FABRICATION AND PROPERTIES OF MULTIFUNCTIONAL, CARBON NANOTUBE YARN REINFORCED 3-D TEXTILE COMPOSITES

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Abstract

Long continuous yarns, 3-D braids, 3-D weaves and other textile reinforcements consisting solely of carbon nanotubes, or hybridized with other fiber materials, may be the future of specialty composites requiring unique multi-functional properties. Although several different methods of processing continuous yarns from single-wall and multi-wall carbon nanotubes have been proposed and demonstrated, those materials are still produced in very small quantities. About 100 m long 'single' yarn was fabricated for this study at the University of Texas at Dallas by drawing it with twist from multi-wall carbon nanotube forest. The yarn was further plied with counter-twist and used in 3-D braiding process (which also incorporated 9 axial bundles of glass fibers). Further, composite materials reinforced with the 5-ply nanotube yarns and nanotube braids were fabricated. The main subject of this work is experimental study of some electrical properties of the produced nanotube yarns, 3-D braids and composites made thereof.

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1 Introduction

Nanocomposites and three dimensionally reinforced fabrics are two composite technologies that have shown a great deal of promise and progress over the last few years. Nanocomposites are composite materials in which the reinforcing phase has the characteristic scale in the order of nanometers. Nanoclays and carbon nanotubes have been the most thoroughly investigated types of nano-reinforcement. Three-dimensional (3-D), multi-directional fabric reinforcements, in their turn, are widely used in various advanced composite materials. Such reinforcements typically consist of 3, 4 or 5 sets of yarns that may lie in mutually orthogonal or non-orthogonal planes. 3-D woven fabrics (commonly having 3 directions of reinforcement) and 3-D braided fabrics (with 4 or 5 directions of reinforcement) are the most popular types of 3-D reinforcement for composites. Presently available 3-D weaving and 3-D braiding processes and automated industrial machines enable for producing near-net shape or even net shape preforms for composites. Such preforms not only provide unique and desirable mechanical properties to composites but also simplify composites fabrication methods and reduce their manufacturing cost. This paper describes some aspects of ongoing work which purpose is integrating the 'state of the art' in both aforementioned fields of research.

2 Some Novel Concepts of 3-D Reinforced Composites

Continuous yarns spun entirely from carbon nanotubes have captured the interest of many researchers because of their unique building blocks. Individually, carbon nanotubes have extreme mechanical, electrical and thermal properties. Transferring these properties to the macro-scale has been the subject of hundreds of research publications. Generally, these studies have at least one common feature: low nanotube volume fraction (often called 'loading') or random nanotube orientation. Contrary to that, nanotube textiles, if used as composite reinforcements, would provide the unique combination of extremely long, stiff and strong basic building blocks (e.g., individual nanotubes), good alignment of those blocks in desirable direction, and high nanotube volume fraction in the composite. These features attract fast growing interest to carbon nanotube yarns, 3-D braids and 3-D weaves as new exciting reinforcements for composites.

3-D textile composites, including 3-D woven and 3-D braided materials, have attracted fast growing industrial interest due to their ability to combine high in-plane mechanical properties with dramatically improved transverse strength, delamination toughness, damage tolerance, impact resistance, and other important characteristics. However, even relatively small volume content of the out-of-plane or off-axis fibers results in considerable increase of interstitial resin pockets, decrease of in-plane fiber volume fraction and, consequently, a significantly lower stiffness and strength in the principal (in-plane or axial) directions. The idea of utilizing carbon nanotube yarns for reinforcement in 3-D textile composite was first presented in [1]. There, it was proposed that they be integrated into 3-D textile preforms to produce hybrid structures containing both conventional yarns and carbon nanotube yarns. As illustrated in Fig. 1 for the case of 3-D woven architecture and in Fig. 2 for the case of 3-D braided architecture, the dilemma can be potentially resolved by replacing traditional types of yarns used in the 'secondary' directions of reinforcement with the new carbon nanotube yarns.

Fig. 1 illustrates the scale of hypothetical 3-D woven preform with nanotube yarn used in through thickness (Z) direction and typical conventional carbon yarns used in the in-plane ('warp' and 'fill') directions. This particular fabric design assumes identical 12K doubled carbon yarn in both warp layers (red) and in the middle fill layer (blue); 6K doubled carbon yarn is used in the outer fill layers (blue).

