Specifying Structural Composites for Architectural Use

Marcel Dery

Saint-Gobain Performance Plastics

May 2013

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Coated structural fabrics utilizing woven reinforcements have been available for well over fifty years. These have been based upon a variety of woven reinforcements including cotton, nylon, and polyester as well as a variety of polymeric coatings including elastomers such as neoprene and plastics such as polyvinyl chloride. Over the past forty years, one particular reinforced composite has become widely accepted for permanent structural end-use as a result of its unique capabilities to provide the necessary **strength and flexibility in tension** to accommodate the very substantial loads associated with long span designs while offering long service life and virtual incombustibility, the requisite behavior for *architectural* applications.

The acceptance of this composite is based largely on the excellent performance of the original architectural composite (**SHEERFILL®**) using glass fibers as the reinforcing elements in a polytetrafluoroethylene (PTFE) (Teflon®) coating matrix. The fiberglass reinforcement represents the major strength element which is, pound for pound, as strong as steel and is virtually incombustible (1). The PTFE matrix represents the most incombustible plastic known to science, requiring an atmosphere of over 95% oxygen to support combustion, and is known to withstand the outdoor environment for over 20 years with virtually no change in physical properties (2). In short, fiberglass and PTFE are highly complementary materials, well suited to the application **if properly combined** to maximize the virtues of each while minimizing their limitations (3). However, the realization of excellent membrane performance in-use is based not simply on the selection of fiberglass and PTFE as input material, but more precisely on the exact nature of the forms of these raw materials employed as well as the exact nature of their combination as a composite.

While it may seem almost self-evident, it should be recognized that the selection of virtually incombustible materials for an architectural composite with great life expectancy in the outdoor environment was viewed as imperative. But, it was also a selection that would demand careful engineering in order to fully realize the benefits of each material. Glass fiber, like many other high modulus fibers, has exceedingly great strength but relatively low elongation. This is a property that must be taken into account at every step when incorporating it into a composite whose virtue is to be its flexibility as well as its strength.

The initial success of this new composite material was very gratifying. The first project to use this material was the Student Center at the University of La Verne in La Verne California in 1973. The project was made of some 6,000 square meters of SHEERFILL product. Within 10 years the Hajj Terminal was built in Saudi Arabia using about 400,000 square meters of material, an incredible accomplishment by any measure.

However, some wondered whether this composite would be limited in penetrating into the market because of cost. They questioned whether certain applications would be excluded from possible use. CHEMFAB (now Saint-Gobain Performance Plastics) and Owens Corning (now AGY) undertook a project to see if other materials could be incorporated to bring down costs. No substitute was contemplated for PTFE. It is a unique material with characteristics that make it the coating matrix of choice. Furthermore other fluoropolymers such as FEP and PFA are quite a bit more costly. This left only one material to study; the fiberglass yarn. A clear choice was to move to a larger diameter yarn (DE – 6 micron, rather than 3 micron *Beta*® yarn) which was more readily available and lower cost.

The first step was to create analogs of present products and look at the physical properties results. This was done by both Owens Corning and CHEMFAB. Physical results are listed below in tables (1 and 2).

