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FEATURE

An introduction to spread tow reinforcements: Part 1 – Manufacture and properties

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Product Development Director

Spread tow reinforcements are being increasingly used within all kinds of industries working with composites and especially those using carbon fiber. In Part 1 of this two-part article Fredrik Ohlsson of Oxeon AB outlines the construction and manufacture of spread tow reinforcements and discusses their benefits over other reinforcements.

Introduction

The usage of spread tow reinforcements has rapidly increased since they were first introduced in 2004. They are now well received in and recognized by many different industries. Benefits like relatively straighter fibers, less crimp and better mechanical performance have been easily understood. With increased usage of spread tow reinforcements other advantages such as improved cutting and handling are also being seen.

Composite reinforcements overview

Continuous composite reinforcements are available in many forms, including unidirectional (UD) tapes, non-crimp fabrics (NCF) and woven fabrics.

UD tapes are available in a wide range of areal weights and consist of highly orientated fibers in only one direction. The unidirectional orientation of fibers makes draping into complex geometries difficult because the UD sheet tends to split, wrinkle and fold, creating uneven fiber distribution.

NCFs provide either two-, three- or four-directional fiber orientations in one construction. The low areal weights achievable are dependent on the count of the tows (usually 3–24k) that are used to build up the layers of the NCF. However, NCF materials present complications in draping, mainly at sharp and tight bends, depending on stitch density and stitching pattern/style. This is because the stitches tend to lock the multi-directionally orientated fibers in their positions and thereby restrict the fibers from sliding past each other easily to conform to the required draping geometry.

In comparison to UD tapes and NCF materials, traditional woven fabrics present fiber orientations in two mutually perpendicular directions and improved draping ability. However, a woven material's mechanical properties are lowered because of the inherent crimp or waviness that is introduced in the fibers. To lessen the loss of mechanical properties arising from crimp, two things are considered. First, tows of low count, usually 1–6k, are used to keep the crimp angle as low as possible. Second, to reduce the frequency of the crimp, and also to enable gentler weaving of carbon fibers, the spacing between the constituent tows/yarns is increased. Different weave patterns such as twills and satins are also employed to achieve lower crimp frequency.

With 1–6k tow counts, the typical areal weights of woven reinforcements achievable are in the range of about 90–300 g/m^2. However, the low areal weight woven fabrics have correspondingly reduced cover factor and uneven fiber distribution. The fabric construction tends to be loose and exhibits gaps/openings, which is undesirable because filling gaps with matrix increases the dead weight of the composite material. A typical such carbon fabric is the commonly available 95 g/m^2 plain weave fabric produced using 1k tow. Its low areal weight is due to its low cover factor and it is not relatively thin either. As a consequence, the composite product incorporating it would tend to be correspondingly heavier.

As the carbon fibers get abraded and damaged easily during the weaving process compared with commonly used fibers like cotton, polyester, glass, aramid etc., there is a limit to how closely they can be packed in the fabric by the weaving process. Because low areal weight woven fabrics are somewhat open in construction, a number of fabrics have to be plied to close the gaps/openings. However, such plying causes the composite material to become relatively thicker and heavier than actually necessary in many cases.

Spread tow reinforcements, not to be mixed up with flat tow products, are defined by the fact that the width of the original tow is substantially widened, often three times or more, during a spreading process.

The history of spread tow reinforcements

The technology for weaving warp and weft tapes that are 20–50 mm wide is quite new even if the technology of weaving has been in practice for over 5000 years. Dr. Nandan Khokar has developed a spread tow technology which is not based on traditional yarn handling looms. Products using this technology are sold under the brand name TeXtreme®, and were introduced to the market in 2004 by Oxeon AB.

The theory behind TeXtreme woven spread tow fabric is relatively simple. By arranging the fibers in the woven structure in the straightest orientation possible, both in the plane and also out of the plane, the fiber properties can be exploited in the most efficient way for carrying tensile and compressive loads. TeXtreme performs are mechanically similar to a UD cross-ply construction in many ways; the difference is that TeXtreme, being a fabric, exhibits exceedingly high draping ability and because of its integrated nature it is not subject to delamination.

Through a controlled operation fiber tows of usually 12k and heavier count are gently spread to form a tape of certain width and stabilized to prevent the tape folding back into the original tow/yarn form. Because of the spreading action the tapes obtained are extremely thin. These tapes are used as warps and wefts for producing spread tow fabrics.

Spread tow reinforcements are constructed of spread tow tapes that are interlaced in a plain, twill or satin weave pattern. In a similar way to traditional fabric reinforcements a set of warp tapes are combined with a set of weft tapes. The tapes in a spread tow fabric can be of widths from about 20 mm upwards.

There are various production methods available to produce the spread tow fabrics. Some are based on modified looms, while other are specially developed to handle spread tow tapes.

Manufacturing of spread tow reinforcements

Spread tow tapes are produced in various widths and areal weights just like traditional dry and prepregged UD. The main difference is the tow size used to produce a certain areal weight or product thickness. Conventional prepregged UD products with an areal weight below 50 g/m^2 will be constructed using tows with a count below 6k that are placed next to each other to close the gaps between each tow, and the prepreg resin will hold the product together. A dry UD product will likely be constructed like a woven UD, comprising a thin weft yarn from either glass or a polymer material. In both materials the filaments will not be highly aligned or tightly packed. There will be spacing between tows which will generate resin pockets and the thickness of each ply will present a high risk of generating transverse matrix cracks upon loading (Figs 1 and 2).