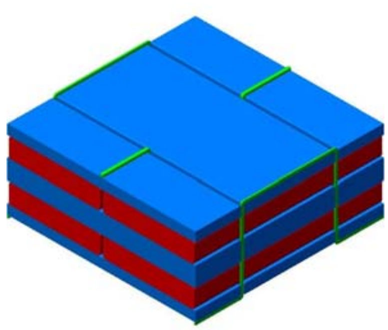

Fig. 1. A hypothetical hybrid 3-D orthogonal weave with Z-directional carbon nanotube yarn [1]

According to the theoretical estimate [1], which assumed 70% fiber volume fraction (V_f) within each warp, fill and Z yarn, the respective 3-D woven composite would reach $V_f = 68\%$ shared almost equally between both in-plane reinforcements. The in-plane moduli would be ~80 GPa in both in-plane directions (with T300 carbon fiber used as an example). The total volume occupied by interstitial pockets would be only ~2% of the preform volume, while in regular 3-D woven preforms this value is typically 15-20%.

Fig. 2 illustrates a hypothetical 3-D braided material that contains a large amount of aligned axial tows (green) with very fine off-axis carbon nanotube yarns (red) being 3-D braided around the axials. The principal design objectives in this case are: (i) to increase as much as possible total V_f, (ii) to improve 'secondary' mechanical properties of a composite (e.g., properties in the directions perpendicular to the braiding axis) with as little sacrifice of its axial properties as possible, and (iii) to improve as much as possible fracture toughness, damage tolerance, impact resistance, fatigue life and other characteristics of special interest. So, it is desirable to use as little braided (e.g., off-axis) fiber amount as possible and also make the braid angle as small as possible in order to minimize the reduction of the longitudinal elastic and strength properties vs. the respective properties of the 'baseline' unidirectional composite. Using continuous carbon nanotube yarns in 3-D braiding is one possible path towards this concept realization.

Fig. 2. A hypothetical hybrid 3-D braid with braided carbon nanotube yarns

When long continuous carbon nanotube yarns become commercially available, it will certainly be a very expensive kind of a structural material. Composites produced solely from these yarns might be cost prohibitive. Therefore, hybrid 3-D textile composites could prove to be a much more economical first application of carbon nanotube yarns. They could capitalize on the best possible combinations of mechanical, thermal, electrical, etc. properties, while the nanotube yarn would only account for a small percentage of the total fiber volume in the preform.

To succeed with the proposed approach at a real life industrial scale, several conditions should be met. First, a reliable source of substantial (meaning, far beyond the laboratory research needs) volume of continuous, sufficiently strong and tough carbon nanotube yarns has to establish its place in the market. Second, those commercially available yarns should be affordable. Third, special 'micro-weaving' and 'micro-braiding' devices and automated machines capable of gently manipulating very fine and relatively expensive nanotube yarns shall be designed and built. Fourth, special composite fabrication methods and tooling have to be developed. Papers [1-4] further dwell into some of these issues, discuss recent research accomplishments and revealed problems. Here, it is worth pointing out again that the major effect of incorporating carbon nanotube yarns into 3-D preforms and composites will be in obtaining unique combinations of various physical properties that cannot be provided by conventional fibers and reinforcement architectures.

Previous research in this area, see [4], has uncovered some of the mechanical characteristics of nanotube yarns, 3-D braids and their composites. This paper will briefly summarize previous approaches and findings, demonstrate the production of the first hybrid 3-D braided specimens and examine some of their properties. Special interest will be paid to electrical conductivity measurement technique and results. The observed experimental effects associated with the role of carbon nanotube yarns will be discussed.

3 Spun Carbon Nanotube Yarns

The continuous yarns fabricated from carbon nanotubes and used in this study were produced by the authors of [2]. In that publication, the newest method for spinning such yarns from multi-wall carbon nanotube forests has been developed. The process is illustrated in Fig. 3. On the right there is an array of billions of nanotubes that were grown vertically from a catalyst laced substrate in a CVD growth process. As was discovered in [2], pulling nanotubes away from the substrate, while twisting at the same time, created a continuous yarn. Such yarn is similar to traditional textile yarns; however, the building blocks are on the nano-scale and the produced yarns themselves are only approximately 10 μm in diameter.

