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APPLICATION OF GLASS FIBER LAMINATES IN AIRCRAFT

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SUBJECT: APPLICATION OF GLASS FIBER LAMINATES IN AIRCRAFT

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1. PURPOSE.

This circular is to provide information on the past and present uses of reinforced plastics in aircraft, the engineering and design considerations, and the manufacturing methods insofar as they relate to and affect the strength and durability characteristics of reinforced plastics.

2. REFERENCES.

This document is for the guidance of persons who are considering designing and manufacturing aircraft parts of reinforced plastics. The suitability and durability of all materials used in aircraft should be demonstrated in accordance with the Civil Air Regulations, Parts 3, 4b, 6, or 7.

3. Additional copies may be obtained from:

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for GEORGE S. MOORE
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Manufacturers of aircraft and of resin reinforced materials have been most generous in providing information, technical advice and illustrations. Any reference to specific materials or manufacturer's product does not constitute FAA's recommendation or endorsement.

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Chapter 1. PAST AND PRESENT USES

1. GENERAL. Reinforced plastics were developed during World War II when polyester resins became commercially available. The first major applications were radomes, body armor, hulls for light combat naval craft, and similar military uses. Reinforced plactics soon found applications in the architectural, electrical, and transportation fields, in consumer products, and in space equipment as well as in military service. Currently there are several aircraft designs as well as a number of aircraft components which are being constructed almost entirely of glass-reinforced plastics. In connection with these designs, it is interesting to note the past uses of this material in aircraft.

2. PAST USES. Some of the earlier uses of reinforced plastics are as follows:

a. In 1944 Wright Air Development Center investigated the structural application of glass-fiber, sandwich-reinforced plastics for the aft fuselage of the Vultee BT–15, a two-place, low wing, 480 horsepower airplane (*20*).[1] The weight of the plastics design was about the same as the standard aluminum or wood fuselage designs being used, but the results of static testing showed the strength-to-weight ratio for the plastic design to be 33 percent as compared to 22 and 18 percent for the other two designs. Failures occurred at the aluminum and wood fittings without any visible failure of the reinforced plastics structure. It was also noted that deflections under equivalent load were less in the plastics-sandwich design than for either the aluminum or wood designs. Having demonstrated the practicability of reinforced plastics, WADC's next structural application was the wing for the AT–6 (*22*). Since the wing was a more highly stressed structure than a fuselage, and the panels were of less curvature it was necessary to develop a stronger core. The core developed consisted of square rods of cellular cellulose acetate, wrapped with glass-fiber cloth. This design proved satisfactory in tests to over 100 percent of ultimate design load. As with the BT–15, the failures occurred at the fittings. WADC concluded that a properly designed reinforced plastics structure compared favorably with aluminum, and that this material in the wing would have proven even more efficient if the airplane originally had been designed for this material. In both cases, the development only reached the experimental stage.

b. In 1947 the trailing edges of ailerons and elevators on Douglas DC–6 airplanes were fabricated of glass-reinforced plastics instead of metal, the latter having been used on earlier airplanes. The advantages cited were an easier installation, resulting in a smoother job, elimination of wrinkles and buckles; a thicker cross section with no increase in weight, thereby providing a greater impact resistance than that offered by a metal surface. Repairs were easier and smoother than with the metal type.

c. The Taylorcraft Model 20, type certificated in 1955, was a forerunner in the use of reinforced plastics in personal type aircraft. In this airplane, the fuselage skin from nose to the fin trailing edge, the wing and stabilizer skins, seats, doors, gas tanks, wheel pants, instrument panel, and many other parts were made of glass-reinforced plastics. As shown in figure 1a, the skin panels of the fuselage and fin were attached to a welded steel tubular structure. The wing panels were attached to a wood spar and an aluminum rib structure.

3. PRESENT USES. Some of the present uses of reinforced plastics are as follows:

a. Today's transports have reinforced plastics in the nose cone, tail cone, miscellaneous fairings, wing tips, antenna, and radome areas. In both the Douglas DC–8 and Convair CV–880, the upper portion of the stabilizer is a radio antenna. In order to electrically isolate this from the aluminum skin and structural members below, a reinforced plastics section, which is molded to the stabilizer contour, forms a separating joint between the lower and upper portions of the stabi-

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[1] NOTE: The numbers in parentheses are referenced authorities listed in the Reference Section of Appendix 2.

lizer. Thus there is no metal-to-metal contact and the integrity of the antenna section depends on the plastic section. Figure 2 shows a large (24-foot diameter) reinforced plastics rotodome mounted on a Grumman W2F-1 aircraft. As illustrated in figure 3, the Fokker F-27 also incorporated glass-reinforced plastics in place of aluminum for the faces of the sandwich structure of the wing leading edge.

b. Personal type aircraft being developed of reinforced plastics are the Piper PA-29, figure 4, and the Beagle-Miles M.218, figure 5b, the latter's construction approximately 63 percent reinforced plastics and 33 percent aluminum (*29*). In other personal type aircraft such components as engine cowlings, wing tips, miscellaneous fairings, landing gear doors, wing-tip fuel tanks and landing gear supports are being fabricated of reinforced plastics. See figures 6a through 6d.

c. Figure 7 shows the Kaman H-43 helicopter's glass-reinforced plastic rotor blade which is reported to have good fatigue resistance and to have made possible major savings in manufacturing and maintenance costs.

d. Missiles and drones have had extensive portions of the structure fabricated from glass-reinforced plastics. The Martin Bullpup B uses a glass resin epoxy wing in place of the original centrifugally cast aluminum wing. Except for the rocket motor and the forged aluminum hinges which transmit the wing loads to the fuselage, the Northrop RP-76 drone is all glass-reinforced plastic construction. Figure 8 shows the RP-76-4 nose and tail cones. These cones attach to the center steel casing which houses the solid propellent rocket engine.

e. In a different manner, glass fabric is being used, not as a laminate of mutilayers of glass and resin, but as a single layer of glass fabric covering to replace or reinforce the conventional fabric covering. Generally dope is used instead or resin.

Chapter 2. MANUFACTURING AIRCRAFT PARTS OF REINFORCED PLASTICS

4. GENERAL. Reinforced plastic laminates are plies of reinforcing material which have been impregnated or coated with thermosetting resin, then bonded and cured together to form a specific part. The principal operations involved in the manufacture of reinforced plastic parts are the lay-up, or arrangement of the reinforcement, and the process of molding.

5. MATERIALS. This report will consider plastic laminates reinforced exclusively with glass fibers.

a. Types of Resins. There are four basic families of resins used in low-pressure reinforced plastics. These are the polyesters, epoxies, phenolics, and silicones. Polyester resins are widely used, largely because of their generally good properties, their relatively easy handling, and low cost. For special uses, however, other types are significant: epoxies for higher strength and greater chemical resistance, phenolics for higher strength and greater heat resistance, and silicones for their electrical properties and heat resistance. In addition, furanes, melamines, and diallyl phthalates (DAP) have some applications. Since all these resins are thermosetting, they must be used in conjunction with a catalyst or curing agent. The catalyst is used to start the polymerization or curing reaction. Accelerators are usually added to polyester resins in combination with catalysts to start a rapid curing reaction without the application of heat. These two materials only work together in certain combinations or pairs. The manufacturer may add stabilizers or inhibitors to polyester resins to prolong storage life, in which case the catalyst quantity may be modified. The amount of all such ingredients strongly affects the properties, storage life, working life, and molding characteristics of the resin. To obtain the highest quality laminates, the manufacturer's recommendations should be followed for quantity and handling of resins, catalysts, accelerators and inhibitors.

b. Fillers and Pigments. Fillers and pigments are added to the molding resins to reduce shrinkage, minimize crazing, lower material costs, impart color or opacity and to improve surface finishes. Addition of an excessive amount of filler can make the resin difficult to work since the resin viscosity is correspondingly increased. Laminates containing fillers may be opaque, and thereby may not be readily inspected for internal flaws.

c. Reinforcements. Reinforcements are the materials used to increase the strength of the plastic. The strength, modulus, shape, size, distribution and geometrical configuration of the reinforcement in the plastic matrix is a primary factor in the properties of the laminate. The reinforcement material is often a fibrous glass, in the form of mats, rovings, chopped fibers, woven roving and reinforcing yarns, or fabric of any one of many styles. Other materials such as asbestos, felts, papers, and synthetic fibers,—nylon, orlon, dacron, and dynel—are used in relatively specialized applications.

(1) Fabrics. There are three types of plastic reinforcing glass fabrics: plain, satin, and unidirectional. These differ in their weave and in the strength of the fibers in the warp and fill directions, as shown in figure 9. Variations of these are the crowfoot satin, leno, eight-harness satin, mock-leno, unidirectional and high modulus weaves. The warp of the fabric (warp yarn or fiber) runs the long direction and is parallel to the sides of the fabric. The fill (fill yarn or fiber) runs the short direction and is at 90° to the warp of the fabric. Table I lists the thicknesses and weaves of the more commonly available fabrics. (See page 6.)

(a) Plain Weave. Each warp and fill (weft) thread passes under one thread and over the next. In the case where the warp and fill yarns are of the same count, the fabric is said to be a "square weave".

(b) Satin Weave. Each warp and fill thread passes under one thread and over the next three threads for the four-harness satin weave or over seven threads for eight-harness satin weave.

(c) ***Unidirectional or Crowfoot Weave.*** Strong warp threads are crossed by relatively few, weaker, fill threads.

(2) ***Mat.*** Mat consists of glass strands distributed in a random pattern and available either in the chopped strand form or continuous strand form. Glass mats are often employed for nonstructural and semistructural parts having complex cross sections, or thicknesses that are great with respect to the other dimenisons. The mats are also used in woven fabric parts as integrally molded reinforcements, such as bosses and inserts.

(3) ***Rovings.*** Rovings are untwisted, ropelike bundles of continuous glass strands. Rovings are used for unidirectional strength characteristics or are woven into heavy, coarse fabrics for bidirectional strength.

(4) ***Glass Finishes.*** During manufacture or forming of the glass strands for weaving, the filaments are coated with a starch like material called sizing, which serves to prevent flaws as the strands are being twisted and later woven into fabric. Fabrics with this original sizing are called "greige goods." The fabric may be heat or a combination of heat and chemically treated so that almost all the organic sizing is removed and a finish applied. Fabrics are sometimes used in the heat cleaned state with epoxy on silicone resins. Also, an epoxy sizing was recently developed which permits direct use of the fabric with an epoxy laminating resin without use of a finish. Finishes were developed primarily to improve the wet strength characteristics of laminates but they also increase the speed and thoroughness of "wetting out" the reinforcement. Hence they result in higher dry strength by bringing the resin and fibrous glass into intimate contact. Resins are generally organic in nature while fibrous glass is inorganic; consequently, an intermediate substance that has both organic and inorganic properties must be applied to the glass if a satisfactory bond is to be attained. This intermediate bond is supplied by various types of finishes. Commercial finishes, to date, can be placed in two classifications, chrome and silane.

6. REINFORCEMENT LAY-UP. Two general methods of lay-up are used, wet and prepreg. With the latter, the reinforcing material which previously has been impregnated with resin is laid up in the form of precut patterns, filaments, ribbons, or tapes. For the wet lay-up procedure, liquid resin is applied to the dry reinforcing material either before or after it is laid in the mold. The workmanship of impregnating the reinforcement with the resin and of eliminating defects such as voids, wrinkles, delamination, washing, resin dryness or richness, crazing and foreign inclusions affects the quality, and consequently the strength, of the laminate. The use of preimpregnated fabrics eliminates or reduces many of the defects just mentioned.

7. MOLDING PROCESSES. Principal considerations in the selection of the molding method are the size and shape of the part, its performance requirements (e.g. strength, appearance, and dimensional tolerance), the type of reinforcement material, and the production quantity requirements. Several basic techniques are described in the following subparagraphs:

a. ***Contact Molding.*** Layers of reinforcing material are placed against the mold surface upon which resin is applied either by spraying or brushing (unless prepreg material is used). The formed part is allowed to cure without external application of pressure at room temperature or under temperature from heat lamps. See figure 10.

b. ***Vacuum Bag Molding.*** This is similar to the contact molding method except that when the layup is completed, a flexible sheeting is placed over the impregnated reinforcement, and a vacuum of 10–14 p.s.i. is drawn between the sheeting and the mold surface. See figure 10.

c. ***Pressure Bag Molding.*** This is similar to the vacuum bag method, except that positive pressures up to 50 p.s.i. are applied to the external surface of the lay-up. See figure 11.

d. ***Autoclave Molding.*** The entire assembly is placed in an autoclave and subjected to hot air or steam under pressure of 50 to 100 p.s.i.

e. ***Matched Die Molding.*** A wet or prepreg lay-up is placed against one of the matching molds and pressure is applied to the lay-up by closing the matching mold between platens of a press. Heat is applied simultaneously. In most cases, mechanical stops are used to control the applied pressure and laminate thickness.

f. ***Filament Winding.*** A filament, band, or sheet is wound by mechanized techniques on to mandrels, which are the shape of the finished part. The filament is usually wound under tension. Windings may be applied dry (preimpregnated), wet (fed through an impregnating resin bath), or applied dry and post-impregnated by brushing or spraying. See figure 12.

8. CONTROL OF THE "CURE". This has been to a large extent the result of trial and error tests on the particular materials in use. Considerable work is being performed in some laboratories to reduce the amount of "rule-of-thumb" techniques. In one study (*33*) which was made of the many variables which influence the cure and the resulting quality of the product, ratios of catalyst and accelerator to resin, methods of mixing, temperature, humidity, thickness of molding, and type of resin were but a few of the factors considered.

9. EFFECT OF THE POLYMERIZATION OR "CURE". Shrinkage of resin and temperature changes occurring in the curing cycle can cause residual stresses in the laminate. The resins shrink in volume due to molecular crosslinking when passing from the liquid to the solid state. The resin forms a bond with the glass during the curing process. Since the glass does not undergo any appreciable change in volume during cure, shrinkage of the resin sets up compressive stresses in the glass and residual tensile stresses in the resin. Added to the volume shrinkage stresses is the internal stress occurring during cure due to thermal shrinkage. (The curing process usually develops a considerable amount of heat in a laminate due to the exothermic chemical reaction.) With resins having a considerably higher coefficient of thermal expansion than glass, a differential thermal shrinkage occurs when the laminate cools after curing. These effects can be minimized by selection of optimum curing methods and proper control of the cycle. Thus, deficiency of cure and undue stress in the resin matrix are two very significant factors governing the strength of the final parts.

10. DEGREE OF "CURE". Even though the laminate appears firm after a relatively short time, the polymerization continues for some period of time. Since the quality of the final part is directly related to the extent and character of the polymerization or "cure" and since the product must be of a stable material, the characteristics of the cure must be known. Improper cure due to mistakes or unknown changes in resin formulation, insufficient mixing, improper mold cycles, etc., means the crosslinking reactions between resin molecules have not gone to completion. For this reason the gel time and peak exotherm[1] (maximum temperature reached during cure) should be determined for each batch or resin. Only after it is established that the material is not going to change any further, can the strength properties be assessed with assurance of reproducibility. As a general index of the degree of cure, the hardness is measured with any one of the various forms of hardness measuring meters. These instruments will identify laminates which are badly undercured but borderline cases may be difficult to detect.

11. EFFECT OF PRESSURE IN THE MOLDING PROCESS. Increasing the molding pressure gives a denser laminate and permits increased glass percentage. As shown in figure 13, strength properties are increased in proportion to increases in the glass content. There is, however, an optimum resin content at which the strength of the laminate is maximum after which the strength drops off with decreasing resin content. The point of the maximum strength depends upon the resin type and reinforcement type. When only contact pressure is used, it is difficult to achieve a dense void free fill or the absence of resin-rich areas. Because of the very low pressure, the resin content will be approximately 50 to 60 percent and the flexural strength will be only about 30,000 to 45,000 p.s.i. for an epoxy resin glass fabric laminate. (Resin content of reinforced laminates is expressed as the ratio of the weight of cured resin to the total weight of the cured laminate.) When the pressure is increased to 25 p.s.i. for instance, the flexural strength is correspondingly increased to about 60,000 to 65,000 p.s.i., the higher glass content accounting for much of the improvement. For glass cloth laminates optimum strength properties normally result when resin contents are within the range of 30 to 40 percent. Resin contents substantially below this range could result in insufficient stabilization in compression, in low strength interlaminate bonds, and reduction of other properties.

