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Designing With Fiber-Reinforced Plastics (Planar Random Composites)

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INTRODUCTION

Resins (thermoplastics and thermosets) randomly reinforced with chopped fibers constitute a versatile structural material for a wide range of applications. The fiber most commonly used is E glass. Continuous fibers and high-performance fibers can also be used for improved stiffness. Hundreds of resins can be used, depending on the application. The thermoplastic resins most frequently used are nylon, polypropylene, polystyrene, acrylonitrile-butadiene-styrene, and styrene-acrylonitrile. Glass fiber reinforcements increase the properties of these resins by a factor of 2 or more, depending on the fiber content. Glass-reinforced thermoplastics are supplied as ready-to-mold compounds. They are also supplied in sheet form for stamping or hot-flow forming of large, thin-wall structural parts.

Thermosets include polyesters, epoxies, phenolics, and silicones. Reinforced polyesters (most commonly used) are low cost and easy to handle and have good mechanical, electrical, and chemical properties, including dimensional stability. Polyesters are supplied in ready-to-mold bulk or sheet form. Epoxies are used where superior properties for electrical and thermal resistance are needed, as compared with polyesters. Phenolics are used mainly for insulating structures. Silicones are used in high-temperature applications, 260° to 371° C (500 to 700° F). Silicones have excellent resistance to moisture absorption as well as to many chemical environments (except strong alkalies).

The randomly oriented reinforcement in all these resin-fiber-reinforced materials lies in the plane of the part. As a result the material is isotropic in the plane but not through the thickness. It is convenient to refer to this type of reinforced material as planar randomly reinforced composites or simply planar random composites (PRC). Since PRC's are made from fiber-reinforced matrices, composite mechanics can be used to describe their mechanical behavior as well as the hygrothermal and time-dependent effects. The main objective of this report is to review and describe the use of composite mechanics to predict the hygrothermomechanical behavior of PRC, including fracture toughness, fatigue, creep, and creep rupture. Lesser objectives are (1) to indicate how these properties can be used in the design and analysis of structural components made from PRC; (2) to describe the various forms of PRC that are available; (3) to discuss typical data for various PRCs; (4) to describe concepts that lead to improved properties of PRC's; and (5) to cite pertinent references where additional information can be obtained.

The composite mechanics consists mainly of the quasi-isotropic laminate analogy (QLA), which embodies laminate theory, composite macromechanics, and composite micromechanics.

Specifically, the report covers (1) quasi-isotropic laminate analogy (QLA); (2) prediction of PRC properties by using QLA; (3) fracture toughness of PRC; (4) fatigue and hygrothermal characteristics; (5) strip hybrid concepts for improved stiffness; (6) creep and creep rupture; (7) molding compounds for PRC; and (8) typical data and design characteristics.

The units used in the text are in both SI and U.S. customary units. The units used in the figures and tables are mainly U.S. customary units since the information included was obtained from several sources that only use those units.

QUASI-ISOTROPIC LAMINATE ANALOGY

Planar randomly reinforced fiber composites and quasi-isotropic laminates are thermoelastically isotropic in their planes. They are said to be thermoelastically equivalent. It is this equivalence that enables us to use laminate theory to characterize planar randomly reinforced composites. This is referred to as the quasi-isotropic laminate analogy. A brief description of the procedure follows.

The simplest orientation combination, for example, is a [0, 60, -60] laminate. This laminate lacks reflection-about-a-plane symmetry and will bend upon stretching and thus yield erroneous measured data. The difficulty is overcome by constructing a laminate with the following combination of ply orientations: [0, 60, -60,-60, 60, 0]. Application of laminate theory (ref. 1) to this laminate yields its thermoelastic properties. Such predictions are in good agreement with experimental data (e.g., ref. 2). The aforementioned laminates are not quasi-isotropic with respect to strength. That is, the strength of the laminate will depend on both load direction (e.g., with respect to 0° plies) and the type of load (e.g., tensile, compressive, or shear). It can be shown theoretically (ref. 1 or 3) that the [0, 60,-60, -60, 60, 0] laminate will have both a minimum and a maximum strength. The minimum is obtained when the load direction coincides with one of the ply orientations, and the maximum when the load direction bisects the angle of two adjacent ply orientations.

The minimum strength of quasi-isotropic laminates is independent of the number of ply orientation combinations (ref.4). This is important since it provides a lower bound on the strength of quasi-isotropic laminates. It can be shown by numerical computation that the maximum strength of quasi-isotropic laminates approaches a lower bound as the number of ply orientation combinations increases. This is illustrated graphically in figure 1 (from ref. 4), where the failure stress is plotted as a function of the number of plies for several quasi-isotropic laminates.

A PRC is, in essence, a quasi-isotropic laminate with a large number of ply orientation combinations. Therefore the strength of the PRC must be equal to or greater than the lower strength bound of quasi-isotropic laminates. The establishment of this condition enables us to use fiber composite micro- and macromechanics and laminate theory to predict the thermal, elastic, and strength properties of PRC. This approach is commonly called the quasi-isotropic laminate analogy (QLA) (ref. 4). In the subsequent discussion the terms quasi-isotropic and random are used interchangeably.

PREDICTED PROPERTIES

The QLA was used to predict physical and mechanical properties of PRC. The physical properties of PRC described herein include heat capacity, in-plane and through-the-thickness heat conductivities, thermal expansion coefficient, and density. These properties are plotted as a function of fiber volume ratio (FVR) in figure 2. The heat capacity and heat conductivity properties are required in heat transfer analyses for determining the temperature in PRC structural components. The thermal expansion coefficients are needed to calculate the thermal stresses associated with temperature changes or gradients.

The normal modulus, the shear modulus, and Poisson's ratio are plotted as a function of FVR in figure 3. All three elastic properties vary nonlinearly with FVR and therefore cannot be extrapolated or interpolated by using a linear relationship when data for only two FVR's are available.

In-plane fracture stresses (strengths) - tension, compression, and shear - are plotted as a function of FVR in figure 4. Tensile strength varies linearly with FVR; compressive and shear strengths vary nonlinearly.

The following rules of thumb (given here without verification) can be used for approximating PRC strengths: (1) The tensile strength is approximately one-fourth the unidirectional-composite, longitudinal tensile strength from the same composite system at the same FVR; (2) the compressive strength is one-half the UDC longitudinal compressive strength; and (3) the in-plane shear strength (measured by the rail test) is approximately one-half the PRC compressive strength or one-fourth the UDC longitudinal compressive strength. The interlaminar shear strength of PRC, as measured by the short-beam-shear test, is about the same as that of the UDC. These approximations are believed to be conservative estimates of the strengths of PRC. If measured values are significantly below these estimates, the fabrication process should be examined for possible improvements. For limited experimental data see reference 5.

Often the amount of fiber, or resin, in PRC is given by weight percent, weight ratio, or weight fraction. Conversion from weight ratio to FVR for either fiber or resin in E glass composites is presented graphically in figure 5. Both volume ratios (fiber and resin) vary nonlinearly with weight ratio. When the weight fraction of a PRC is given, figure 5 can be used to obtain the corresponding FVR. This FVR can then be used to obtain the thermal and mechanical properties from figures 2 to 4.

The preceding discussion illustrates that composite mechanics can be used to predict physical and mechanical properties of PRC for preliminary design.

FRACTURE TOUGHNESS

The fracture toughness of PRC can be estimated by concepts described in reference 6. The equation for estimating the PRC fracture toughness K_q is given by (in PRC with fiber content up to 40 percent by weight)

$$K_q = S_c \, (2\pi l_f^*)^{1/2} \tag{1}$$

where S_c is the PRC tensile strength and l_f^* is the length of the longer fibers in the PRC. The corresponding strain energy release rate G_c is given by

$$G_c = \frac{2\pi l_f^* \, S_c^2}{E_c} \tag{2}$$

where E_c is the modulus of the PRC. Values for K_q and G_c for specific composites can be determined from these equations with E_c and S_c obtained from figures 3 and 4. For example, $K_q = 313 \text{ MPa}/\sqrt{\text{cm}}$ ($28.5 \text{ ksi}/\sqrt{\text{in.}}$); G_c = 11.9 MPa-cm; (678 psi-in.) for a PRC with 40 percent fiber content by weight and l^* = 1.0 cm (0.40 in.). Note that equations (1) and (2) are empirical and are suitable when l^* is less than or equal to $(1/2)\pi$.