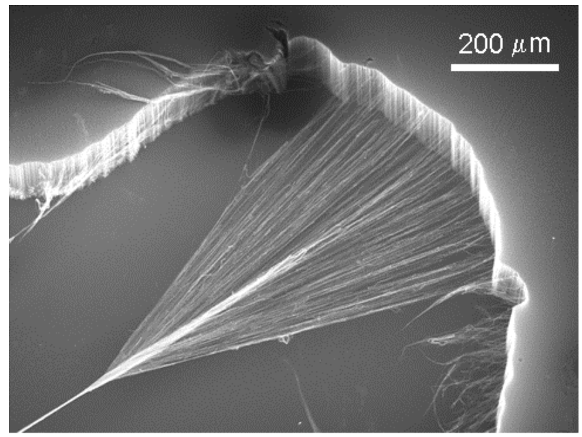

Fig. 3. SEM image of a carbon nanotube yarn being drawn with twist from a carbon nanotube forest [2]

The yarns used in the present study contained nanotubes approximately 300 μm long and had a twist rate of 25 turns/mm in the counter clockwise direction. Subsequently, a group of five yarns was plied together with the counter-directional twist applied. The result was a larger cross section structure that showed strong enough to be used in the 3-D braiding and composite fabrication steps.

4 Carbon Nanotube 3-D Braids and Composites

Plied nanotubes yarns, produced by the methods described in Section 2, were used to fabricate the first 6-cm long 3-D braid sample, as reported in [3]. The production of much longer, about 50-cm long carbon nanotube 3-D braid samples and their SEM studies were reported in [4]. A SEM image of one such braid is shown in Fig. 4. The braid was fabricated on a hand operated 3-D braiding device developed by 3TEX, Inc. which utilizes, in a scaled down version, their patented 3-D rotary braiding method.

By making such a large (compared to the individual yarns) structure from these yarns, the goals in [4] were to (1) add one more level of the structural hierarchy, (2) evaluate mechanical properties of the 3-D braid vs. original 5-ply yarn, and (3) further use the braid as through-thickness component in 3TEX's 3WEAVE™ process. A comprehensive mechanical testing of the plied yarns, 3-D braids, and their composites was performed in [4]. By mutually comparing tensile properties of the dry structures in the first step and then comparing them to tensile properties of their respective composites, the deformation, damage and failure mechanisms were discerned. Particularly, it was found that 3-D braiding of nanotube yarns did not impart considerable damage. Also, SEM images of the failure surfaces of the 3-D braided carbon nanotube composites indicated that regular epoxy resin penetrated well into the yarns and bonded together individual nanotubes (or, alternatively, bundles of nanotubes if such exist).

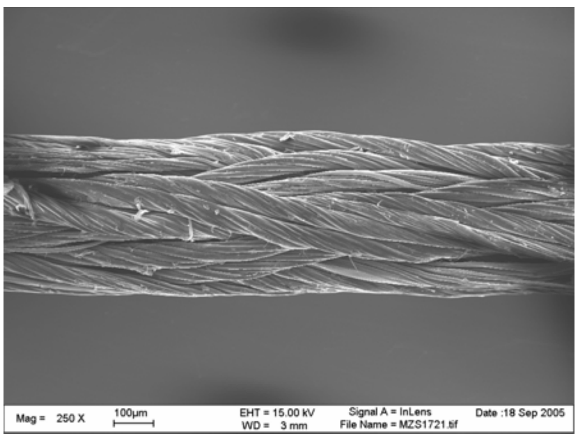

Fig. 4. SEM of 3-D braid made from 36 five-ply nanotube yarns [4]

Particularly, it was concluded from the obtained experimental results that the true reinforcing constituent of the composites made with nanotube yarns (either single or plied) and their 3-D braids, is either individual nanotube or nanotube bundle. When individual yarn was viewed as the reinforcing constituent of the composite, the Rule of Mixtures predicted totally wrong effective elastic modulus under longitudinal tensile loading.

The described types of plied carbon nanotube yarns, 3-D braids and their composites will be used later in this paper when studying their electrical conductivity.

