ADVANCEMENTS IN MANUFACTURING AND APPLICATIONS OF 3-D WOVEN PREFORMS AND COMPOSITES

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Abstract

This paper describes recent advancements in one of the fastest growing areas of modern composite materials – thick unitary composites manufactured from 3-D woven single layer preforms. The manufacturing advantages and cost benefits offered by 3WEAVE® preforms used conjointly with VARTM, RTM or other suitable closed-mold method, are discussed in detail. Some new considerations aimed at design and optimization of the complex (including hybrid) 3-D fiber architectures, are proposed. The trade-offs between in-plane and out-of-plane mechanical properties, particularly between in-plane stiffness on one side and intralaminar fracture toughness on the other, are analyzed. Mechanical properties of some typical 3-D woven composites are presented and compared with those of traditional laminates. Some applications of 3WEAVE® composites in various military, aerospace and industrial products are briefly discussed. Finally, the reader is directed to publications on computational modeling and analysis methods applicable to 3-D woven fabrics, composites made thereof, and their structures.

1 Introduction

The new efficient methods developed for low-cost manufacturing of relatively thick, unitary 3-D woven preforms for composites raise high expectations that this class of materials will gain significant place in industrial, aerospace and military markets. Such expectations are justified by the ability of 3-D woven composites to privide sufficiently high in-plane mechanical properties and, at the same time, suppress delamination and markedly improve transverse strength, fracture toughness, damage tolerance, impact, ballistic, blast performances, as well as some other characteristics.

At the same time, faster and broader acceptance and practical utilization of 3-D woven composites faces several serious roadblocks. Among them are: (i) very small amount of mechanical characterization data and lack of any significant property database; (ii) difficulties with joining thick unitary preforms and composites, (iii) serious concerns about applicability of the standard mechanical characterization methods and data processing approaches, (iv) lack of universally accepted, versatile, experimentally verified and computationally efficient mathematical models, analysis and design tools. In the situation where it is problematic to accurately predict mechanical properties and structural response of existing or projected 3-D textile composite, the material itself may be disqualified from intended application.

This paper addresses recent advancements in the area of manufacturing 3-D woven fabric preforms and composites, presents some new concepts of optimal design, which is specific for this class of materials, and briefly addresses current applications.

2 Three-Dimensional Weaving

There are several known 3-D weaving processes and respective machines which are used by a number of universities, research organizations and industrial manufacturers. Very often '3-D weaving' and '3-D weave' are referred to as a group of textile processes, machines and products, with no distinctions made among substantially different sub-categories within. With a little more insight, 3-D weave is commonly subdivided into '3-D through-thickness interlock weave', '3-D layer-to-layer interlock weave', and '3-D orthogonal weave'. These historically established sub-categories help to distinguish among the three typical fabric architectures, but they do not relate to any specific process or machine used to manufacture either of the three fabric types. Due to '3-D weaving' and '3-D weave' are commonly used as generic names, this often causes confusion among researchers and industrial end users who are not intimately familiar with various existing 3-D weaving processes and machines and cannot easily identify the type of fabric they are using or intend to use. In particular, 3-D orthogonal weaves can be made on totally different machines, and with the use of very different processes; however, the produced fabrics may be hardly distinguishable.

Though in the author's opinion the time has come when this subject matter deserves a clear, objective yet not overloaded with textile machinery specifics treatise, it is not the subject of this paper. Here, only one type of 3-D weaving technology (often called '3-D orthogonal weaving') and one type of 3-D woven products, known under trademark 3WEAVE®, will be considered. This technology has been developed by Dr. Mansour Mohamed and co-workers at North Carolina State University in late 1980s - early 1990s and is distinguished by the US patent [1]. Also, a number of publications [2-10] are available for those who are interested in more details of this 3-D weaving approach, the developed machinery, products and their properties. In this particular 3-D woven fabric formation process, Z yarns interconnect all individual warp- and fill-directional yarns and thus solidify the fabric. Simple schematics of warp, fill and Z fiber placement is shown in Fig. 1.