12. QUALITY OF A PART. A number of investigators have studied the variations in quality between superficially similar laminates when there

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[1] NOTE: The Society of Plastics Industry has an established method for determining the "exotherm curve" of an uncured polyester resin, or reference may be made to MIL–R–7575, Resin, Low Pressure Laminating.

are changes in the atomspheric conditions during lay-up, or in the type of catalyst, or the proportion of catalyst to resin, or the type of finish on the glass or the use of additives (stabilizers, thinners, etc.) in the resin. These studies show that a seemingly minor variation in materials, procedure, or equipment, such as a change in a source of supply, or in the chemical composition of one of the ingredients, or in the performance of pressure and temperature controls and sequence times, may result in a major change in the strength and durability of the part. Tests have shown that there will be variations between panels laid up by the same operator, even though the panels are pressed at the same time, as well as variation between panels laid up by different operators, and variation within a panel.

13. PROCESS DEVELOPMENT. The fabrication of a component which is either large in area, complex in shape, or relatively thick in cross section usually requires process development before a satisfactory component can be produced. The necessity for process development can be be attributed to many variables in fabrication such as:

a. Different amounts of exotherm resulting from varying thickness of a laminate.
b. Deviations from optimum heating and cooling rates of the laminate.
c. Deviations from optimum curing pressures to control resin flow and resin content.
d. Differences in pot-life of various resins.
e. The evolution of gases in the cure and post cure of some resins.
f. The high viscosity of some resins.

Appendix 1 outlines the type of information to be included in a process specification.

TABLE I.—*Glass Fabrics*

Style No.	Average thickness in.	Weave
108	0.002	Plain.
112	0.003	Plain.
116	0.004	Plain.
164	0.015	Plain.
143	0.009	Unidirectional.
120	0.004	4-Harness Satin.
181	0.0085	8-Harness Satin.
182	0.013	8-Harness Satin.

Chapter 3. ENGINEERING PROPERTIES OF GLASS REINFORCED PLASTICS

14. GENERAL. An understanding of the basic properties of a material is essential to developing an efficient and effective design. Reinforced plastics, being fibrous in structure, differ fundamentally from metals which are crystalline in structure. The more common aluminum and steel alloys have been available for many years, the metallurgy has been standardized and design mechanical properties have been established. With reinforced plastics the strength properties are dependent upon the type of resin and orientation of reinforcement and on the action of the resin with respect to the reinforcement. Numerous possible combinations of resins, catalysts, reinforcements, finishes, and molding processes can result in almost an infinite number of materials and corresponding mechanical and physical properties. Information on the more commonly used laminates is contained in MIL–HDBK–17, "Plastics for Flight Vehicles". The data in MIL–HDBK–17 are reduced values which were derived by reducing average test results to correspond to the values required by the appropriate specifications for testing laminates in the wet condition. With constant advances being made with resins and reinforcements, material property data may not be available on a particular material. Test programs to acquire such data should be conducted using the recognized test procedures listed in table II. (See page 11.) These test methods are, in general, a direct adoption of those procedures developed for metals, plywood, or nonreinforced plastic materials. There is a continuing effort to provide more representative test methods.

15. RESIN-GLASS FIBER BOND CHARACTERISTICS. Reinforced plastic parts are made of two widely dissimilar materials—glass which is a high modulus, high strength, low elongation material and a resin which is a low modulus, low strength and relatively higher elongation material. The joining of the reinforcement material to the resin is extremely critical in obtaining good strength and durability characteristics of the reinforced plastic. Research on resins, fibers, and finishes, to improve the bond between the resin and the fiber, is continually being conducted in an effort to improve:

a. the physical properties of the reinforcement and matrix materials,
b. the mechanical interlocking, friction, wetting and/or chemical bond between the materials, and
c. the basic geometry of the reinforcement within the matrix.

16. REINFORCEMENT DIRECTIONAL CHARACTERISTICS. For a given resin type, the strength of a plastic laminate depends largely upon the reinforcement material. If it is a glass fiber cloth or woven roving, then the weave may be such as to make the material stronger in one direction than in the other. Further versatility is possible by cross-laminating or by combining various cloths in a single parallel laminate. If the laminate can be described as having the warp of all layers in the same direction, it is said to be parallel laminated. If the warp directions of the layers are not parallel, this is a cross-laminate, i.e., each layer is rotated with respect to the layers immediately above and below. Through the use of this directionality of the fabric and the placement or orientation of the fabric layers with respect to one another, a laminate may be highly unidirectional or have almost no directional strength differences as illustrated in figure 14. The variation of material strength properties with direction is analogous to the difference in the physical properties of wood measured with and across the grain. Materials which exhibit this characteristic are referred to as orthotropic. Materials whose properties are essentially the same in all directions are termed isotropic. Laminates with chopped strands or mat are considered isotropic, provided the applied stresses are in the plane of the laminate.

17. MECHANICAL STRENGTH PROPERTIES

a. Tension

(1) A typical glass-fabric-reinforced polyester laminate under standard hand lay-up conditions has a tensile strength of 40,000 p.s.i. Since reinforced plastics are weakened by moisture, the tensile strength of the same material is 38,000 p.s.i. after being subjected to wet conditioning.[1]

(2) The tensile modulus of elasticity "E" of reinforced plastics is among the lowest of structural materials. A typical glass fabric laminate has an E of about 2.5 million. Thus the critical design criterion on most components is stiffness rather than strength. Tensile stress-strain curves reveal that there are two moduli. At a certain point which may be in the range of 30 to 50 percent of ultimate strength, the tensile stress strain curve breaks sharply and assumes a second slope with a resulting decrease of about 10 percent in modulus. This "secondary modulus" curve proceeds essentially as a straight line to failure. Resin-glass fiber bond strength tests reveal that the load carrying ability of the laminate is reduced because of partial rupture of the resin-reinforcement bond.

(3) Tensile stress-strain curves in figures 15 and 16 for polyester and epoxy resin glass laminates, respectively, illustrate the two slopes while the curves in figure 17 indicate that this dual characteristic tends to change or disappear after loading to a stress beyond the initial proportional limit. If the design is such that the component will be stressed near its upper strength limit, the secondary tangent modulus of elasticity is the value of most concern. For lightly loaded elements, use of the secondary modulus may give slightly conservative results, in which case it may be acceptable to use the primary tangent modulus. Where both loading conditions are prevalent, possibly the secant modulus is the best value to use, as it tends to be a conservative average of primary and secondary moduli. Since each of three moduli can be reported—initial tangent, secondary tangent and 70 percent secant—the user must be aware of which modulus is being reported.

(4) Tensile test methods in Federal, Aerospace Industries Association, and American Society for Testing Materials Specifications are similar. A "dumbell" or "dogbone" type of specimen shown in figure 18 is loaded uniformly to failure, usually at a rate of 0.05 inches per minute. The specimens sometimes fail in the radius instead of in the width of the 2-inch gage length. Tensile and compression specimens must be prepared with care since roughly made specimens will give such a scatter in results that the data will be questionable.

(5) No value of yield strength is given in tables of mechanical property data since the yield strength of laminates at zero degrees to the fibers is practically equal to the ultimate strength, very little plastic strain taking place before rupture occurs.

b. ***Compression.*** Laminates exhibit dry and wet ultimate compressive strengths of 38,000 p.s.i. and 30,000 p.s.i., respectively, for the same typical material having corresponding tensile strengths of 40,000 p.s.i. and 38,000 p.s.i. Dual values for compressive modulus of elasticity, such as were described under tensile strength, do not generally appear in the dry or wet condition; therefore, a single value of modulus of elasticity and of proportional limit are used in design for compression. The Federal and ARTC methods measure edgewise compression with a specimen 3x0.5x⅛ inch and with the ends flared so as to reduce crushing. See figure 19. In order to prevent failure by column buckling, special holding fixtures are used with the specimen. See figure 20. The ASTM compression test is a free column test which measures flatwise compression (perpendicular to lamination), not edgewise compression. The specimen is made from stacked plates to form a rod ⅛- to 1-inch diameter and ½ to 2 inches long.

c. ***Flexure.*** Reinforced plastics exhibit relatively low moduli of elasticity which results in large slope deflections. Flexural strength should not be the only mechanical property obtained on a material since any analysis of such results, using the standard beam theory is subject to question when large deflections are involved. The beam test is, however, easy to perform and provides for rapid assessment of materials or processes. The three test methods (AIA, Federal, and ASTM) use a test specimen with the same dimensions, i.e., 4x1x⅛ with a 2-inch span between supports. There is some difference in loading rates: ASTM requires 0.05 inch per minute of head travel, ARTC

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[1] Wet conditioning is defined as a 2-hour immersion of the specimen in boiling distilled water. The specimen is cooled in water and tested wet immediately after removal from the water. When validity of the test results is questioned, the specimen is soaked for 30 days in distilled water at room temperature and then tested wet immediately after removal from the water.

requires 2 to 3 minutes to failure and the Federal requires 0.20–0.25 inch per minute of head travel. Slower rates are required in all methods when determining modulus values.

d. *Shear Strength.* The shear properties must be related, as shown in figure 21, to the manner of application of the shear forces, either edgewise or interlaminar. Data on either type of loading are relatively limited. Panel shear testing, as shown in figure 22, provides data which is limited by the maximum fiber stress. The geometric configuration of the test specimen is designed so that, upon loading, an area consisting of the specimen thickness along a line on the face of the specimen is placed in shear. Interlaminar shear testing, as shown in figure 23, measures the effectiveness of the laminating process and the strength of the resin used.

e. *Bearing Strength.* No fixed relation of bearing strength to compressive strength appears to exist. Bearing properties decrease significantly with increasing values of D/t. The low values of maximum stress in bearing at small edge and side distances result from failure by shearing out at the ends or from failure in tension at the net section before development of the full bearing stress which the laminate is capable of carrying.

(1) Test methods for bearing are fairly standard, except that the ARTC method may yield slightly higher values than the ASTM or Federal method. Test specimens are relatively easy to produce except that final reaming of the bearing hole after drilling is a critical operation. In general, good agreement is obtained between test specimens.

(2) Bolt bearing properties of polyester and epoxy laminates are being reported for three different load conditions:

(a) at proportional limit,
(b) at a deformation equivalent to 4 percent of the bolt diameter, and
(c) at ultimate.

f. *Fatigue.* As with other structural materials, the continual application of stresses, either alternating, steady, or a combination of both, causes failure even though the stress is less than the short-time static ultimate strength. The fatigue cracks propagate from one fibrous element to the next and from one layer to the next. This generally occurs in delayed stages as opposed to the rapidly propagating crack which may be expected with metals. Angle of loading with respect to warp, notches, moisture, and temperature are a few of the effects that have been evaluated in the development of fatigue strength data. The difference in fatigue strength with angle of loading is illustrated in figure 24. Generally with tests up to 10 million cycles no endurance limit is reached; however, when the loading is at an angle with the direction of the reinforcing fibers, there is some indication that the curves are approaching an endurance limit.

g. *Creep.* As shown in figure 25, tensile creep at room temperature parallel and perpendicular to the warp of parallel or cross laminated glass-cloth-reinforced plastics is negligible. If the loading, however, is at some angle, such as 45° to the warp, creep becomes substantially higher. In flexure or compression long term static loading, creep may need to be considered.

h. *Stress Rupture.* As in the case of other structural materials, reinforced plastic laminates will fail under longterm continuous loading at stresses below the ultimate stress for short term loading. Test data indicates a reduction in the tensile and compressive stress rupture characteristics for the relatively short period of 0.1 hour. Figure 26 illustrates the percent reduction in strength versus the time of the duration of stress.

i. *Impact.* Large areas of reinforced plastics, when struck perpendicular to the direction of lamination, tend to distribute the impact force due to the arrangement of the reinforcement and due to their relatively low moduli. Failure of a laminate under heavy impact involves complex shearing and delamination effects. For laminates using a fabric reinforcement, the strength will vary with the amount of crimp in the yarn. Each yarn in passing under and over the crossing yarns deviates from a straight path, thereby resulting in a crimp. The amount of crimp depends on the weave of the cloth and on the diameter of the crossing yarns. Plain weave fabrics have the greatest amount of crimp and satin weave, particularly eight shaft fabrics, have the least amount of crimp. Thus, with the latter, very high tensile and compressive strengths can be obtained. The former will have high impact strength, since the crimp effect tends to absorb the impact energy before the fiber column is fully stressed. The Izod and falling ball impact test methods have been used to give relative impact resistance of laminates with various reinforcements. The Izod test is less applicable to laminate materials than to homogeneous materials because this test gives the energy absorbed at failure and not at a partial failure. Since a partial failure more often occurs in laminated materials, the Izod test results are less meaningful. Measuring toughness by a summation of the area under the tensile stress-strain curve may be more satisfactory.

j. Abrasion. Abrasion due to rubbing of laminates or from water impingement may wear away the resin surface and expose the glass filaments and consequently deteriorate successive layers of the laminate. Rain erosion coatings have been developed to provide protection of exterior plastic surfaces on high speed aircraft.

18. ENVIRONMENTAL EFFECTS

a. General. The use of reinforced plastics in structural applications requires a knowledge of the effects of various environmental conditions on the durability of the materials.

b. Weathering. Several investigations have shown that reinforced plastics deteriorate under weathering conditions. The loss in structural strength and durability depends on the climatological conditions of sunlight, clouds, and haze, the geographical location, the manner in which the material is exposed, the type of laminate and the resin content. A reinforced plastic is a heterogeneous structure composed of two materials differing in their reactions to weather exposure. The resulting effects depend on the resin properties, the glass fiber properties, the attachment between the resin and glass, and the geometry of the construction.

(1) Types of Deterioration.

(a) Some investigations have disclosed that after a year or two of exposure, there is a crazing of the resin around the glass fibers. It has been suggested that resin failure is largely due to a type of stress fatigue caused primarily by (1) the difference in the coefficients of linear thermal expansion of the resin versus the glass, and (2) the difference in the dimensional change with water absorption of the resin versus the glass. Perhaps the greatest cause for the resin failure, however, is the destructive effect of the sun's rays. This radiation, particularly the ultraviolet range, is known to be damaging to polymers, as evidenced by color development and polymer breakdown.

(b) Unpainted panels have been exposed to arid, arctic, and tropical temperatures and salt air conditions. The latter has usually been the most destructive condition resulting in substantial erosion of the surface resin and consequently severe reductions in strength. A reduction in hardness should be expected where there is any substantial erosion of the surface resin.

(2) Time factor. Generally, periods of 2 to 3 years are required to show significant weathering effects for most types of laminates. About 5 to 20 percent reduction in tensile, compressive, or flexural strength occurs after 1 year's exposure and about 15 to 25 percent after 3 years' exposure. However, the effect can vary greatly with the type of laminate. Losses of strength up to 50 percent resulted after 3 years' exposure of a heat resistant polyester laminate. Laminates in a controlled atmosphere of 73° F. and 50 percent humidity for 3 years had about the same properties as samples of the original material.

(3) Strength reduction.

(a) One investigation (*67*) has been made of the effect of painting each 6 months with a MIL-E-7729 enamel. The test specimens used were of a sandwich construction with polyester resin-glass fabric reinforced facings and honeycomb core. Three years weathering on unpainted and painted panels resulted in the following strength reductions:

Type of Test	*Unpainted (Percent)*	*Painted (Percent)*
Edgewise Compression	40	22
Flexure	30	30

Protection from surface erosion appears to be a beneficial factor in edgewise compressive strength retention but does not reduce deterioration of core to facing bond strength. (The problem of panel deterioration because of water accumulation within the sandwich core is considered in reference 19.