Using the rules of thumb described previously, we can express K_q and G_c in terms of fiber tensile strength and modulus. The resulting equations are

$$K_q = k_f S_{ft} \left(\frac{\pi l_f^*}{8} \right)^{1/2} \tag{3}$$

and

$$G_c = \frac{3}{8} \frac{k_f l_f^* S_{ft}^2}{E_f} \tag{4}$$

where k_f is the fiber volume ratio, S_{ft} is the fiber tensile strength, and E_f is the fiber longitudinal modulus. Equation (3) shows that the fracture toughness varies linearly with fiber volume fraction and fiber tensile strength. Equation (4) indicates that the strain energy release rate also varies linearly with fiber volume ratio and the square of the fiber tensile strength and inversely with the fiber modulus. Equations (1) to (4) collectively suggest that the PRC resistance to crack propagation is fiber dominated. Though this may be intuitively anticipated, it is not easily quantifiable without equation (1), which is based on experimental observation.

Experimental observation shows considerable damage (crazing) ahead of the crack tip in PRC (ref. 6). This damage becomes unstable and starts propagating after fibers that are longer than the damaged-region radius ("plastic" radius) are broken. These longer fibers bridge the damaged region and act as local toughening mechanisms. A graphical representation of the damaged-region radius as a function of fiber length, where at least 5 percent of the fibers exceed this radius, is shown in figure 6 (from ref. 6) for a variety of PRC's. The results in this figure provided the basis and empirical correlation for equation (1).

FATIGUE AND HYGROTHERMAL CHARACTERISTICS

The fatigue characteristics of PRC have been investigated extensively (refs. 7 and 8). Experimental results from this investigation showed that the fatigue strengths degrades linearly with log cycles N to failure. This is illustrated graphically in figure 7 (from ref. 8). In addition, the experimental results showed that the degradation is about 10 percent per decade of cycles for a large variety of composites, as is illustrated graphically in figure 8 (from ref. 8).

Fatigue resistance and matrix cracking are influenced by increases in fiber volume ratio and/or rubber toughening of the matrix (ref. 9). Debonding usually precedes matrix cracking. Both debonding and matrix cracking follow the fatigue failure S-N curve but are considerably below it, as is illustrated in figure 9 (from ref. 9). Matrix cracking density at failure is independent of load history. The frequency of fibers bridging the cracked region, however, may increase with fatigue life especially at high fiber content (about 50 percent by weight).

The fatigue characteristics described previously can be combined with the hygrothermal degradation effects (ref. 2). This combination results in a predictive model (equations) to estimate the hygrothermomechanical degradation effects (durability and life) in PRC. The equation for predicting cyclic load effects only is given by

$$S_{cyc} = (1.0 - B \log_{10} N)S_0 \tag{5}$$

where S_{cyc} is the cyclic stress, N is the number of cycles, S_0 is the single-cycle strength (static fracture stress), and B is the degradation coefficient (about 0.1) determined from experimental data (figs. 7 and 8). The graphical representation of equation (5) for different values of B (0.07 to 0.20) is shown in figure 10. The cyclic stress from figure 10 for 10-million-cycle life of a PRC structural part is about 10 percent for B = 0.13, 30 percent for B = 0.10, and 55 percent for B = 0.07 of the static strength.

The equations for predicting the hygrothermal effects are

$$\frac{T_{gw}}{T_{g0}} = 0.01\ M^2 - 0.10\ M + 1.00 \qquad (M \leq 5 \text{ percent}) \tag{6}$$

$$S = \left(\frac{T_{gw} - T}{T_{g0} - T_0} \right)^{1/2} S_0 \tag{7}$$

where T_{gw} is the glass transition temperature (any consistent units) at M, where M is the moisture in the composite (percent by weight), T_{g0} is the glass transition temperature for the reference conditions (usually dry conditions), T_0 is the reference-condition temperature, T is the use temperature, and S_0 is the reference-condition strength corresponding to T_{g0} and T_0. The equation for the combined hygrothermomechanical effects is

$$S_{cyc} = \left[\left(\frac{T_{gw} - T}{T_{g0} - T_0} \right)^{1/2} - B \log_{10} N \right] S_0 \tag{8}$$

where all the symbols have been defined previously. The degradation coefficient B can be taken as 0.10 or from select measured data for specific designs. The graphical representation of equations (7) and (8) is shown in figure 11 in a form of a universal plot comparable to a Goodman diagram. Combined hygrothermomechanical degradation effects can be determined from this plot once the loading conditions have been selected and the environmental conditions established.

The following example illustrates use of the equations and the figures: Determine the tensile cyclic stress of a PRC panel to survive 10 million cycles when it is subjected to a steady-state tensile stress S_{td} = 69 MPa (10 ksi) and is exposed to 1 percent moisture, by weight, and to 66° C (150° F) temperature. The PRC panel is made from a composite that has T_{g0} equal to 204° C (400° F) and S_C equal to 207 MPa (30 ksi) at T_0 equal to 21° C (70° F). From equation (6) T_{gw} equals 184° C (364° F). From equation (7) S equals about 166 MPa (24 ksi). The ratio S_{td}/S equals about 0.4. Using this ratio in figure 11, we obtain 0.6 for the ratio S_{cm}/S_{cyc}. From equation (8) S_{cyc} equals 22 MPa (3.2 ksi). The cyclic stress S_{cm} therefore is 14 MPa (2.0 ksi). The corresponding cyclic stress S_{cm} would be 43 MPa (6.3 ksi) in the absence of the hygrothermal environment. Obviously the hygrothermal environment has severe degradation effects.

STRIP HYBRID CONCEPTS FOR IMPROVED PRC STIFFNESS

Strip hybrid composites consist of high-modulus unidirectional strips embedded in PRC in a net form (ref. 10). This results in a much stiffer composite than PRC. Analysis and design of structural parts from strip hybrids usually requires finite element analysis (ref. 10).

The strips can be selected to decrease deflections to minimize stresses in the PRC, to increase buckling load resistance, and to increase vibration frequencies. These variables are plotted as a function of strip modulus in figure 12 (from ref. 10). These results indicate that the strip hybrid concept is an effective means to design PRC to meet displacement buckling and frequency requirements at minimum weight and thickness. The comparative performance of strip hybrid square plates with other materials is summarized in table I (from ref. 10), where design parameters such as displacement, stress, buckling, frequency, periodic excitation, and impulsive load are considered. In addition, strip hybrids offer an effective way to minimize creep.

The advantages of strip hybrids will need to be balanced against costs in an actual design since the cost of the strips is relatively high as compared with the cost of PRC. For example, UDC composite strips from high-modulus graphite/resin (HM/R) ($30/lb), intermediate-modulus graphite/resin (T300/R) S18/lb), or Kevlar-49/R ($8/lb) can be embedded in planar random E glass/resin (EG/R) composites ($0.50/lb). These costs show that HM/R is about 60 times more expensive than EG/R, T300/R is about 36 times more expensive, and Kevlar-49/R is only 16 times more expensive.

CREEP AND CREEP RUPTURE

Planar randomly reinforced plastics creep under sustained stress (ref. 11). The creep magnitude depends on stress, temperature, and time. The important properties used in designing PRC for creep are creep rupture strength, creep strain, and creep modulus. The information for these properties is obtained from creep-strain-versus-time plots at desired temperatures. The design stress is determined from the creep rupture envelope (refs. 11 and 12), which defines the maximum stress below which it is safe to use creep curves to predict long-time behavior. This enveloped is illustrated in figure 13 (from ref. 11).

