Non woven technical Textile in aerospace applications

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Nomenclature

CT	=Cubic Tech Corp.
FAW	=Fiber Areal Weight
LTA	= Lighter-Than-Air
MDA	=Missile Defense Agency
PBO	= Poly(p-phenylene-2,6-benzobisoxazole)
PEN	=Polyethylene Naphthalate
PET	=Polyethylene Terephthalate
PVF	=Polyvinyl Flouride
SBIR	= Small Business Innovation Research
UHMWPE	= Ultra High Molecular Weight Polyethylene
USASMDC	=United States Army Space and Missile Defense Command

I. INTRODUCTION

The development of advanced materials will continue to enable previously impossible aerospace applications. Research continues on novel materials that minimize weight and improve strength, while addressing other critical properties. Flexible composites, owing their heritage to high performance, low stretch sails used in yacht racing competitions, including around the world races, continue to be developed by Cubic Tech Corp. (CT). These materials take advantage of the newest in high strength-to-weight ratio fibers, technical films, woven fabrics, and other high performance materials.

Lightweight outdoor products, medical devices, inflatable tubes, parachutes, parafoils, large kites, and most recently high altitude airships have been developed using this technology. CT received funding from the MDA (a program transferred to the USASMDC) for two phases of SBIR work on the development of “Very Lightweight High Tenacity Fabrics” for high altitude lighter-than-air systems.

This paper will introduce concepts of flexible composite technology and the potential advancement in the state-of-the-art of materials for LTA, terrestrial inflatables, space inflatables, and decelerator systems. To encompass the spectrum of potential material properties, examples of ultra-light, medium, and heavyweight materials of various constructions will be presented. The intuitive engineer may find utility in these materials for applications requiring similar weight materials or anything in-between.

II. MATERIAL CHALLENGES

Material challenges in aerospace applications have been well documented in previous publications. For high altitude, LTA systems, strength-to-weight ratio of the material is critical to payload capability, the size of the system, and maximum operational altitude. Materials must be able to survive tough stratospheric environmental conditions, which include low temperature, intense UV radiation, and high ozone concentration; low gas transmission, through the hull and ballonet, is necessary to maintain lift for long duration missions, high tear resistance ensures the durability of thevehicle Recent advances in high performance fibers, including Dyneema®, Zylon, and Vectran meet and exceed many of the material requirements in these applications. These materials maintain a significant advantage over traditional materials, such as those made from polyester or nylon, whose strength-to-weight ratios are too low for advanced aerospace applications.

III. FLEXIBLE COMPOSITE OVERVIEW

A. Flexible Composite Implementations

CT produces flexible, multidirectional, non-woven laminates from oriented filament layers and high Performance films or surface coatings. The resulting composite laminates are tailored and optimized for strength, stretch properties, and minimum thickness. These materials are easily customizable to a wide variety of weights, ranging from 0.3 oz/yd2 to over 20 oz/yd 2, and may be formed in 2 and 3-dimensional parts. CT’s laminates can utilize most of the advanced engineering fiber materials available, and design is based on the required operating conditions and parameters of the specific application. Available fiber choices include, but are not limited to: UHMWPE (Dyneema®, Spectra), liquid crystal polymer (Vectran), PBO (Zylon), para-aramids (Kevlar, Twaron, Technora), carbon, glass, nylon, and polyester. A variety of surface films, foils, or coatings can be incorporated including, but not limited to: PET (Mylar), polyamide (Nylon), polyimide (Kapton, Upilex, LaRC-CP1), PVF (Tedlar), and urethane. These surface materials add customizable properties including toughness, low gas permeability, low and high temperature operating capability, and visible and UV light protection, to name a few. There are also woven backing options for improved durability and abrasion resistance, although these often add to the weight and thickness of the material.

B. Internal Reinforcement / Complex Geometries

The laminated construction of composite fabrics enables the introduction of internal reinforcement patterns that minimize weight and are structurally sound locations for attachment points. Reinforcements may include attachment loops, corner patches, radial and edge load point reinforcement, and feathered patterns. Figure 3 demonstrates an integrated 360° radial reinforcement pattern, and a large integrated structure panel.

