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DESIGN AND:
DEVELOPMENT OF
A THREE-DIMENSIONAL
INTERLOCKED,
FILAMENT-WOUND
COMPOSITE

BDX-613-143

MASTER

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ABSTRACT

Conventional filament-wound composites exhibit high strength characteristics in the direction of the wound fibers, but are relatively weak in shear strength between layers. Improved "third-direction" strength is provided by a weave pattern in which adjacent layers are interwound. Relative strengths in the three directions of a multi-layer woven composite depend upon band width and thickness of the filaments or tapes employed.

CONTENTS

Section	Page
1. INTRODUCTION	1
2. DESCRIPTION OF THREE-DIMENSIONAL WEAVE MATERIALS	3
3. FABRICATION TECHNIQUE	7
4. STRENGTH PREDICTION AND TESTS	14
5. EXAMPLE	18
6. RECOMMENDATIONS	19
REFERENCES	20

ILLUSTRATIONS

Figure		Page
1.	Cut-Away View of Interlocked Three-Dimensional Weave . . .	2
2.	Hand Woven Cylinder, 3-1/2 inch O. D. One Inch Woven Tape - Simple Lock Weave	4
3.	Simple Lock Weave - One Inch Woven Tape	5
4.	Simple Lock Weave - Unidirectional Fibers and Woven Tape	6
5.	Placement of Warp and Fill Tapes at Start of Weave	8
6.	Staggering Fill Tapes	8
7.	Voids at Corner Intersections of Warp and Fill Tapes (Simple Lock Weave)	9
8.	Overlap Lock Weave, Simple Skip-One Pattern (Two Cycle). .	10
9.	Overlap Lock Weave - Three Cycle	11
10.	Section of Composite Perpendicular to Warp Elements (Overlap Lock Weave - Three Cycle)	12
11.	Sectional Isometric View (Three Cycle Overlap Lock Weave) .	13
12.	Composite Specimen Containing Resin and Longitudinal Fibers	14
13.	Fiber Content vs Fiber Strength Developed	16
14.	Fiber Strength vs Resin Strength	17

1. INTRODUCTION

The high strength of small diameter fibers (of which glass is most common) has been utilized to produce light weight composites for structural products. The fibers, held in position by a matrix material such as epoxy plastic, are placed in the direction of stress to obtain optimum use of the strength potential. The plastic adds sufficient interlaminar strength in many applications in which loads that tend to create interlaminar shear-stress or tensile stress in a direction perpendicular to the fiber plane are of little concern.

An improved interlaminar strength for numerous prospective applications of filament-wound composites has suggested placement of some of the fibers in a direction perpendicular to the principle-lay ~~direction~~ direction.

The purpose of this investigation was to derive a suitable method of producing an interlocked filament-wound composite in which improved interlaminar strength is attained by an interlayer weave pattern. An interlocked three-dimensional weave was employed to produce a composite in which any complete interlaminar separation can occur only if the interlocking fibers are fractured. A cut-away view of the simple form of interlocked weaving pattern used is shown in Figure 1. By using this method, a composite of any desired thickness may be fabricated, maintaining a continuous cross-weave between adjacent layers for maximum interlaminar strength.

Figure 1.
Cut-Away View of Interlocked Three-Dimensional Weave.

2. DESCRIPTION OF THREE-DIMENSIONAL WEAVE MATERIALS

There are currently available a number of multi-ply fabrics, such as those used in tires, paper making drier felt, power belts, fuel cells, reinforced plastics, floor coverings, etc. (See References 1 through 5.) These records of invention disclose little information regarding machines and methods used in fabrication. However, the design of any multi-ply fabric must be limited by the production techniques to be employed.

A multi-ply fabric can be produced by sewing several plies of woven cloth together. This method offers design flexibility, but has two disadvantages; (1) some damage to the woven plies is produced by the sewing needle, and (2) the back side of the composite must be accessible to use conventional sewing machines. It is probable that a sewed composite would be satisfactory for most potential commercial applications. Several layers of a filament-wound composite, such as that now conventionally used for tanks, pipes, etc., could be sewed together to provide third-direction strength. However, as an alternate to sewing, a method of winding and weaving the layers to produce a third-direction interlock has been investigated.