(b) The effect of weathering on the mechanical properties of a reinforced panel while under stress has been questioned. Epoxy, polyester, and heat-resistant phenolic resin glass fabric reinforced panels were exposed in the stressed and unstressed condition for periods up to 3 years. Some of the panels were exposed to semitropical salt air and others were stored under normal conditions (73° F., 50 percent Humidity). After 3, 12, and 36 months, tensile, compressive and flexural properties were determined. Weathering was found to have about the same effect on strength properties of stressed panels as on those of nonstressed ones.

c. Simulated weather testing. The length of time required to obtain useful results from outdoor weathering tests has stimulated the use of environmental test chambers in which attempts are made to obtain more rapid indications of deterioration effects. At the present time there is little correlation between such tests and the long periods of outdoor exposure. The short time tests such as the boil test and the water-immersion test specified in MIL–P–8013 and other materials specifications do not necessarily produce deterioration representative of that caused by true weathering conditions. Tests which provide a reasonable correlation for one material are not always satisfactory with other materials. Since very little is known of the nature of the factors producing deterioration and virtually nothing is known of the quantitative aspects of these factors, an accelerated test procedure has not been developed in theory.

d. Humidity. The exposure of reinforced plastics to moisture for a considerable length of time results in some reduction in mechanical properties. The amount of moisture absorbed depends on factors such as the type of resin, finish on the glass fiber, curing pressure (this determining in part the porosity or percentage of voids in the laminate), the relative humidity, temperature and length of exposure. As outlined earlier, the adhesive bond between the glass fiber and resin may be broken by stressing. The absorption of moisture then has a lubricating effect between the resin and fiber and the strength of the laminate is thereby reduced. Similarly, any other agent which may have this effect, or cause the resin to swell or dissolve, will reduce the strength. Military specification R–7575 limits the strength loss, after water immersion for 30 days to 10 percent or less depending on the property. Reduction in strength is seemingly less in tension and compression than it is in flexure, where loss in strength of 20 to 30 percent has resulted after exposure of one year at high humidity. As illustrated in figure 27 the greatest part of the loss in strength occurs early in the exposure period, but even after 6 months there appears to be a slight but continuing decrease in strength.

TABLE II.—*Conventional Methods of Testing for Mechanical and Physical Properties of Reinforced Plastics*

Method	Test methods		
	ASTM	AIA-ARTC	Federal Standard
Tension	D638, D759	II	1011
Tension Notch Sensitivity	------	III	------
Compression—Edgewise	D695, D759	I	1021
Flexure	D790	VIII	1031.1
Shear	D732	V	1041
Interlaminar Shear	D952	VI	1042
Bearing	D953	IV	1051
Hardness	D785	------	------
Izod Impact (Notched ½ inc. sq. Bar).	D256	------	1071
Failing Ball Impact	------	------	1074
Bond Strength	D952	------	------
Accelerated Weathering	E42	------	------
Outdoor Weathering	Bulletin No. 173	------	------
Water Absorption	D570	------	7031
Specific Gravity	D792	------	5011

Chapter 4. DESIGNING WITH GLASS REINFORCED PLASTICS

19. ENGINEERING ASSUMPTIONS

a. In engineering design of glass reinforced plastics certain assumptions are generally made. The first and most fundamental is that the resin and glass fibers act together and that the stretching, compression, and twisting of fibers and of resin under load is the same; that is, the strains in fiber and resin are equal. This assumption implies that a good bond exists between the resin and fibers, either inherently or because of surface treatment of the glass. The bond need not be absolutely continuous if the bonded points are spaced closely enough to develop the combined action of resin and glass, which is basic to engineering design of these materials.

b. The second major assumption is that glass reinforced plastics are elastic; that is, strains are directly proportional to the stresses applied, and when a load is removed the deformation disappears, i.e., the material is assumed to obey Hooke's Law. This assumption is probably a close approximation of the actual behavior in direct stress below the proportional limit, particularly in tension, where the glass fibers carry essentially all of the stress. The assumption is probably less valid in shear where the resin carries a substantial portion of the stress. The resin can be expected to undergo plastic flow leading to creep or to stress relaxation, especially when stresses are high. More or less implicit in the theory of materials of this type is the assumption that all of the fibers are straight and unstressed, or that the initial stresses in the individual fibers are essentially equal. In practice it is quite unlikely that this is true. It is to be expected, therefore, that as the load is increased some fibers reach their breaking points first, and as they fail their loads are transferred to other, as yet unbroken, fibers, with the consequence that failure is caused by the successive breaking of fibers, rather than by the simultaneous breaking of all of them. The effect is to reduce the overall strength and to reduce the allowable working stresses accordingly, but the design theory is otherwise largely unaffected, as long as essentially elastic behavior occurs. The development of higher working stresses is, therefore, largely a question of devising fabricating techniques to make the fibers work together to obtain maximum strength.

20. STRENGTH AND ELASTIC RELATIONS. Reference 7 presents equations for determining the strength and elastic relations along any axis for laminates having plies of reinforcement oriented at various angles. These equations are also presented in the reduced form for materials which are isotropic. These relationships between stress and strain can be defined if the modulus of rigidity, Poisson's ratio, x and y directions are known. As illustrated in figure 28, the relationship between the direction of the laminations and the direction of the application of the load is important.

21. FACTORS AFFECTING STRENGTH PROPERTIES

a. *General.* Mechanical property data should be modified for use in design in order to account for the effects of the applicable fabrication, specimen thickness, loading, and environmental conditions.

b. *Fabrication.* In some degree with all structural materials, there is a difference in mechanical response behavior between test panel and end item. The "typical" values of properties reported in manufacturers' data sheets generally indicate an average value for an average material. This data should be validated by tests of material fabricated under the conditions assumed in design. The scatter-band of strengths for reinforced plastics is much larger than for metals. Since it is generally inconceivable to test sufficiently to establish some degree of reliability, it is necessary to arbitrarily apply a reduction factor of such magnitude as will result in a reliable structure. For laminates in MIL HDBK-17, this has been accomplished, but it is important to note that the military specifications referenced in the mechanical property data tables are for materials conforming to a specific molding process and cycle of time, temperature, and pressure. Thus the use of materials qualified to military specifications does not mean that the strength properties of MIL HDBK-17 can be assumed, unless the laminate was formed in accordance with the process under which the material properties had been established.

c. *Specimen Thickness.* Mechanical property data are generally reported on test specimens ⅛ to ¼ inch thick and consisting of one or more plies. The results may not be valid for designs involving thinner or thicker sections. Tests of polyester, phenolic and epoxy laminates have shown that all strength and modulus properties are reduced as the thickness is reduced from ¼ inch down to 1/100 inch. Since sandwich constructions use thin facings, this factor should be taken into account. Limited data indicates that flexural strength decreases somewhat for thicknesses greater than the ⅛- to ¼-inch range. There is, however, no similar trend for tensile or compressive strength:

d. *Loading.* The loading time intervals, as well as the direction and magnitude of the applied loads, must be considered. The judicious selection of working stress levels to allow for sustained loading, fluctuating, and repeated loadings, or impact loading, is necessary to provide an adequate structure.

e. *Environment.* Reinforced plastics can be adversely affected by environmental conditions of weathering and humidity. The effect on the strength properties should be considered. If materials other than those on which weathering durability data has been obtained are to be used, then one of the following procedures should be followed:

(1) The resin-reinforcement system may be shown to be similar to a system which already has been tested and corresponding reductions in strength properties should be assumed, or

(2) The weathering durability should be demonstrated.

22. DESIGNING FOR RIGIDITY. Compared to most metallic materials, reinforced plastics are not very rigid. Several design techniques are used to compensate for this:

a. increase the glass content

b. use unidirectional reinforcement where practical

c. place flanges and lips on edges

d. use ribs, corrugations, beads, and dimples

e. increase wall thickness

f. use curved sections rather than flat areas where possible

g. use sandwich construction

h. use high modulus resin

i. use glass fibers with high performance finish.

23. STRESS CONCENTRATIONS. The lack of ductility of reinforced plastics has an important bearing on design. Stress concentrations cannot relieve themselves by plastic flow, so attachments must be accurately designed and fabricated. Reinforced plastics have excellent dimensional stability, Parts which are properly and completely cured will not yield, therefore they must be molded to exact dimensions, i.e., they should not be "sprung" into place. Stress concentrations due to holes, notches, and abrupt changes in the geometric property, such as area or section modulus, result in stresses much higher than calculations indicate. Although there is considerable theoretical and experimental data on stress concentrations in elastic, isotropic materials, very little information has been developed on reinforced plastics. It may be necessary to test representative specimens of the structure under static and fatigue loading.

24. FASTENING.

a. Designing with reinforced plastics eliminates assembly of numerous parts by providing for integral molding of large complex shapes. Nevertheless, joining operations may still be necessary. As with metal fabrication, adhesives, rivets, and screw fasteners may be used; however, plastic joints should be designed with an awareness of certain material property characteristics. Plastics have lower values of shear and bearing strengths than metals, thus greater thicknesses and edge distances are used than with metals. Also, the lack of ductility of reinforced plastic can cause local stress concentration and result in unequal load distribution.

b. Sufficient plastic material should be provided between the hole and the edge of the laminate, as well as between centers of holes, if the plastic is to develop its full bearing strength. Allowing for a stress concentration factor of 3 at the hole results in a recommended edge distance of 4.5 diameters and a side distance of 3.5 diameters. Mat laminates, because of the random arrangement of the fibers, are susceptible to stress concentration in all directions of loading. Glass fabric laminates show less notch sensitivity at holes when the load is applied in the direction of the warp.

c. Misalignment of holes in mating parts, or an improper size hole for the fastener diameter used, may set up considerable stress when a fastener is inserted, and the connection may not prove serviceable. Holes should be perpendicular to the plane of lamination to avoid cracking or splitting of the laminate. A fastener-diameter-to-laminate-thickness ratio (D/t) of 1 permits the plastic to develop full bearing strength (stress at hole deformation of 4 percent of bolt diameter), but use of a D/t of less than 1 may result in shearing of the fastener.

d. Specific data on bolt bearing properties is given in references 7, 79, 80, and 83.

Appendix 1. INFORMATION TO BE INCLUDED IN PROCESS SPECIFICATIONS FOR STRUCTURAL GLASS FIBER BASE PLASTIC LAMINATE AND SANDWICH CONSTRUCTION PARTS

1. RAW MATERIAL PREPARATION, LAYUP, AND FABRICATING PROCEDURE. Each step in the manufacture of the laminate or sandwich part and the methods of controlling manufacturing variables should be completely described as follows:

a. Materials and their applicable approved specifications.

b. Standards for the control of materials affected by temperature, humidity or age.

c. The procedures and equipment used for preparation of resins, including use of catalysts, accelerators and promotors. (The catalyst system also should be described and the percent concentration of catalyst based on weight of resin should be given.) If any ingredients are used which differ from those used at the time the resin was qualified to an approved specification, resin should be retested and qualified.

d. The control of materials being used in production which have a limited work life.

e. The preparation of the mold surfaces.

f. The impregnation of fabric or mat in terms of percent resin content, or the preparation, application and precuring of preimpregnated fabrics.

g. The fabric or mat layup on the mold, including the number of plies of various fabrics, their position and direction, the type, grades and class of the material and the surface preparation.

h. The procedure and equipment used for prefabrication and preparation of the core.

i. The molding and fabricating equipment and procedures, including the method of applying pressure to the layup, the approximate amount of pressure applied, the cure temperature and time of curing or cure cycle, if varying conditions are used, and the method of applying heat. (The curing must conform to that used in qualifying the resin. The procedure for the use and curing of resin should not conflict with the resin manufacturer's instruction sheet unless a change has been demonstrated to be acceptable.)

j. The application of sealants.

k. The application of coatings or paints.

l. When special precautions must be established to initially accomplish and thereafter maintain freedom from all types of contamination, this should be noted in the above items.

2. SECONDARY BONDING PROCEDURES. The materials and procedures for secondary bonding of parts should be described.

3. QUALITY ASSURANCE. The quality of the part should be controlled by process tests and by maintaining the overall surveillance necessary to ensure that all operations connected with the production of the part conform to the approved process specification. All structural parts should undergo 100 percent testing until an accepted quality level is attained. Thereafter these parts are subject to an approved sampling program. The type of testing to be conducted will depend on the materials used, the type of construction, and the loading conditions for which the part is designed. Insofar as possible, test specimens should be fabricated simultaneously as an integral section of the part or located adjacent to the part and processed with the part, or identically to the part which it is to represent.

4. PERMISSIBLE DEFECTS. Limitations should be established on the extent to which defects, such as the following, are permissible: air bubbles, laps, porosity, blisters, holes, starved areas, resin pockets, cracks, tackiness, wrinkles, delamination, unbonded areas, or inclusion of foreign substances. Also, repairable defects and the repair methods should be described.

5. MECHANICAL AND ELECTRICAL PROPERTIES. The means for determining mechanical and electrical properties, the frequency with which the values are checked and their relationship to design values should be described.

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Appendix 3. FIGURE

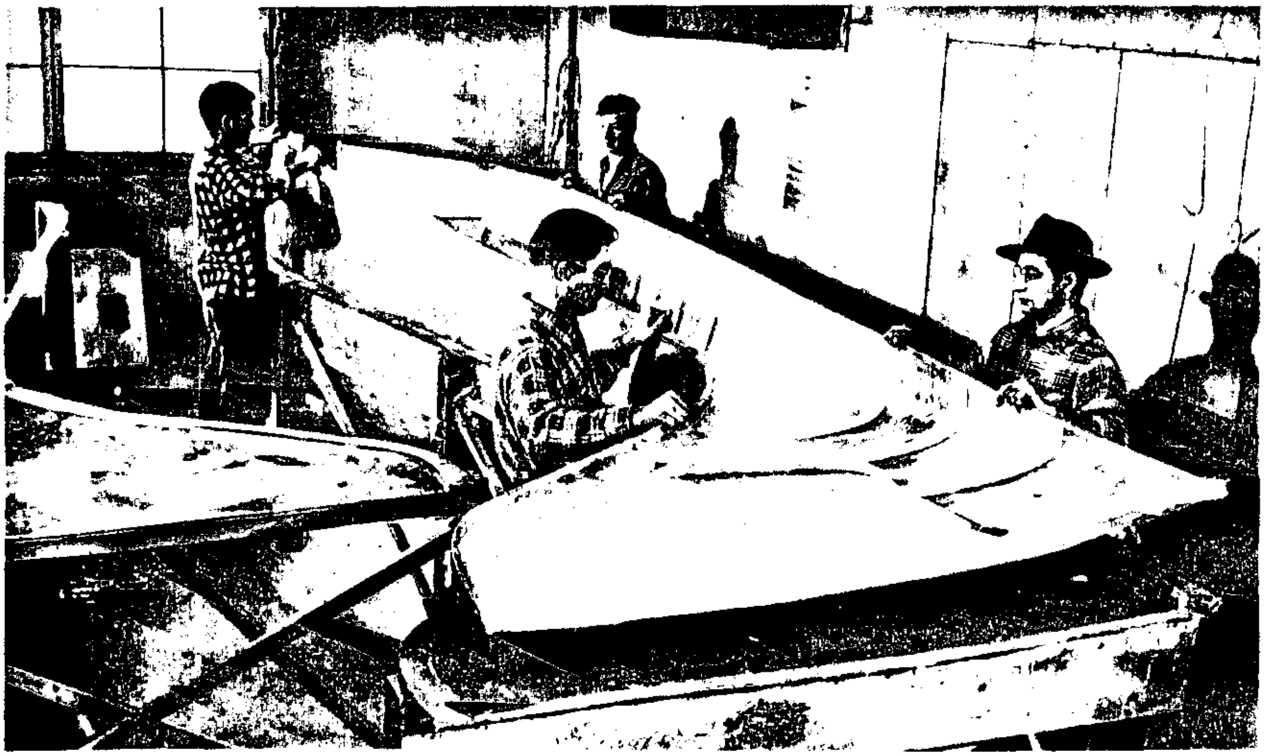


FIGURE 1a.—Taylorcraft Model 20 half fuselage being removed from mold.