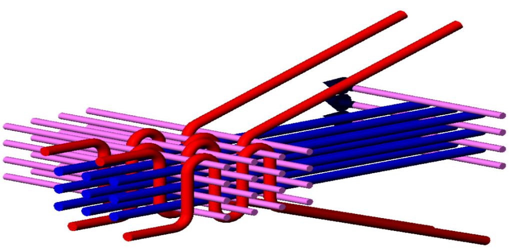


Fig. 1. Schematics of the yarn placement in 3WEAVE® fabric with three warp (blue) and four fill (pink) yarn layers; Z yarns colored red [14]

Without dwelling too much into the technical aspects here, it can be fairly stated that the principal innovative features of the approach manifest in (a) the way how 3-D orthogonal weave is formed from multiple layers of longitudinal ('warp') and transverse ('fill', a.k.a. 'weft') sets of yarns without interlacing them, (b) simultaneous insertion of all of the fill-directional yarns by special system of 'rapiers' moved between the layers of warp-directional yarns in each cycle of weaving operation, (c) the use of special multi-harness system for through-thickness ('Z-directional') yarn insertion enabling to produce certain complex shapes and various hybrid fiber architectures, (d) 'gentleness' of the weaving method to all fibers, owed to a relatively low machine speed, and (e) especially gentle treatment of warp-directional fibers which do not go through harness frames. The aspects (d) and (e) significantly reduce damage imparted to fibers during 3-D weaving process and allowed 3TEX to successfully work with high modulus graphite and ceramic yarns, metallic yarns and wires, optical fibers and some others which would be hardly possible to weave on other machines. Further technical details and discussions can be found in the aforementioned publications and also in [11-14].

By nature of the described 3-D weaving process, a "no-crimp" fabric is produced, which means that all warp- and fill-directional yarns remain practically straight, as seen in Fig. 2. This feature immediately distinguishes this kind of fabric from conventional 2-D woven fabrics which are crimped due to all warp- and weft-directional yarns are interlaced. Note that crimp is also present in some other types of 3-D woven fabrics.

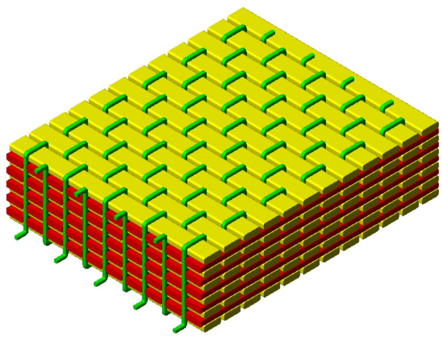


Fig. 2. Geometric model of 3WEAVE® fabric with 5 warp (red) and 6 fill (yellow) yarn layers; Z yarns colored green [14]

3 3WEAVE® Preforms and Composites – Specific Features and Properties

3.1 Manufacturing

Having a no-crimp fabric as composite reinforcement is obviously beneficial, because significantly higher in-plane stiffness and strength can be achieved. Also importantly, 3WEAVE® preforms have well-defined fiber architecture and its repeatability in practical manufacturing. The infamous 'manufacturing artifacts', such as random 'waviness', 'misalignment' and different 'flaws' of the reinforcement which are known in 3-D interlock weaves and have been extensively discussed in the literature, see [15-17] for example, are reduced to a minimum in the case of 3WEAVE® fabrics.

Another former issue is that manufacturing cost of 3-D woven fabrics was presumed much higher compared to the cost of their 2-D woven counterparts. However, in the case of 3WEAVE® this is not true anymore. Recall the aforementioned process feature, that all fill-directional yarns are inserted simultaneously within each fabric formation cycle. This means that the volume of fabric produced during one cycle does not depend on the number of warp/fill layers and, consequently, on the fabric thickness. Therefore, as thicker the fabric is, as more material is produced by 3-D weaving machine within one cycle of its operation. For example, if thickness of 3-D weave is 10 times of that of 2-D weave, the 2-D weaving machine has to make 10 times longer fabric (i.e. work 10 times more) as to produce equivalent volume of product. Or, inversely, in order to produce same volume of fabric within given time interval, 2-D weaving machine has to operate 10 times faster. In reality, the difference in operational speeds of conventional 2-D weaving machines and 3TEX's 3-D weaving machines is such as it makes the 3WEAVE® production economically viable and the product cost comparable. Besides, apart from the fabric production rate there are several additional cost-related factors worth attention.

