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FILAMENT-WINDING A THIN-WALL
FIBERGLASS HEMISPHERE

A Report for the
University of Missouri
Engineering Graduate Program

Prepared by:
D. C. Bruegge

March 1973

Prepared for the
United States Atomic Energy Commission
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**Kansas City
Division**

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SECTION I

INTRODUCTION

The objective of this project was to establish a method of filament-winding a constant-thickness, thin-wall ($R/t = 150$), high-strength, fiberglass hemisphere.

Previous investigations had indicated that the filament-winding fabrication approach would offer the best potential for obtaining the highest-strength shell. However, the thin-wall and the hemispherical configuration caused some fabrication problems. Associated problems were encountered in obtaining the required fiber arrangements and a constant thickness during winding.

Fabrication methods were established for a $1/32$ -inch wall thickness, which is expected to be the smallest standard size. Thicknesses of $1/16$, $1/8$, $1/4$ inch, and larger could be fabricated by using the same technique established for the $1/32$ -inch thickness.

A hemispherically-shaped configuration has been selected as a general case of an experimental domed shell for this study.

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SECTION II

SUMMARY

The process by which a fiber-reinforced plastic (FRP) product is made can influence the material properties of the end products because of variations in the fiber distribution. Significant directional property variation can exist, and some variations may prevent an efficient utilization of the available fiber strength.

A survey of materials and processes was conducted, and several methods of fiber reinforcement, such as continuous fiber strands, fabrics, and chopped fiber, were considered prior to the selection of the filament-winding process. The continuous fiber strand used in a filament-winding process was selected, because it exhibited the greatest composite tensile strength capability.

Two filament-winding methods (helical and "gyro") were investigated for winding thin-wall, high-strength domes with R/t ratios up to 150. Hemispherical test specimens with an R/t ratio of 150 were fabricated and tested for tensile strength and for load-deflection characteristics. The helically-wound specimens exhibited a tensile strength of 13,000 psi and a load-deflection characteristic of an anisotropic material, while the gyro-wound specimens exhibited a tensile strength of 55,000 psi and a load-deflection characteristic of an isotropic material.

The winding methods were studied, and an R/t ratio was calculated for which specimens having the same strength and load-deflection characteristics could be produced by either the helical- or gyro-winding method. It was calculated that for R/t ratios up to 20, either winding method could be used; but for R/t ratios greater than 20, the gyro-winding method becomes increasingly more efficient.

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SECTION III

PREVIOUS INVESTIGATIONS

A survey of materials and processes was conducted, and several methods of fiber reinforcement were considered prior to the selection of the filament-winding process. In general, fiber forms commonly used for fiber-reinforced-plastic applications consist of continuous fiber strands, fabrics, and chopped fibers. Table 1 compares expected tensile strength capabilities typically found in literature for the different types of reinforcement.

Table 1. Comparison of Fiber Forms and Composite Strength of Glass-Fiber-Reinforced Plastic

Form of Reinforcement	Ultimate Tensile Strength (psi)
Chopped Fibers	5,000 to 20,000
Woven Fiber Fabric	20,000 to 50,000
Continuous Fiber (Filament-wound, isotropically-reinforced)	50,000 to 150,000
Continuous Fiber (Filament-wound unidirectionally-reinforced)	150,000 to 300,000

The filament-winding fabrication approach was thus begun, since the chopped fiber and fabric types of reinforcement were not considered strong enough to be competitive as a structural material. It was considered that an ultimate tensile strength above 40,000 psi would be required to compete with other materials where strength was an important consideration for selection.

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SECTION IV

GENERAL CHARACTERISTICS OF FIBER-REINFORCED PLASTICS

Fiber-reinforced plastics comprise a class of composite materials, the principal objective of which is to provide an improved set of properties compared to the properties of the individual component materials. For example, the fibers of FRP materials can significantly improve the mechanical properties of a low-strength plastic material which otherwise has good electrical insulation and non-corrosive qualities.

The selection of the plastic matrix and fiber material, and the fiber arrangement and content, determine the FRP material properties. The mechanical properties result primarily from the arrangement, amount, and type of fibers, while the chemical, electrical, and thermal performance result primarily from the matrix material.

