A NEW APPROACH TO PRODUCING TUBULAR ITEMS USING +α/-β SPREAD TOW FABRICS

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ABSTRACT

The recent development of continuous-length +α/-β Spread Tow Fabric manufacture, wherein spread tow tapes are incorporated at angles other than conventional 0°/90°, opens up new opportunities in manufacturing tubular items. With continuous-length +α/-β Spread Tow Fabrics becoming available now, the roll-wrapping method could be a new, direct and cost-effective way to manufacture tubular composite material products such as power and transmission poles, lamp posts, pipes, industrial rollers, oars, casings, golf clubs, masts etc., which are presently extensively produced employing the filament winding process.

As tubular items are usually subjected to a combination of loads, use of +α/-β Spread Tow Fabrics, together with 0°/90° Spread Tow Fabric, presents new possibilities of achieving improved properties over the structure produced by laying tows in angular plies by the filament winding process. To exemplify, a tubular item could be produced by plying different +α/-β Spread Tow Fabrics each of which have their constituent spread tow tapes incorporated in suitable different angles to withstand crushing and bursting pressures. The new approach to manufacture of tubular items using +α/-β Spread Tow Fabric is introduced in this Paper.

Key words: Spread Tow Fabrics (STF), +α/-β STF, Ultra lightweight carbon reinforcements

INTRODUCTION

A variety of tubular composite material products such as poles, pipes, rollers, pressure vessels etc. are presently produced by the filament winding method. In absence of a suitable fabric comprising yarns/tows in orientations other than that in length and width directions (i.e. unlike woven material), the filament winding method finds extensive use because it lays the tows/yarns at an angle relative to the longitudinal axis of the tubular product.

A fabric comprising yarns/tows in angular orientations relative to fabric’s length (or width) direction has been desired for long as its use would simplify and quicken production of above-mentioned items by directly rolling them in ply with conventional 0°/90° orientation fabrics. Through use of such fabrics not only the cost of production of indicated items would get reduced but also their mechanical performance would tend to improve due to fabric’s structural integrity and new products got engineered such as thin-walled tubular objects and crash tubes.

To realize these and other advantages a completely new textile process, OFT (for Oblique Fabric Technology), has been developed recently by Khokar [1] to produce a variety of continuous-length fabrics using tapes which are directly incorporated in angular orientations relative to fabric’s length direction as shown in Fig. 1. Such a fabric is commercially called +α/-β Spread Tow Fabric (STF) and produced in continuous-length.
Figure 1. The +α/-β Spread Tow Fabric; (a) general structure and (b) continuous length fabric producible by the new OFT process.

For producing the textile reinforcement required for manufacturing tubular composite material items, the +α/-β STF manufactured using carbon spread tow tapes could be used. The availability of +α/-β STF opens new opportunities in automating the production of tubular composite material items and extending the benefits of composite materials widely. To explain the technical and economic suitability of +α/-β STF, other textile products and their processes are considered in the following.

**AVAILABLE TEXTILE PRODUCTS FOR MANUFACTURING TUBULAR PRODUCTS**

Production of tubular composite material items requires a textile reinforcement that has the constituent fibers oriented in desired angles to bear either axial or radial or circumferential or combination loads, which could be either crushing (compressive) or bursting (tensile) or torsional or combination types. Most products would also require a defined bending and torsion resistance to suit the intended application. Such a complex load bearing situation requires the fibers of a textile reinforcement to be oriented in different angles. Further, to be more advantageous, such fibers should have least crimp.

Methods available for manufacturing textile reinforcements for tubular composite material products include braiding and weaving. Though knitting produces tubular products, it does not create a structure that is favorable for composite materials’ application. Filament winding is technically not a textile process. It is pertinent to briefly consider here the relevant processes for comparison with the new OFT process for technical suitability and economic viability. Knitting process is excluded for the said reason.