5 Electrical Properties of Carbon Nanotube Composites

Carbon nanotubes are believed to be excellent conductors of electrons because of their unique graphitic tube structure. Extremely high current densities of $1x10^6$ A/cm^2 [5] and $2x10^7$ A/cm^2 [6] have been measured for carbon nanotubes. These are orders of magnitude above the maximum current density for copper wires used today. Resistivity measurements of carbon nanotubes have been measured as low as $5.1x10^{-6}$ ohm-cm using a four point probe method, see [7].

Nanotubes have been used as fillers in various matrix composites due to their extremely long aspect ratios enabling to create electrically conductive networks at very low volume fractions. For this reason, nanotubes have been added to epoxy matrices in many cases, see for example [8-10]. However, the conductivity of such networks is very low, right above the conductive percolation threshold. The range of electrical conductivity obtained in the above cited works was from 0.001 to 0.8 S/cm. Nanotube yarns studied for the first time in [2] have shown much better electrical conductivity; it was found to be 300 S/cm with the use of four point probe method. However, this is still orders of magnitude away from the theoretically predicted electrical conductivity of individual carbon nanotubes.

The limiting factor for the electrical properties of conductive carbon nanotubes and carbon nanotube networks is the contact resistance between crossing nanotubes, contact resistance between nanotube and matrix, conductivity of the matrix and, most importantly, the number of contact points between nanotubes in the network. In dispersed nanotube composites with insulating matrices, the high resistance is a result of few nanotube contacts that have a small conducting surface area. Contrary to a trivial case of two flat continuous contact surfaces, the least resistive path for electrons to flow within the nanotube network is through the small contact surfaces between adjacent tubes. The contact area has been theoretically estimated as ~1 nm^2 for SWNT [11].

The much denser and better organized carbon nanotube yarns exhibit substantially better electrical conductivity than dispersed nanotube networks due to the much larger number of contact points between nanotubes. In dispersed nanotube composites, short nanotubes may make intimate contact with tens of other tubes. In nanotube yarns, in turn, a single long nanotube could make thousands of contacts with other tubes. This is due to much higher packing density, better alignment and preferred orientation of nanotubes in the spun yarns. In dispersed nanotube composites, the nanotubes are deliberately separated from each other to maximize the physical properties of interest with the lowest volume fraction ('loading') of nanotubes. In carbon nanotube yarns, the nanotubes and nanotube bundles remain in the as spun form and therefore contain numerous contact points. For this reason, when carbon nanotube yarns were infiltrated with a polyvinyl alcohol solution, as in [2], the electrical conductivity was decreased by only 30%. The majority of original contacts among nanotubes remained; therefore, the electrical conductivity was only moderately affected.

6 A Novel Hybrid 3-D Carbon Nanotube Braid

The first hybrid 3-D braid containing carbon nanotube yarns and axial bundles of S-2 glass fibers has been produced for this study by Dr. Dmitri Mungalov (3TEX). That was done on the same hand operated rotary 3-D braider described in [3,4]. As with much larger commercial braiding machines, the manual device has the ability to add axial tows between the braiding yarns, which remain nearly straight in the final preform. S-2 glass fiber bundles were chosen as the axial reinforcement for two reasons. One is that they provide a bright color contrast with carbon nanotube yarns and thus allow one to visually study the texture of the hybrid 3-D braided structure. The other is that, like any kind of glass material, S-2 glass provides a non-conductive fiber component for the hybrid 3-D braid. Hybridizing the carbon nanotube yarns with another conductive material, such as carbon fiber, would have resulted in a 'smearing' of electrical conductivity between the two components. The fiberglass is an insulator, so any electrical conductivity gain in the hybrid braid has to be attributed the carbon nanotube yarns.

In order to meet the objective of high axial fiber volume fraction (i.e. staying close to unidirectional composite, as suggested in Section 2), a majority of the preform consisted of 9 relatively thick axial fiber bundles. Those were extracted from an AGY 463-1250 S-2 glass roving. That particular roving type consists of 12 fiber bundles which are sized individually, so they can be easily separated. Nine of such 12 fiber bundles were removed from the roving and used as the axial reinforcement.