One important effect, which was first discovered by authors of [13] and since then confirmed by other independent researchers and 3WEAVE® fabric users is attributed to the same features mentioned above, i.e. single-layer preform construction, straightness of the warp and fill yarns in 3WEAVE® preforms, and well-defined fiber architecture. It was found that polymeric resins propagate much faster in this type of 3-D woven fabric and completely fill it within much shorter time than same volume of different 2-D fabric stacks are filled. Indeed, a very regular, well-defined cubic grid-like fiber architecture of 3WEAVE® fabrics provides straight and relatively open channels in the three orthogonal directions, and such channels allow the resin to much easier propagate within the preform. Also importantly, having single-layer preform means that there are no negative effects of random fabric layer 'nesting' which slows down resin penetration in through-thickness direction.

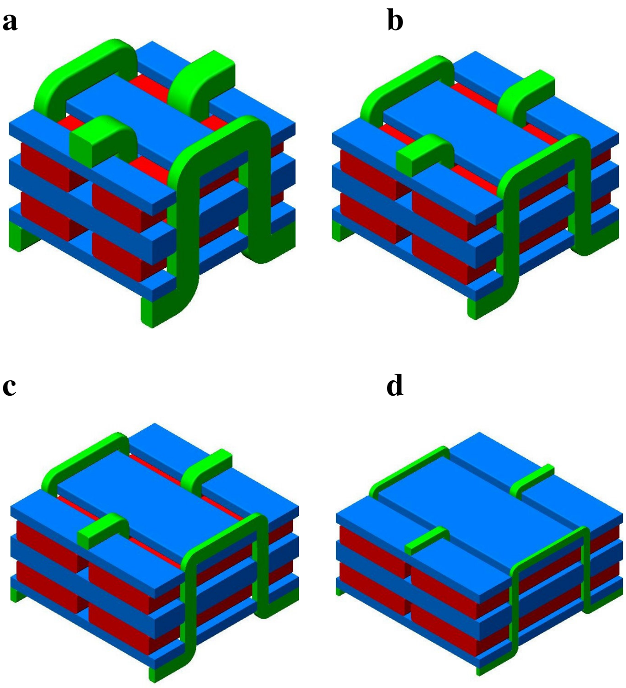
With this in mind, one can explore three optional benefits of using 3WEAVE® fabrics: (i) preform of given dimensions can be infused much faster, (ii) significantly larger preform can be infused during the given resin gel time, and (iii) a higher viscosity resin (with smaller gel time) can be fully infused into the given size preform. The latter factor is especially important for high performance aerospace composites, because aerospace grade thermoset resins are much more viscous than regular epoxies, vinyl esters and polyesters.

Further on, the above features (i) and (ii) directly affect the manufacturing cost of composite structures. The cost is lowered as the result of either reducing the manufacturing cycle time or making larger volume of product within given time. At least three principal cost reduction aspects associated with the use of 3WEAVE® preforms in composites manufacturing have to be noticed. One of them manifests in at least partial (if not complete) elimination of a very labor extensive and time consuming wet hand lay-ups of tens or even hundreds of layers of prepreg, tape or 2-D fabrics. The other one shows in increasing robustness of the manufacturing process. Obviously, utilization of a single-layer preform or a few layers of such preform combined with advanced, automatically controlled closed-mold resin infusion system, allows one to avoid a lot of flaws and irregularities which are inevitable with the use of hand lay-up technique. That, in turn, significantly reduces the probability of (usually very costly) structural failure. Third benefit is important to those composite manufacturers who have to deal with environmental protection regulations. It is well known that traditional open-mold techniques are being gradually replaced with closed-mold methods, and the primary driver in this transition is reduction in volatile emissions. The increasingly severe regulations are aimed at improving work environment, reducing factory emissions and, ultimately, reducing the danger of global warming. Respectively, violations become more and more expensive and business damaging. Many progressive boat and yacht manufacturers already use pre-impregnated reinforcements (3WEAVE® preforms in particular), together with polymer foam, balsa wood or honeycomb cores. The polymer matrix is cross-linked under vacuum; if necessary at elevated temperature.