**BRAIDING**

This process produces tubular textile products using only one set of yarns/tows that are intertwined in the axial direction of the braided fabric (or braid). As a consequence, the yarns/tows are incorporated angularly relative to the longitudinal direction of the braid. Its structural integrity comes by intertwining yarns. The angular incorporation of yarns/tows advantageously accords the braided fabric to extend in radial and axial directions for snugly cladding on a mandrel. The braiding process incorporates the yarns in a wide range of angles. The set of yarns/tows fed to a braider comprises at least three yarns/tows which are intertwined (just like plaiting hair) such that no two yarns/tows are twisted. The braiding process is of flat and tubular types and they produce corresponding types of braids. Advanced braiding systems can additionally incorporate yarns/tows in the axial direction of the braid. Accordingly, the braid will comprise yarns/tows in three orientations: two angular (or bias) and one axial (or longitudinal).

Most braids are of seamless tubular form, though narrow flat band-like braids are also producible. A flat braid is also indirectly obtained by cutting longitudinally a tubular braid.
However, the cutting results in the flat braid having open edges (which then has to be stitched for ease of handling). In any case, the braids, and their production processes, present some problems in the present context.

a) It is inherently limited to processing tows/yarns. It cannot process tapes without causing their deformation by twisting, crumpling etc. A textile reinforcement comprising deformed tapes is unsuitable for use and hence unacceptable. As a consequence, the braiding process can produce only a limited minimum wall thickness. To exemplify, thickness of a braid produced using 1k carbon fiber tow will be greater than that of a fabric which is produced using 1k spread carbon tow tapes.

b) The working geometry of braiding process is suitable for handling yarns/tows but not tapes. As a consequence, use of yarns/tows directly increases their crimp angle and crimp frequency whereby the braid exhibits a lower mechanical performance (for example, in comparison with a tape-woven fabric). As is well understood now, a high angle and frequency of crimp creates valleys in which matrix accumulates whereby the dead-weight of the final composite material increases unnecessarily.

c) Relatively large diameter braids are not producible because the braiding machines tend to become relatively enormous and complex and cause practical processing and handling difficulties. Multiple layer or jacketed braids are not simultaneously producible.

d) Certain fibers, such as brittle ones, cannot be processed as the process inherently causes abrasion of the fibers leading to filament breaks.

e) Close fiber packing (for higher fiber volume fraction) is difficult to achieve.

f) Braiding is a continuous process and it is not designed for producing braids in batch-lengths. Making it work discontinuously for batch production (i.e. one item at a time) makes it cost-ineffective for manufacturing reinforcements for tubular composite material products.

**WEAVING**

Conventional or 2D-weaving process produces flat and tubular fabrics using two sets of yarns: warps and wefts. While warps are fed in the fabric's length direction, the wefts are fed perpendicularly to the warps. As a result the woven fabric comprises warp and weft yarns in mutually perpendicular orientations with warp running parallel to the fabric's length direction. The woven fabric's structural integrity comes from the interlacing between the warps and wefts. The process involves three main operations – (1) shedding warps, (2) inserting weft in the created shed, and (3) beating-up (or pushing) the inserted weft to the point of fabric formation.

The above description, though essentially reflecting flat weaving for producing sheet materials, is equally applicable to circular weaving whereby a tubular woven fabric is directly produced. In circular weaving the warp is arranged to be fed longitudinally in a circular configuration and the weft is continually laid circumferentially. This approach, which is extensively employed for manufacturing sacks, has not been considered for producing tubular fabrics for reinforcing tubular composite material objects because they present certain disadvantages in the present context as follows.

a) The angle mutually subtended between the warp and weft remains fixed at more or less 90°.
b) The warp is oriented in fabric’s longitudinal direction and the weft remains perpendicular to warps. Thus, an angular orientation of warp and weft is not possible relative to axial direction. As a consequence, the circular woven material does not have the ability to extend in either longitudinal/axial or radial directions (it is unlike a braid) and thereby it has virtually no flexibility to drape snugly over a mandrel.

c) Use of yarns/tows to interlace warps and wefts creates crimp, the angle and frequency of which correspondingly reduces the mechanical performance of the woven reinforcement.

d) Available weaving process, whether flat or circular type, is not designed for batch manufacture of woven materials. It is not suitable for producing individual ‘small’ length tubular fabric items.