The strength of the finished FRP is directly related to the amount of fiber in the finished object, as illustrated by Figure 1.

Figure 1. Relationship Between Composite Strength and Fiber Volume

Equally important, strength is related to the arrangement of fibers in the finished object.¹ When all the fibers are laid parallel to each other, maximum strength results in that one direction, although the strength transverse to the fibers is significantly less and is essentially that of the plastic matrix. When half the fibers are laid at right angles to the other half, strength is greatest in those two directions. When fibers are arranged equally in all directions, the strength is no longer concentrated, and this arrangement results in equal strength in all directions.

The relationship of the fiber arrangement to the strength characteristics is illustrated in Figure 2. As noted above, a parallel fiber arrangement offers the greatest strength capability uniaxially; but it is anisotropic, and the strength transverse to the fiber is significantly less. The orthogonal and isotropic (equal angle dispersion) fiber arrangements have a maximum strength capability of one-half the uniaxial value for a given fiber content. It is noted that for small included angles, the equal angle dispersion fiber arrangement approaches optimization of isotropic properties.

* MAXIMUM STRESS FOR PARTICULAR
FIBER AND VOLUME LOADING IN
COMPOSITE

Figure 2. Directional Strength and Modulus Variation of FRP Laminates for Various Arrangements of Continuous Fibers

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SECTION V

THEORETICAL STRENGTH

A design technique called the "netting analysis," which is used most commonly for predicting performance of a filament-wound structure, treats the system as if only the fibers exist. This technique has gained wide acceptance by industrial suppliers of filament-wound structures.²

Another technique for predicting composite properties is the "rule-of-mixtures analysis," which includes the basic contributions of the fiber and resin matrix. This technique predicts more accurately composite properties in the fiber direction.

The rule-of-mixtures analysis of an element of a unidirectional, fiber-reinforced plastic is presented below. As illustrated in Figure 3, the fibers are arranged parallel to one another and are embedded in a plastic matrix.

Figure 3. Unidirectional Element of Fiber-Reinforced Plastic

Subscript (m) denotes matrix; (f) denotes fiber; and (c) denotes composite. The load (P) carried by the element is a function of the combination of the individual properties of the fiber and matrix materials.

$$P = \sigma_f A_f + \sigma_m A_m.$$

Since the fiber and matrix are assumed to be bonded together and to act as a unit,

$$\epsilon_c = \epsilon_f = \epsilon_m = \epsilon.$$

From Hooke's law

$$\sigma_f = E_f \epsilon_f \text{ and } \sigma_m = E_m \epsilon_m.$$

Therefore,

$$P = \epsilon [E_f A_f + E_m A_m].$$

The equation for the composite stress is

$$\sigma_c = \frac{P_c}{A_c} = \frac{\epsilon [E_f A_f + E_m A_m]}{A_f + A_m}.$$

The equation for the composite modulus is

$$E_c = \frac{\sigma_c}{\epsilon} = \frac{E_f A_f + E_m A_m}{A_f + A_m}.$$

If the composite area is selected as unity,

$$A_c = A_f + A_m = 1,$$

then stress and modulus equations are simplified as follows:

$$\sigma_c = \epsilon [E_f A_f + E_m A_m] \quad (\text{Equation 5.1})$$

$$E_c = E_f A_f + E_m A_m \quad (\text{Equation 5.2})$$

The tensile strength and modulus equations for the parallel fiber element are valid only in the direction of the fibers.

The parallel fiber arrangement can be suitable for applications of unidirectional loading. But if bidirectional loading is required, the fibers should be oriented in the principal stress directions for maximum strength.

Figure 4 illustrates an element of an orthogonal-fiber-reinforced plastic. The element is composed of two unidirectional-fiber-element layers. The fiber direction of the second layer is oriented 90 degrees to the fiber direction of the first layer.

