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Abstract approved

The present status of plastics is one of constant change, but this thesis attempts to focus attention on the state of the industry as of 1967. Beginning with a brief title definition and history of plastics, the writer proceeds to a discussion on the structural characteristics of plastics. Under this heading, a brief molecular description of plastic is given followed by a discussion on strength characteristics such as stress-strain diagrams, creep, stress relaxation, and the effects of environment. It is noted, however, that such strength characteristics can be markedly altered by proper selection of additives. Such additives are broken into three classes: reinforcements, fillers, and others. These additives greatly complicate design, however, increasing the need for accurate property data; mention is made of the difficulty of obtaining such design data.

Design of plastics, as of 1967, is usually done with standard engineering formulas. For plastics, this is a very inaccurate method

of design and requires a large factor of safety. However, design advancements are being made, such as the development of the time dependent modulus, Boltzmann modulus, and percentage of ultimate concept.

Structural plastics today find a wide range of application: they are being used in aircraft; they are being used for wood-plastic alloys; automobile bodies have been constructed of them for many years; and marine applications vary from production of nine foot boats to 160 foot long ships. Yet, the future is even more promising. The writer concludes by mentioning some of the promising areas of current research; the most promising of which is improved resin reinforcement.

The Present Status of Plastics as an Engineering Material

by

John Steve Summersett

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INTRODUCTION

Plastics today have one of the greatest growth potentials of any material in existence; and it is because of this that it is also one of the most dynamic materials. New applications for plastic resins are constantly being discovered while existing resins are continually being improved. It is for this reason that the writer feels that it is worthwhile to note the present status of plastics as an engineering material.

Present status shall mean the properties, design methods, and relative importance as of July, 1967. Plastic as defined by many building codes (Perrine, 1966) is

> a material that contains as an essential ingredient an organic substance of large molecular weight, is solid in its finished state, and at some stage in its manufacture or in its processing into finished articles, can be shaped by flow.

It should be noted that this definition allows plastics to be a composite material containing some ingredients that do not fit the above definition. Therefore, reinforced and filled plastics also fit the above definition of plastics. Finally, an engineering material will be defined as a material than can be designed to function efficiently as a load bearing member.

The title, as defined, limits the field of plastics, but due to the multitude of uses of plastics as an engineering material and the myriad of materials added to the plastic resin to improve its properties and the many stages in the production of an engineering material, the scope of this thesis must be narrowed even more. This thesis will not cover processing, fabricating, finishing, machinery or methods of molding and forming. It will not cover the properties of the molding compound or the chemical nature of plastics. Rather, it will attempt to explain the direction the plastics industry is taking as well as the current properties of the plastic materials, modern methods of designing with them, and what the future holds for plastics.

HISTORY OF PLASTICS

Let the writer say first that the plastics industry today is being slowed in its development because of its history more than any other factor. As an example consider the fact that much of the 3, 500 square feet of structural plastics used in the Boeing 737 airplane or the 8,000 square feet in the 747 airplane is painted with aluminum paint. There are several functional reasons for this, but Bud Cole (1967) general supervisor of the fiberglass development group for Boeing, says that one of the main reasons is so "people won't know they're riding in a plastic airplane." It is because the history of plastics is filled with examples of poor performance that the general attitude of the population is against the use of plastics and consider them cheap, inferior materials; and it is largely because of this attitude of disapproval that building codes unduly restrict the use of plastics. But it is not the fault of the plastic materials that junior's toys break when they are dropped or that a hard bump will chip the corner off the radio. Rather it is the fault of the designer who has so often misused plastics. For example Union Carbide Corporation makes a carbon reinforced epoxy composite designated Thornel 25 which has a tensile strength of 95.9×10^3 psi and a bending modulus of elasticity of 15.3×10^6 psi while its density is only 1.40 times that of water. This is not an inferior material, but of course plastics were not always available with such properties.

Natural resins such as shellac, a secretion of an insect found in the Orient, have been in existence for centuries, but synthetic resins have a much shorter history. It was not until the middle of the nineteenth century that the earliest development of synthetic plastics took place. Many advancements occurred from that time on. However, it was during the years of 1908 to 1912 that synthetic resins began to have commercial possibilities, when Dr. L.H. Bakeland secured patents on a practical process of utilizing the reaction between phenol and formaldehyde (Mansperger, 1938). It was about the third decade of this century before plastics were being produced in any significant quantity. Since 1929 the growth of plastics has skyrocketed, increasing in production 1000 percent within the first four years. In 1958 there were 4.66 billion pounds of plastics produced in the U.S.A. By 1964 this figure had jumped to 9.6 billion pounds with 2.3 billion being consumed by the construction industry. And to give some idea of future production, the construction industry is expected to utilize 6.2 billion pounds annually by 1970 (Skeist, 1966).