The next question is: are mechanical properties and structural performance characteristics of composites made with 3WEAVE® preforms good enough to consider them as potential replacement for current structural composites. Specifically, three principal groups of properties will be illustrated and discussed in the following sections: (a) in-plane stiffness and strength, (b) interlaminar fracture toughness, and (c) impact, ballistic and blast response characteristics.

3.2 In-plane Mechanical Properties

Basically, there are three principal factors which control in-plane stiffness of 3WEAVE® fabric composites – (1) total fiber volume fraction, (2) distribution of fiber volume among warp, fill and Z directions and (3) straightness and alignment of fibers in all three directions. To illustrate the effects of factor (1), we reproduce in Fig. 3 several designs of 3WEAVE® considered in [18] in the context of the author's search for 'perfect' composite. The designs (a)-(e) use identical 12K doubled carbon yarn for both the warp layers (red) and for the middle fill layer (blue); 6K doubled carbon yarn is used for two outer fill layers (blue), which are twice thinner than all others. These five designs provide a 'balanced' preform, meaning that there is equal total volume of fibers in the warp and fill directions. At the same time, the size of Z-yarn (green) is different; it gradually reduces from 12K in case (a) to 6K (b), 3K (c), 1K (d), and 0.1K (e).



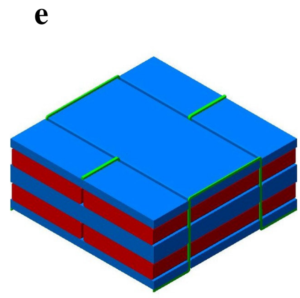


Fig. 3. Comparative designs of 3WEAVE® fabrics with different size Z-yarn: 12K (a), 6K (b), 3K (c), 1K (d) and 0.1K (e)

The designs (a)-(d) are practical, while (e) is hypothetical - no commercial carbon yarn containing 100 fibers exist. The presented designs clearly illustrate how the spacing between in-plane yarns (and, accordingly, the size of interstitial pockets) diminishes with reducing size of Z yarn. Interestingly, in case (e) the 3-D woven composite looks very much like a conventional cross-ply laminate made of five unidirectional layers, but with barely visible Z reinforcement. If taking diameter of carbon fiber 8 μm and yarn packing factor 70%, we obtain that 0.1K square has 85 μm side, which is the gap size between adjacent yarns in Fig. 3e.

Fig. 4 quantifies some principal characteristics of composite materials corresponding to preform designs (a)-(e). Geometric parameters and fiber volume fraction in each case were determined directly from the geometrical models. Elastic moduli were predicted by Stiffness Averaging Method. The yarn packing factor was taken 0.7; T300 PAN carbon fiber and typical epoxy resin properties were assumed in the modulus predictions.

It is seen in Fig. 4a that the increase of Z-fiber content is nearly linear, while Fig. 4b shows that total V_f has significantly nonlinear variation for small K values (naturally, it must reach 70% at K=0). It drops from 67.5% at K=0.1 to 58% at K=3 and to 49% at K=12. Further, Fig. 4c shows that elastic moduli in warp and fill directions vary with K similarly to the total fiber volume fraction variation. In the case of K=0.1 the in-plane elastic moduli can theoretically reach 80 GPa (which is a typical value for T300/epoxy cross-ply prepreg laminates with $V_f \approx 0.7$). This level of in-plane moduli has not been yet achieved for in-plane balanced 3WEAVE® carbon fiber composites. The typical values reached up to date are between 60 and 70 GPa; they were obtained for 3TEX produced 3WEAVE® composites with 3K Z yarn and total fiber volume fraction ~53%; some data can be found in [19].