On this particular 3-D braider setup, 36 yarns (each of them being a 6-ply carbon nanotube yarn) were tied to the movable braiding positions. The total cross sectional area of S-2 glass fibers, 0.131 mm^2, was taken from the manufacturer's data sheets. The total cross-sectional area of the carbon nanotube yarns was evaluated as 0.047 mm^2 (the cross-sectional area measurement technique described in [4] was used for this purpose). The side length of the preform is approximately 0.45 mm. The volume fraction of axial fiber in the preform was calculated to be 74%.

An optical micrograph of the produced hybrid 3-D braid is shown in Fig. 5. The fabric architecture is clearly seen on one side of the square-shaped braid. Three of the nine S-2 glass axial bundles can be seen along the length of the preform. The produced braid is very uniform along its length, and it appears from the optical microscope pictures that the braiding produced a very tight structure.

Fig. 5. Hybrid glass fiber/carbon nanotube yarn 3-D braid, 40x magnification

Fig. 6. Illustration of comparative bending stiffness of the hybrid 3-D braid and the bundle of individual S-2 glass fibers

One interesting feature of 3-D braided preforms is that the braiding yarns 'consolidate' entire structure and provide support for the axial yarns.

This effect was observed even for the small samples produced in this study. Fig. 6 shows two structures being suspended horizontally. The one, which stays nearly horizontal, is the hybrid 3-D braid of Fig. 5. The other one, which is bent by its own weight, is a loose fiber assembly containing same nine fiber bundles (i.e. same total number of glass fibers but without nanotube yarn). Both samples are 15 cm long.

7 Experimental Study of Electrical Conductivity

Electrical resistivity, or the inverse, electrical conductivity, is a bulk material property. The conductivity of a solid material can be calculated using Eq. 1:

$$\sigma = L / (R*A) \qquad (1)$$

where R is the measured resistance over length L, while A is the cross sectional area of the sample. This equation for bulk conductivity can be only applied to solid, macroscopically homogeneous materials. A solid metal wire would fall under this category.

If the sample is discontinuous along its width or length, internal contact resistances within the sample must be taken into account. The example of this kind is a tow of carbon fibers. Each single carbon fiber can be viewed as continuous material, therefore electrical conductivity measurements can be taken by placing probes on the surface of the material. Using the same procedure to find the resistivity of a carbon fiber tow would yield a much different result. Indeed, in this case the probe lies on the surface layer of fibers in the tow. The fibers within the core of the tow will contribute to electrical conduction, but their contribution will be a function of the number and closeness of the contacts made from fiber to fiber. Obviously, this creates additional resistance in the material and so the conductivity appears to be lower.

The same considerations readily apply to the cases of plied nanotube yarns and 3-D nanotube braids. Those single yarns in this type of structure which are exposed to the surfaces, may be in direct contact with the probes while the others, which are located inside the structure, are at some distances away from the probes. Even though the measured values of electrical resistance of the aforementioned structures cannot be used to evaluate their bulk conductivity, Eq. 1 can still be used to compare the relative conductivities based on the dimensions of the samples.

The described method was used to compare the relative conductivities of four types of samples: (i) AS4 3K carbon fiber tow, (ii) 5-ply carbon nanotube yarn, (iii) 3-D braid made with solely carbon nanotube yarns, and (iv) the hybrid 3-D braid made with 9 bundles of S-2 glass fiber and 36 carbon nanotube yarns, as described above in Section 6.

The samples were all tested on a Hewlett Packard 4145A Semiconductor Parameter Analyzer using two probes at room temperature. The resistance was calculated from the slope of the voltage vs. current plot during a current sweep of -100 to 100 mA for the carbon fiber tows, the 3-D braided nanotube yarns and the hybrid 3-D braid. The current sweep for the smallest structure, the plied nanotube yarns, was -1 to 1 mA.

Conductive silver epoxy was used to create contacts on each of the structures. This was done because the testing probes were very small and would not come into contact with a very large surface area on the samples. On the hybrid 3-D braid, the probe would only touch a single (non-plied) nanotube yarn. The epoxy material had surrounded each sample completely at each contact point, so that multiple fibers or yarns would be contacted. On a glass microscope slide, the mixed silver epoxy was put down in thin lines. The sample was then placed on the slide and a second thin line of epoxy was deposited over the first, encapsulating the surface of the sample. The epoxy was extremely viscous, almost paste like, due to the presence of silver particles. With this extremely high viscosity, it was assumed that none of the silver epoxy penetrated into the structures but rather coated the surface. The epoxy was allowed to cure overnight. Fig. 7 shows two contacts on the hybrid 3-D braid sample. Each sample had four different contact points spaced apart at approximately same distance. The spacing between contacts was measured with a digital caliper. The multiple contact points allowed the resistance as a function of length to be determined.