PROPERTIES OF PLASTICS

Basic Nature of Plastics

Although the chemical nature of plastics is beyond the scope of this thesis, a superficial understanding of the nature of plastics is necessary. Briefly, a plastic resin is produced by allowing the molecules of a high molecular weight chemical compound, called monomer, to bond to each other under heat and pressure forming chain-like molecules called polymers. This process of bonding is called polymerization and is analogous to the process of joining railroad cars to form a train. There are four types of polymerization, but each type has the same four requirements in order for a polymer to crystallize.

1. repeating chemical units.
2. geometrically regular repeating units.
3. intermolecular chain forces.
4. reasonably rapid crystallization rate.[1]

When the polymer is derived from a single monomeric compound having only one active double bond it can be represented by:

$$A - A - A - A - A - A$$

However, if the polymer is derived from several monomeric

[1] It should be noted that branching of the polymer during polymerization causes degradation of properties such as crystallinity, density, and stiffness and should be held to a minimum.

substances so that it might be represented by:

A - A - B - A - A - B

then the process is called copolymerization and is analogous to the process of alloying in metals.

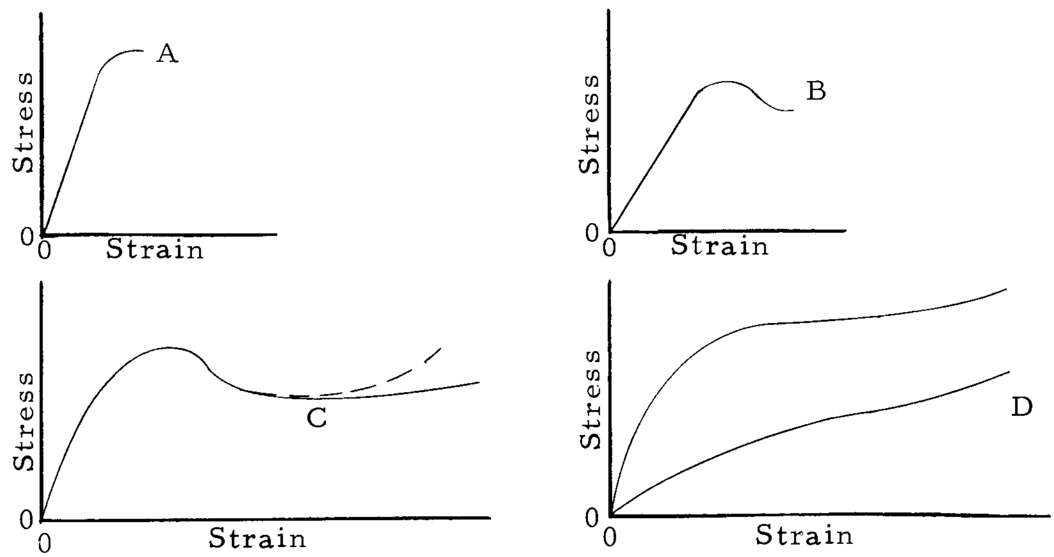
Linear polymers of the first type represent a class of plastics called thermoplastic resins whereas three-dimensional polymers of the latter type are called thermosetting resins. In general, thermoplastic resins are softer and weaker with far more inferior structural characteristics than the thermosetting resins. The major differences between the two is that thermoplastic resins may be softened and resoftened with heat without undergoing a chemical change whereas thermosetting resins undergo a chemical change with application of heat and cannot be resoftened. With these facts in mind, it is easy to understand that nearly all plastics used under the definition of an engineering material are thermosetting resins.

Yet even the superior thermosetting resins are far from an engineering material. Their dimensional stability, heat and fire resistance, durability, water absorption rate, density, structural strength, electrical characteristics, and chemical resistance all must be improved. But the true advantage of plastics is that they are composite materials. For each inadequate property of the resin, another material is added to change or replace that property. The added materials may be fillers, reinforcements, or other materials, all of which will be considered later. In accordance with the composite nature of plastics the resin will hereafter be referred to as a matrix or resin matrix.

Structural Characteristics of Plastics

When plastics are compared to conventional materials many advantages become apparent. Plastics have light weight, a high strength to weight ratio, a great cost savings potential, corrosion resistance, ease and versatility of fabrication, excellent thermal and electrical insulation properties, decorative appeal, many specialized properties of certain resins, and easy maintenance. In addition, during March of this year Dr. Ballester of the University of Barcelona, Spain, reported that as a result of his research, plastics may soon be able to conduct electricity as well as serve as an insulator (Magnetic Plastics, 1967).