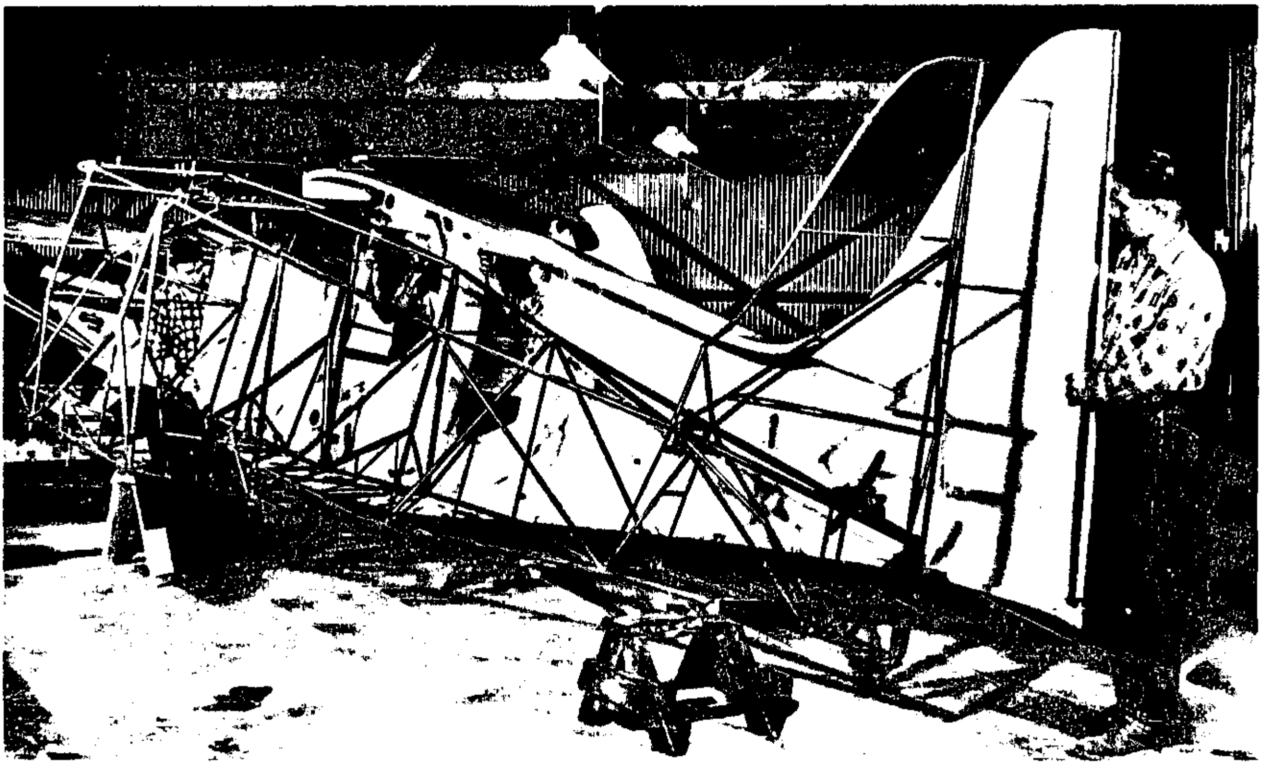


FIGURE 1b.—The reinforced plastics covering being mated to frame.

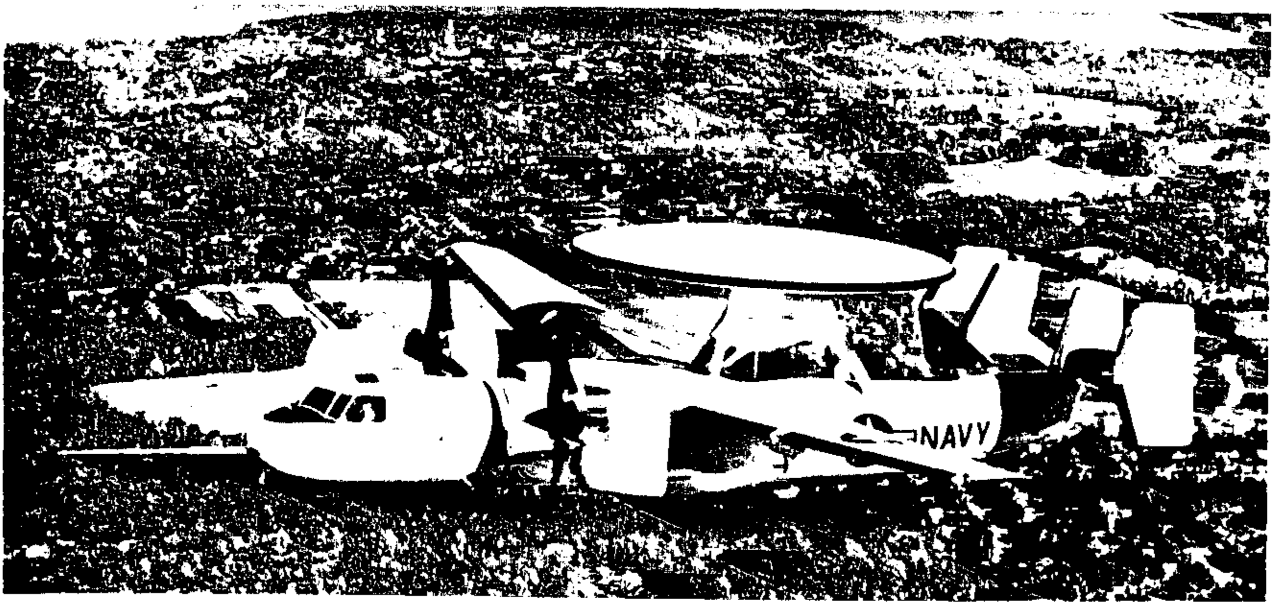


FIGURE 2.—Reinforced plastic rotodome on a Grumman W2F-1 aircraft.

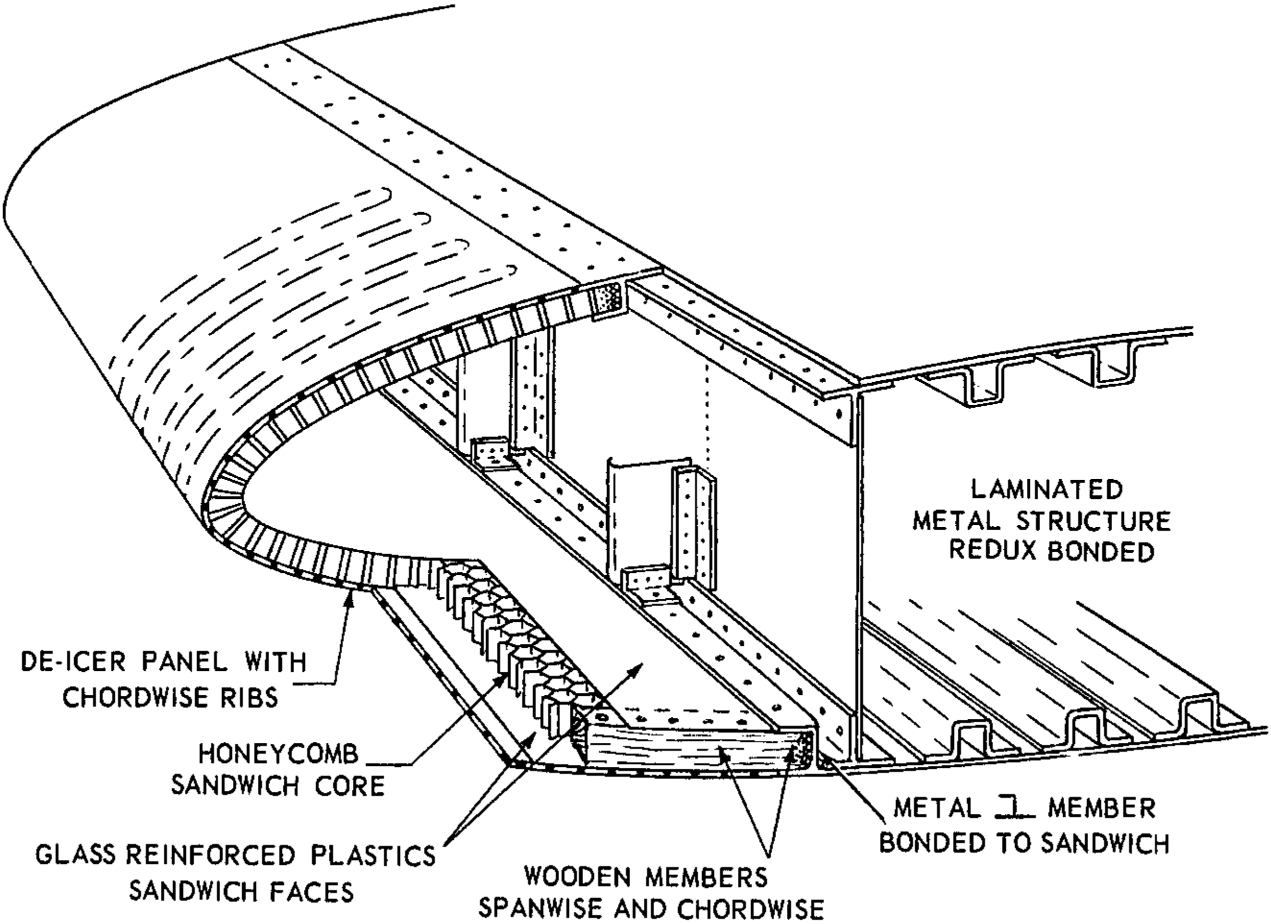


FIGURE 3.—Wing construction of Fokker Friendship aircraft showing sandwich structure of leading edge and integrally bonded de-icer panel. (Ref. 12.)

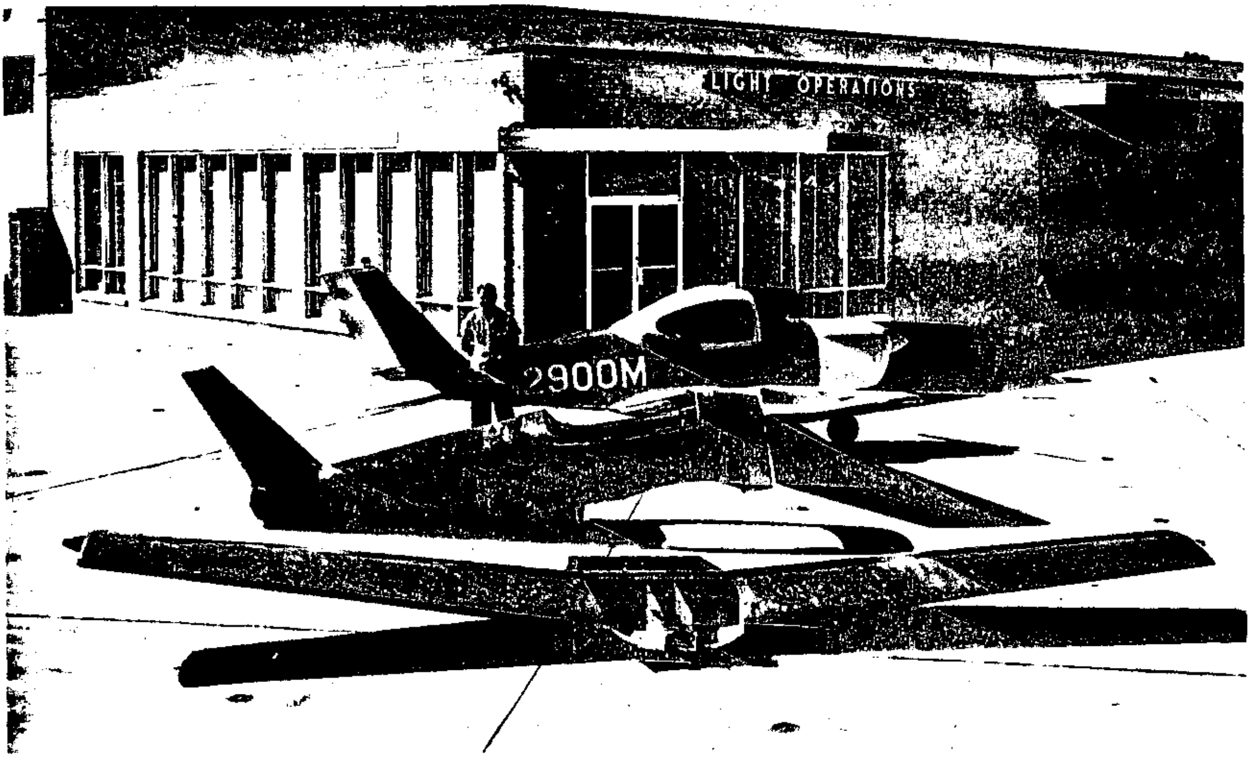


FIGURE 4.—The Piper PA-29 and the wing and fuselage glass fabric reinforced plastic sandwich moldings.

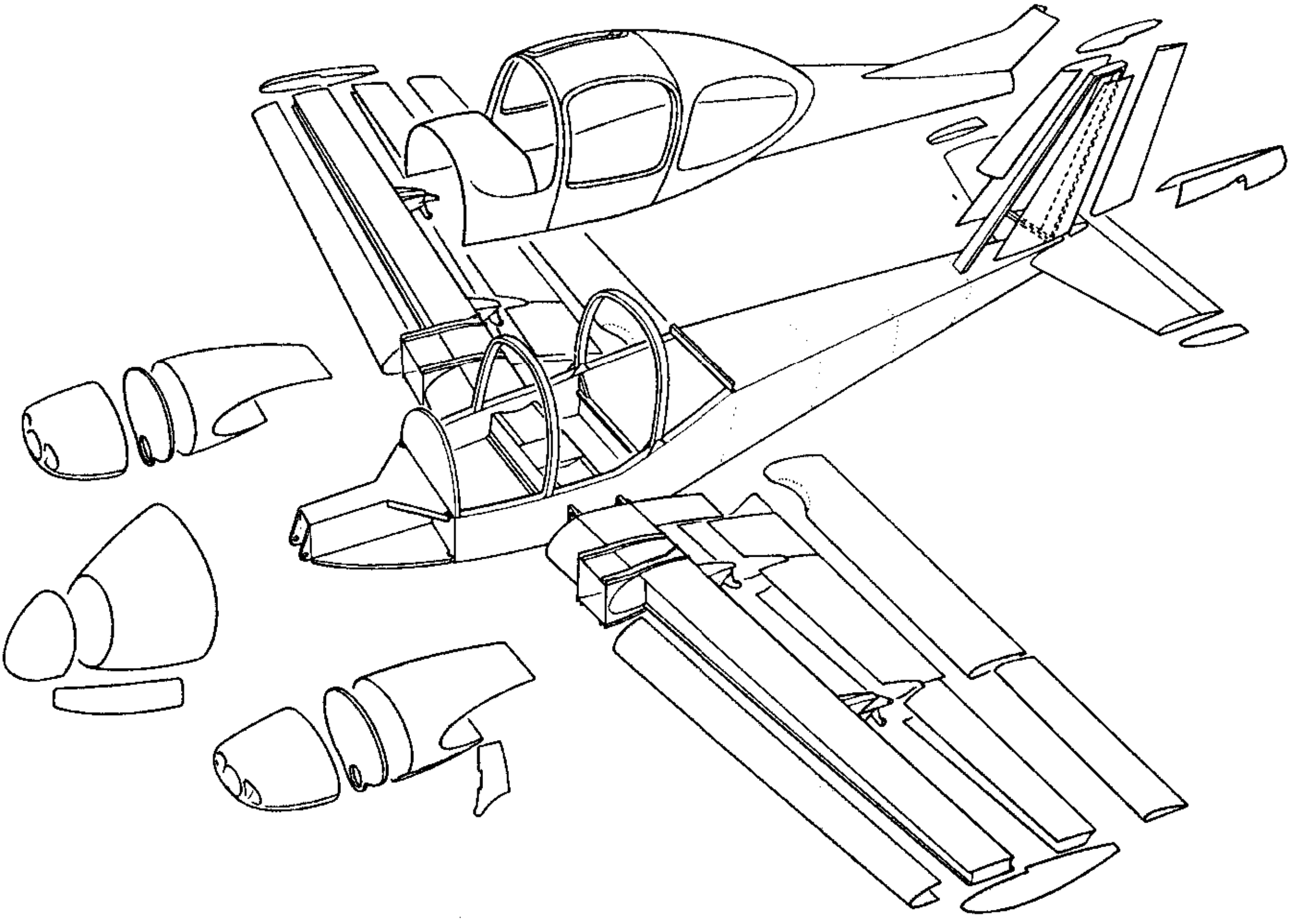


FIGURE 5a.—The gray areas denote the portions of the Beagle-Miles M.218 airplane which are constructed of reinforced plastics.