Figure 4. Orthogonal Element of Fiber-Reinforced Plastic

Formulae 5.1 and 5.2 for tensile strength and modulus for a unidirectional fiber element can be used for the orthogonal element with a modification in the treatment of the fiber and matrix area fraction. The tensile strength and modulus of the principal stress directions (σ_1 and σ_2) are determined with Equations 5.1 and 5.2 by noting the area fraction of fiber in each separate principal stress direction. Thus, the area fraction of fiber in each of the two principal stress directions of a balanced orthogonal element is one-half that of the unidirectional element, since half of the fibers have been laid at right angles to the other half.

The FRP tensile strength is controlled primarily by the tensile strength of the fiber, due to the significant difference in modulus between the fiber and resin materials. The resin acts as a medium of load transfer

from fiber to fiber and thus is required to have a good bond strength to the fiber. In addition, the elongation of the resin must be at least as great as the elongation of the fiber to preclude early crack formation and premature failure of the part.

The fiber and matrix materials selected for fabricating the test shells were a high-strength grade of glass fiber and epoxy thermosetting resin. Table 2 lists some of the properties of the glass fiber and epoxy resin system.

Table 2. Properties of Fiber and Resin Materials for Test Shells

Property	Fiber	Matrix
	S-Glass Filaments	Thermosetting Epoxy Resin
Specific Gravity	2.49	1.20
Tensile Strength (psi)	360,000*	14,800
Modulus of Elasticity (psi)	12.6×10^6	0.6×10^6
Ultimate Elongation (Percent)	2.8	3.6
*Statistical average bundle strength, 10-inch gage		

The ultimate elongation and tensile strength of glass fibers are dependent upon the fiber aspect ratio or the fiber length over diameter (L/D). Figure 5 illustrates the variation of fiber tensile strength versus aspect ratio.³ The ultimate elongation and tensile strength commonly used for continuous-fiber filament-winding is 2.8 percent and 360,000 psi, based on a 10-inch fiber length.

Figure 6 is a graph of the theoretical composite tensile strength and modulus versus fiber content for a unidirectional and isotropic fiber arrangement.

Figure 7 is a graph of generalized limits of empirical tensile strength found in literature for filament-wound glass-fiber-reinforced-plastic composites. The upper limits reflect results of samples produced under more ideal and highly controlled conditions, while the lower limits reflect, more typically, the results achieved in end-use applications. Tables 3 and 4 present the tabulated data used to generate the curves in Figures 6 and 7.

Figure 5. Fiber Tensile Strength Versus Aspect Ratio

The tensile strength predicted for the hemispherical test shell was based on an isotropic fiber arrangement, a strain at failure between 2.0 and 3.5 percent, and a glass-fiber content of 40 percent by volume.

Thus, the expected tensile strength was expected to be between 54,000 and 94,000 psi, depending on the actual strain at failure. The variation in actual strain at failure would be controlled primarily by the actual variations in fiber content and arrangement from an ideally uniform condition.

Figure 6. Theoretical Tensile Strength and Modulus for "S"-Glass Fiber/Epoxy Composite (at 2.8 Percent Strain)

Figure 7. Typical Empirical Tensile Strength Range for "S"-Glass Fiber/Epoxy Composite

Table 3. Composite Theoretical Tensile Strength for "S"-Glass Fiber/Epoxy Resin

Fiber Content (Percent Volume)	Unidirectional (Percent Strain)			Isotropic (Percent Strain)		
	2.0	2.8	3.5	2.0	2.8	3.5
	(psi x 10 ³)					
10	36	50	63	18	25	31
20	60	84	105	30	42	52
30	84	118	147	42	59	73
40	108	151	189	54	75	94
50	132	185	231	66	92	115
60	156	218	273	78	109	136
70	180	252	315	90	126	157
80	204	286	357	102	143	178
90	239	320	418	---	---	---

Table 4. Composite Theoretical Tensile Modulus for "S"-Glass Fiber/Epoxy Resin

Fiber Content (Percent Volume)	Unidirectional	Isotropic
	(psi x 10 ⁶)	
10	1.80	0.90
20	3.00	1.50
30	4.20	2.10
40	5.40	2.70
50	6.60	3.30
60	7.80	3.90
70	9.00	4.50
80	10.20	5.10
90	11.40	

SECTION VI

TEST SPECIMEN FABRICATION

Hemispherical test specimens were fabricated by two filament-winding methods and tested for tensile strength and load-deflection characteristics. The test specimen configuration is illustrated in Figure 8. Test specimens were initially fabricated by a helical-winding method, which did not result in a high-strength hemisphere. A second winding method, called gyro winding, was investigated, which provided higher strength hemispheres.