When spreading a carbon fiber tow the filaments will not only widen so that the tow transforms into a tape but the filaments will also align tightly next to each other. With proper techniques combinations of several tows can create a wide tape material in the requested width and weight with almost no spacing between the tows as can be seen in Fig. 3.

Spread tow tapes are preferably stabilized with a binder material to keep the spread tows from falling back into their narrow yarn shape upon handling. The binder material can be thermoplastic, thermoset or fibrous based materials.

The main constructional differences between spread tow fabrics and the traditional tow/yarn woven carbon fabrics are shown in Fig. 4.

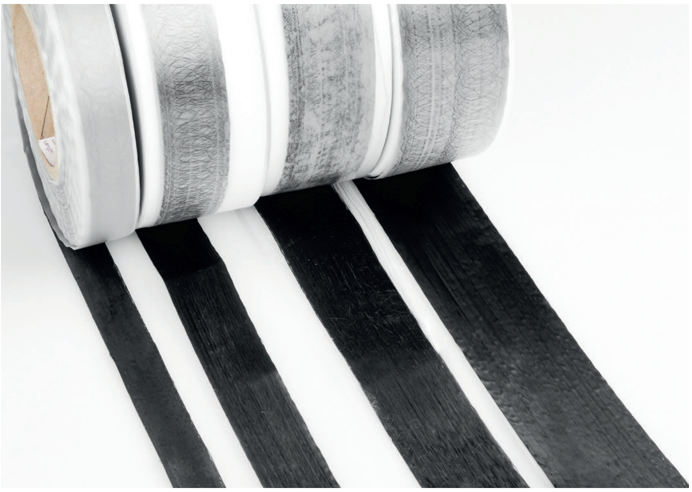

FIGURE 1
TeXtreme spread tow carbon fiber tapes in various widths (Picture courtesy of Oxeon.).

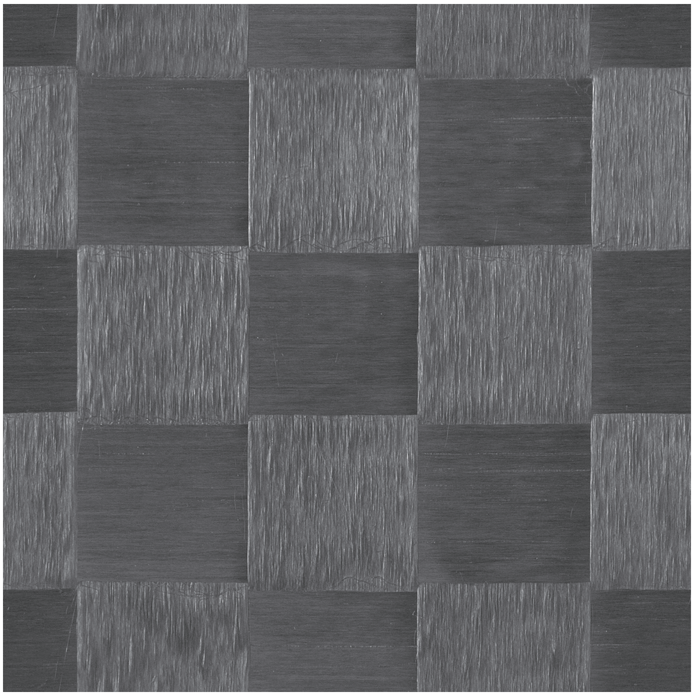

FIGURE 2
TeXtreme spread tow carbon fiber fabrics in 0°/90° direction (Picture courtesy of Oxeon.).

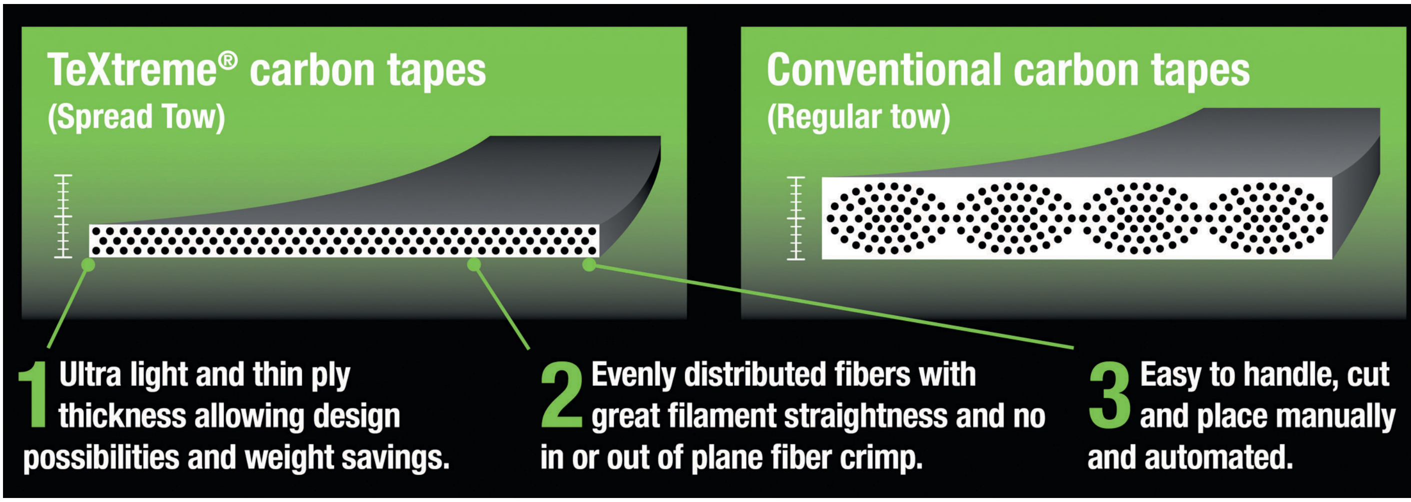

FIGURE 3

Compared to conventional carbon fiber tapes using tows placed next one another the spread tow tapes are spread into a thinner, more evenly distributed unit (Diagram courtesy of Oxeon.).

