocity steps as each projectile is viewed to either be a partial or complete puncture of the composite panel. The panel is placed in the appropriate holder with a specified projectile being shot at the target at a beginning velocity as defined in Section 5.4.3 in MIL-STD-662F [20]. If this projectile is seen to be a partial penetration (i.e. did not pass fully through the panel into a witness panel placed behind the tested panel), the next projectile is shot at an increased velocity as defined in Section 5.3.5. When the first projectile is observed to be a complete penetration, the velocity is subsequently reduced by a defined amount as described in Section 5.3.5. This pattern of increasing and decreasing velocities of projectiles after observed partial or complete penetrations is continued until an equal number of partial and complete
penetrations are observed, with their velocities being averaged. Due to the multiple data points, statistical significance of results is achieved. This testing will be utilized to evaluate the ballistic performance of the various composite panels.

3. Results and discussion

3.1. V50 ballistic testing results

Three different types of composite armor panels were tested for ballistic performance, as described in the following three subsections.

3.1.1. MWCNT nanopaper composite panel

The composite panels made with woven S2 glass in phenolic resin were shot with 44 mag soft-point rounds to obtain the V50 ballistic limit as per MIL-STD-662 F [20]. No significant improvement in ballistic resistance was found, as shown in Table 1. After reviewing the panels post shooting, it was evident that the CNT impregnated paper did not allow for bonding between plies of the phenolic impregnated woven S2 glass, except for along the edge. When the projectile struck the panel, the first and second plies delaminated without crack propagation and MWCNT particles were displaced without any appreciable effect of absorption of the kinetic energy of the projectile.

3.1.2. MWCNT dispersed in epoxy resin of prepreg

A total of four baseline panels without CNTs and four panels enhanced with CNTs were produced to allow for testing with both 30 caliber fsp and 44 mag soft point bullets. The resin content was held at 30% by weight, with loading of CNTs for the enhanced panels at 0.5% by weight. Sixteen plies of woven Kevlar® were used for the 44 mag testing for an aerial density of 2.3 lb ft$^{-2}$. Thirty-two plies of woven Kevlar® were used for the 30 caliber fsp testing for an aerial density of 4.6 lb ft$^{-2}$. The panels for the 30 caliber testing are shown in Figure 1. There were no noticeable improvements in V50 for either 30 caliber fsp or 44 mag testing.

3.1.3. MWCNT and milled fiber dispersed in epoxy resin of prepreg

The final set of panels were constructed using 3000 denier Kevlar®29, 17 × 17 pick count standard woven 14 oz yd$^{-2}$ material with epoxy prepreg from Zyvex Performance Materials’ Arovex product line. The resin content ranged from 18.6% to 22.7% by weight.

| Aerial density (lbs sqft$^{-1}$) | Overlap plies of CNT paper | V50 (ft sec$^{-1}$) |
|---------------------------------|-----------------------------|-------------------|
| 1.5                             |                             | 1226              |
| 1                               |                             | 1091              |
| 0.97                            | 1                           | 1047              |
| 0.97                            | 2                           | 1042              |
| 0.97                            | 4                           | 1084              |
for all panels. The panels were limited to 12” × 12”, and two panels were constructed for both baseline and enhanced versions to allow for testing with 44 mag soft point bullets. All panels had an aerial density of 2.3 psf with an average thickness of 0.306”. The enhanced panels were limited to a loading of 1.65% for CNTs and 1.65% for milled fiber due to the viscosity becoming too high for higher loadings, keeping it from running through the impregnation machine properly. Pictures of the panels before and after testing

Figure 1. (a) Baseline panels post 30 caliber fsp test. (b) Enhanced panels post 30 caliber fsp test.

Figure 2. (a) Combination CNT and milled fiber panels before 44 mag testing. (b) Combination CNT and milled fiber panels after 44 mag testing.
are shown in Figure 2. The V50 results were 6.57% higher for the enhanced panels. The loading of CNTs and milled fiber, due to an increase in the fracture toughness, increases the amount of energy absorbed during the crack propagation. This increased toughness manifests itself in higher V50 performance, due to the energy absorption through crack propagation during the delamination process.