e) The suitability of circular weaving process, with regard to processing carbon fibers, which is the most preferred and used reinforcement material, is not established yet. (Even if the process is suitable, the circular woven material will not be acceptable in the present application context because of its unfavorable orientations of constituent warps and wefts.)

f) A usual flat woven material could be cut in bias, or diagonally, to obtain a cut piece which would have the warp and weft oriented in +/- 45° relative to the cut direction. Such a cut patch could be rolled up to obtain a tubular reinforcement. However, such a patch is too small for manufacturing products such as pipes, poles, rollers, pressure vessels etc. More importantly, use of relatively small patches of woven material is not a proper reinforcement because of the attending fiber discontinuities, thickness variations from lapping and the unalterable mutual 90° relationship of the warps and wefts. A tubular woven material could be also cut in a helical manner and a continuous bias fabric obtained. However, such a bias fabric will still continue to possess most of the indicated drawbacks associated with the flat woven fabric besides handling difficulties due to fabric unraveling.

**FILAMENT WINDING**

The process of filament winding does not lead to production of any fabric that has inherent structural integrity and for this reason it is not regarded a textile process. This process has evolved in the composite materials' industry to produce specific reinforcements for manufacturing mostly tubular type composite material objects.

In this process, resin impregnated yarns/tows in flat form (resembling a tape) are wound on the surface of a mandrel according to the predetermined angular laying pattern. The process involves rotating a mandrel about its longitudinal axis and reciprocating a fiber laying head (usually one) parallel to the mandrel axis. Through such an arrangement the tape-like yarns/tows are continuously wound on the mandrel until the mandrel is fully covered by the fibrous tape and the required thickness of the tubular reinforcement is reached.

The material wound on the mandrel is subsequently subjected to curing before removing it from the mandrel. (For certain products the mandrel could be left inside.) The fiber laying head of a winding machine can have one or up to five axes of motions (such as through use of a robot). The multiple axes head is employed to maintain proper spread of yarns/tows at bends and to control their laying angles precisely for producing parts having complex geometries and high-performance requirements.
Though filament winding is the most widely practiced method for manufacturing reinforcements for tubular objects, its common drawbacks, setting aside the lack of fundamental structural integrity, are as follows.

a) As a number of different yarns/tows have to be fed simultaneously, the tensions in each one of them varies resulting in uneven spread of fibers which in turn creates correspondingly uneven fiber distribution and associated voids. This cannot be completely avoided because twists also exist in yarns/tows and they naturally cause the narrowing of yarns/tows in regular frequency.

b) As the yarns/tows run continuously at relatively high speeds, the wear and tear at the spreading head causes filament breakage, fuzziness, entanglements etc. causing quality problems.

c) The mandrel’s surface has to be maintained in good condition at all times to enable smooth removal of the cured product. Damage to mandrel usually happens during curing of product and removal of the cured product. Any damage to it can be expensive not only in terms of replacing/repairing the mandrel, but also loss of the wound fibrous material and final product besides effort and time.

d) As a single tape-like arrangement of yarns/tows is laid continuously, it requires considerable time to achieve full and proper covering of the mandrel with fibers. It is not possible to achieve the cover by a single lay. The tape has to be laid several times back and forth over the mandrel to achieve proper covering and wall thickness. This in turn makes the process relatively slower and causes difficulty in producing thin-walled tubular objects. In other words, to achieve a certain performance, relatively greater amount of fibers have to be used.

e) Because resin is applied to the yarns/tows, the process tends to become sensitive as stoppages can cause material contamination, degradation, subsequent curing problems, poor finish, fiber running difficulties, clogging guides etc.

f) The complexity of the process makes the filament winding machine expensive to produce, operate and maintain.