Creep of PRC is described by viscoelastic theory for computational purposes. Findley's viscoelastic theory (ref. 11) has been used for the past three decades to estimate creep behavior. A simplified equation from this theory for creep strain is

$$\varepsilon = \frac{\sigma}{E_v} \tag{9}$$

$$E_v = \frac{E_0}{1 + t^n \dfrac{E_0}{E_t}} \tag{10}$$

where ε is the creep strain at sustained stress σ, E_v is the viscoelastic modulus, E_0 is the elastic (time independent) modulus, t is the desired time, n is the exponent of t, and E_t is the time-dependent modulus. The empirical constants associated with equations (9) and (10) are summarized in table II (ref. 11). Equations (9) and (10) can be used to estimate creep rupture under sustained stress. It is important to note that creep rupture estimates must be based on measured creep data under the anticipated service conditions. When extrapolation is unavoidable, it should be kept to only one decade on semi-log or log-log plots of creep data.

The following example illustrates the use of equations (9) and (10) and table II: Select the sustained stress in a PRC, made from glass reinforced polyester resin that will not exceed a creep strain of 0.3 percent in 10 years in a 23° C (73° F), 50-percent-relative-humidity environment. Using values from table II for glass cloth in equation (10), we obtain the viscoelastic modulus (in pounds per square inch)

$$E_v = \frac{4.416\mathrm{x}10^6}{1 + 10^{0.09}\ (4.416\mathrm{x}10^6/31.5\mathrm{x}10^6)} = 3.76\mathrm{x}10^6$$

Using this value for the viscoelastic modulus in equation (9) and solving for stress σ, we obtain

$$\sigma_v = \varepsilon E_v = 0.003 \times 3.76\mathrm{x}10^6 = 11\ 280 \text{ psi}$$

This stress is about 75 percent of the corresponding static value. A safety factor of 2 is recommended in sizing the structural part. For this example the thickness should be selected to yield a sustained stress of about 6000 psi. The stress value (11 280 psi) can be used in equations (5), (6), and (8) to estimate cyclic stress, hygrothermal, and hygrothermomechanical effects, respectively.

The approach just described is convenient and should be used only as a guide. For improved estimates, consult references 11 to 14.

MOLDING COMPOUNDS FOR PLANAR COMPOSITES

Several molding compounds are used to make planar random composites and planar random composites with selected unidirectional reinforcement. Some of the most common ones are summarized below (refs. 15 and 16).

Sheet molding compound (SMC). - SMC is mostly made from polyester resins reinforced with chopped randomly oriented glass fibers (25 mm (1 in.) long). Thermosetting resins are also used. Typical glass content is 20 to 35 percent by weight.

Bulk molding compound (BMC). - BMC is also made from polyester resins reinforced with chopped random fibers (3 to 13 mm, 1/8 to 1/2 in.). These compounds are mainly used for structural parts amenable to extrusion. Typical glass content is 10 to 30 percent by weight.

Elastic reservoir molding (ERM). - ERM is made in a continuous sandwich with foam core and glass-fiber-mat-reinforced resins. The glass content is about 30 to 70 percent. Unidirectional cloth can also be used for the faces.

High-strength molding compound (HMC). - HMC is a sheet molding compound designed for strength. It is similar to SMC but with fiber (random 13 to 38 mm (1/2 to 1-1/2 in.) long) content about 65 percent by weight.

Low-pressure molding compound (LMC). - LMC is similar to SMC but is made at lower pressures. As a result, longer structural parts can be made at lower cost and by using low-cost molding processes.

Solid polyester molding compound (SPMC). - SPMC is a pelletized thermosetting polyester reinforced with random fiber, commonly 10 to 14 percent by weight. It is similar to BMC but with better processibility.

Thick molding compound (TMC). - TMC is designed to make thick parts, up to 51 mm (2 in.) as compared with 5 mm (3/16 in.) thick for SMC. The glass fiber varies from 6 to 51 mm (1/4 to 2 in. long) as needed. TMC has several advantages over other compounds, including cost, fewer layers per part, shorter handling time, higher fiber content, and more flexibility.

Unidirectional molding compound (UMC). - UMC is a compound made from continuous or chopped fibers. The fibers can be glass, aramid (Kevlar), graphite, or combinations. The fiber content can be as high as 70 percent by weight.

Directionally reinforced molding compound (XMC). - XMC is made from continuous fibers embedded (in an X pattern) in a polyester (SMC like) compound. Because the X pattern is wound at about 7.5°, it provides strength in the selected direction. The X-pattern continuous glass fiber is about 75 percent by weight; the chopped fiber in the compound is about 25 percent. The strength along the directional reinforcement is about three times that of HMC.

Combinations of compounds. - Combinations of molding compounds are usually indicated by the acronyms SMC-C, -D, -R denoting, respectively, continuous-fiber, directional-fiber, or random-fiber SMC. The designation includes the percentage of continuous, directional, or random fibers. For example, SMC-C30/R20 denotes a sheet molding compound reinforced with 30 percent of continuous fibers (C30) and 20 percent of random fibers (R20).

Additional details on these compounds, including process schematics and trade names, are given in reference 16. Various fibers that are used or can be used are described in reference 17, and fillers in general are described in reference 18. Toughening additives for BMC and SMC are described in reference 19, and additives for damage resistance in reference 20. A concise description of reinforced thermoplastics and thermosets is given in reference 21, including advantages, disadvantages, and applications.

This brief description above, with suitable references is given to facilitate discussion of typical data included in the following section.

TYPICAL DATA AND DESIGN CONSIDERATIONS

Selected properties (data) of PRC are included in order to provide (1) an indication of the wide range of these properties and (2) data that can be used as a guide in preliminary designs and in initial structural component sizing.

Properties of thermoplastic PRC's are summarized in table III (from ref. 22). The properties in this table indicate that PRC's have a wide range of strength, modulus, heat distortion, and shrinkage characteristics. Strength and stiffness properties of structural SMC with different fiber content are compared with steel and aluminum in table IV (from ref. 23) in terms of weight (in pounds) and cost (in dollars) for equivalent performance. Structural SMC's outperform steel and aluminum on a per-pound basis. In general, they tend to be more expensive than steel but less expensive than aluminum.

Properties of PRC (fiber-reinforced nylon 6/6) for various fillers and fibers are shown in table V (from ref. 24). All properties shown in this table are enhanced with reinforcement, relative to unreinforced material. Improvement in the properties of the nylon 6/6 that can be made by increasing fiber content is summarized in table 6 (from ref. 24). Elongation to fracture is decreased from 60 percent for the unreinforced matrix to 1.5 percent for the PRC with 60 percent fiber content by weight. This is a very large reduction of about 40 times. The effects of thermal aging on PRC from different thermoplastic matrices is shown in table VII (from ref. 24). Thermal aging at long exposures (500 hr) degrades PRC's in general, except for those made from polyimide matrices.

E glass fiber has been mainly used for reinforcement in PRC's. S-2 glass fiber is also available for use. Comparative data for these two fibers are shown in table VIII (from ref. 25). S-2 glass is stronger, stiffer, and more expensive. Properties of PRC from sheet molding compounds with S-2 and E glass fibers are compared in table IX (from ref. 25). Comparable properties for injection-molded PRC are shown in table X (from ref. 25). Properties of PRC with directional reinforcement are shown in table XI (from ref. 5). The direction and amount of directional reinforcement can be selected to obtain planar composites with desired properties in one or both directions. The properties included in tables III to XI are only a representative sample of what is available. References 12 and 15 contain properties on hundreds of these composites, as was previously mentioned.