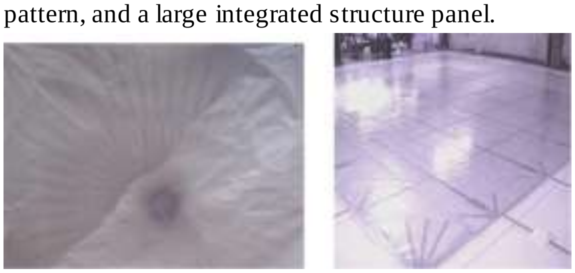

Figure 3. (Left) 3D 360° Radial Reinforced Panel & (Right) Large 40ft x 40ft Integrated Structure Panel for Decelerator Applications

C. Woven vs. Non-Woven Construction

Non-woven fabrics have a number of technical and performance advantages over woven fabrics. Lightweight woven products must use a multitude of low denier tows, while CT is able to produce similar, and oftentimes-lighter weight, materials from a lower number of high denier tows. This eases manufacturability, while allowing for weight and thickness optimization. Additionally, woven fabrics suffer from crimp, which is caused by fibers passing over and under each other in the weave. Tensile loading of woven fabric induces transverse loads at fiber overlap sections as crimped fibers attempt to straighten; this reduces the translation of fiber strength to fabric strength and decreases long-term fatigue and creep rupture performance. Crimp related reduction in properties is particularly pronounced with higher performance engineering fibers where optimization of axial filaments properties weakens transverse properties of the filaments. Figure 4 is a magnified image of a woven polyester fabric followed by an illustration of crimp in woven fabrics as load is applied.7, 8 Non-woven oriented composite laminates are free from these limitations and may be produced with an unlimited range of fiber areal weights having multiple oriented layers positioned at any angle. The most significant advantages of oriented laminates are the ability to optimize weight, thickness, and strengths at particular locations or along predetermined load paths. Non-woven flexible composites constructed from high modulus fibers have predictable and linear properties for engineered designs. Figure 5 illustrates this point with a stress-strain graph of a non-woven material, with no crimp, and a woven fabric having crimp. A conceptual drawing of a non-woven fabric is also included in Fig. 5.

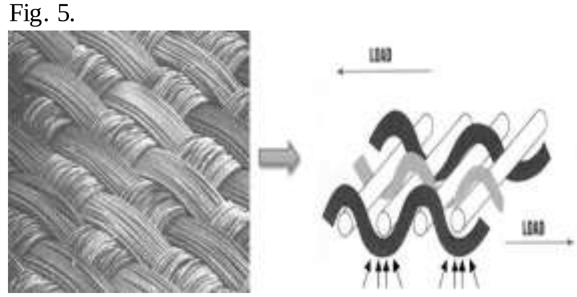

Figure 4. Magnified Image of Woven Polyester and Crimp Diagram.7,8 Tensile loading of woven fabric induces transverse loads at thread overlap intersections due to straightening of crimped fibers

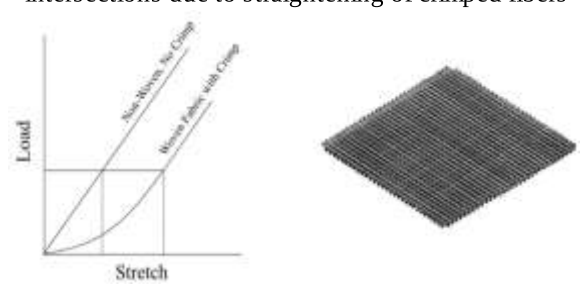

Figure 5. (Left) Comparative Stress-Strain of materials with and without creep. (Right) Conceptual Drawing of a non-woven material.

IV. MATERIALS OVERVIEW

CT has experience engineering laminates using a wide variety of high performance fibers that are chosen depending on the specific application and technical requirements. Engineering fibers each exhibit a particular blend of properties and differing applications require fibers that have differing property tradeoffs. A thorough understanding of material properties along with the use of appropriate safety factors simplifies application specific fiber selection and minimizes risk.9,10 An overview of the material properties for the Dyneema®, Zylon, and Vectran fibers is presented in the following paragraphs. CT can also produce composites from UHMWPE, para-aramid, carbon, glass, nylon, polyester, and most other engineering fibers. The fiber descriptions are followed by a brief overview of typical surface coating options. For aerospace applications requiring specific surface properties, CT will work with specialized surface coating manufacturers to meet project requirements.