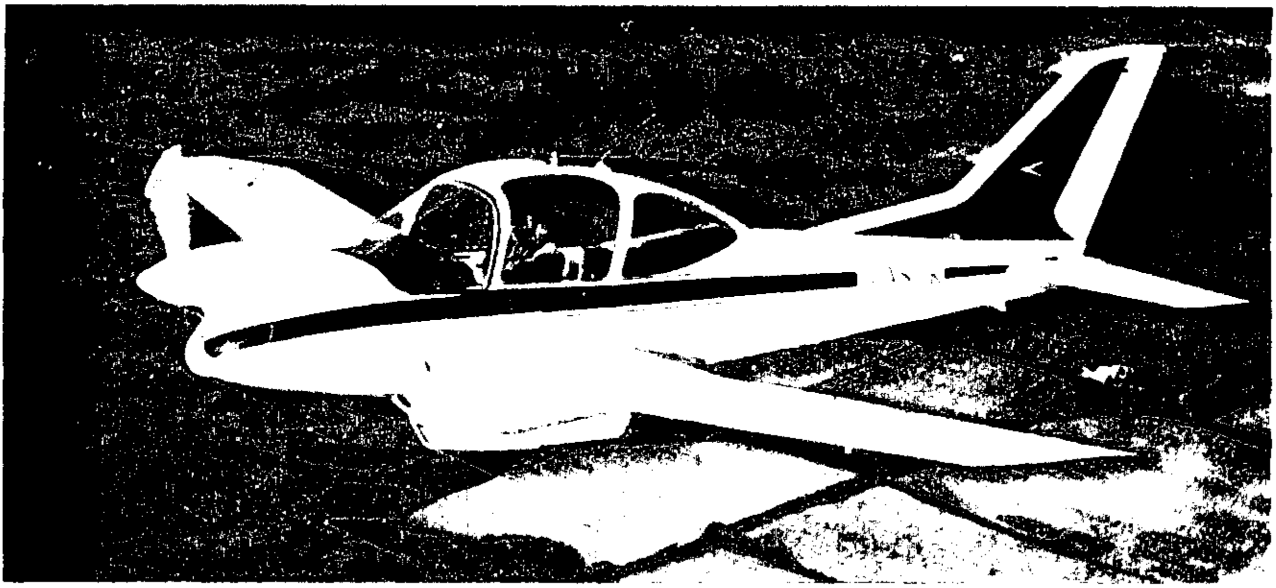


FIGURE 5b.—A view of the Beagle-Miles M.218 aircraft.

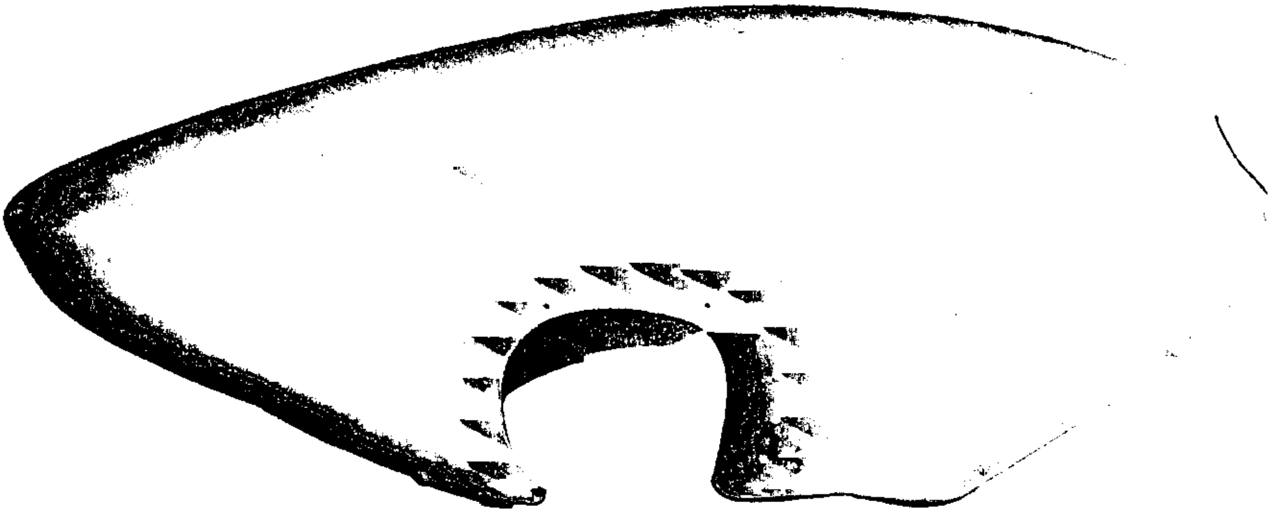


FIGURE 6a.—Speed fairing for Cessna fixed gear aircraft.

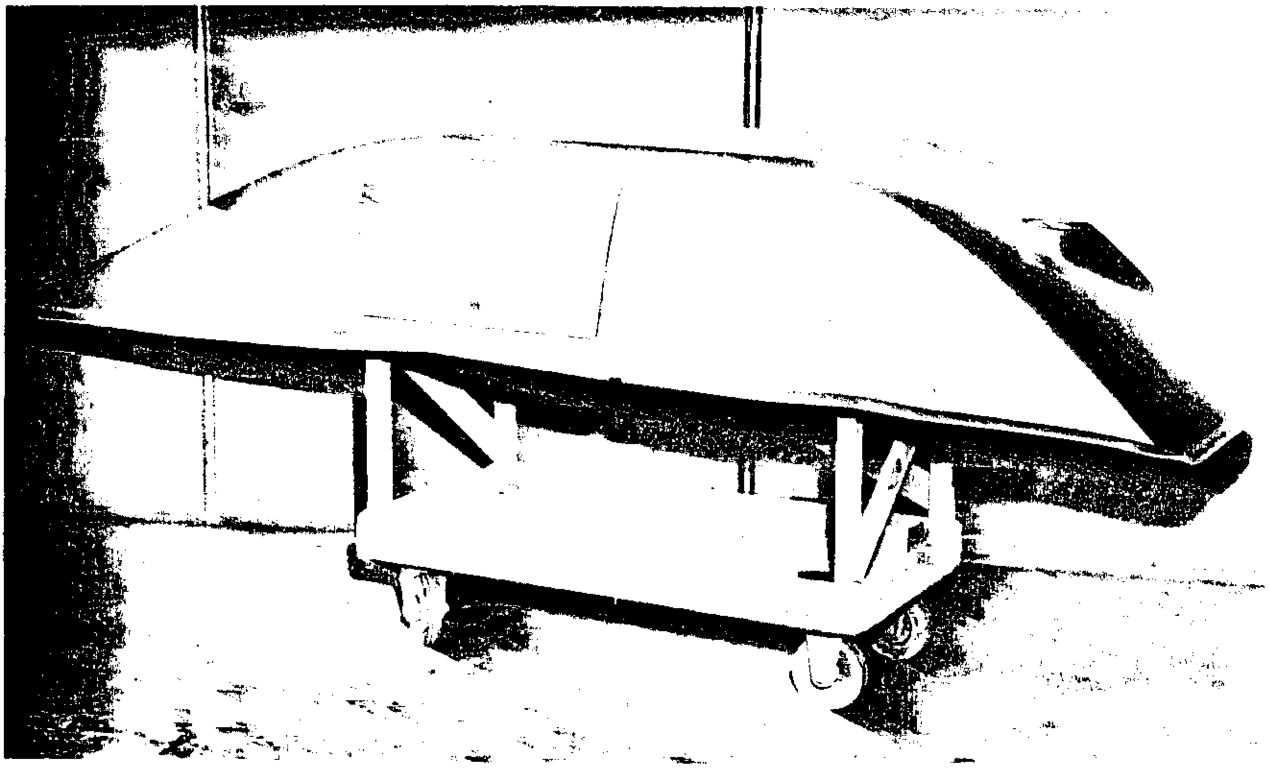


FIGURE 6b.—Cargo pack for Cessna Model 185.

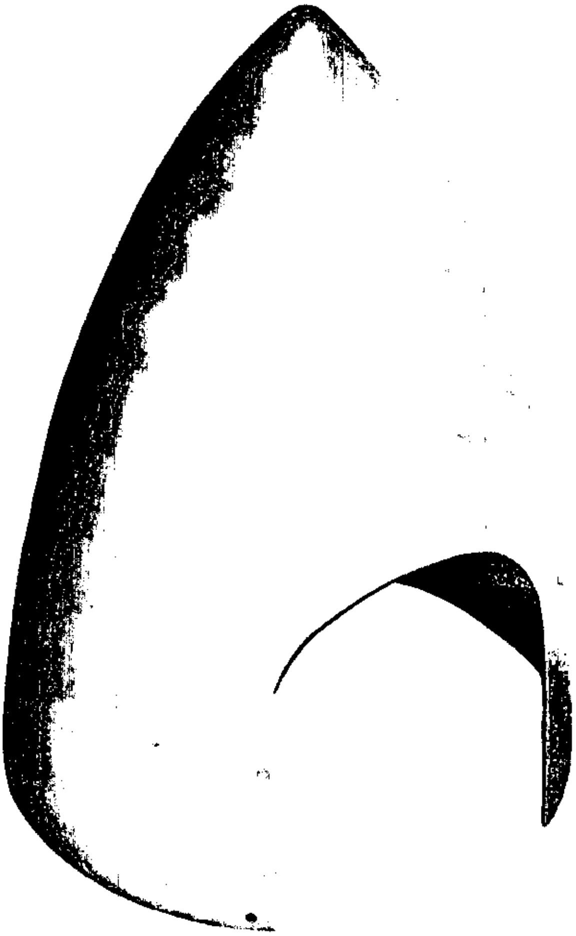


FIGURE 6c.—Spinner for Cessna Model 150.

FIGURE 6d.—Wing tip for Cessna Model 210.

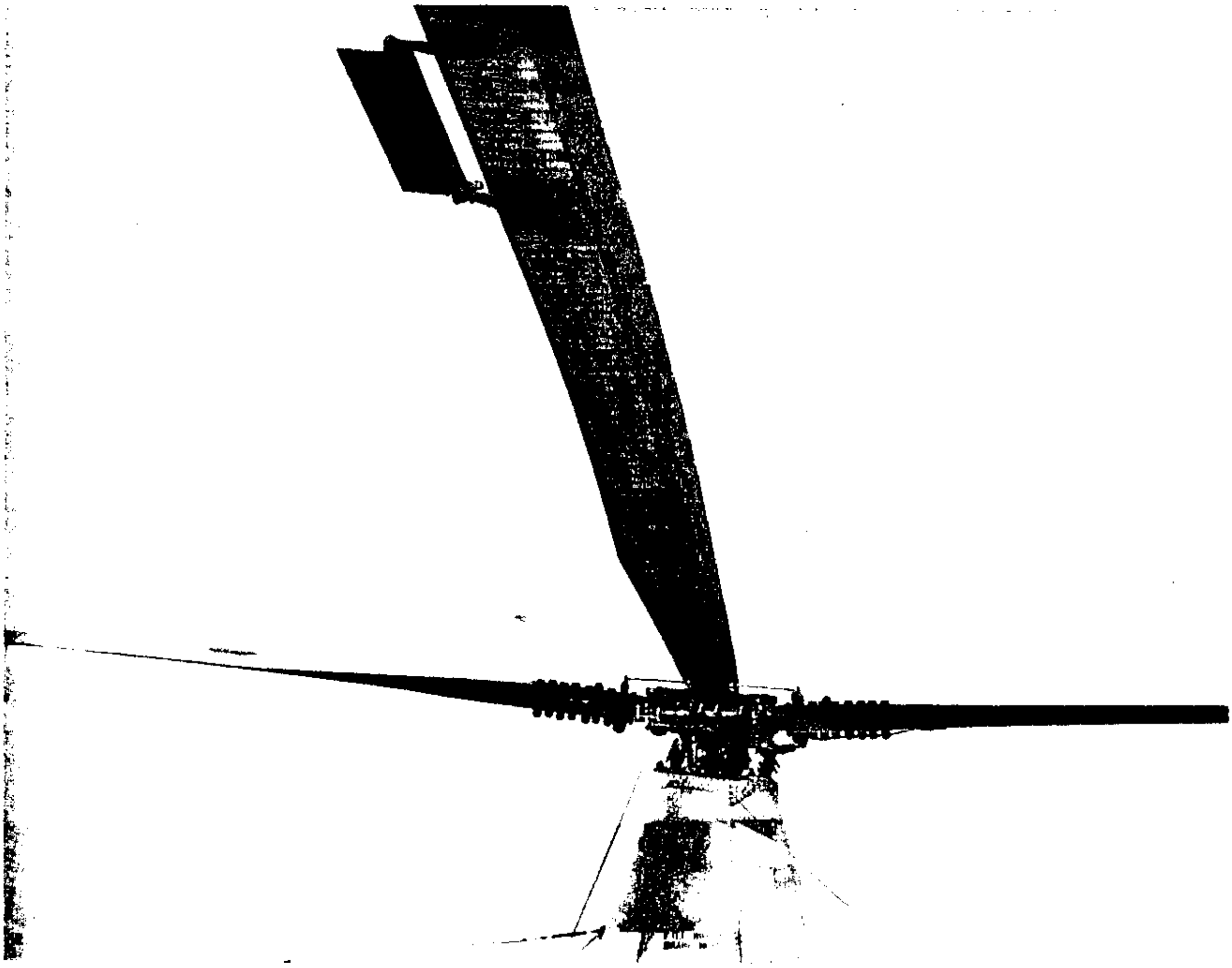


FIGURE 7.—Glass-fiber rotor blades on Kaman H–43 helicopter.