Structural analysis methods for composites made from PRC are the same as those used for conventional isotropic materials. The structural analyses referred to here include analyses for deflections, buckling loads, frequencies, dynamic response, and stress concentrations. In all these analyses the PRC is assumed to be homogeneous through the thickness and homogeneous and transversly isotropic in the plane. Equations for the analysis of beams, plates, and shells in the well-known references 26 and 27 are applicable to similar components made from PRC. However, the stress concentration effects through the thickness need special attention. In this case finite element analysis may be needed. Also finite element analysis can be used to predict deflections, buckling loads, frequencies, dynamic response, and stress concentrations as was done for the strip hybrids described previously. The properties needed for the finite element analysis can be obtained as described previously, in the section PREDICTED PROPERTIES.

Structural components made from directionally reinforced PRC are considered to be homogeneous and orthotropic. Analysis methods for orthotropic materials are described extensively in reference 28. In general, however, finite element analysis is preferred. The strip hybrids described previously were analyzed by using finite element analysis. Several general-purpose finite element computer programs are available for structural analysis (ref. 29). Structural design and analysis methods for composites in general are described in reference 30. Once the stresses and/or strains have been determined, they can be assessed with respect to requirements for fracture toughness, fatigue, creep, and environmental effects as described previously.

Environmental effects on mechanical properties (figs. 3 and 4) can be estimated by generalizing equation (7) as follows:

$$\frac{P_m}{P_{m0}} = \left(\frac{T_{gw} - T}{T_{g0} - T_0} \right)^{1/2} \tag{11}$$

where P_m is any mechanical property at the required moisture and temperature conditions and P_{m0} is the reference property corresponding to T_0. The Poisson's ratios can be assumed to be independent of temperature and moisture. The environmental effects on thermal properties (fig. 2) can be estimated from the inverse of equation (11), or

$$\frac{P_t}{P_{t0}} = \left(\frac{T_{g0} - T_0}{T_{gw} - T} \right)^{1/2} \tag{12}$$

where P_t and P_{t0} are similar to P_m and P_{m0}, respectively. The glass transition temperature at dry conditions T_{g0} can be selected from the last column of table III if it is not known. Then for any moisture M ($M \leq 5$ percent) the glass transition temperature corresponding to M can be estimated by using equation (6). Note, in addition, that the discussion has been limited to moisture, temperature, and time dependence (eqs. (6) and (9) to (12)) for uniform conditions through the thickness. Proper integration is needed to determine the properties and effects when the conditions are not uniform.

CONCLUSIONS

Composite mechanics that can be used to predict the hygrothermomechanical behavior of planar random composites (PRC) has been reviewed and described. The description includes use of the quasi-isotropic analogy, summary of predicted properties, fracture toughness, fatigue and hygrothermal characteristics, strip hybrid concepts and directional stiffening for improved properties, creep, and creep rupture.

Predicted properties are presented in graphical form for convenience, with selected sample calculations to illustrate their use.

Various resins, fibers, and molding compounds that are used to make PRC are described. Typical data are included for use in preliminary design of structural PRC. Structural analysis and design methods that can be used are briefly discussed. Pertinent references where additional information can be obtained are cited.

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TABLE I. - PREDICTED STRUCTURAL RESPONSES OF SQUARE PLATES MADE FROM STRIP HYBRIDS AND OTHER MATERIALS (REF. 10)

[Strips 20 percent by volume; panel size: 20 by 20.]

Material	Structural response						[d]Impulsive load	
	[a]Concentrated load		[b]Buckling	Natural lowest frequency, cps	[c]Periodic excitation		Displacement, in.	Stress in base material, ksi
	Displacement, in.	Stress in base material, ksi	Load, lb/in.		Displacement, in.	Stress in base material, ksi		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
E-Glass/resin random (0.05 in. thick base panel)	0.97	3.5	4.3	23	23.3	64.8	4.3	18.0
[e]Strip hybrids (0.05 in. thick) E-Glass/resin with								
Kevlar-49/resin	.61	2.4	6.4	30	3.5	11.8	3.2	12.0
Thornel 300/resin	.42	1.7	8.9	36	1.9	6.8	2.4	8.9
HM-Graphite/resin	.30	1.3	12.0	43	1.2	4.6	1.9	7.9
[f]Steel	.06	3.5	71.8	45	.2	12.5	.4	25.0
E-Glass/resin random (0.10 in. thick base panel)	.12	.87	34.5	46	.49	2.4	.9	5.3
Steel (0.035 in. thick)	.18	7.1	24	32	1.0	33	1.1	48.9

[a]Concentrated load at center, 10 lb.
[b]Buckling load parallel to x direction, fig. 6.
[c]Periodic excitation force $F(f) = (23 + 0.3 f) \sin(2\pi ft)$ (evaluated at $f = 22$ cps).
[d]Impulsive load at center: $F(t) = 5000\, t$ $(0 \le t \le 0.002)$; $F(t) = 150 - 25\, t$ $(0.002 \le t \le 0.006)$.
[e]Strips made from unidirectional advanced composite.
[f]Included for comparison.
Conversion factors: 1 in. = 2.54 cm; 1 lb = 4.46 N; 1 ksi = 6.9 MPa; lb/in. = 176 N/m.

TABLE II. - CONSTANTS FOR ESTIMATING CREEP IN PLANAR FIBER COMPOSITES (SELECTED DATA FROM REF. 11)

MATERIAL	TEST CONDITION		VISCOELASTIC EMPIRICAL CONSTANTS		
	TEMP. ^oF	REL. HUMID. %	EXPON. N	TIME INDEP. MODULUS E_o (10^6 psi)	TIME DEPEND. MODULUS E_t (10^6 psi)
POLYESTER-RESIN/ 181 GLASS FABRIC	73	50	0.090	4.41	31.5
POLYESTER-RESIN/ 181 GLASS FABRIC	73	IMMERSED IN WATER	0.210	2.42	76.5
POLYESTER-RESIN/ GLASS FIBER MAT	73	50	0.190	1.27	7.73
EPOXY-RESIN/ 181 GLASS FABRIC	73	50	0.160	4.39	100.0
EPOXY-RESIN/ 181 GLASS FABRIC	73	IMMERSED IN WATER	0.220	3.20	200.0
POLYESTER/GLASS WOVEN ROVING	73	50	0.200	2.20	22.0

CONVERSION FACTORS: $^oC = \frac{5}{9}(^oF - 32)$; 10^6 psi = 6.89 G_{pa}

TABLE III. - PROPERTIES OF GLASS-REINFORCED THERMOPLASTICS (20 PERCENT BY WEIGHT, REF. 22)

RTP	SPECIFIC GRAVITY	SHRINKAGE 1/8" SECT.	IMPACT 1/4" NOTCHED	TENSILE STRENGTH, PSI	FLEXURAL STRENGTH, PSI	FLEXURAL MODULUS, PSI	HEAT DISTORTION AT 264 PSI, ^oF
103 POLYPROPYLENE	1.05	0.004	1.2	7,200	8,600	$0.52x10^6$	285
103CC POLYPROPYLENE	1.05	0.004	1.8	12,000	14,000	$0.55x10^6$	290
203 NYLON 6/6	1.28	0.005	1.3	19,000	28,500	$1.0 x10^6$	470
203A NYLON 6	1.27	0.004	1.3	20,000	23,000	$0.7 x10^6$	390
303 POLYCARBONATE	1.34	0.002	1.4	17,000	19,000	$0.8 x10^6$	290
403 STYRENE	1.20	0.001	1.0	11,000	16,500	$1.1 x10^6$	200
503 SAN	1.22	0.001	1.0	18,000	20,000	$1.0 x10^6$	210
603 ABS	1.18	0.001	1.4	13,000	17,000	$0.8 x10^6$	220
703 HDPE	1.1	0.003	1.2	7,000	9,000	$0.55x10^6$	240
803 ACETAL	1.55	0.006	0.9	12,000	16,500	$0.9 x10^6$	325
903 POLYSULFONE	1.38	0.002	1.1	15,000	20,000	$0.7 x10^6$	360
1003 PBT	1.45	0.004	1.0	16,500	23,000	$0.8 x10^6$	400
1203 POLYURETHANE	1.37	0.004	1.5	14,000	19,000	$0.62x10^6$	170
1303 PPS	1.44	0.003	1.2	14,000	20,000	$1.1 x10^6$	500
1403 PES	1.51	0.002	1.6	20,000	27,000	$0.9 x10^6$	408