A. High Performance Engineering Fibers

DSM and Honeywell produce similar UHMWPE fiber under the trade names of Dyneema® and Spectra respectively. Dyneema® has the 2nd highest strength-to-weight ratio (second only to PBO for commercially available fibers), and outperforms Zylon and Vectran in flex fatigue and resistance to moisture and UV light. Dyneema® products are often a preferred choice for flexible composites based on these properties. Performance concerns with Dyneema® include creep, which increases with temperature and load, adhesion, and its low melting temperature.2,5 This tradeoff of less than ideal creep but excellent UV performance may be easier to design for, and determine life factors from, than from materials with opposite trade-offs. Creep may be modeled from existing parameters based on temperature and load conditions11,12, while the environmental degradation of PBO or Vectran is less quantified and more difficult to monitor in situ. References 13-16 provide information on the mechanisms and test results for the creep behavior of Dyneema®.

Zylon fiber is made from rigid-rod chain molecules of PBO. It is available with slightly higher strength-to-weight ratio than Dyneema®. In addition, Zylon has a high decomposition temperature and excellent creep resistance. The fiber has good abrasion resistance, but performs significantly lower than Dyneema®. The strength of Zylon is significantly decreased by exposure to high humidity/high temperature, and UV/visible light. As a result it must be very carefully protected from these conditions.2,17 For additional information on environmental effects on the performance of Zylon see references 18-22.

Vectran offers a unique balance of properties in comparison to other high performance fibers. Vectran is a liquid crystal polymer having strength and modulus lower than Dyneema® or Zylon but other properties falling between those of Dyneema® and Zylon including: creep, abrasion, UV performance and flex/fold resistance.2,5,23,24 Vectran was qualified for use in the Mars Pathfinder landing system, due to its performance over a wide temperature range and flex fatigue resistance.6

Figure 6 compares the density, strength, and modulus for Dyneema®, Zylon, and Vectran. Specific strength and specific modulus is based on the tensile strength and modulus divided by each fiber's density. These values provide a better point for comparison.

Fiber Type	Density (g/cm^3)	Tensile Strength (GPa)	Specific Strength (Strength / Density)	Tensile Modulus (GPa)	Specific Modulus (Modulus / Density)
Zylon AS	1.54	5.8	3.8	180	116.9
Zylon HM	1.56	5.8	3.7	270	173.1
Dyneema®	0.97	3.4	3.5	111	114.4
Vectran HT	1.41	3.2	2.3	75	53.2
Vectran UM	1.4	3.0	2.1	103	73.6

Figure 6. Fiber Properties Comparison Table[12,15,21]

B. Surface Coatings

Film coatings, such as Mylar (a biaxially oriented PET), are used for their high tensile strength, toughness, chemical and dimensional stability, gas barrier properties, high temperature resistance and low coefficient of friction. For space related applications polyimide coatings and films, such as

Kapton or Upilex, remain stable over a wide range of temperatures and have good electric properties. For weatherability, PVF films such as Tedlar, provide long-term durability and environmental stability. Nylon and Urethane coatings offer excellent toughness and flexibility, at a lower cost than other options, but have lower mechanical and permeability properties.

Woven coatings are often incorporated into CT laminates when high abrasion resistance is the priority. The use of woven materials on one side of composite, or on both, creates a laminate hybrid that blends the high strength, dimensionally stable flexible composite construction with the limited benefits of woven technology. Woven coatings are typically heavier than other types of surface coatings but can be the best choice in areas of the part design where abrasion resistance is the driving factor.

C. Bondability & Seaming

Regardless of the strength of an aerospace quality material, the strength or dimensional stability of joints used to construct the structure is often a limiting factor in structures made using flexible materials. Due to the high strength, low elongation and homogenous distribution of fibers within the laminate, flexible composite laminates can be constructed with seams that are actually stronger than the base materials and are capable of carrying high structural loads for long periods of time without failure, seam slippage, seam distortion, or creep. Depending on the composite's design, most standard forms of seaming are suitable for fabrication including sewing, adhesive bonding, heat welding, ultrasonic welding, and laser enhanced bonding.