A significant characteristic of spread tow fabrics is the low crimp angle that results from the interlacing of very thin tapes. The thinner the tapes, the lower the crimp angle and the straighter the fibers will be presented, making the best use of the fiber properties.

Because the spread tow fabrics are constructed from thin and wide tapes the crimp frequency is also kept low, even when considering a plain weave structure. With the crimp frequency low the interlacing points are few, therefore reducing risks such as possible pin holes and areas of resin shrinkage. The cover factor compared to traditional yarn woven reinforcements is significantly higher in a spread tow fabric.

Fig. 5 compares fabric cover factor (fabric density) of traditional 1k with flat tow and TeXtreme produced using 12k tows. As can be observed, the traditional fabric and flat tow fabric have air gaps/openings at every interlacing point whereas TeXtreme is solid.

Spread tow fabrics with fiber orientations other that 0° and 90° are available. Fabrics are available with fiber angles oriented in $+\alpha/-\beta$ degrees, for example $+45^\circ/-45^\circ$.

Mechanical property improvements

The relatively lower mechanical performance of traditional woven reinforcement fabrics is known and can be attributed to crimp angle and crimp frequency. These factors, which adversely affect the performance of a woven material for composites applications, are virtually eliminated by weaving spread tow tapes.

TeXtreme has been tested by the independent research institute Swerea SICOMP. They carried out tests comparing the mechanical properties of different composite reinforcements: spread tow, NCF, plain weave 1k and 3k, and woven UD. TeXtreme proved to provide better or equal mechanical performance to other composite reinforcements in six out of seven tests.

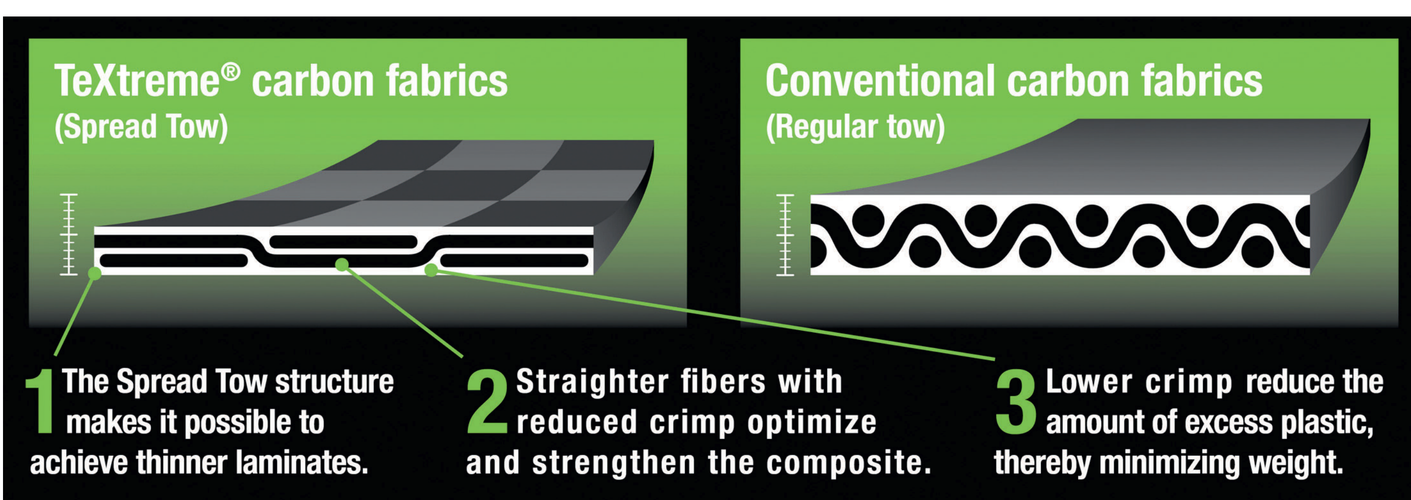

FIGURE 4

Compared to woven fabrics produced using tows, the spread tow fabrics combines flatness, thinness, improved performance and smoothness as well as good draping ability (Diagram courtesy of Oxeon.).