With all of these advantages, one might think plastics would overrun the building industry; but plastics have several very limiting disadvantages at present. The most important limitation is that the resin matrix, which, without reinforcement, is the simplest form of plastic, has a viscoelastic nature. This means that the material behaves as a combination of elastic solids and viscous liquids. Steel, it might be noted, is viscoelastic at its upper temperature ranges whereas plastic has these characteristics over nearly all of its temperature range. The plastics industry needs information concerning engineering properties such as stress-strain relationships, rigidity, and fatigue resistance such as the information available to designers of metals, woods, and other traditional materials. But the viscoelastic as well as the composite nature of plastics, makes this accumulation of accurate information extremely difficult. The problem is compounded further by the fact that the properties of plastics vary so greatly among themselves. Some characteristics of the reinforced amino molding compounds approach the properties of metals whereas some of the softer thermoplastic materials have a serious cold flow problem under stress. In general, there are the following four types of stress-strain diagrams for resin matrices.[2]



[2]Much of the following information in this section on the structural characteristics of plastics may be found in the 1966 and 1967 edition of the Modern Plastics Encyclopedia. (Frados, 1965 and 1966)

Curve A exhibits nearly elastic behavior and is typical of the hard rigid thermosetting matrices such as urea and melamine. For these matrices, the strain at rupture is only a few percent and there is little variation in its properties due to temperature change until its decomposition temperature is reached. Also, these materials are relatively insensitive to stressing speed and are similar in many respects to metals.

Curve B also exhibits nearly elastic behavior and is typical of the more brittle thermoplastics such as unmodified polystyrene or the less rigid thermosets. For these materials, the strain at rupture is usually 25 percent or less and the effects of temperature and strain rate may be significant.

Curve C is typical of the thermoplastic materials that neck down and draw out with elongations at failure from 100 percent to 700 percent. Such a curve might represent nylon or rigid polyvinyl chloride. These materials are extremely sensitive to both temperature and strain rate and consequently, the stress-strain properties can be very misleading. Matrices such as that represented by the dotted line, that increase in strength as they are drawn, are typical of materials such as nylon. The strength increase is believed to be due to fiber orientation.

Materials that exhibit behavior as indicated by curve D are also thermoplastic materials. They are similar to curve C materials except that they do not neck down during most of their extention and behave very much like rubber. The upper curve D might represent polytetrafluoroethylene (TFE) and the lower, plasticized polyvinyl chloride (PVC).

All of the above curves are representative at room temperature and under normal testing speeds. Varying either of these may have a pronounced effect on the shape of the curves. For example, consider the effects of temperature. Polymers have a specific temperature called their glass transition temperature, Tg, at which profound changes take place. This temperature may be determined for a particular polymer by an abrupt change in slope or discontinuity in a thermal expansion curve or an elastic modulus versus temperature curve. Below the glass transition temperature the long chain-like molecules are restricted in their movement and the matrix is relatively elastic and glassy with high stiffness, low impact resistance, and comparatively small creep and stress relaxation. Fatigue characteristics depend upon whether or not the heat built up in the matrix by repeated deformation is sufficient to raise the temperature of the matrix to its Tg.

Above the Tg the chain-like molecules of the polymer are more free to slide relative to one another as if they were lubricated by the high temperature. As a result, the elastic modulus drops appreciably, impact resistance is improved, creep and stress relaxation become significant, and the fatigue characteristics become more heavily dependent upon the amount of repeated deformation. In general, above the Tg the resin matrix becomes softer and more viscoelastic. Although the most dramatic property changes take place at the Tg, there are also significant changes in the matrix throughout its useful temperature range. For example, consider the graph on the following page of stress versus strain for TFE for various temperatures.

Consider next the effect on the stress-strain diagram of varying the strain rate. In general, increasing the strain rate makes the matrix appear more brittle by not allowing time for the creep and cold flow characteristics of the resin matrix to appear. Increasing the strain rate from one or two inches per minute to 10,000 inches per minute can double or triple the elastic modulus of the matrix and increase the yield point by as much as five times.[3] It should be apparent that increasing the strain rate eliminates the most undesirable characteristic of plastics, their viscoelastic nature. The graph on page 13 exhibits this fact. Due to the nature of plastics, therefore, stress-strain diagrams are of very limited use and often lead to erroneous conclusions. Even when stress-strain data are fairly reliable for a given application of plastic, it pertains only to static

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[3]Normal ASTM strain rates are 0.2, 0.5, 2.0, or 20.0 inches per minute.