Figure 8. Test Specimen Configuration

Filament Winding

The filament-winding fabrication method is usually selected when it is necessary to make maximum utilization of the fiber strength in a fiber-reinforced plastic. The part is made by winding the fibers on a mandrel shaped to the part configuration. The fibers are wound over the entire mandrel surface by repeated revolutions of the mandrel, which is coordinated with the fiber delivery system to obtain a particular winding pattern.

The basic winding modes illustrated in Figure 9, are usually defined as follows:

1. HELICAL (Figure 9A). The winding of fibers at angles between perpendicular and parallel to the mandrel centerline.
2. CIRCUMFERENTIAL (Figure 9B). The fibers are wound side-by-side, similar to very fine threads on a shaft, nearly perpendicular to the mandrel centerline. Circumferential winding is normally restricted to cylindrical shapes.
3. LONGITUDINAL (Figure 9C). The winding of fibers nearly parallel to the mandrel centerline. This winding mode is also referred to as low-angle helical winding.

When winding a part, usually a combination of the winding modes is used to obtain bi-axial reinforcement. However, the ability to use the different modes is limited by part configuration. The part configuration can limit the winding freedom and restrict the ability to obtain a desired fiber arrangement. The fibers have to be wound on a stable path of the mandrel to prevent the fibers from slipping off of the mandrel. This stable path is the shortest distance between two points on the mandrel surface. For a hemisphere, the stable path is the great circle of the hemisphere.

Helical-Wound Test Specimen

As mentioned above, the test specimen was initially filament-wound, using the helical-winding process. When helically-winding domes, fibers initially are wound at a very low winding angle (α) to cover the pole of the dome. To obtain bi-axial reinforcement, the winding angle is progressively increased with each layer of material wound on the mandrel (Figure 10). Due to the resultant irregular surface and thickness, the helical specimens required machining to obtain the 0.030-inch wall thickness of the specimen. After the test specimen was filament-wound and machined, a clamping ring was bonded to the taper section for fixturing purposes during tensile testing.

Gyro-Wound Test Specimen

The gyro filament-winding method was so named because the winding machine motions appear similar to those of an oscillating gyroscope. Figure 11 illustrates the winding control axis and the type of winding pattern generated.

When gyro-winding the test specimens a wide band of fibers was generated, with fibers typically arranged transverse to one another in the band (Figure 12). To completely cover the mandrel, succeeding bands were placed on the mandrel by incremental rotation of the mandrel about its centerline. As this was done, fibers in the new band were arranged at

Figure 9. Filament Path for Conventional Winding Modes

Figure 10. Winding Angle and Layer Sequence
for Helically-Wound Test Specimen

Figure 11. Gyro-Winding Control Axis, Showing
Typical Winding Pattern

Figure 12. Winding Band, Gyro Test Specimen

an angle to the fibers in the previous band, equivalent to the incremental rotation (Figure 13). The result of this was a network of continuous fibers that crossed one another at small, included angles, imparting uniform directional (isotropic) properties. Equally important, the layer thickness achieved was quite thin ($R/t \approx 150$) and uniform for filament-wound domes.

A photograph of the as-wound gyro test specimen and gyro-type winding machine are shown in Figure 14. A close-up of the network of fibers is shown in Figure 15. In this photograph the taper section of the test specimen is being made by circumferential winding. Subsequently, the test specimen is impregnated with resin and the outer contour molded to a constant 0.030-inch wall thickness. After the specimen has been impregnated and cured, a clamping ring is bonded to the taper section for fixturing purposes during tensile testing.