V.EXAMPLE MATERIALS

One of the unique characteristics of the CT flexible composite manufacturing method is the ability to produce uniform materials, with engineered and multidirectional tailored properties, in weights ranging from 0.3 oz/yd2 to over 20 oz/yd2, while utilizing a wide variety of engineering fibers and coatings, but only a single process technology. Listed below are several classes of implementations using various engineering fibers that are suitable for a wide range of applications.

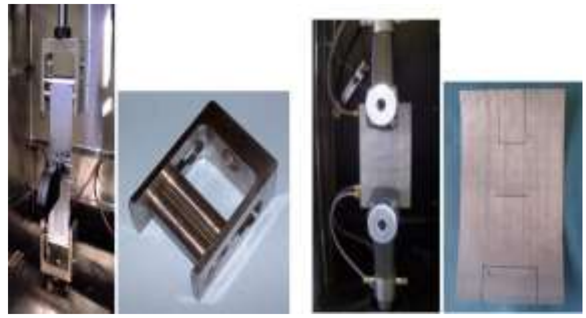

Figure 7. Bollard Grips. Pictured during tensile testing with loaded specimen and attached Instron extensometer.

Figure 8. Slit-Tear Specimen (Mil-C-21189 10.2.4). Pictured during tear testing using Pneumatic/Hydraulic grips.

A. Test Methods

Materials were tensile tested using the ASTM D3039M test method and also a non-standard test method for tensile testing. ASTM D3039M utilizes tabbed specimens to relieve gripping stresses caused by mechanical gripping forces. For more rapid testing without the need for tabbed specimens, self-tightening Bollard grips (Fig. 7) are often used. The Bollard grips show utility for tests up to a few hundred pounds but may not provide optimal gripping for tests reaching higher loads. Most of the tensile tests in this paper were conducted using the Bollard grip test method at an approximate strain rate of 30%/min. Instron 5567 and Instron 5568 load frames with appropriate load cells, Instron Bluehill software, and Instron clip on extensometers were used.

The slit tear method is specified by Mil-C-21189 Method 10.2.4, and similarly FAA-P-8110-2, both specifically developed as airship design criteria. The slit tear specimen is 4in by 6in having a 1.25in long cut in the center of the specimen (Fig. 8). Ref. 1 is also a good resource on appropriate tear test methods for airship materials.

B. Lightweight Flexible Composites

Lightweight oriented multidirectional composite laminates may offer a higher performance alternative to nylon or polyester woven materials in applications such as parachutes, parafoils, balloons, and other applications where very thin, lightweight, strong, and tear resistant material is required. Compared to silicone coated nylon of similar weight and thickness, CT's laminate is 80% stronger, has 10 times higher modulus, and 4 times higher tear strength. For a comparative strength to the silicone coated woven nylon, an ultra-light CT material (CT0.3HB UHMWPE Composite), weighing 0.5 oz/yd^2 is included in the table below (Fig. 9). While woven fabrics have very little strength in the bias directions, the CT0.3HB and CT1.5HB UHMWPE composites have been designed with quasi-isotropic properties. As a result, the shear properties of CT composites significantly outperform woven fabrics.

Although there is some strength contribution from coatings and films, which is not accounted for, high conversion efficiency means that the fiber strength is successfully transferred to the strength of the composite. The theoretical strength of the CT1.5HB UHMWPE Composite, based on fiber density alone, is 75 lbf/in. In comparison to the tested tensile strength of 87 lbf/in, this represents a conversion efficiency of 116%. The theoretical strength of the CT0.3HB UHMWPE composite is 28 lbf/in, when compared to a tested tensile strength of 41 lbf/in, the CT0.3HB conversion efficiency is 146%.

Product	Silicone Coated Woven Nylon	CT1.5HB UHMWPE Composite	CT0.3HB UHMWPE Composite
Weight (oz/yd^2)	1.3	1.2	0.5
Thickness (in)	0.002	0.002	0.001
Tensile Strength (lbf/in)	48	87	41
Theoretical Strength @ 23°C (lbf/in)	--	75	28
Conversion Efficiency @ 23°C (%)	--	116	146
Modulus ((lbf/in)/(in/in))	237	2774	1670
Strain to Failure (%)	33.0	3.2	2.9
Slit Tear Strength (lbf)	26	108	38
Bias Tensile Strength (lbf/in)	--	87	41
Bias Modulus ((lbf/in)/(in/in))	--	2774	1670
Helium Gas Permeability ($L/m^2/24hrs$)	--	<0.2	<0.2

Figure 9. Properties of Silicone Coated Woven Nylon and CT Lightweight Composites

C. Medium Weight Flexible Composites

The properties of medium-weight laminates constructed from Vectran and Aramid fibers are included in the table below (Fig. 10). Materials of these weights may be utilized for LTA or other inflatable structure applications. In addition to low gas permeability, these composites have excellent low temperature performance and pressure retention. The high conversion efficiencies reflect the excellent transfer of fiber mechanical properties to laminate mechanical properties that allows for predictable and repeatable material elastic properties.