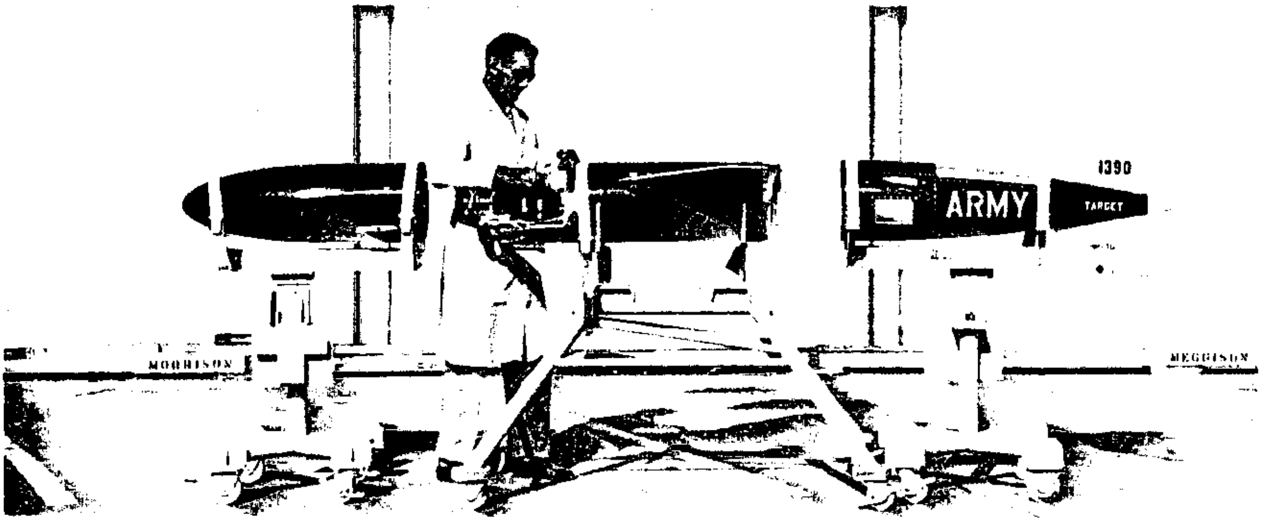
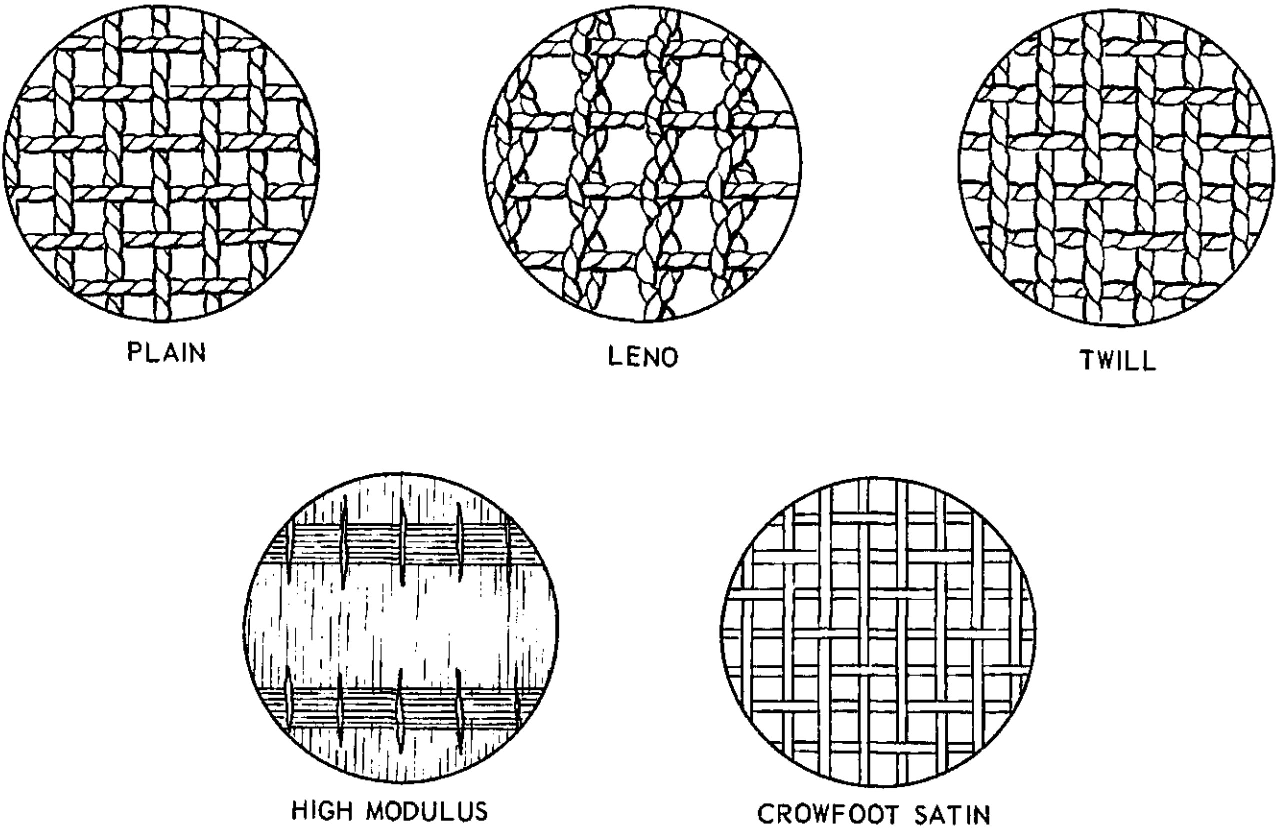


FIGURE 8.—Target missile has nose cone and tail section of reinforced plastics.



PLAIN

LENO

TWILL

HIGH MODULUS

CROWFOOT SATIN

Figure 9.—Types of weave in glass fiber fabric.

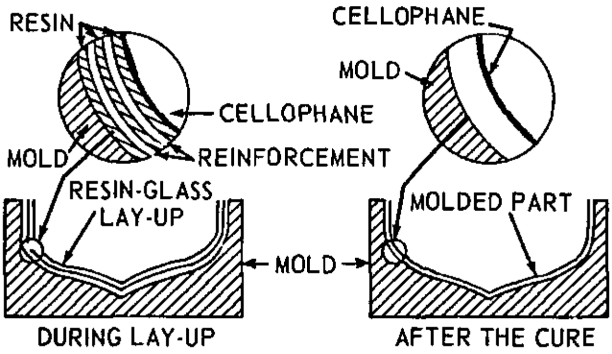


FIGURE 10.—Contact molding.

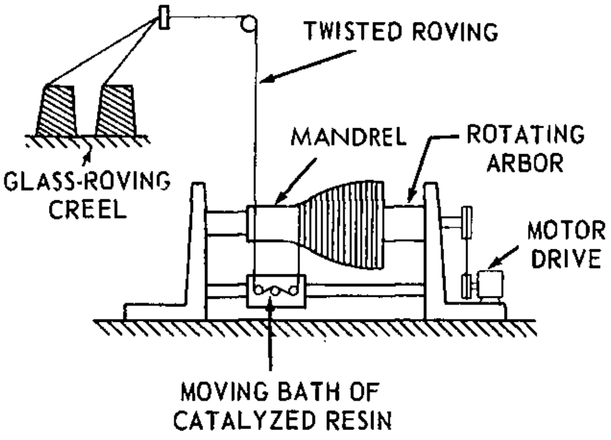


FIGURE 12.—Filament winding.

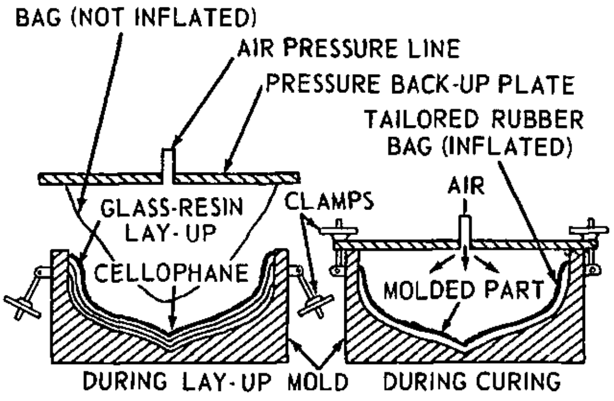


FIGURE 11.—Pressure bag molding.

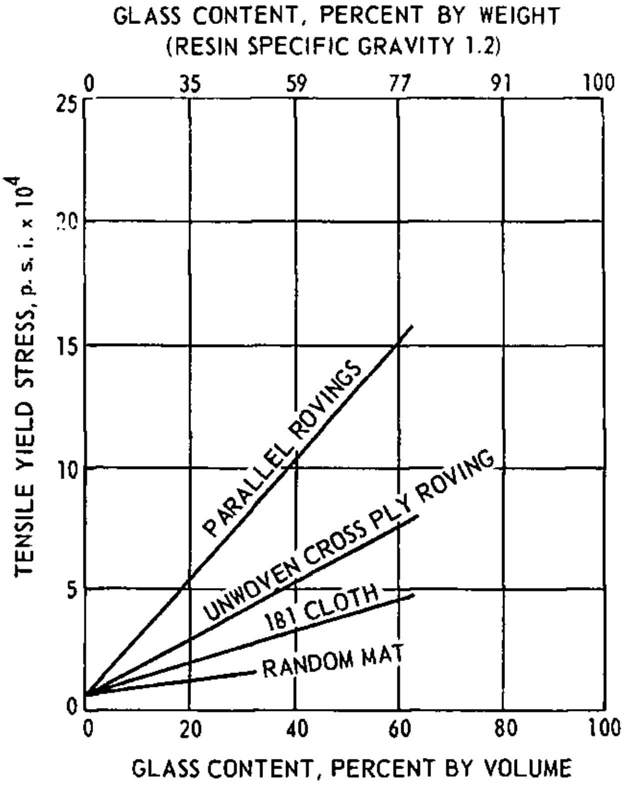
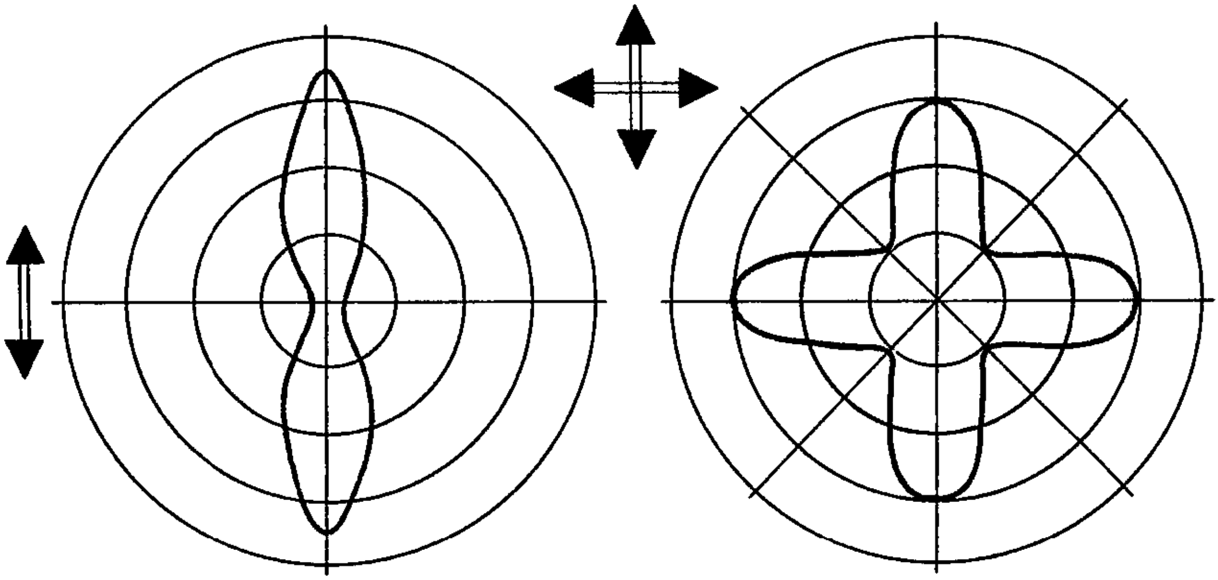
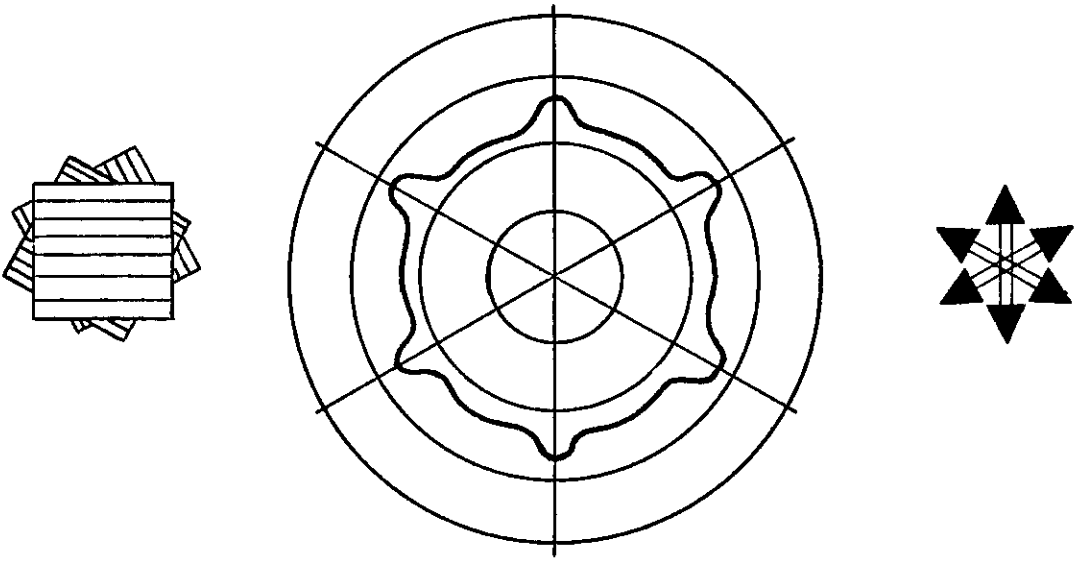


FIGURE 13.—Variation of strength with glass content. (Ref. 43.)



FIBERS ARE ORIENTED AT 0° TO EACH OTHER, GIVING MAXIMUM STRENGTH PARALLEL TO WARP.

THE 90° ORIENTATION GIVES LESS MAXIMUM STRENGTH, BUT EQUAL STRENGTH FOR PARALLEL AND PERPENDICULAR LOADING.



THIS FABRIC ORIENTATION YIELDS STILL LESS MAXIMUM STRENGTH BUT EQUAL STRENGTH IN EACH DIRECTION OF FIBER WARP.

FIGURE 14.—Strength versus angle of stress in tension for unidirectional and multidirectional layups of equivalent material and thickness.

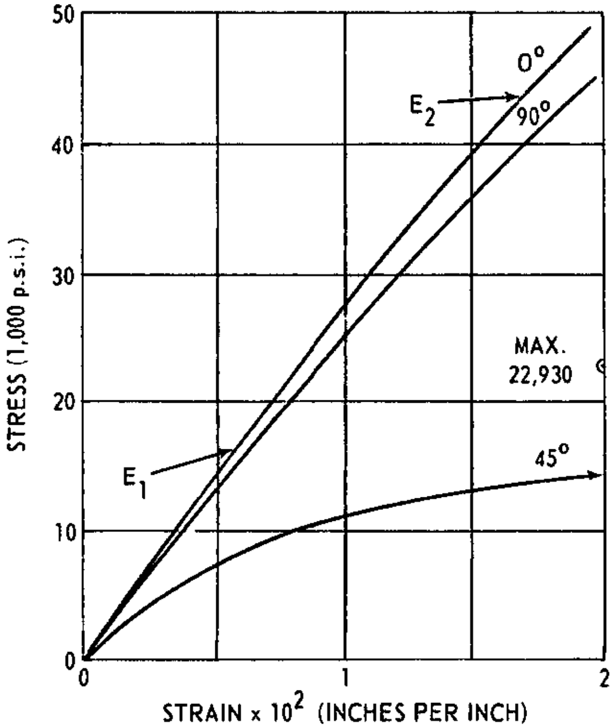


FIGURE 15.—Typical tensile stress-strain curves for parallel laminate made with 181 glass fabric and polyester resin (MIL-R-7575) for 0°, 45°, and 90° to the warp direction of the fabric. (Ref. 7.)

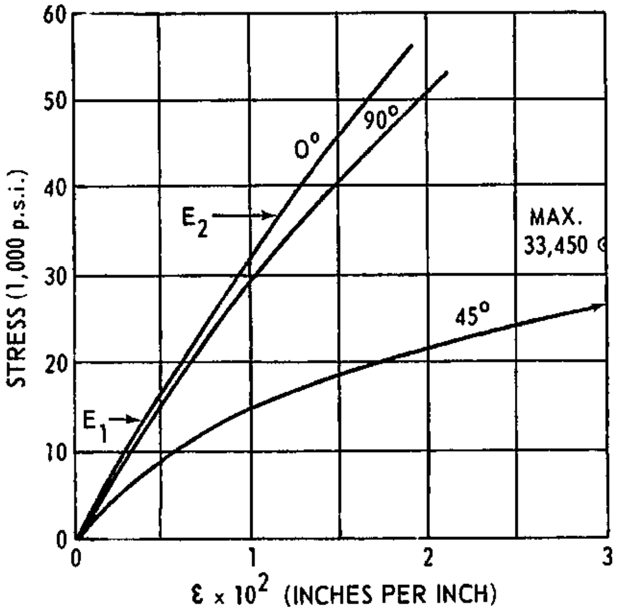


FIGURE 16.—Typical tensile stress-strain curves for parallel laminate made with 112 glass fabric and an epoxy resin (MIL-R-9300). (Ref. 7.)