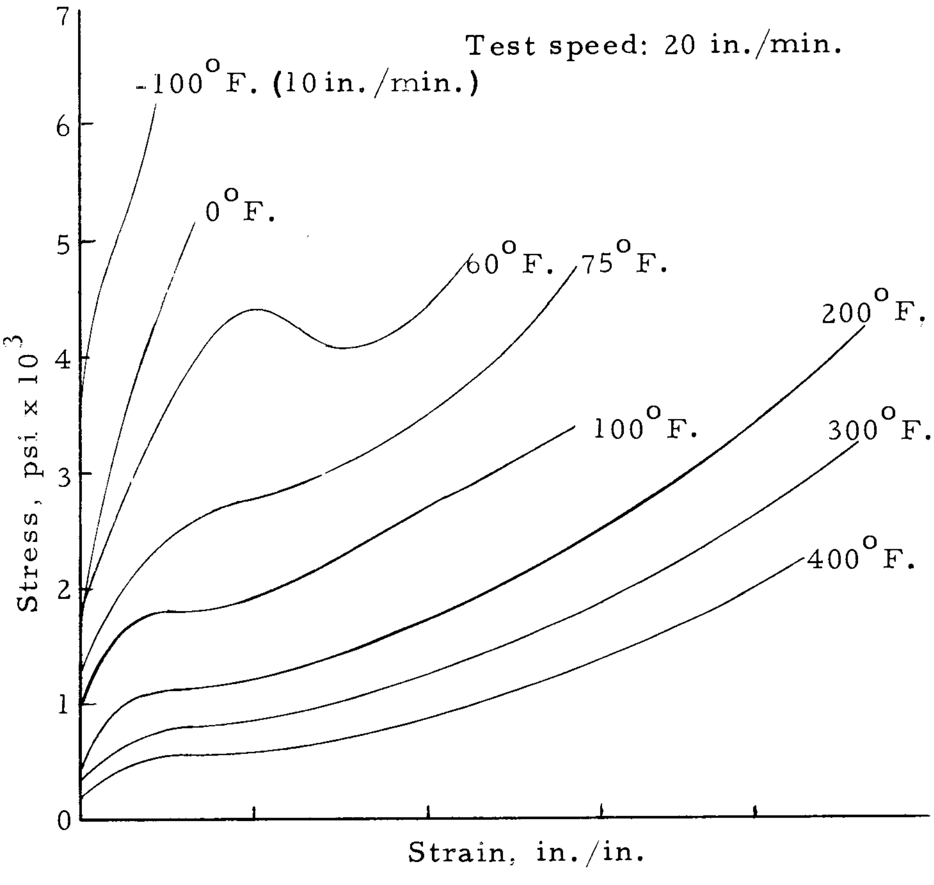

Figure 1. Effect of temperature on the stress-strain behavior of TFE-fluorocarbon plastics (Frados, 1965).

loadings. As will be shown shortly, creep tests, therefore, should be used to measure rigidity, creep rupture tests for strength, and dynamic tests for impact.

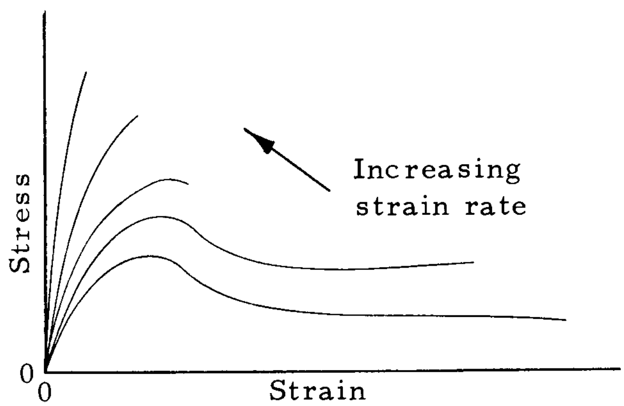

Figure 2. Effect of strain rate on the stress-strain behavior of a typical ductile polymer (Frados, 1965).

Creep rupture tests are made by stressing a plastic specimen to a high but constant degree and measuring the strain until rupture. Then the plastic is subjected to lower and lower stress values, each time measuring the strain until failure. With the data from these tests, graphs of what is called the apparent modulus versus time are made. The apparent modulus is defined as the applied original stress divided by measured strain at any particular time. This modulus, of course, will then vary according to the resin matrix used, the stressing time, the temperature of the matrix, and the value of the applied stress. With a complete set of this information, a designer, for a given material, temperature, and stress, will be able to determine the amount of deformation at any given time. Therefore, creep tests are much more relevant to design than are stress-strain tests. The creep tests reflect more accurately the actual behavior of plastics by considering their viscoelastic nature. In addition, the creep tests are more useful in that the appropriate apparent modulus obtained can be substituted into traditional engineering formulas without great error. Keep in mind that the elastic modulus as used in design of conventional materials such as steel is not the same as the apparent modulus that should be used for plastics.[4] Throughout the remainder of this thesis, if apparent modulus is meant, it will be so stated. Otherwise, any reference to elastic modulus should be considered to be that modulus obtained from a stress-strain test conducted under standard ASTM conditions.

Normally, creep tests are run to 10,000 hours, just over one year, and then extrapolated to either 100,000 hours or 50 years.[5] The extrapolation procedure is simplified by the fact that the apparent modulus versus time will usually plot as a straight line when plotted on log-log paper. For instance, see the graphs on the following page

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[4] Another empirical method for accounting for the time effects on strength is given in the Appendix.

[5] The 100,000 hour stress divided by a factor of safety is used as the design stress for calculating pipe wall thickness.