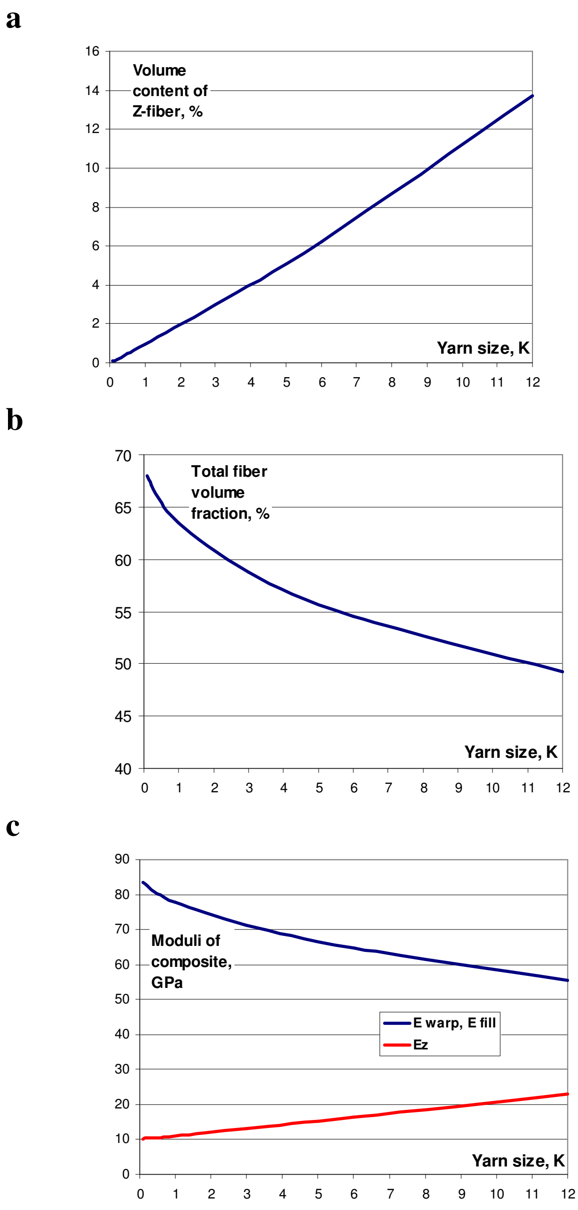


Fig. 4. Variations of Z fiber volume content (a), total fiber volume fraction in composite (b) and elastic moduli of composite (c) vs. size of Z yarn

We can compare now these experimental values with the predicted value corresponding to K=3 in Fig. 4c (in this case $V_f = 57\%$ according to Fig. 4b). It is seen that 70 GPa is at the upper end of the experimental values, which indicates some loss of in-plane moduli (typically more pronounced in the fill direction). That may be due to a lower V_f and a minor fiber waviness.

Fig. 4c also shows that there is predicted linear growth of elastic modulus in Z direction with increasing K. This modulus varies between 10 GPa at K=0.1 and 22 GPa at K=12. Experimental verification of these predictions by tensile tests is virtually impossible due to a small (in the range of several mm) thickness of composites produced. Probably, through thickness compression test is the only realistic way to obtain some data for transverse modulus. 3TEX does not possess such data at this point for carbon fiber 3WEAVE® composites. In-plane strength characteristics of some 3WEAVE® carbon fiber/epoxy composites can also be found in [19]. Those results show values between 900 and 1200 MPa; at the upper end these values are close to typical in-plane strengths of high-performance cross-ply graphite laminates with V_f above 60%.

The other two important fiber types extensively used in 3WEAVE® applications are E-glass and S-2 glass. Products made from E-glass fiber are mainly consumed by boat and yacht manufacturers, while S-2 glass preforms are used primarily in the area of personnel and ground vehicle protective armor systems. Besides, both E-glass and S-2 glass fiber 3WEAVE® preforms are of interest for various composite blast mitigation systems.

To conclude this part of discussion, it is worth noting that 3WEAVE® fabrics can be produced with the ratio of warp to fill fiber volume varying in a wide range. The fabric can be made as quasi-unidirectional in either one in-plane direction. Accordingly, the fabric can be tailored to specific biaxial loading conditions simply by changing the yarn size and insertion spacing in the warp and fill directions. Additionally, a hybridization of different fiber types can be used to further optimize composite design. For example, higher performance fibers can be used in the 'primary' loading direction to ensure maximum stiffness and strength, while more compliant fibers can be used in the 'secondary' direction just to prevent transverse crack initiation and development. Next we will analyze how Z-directional reinforcement should be optimized.