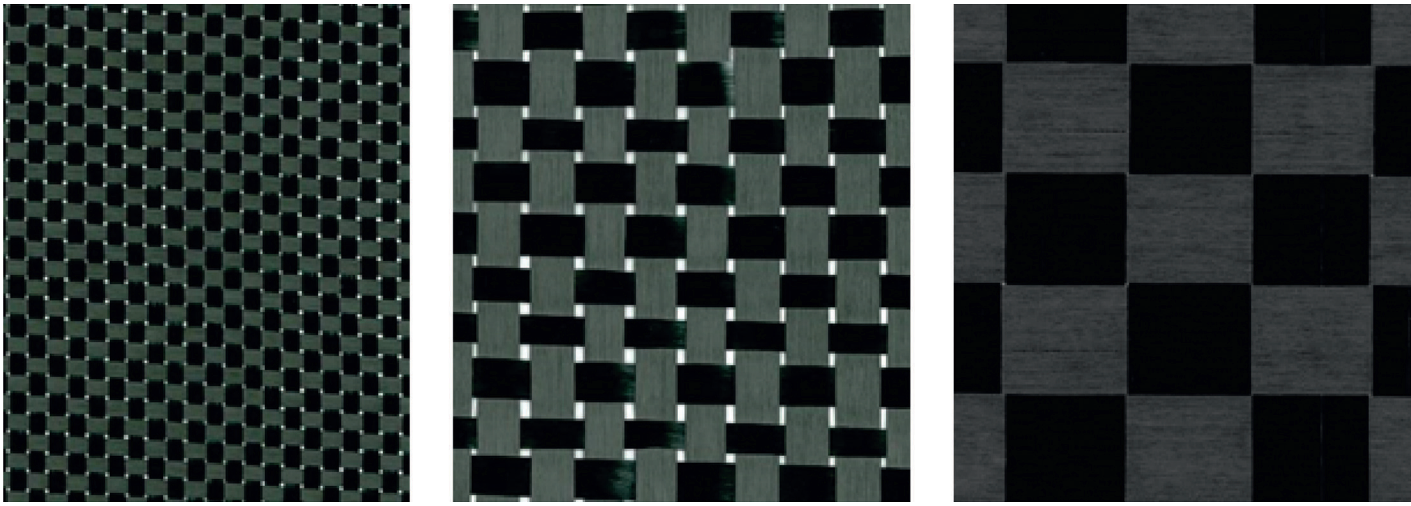

FIGURE 5

The traditional 1k fabric (left) and the flat tow fabric (center) present lower cover factor in comparison with TeXtreme spread tow fabric (right).

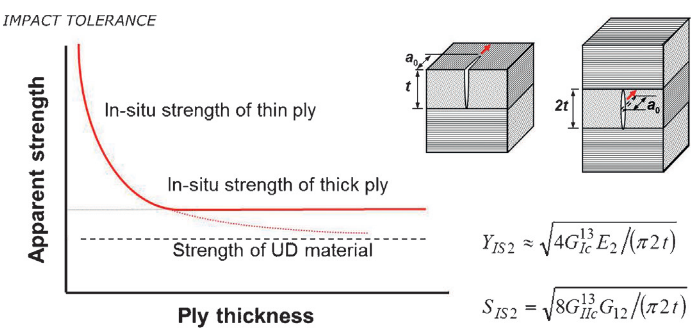

FIGURE 6

Illustration of increased in situ strength by using thin plies (Source: Oxeon.).

Swerea SICOMP also performed simulation modeling and found that the extremely low crimp of TeXtreme only gives a stiffness knock-down of 0.08% compared to a cross ply UD. The low crimp in TeXtreme thus basically eliminates the difference in performance from an UD and has all the benefits of a woven fabric.

Fig. 6 demonstrates that the traverse strength of a UD material (dashed line) with fibers in only one direction is constant and not dependent of ply thickness. This strength is lower than that of a ply with supporting layers in other fiber angles. The diagram however explains that when the ply thickness gets thinner it approaches a certain thickness where the in situ strength of thin plies will be greater than that of thick plies. The apparent strength will at this ply thickness vary with the thickness.

The ply thickness of each separate layer is hence clearly connected to the strength of the composite part.

Surface smoothness

The smoothness of a composite surface depends on several different factors, such as the type of reinforcement used, the choice of resin, the manufacturing method and the curing parameters, including temperature, pressure and curing-cycle variations. Surface distortions often appear after a certain time as the composite is exposed to unintended post-cure.

When constructing composite materials it has often been noted that the surface displays a sort of 'orange peel' pattern which often intensifies as the surface is painted. Numerous fillers, gel-coat systems and different curing cycles have been developed and investigated to reduce these defects. One way to minimize the easily seen large pattern print-through which is created from bulky reinforcements is to use surface plies with low areal weight and hence very fine weave pattern for reduced fiber crimp and associated waviness. The magnitude of the print-through with the use of low areal weight fabrics reduces but is still visibly large.