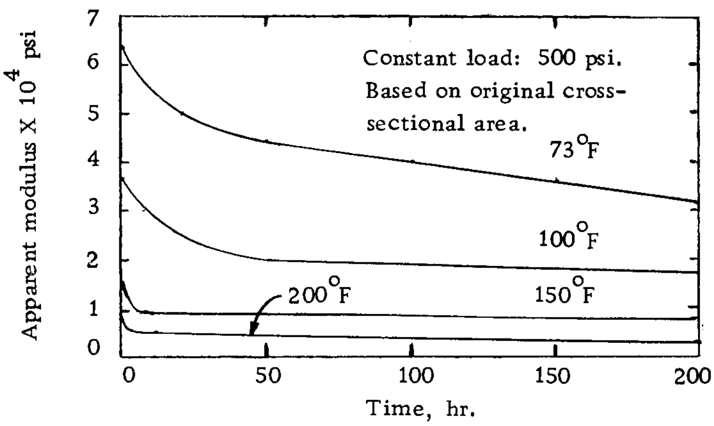

Figure 3. Tensile creep of TFE on a linear scale (Frados, 1965)

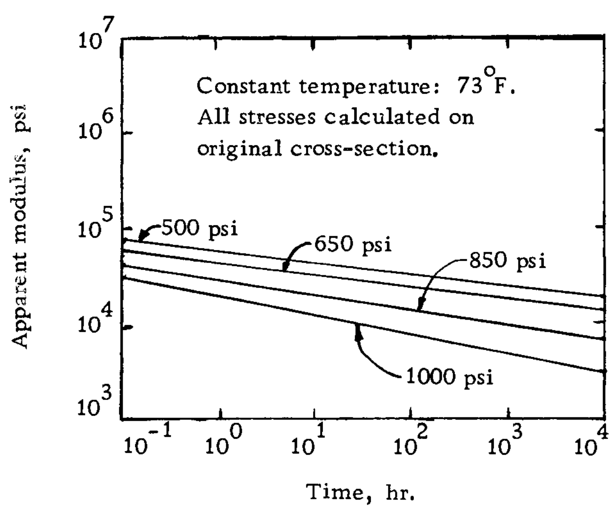

Figure 4. Tensile creep of TFE at various stresses (Frados, 1965).

taken from the 1966 edition of the Modern Plastics Encyclopedia.

As an illustrative design example, consider a weight that is to be suspended by means of a TFE rod.[6] It is desired to calculate the required cross sectional area of the supporting rod. Architectural considerations dictate a maximum strain after 10,000 hours of 0.02 inches per inch. The weight to be supported is 800 pounds and the rod will be subjected to 73°F. From the graph of apparent modulus, E_{app}, versus time for 73°F one finds that $E_{app} = 30,000\ \text{lb/in}^2$ for an assumed stress of 650 psi. Therefore,

$$\frac{\text{design stress}}{\text{allowable strain}} = 30,000 \frac{\text{lb}}{\text{in}^2}$$

$$\text{design stress} = 30,000 \frac{\text{lb}}{\text{in}^2} \left(0.02 \frac{\text{in}}{\text{in}}\right)$$

$$= 600 \frac{\text{lb}}{\text{in}^2}$$ (Therefore assumed stress of 650 psi is good)

$$\text{area of supporting rod} = \frac{\text{weight}}{\text{design stress}} = \frac{800\ \text{lb}}{600\ \text{lb/in}^2}$$

$$= 1.33\ \text{in}^2$$

Another important property of plastics related to creep is called stress relaxation. It is most important in regard to bolted

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[6] TFE is not a structural plastic but is being used in this example because creep test data are readily available.

connections as well as plastic sealing and gasketing. Data are therefore usually available in the form of compression stress relaxation although tensile data are also available. Stress relaxation is simply a decay of stress at constant strain, thus rendering a plastic unable to regain its former shape upon removal of forces causing the strain. This is often referred to as the "plastic taking a set."

Finally, in any discussion on the structural characteristics of plastics, mention should be made of the effects of environment. Temperature effects have already been mentioned, but there are other effects due to ultraviolet light and moisture. Ultraviolet light causes a slow reaction in plastics that results in darkening of the lighter colored plastics and a general degradation of all properties. Likewise plastics absorb moisture resulting in a degradation of their properties. Some plastics such as nylon are severely affected by moisture absorption. In most cases, the effect of environment on plastics is significant enough to require attention. In fact, with addition of carbon black sun protection coating on wires exposed to a Florida climate, wire life increased from six months to over 18 years (Quackenbos and Samuels, 1967). The only way to predict the effect of environment on a plastic is by test or experience. The American Society for Testing and Materials (ASTM) has a series of tests to provide this information. They have established an outdoor weathering test (D1435), an accelerated weathering test (E42), an Atlas type fadeometer test (FDA-R), an environmental stress cracking test (D1693), and a water absorption test (D570). There are many plastics producers as well that conduct the same tests on their products. This is not a complete list of the available tests, but it covers the more significant ones.

Additives

Up to this time the writer has been discussing only the resin matrix. This is plastic in its simplest form and yet its viscoelastic nature still makes design rather complicated. However, the matrix by itself is, in general, a poor material for structural uses. When its strength is adequate, it is too brittle, and when ductile enough to absorb a dynamic load, it is too weak. Consequently, various materials called additives are combined within the matrix to improve its properties, thus giving plastic its composite nature and greatly complicating design.