3.3 Through-Thickness Properties and Interlaminar Fracture Toughness

As shown in the previous section, the in-plane mechanical properties of 3WEAVE® fabric composites can be controlled, in a quite wide range, by the amount of fiber used in Z direction. Of course, the reduction of Z fiber amount cannot go below certain limit. Simply recall that Z-directional reinforcement has two principal functions in 3WEAVE® fabrics – to hold all fibers together and to prevent macrocracks between adjacent layers of warp and fill fibers.

The sequence of fabric designs shown in Fig. 3 helps to further elaborate the concept of optimal Z fiber amount. Let us adopt the concept that any structural material would be optimal if all failure modes which can lead to catastrophic failure are initiated simultaneously. From this point of view a unidirectional composite is not optimized if it is far from failure in the fiber direction, but allows macrocracks to propagate along the fibers. As another example, laminated material is not optimized if its layers are far from failure, while premature delamination disjoints them. Obviously, having controllable amount of integrated Z-directional fiber adds the required capability to optimize 3-D woven composite against any triaxial loading case.

The current methodology of choosing the amount of Z fiber in 3WEAVE® fabric designs is purely empirical and based on the designer's prior experience and intuition. Specifically, the collective 'rule of thumb' developed by 3TEX is that 2-4% by volume of all fiber should be placed in Z direction. It is believed that such amount is sufficient for full suppression of delamination and, at the same time, does not reduce the in-plane properties below acceptable level. Fig. 4a tells us that for the carbon fiber fabrics considered in Section 3.2 this falls into the range of 2K-4K yarn size and 3% exactly corresponds to commercially available 3K yarn. Further, it is obtained from Fig. 4b that the total fiber volume fraction in the case of 3K is limited to 58%. Next question is: what could have happened to 3WEAVE® fabric composite if 1K Z yarn was used instead of 3K one? Would the composite delaminate (meaning, split between layers of warp and fill fibers with complete breakage of Z fibers)? If so, what type of loading is needed to cause such failure? These are very interesting and practical questions, but they remain unanswered due to the lack of experimental and theoretical information. Yet, if the answer would be that 1K Z yarn is acceptable for loading cases of interest, the total fiber volume fraction in the composite could be increased to 63%.

Analogous situation exists for 3WEAVE® fabrics made from S-2 glass and E-glass fibers. Like in the case of carbon, the empirical rule of thumb is to use 2-4% of all fiber volume in Z direction. In the case of S-2 glass this basically gives the designer a single choice – 1250 yield/lb roving, because even 750 yield/lb roving would result in significantly higher Z amount than 4%. In the case of E-glass fiber, two roving sizes are used in most of the cases: 675 yield/lb, which provides 2.5-4% of all fiber volume in Z direction and 1800 yield/lb, which results in 0.5-1% Z fiber volume content.

Thus, commercial availability of yarn/roving sizes appears to be a significant factor limiting designer's choice. It further affects possible Z fiber volume contents in the preform and, consequently, total fiber volume fraction and in-plane mechanical properties. Of course, it is not mandatory to use same kind of Z fiber as the one used for the warp and fill directions. As pointed out before, all kinds of hybridization are possible in 3WEAVE® preforms. In some particular products 3TEX used Z yarns made of carbon PAN and pitch, E-glass, S-2 glass, ceramic, Kevlar, Spectra and polyester fibers; also, stainless steel yarns and some metallic wires have been used. Any of them can be combined with various warp and fill yarn materials.

Probably, among most exotic Z-directional fiber types ever used in weaving were optical fibers carrying Extrinsic Fabry-Perot strain sensors [20-21] and arrays of hundreds Bragg grating strain sensors [22], which enable for unique through-thickness in-situ strain monitoring of 3-D woven composites and their bonded and bolted joints. Another exotic examples are 3WEAVE® fabrics made with continuous Z-directional carbon nanotube spun yarns and 3-D braids [23]. Those fabrics were made on special 3TEX's 'micro-weaving' machine capable of manipulating very delicate small diameter yarns. As projected in [18], nanotechnology may open new avenue in the development of very fine, light and strong reinforcements for composites.