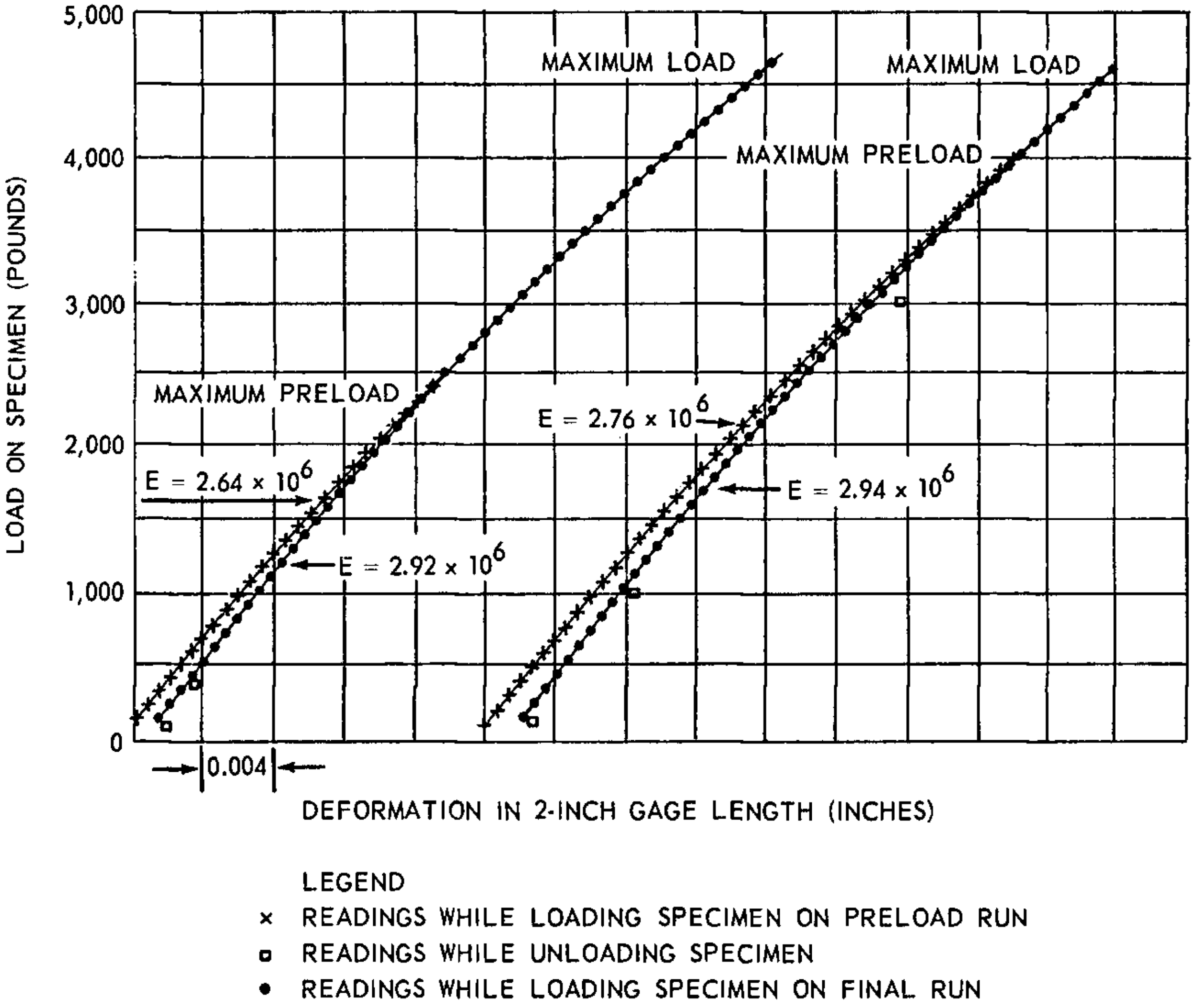


FIGURE 17.—Typical load-deformation curves for two tension specimens of 181 glass fabric laminate made with polyester resin (MIL–R–7575). Each specimen was loaded once to the maximum preload, the load was removed to the initial load, and then the specimen was loaded to failure.

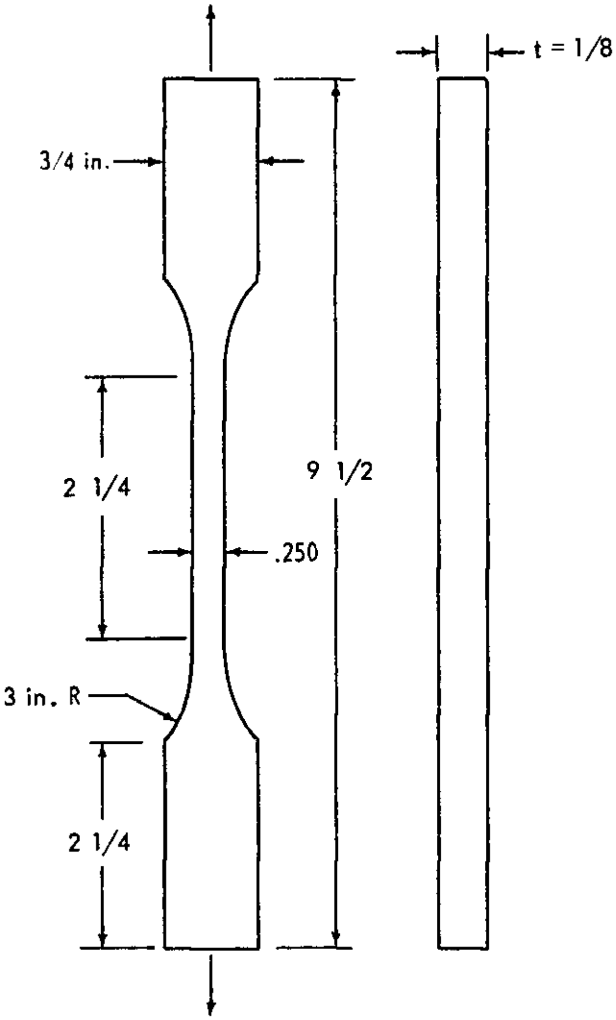


FIGURE 18.—Typical test specimen for tensile test.

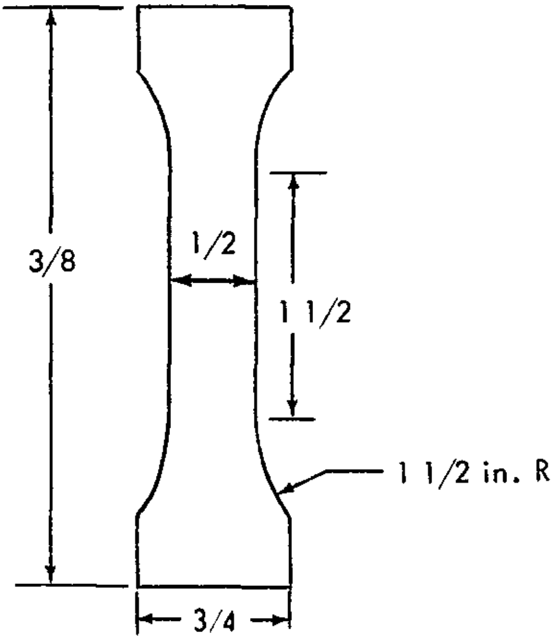


FIGURE 19.—Typical test specimen for compression test.

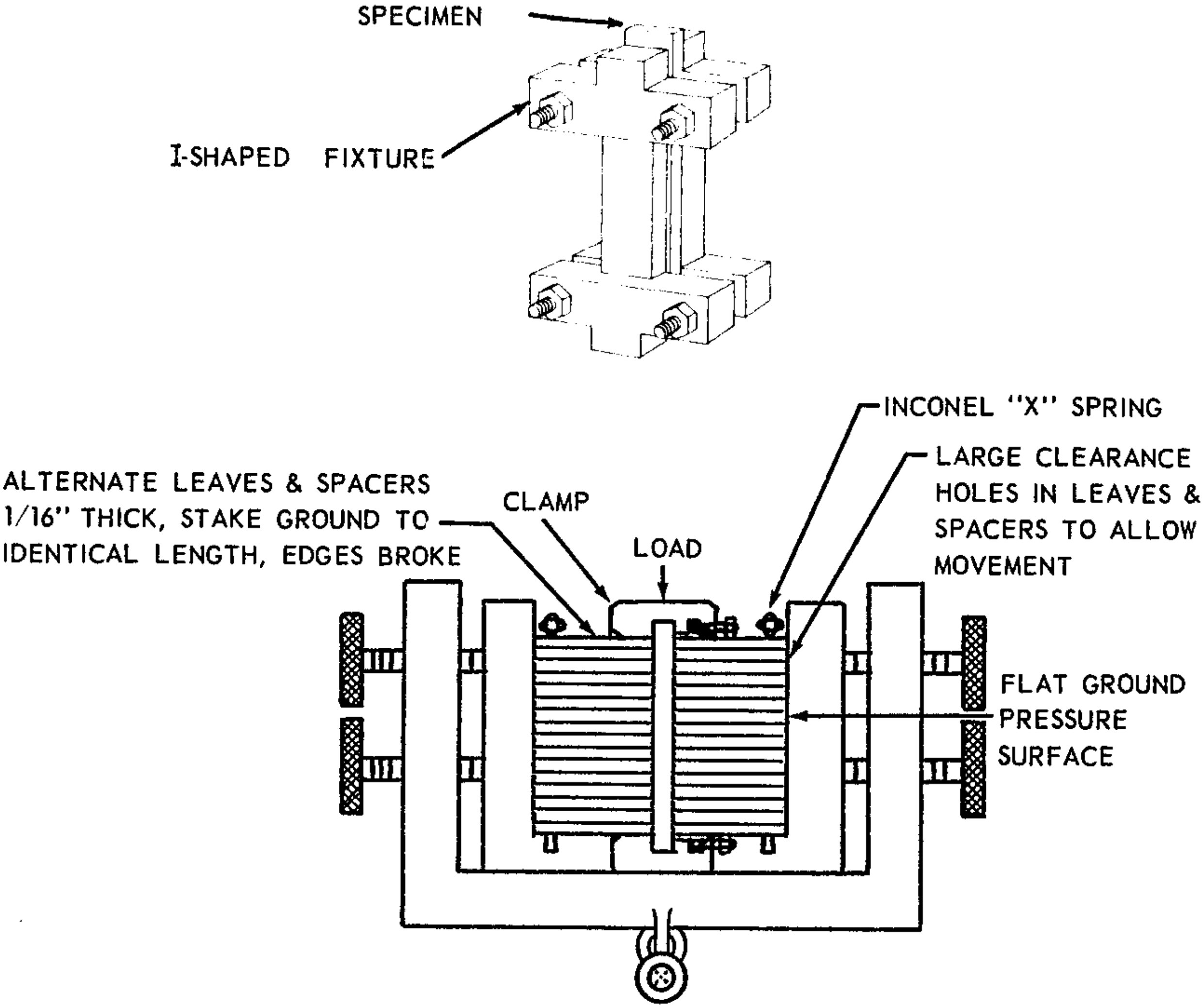
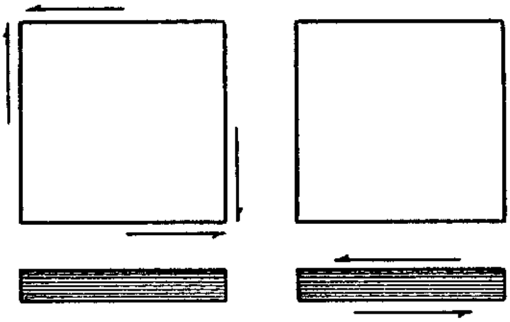


FIGURE 20.—Two types of compression test fixtures; the I-Shaped Fixture specified by Federal Test Method Standard No. 406 and the Multifinger Fixture specified in ARTC Test Method.



A. EDGEWISE SHEAR B. INTERLAMINAR SHEAR

FIGURE 21.—Sketch of panels showing application forces that will produce, A, edgewise shear and, B, interlaminar shear.

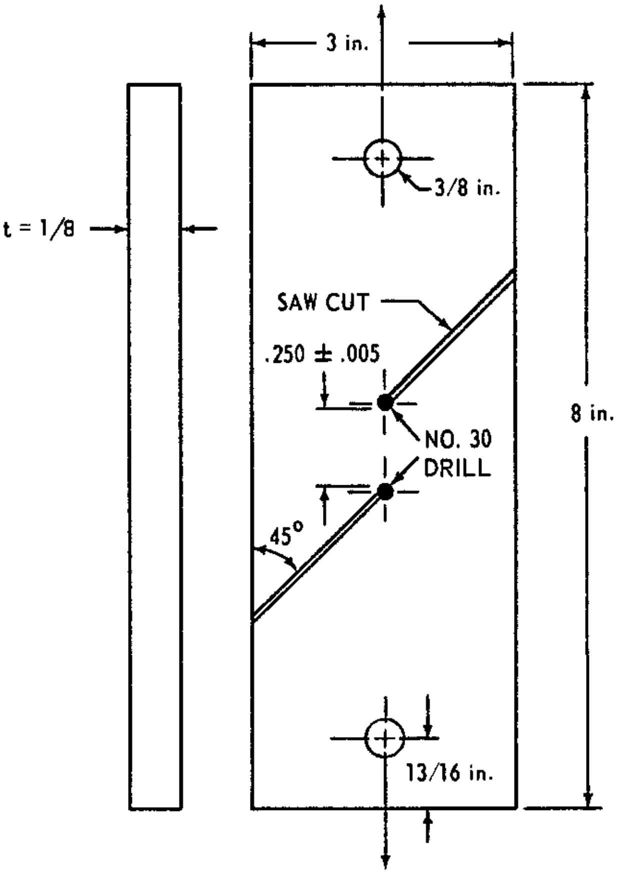


FIGURE 22.—Typical test specimen for panel shear testing.