Figure 13. Band Advance, Gyro Test Specimen

Figure 14. Gyro-Type Winding Machine

Figure 15. As-Wound Gyro Test Specimen

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SECTION VII

TEST RESULTS

The hemispherical test specimens were pressure tested to determine the tensile strength and deformation characteristics.

The pressure test consisted of internal hydraulic pressurization of the specimens at a strain rate of 1 percent per minute. The test fixture and specimen setup for testing are shown in Figure 16. Transducers mounted in a longitudinal plane of the specimen were used to record radial deflection. The test specimens were monitored for load-deflection to determine deformation characteristics of the dome as a whole.

The glass-fiber content of specimens was determined by ASTM standard D2584 for ignition loss of cured reinforced resins.⁴ In this test the cured resin is oxidized at elevated temperatures, leaving the glass-fiber residue. The glass residue is determined as a weight percent of the initial sample weight. In addition, the specific gravity of specimens was determined by water displacement methods.

Table 5 lists the test results of the filament-wound test specimens.

Accuracies of Test

The variance of shell wall thickness is estimated to be potentially the greatest source of error in the determination of experimental tensile strength. The variance of the shell wall thickness from the nominal thickness was typically within ± 0.003 inch. This is potentially a ± 10 -percent variation, based on a nominal thickness of 0.030 inch.

The accuracy of the pressure test equipment is expected to be within ± 3 percent, and the accuracy of determination of the glass-fiber content is expected to be within ± 1 percent.

The cumulative error of the pressure test and thickness for the determination of tensile strength is thus potentially as much as ± 14 percent.

Calculations

The empirical tensile strength from pressure tests was calculated, using Equation 7.1 for spherical thin wall stress.

$$\sigma = \frac{Pr}{2t} \quad (\text{Equation 7.1})$$

where P = load in pounds
r = spherical radius in inches
t = wall thickness.

Figure 16. Tensile Test Fixture and Specimen Setup

Table 5. Test Results for Hemispherical Test Specimens

Specimen Type and Number	Specific Gravity (g/cc)	Fiber Content (Percent Volume)	Average Thickness (Inch)	Burst Pressure (psig)	Strain at Failure (Percent)	Ultimate Tensile Strength (psi)
<u>Polar-Wound</u>						
1	1.71	40	0.032	168	---	11,348
2	1.69	39	0.030	220	0.6	15,851
<u>Gyro-Wound</u>						
1	1.60	32	0.038	920	2.5	52,331
2	1.61	35	0.038	860	2.3	48,918
3	1.58	30	0.035	900	2.4	55,080
4	1.64	35	0.034	937	2.5	59,700
5*	1.62	33	0.031	870	2.4	60,600
Gyro Test Average	1.61	33	0.035	897	2.4	55,300
Expected Theoretical Isotropic	1.72	40	0.030	745	2.0	54,000
*Shear failure of clamping ring on specimen; specimen did not fail in the hemisphere test section.						

The theoretical tensile strength was calculated for an isotropic fiber arrangement, using Equation 7.2.

$$\sigma = \frac{\epsilon}{2} \left[E_f V_f + E_m V_m \right] \quad (\text{Equation 7.2})$$

where ϵ = composite strain

E_f = fiber modulus

V_f = volume fraction of fiber

E_m = matrix modulus

V_m = volume fraction of matrix

SECTION VIII

ANALYSIS OF TEST RESULTS

General

Tests showed that the typical tensile strength of the helical-wound specimens was 13,000 psi, while that of the gyro-wound specimens was 55,000 psi. Table 6 compares the empirical and the expected theoretical tensile strengths of the test specimens. It is noted that the helical specimens only achieved approximately 25 percent of theoretical, compared with nearly 100 percent achieved by the gyro specimens.

Table 6. Comparison of Empirical and Theoretical Strength of the Test Specimens

Type of Specimen	Theoretical Tensile Strength (psi)	Empirical Tensile Strength (psi)	Empirical Percent of Theoretical
Helically-Wound	54,000	11,348	21
		15,851	29
Gyro-Wound	54,000	52,331	97
		48,918	91
		55,080	102
		59,700	110
		60,600	112

The load-deflection characteristics of the helical specimens were typically anisotropic, while those of the gyro specimens were typically isotropic. Figure 17 depicts the deformations of the specimens. Figure 17A shows the change in contour of the helical specimen when pressurized. The collapse of the pole and expansion of the lines of latitude would be expected with an axial (through pole) fiber arrangement, which would yield a lower modulus in directions of latitude compared to longitude. Figure 17B shows the change in contour of the gyro specimens when pressurized. The greater expansion of the pole would be expected for a constant-wall isotropic hemisphere with the end restrained.