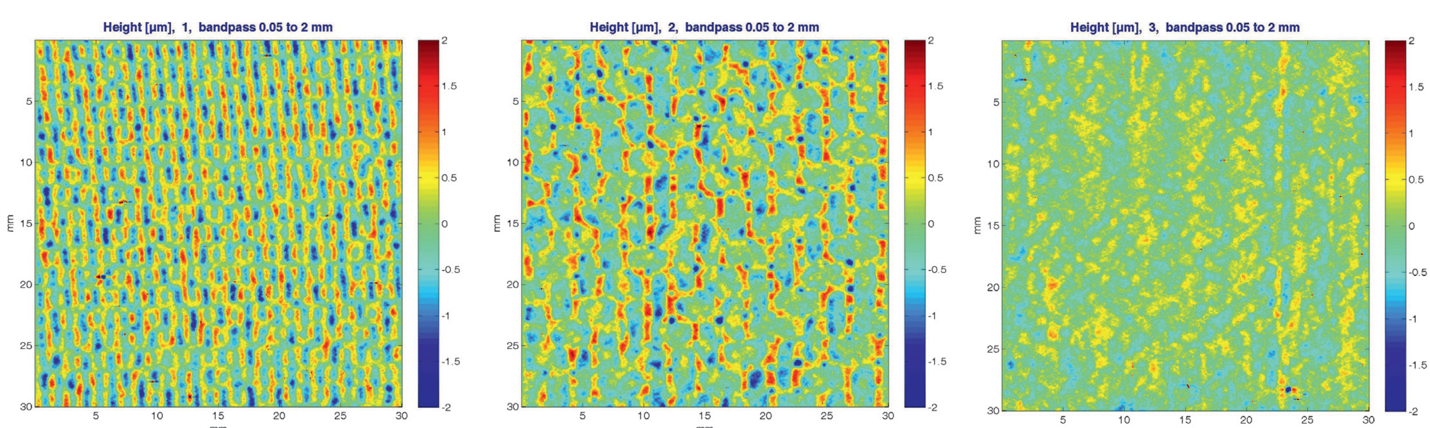

FIGURE 7

Surface smoothness comparison between glass fiber, 3k carbon fiber and TeXtreme spread tow carbon fiber fabrics (Source: Oxeon.).

In an experimental investigation made on a boat hull construction with three different surface reinforcement materials, glass fiber fabric, carbon fiber 3k fabric and spread tow fabric, the latter provided a relatively smoother surface compared to the traditional yarn woven alternatives. All materials were temperature and humidity cycled equally before being measured.

The measurement was conducted via an Opti-Topo surface topography unit on a 30 mm $\times$ 30 mm surface area. Fig. 7 shows the height differences between the various materials.

Due the spreading process and its thin flat layers, TeXtreme spread tow fabric has been shown to improve the surface smoothness of composites, resulting in reduced print-through.

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FEATURE

An introduction to spread tow reinforcements. Part 2: Design and applications

Fredrik Ohlsson

In Part 1 of this two-part article Fredrik Ohlsson of Oxeon AB outlined the construction and manufacture of spread tow reinforcements and discussed their benefits over other reinforcements. In Part 2 he looks at their design possibilities, and provides some case studies.

Increased design possibilities

When using homogeneous materials like steel or aluminum the construction of a product is often designed to fit the material's structural properties. When using composites, however, the material is designed according to the engineering needs of the product. In this way the structure will be more optimized and hence unnecessary weight can be eliminated.

To enable production of different areal weights of carbon fiber reinforcements fiber producers must produce different tow sizes. Table 1 shows available tow counts for some commonly used carbon fiber products, reflecting this flexibility in supply. Such flexibility, however, comes with increased production cost.

To make so many different tow counts of a fiber type available presents a challenge to the fiber producers. On one hand they have to meet the varying demands of the market, and on the other they have to consider uninterrupted production. Changing settings to produce different counts of tows involves considerable time and effort and causes production loss, which at times could be up to 30% of installed capacity. As a consequence, it becomes difficult to run the production process steadily and there is fluctuation in fiber quality (between lots) and a drop in output. This loss in production has to be made up with higher prices for low tow counts (1k–6k).

Conventional fabric constructions and the areal weights obtainable have until now been strictly connected and limited to the tow sizes being used. Therefore complete optimization has not been possible. Spread tow fabrics do not follow these set rules. Instead, a few tow sizes are enough to create a large areal weight span; even lighter areal weight spread tow fabrics are possible than conventional fabrics produced using 1k fiber.

A simple overview of the strong link between carbon fiber tow counts and fabric areal weight produced in the conventional manner is shown in Table 2.

To explain Table 2 in relation to the flexibility in producing spread tow fabrics with a wide range of areal weights, the following may be considered. By spreading and stabilizing one or several Torayca T700SC 12k fiber tows to 20 mm width, four different tape areal weights could be achieved: 40, 80, 120 and 160. These different areal weight tape constructions can be used as warp and weft in 16 different fabric areal weight combinations, wherein four constructions will be balanced as shown in Fig. 1 as the shaded ones.

If the numbers of fiber types are increased to seven, as shown in Fig. 2, the possibilities of engineering different areal weights and fiber combinations increase enormously. The fabric areal weight–fiber type matrix can grow almost infinitely large if more fibers are considered and also if the tape width is not limited to 20 mm but varied.

Flexibility

Oxeon's TeXtreme spread tow reinforcements are available in a wide variety of configurations. Below are some of the possibilities.

Product categories within spread tow reinforcements:

- 0/90
- +45/−45
- Unidirectional (UD) tapes
- Hybrids

0/90 and +45/−45 are both fabrics but differ in fiber orientation, and UD tapes includes all kinds of tape variants.

Hybrids involve mixing different kind of materials, such as carbon fiber and aramids, PBO and Innegra for example. Incorporating other materials with longer elongation can help avoid the instant breakage associated with pure carbon composite parts and improve safety.

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TABLE 1

Tow count availability of different carbon fiber products.

Fiber producer	Fiber product	Tow counts available
Tenax	HTA40/HTS40	1k, 3k, 6k, 12k, 24k
Toray	T300	1k, 3k, 6k, 12k
Hexcel	AS4	3k, 6k, 12k
Formosa	TC33	1.5k, 3k, 6k, 12k, 24k
Mitsubishi Rayon	TR50	6k, 12k, 15k, 18k

TABLE 2

Comparison of approximate areal weights.