3.2. Failure analysis after V50 ballistic testing

SEM imaging was first completed for the composite panels made without milled fiber. Scans were taken from a fiber cut-out from the location where the bullet passed through the panel. Figure 3 shows the Kevlar® fibers elongated prior to breaking at this location. Figure 4 illustrates an indent in the resin from where the Kevlar fiber was embedded in the resin, as well as traces of filaments from the fiber. The rough nature of the resin indicates that CNTs created a tearing of the resin, rather than a typical straight brittle fracture typical in thermoset resins during failure. Figure 5 shows magnification of the resin tearing in Figure 4 allowing for viewing of the CNT that is bonded into the resin system. The bonding creates the mechanism for ‘tearing-apart’ of the resin during failure. In Figure 6, there are noticeable voids or porosity. Figure 7 shows the baseline panel where no CNTs were added. These are at the same magnification of images in Figure 6. Due to the lack of porosity in Figure 7, the porosity shown in Figure 6 was created from the shearing of the
Figure 4. SEM image of CNT enhanced epoxy with fiber indentations.

Figure 5. SEM image showing MWCNT in resin matrix.
Figure 6. SEM image showing porosity in resin matrix for CNT enhanced panel.

Figure 7. SEM image of baseline panel.
CNTs into the resin matrix during the mixing process. The effects of the porosity are counteracting the benefits of the CNTs in the resin matrix.

Further SEM images were made of the composite panels that had been constructed with both 1.65 wt% MWCNT and 1.65 wt% milled glass fiber. These images show the presence of milled fiber with surrounding CNTs which improves the $K_C$ value for the brittle epoxy polymer. This is shown in the SEM image in Figure 8. Figure 9(b) demonstrates that the epoxy resin matrix during failure resulted in a graduated ‘tearing’ of the resin, due to the influence of the CNTs and milled fiber. This can be seen in the left side of Figure 9(b) by the curved and stepped crack propagation lines. Comparing the fracture lines in Figure 9(b) of the enhanced panels to the fracture lines of the baseline panel in Figure 9(a), there is a distinct difference in the brittle nature of the crack propagation lines for the baseline panels as compared to the curved and stepped crack propagation lines for the enhanced panel.

### 3.3. Raman Spectroscopy for evaluation of residual strain in Kevlar®29

Raman Spectroscopy was utilized to evaluate the residual strain in the fibers of various panels. Strain in the sample has been shown to cause a Raman shift, and can be measured directly [25,26]. To calculate the relation between the Raman shift and strain, the ‘secular equation’ must be solved [27]. This change in Raman frequency $\Delta \omega$ is calculated from the frequency of the Raman signal under study $\omega$, and the stress-free value $\omega_0$ as shown in Equation (1):
Figure 9. (a) SEM image of fracturing of epoxy resin matrix in baseline panel. (b) SEM image of fracturing of epoxy resin matrix in enhanced panel.
where $\lambda$ is the eigenvalue of the equation, $\varepsilon_{ij}$ is the strain tensor, and $f$ is the function of the strain tensor.

In order to solve the secular equation mentioned before, assumptions must be made about the stress or strain distribution in the sample, for the strain tensor components to be simplified [27]. For a uniaxial stress, the linear relation between the fiber axial stress and Raman band shift at 1611 cm$^{-1}$ for Kevlar®29 aramid fiber is shown in Equation (2) [25]:

$$\sigma^{-1} = -\frac{K}{\Delta\omega} \text{(GPa)}$$

where $\sigma$ is the fiber axial stress; $K$ is stress sensitivity which is determined by the material properties. For Kevlar®29 aramid fiber at 1611 cm$^{-1}$, the value of $K$ is 4.0 ± 0.5 cm$^{-1}$ GPa$^{-1}$ [28]; $\Delta\omega$ is the band Raman shift at 1611 cm$^{-1}$.