In application to composites, the electrical properties of the constituent materials or preforms are not as important as the electrical properties of the final composite part. The addition of an epoxy matrix can reduce the conductivity of the composite preform because the insulating matrix may coat the fibers, thus eliminating many electrical contact points between them. Hence, it was also important to measure the electrical conductivity of composites made from the previously tested samples.

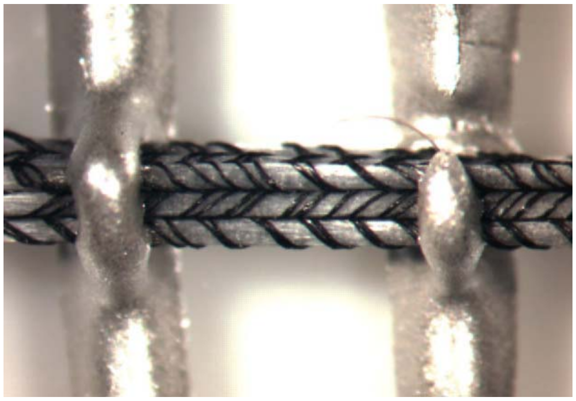

Fig. 7. Test setup for a dry hybrid 3-D braided material with electrical contacts

Composites were made from the same preform samples used in the previous resistance testing for consistency. Using a syringe with a needle point opening, mixed epoxy resin was placed on the surface of each structure. As the structure absorbed the epoxy, more was added to the surface until the structure was saturated. At that point, extra epoxy began to pool around the structure. The samples were cured by heating in an oven for 3 hours at 90^{o}C. Fig. 8 shows the hybrid 3-D braid after infusion and curing of the epoxy, taken with an optical microscope.

(a)

(b)

Fig. 8. Hybrid 3-D braided composite illuminated from above (a) and below (b)

In Fig. 8 (a), the epoxy appears to be evenly distributed across the hybrid structure. Fig. 8 (b) shows the same structure being illuminated from below. The glass fibers became translucent with the addition of epoxy, so that the dark nanotube yarns within the structure can be discerned. Notice the difference in appearance from Fig. 7.

The use of the extra fine syringe tip allowed the epoxy to be placed precisely, so that the silver epoxy contacts would be free of epoxy for testing. The method used here to test the composites was identical to the above described method used for testing dry yarns and braids. Therefore, the differences between results for the composites and their respective preforms can be attributed entirely to the presence of the epoxy matrix.

8 Experimental Results and Discussion

The measured resistances and the relative conductivities based on the geometry of each sample type are listed in Table 1. It is not surprising that the carbon fiber tow had the highest conductivity of all of the samples, considering that individual PAN based carbon fibers have a bulk conductivity of approximately 650 S/cm [12], while individual carbon nanotube yarns have a bulk conductivity of 300 S/cm [2]. However, the 5-ply nanotube yarn and the 3-D nanotube braid were very close behind. Possibly, this is due to the size of each structure. The 3K carbon fiber tow has the largest cross section among the three comparable samples, therefore it would have the least amount of fiber surface contact regions.

The relative conductivity of the 3-D nanotube braid was lower than that of the 5-ply nanotube yarn due to the fact that not every yarn in the 3-D braid made contact with the silver epoxy. Only part of all yarns are simultaneously on the surfaces of the braid; the rest of the yarns are entirely inside. Those yarns which are in the interior of the braid could have contributed to electrical conduction, but the added contact resistance between the yarns lowered its overall value. Further, as is seen from Table 1, the electrical conductivity of the hybrid 3-D braid is lower than that of the 3-D braid made from nanotube yarns only. This can be explained by the increase in the preform size due to the addition of the insulating S-2 glass fibers. The drop in conductivity well correlates with the change in the fiber volume content of the nanotube yarns within the preform. For example, in the hybrid 3-D braid, the nanotube yarns made up 26% of the yarns in the structure, while the conductivity was 23% of that of the 3-D braided structure containing only nanotube yarns.