**Production and Features of +α/-β STF**

The OFT process for producing +α/-β STF is entirely new and technically unlike either weaving or braiding processes. The OFT process has been especially designed for manufacturing fabrics using spread tow tapes of carbon, not yarns/tows. It organizes the spread tow tapes into desired angular orientations +α/-β with respect to the longitudinal (or lateral) direction of the STF being produced. The mutual angle subtended between the tapes could be either acute or right or obtuse as shown in Figs. 2a-2c. Further, the +α/-β tapes could be incorporated in either equal (Figs. 2a–2c) or unequal (Fig. 2d) angles as shown in Fig. 2. The process is virtually never-ending provided the two sources of tape supply are not allowed to exhaust. As a consequence, the OFT process produces +α/-β STF in continuous lengths. The tapes are inherently interconnected to create the novel +α/-β STF structure. The interconnection of tapes is technically neither interlacing (as associated with weaving) nor intertwining (as associated with braiding).

The main benefits of +α/-β STF was first described by Ohlsson and Khokar [2] and they are summarized here as follows:

(a) Availability of continuous-length +α/-β STF eliminates the need to cut woven materials in bias for obtaining relatively small patches of woven material that have
+/−45 fiber orientations relative to cut direction. Use of +α/−β STF thus eliminates splicing and jointing associated with use of patches.

(b) Use of +α/−β STF eliminates thickness variations and misalignment of discontinuous fibers arising from overlapping of patches associated with use of oriented woven patches.

(c) As +α/−β STF is a well integrated structure and naturally symmetrically balanced material, its handling is easy and enables direct and quicker plying to improve efficiency of composite materials’ manufacture.

(d) By using spread tapes of different widths, relatively low areal weight +α/−β STF can be directly obtained and a high-performance thin-walled tubular items directly produced.

(e) The virtual absence of crimp in +α/−β STF directly results in improving mechanical performance of composite materials.

(f) Use of +α/−β STF accords substantial savings in time, effort, material and costs.

Figure .2 To be suitable for use as reinforcement in tubular applications, +α/−β STF is producible in equal (a-c) and unequal (d) angular orientations of the constituent tapes.

**Comparative Advantages of Using +α/−β STF**

On the basis of the above discussions, it is pertinent to explore now the new alternative approach to production of tubular reinforcement products and evaluate its technical and economic advantages. It is largely accepted now that the angle of fiber orientation for tubular objects is not fixed but varies in the range +/-50° to +/-55°. Shultz and Smith [3] found that +/-50° angle of fiber orientation withstood a higher burst pressure. The higher performance of +/-50° fiber orientation took into consideration the contribution of matrix. They also observed that fiber orientations below +/-50° exhibited circumferential failure and above +/- 50° exhibited axial failure. Accordingly, fabrics providing varying fiber orientations from +/-50° to +/-55° are needed, together with 0°/90° orientations, for most tubular applications.
The possibility of producing $+\alpha/-\beta$ STF in a range of angles, as shown in Fig. 2, enables direct production of tube-like reinforcements that are suitable for manufacturing circular and non-circular cross-section tubular items by roll-wrapping the $+\alpha/-\beta$ STF. Depending on the physical and performance requirements of the end product, either one or different types of $+\alpha/-\beta$ STF can be used in combination. For example, either fabric type $+/50$ is used singly for producing a given product or different fabric types such as $+/-45$, $+/-52$ and $+/-55$ are combined by plying them for achieving the required performance. A 0°/90° STF could be also combined with $+\alpha/-\beta$ STF during roll-wrapping process, as indicated in Fig. 3, if fiber orientations in those directions are also needed.

![Figure 3](image)

Figure 3. (a) $+\alpha/-\beta$ STFs can be directly roll-wrapped on a suitable mandrel in an automated way to produce a variety of tubular reinforcements such as hollow plates, tubes with similar and dissimilar cross-sectional shapes, and with different end diameters and shapes for different applications.

Tubular fabric reinforcements can be directly obtained by roll-wrapping one or more angular orientation types of STFs over a mandrel until the required thickness is achieved. Alternatively, combination of suitable pre-impregnated $+\alpha/-\beta$ STFs could be also directly roll-wrapped on the mandrel.

If different angular orientations of fibers are required in a tubular reinforcement, then suitable different pre-impregnated $+\alpha/-\beta$ STFs can be combined and used. Accordingly, a tubular reinforcement could be produced by either directly plying different pre-impregnated $+\alpha/-\beta$ STFs at the point of roll-wrapping or using directly a previously plied pre-impregnated $+\alpha/-\beta$ STF for roll-wrapping.