A. HELICALLY-WOUND SPECIMEN

B. GYRO-WOUND SPECIMEN

Figure 17. Load-Deflection Characteristics of Test Specimens

Helical Specimen Analysis

It was concluded from the test results that bi-axial reinforcement was not being obtained in the helical-wound specimens. The helical winding process was thus studied to determine the reasons why the specimens were anisotropic.

When helically-winding hemispheres the layer thickness increases progressively from the equatorial to the polar region.⁵ The relationship between the layer thickness and position on the dome is illustrated in Figure 18. To obtain bi-axial reinforcement, the winding angle is progressively increased with each layer of material wound on the mandrel. As this is done the dome tends toward a constant wall thickness, although the surface roughness is large (approximately ± 20 percent of average).

It has been mentioned previously that because of the irregular surface finish and the oversize wall thickness, the helically-wound specimens required machining to obtain the 0.030-inch wall thickness. The wall thickness of the helical specimen (as-wound) was approximately 0.270 inch. It was calculated that the average angle of fibers in the finished specimens was approximately 12 degrees, since the 0.030-inch wall thickness was built up before a significant amount of the bi-axial fibers could be included. Because of this, the fiber reinforcement was primarily uni-axial, and the resin matrix was the load-carrying member in the transverse direction. It would, therefore, be expected that the helical specimen would fail at a tensile strength approximately that of the resin.

The helical-winding process was also studied to determine the minimum wall thickness for obtaining uniform bi-axial reinforced specimens. A minimum wall thickness was calculated, based on a winding strand width of 0.15R, a strand thickness of 0.005 inch, a constant increase of wrap angle for succeeding layers, and a constant wall thickness without machining. The resultant minimum wall thickness for the test specimen was calculated to be 0.210 inch. This yields a maximum R/t ratio of approximately 20 for a helically-wound, uniform, bi-axial, reinforced specimen.

Figure 18. Layer Thickness Variation for Various Helical-Winding Angles.

Gyro Specimen Analysis

It was concluded from test results that the gyro specimens achieved the expected tensile strength. This was attributed to the isotropic fiber arrangement obtained with the gyro filament-winding method.

As mentioned in Section IV, the fiber arrangement dictates the directional stress and strain characteristics of a fiber-reinforced plastic. Achieving an isotropic fiber arrangement is dependent upon obtaining an equal amount of fibers in all directions.

Figure 19 illustrates the fiber arrangement of the polar-wound and gyro-wound test specimens. The tensile strength in the x and y directions was calculated by using Netting Analysis, described below. Because of the unbalanced fiber arrangement of the polar-wound specimen, the strength is much lower in the x direction than it is in the y direction. The strength of the gyro-wound specimen is not dependent upon direction, but upon the balanced fiber arrangement and the small included angle between fiber directions.

Equal bi-axial loads occur during pressurization of a hemispherical shape (Figure 20). As such, the low tensile strength of the polar-wound specimen would be expected because of the lower strength in the x direction. Also, since the strength in the gyro specimen is independent of direction, it would be expected to achieve the predicted strength.

A. POLAR-WOUND SPECIMEN

B. GYRO-WOUND SPECIMEN

Figure 19. Fiber Arrangement and Resultant Stress Effects

Netting Analysis

A description of the Netting Analysis calculation follows. Netting Analysis assumes that the fiber reinforcement carries all the load. In addition, it is assumed that the fibers are equally stressed.