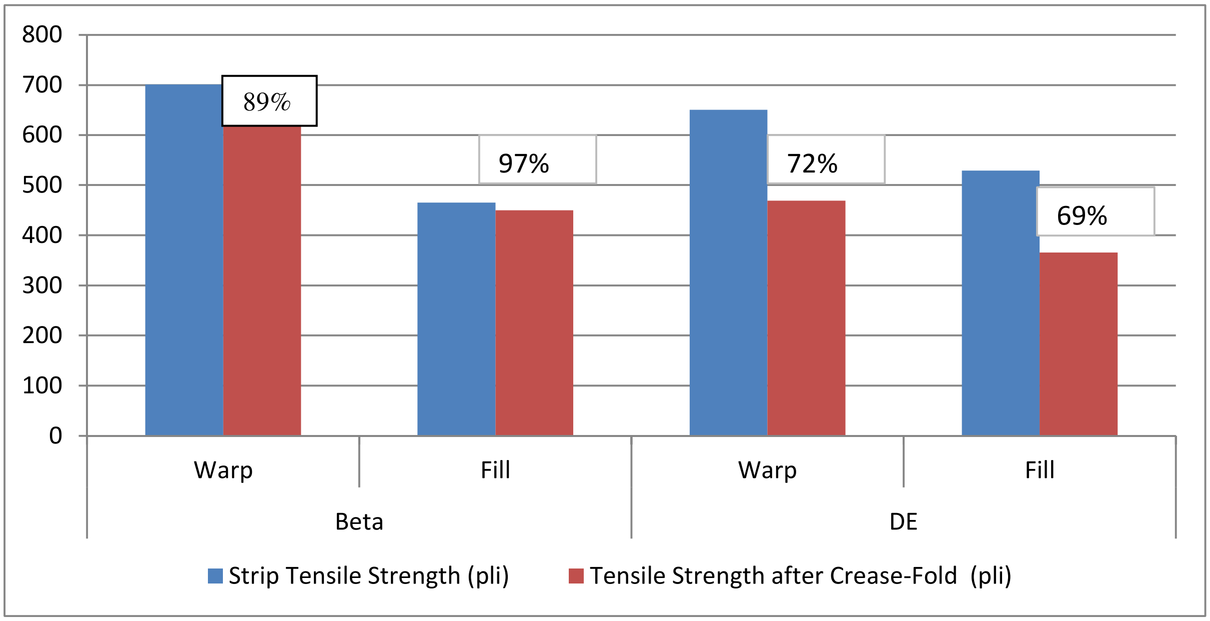
Table 1: Uniaxial Test Results for *Beta* and DE based Composite Membranes

CHEMFAB	Filament Diameter			
	Beta (3µm)		DE *(6µm)*	
Property	Warp	Fill	Warp	Fill
Weight (oz/sq. yd.)	38.7		37.1	
Strip Tensile Strength (pli)	943	739	734	670
Trapezoidal Tear Strength (lbs)	83	101	68	80

Table 2: Uniaxial Test Data for Lab samples of Medium-Weight Fabrics

Owens Corning	Filament Diameter					
	Beta (3µm)		DE *(6µm)*		G *(9µm)*	
Property	Warp	Fill	Warp	Fill	Warp	Fill
Weight (oz/sq.yd.)	38.4		37.3		34.9	
Strip Tensile Strength (pli)	701	465	650	529	508	430
Tensile Strength after Crease-Fold (pli)	622	450	469	366	504	400
Trapezoidal Tear Strength (lb)	65.1	77.0	58.1	70.8	49.1	71.0

Chart 1: Graphical Representation of Strip Tensile Strength vs. Tensile Strength after Crease-Fold Tests by Owen-Corning, for BC and DE reinforced fabrics



Further testing was done to look at biaxial strength of these products. This would provide information relative to installed material and its ability to withstand wide span loads (Table 3).

Table 3: Ultimate As-Manufactured Biaxial Strength

	Beta	DE
Maximum Stress (pli) 1:1 Biaxial Load	475	469

Based on these experiments and results, one might conclude that the DE version of these products would be acceptable in use for a tensioned structure.

The next step was to look at the ability of the finished composite to withstand the rigors of fabrication, shipping to the construction site and actual installation. This involves taking a roll good, cutting panels of different shapes and sizes, heat sealing seams, folding the finished product, placing into a box for transportation, unpacking the box at the construction site and proceeding to install the finished, fabricated unit. The fabric is put under severe mechanical stress during these operations. The fabric should be able to withstand these operations and retain as much strength as possible. To ensure the safety and long-term performance of the structure, DE (6 micron) yarn reinforced composite would need to exhibit properties similar to the Beta yarn.

To assess each fabric’s ability to withstand these mechanical stresses, the MIT flexfold endurance test was used. (MIT Tester pictured at right.) In this test, strips of fabric are repeatedly flexed over a small radius (approximately 0.015 inches) by oscillating them through an angle of 135 degrees in each direction while under modest tension (ASTM D2176).

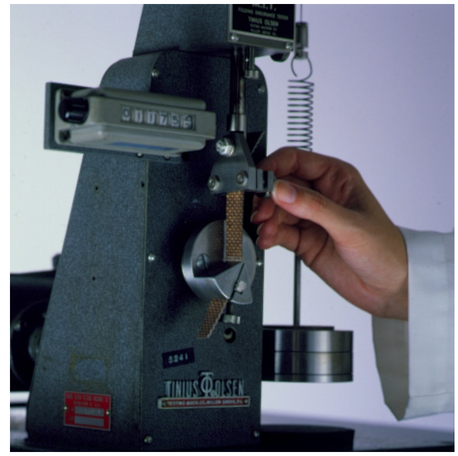


Table 4 and 5: MIT flexfold testing (CHEMFAB and Owens Corning) show the results of MIT Folding Endurance. The data shows the number of flex cycles the fabric was able to withstand prior to failure.