Product	CT35HB Vectran Composite	CT35HB Aramid Composite
Weight (oz/yd^2)	4.1	4.7
Thickness (in)	0.006	0.005
Tensile Strength @ 23°C / -60°C (lbf/in)	523 / 670	587 / 650
Theoretical Strength @ 23°C (lbf/in)	501	546
Conversion Efficiency @ 23°C (%)	104	107
Modulus @ 23°C / -60°C ((lbf/in)/(in/in))	18951 / 22285	26556 / 28645
Strain to Failure @ 23°C / -60°C (%)	2.6 / 2.8	2.2 / 2.2
Slit Tear Strength @ 23°C / -60°C (lbf)	205 / 229	131 / 125

Figure 10. Properties of CT Vectran and Aramid Medium Weight Composites

D.Heavyweight Flexible Composites

CT's heavyweight composites may be used in tension structures having high strength, low elongation, linear stress-strain behavior, tear and damage resistant requirements, and/or application requiring multi-axial structural reinforcement. Examples of potential applications include: large-scale heavy lift airships, inflatable structures or beams, tension structures and flexible pressure vessels. Examples of these material's characteristics are included in the table below (Fig 11).

Tabbed specimens were tested in addition to Bollard grip specimens when the Bollard grip method resulted in low strength results. It is likely that the Bollard grips are not sufficient to provide adequate gripping and may cause stress concentration and edge effects at high loads. Using Bollard grips, the conversion efficiencies for the CT155HB UHMWPE Composite and CT135HB PBO composite are only 75% and 72% respectively. However, tests using the ASTM D3039M method using tabbed specimens resulted in an improvement in conversion efficiency of 90% for the CT155HB UHMWPE Composite, and 85% for the CT135HB PBO Composite.

	CT155HB UHMWPE	CT135HB PBO

Product	Composite	Composite
Weight (oz/yd^2)	13.0	10.3
Thickness (in)	0.016	0.011
Bollard Grip Method		
Tensile Strength @ 23°C / -60°C (lbf/in)	1813 / 2122	1618 / 1924
Theoretical Strength @ 23°C (lbf/in)	2402	2250
Conversion Efficiency @ 23°C (%)	75	72
Modulus @ 23°C / -60°C ((lbf/in)/(in/in))	85820 / 109965	72794 / 81682
Strain to Failure @ 23°C / -60°C (%)	2.1 / 1.9	2.0 / 2.4
Tabbed Specimen Method (ASTM D3039)		
Tensile Strength @ 23°C (lbf/in)	2167	1934
Theoretical Strength @ 23°C (lbf/in)	2402	2250
Conversion Efficiency @ 23°C (%)	90	86
Slit Tear Strength @ 23°C / -60°C (lbf)	313 / 504	250 / 423
Helium Gas Permeability ($L/m^2/24hrs$)	<0.2	<0.2

Figure 11. Properties of CT UHMWPE and PBO Heavyweight Composites

VI. CONCLUSION

CT is developing materials to meet the challenges of current and future aerospace applications. High performance fibers and surface coatings are enabling this technology along with a unique manufacturing process that produces customizable flexible composites with optimum strengths and weights (weights ranging from 0.3 to over 20.0 oz/yd2). Material properties of these materials can be tailored for strength and modulus in multiple arbitrary directions and can be produced in seamless two-dimensional flat or three-dimensional complex curved structures exceeding 40 ft in width and exceeding 100 ft in length. Materials can be joined with seams that are stronger than the base laminate materials and capable of carrying structural loads for extended periods without failure, slippage, or creep. Laminates can be engineered for pressure retention, low gas permeability, environmental resistance and abrasion resistance.

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