Table 1. A comparison of electrical resistances and conductivities of dry yarns and 3-D braids, and composite made thereof

Material Type	Cross sectional area (mm^2)	Contact distance (cm)	Resistance (ohms)	Conductivity (S/cm)
AS4 3K carbon	0.119	0.527	4.52	97.977
5-ply nanotube yarn	0.00114	0.637	607	92.055
3-D nanotube braid	0.0472	0.489	13.38	77.430
Hybrid 3-D braid	0.178	0.402	12.63	17.881
AS4 3K carbon composite	0.119	0.527	6.96	63.629
5-ply nanotube yarn composite	0.00114	0.637	688	81.217
3-D nanotube braid composite	0.0472	0.489	16.7	62.037
Hybrid 3-D braid composite	0.178	0.402	14.68	15.384

Infiltration of epoxy resin into the different studied textile structures lowered the electrical conductivity of each of them, which was expected. The electrical resistance and conductivity values for each composite structure are also shown in Table 1. Surprisingly, the nanotube yarn structures were the least affected by the addition of epoxy matrix. Specifically, the hybrid 3-D braid's electrical conductivity was only lowered by 14%, while it was lowered by 35% in the case of AS4 carbon fiber tow. Also quite surprisingly, the electrical conductivity of the 5-ply nanotube yarn composite shows higher than that of the AS4 carbon fiber tow composite. This is a significant find, considering that the carbon fibers are continuous across the contacts, while the carbon nanotube yarns are made up of discontinuous nanotubes. This result could be understood if the resin failed to penetrate into the carbon nanotube yarns. However, the same resin as used here was seen penetrating thoroughly into the nanotube yarn in previous work [4].

The preservation of the conductivity in the nanotube yarn composite could be also due to the presence of nanotube bundling within the yarns. In addition, the extreme length of the nanotubes in the yarns ensures that nanotubes will meander from bundle to bundle creating a continuous network. The spacing between nanotubes in the nanotube bundles is small enough to prevent epoxy penetration into those areas. Thus, the resin infusion would not have as large effect on the conductivity of the overall structure as in the case of AS4 unidirectional composite. The spacing between fibers in the carbon fiber tow allowed resin to penetrate and cover many of the fibers, thus reducing the amount of fiber contact area in the structure.

9 Conclusions

The major goals of this study were achieved. It was shown that carbon nanotube yarns could be integrated with traditional fibers to produce a hybrid composite preform. To the best of the authors' knowledge, this is the first example of a composite of this type ever made.

The techniques used in this study of electrical conductivity of various type dry textiles and composites made thereof did not provide absolute conductivity values for the structures tested. Contact resistance between the probes and the silver epoxy as well as contact resistance between the silver epoxy and the structures was included in the resistance measurements. This indicates that the bulk conductivity of these structures could be higher than the values given. The consistent mounting and testing techniques between sample types do provide useful information. The calculated relative conductivities provide insight into the effective electrical properties of carbon nanotube yarns and 3-D braids in composites.

The nanotube yarns and 3-D braids tested here acted as networks of electrically conductive paths in the composite whose conductivity was many orders of magnitude greater than that of pure insulating S-2 glass. The electrical conductivity of the hybrid 3-

D braided composite was found to be 15-1000 times greater than that of the composites made from dispersions of carbon nanotubes in epoxy [8-10].

Although the conductivity of the hybrid 3-D braided composites was found much greater than that of fiberglass, integrating the carbon nanotubes with carbon fiber tows would create negligible electrical conductivity enhancement. However, there is much room for improvement for the electrical properties of carbon nanotube yarns. As the length of the nanotubes increase and the methods to selectively grow only conducting nanotubes are discovered, the electrical conductivity of the yarns will increase.

With further development, carbon nanotube yarns could be the future of specialty high performance composites that demand multifunctional properties. As the yarns are further improved and become commercially available, continued research is needed to evaluate how these yarns perform both in a dry form and within composites. Future work of these authors will characterize the thermal properties and fracture toughness of the hybrid 3-D braided and 3-D woven composites that incorporate carbon nanotube yarns.

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