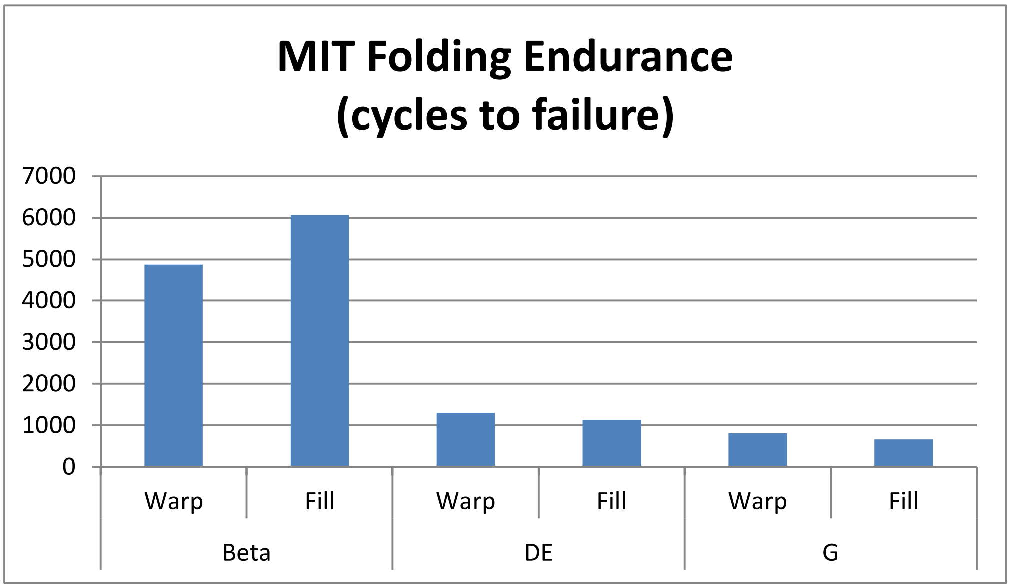
Table 4

CHEMFAB	Filament Diameter			
	Beta		DE	
Property	Warp	Fill	Warp	Fill
MIT Folding Endurance (cycles to failure)	10776	7140	4725	5344

Table 5

Owens Corning	Filament Diameter					
	Beta		DE		G	
Property	Warp	Fill	Warp	Fill	Warp	Fill
MIT Folding Endurance (cycles to failure)	4872	6069	1302	1128	810	663

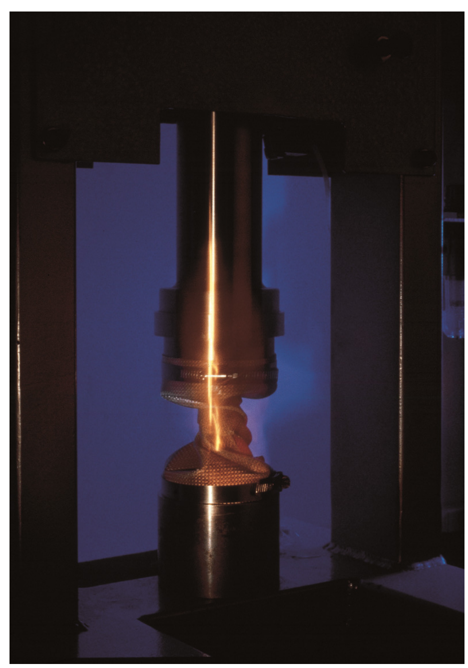
Chart 2: Graphical Representation of MIT Folding Endurance Test, Owens-Corning Data for Fabrics made with Three Different Yarns – BC, DE, G



The effect of filament diameter on the flexibility of the composite membranes is clearly evidenced by the results of the MIT folding endurance test. These results brought the use of an alternate yarn into question.

The behavior of biaxially flexed composite membranes was studied extensively in Owens-Corning laboratories. The specimen configuration used for those studies consisted of a fabricated cylindrical tube with the ends fixed to a metal plate. The fabric could be placed in biaxial tension by pressurizing the cylinder and tensioning in the axial direction through the use of an MTS tensile tester. This permitted a range of biaxial stress ratios to be studied.