Fiber type and tow count	Traditional woven fabrics (g/m^2)	Spread tow fabrics (g/m^2)
HS-1k	90–120	–
-3k	200–400	–
-6k	300–500	–
-12k	500–600	64–400
-48k, 60k	Not available	320–600
IM-6k	200–400	–
-12k	300–400	–
-18k	Not available	76–400
-24k	Not available	82–400
HM-6k	200–500	–
-12k	300–500	60–480

		WEFT			
		T700SC			
		40	80	120	160
WARP T700SC	40	80	120	160	200
	80	120	160	200	240
	120	160	200	240	280
	160	200	240	280	320

FIGURE 1

Areal weight variations on a 20 mm wide tape made from Torayca T700SC 12k fiber tow.

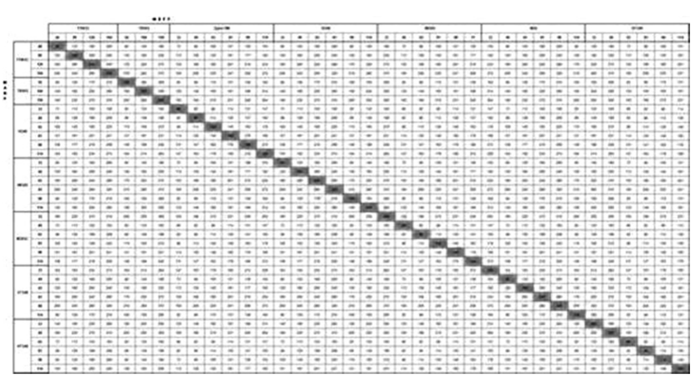

FIGURE 2

The number of spread tow fabrics possible could be almost infinitely large as the tape width can vary and many more fibers are available.

Due to the flexible production process hybrids can be produced with different materials in tapes used in, for example, the 0/90 direction in a fabric, or by mixing the two materials already in the same UD tapes. In some cases one fiber type will be present in 0° direction and one in the 90° direction. Such hybrid fabric styles are not unique for spread tow fabrics; they are also readily available in traditional yarn woven fabrics.

A co-mingled hybrid is a product in which two or more fiber types are mixed so that there is no clearly identified interface between the different fibers. Such fabric constructions are especially suitable for spread tow constructions as the tows from the different materials can achieve a high degree of mixing as the filaments are spread out over the width. Hybrid materials of the co-mingled type are a relatively new development but have already displayed increased impact toughness and residual strength.

There are also many different parameters to consider when producing the reinforcement.

Optimization variables:

- Areal weights
- Fiber type
- Fiber angle
- Fiber distribution
- Tape width
- Fabric width

Considering all the variations available there are several hundreds of products possible, which puts larger demands on the producer to optimize based on the actual needs for the composite product.

To fully exploit the design opportunities and flexibility of spread tow reinforcements Oxeon is taking a larger role in the process than is normally done by a converter. The company provides a range of services, including calculation and simulation, lay-up optimization, know-how in reinforcements, manufacturing support and marketing support.

Manufacturing and process benefits

Utilizing spread tow reinforcements it is possible to make savings in the total production cost of the composite. Reduced machine, labor and material cost result from the better surface smoothness, faster lay-up sequence and less plies required with spread tow reinforcements.

By looking at the total cost of producing the composite parts rather than the price of a carbon fiber fabric per m^2, the cost can sometimes be reduced even if the fabric itself is more expensive per m^2.

Since spread tow fabrics (STF) are balanced in one ply one it is possible to achieve savings in both the use of material and the lay-up time (through using fewer plies) and still be able to achieve a symmetrically balanced laminate as shown in Figs 3, 4.

Case studies

Formula 1

TeXtreme spread tow fabrics have long been used in Formula 1 motor sport and in the 2014 season the majority of teams drove in cars reinforced by TeXtreme.

TeXtreme entered this market in 2008, offering a bi-directional reinforcement with a mechanical performance close to that of cross-plied UD tapes. This combined the drapeability of a

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SYMMETRICAL BI-DIRECTIONAL CONSTRUCTION

Material	Ply sequence	No. of fiber layers to achieve symmetry
UD	[+45/-45/-45/+45]	4
NCF	[$NCF_{(+45/-45)}$/$NCF_{(-45/+45)}$]	4
STF	[$STF_{(+45/-45)}$]	2