For the purposes of this thesis, additives will be broken down into three classes: reinforcements, fillers, and others. Reinforcements are used exclusively to strengthen the matrix. Fillers, although they may add strength to the matrix, should not be considered reinforcement. Rather their purpose is to improve characteristics such as chemical resistance, heat resistance, ultraviolet light degradation, and others. In the class designated as "others", will be stabilizers, colorants, and catalysts.

Beginning with this latter class, each of the three types of additives will now be considered. A stabilizer "is a chemical substance added to the base resin to increase chemical stability and durability of the base resin," (U.S.D.O.D., 1965). Colorants are merely dyes added to the matrix for color effects, and catalysts are chemicals added to the base resin to accelerate reactions.

Many additives fall under the designation of fillers. For a summary of the more important fillers and the properties they impart to the resin, see the next page, reproduced from the 1967 edition of <u>Modern Plastics Encyclopedia</u>. Some of these fillers are plasticizers which are substances added to the resin to impart ductility, flexibility, and workability. Others are merely substances to reduce the density of the matrix while giving the resin something to bond to, thus increasing the strength. But a more important type of filler are flame resistant additives.

Since all plastics are organic in nature, they will burn, just as wood. It is partly because of this that building codes have been very restrictive on the use of plastics even though this problem can be almost totally overcome by proper additives or coatings. The additives are of two types, those which are blended physically with the matrix and those which are reactive and unite chemically with the matrix becoming an integral part of the plastic. Fire protection coatings are

Table 1. Properties Imparted to Resins by Various Fillers and Reinforcements.

Filler or reinforcement \ Properties improved	Chemical resistance	Heat resistance	Electrical insulation	Impact strength	Tensile strength	Dimensional stability	Stiffness	Hardness	Lubricity	Electrical conductivity	Thermal conductivity	Moisture resistance	Processability	Recommended for use in
Alumina tabular	X	X				X								S/P
Alumina trihydrate, fine particle			X				X					X	X	P
Aluminum powder										X	X			S
Asbestos	X	X	X	X		X	X	X						S/P
Bronze							X	X		X	X			S
Calcium carbonate		X				X	X	X					X	S/P
Calcium metasilicate	X	X				X	X	X				X		S
Calcium silicate		X				X	X	X						S
Carbon black		X				X	X			X	X		X	S/P
Carbon fiber										X	X			S
Cellulose				X	X	X	X	X						S/P
Alpha cellulose			X		X	X								S
Coal, powdered	X											X		S
Cotton (macerated/ chopped fibers)			X	X	X	X	X	X						S
Fibrous glass	X	X	X	X	X	X	X	X				X		S/P
Fir bark													X	S
Graphite	X				X	X	X	X	X	X	X			S/P
Jute				X			X							S
Kaolin	X	X				X	X	X	X			X	X	S/P
Kaolin (calcined)	X	X	X			X	X	X				X	X	S/P
Mica	X	X	X			X	X	X	X			X		S/P
Molybdenum disulphide							X	X	X			X	X	P
Nylon (macerated/ chopped fibers)	X	X	X	X	X	X	X	X	X				X	S/P
Orlon	X	X	X	X	X	X	X	X				X	X	S/P
Rayon			X	X	X	X	X	X						S
Silica, amorphous			X									X	X	S/P
Sisal fibers	X			X	X	X	X	X				X		S/P
TFE-fluorocarbon						X	X	X	X					S/P
Talc	X	X	X			X	X	X	X			X	X	S/P
Wood flour			X		X	X								S

P - in thermoplastics only; S - in thermosets only; S/P - in both thermoplastics and thermosets.

also of two types, intumescent and non-intumescent. The intumescent coatings decompose when heated and form a protecting foam which results in an ASTM flame spread rating of 10-20 which is considered noncombustible. This type of coating is less expensive than the additive types but will not cover well and has poor hydrolytic stability. The non-intumescent coatings are less effective than the intumescent having a flame spread rating as high as 80, but are easier to apply and have better hydrolytic stability. As an example of the need for fire protection of some sort, the writer subjected a sample of Acrylic plastic, which is used extensively for skylights and windows due to its transparent nature and excellent weatherability, to the heat from a match. Almost immediately, the plastic caught fire, burning with a vigorous flame and giving off dark smoke and fumes. Such fumes could suffocate people in a building containing much of this burning plastic. When the match was removed from the Acrylic, it continued to support combustion. Again ASTM has several tests to measure flame spread and combustibility.

Other important fillers are the ultraviolet light absorbers. Examination of plastics in the field lead to the following conclusions:

> Some plastics have inherent weatherability and have exhibited no significant degradation over long periods of time...those that are inadequate can be made adequate by light 'screens', ultraviolet light absorbers, and antioxidant compounds that arrest the effects of oxygen. Special protective finishes, copolymerization, and cross-linking can be used in some circumstances. (Quackenbox and Samuels, 1967).

A carbon black protective covering works better than the best ultra-violet light absorbers, sometimes increasing the life of the plastic from six months to over 18 years as has been mentioned. However, this operation of coating is expensive and restricts the color of the plastic to black. Also, the black covering absorbs heat. In general, there is a great deal that is not known about the variables in weathering preformance.