TABLE IV. - STRUCTURAL SHEET MOLDING COMPOUNDS (SMC) COMPARED WITH METALS (REF. 23)

	WEIGHT: POUNDS FOR EQUIVALENT PERFORMANCE			
	SPACE FILLING	FLEXURAL STRENGTH	STIFFNESS	TENSILE STRENGTH
STEEL (HSLA) 950	1.00	1.00	1.00	1.00
SMC-R30	0.24	0.36	0.62	1.11
SMC-R40	0.24	0.31	0.62	0.72
SMC-R50	0.24	0.28	0.62	0.52
SMC-R65	0.24	0.25	0.59	0.38
SMC-C30/R20	0.24	0.18	0.53	0.18
UNIDIRECTIONAL SMC-C30/R20	0.24	0.21	0.59	1.20
SMC-C60/R5	0.24	0.17	0.45	0.20
SMC-C60	0.24	0.15	0.42	0.15
ALUMINUM (7021-T6)	0.33	0.33	0.48	0.332

	COST: DOLLARS FOR EQUIVALENT PERFORMANCE			
	SPACE FILLING	FLEXURAL STRENGTH	STIFFNESS	TENSILE STRENGTH
STEEL (HSLA) 950	1.00	1.00	1.00	1.00
SMC-R30	0.47	0.69	1.18	2.14
SMC-R40	0.52	0.69	1.32	1.57
SMC-R50	0.58	0.69	1.47	1.28
SMC-R65	0.67	0.69	1.62	1.07
SMC-C30/R20	0.58	0.44	1.27	0.42
UNIDIRECTIONAL SMC-C30/R20	0.67	0.57	1.62	3.35
SMC-C60/R5	0.67	0.48	1.22	0.57
SMC-C60	0.64	0.41	1.11	0.35
ALUMINUM (7021-T6)	1.40	1.40	2.03	1.42

TABLE V. - PROPERTIES OF FIBER-REINFORCED NYLON 6/6 (REF. 24)

PROPERTY	UNREIN-FORCED	GLASS FIBER	CARBON (GRAPHITE)	MINERAL	CARBON/ GLASS FIBER	MINERAL/ GLASS FIBER	GLASS BEAD
REINFORCEMENT CONTENT (% BY WT.)	0	40	40	40	20C/20G	20 M/16.5G	40
SPECIFIC GRAVITY	1.14	1.46	1.34	1.50	1.40	1.42	1.44
TENSILE STRENGTH (psi x 10^3)	12	31	40	15	34	17.5	13
FLEXURAL MODULUS (psi x 10^5)	4.0	16	34	11	28	9.5	8
IMPACT STRENGTH, NOTCHED/UNNOTCHED (ft-lb/in.)	0.9/6	2.6/19	1.6/13	0.7/8	1.8/16	1/13	1/5.5
HEAT DEFLECTION TEMPERATURE @ 264 psi (^{0}F)	150	500	500	440	500	470	190
THERMAL EXPANSION (10^{-5} in./in./^{0}F)	4.5	1.4	0.8	3.0	1.15	2.5	2.0
MOLD SHRINKAGE (10^{-3} in./in.)	15	4	---	9	---	7	---
WATER ABSORPTION, 24 hr. (% BY WT)	1.6	0.6	0.4	0.45	0.5	0.5	0.65

TABLE VI. - FIBER CONTENT EFFECTS ON PROPERTIES OF NYLON 6/6 (REF. 24)

	% OF GLASS FIBER, BY WT						
PROPERTY	0	10	20	30	40	50	60
SPECIFIC GRAVITY	1.14	1.21	1.28	1.37	1.46	1.57	1.70
SPECIFIC VOLUME (cu. in./lb.)	24.3	22.9	21.6	20.1	19.0	17.6	16.3
TENSILE STRENGTH (psi x 10^3)	12	13	19	25	31	32	33
TENSILE ELONGATION (%)	60	3.5	3.5	3.0	2.5	2.5	1.5
FLEXURAL STRENGTH (psi x 10^3)	15	20	29	34	42	46	50
FLEXURAL MODULUS (psi x 10^5)	4.0	6.0	9.0	13	16	22	28
COMPRESSIVE STRENGTH (psi x 10^3)	4.9	13	23	27	28	29	30
HEAT DEFLECTION TEMP. @ 264 psi (^{0}F)	150	470	475	485	500	500	500
THERMAL EXPANSION (10^{-5} in./in./^{0}F)	4.5	1.6	1.4	1.3	1.2	1.0	0.9
WATER ABSORPTION, 24 hr. (%)	1.6	1.1	0.9	0.9	0.6	0.5	0.4
MOLD SHRINKAGE (10^{-3} in./in.)	15	6.5	5	4.0	3.5	3.0	2.0

DATA FROM COMMERCIALLY AVAILABLE MATERIALS

TABLE VII. - THERMAL AGING EFFECTS ON TENSILE STRENGTH* OF THERMOPLASTICS (REF. 24)

	AGING TIME (hr) AT 500^0 F						
RESIN (% GLASS FIBER BY WEIGHT)	0	100	250	500	750	1000	1500
ETHYLENE-TETRAFLUORO ETHYLENE (ETFE) (20)	11,300	11,500	10,000	7000	5000	3800	2300
FLUORINATED ETHYLENE PROPYLENE (FEP) (20)	5000	5100	4800	4700	4700	4600	4500
POLYAMIDE-IMIDE (0)	27,400	27,200	26,600	26,000	24,500	23,500	22,000
POLYARYLSULFONE (0)	13,100	11,500	10,500	10,000	9500	8400	7600
POLYETHERSULFONE (40)	22,700	15,600	14,800	14,300	13,700	12,200	10,500
POLYIMIDE (30)	13,000	15,000	14,300	13,400	12,800	12,000	11,200
POLY-P-OXYBENZOATE (0)	23,000	18,000	16,300	16,000	15,500	15,100	13,000
POLYPHENYLENE SULFIDE (40	23,200	16,400	16,000	15,500	15,000	14,500	13,800

* STRENGTH IN psi

TABLE VIII. - COMPARATIVE DATA OF E AND S GLASS FIBERS (REF. 25)

PROPERTIES OF GLASS FIBERS	S GLASS S-2 GLASS	E GLASS
PHYSICAL PROPERTIES*		
SPECIFIC GRAVITY - FIBERS gms/cc	2.49	2.60
DENSITY - lb./cu. in.	.090	.094
MECHANICAL PROPERTIES*		
VIRGIN TENSILE STRENGTH 70°F, psi x 10^3	665	500
MODULUS OF ELASTICITY		
72°F, psi x 10^6	12.6	10.5
72°F, psi x 10^6 (AFTER HEAT COMPACTION)	13.5	12.4
1000°F, psi x 10^6 (AFTER HEAT COMPACTION)	12.9	11.8
ELONGATION AT 72°F, %	5.4	4.8
THERMAL PROPERTIES**		
COEFFICIENT OF EXPANSION in./in./°F x 10^6	3.1	2.8
SPECIFIC HEAT AT 75°F	0.176	0.192
SOFTENING POINT °F	1,778	1,155
STRAIN POINT °F	1,400	1,140
ANNEALING POINT °F	1,490	1,215

* PROPERTIES WERE DETERMINED ON GLASS FIBERS
** PROPERTIES WERE DETERMINED ON BULK GLASS

TABLE IX. - MECHANICAL PROPERTIES OF SHEET MOLDING COMPOUND (ISOPHTHALIC POLYESTER RESIN WITH 30 PERCENT GLASS BY WEIGHT) (REF. 25)