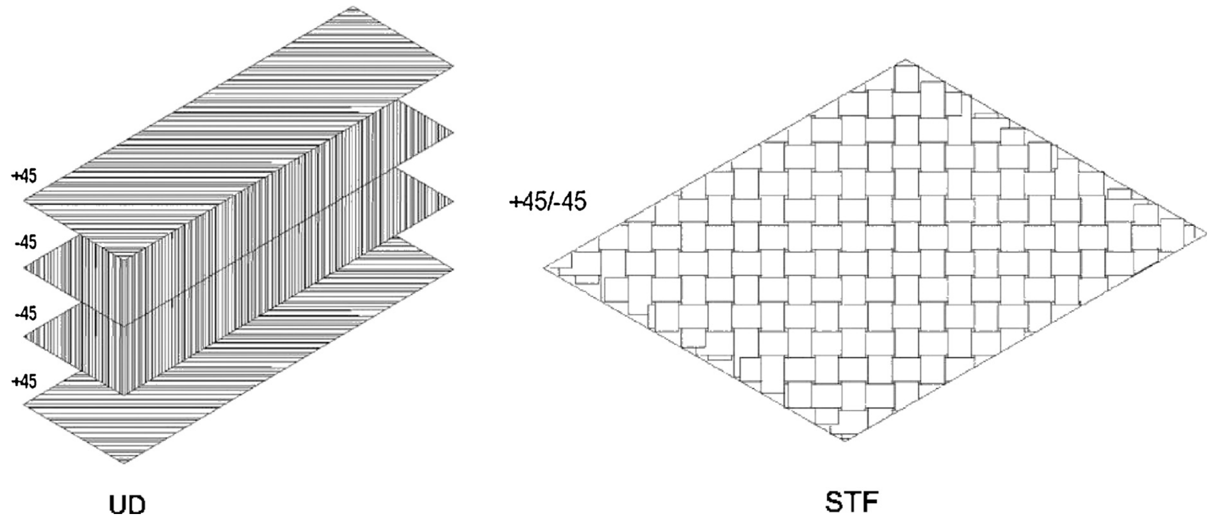

FIGURE 3
Images showing the number of layers needed in bi-directional construction.

SYMMETRICAL QUASI-ISOTROPIC CONSTRUCTION

Material	Ply sequence	No. of fiber layers to achieve symmetry
UD	[0/90/+45/-45/-45/+45/90/0]	8
NCF	[$NCF_{(0/90/+45/-45)}$/$NCF_{(-45/+45/90/0)}$]	8
STF	[$STF_{(0/90)}$/$STF_{(+45/-45)}$/$STF_{(0/90)}$]	6

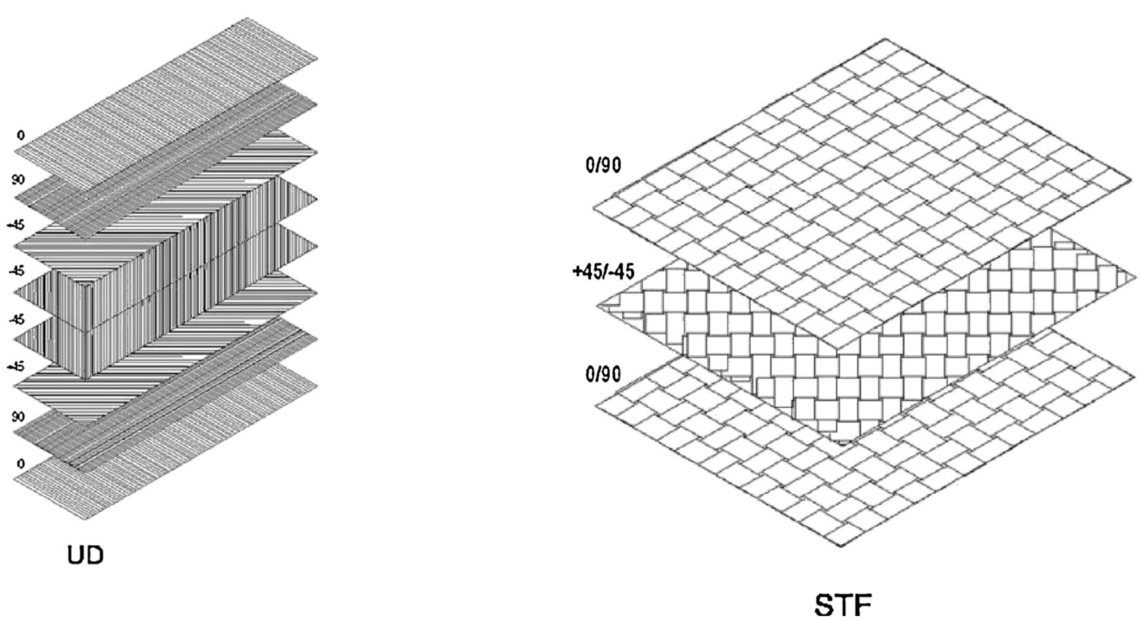

FIGURE 4
The number of layers needed in quasi-isotropic construction.

traditional fabric with intermediate modulus and high modulus fibers in areal weights that were lighter than those available from 1k high strength fibers.

The lightweight 1k fabrics that were used previously displayed a relatively poor cover factor leading to excessive usage of padding and fillers to handle defects in the thin single or sandwich skins. Spread tow fabrics have reduced this extra work a lot and have also removed the weight associated with the filler.

America's Cup

The America's Cup has always been a quest for better and lighter structures and the 34th edition of the competition was no exception. What was different from previous campaigns was that the financial climate at the time dictated that cost-effective solutions had to play a larger role. To meet these demands Oracle Team USA turned to TeXtreme spread tow carbon reinforcements, with which substantial weight savings were ultimately realized (Fig. 5).

The New Zealand-based boat builder Core Builders Composites constructed and built the AC72 for ORACLE TEAM USA.

One of the paradoxes with carbon fiber reinforcements and prepreg is that the less they weigh the more expensive they become. This is especially true for traditional woven cloths and unidirectional prepregs with fiber areal weights lower than 200 g/m^2 – and once below 100 g/m^2 the price per kilo of fiber increases rapidly.

TeXtreme is less expensive than traditional 1k carbon woven reinforcements and brings unique benefits in terms of weight savings and surface finish, which is critical to the untreated and unpainted surfaces that a weight-driven program demands. Carbon unidirectionals can go lower in areal weight – commonly available down to 50 g/m^2 and in some cases even lower. However, all the laminates used in Oracle Team's AC72 require reinforcements in at least two directions, and consequently a 80 g/m^2 TeXtreme fabric offers a 20% weight saving compared with two layers of 50 g/m^2 UD tape.