$$\sigma^{-1} = -\frac{K}{\Delta\omega} = -\frac{4 \text{ (cm}^{-1} \text{ GPa})}{25 \text{ (cm}^{-1})} = -0.16 \text{ (GPa}^{-1}) \Rightarrow \sigma = 6.25 \text{ (GPa)} = 906.5 \text{ ksi}$$

Figure 10 shows the Raman Spectroscopy results for three different panels that were tested per MIL-STD-662 F [20] with 44 caliber soft-point rounds. The light blue line represents the baseline panel constructed using 3000 denier Kevlar®29, 17 × 17 pick count standard woven 14 oz yd$^{-2}$ material with epoxy prepreg from Zyvex Performance Materials’ Arovex product line. The magnified view in the upper left corner of the figure zooms into the Raman shift band at 1611 cm$^{-1}$. The green line shows the panels...
constructed with the same materials, but with an addition of 0.5 wt% MWCNTs. The red line represents the panels that were enhanced with 1.65 wt% MWCNTs, and 1.65 wt% milled glass fiber. The band shift for the milled fiber and CNT panel is approximately 25 cm$^{-1}$. When this band shift is inserted into Equation (2), a fiber axial stress of 906.5 ksi is obtained, as shown in Equation (3). However, this data only represents a single scan on each panel. In order to improve the level of confidence of this data, averages of three scans for each line with an exposure between 3 and 10 seconds were done for multiple points on both the CNT only panel and the milled fiber and CNT panel. Figure 11 illustrates that this same Raman shift was seen for the CNT and milled fiber panel that had the improved ballistic performance. The absorbed stress seen by residual strain from the stress wave during the ballistic event is measured by this Raman shift. The panel with the improved ballistic performance measures a higher absorption of this stress wave.

In order to validate that these results are not tainted by either polarization of the monochromatic laser light or contamination of the bullet, further testing was conducted. The Raman shift was measured again on the CNT enhanced panel that showed no V50 ballistic improvement. Figure 12 shows how the three measurements were taken parallel, at a 45° angle, and perpendicular to the fiber orientation, with the results graphed. The orientation of the Kevlar®29 fiber did not have an effect on the Raman shift; however, at measurements taken off of the parallel orientation had a higher intensity measurement. This is due to the wavelength of the monochromatic laser light hitting a higher portion of the Kevlar® fiber, resulting in a higher intensity measurement. The polarization has no effect on the band shift; therefore, it does not taint the residual strain data.

In order to rule out the contamination from the bullet on the Raman shift data, measurements were taken from a bullet post-shoot of both the copper jacketing and the lead core. These results are shown in Figure 13. The general noise of the data without any significant peaks demonstrates that any contamination of the bullet on the fibers would
Figure 12. Effect of polarization on Raman Spectroscopy data.

Figure 13. Raman Spectroscopy data for (a) copper and (b) lead pieces of bullet.
have a negligible effect on the Raman band shift measurements. Due to the elimination of concern for contamination of the Raman shift data from either polarization effects, or contamination from the projectile, we can estimate that the Raman shift of \(-25 \text{ cm}^{-1}\) measured in the panels with a 6.57\% improvement of V50 is a representation of the amount of the stress wave absorbed by the composite panel.

4. Conclusions

In this study, MWCNTs were utilized in both interleaving and dispersion into composite laminates and evaluated for their ballistic performance. The enhancement mechanism for ballistic performance from the use of these nanoparticles was investigated based upon SEM imaging and Raman Spectroscopy data. Raman Spectroscopy was successfully utilized to get a representation of the amount of kinetic energy absorbed during stress wave propagation in a ballistic event through the measurement of residual strain in Kevlar®29 fibers. The increased V50 performance for the enhanced panels with a combination of milled fiber and MWCNTs was due to an improvement in the critical stress intensity factor, \(K_C\) value for the brittle epoxy polymer. This improvement was not seen in the earlier trial, due to both a lower loading of CNTs at 0.5\% and an absence of the synergistic effects of the CNTs acting in unison with the larger milled fiber resulting in a better aggregate to limit the crack propagation during ballistic failure.

Acknowledgments

The materials presented here are based upon work supported by Florida Space Grant Consortium (FSGC) under grant number NASA NNX10AM01H.

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