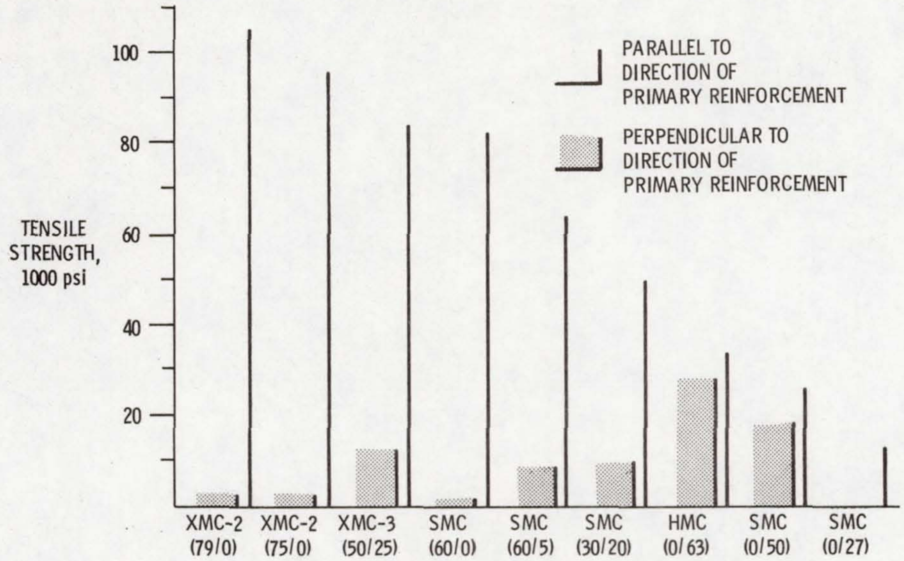
PROPERTY	S-2 GLASS	E GLASS	% IMPROVEMENT
TENSILE STRENGTH (psi x 10^3)	18.8	10.8 - 13.1	57
TENSILE MODULUS (psi x 10^6)	2.0 - 2.2	1.9 - 2.4	---
FLEXURAL STRENGTH (psi x 10^3)	30 - 34	22 - 24	39
FLEXURAL MODULUS (psi x 10^6)	1.9 - 2.2	1.8 - 2.6	---
COMPRESSIVE STRENGTH (psi x 10^3)	32.9 - 33.3	27.2 - 36.0	---
NOTCHED IZOD IMPACT STRENGTH (ft. lb./in.)	12.3 - 14.1	9.2 - 17.0	---

TABLE X. - MECHANICAL PROPERTIES OF INJECTION-MOLDED THERMOPLASTICS (NYLON 6/6) (REF. 25)

PROPERTY	S-2 GLASS	E GLASS	% IMPROVEMENT
TENSILE STRENGTH (psi x 10^3)	25.7	24.7	4
TENSILE MODULUS (psi x 10^6)	1.45	1.35	7
FLEXURAL STRENGTH (psi x 10^3)	45.4	42.7	6
FLEXURAL MODULUS (psi x 10^6)	1.47	1.38	7
NOTCHED IZOD IMPACT (ft. lb./in.)	3.0	2.9	3
UN-NOTCHED IZOD IMPACT (ft. lb./in.)	27.9	26.2	6
GLASS CONTENT (%)	32.2	32.7	

TABLE XI. - MECHANICAL PROPERTIES OF VARIOUS GLASS MOLDING COMPOUNDS (REF. 5)

COMPARATIVE TENSILE STRENGTH OF VARIOUS GLASS FIBER COMPOSITES



NOTE: NUMBERS IN ( ) REPRESENT THE WEIGHT PERCENT OF CONTINUOUS AND 1-in. CHOPPED GLASS

HOW ADDITION OF RANDOM FIBERS AFFECTS PROPERTIES OF FILAMENT-WOUND COMPOSITE

	ALL CONTINUOUS FIBER (XMC-2)	CONTINUOUS WITH RANDOM FIBER (XCM-3)
CONTINUOUS GLASS	75%	60%
CHOPPED STRANDS	---	15%
COMPOSITE THICKNESS, in.	0.10	0.10
PROPERTY PARALLEL TO REINFORCEMENT		
TENSILE STRENGTH, 10^3 psi	90	75
FLEXURAL STRENGTH, 10^3 psi	155	125
FLEXURAL MODULUS, 10^6 psi	5.5	5.5
SHORT BEAM SHEAR, 10^3 psi	9	7.5
PROPERTY PERPENDICULAR TO PRIME REINFORCEMENT		
TENSILE STRENGTH, 10^3 psi	2.4	12.0
FLEXURAL STRENGTH, 10^3 psi	6.15	23.0
FLEXURAL MODULUS, 10^6 psi	1.3	1.3
SOURCE: PPG INDUSTRIES		

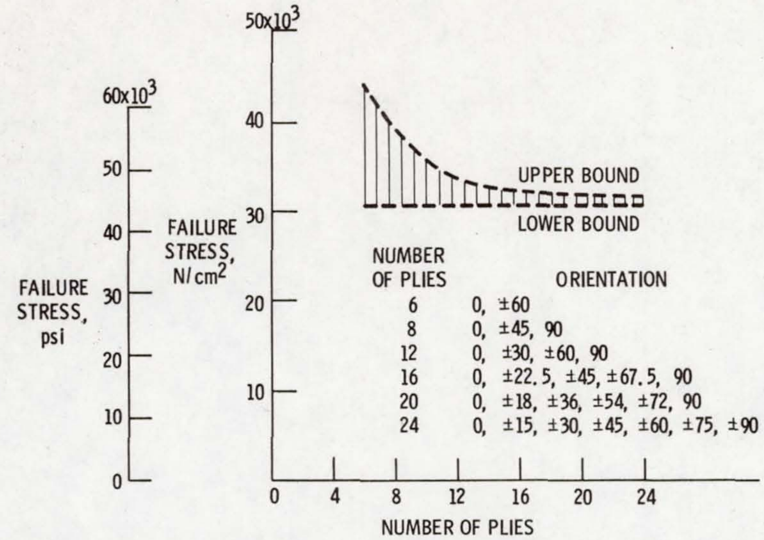


Figure 1. - Upper and lower bounds for strength of various pseudoisotropic composites from Modmor-1/epoxy at 0.50 fiber volume content with zero voids and no residual stress. (From ref. 4.)

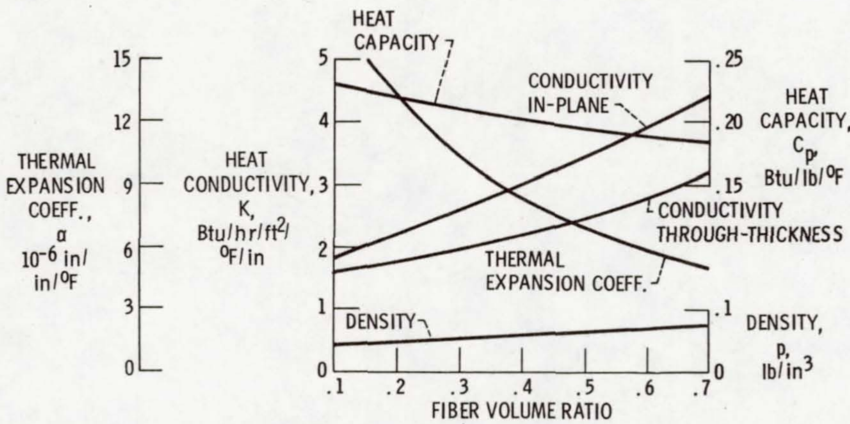


Figure 2. - Physical properties of planar random E glass/resin composites predicted using the quasi-isotropic analogy (ref. 1). SI unit conversion factors: α, in/in/°F = 0.56 cm/cm/K; K, Btu/hr/ft^2/in = 6.94 W/m/K; C_p, Btu/lb/°F = 4.19x10^3 J/kg/K; ρ, lb/in^3 = 27.7 g/cm^3. (From ref. 10.)