There were other advantages with using TeXtreme fabrics over two layers of UD tape. First there was reduced labor costs. It was possible to put down half the number of plies as opposed to the two layers of UD tape. Depending on the application TeXtreme was used both at +45/−45 and 0/90.

FIGURE 5

The ORACLE TEAM USA AC72 boat winning the 34th America's Cup (picture courtesy of ORACLE TEAM USA/Guilain GRENIER).

Normally, placing unidirectional fibers on the bias is very time consuming as the unidirectionals need to be cut and placed manually at the exact angles desired. The spread tow tapes in TeXtreme fabrics are always perfectly aligned, so putting down +45/−45 became very efficient.

Another time-saving aspect is the handling properties of TeXtreme, especially of the dry cloth. Conventional dry materials have nothing but a selvedge to hold them together, which means that as soon as you start cutting them they need to be handled very gently if they are not to fall apart. With TeXtreme cloths this is not a problem thanks to the binder that keeps the fabric together. An additional advantage is the increased toughness resulting from the interleaved spread tows of unidirectional fibers.

The results were good, as ORACLE TEAM USA won the 34th Americas Cup in the summer of 2013.

Ice hockey

Bauer Hockey has been using TeXtreme spread tow fabrics since 2007. Starting with a goalie stick and moving it into player sticks and new models, TeXtreme is now a vital part of all premium sticks produced (Fig. 6).

TeXtreme has provided Bauer Hockey with a number of improvements.

'By using TeXtreme, BAUER has benefitted from the standard weight savings and mechanical improvements,' says Adam Gans, Director of Product Development for sticks at BAUER Hockey Inc. 'At the same time, we have found the surface finish to be noticeably better with TeXtreme than with conventional 3k weaves. In the APX stick TeXtreme has contributed to the lighter blade and to the torsional stiffness that prevents blade deflection when shooting, which increases accuracy and improves balance.'

'TeXtreme has not only helped us make the sticks lighter it has also aided in improving the mechanical properties to provide better dynamic response, balance and consistency that no other carbon fabric could do. TeXtreme has been a valuable ingredient in giving players a higher performance stick, and giving us the extra technical and marketing value that is expected from a Bauer stick.'

Surf boards

When developing a high-performance kiteboard, the technical demands are quite challenging. The board has to be extremely

FIGURE 6

Bauer Hockey Vapor APX2 Limited Edition reinforced by TeXtreme (picture courtesy of Bauer Hockey).

FIGURE 7
North Kiteboarding rider using the Select board built with TeXtreme (picture courtesy of North Kiteboarding).

stiff, but it also needs to be highly flexible in other ways. The objective is to ensure the ultimate ride for the user (Fig. 7).

From a manufacturing perspective, achieving the ideal balance between stiffness and flexibility lies in constructing a board that while being very responsive still retains control in all kinds of waters. This requirement places strong demands on the carbon fiber reinforcement used in the board manufacture as it must ensure that different levels of stiffness are provided in different directions.

North Kiteboarding focused the development of its new Select and Team Series premium boards on further optimizing the carbon fiber reinforcement used. The decision was made to use TeXtreme spread tow carbon fabric to achieve weight savings and achieve the mechanical performance required in all of the board's directions. Oxeon provided its input into materials selection and the best solution proved to be an unbalanced 140 g/m^2 TeXtreme fabric, which ensures extreme stiffness in one direction.

Based on the strength and stiffness requirements provided by North Kiteboarding Oxeon were able to suggest several unbalanced TeXtreme spread tow fabric variants with different fiber types, areal weights and balance ratios. Following a selection process North Kiteboarding decided that a 140 g/m^2 high strength fabric with 5/7 of the fibers in the 0-direction suited their needs best.

'The biggest difference between the Select/Team Series and other boards on the market is the weight,' reports Jürgen May, Product Engineering BOARDS & MORE GmbH. 'They are probably some of the lightest and strongest boards out there. The unique structure of TeXtreme and the performance benefits that it delivers are more or less impossible to find in other carbon fabrics. By having a fabric that is tailor-made for the Select and Team Series boards we obtained the best possible material that meets our requirements for taking this board to the next level.'

Future developments

A lot has happened in the first ten years that spread tow reinforcements have been available on the market. This new category of composite reinforcement, like all new technologies, has fought its way into limelight and is being more extensively used. Further development will certainly happen with the technology of placing the spread tow tapes in any angle, $+\alpha/-\beta$, as demand for fabric variants other than 0/90 and +45/−45 increases.

The majority of development will be customer driven, since the full optimization of the reinforcement is performed for specific applications and their specific needs.

The aerospace sector is one interesting area for future development. TeXtreme could substantially reduce the weight of existing aircraft and thereby enable significant savings in fuel costs for the airlines while contributing to a greener world. For example, a conservative replacement of current traditional materials with TeXtreme carbon fiber fabrics, for example in composite panels in aircraft, could lower the weight of aircraft to the extent that potential fuel cost savings could be in excess of €43,000,000 per annum for 20 major airlines. The reduction of CO_2 emissions resulting from weight savings of this magnitude, is enormous – equaling about 1,000,000 laps around the world counted in flight miles.

Looking forward, if all airlines worldwide could capture the potential in weight savings offered by TeXtreme they could save enormous sums of money that could lead to better profits and/or allow enhanced service levels, availability and prices for travelers globally.

Further information

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