The photograph of Figure 2 shows a hand-woven cylinder made of one-inch by 0.020-inch carbon preimpregnated tape. Figure 3 shows a flat mat section woven from the same material. Three different samples woven from 1/4-inch glass tapes are shown in Figure 4. The external surfaces have a "basket-weave" appearance, but differ from one-ply mats in that the tapes undulate two layers, rather than a single ply; thereby interweaving the plies. This results in improved third-direction strength.

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Figure 2.

Hand Woven Cylinder, 3-1/2 in. O. D.
One Inch Woven Tape - Simple Lock Weave

P-45758

Figure 3.
Simple Lock Weave - One Inch Woven Tape

UNIDIRECTIONAL-FIBER TAPE

WOVEN TAPE
AIR CURED

P 45757

WOVEN TAPE
PRESS CURED

Figure 4.

Simple Lock Weave - Unidirectional Fibers and Woven Tape

3. FABRICATION TECHNIQUE

The sequence of placement of the tapes in fabricating the simple lock weave (i. e. , adjacent layer interlock) begins with positioning two tapes directly on top of each other and in alternate positions along the mandrel. A complete weave pattern requires an even number of "warp" members. (As produced on a cylindrical mandrel, longitudinal tapes are the warp.) At starting, two warp tapes are placed on the mandrel at positions 1, 3, 5, etc. The first fill tape is then placed on top of and perpendicular to the warp tapes. (The "fill" tape is the circumferential tape on the cylindrical mandrel.) One complete set of of warp members is then placed on top of the first fill tape, followed by placement of the second fill tape. A full set of additional warp tapes are then positioned, and the next fill tape is placed on top. This sequence is followed until the total desired thickness of the composite is completed. This completes fabrication of one continuous band of the desired thickness. When "weave-winding" on a cylindrical mandrel, one continuous circumferential tape serves as the fill, and is cut and fixed in position (sealed or straited) at the finish position on the outside of the band. The second band is started by positioning two warp members against the mandrel. The procedure is the same as for the first band, except that warp positions 2, 4, 6, etc. , are used in starting. As for band one, the second band is built to the required thickness by repeating the warp and fill placement sequence. . Band three and all following odd numbered bands are identical to band one, and all even numbered bands are like band two.

The procedure just described requires that the longitudinal warp tapes be flexed back over a completed band when starting the next band as shown in Figure 5. Unless the warp is very flexible, this may present a problem. This may be largely overcome by staggering the members as shown in Figure 6.

Figure 5.
Placement of Warp and Fill Tapes at Start of Weave.

Figure 6.
Staggering Fill Tapes.

Since the tape corner intersections fall in direct line in the simple lock-weave pattern, as shown in Figure 7, connected voids are present throughout the thickness of the weave. This may be avoided only if the layers are offset in both directions (longitudinal and circumferential) so each corner lies in the center of the tapes of the adjacent layers. This is not possible in the simple lock-weave pattern shown in Figure 7.

Figure 7.
Voids at Corner Intersections of Warp and Fill Tapes
(Simple Lock Weave)

Connected voids through multi-layer composites may be avoided by use of an overlap weaving pattern such as that shown in Figure 8 and further illustrated in Figures 9 and 10. The overlap lock weave is shown more clearly in the sectional isometric view of Figure 11. Although a structure of this complexity is difficult to delineate on a small drawing, it is readily evident that no connected voids extend through the thickness of this composite.

Figure 8.
Overlap Lock Weave, Simple Skip-One Pattern.
(Two Cycle)

Figure 9. Overlap Lock Weave - Three Cycle

Figure 10.

Section of Composite Perpendicular to Warp Elements
(Overlap Lock Weave - Three Cycle)

Figure 11.
Sectioned Isometric View
(Three Cycle Overlap Lock Weave)

4. STRENGTH PREDICTION AND TESTS

For design use, tensile and shear strength information is required. Strength in any of the three directions will be provided by both the fibers and the resin, acting together. Under tensile stress the fiber material will have a modulus of elasticity much higher than the resin, and a negligible contribution to total strength may be expected from the resin unless the fiber content is virtually nil. This is shown quantitatively by considering a unit area of composite as illustrated in Figure 12.

Figure 12.