The final type of filler that the writer will discuss can also be very necessary. It is the antistatic additive. Again, there is very little known about electrical conduction in organic compounds. Plastics are very poor conductors and, as a result, electrical charges build up. Some experts feel that the static charges are a surface phenomenon, whereas others believe it is a buildup of static charges throughout the volume of the plastic. One fact that is known is that these charges cause trouble and their intensity is related to the composition and shape of the plastic, climatic conditions, and the physical contact with other objects and the air. Plastics at rest are affected as well as plastics in motion. When the plastic is at rest, the charges can attract and hold dust causing a maintenance problem. Plastics in motion are mainly a manufacturing problem and involve charges of a much higher magnitude than plastics at rest. Problems that result here may be improper film-to-machine alignments, severe shocks, fires, and even explosions. The solution to these problems is either to install devices to remove static electricity or slow the speed of production, neither of which is very economical, or add antistatic additives. Such antistatic additives have been used for years as a surface coating, but they rub or wear off. More recently, internal antistatic additives have been used. The earliest ones were long-chain aliphatic amines, phosphate esters, or ammonium salts and were used in quantities of 0.5 to 1.5 parts per 100 parts of resin. Today we are using polyethylene glycols, polyethylene glycol esters, and ethoxylated long-chain aliphatic amines in quantities of 0.1 to 0.2 percent. The development of effective antistatic additives has been slow due to the lack of accurate reproducible testing methods. It is widely believed, however, that these shortcomings will soon be eliminated and the future development of antistatic additives will be more rapid (Frados, 1965).

The next and final type of additive to be considered are the reinforcements. There are a multitude of materials currently being used for reinforcement, and there is exciting research being conducted at present on new types of reinforcements. Some of the more exotic products of this research will be considered in a later chapter of this thesis. For now, the discussion will be restricted to the more familiar reinforcement materials such as fiberglass and some of the problems that are pertinent to such fibrous reinforcements.

Fiberglass is, and has been for several years, the most often used reinforcement for plastics that are to serve as an engineering material. It is used extensively in the air for rockets, missiles, and airplanes, and used on the ground for buildings and automobiles, and it is used on and under the sea for boats, ships, and marine structures. Obviously, fiberglass reinforced plastics must have some very important attributes. Most important, it is very easy to fabricate and the fabrication method can be selected to fit production needs. It permits a wide range in the choice of geometry and allows ribs and stiffeners to be added at critical points without difficulty. Also it has a short term ultimate strength of from 10,000 psi to over 200,000 psi with a modulus of elasticity of from 0.5 to over seven times 10^6 psi. It has a low weight of about 100 lb/ft^3, has good corrosion characteristics, and can provide good insulation. Then too, it is not an expensive reinforcement. But as widespread as the use of fiberglass for plastic reinforcement is, it will soon begin to provide a smaller percentage of the structural plastics. For today there are much more structurally superior reinforcements, some of which are already in production, whose only disadvantage is that they are temporarily expensive. Why even mention fiberglass reinforcement then in a thesis concerned mainly with the present and future? Because, like fiberglass, many of the newer reinforcements are fibrous in nature and much can be learned from fiberglass concerning design considerations for other fiber reinforced materials. One might think that plastic is a composite material similar to reinforced concrete. Why not design reinforced plastics just as reinforced concrete? This has been attempted using transformed section theory and found to be inadequate. Although the reason is not clearly understood, it is believed that the poor performance of transformed section design theory, when applied to plastics, is due to the unpredictable strength of each glass reinforcing fiber. These fibers are produced by drawing, steam blowing, or air blowing, and when tested for strength, give a wide scatter of results. This problem is compounded when one considers the relatively more important role reinforcement plays in plastics than in concrete. For example, the ratio of modulus of elasticity of the reinforcement to the matrix is 20 or greater for fiberglass reinforced plastics and lies between six and 15 for reinforced concrete (Chambers, 1966). Also reinforcing steel for concrete provides only a few percent of the total cross sectional area of a concrete member. Yet for plastics, the glass may cover from 10 to 90 percent of the area.

How then should one design reinforced plastics? Well, the answer is not yet fully prepared. Richard E. Chambers (1966) of Simpson, Gumpertz and Heger Inc., consulting engineers, makes some pertinent observations on the behavior of fiberglass reinforced laminates and these will now be reviewed.

Consider a unidirectional laminate. This may be produced by either filament winding a structure or by laminating sheets of a non-woven unidirectional fabric. With the extreme differences between the properties of the resin matrix and the reinforcement, one might expect the properties of the unidirectional laminate to vary when stressed at various angles. Indeed, when the laminate is stressed parallel to the warp[7] it exhibits properties similar to the reinforcement and when stressed in a direction parallel to the fill, its properties resemble that of the resin matrix. As mentioned, it seems, that for a unidirectional laminate one could design on the basis of the transformed section. The writer has mentioned several reasons why this method cannot be accurately used. But, at any rate, such laminates are of limited use having only one direction of strength.