Figure 20. Stress Element of Hemispherical Configuration

$$F_1 = F_2 = F$$

$$F_x = F \cos \theta$$

$$F_y = F \sin \theta$$

$$A_1 = A_2 = A$$

$$W_x = \frac{W}{\cos \theta}$$

$$W_y = \frac{W}{\sin \theta}$$

$$A = A_f + A_r = Wt$$

$$A_f = \text{Area fiber}$$

$$A_r = \text{Area resin}$$

$$A_x = W_x t = \frac{Wt}{\cos \theta} = \frac{A}{\cos \theta}$$

$$A_y = W_y t = \frac{Wt}{\sin \theta} = \frac{A}{\sin \theta}$$

Determination of stress in the x and y directions follows.

$$\sigma_x = \frac{F_x}{A_x} = \frac{F \cos \theta}{\frac{A}{\cos \theta}} = \frac{F}{A} \cos^2 \theta$$

$$\sigma_y = \frac{F_y}{A_y} = \frac{F \sin \theta}{\frac{A}{\sin \theta}} = \frac{F}{A} \sin^2 \theta$$

Since the load is carried by the fibers,

$$\sigma_x = \frac{F}{A} \cos^2 \theta = \left[\frac{A_f}{A_f + A_r} \right] \left[\frac{F}{A_f + A_r} \right] \cos^2 \theta$$

$$\sigma_x = \left[\frac{F}{A_f} \right] \left[\frac{A_f}{A_f + A_r} \right] \cos^2 \theta,$$

where $\left[\frac{F}{A_f} \right] = S_f$ (Fiber stress)

$$\left[\frac{A_f}{A_f + A_r} \right] = K \text{ (Area fraction which is fiber)}$$

$$S_x = K S_f \cos^2 \theta$$

$$S_y = K S_f \sin^2 \theta$$

For multiple angle reinforcement with equal stress fibers

$$S_x = K S_f \frac{1}{n} \left[\cos^2 \theta_1 + \cos^2 \theta_2 + \dots + \cos^2 \theta_n \right]$$

$$S_y = K S_f \frac{1}{n} \left[\sin^2 \theta_1 + \sin^2 \theta_2 + \dots + \sin^2 \theta_n \right]$$

The equations for multiple angle reinforcement with an equal included angle between fibers reduces to the following equations because the

$\frac{\sin^2 \theta_n}{n}$ and $\frac{\cos^2 \theta_n}{n}$ functions reduce to a value of 0.5.

$$S_x = \frac{K S_f}{2}$$

$$S_y = \frac{K S_f}{2}$$

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SECTION IX

CONCLUSIONS

Two filament-winding methods were investigated for winding high-strength, thin-wall domes. Tests showed the capability of the helical-winding process to be limited to winding constant wall domes with a radius-over-thickness ratio (R/t) less than 20. The limitation is due to non-uniform layer thicknesses during winding. The gyro-winding method produced high-strength (55,000-psi wall stress) and thin-wall ($R/t = 150$) domes.

It has been shown that different filament-winding methods do not necessarily achieve the same degree of isotropicity and strength. The reasons for the differences were related to the limitations of the type of winding process. In general, helical and gyro filament-winding methods may achieve high strength isotropic domes with R/t ratios less than 20. However, for R/t ratios greater than 20, the gyro winding method becomes increasingly better suited for high strength and isotropic properties.

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SECTION X

RECOMMENDATIONS

Recommendations for future work on this investigation would include the following two areas:

- Verification of the maximum R/t ratio for helically-winding constant-wall, high-strength isotropic domes; and
- Optimization of the gyro winding method for greater tensile strength.

In Section VIII, "Analysis of Test Results", the writer presented his opinion of the maximum R/t ratio for helically-winding constant-wall, high-strength, isotropic domes. In developing this opinion, the attempt was made to keep assumptions within conventional limits of helical-winding processes. While it is believed these assumptions are accurate for the existing technology, they were not verified by experimentation. Thus, future work would include this verification.

The achievement of greater tensile strength of the gyro specimens is expected by increasing the glass content, which was 33 volume percent in this investigation and yielded a tensile strength of 55,000 psi. It is expected that the glass content could be increased to 50 volume percent with minimum modification of the process. Accordingly, this should yield a tensile strength of 80,000 psi.

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SECTION XI

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