Using Owens-Corning's biaxial test fixture (pictured at right), any given specimen could be mechanically challenged (pre-damaged) by lowering the 90-pound upper end-cap of the cylinder to provide an axial crushing action (called the 'crumpled cylinder test')[8]. It is thought that this crumpling damage simulates the folding and flexing that can occur during fabrication, shipping and installation. Crumpled specimens were examined for rupture strength and biaxial fatigue. While the crumpled cylinder test represents a severe mechanical challenge to the composite, it offers convincing evidence of the dramatically different responses that can be expected as a result of changing filament diameter in "comparably strong yarns" of a given woven construction.



In the biaxial stress rupture test, the cylinders were crumpled as described above and then loaded biaxially (1:1) and time to failure recorded. The results of these tests indicated that ‘the DE based membrane has a long-term, ultimate (biaxial) strength between 125 and 150 pli. By comparison the long-term strength of the *Beta* based membrane is approximately 175 pli’ [6].

The requirements for wind and snow load safety factors will vary from structure to structure based on environment and the engineer’s analysis of the design of the structure. However, using a typical prestress load of 35 pli, the remaining long-term biaxial load bearing capability after folding damage provides the DE based membrane a safety factor of 3.9 compared to a factor of 5.0 for the *Beta* based membranes when tested under similar conditions. It is important to note that the actual level of stress required for rupture under biaxial loading conditions is considerably lower than the ultimate tensile strength of the composite measured uniaxially. While this fact is not surprising, it underscores the reality of damageability, in-situ, at stress levels that may be encountered in a membrane structure under significant wind or snow loads.

Perhaps even more convincing of the superiority of a very fine filament analog (*Beta*) as opposed to a thicker filament analog (DE) in membrane structures is the extent to which damage can occur on repeated biaxial flexing (flexural fatigue). In this test cylindrical specimens were subjected to cyclic biaxial loading after a single episode of crumpling. Data for composite membranes obtained in Owens-Corning laboratories are shown in Table 6 [6]. This type of damage is analogous to that which may occur due to the cumulative effects of wind or snow pressure over extended periods of time.

Table 6: Biaxial Fatigue (1:1 biaxial load ratio)

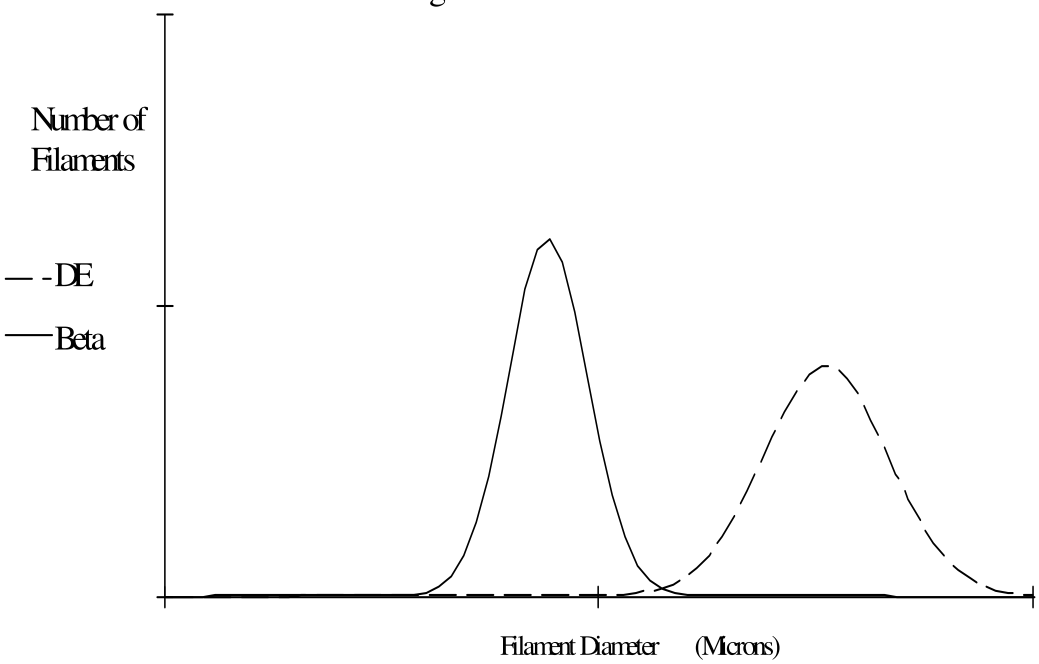
	Cycles to failure	
Applied stress cycle (pli)	*Beta*	DE
70 ± 40	>1,000,000	470
50 ± 30	Not tested	39,960

After applying a cyclical biaxial stress centered at 70 pli, the *Beta* analog survived over 2000 times as long as the “comparably strong” DE filament based product. Reducing the stress load to 50 pli permitted the DE filament analog to survive only 4% as long as the *Beta* filament analog at the higher stress level!