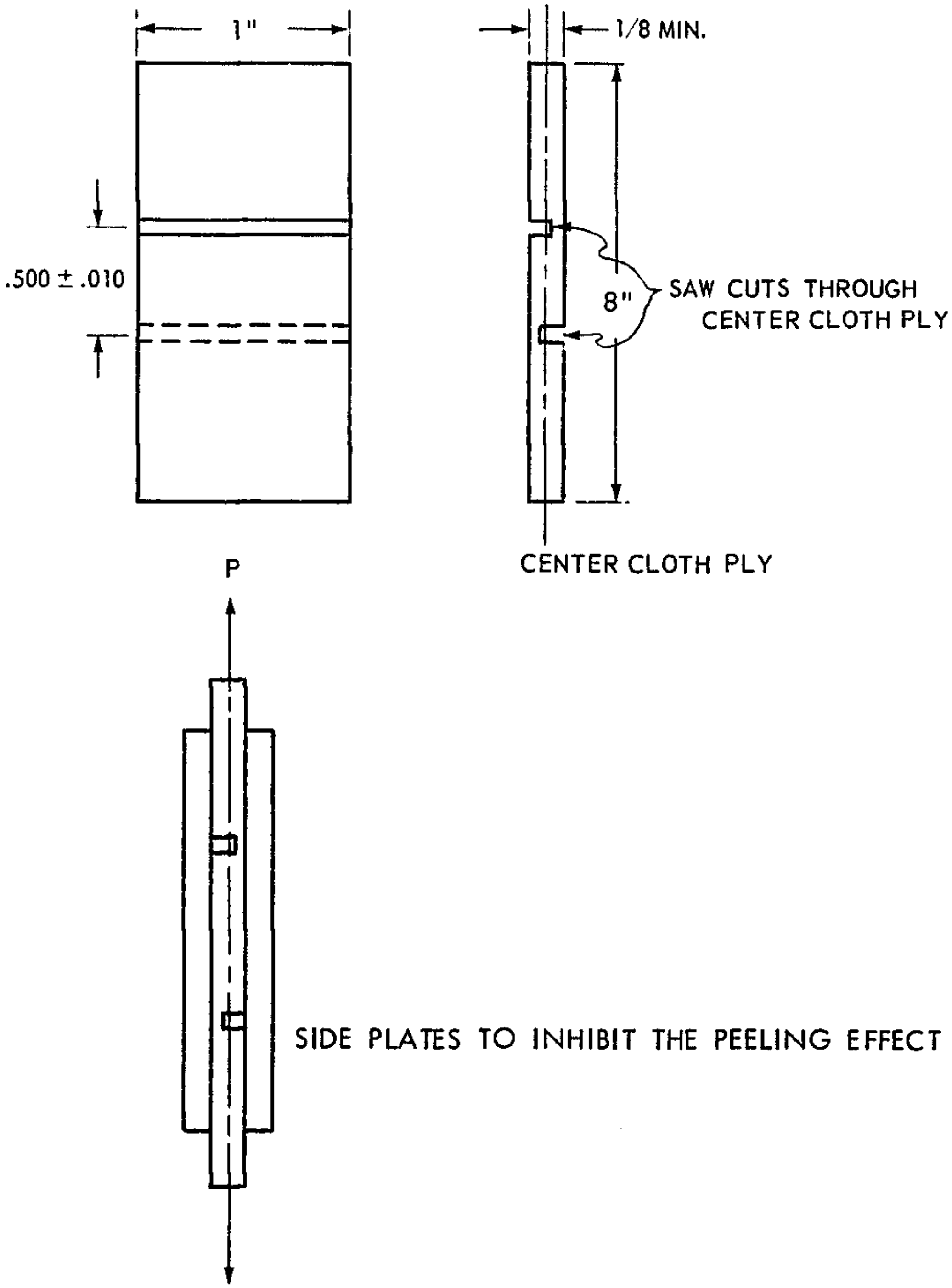


Figure 28.—Typical test specimen for interlaminar shear testing.

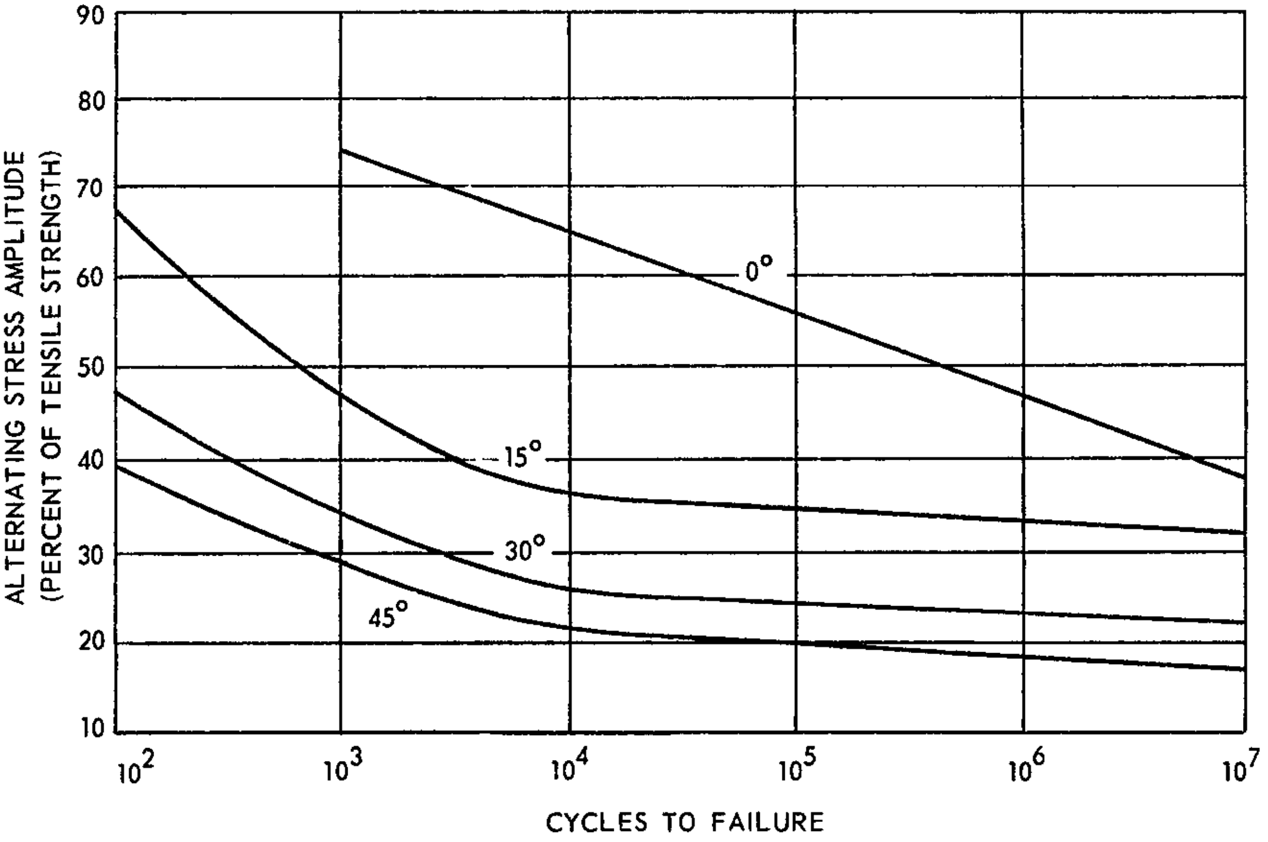


Figure 24.—Variation in fatigue strength with angle of loading to fiber warp on unnotched specimens at zero mean stress. Parallel-laminated 181 glass fabric with an epoxy resin. (Ref. 7.)

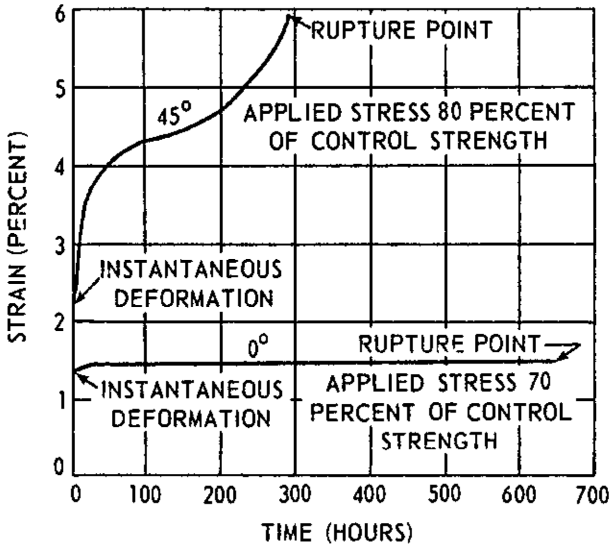


Figure 25.—Typical creep-rupture curves for a 181 epoxy laminate at normal conditions, tested in tension at 0° and 45° to the warp direction. (Ref. 7.)

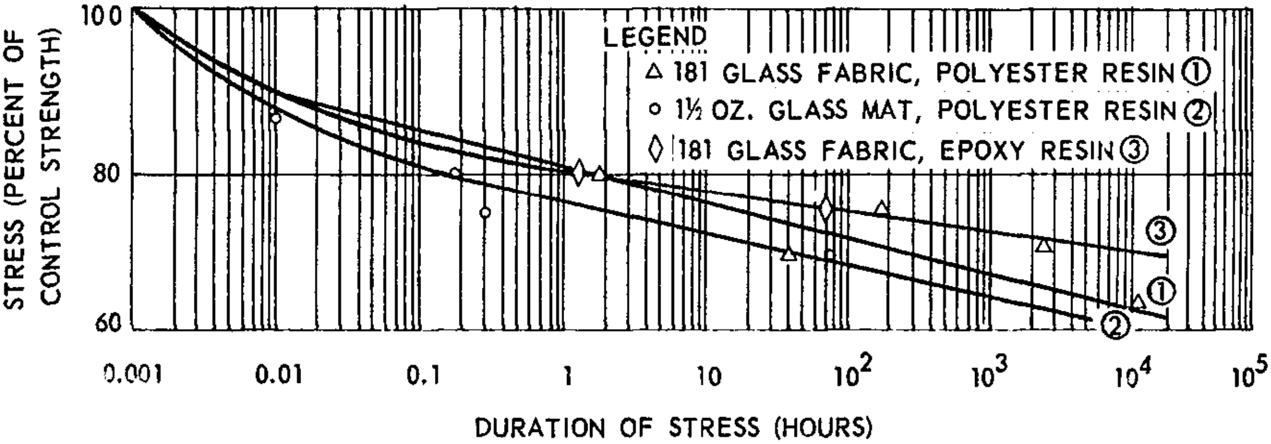


FIGURE 26.—Tensile stress-rupture data for laminates at 73° F., and 50 percent relative humidity. (Ref. 7.)

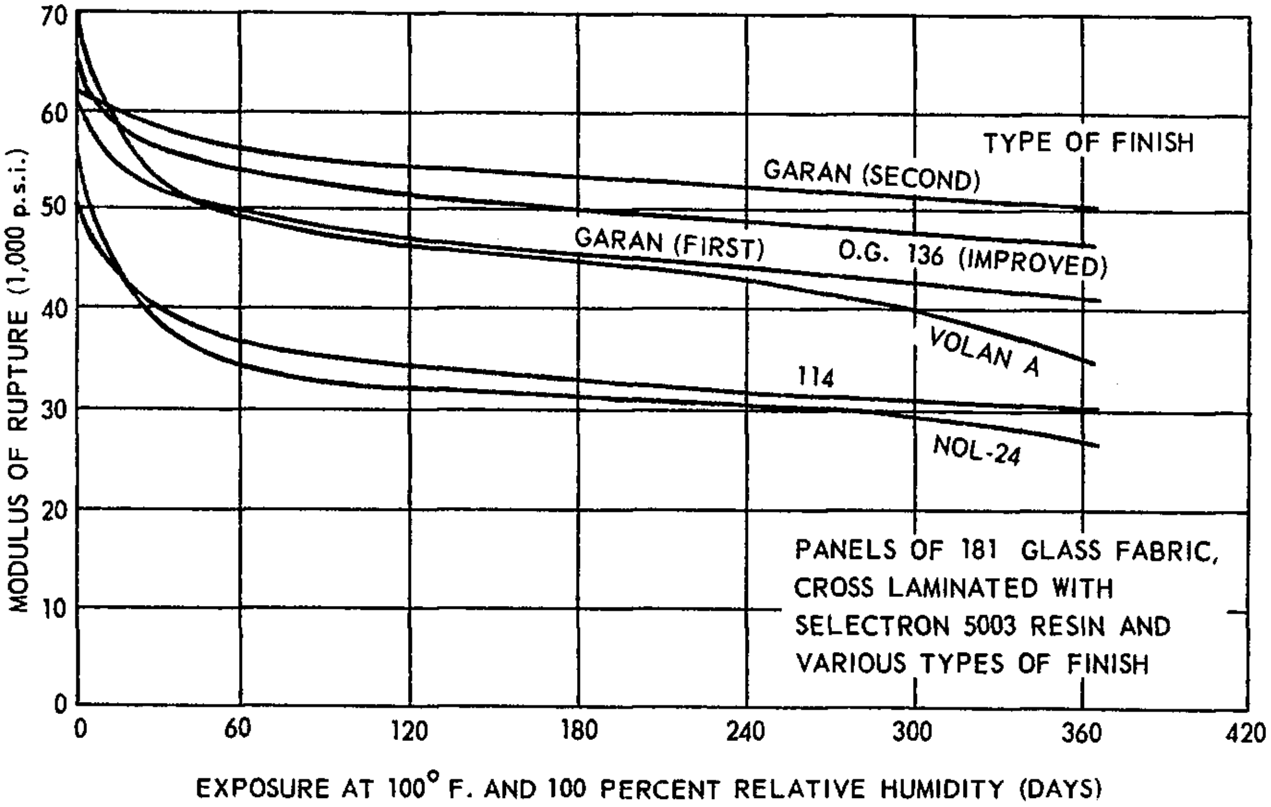
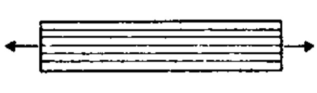


FIGURE 27.—Empirical curves showing the effect of longtime wet exposure on the modulus of rupture of 6 different polyester laminates. (Ref. 7.)

TENSION

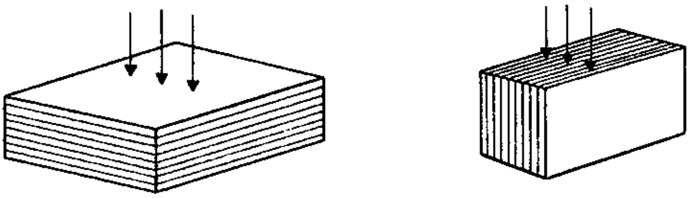


RECOMMENDED

UNDESIRABLE

TENSILE STRESSES SHOULD BE SUSTAINED BY THE LAMINATIONS AND NOT ACROSS THE BONDING PLANE.

COMPRESSION

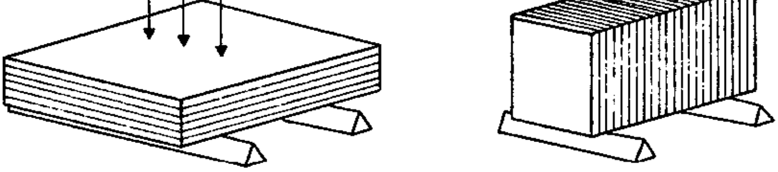


RECOMMENDED - FLATWISE
AT RIGHT ANGLE TO LAMINATIONS

UNDESIRABLE - EDGEWISE
PARALLEL TO LAMINATIONS

THE COMPRESSIVE STRENGTH OF LAMINATES IS GREATER FLATWISE THAN EDGEWISE

FLEXURE

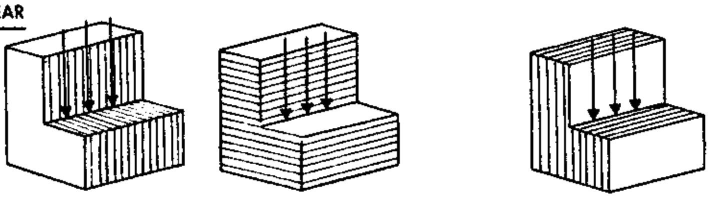


RECOMMENDED - FLATWISE
AT RIGHT ANGLE TO SPAN

UNDESIRABLE - LAMINATIONS
AT RIGHT ANGLE TO SPAN

TENSILE STRESSES SHOULD BE SUSTAINED BY THE LAMINATIONS AND NOT ACROSS THE BONDING PLANE

SHEAR



RECOMMENDED - FLATWISE
AT RIGHT ANGLES TO LAMINATIONS

UNDESIRABLE - EDGEWISE
PARALLEL TO LAMINATIONS

SHEARING STRESSES SHOULD OCCUR IN A PLANE NORMAL TO THE LAMINATIONS TO PREVENT CLEAVAGE ACROSS THE BONDING PLANES.

BEARING

RECOMMENDED - LOAD
DISTRIBUTED TO THE
LAMINATIONS

UNDESIRABLE - LOAD
CARRIED
THROUGH BOND

BEARING STRESSES SHOULD BE APPLIED THROUGH THE LAMINATIONS RATHER THAN ACROSS THE BONDING PLANES.

FIGURE 28.—Direction of loads. Relation between the direction of the laminations and the direction of the load application.

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