The best scientific way to optimize Z fiber volume content in 3WEAVE® preform for some given structural application is to determine its relation to the critical 'intralaminar' fracture characteristics (those may be critical stress intensity factors or critical strain energy release rates for fracture Modes I, II and III). The term 'intralaminar' is used here to emphasize that though composite is made from single-layer preform, there still are relatively weak planes parallel to the planes of warp and fill reinforcement. Figure 3e helps to visualize this definition. Imagine that there are no Z yarns at all; in such a way 3-D weave composite is reduced to a conventional cross-ply laminate. The planes between adjacent unidirectional warp layers and unidirectional fill layers now contain only resin and, naturally, they are the primary suspects for delamination. If a small trial crack is imbedded along these planes, then G_{IC}, K_{IC} and other similar characteristics can be determined from some standard fracture mechanics test.

The same characteristics from the same standard experiments can be, in principle, obtained in the presence of Z yarns which 'bridge' adjacent warp and fill fiber layers and create additional resistance to the intralaminar crack propagation. Now, in order to move forward, the crack needs not only to fracture the matrix material, but also break, row-by-row, Z yarn segments discretely inserted in the through-thickness direction. Obviously, as thicker Z yarns and as smaller their spacing, the more difficult crack propagation would be, and the higher values of G_{IC}, K_{IC}, etc. could be achieved.

Now we can reformulate the above task of optimizing Z yarn size and their insertion spacing in clear and quantifiable terms by two simple questions. The first is: what are relations between intralaminar fracture toughness characteristics on one side and Z yarn size and insertion spacing on the other? The second question is: what minimal values of the fracture toughness characteristics are required to suppress all virtual intralaminar cracks in 3-D woven composite up to the point where some other failure mode, insensitive to the presence of Z yarns, becomes catastrophic? Obviously, answers to these questions are not simple. In any specific case of 3-D woven composite, its structural application and loading situation, the answers can be obtained only in the result of complex, combined experimental and theoretical study. The author could not find any example of complete study of this kind in the literature. A few research publications have reported experimental determination of some fracture toughness characteristics for 3-D woven composites (one example of this kind will be presented next), some others attempted modeling fracture of Z yarns, but none of them tried to predict what size of Z yarns and their spacing would be optimal for one or the other real-life loading case. Not a surprise that the determination of Z yarn size and its insertion spacing is still up to product designer's knowledge, experience and intuition.

Probably, the most comprehensive up to date experimental study of intralaminar crack propagation in 3WEAVE® fabric composite has been presented in [24-26]. The objects of study were 3TEX fabricated S-2 glass/Dow Derakane 8084 Epoxy-Vinyl Ester matrix 3WEAVE® composite specimens loaded in DCB scheme. The testing of material with ~2.5% Z fiber volume appeared not a routine task. After extensive experimentation with the loading device, metal tabs bonded to the specimen, specimen width and other important experiment set-up features, the authors managed to propagate initial implanted intralaminar crack to considerable distance inside the specimen and determine Mode I critical strain energy release rate as the function of crack length. Fig. 5 shows one of the specimens after DCB testing. The broken Z yarns and originated 'wavy' secondary cracks indicate how 'difficult' the crack propagation was. This picture clearly illustrates that the material has very high fracture toughness.

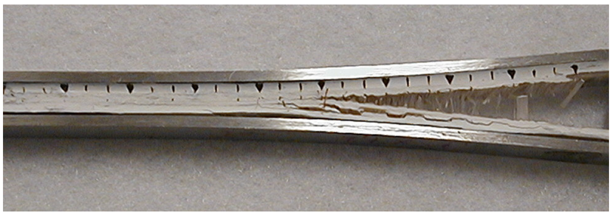


Fig. 5. S-2 glass 3WEAVE® composite specimen after DCB testing

Fig. 6 shows variations of the G_{IC} with crack length for several tested specimens. It is seen that the maximal achieved crack length was close to 80 mm, while the specimen length was 160 mm. It was obtained in the tests that the G_{IC} of 'benchmark' material made from 2 layers of 3WEAVE® composite (Z yarns did not connect those layers) was close to common data for laminated composites, namely ~0.2 kJ/m^2. The microcracking at the tip of the crack in single-layer 3-D woven composite started at about the same G_{IC} as for the net matrix cracking value. However, as soon as crack opening involved Z yarn stretching and breaking, the crack propagation resistance increased dramatically and exceeded the initial value by 40-50 times. Fig. 6 also shows that the steady state crack propagation regime has been obtained only for one specimen.