These dramatically different responses of DE filament-based and *Beta* filament-based membranes to biaxial stress under dynamic loads lend substantial credibility to the specification of *Beta* filament based yarns in architectural membranes when damageability issues in handling or in-use are taken into account.

The flexibility of the fabric is directly related to the ability of the reinforcing yarns to be bent over a small radius, which is, in turn, a function of the filament diameter and the packing of the filaments within the yarn. Directly from mechanics, the bending stiffness of a cylindrical filament is a function of the fourth power of its diameter. Typical filament diameter distributions for Beta® (3 micron) and DE (6 micron) yarns are shown in Figure 1[5]. The average DE filament is about 1.5 times greater in diameter than the average *Beta* filament. That means that a DE filament is at least 5 times stiffer than a *Beta* filament. The stiffness of a glass yarn constructed from a multitude of filaments is determined by the number, diameter and cabling of the glass filaments. If one takes all of these into account, the durability of a fabric made from DE yarn after being bent over a small radius is even more dramatically reduced as compared to a *Beta* yarn constructed fabric than the single filament analysis would suggest.

Figure 1: Filament Diameter Distribution



As the folding motion proceeds and continuously reduces the radius of curvature, the glass filaments fracture, starting with the largest diameter fibers (right side of Figure 1) and continues to fracture successively smaller diameter filaments (toward left side of Figure 1). Essentially, any fold that fractures all of the DE filaments will have fractured only a very small fraction (<5%) of the *Beta* filaments. Not only will the *Beta* fabric tolerate a tighter crease (smaller bending radius) but the fabric is much more damage tolerant when folded to any given radius.

What this testing clearly pointed out was the absolute need to not only look at uniaxial behavior of any membrane material but actual use handling and biaxial behavior could show dramatically different results.

In this paper, *Beta* and DE based composite membranes were compared with respect to their uniaxial (as manufactured) properties as well as after various simulations of flexural and fatigue damage under uniaxial and biaxial load conditions. Taken individually, each test:

- analysis of bending radii and filament breakage,
- retention of strength after uniaxial (MIT) flexing,
- relative levels of sustainable biaxial stress after crumpling damage, and
- ability to resist biaxial flexural fatigue

provides some indication of a need to be cautious in composite design and use. Taken in combination, they offer a highly persuasive argument for the selection of *Beta* filaments in the construction of membrane composites for structural applications.

Furthermore, nothing speaks more convincingly to the viability and suitability of *Beta* filaments in architectural composite membranes than the 40-year history of their use in a variety of structural applications and environments all over the world. Conversely, laboratory data suggest that there could be totally unacceptable risk in the application of unproven composites employing heavier filaments in otherwise similar composites.

Strength or extensibility *that cannot be accessed and maintained* during the anticipated use of such a composite in an appropriately designed and built structure must be avoided if structural integrity is to be attained. For this reason, changes to the original detailed raw material and process specifications for these *architectural membranes* should be undertaken only after a thorough review of their impact on sustainable strength and extensibility under tension.

(1) "Textile Fibers for Industry", OCF, Pub. No. 5-TEX-18027, 1994.
(2) Sperati, C.A., "Physical Constants of Fluoropolymers", Polymer Handbook, 3rd Edition, 1989.
(3) Effenberger, J.A., "SHEERFILL® Permanent Architectural Fabrics and Structures From CHEMFAB", Presented at a Symposium on Air-Supported Structures: State of The Art, London, 1980.
(4) Effenberger, J.A., "Choice of *Beta* Filaments for Structural Fabrics", CHEMFAB Internal Communication 1979.
(5) Lyle, D., Personal Communication, August 2000.
(6) Helwig, G.S., "Technical Report 83-T-21: Effect of Filament Diameter on Properties of Teflon-Coated Fiberglas Architectural Fabrics", OCF, 1983.
(7) Sahlin, K.M., Internal Communication kms9-40, 1999.
(8) Leewood, A. R., "Technical Report 81-T-323: HAJ Material Investigation Program", OCF, 1981.