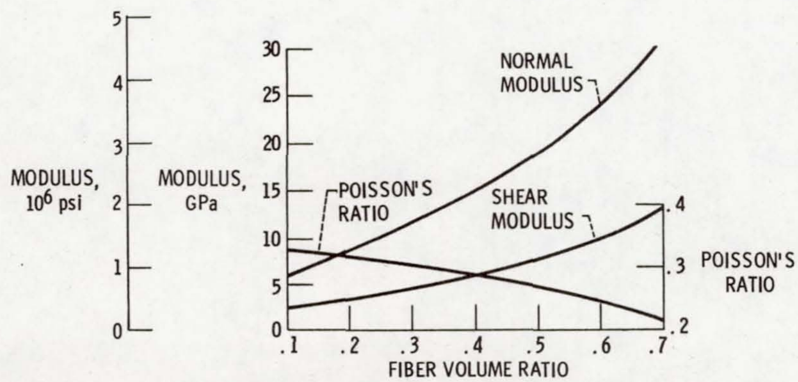


Figure 3. - Elastic properties of planar random E glass/resin composites predicted using the quasi-isotropic analogy. (From ref. 10.)

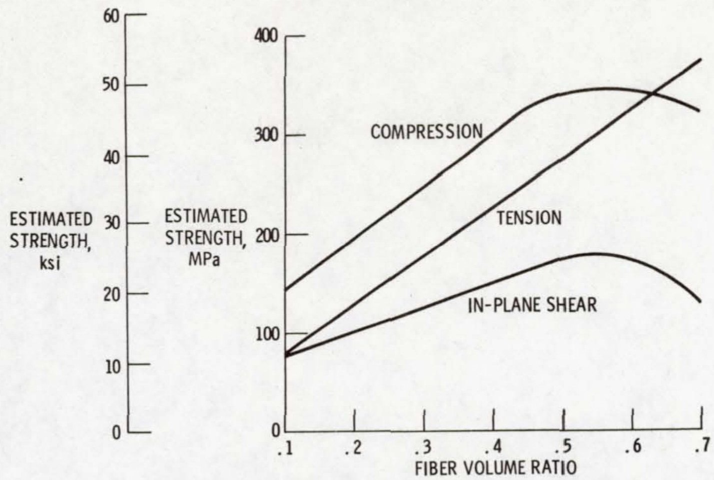


Figure 4. - Estimated fracture stresses (strengths) of planar random E glass/ resin composites. (From ref. 10.)

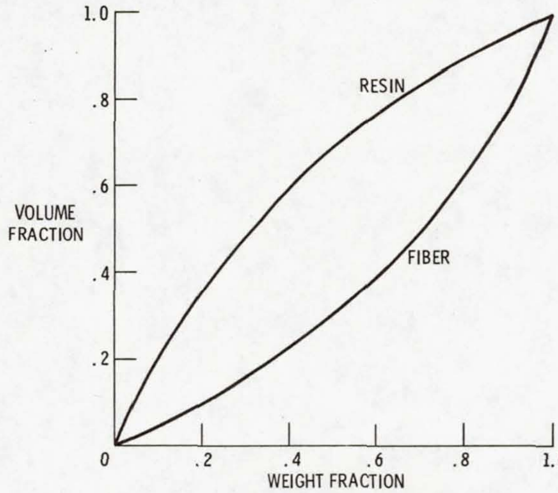


Figure 5. - Volume fraction versus weight fraction for glass-resin system (fiber density = 2.60 g/cm^3 (0.094 lb/in^3), resin density = 1.19 g/cm^3 (0.042 lb/in^3)). (From ref. 10.)

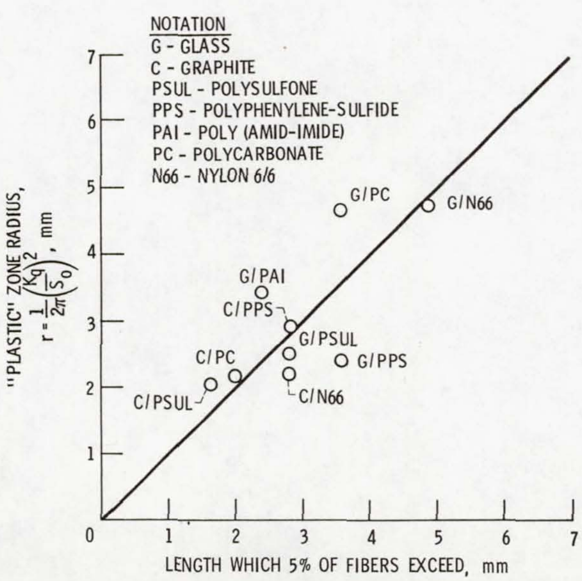


Figure 6. - Effects of chopped fiber length on "plastic zone radius" in graphite- or glass-reinforced thermoplastics. (30 to 40 percent fiber by weight. (From ref. 6.)

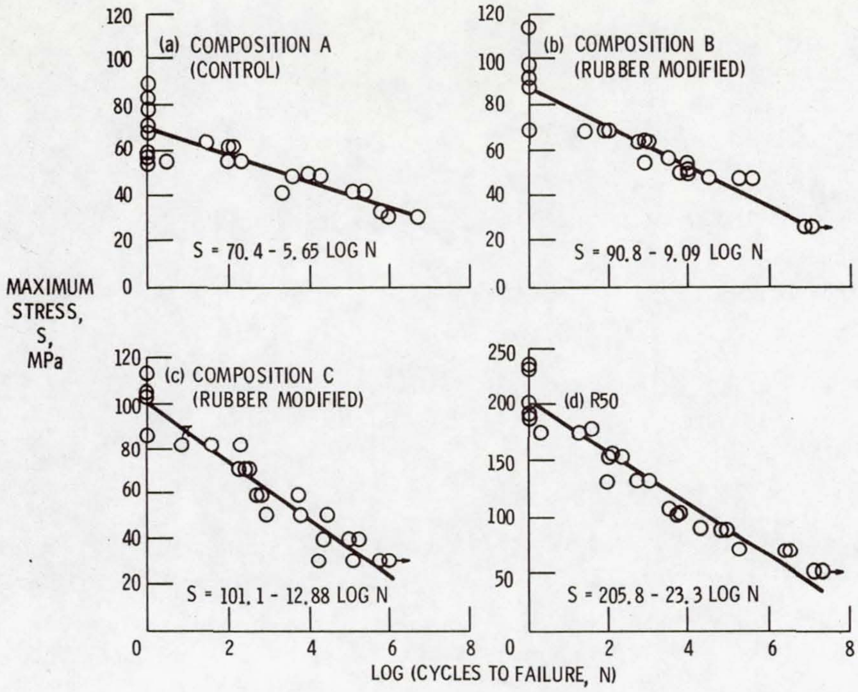


Figure 7. - S-N curves for several sheet molding compounds (R = 0.1) (a), (b), (c), 6.5 Hz; (d) 5 to 20 Hz. (From ref. 8.)

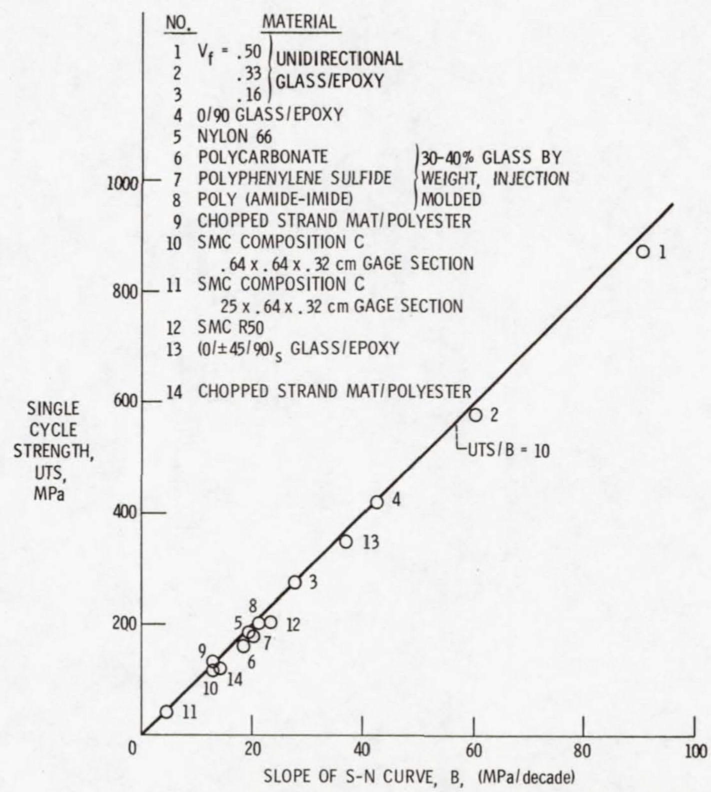


Figure 8. - Degradation of nonwoven, glass-fiber-reinforced plastics (about 10 percent per decade) by tension-tension fatigue (R = 0 to 0.1). (From ref. 8.)