In any case, use of a pressure roller to press the plied $+\alpha/-\beta$ STFs that are being roll-wrapped on the mandrel would be required to help achieve material compactness and evenness. Further, by incorporating a suitable means for cutting the pre-impregnated and plied $+\alpha/-\beta$ STFs, such as rolling blades, laser cutter, shears etc., the process for producing tubular reinforcements could be automated. Through these and other necessary equipment, automated batch-wise manufacture of thin-walled tubular reinforcements and other tubular items can be achieved directly and quickly.

Depending on the end-application’s length requirement, a $+\alpha/-\beta$ STF could be roll-wrapped by feeding it in either its length-wise or width-wise orientations (as indicated in Fig. 1a). Whereas relatively small length - large diameter objects could be produced by the former feeding orientation, the latter feeding orientation could be suitable for long length-small diameter objects without causing fiber discontinuities in the reinforcement. While the present width of $+\alpha/-\beta$ STF is 1m, it could be produced in greater widths if its demand ensures return of investment.

In view of the above-presented aspects of $+\alpha/-\beta$ STF, the following chief technical and economic related advantages emerge:
**TECHNICAL**

a) As angular orientation of fibers is directly available in the +α/-β STFs, plying different +α/-β STFs, together with 0°/90° STF if necessary, will help directly to engineer the required mechanical performance.

b) Fiber continuity in and structural integrity of +α/-β STF continues to remain in the roll-wrapped tubular reinforcement whereby high-performance characteristics of +α/-β STF are fully carried forward in the next product.

c) The low crimp angle and crimp frequency in +α/-β STF due to use of thin spread tows, makes it flat and compact. Combined with its good structural integrity, the mechanical properties of the tubular reinforcement improve and the surface is rendered relatively smoother.

d) A single wrap of +α/-β STF on mandrel covers it completely and directly making it possible to produce thin-walled and relatively lighter tubular objects through fewer wrappings.

e) Varying diameter objects, such as expanded ends of a tube for direct coupling, can be directly produced by application of heat and pressure on roll-wrapped +α/-β STF without disintegrating fabric’s structure. The reinforcement thus tends to be relatively more reliable.

f) Single and plied +α/-β STF can be wrapped on non-circular cross-section forms (such as plate and bars with hexagon / square etc. cross-sectional shape) equally well and easily to produce other types of tubular products.

**ECONOMIC**

a) Through use of +α/-β STF, production of tubular reinforcements by its direct roll-wrapping becomes relatively simpler and quicker, and thereby less expensive. The simplicity of the process in turn would require the roll-wrapping machine to be composed of relatively fewer components and hence be correspondingly less expensive.

b) Use of +α/-β STF material creates virtually no material wastage when roll-wrapped into a tubular reinforcement. Also, because of improved properties of +α/-β STF, its consumption would be relatively low for producing high-performance tubular reinforcements.

c) Availability of +α/-β STF lends itself to automate the production of tubular reinforcements by roll-wrapping process whereby the cost of unit production gets lowered.

d) By using +α/-β STF, causes for product rejection can be lowered as the number of process variables gets reduced.

e) The smooth surface obtainable through use of +α/-β STF reduces the time, effort and cost required for achieving a good surface finish of the final product.

f) The possibility of using different areal weights of +α/-β STF enables engineering cost-effective tubular items to meet performance-cost of a given application.
CONCLUSIONS

Availability of $+\alpha/-\beta$ STF enables direct manufacture of tubular textile reinforcements by roll-wrapping process. As $+\alpha/-\beta$ STF is produced with an integrated structure in different fiber angle orientations, different $+\alpha/-\beta$ STF types can be readily plied to engineer the required performance. It can be also plied with $0^\circ/90^\circ$ STF if required. There are technical and economic advantages in using $+\alpha/-\beta$ STF as reinforcement for manufacturing circular and non-circular cross-section tubular composite material products. Through use of $+\alpha/-\beta$ STF, circular and non-circular types of thin-walled tubular composite material products can be produced. The $+\alpha/-\beta$ STF provides a naturally symmetrically balanced and integrated structure.

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