Composite Specimen Containing Resin and Longitudinal Fibers

Let δ_f = Stress in Fiber, psi

δ_r = Stress in Resin, psi

δ_c = Stress in the Composite (Gross Stress), psi

E = Modulus of Elasticity

F = Force per unit area of the Composite, lbs.

$$F = \delta_f A_f + \delta_r A_r = \delta_c (A_f + A_r) \quad (1)$$

For tensile strains to be alike,

$$\frac{\delta_f}{E_f} = \frac{\delta_r}{E_r} \quad (2)$$

For $A_f + A_r = 1$, EQ (1) combined with (2) gives

$$\delta_c = \delta_f A_f + \frac{E_r}{E_f} \delta_f (1 - A_f) \quad \text{or,}$$

$$\frac{\delta_c}{\delta_f} = A_f \left(1 - \frac{E_r}{E_f} \right) + \frac{E_r}{E_f} \quad (3)$$

If rupture of the fibers is taken as the failure mode, the ratio

δ_c / δ_r is a stress ratio which indicates the fraction of fiber strength developed by the composite. Figure 13 is a plot of this strength factor.

In a parallel manner, the composite strength in terms of resin strength may be expressed as:

$$\frac{\delta_c}{\delta_r} = 1 + A_f \left(\frac{E_f}{E_r} - 1 \right) \quad (4)$$

Data obtained from EQ (4) is plotted in Figure 14.

Figure 13. Fiber Content vs Fiber Strength Developed.

The ratio δ_c / δ_r may be considered as a factor by which the resin is strengthened by the use of high strength fibers. This relation is plotted in Figure 14.

Figure 14. Fiber Content vs Resin Strength.

5. EXAMPLE

A composite is formed so that it contains 2% cross section area of glass fiber for which $\delta_{ult} = 300,000$ psi and $E = 5 \times 10^6$ psi. The remain has a strength of 14,000 psi and a modulus of 600,000 psi. What is the estimated composite strength?

$$\text{By EQ(3), } \delta_c = 300,000 \left[0.02 \left(1 - \frac{0.6 \times 10^6}{5 \times 10^6} \right) + \frac{0.6 \times 10^6}{5 \times 10^6} \right]$$

$$\text{Or } \delta_c = 41,280$$

$$\text{By EQ(4) } \delta_c = 14,000 \left[1 + 0.02 \left(\frac{5 \times 10^6}{0.6 \times 10^6} - 1 \right) \right]$$

$$\delta_c = 16,053$$

Thus the composite fails first in the resin, and the use of glass fiber does little to increase the bulk strength. If the resin had a modulus of 300,000, then the composite strength, based upon fiber failure, is 23,640, and 18,380 based upon resin failure. The resin again fails first, but with improved composite strength.

This method of predicting tensile strength may be applied to any of the three principle directions of lock-weave material. The accuracy of this prediction in a direction perpendicular to the axes of the warp and fill tapes has not been established. Actual failure of the lock intersections should occur as a shear failure. This prediction, however, should be conservative, since the shear strength of brittle materials (fiber at the lock intersection) is generally greater than the tensile strength. Beam tests for horizontal shear indicate that progression of an interlaminar shear failure is stopped at points of weave interlock.

6. RECOMMENDATIONS

FIRST LINE

The analyses, as previously presented, indicate that the strength of the composite in the third direction increases as the ratio of fiber area to the resin content. For this reason, the smaller widths of tapes, when woven into a composite, are predicted to offer a greater strength in the "Z" direction. The use of smaller tapes will produce a greater number of "locks" per unit of volume, thereby resulting in a greater and more uniform "tie" between adjacent fiber layers.

LAST LINE (EVEN)

LAST LINE (ODD PAGE)

LAST LINE (EVEN)

1. U. S. Patent 1, 335, 311 Tire Fabric
2. U. S. Patent 2, 180, 054 Paper Maker's Drier Felt
3. U. S. Patent 2, 495, 808 Process of Impregnating Thick Fabrics With Gum
4. U. S. Patent 2, 779, 702 Fuel Cell Supporting Panel
5. U. S. Patent 2, 893, 442 Reinforcing Woven Materials for Making Laminated Articles
6. U. S. Patent 2, 948, 950 Reinforced Translucent Panel
7. U. S. Patent 2, 964, 067 Floor Covering and Method of Making Same
8. U. S. Patent 3, 090, 406 Woven Panel and Method of Making Same