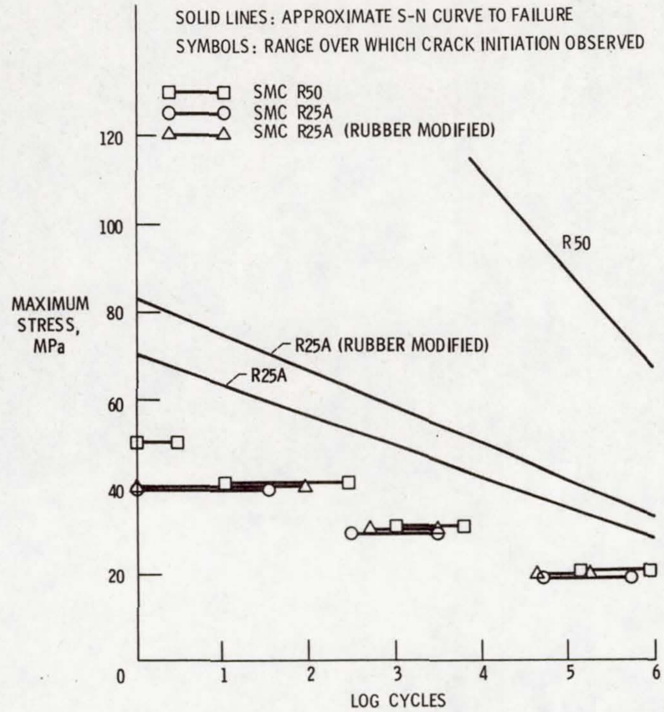


Figure 9. - Fatigue cycles to crack initiation and failure for SMC (R = 0.1 at 5 to 15 Hz). (From ref. 9.)

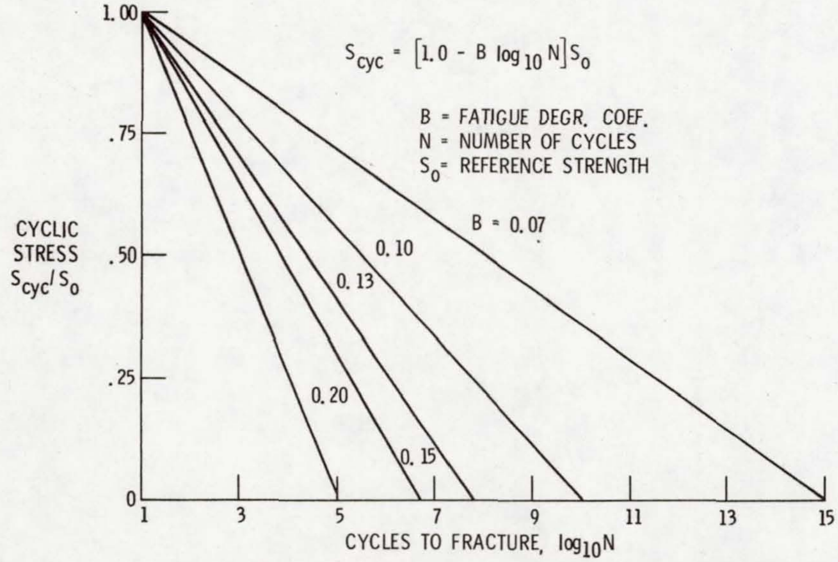


Figure 10. - Fatigue strength for various values of fatigue degradation coefficient B at reference (dry) conditions.

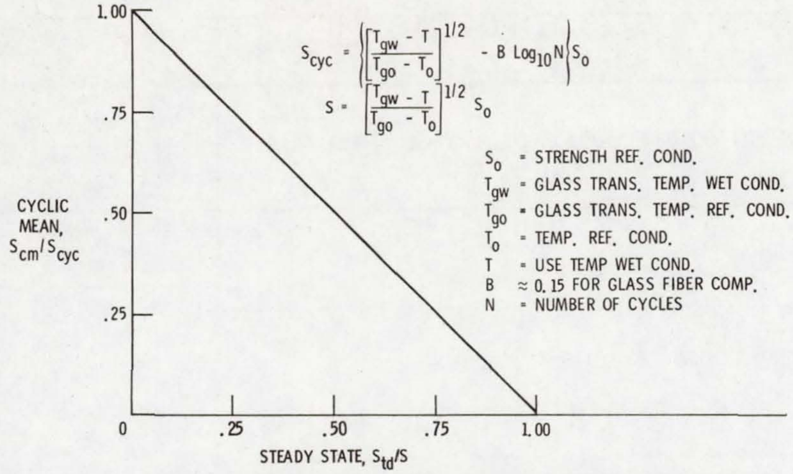


Figure 11. - Universal plot for estimating fatigue strength with steady-state stress.

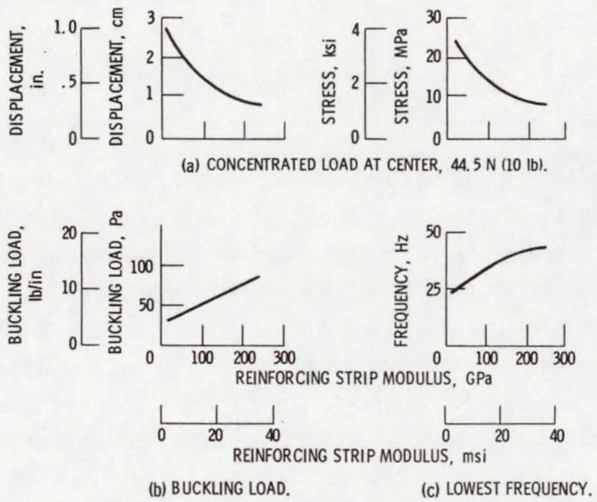


Figure 12. - Structural responses of strip hybrid square plates with fixed edges. E glass/resin planar random composite reinforced with two-way unidirectional composite strips 20 percent by volume (50.8 by 50.8 by 0.127 cm (20 by 20 by 0.05 in.). (From ref. 10.)

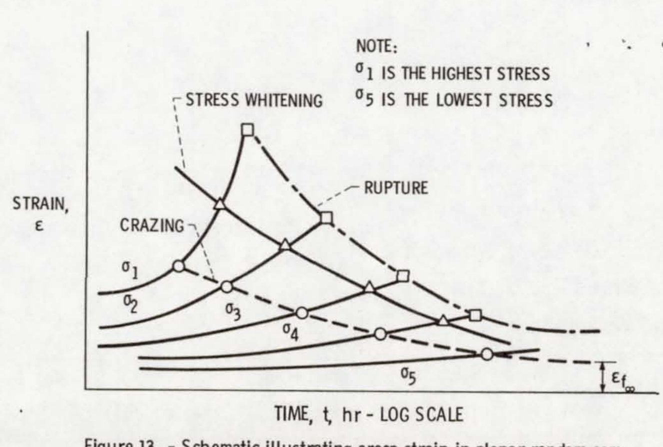


Figure 13. - Schematic illustrating creep strain in planar random composites. (From ref. 11.)

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