The conclusion made from these tests was that the amount of Z fiber, 2.5% by volume, was excessive, because it is difficult to imagine a composite structure where so high fracture toughness would be necessary. Also interestingly, the other set of DCB tests performed by the same group of authors for carbon/epoxy 3WEAVE® composite with ~8% volume content of Z fiber showed total impossibility to propagate implanted crack beyond the first row of Z yarns.

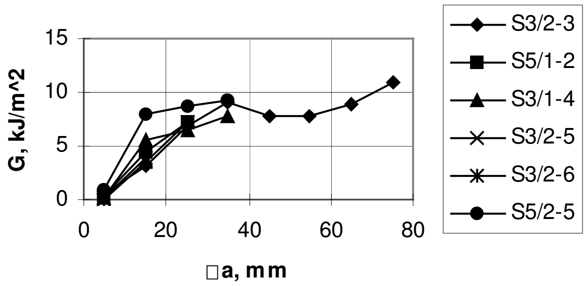


Fig. 6. R-curves for S-2 glass 3WEAVE® composite specimens calculated by area method

3.4 Impact, Ballistics and Blast

Substantial amount of experimental and theoretical work has been devoted lately to various dynamic properties and structural performance characteristics of 3WEAVE® composites exposed to impact, ballistic and blast loads, see [27-39]. The principal effects revealed there are, of course, related to the presence of trough-thickness reinforcement, delamination suppression, and alteration of dominant failure modes. Specifically, it has been demonstrated that composite panels reinforced with 3WEAVE® fabrics have much higher survivability under repeated drop weight impact applied at the same site, and under closely spaced multiple ballistic hits. Other tests showed substantially improved blast resistance. The obtained impressive experimental and theoretical results have raised significant practical interest to this type of composite reinforcements and their application in various protective armor systems. The above references provide some information in this regard. However, it should be noted that in spite of initial success, a lot of theoretical and experimental work has to be done to achieve sufficient understanding of the complex 3-D transient deformation and failure processes in complex 3-D reinforced composites. Some fundamental issues discussed in this paper, like the trade-offs between in-plane and out-of-plane mechanical properties, and between stiffness, strength and fracture toughness, have to be comprehensively studied.

3.5 Other Applications

A number of recent publications [40-47] describe various industrial and some aerospace composites and structures made with 3WEAVE® preforms. The existing applications include composite boat/yacht hulls and other structural components, automotive parts, bridge decks, windmill blades, thermal protection tiles, thermal management systems, etc. The above papers present various application concepts and case studies. The commercial success of these materials in uneven among different application areas, but it is visible in all of them.

3.6 Modeling and Predictive Analysis

Due to a limited length of the paper, this important topic is addressed here very briefly. There is a variety of theoretical approaches and computational tools which can be applied to 3WEAVE® fabrics and composites made thereof. Those include Orientational Averaging Method and Modified Matrix Method (both can only predict effective elastic properties), and various conventional and specialty 3-D finite element analysis approaches and computer codes. Recent article [48] provides a comprehensive historic overview, discussion of different existing models and computational tools applicable to 3-D woven composites. We can only add here that initial theoretical efforts in the area of modeling and analysis of this class of composites under impact, ballistic and blast loads [32,34,35] showed promise that certain computational tools can be useful for structural response predictions even in these most complex analysis cases.

4 Conclusions

A broad spectrum of recent advancements in manufacturing, property characterization and applications of one class of 3-D woven preforms and composites has been reviewed in this paper. There are numerous manufacturing and cost advantages offered by unitary single-layer 3WEAVE® preforms when they are used conjointly with advanced closed-mold composites fabrication methods. Though these materials and manufacturing methods attract fast growing interest within composites community, their advantages have to be persistently and convincingly demonstrated before end users. To succeed with this mission, several important problems have to be addressed. One of them is that practical design methodology of these materials is still empirical. It is not supported by the necessary material property database on one side and by computational tools enabling to analyze and optimize material properties and performance characteristics on the other. Particularly, no scientific methodology is currently available for design optimization of the Z yarn size, insertion spacing and fiber material.

5 Acknowledgements

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