Bidirectional laminates, on the other hand, have two directions of strength and are analogous to plywood. For this case, the use of the transformed section becomes even more inadequate for two reasons. First, the existence of transverse fibers restrains normal Poisson expansion. Secondly, in woven fabrics such as are used for bidirectional laminates there is a serious problem of fiber crimp. These cause hidden stress discontinuities that greatly weaken the composite.

There is another interesting characteristic of bidirectional

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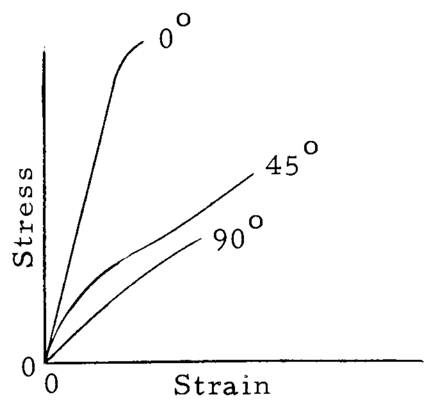
[7]Warp is the main reinforcement and fill is the reinforcement perpendicular to it.

laminates: when stressed in either direction of warp or fill, they exhibit an abrupt change in elastic modulus resulting in a bilinear stress-strain diagram. The reason for this is unknown, but some believe it is due to stresses arising in the transverse fibers that eventually crack the matrix changing the modulus instantaneously.

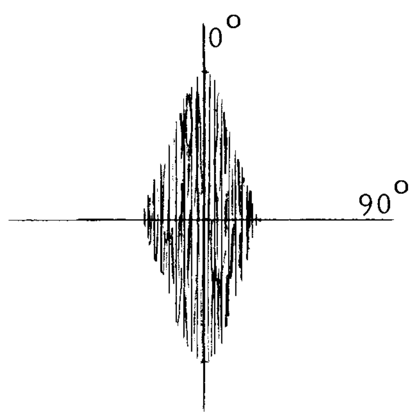
Finally, there are isotropic laminates composed of mats of randomly placed chopped glass fibers. As would be expected, the composite has isotropic properties within the plane of the mat. Design for the mat system becomes even more complicated than for the bidirectional laminates in spite of its isotropic nature. Because of the complex nature of the bonding between the random fiber and the matrix, properties are hard to predict. In general, the isotropic laminate will exhibit more of the properties of the matrix than either the unidirectional or bidirectional laminates. This is because the random orientation of the fibers will not allow tight packing and the resin content is consequently higher.

Thus far in the discussion of the properties of reinforced plastics, the writer has been concerned with tensile properties. However, the laminates will have the same general properties in compression except that the compression modulus will be slightly lower than the tensile. This is probably due to buckling instability of the fibers.

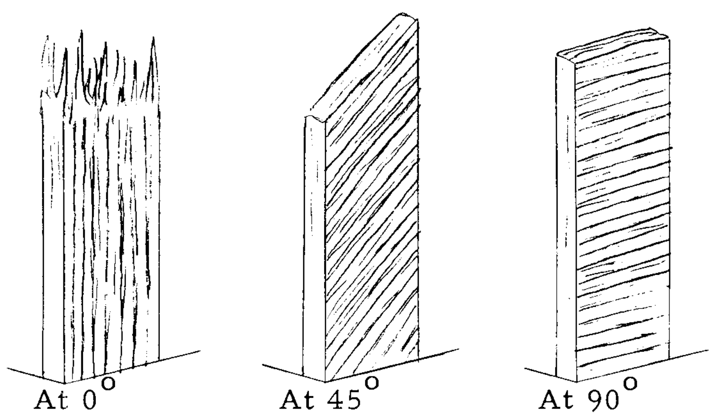
Laminates in flexure will also possess many of the same



Stress vs. strain at various angles.

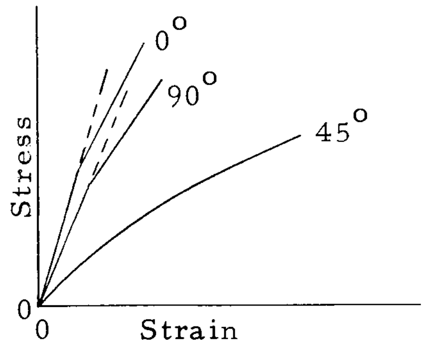


Variations in properties with angle to warp.

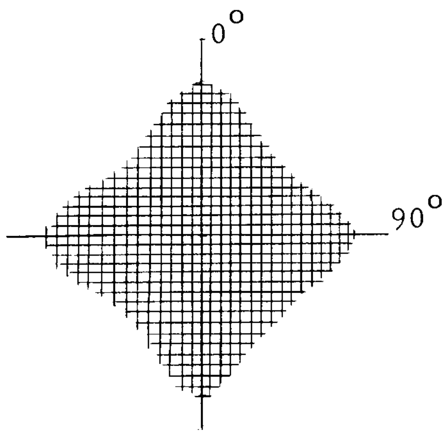


Tensile fracture characteristics.

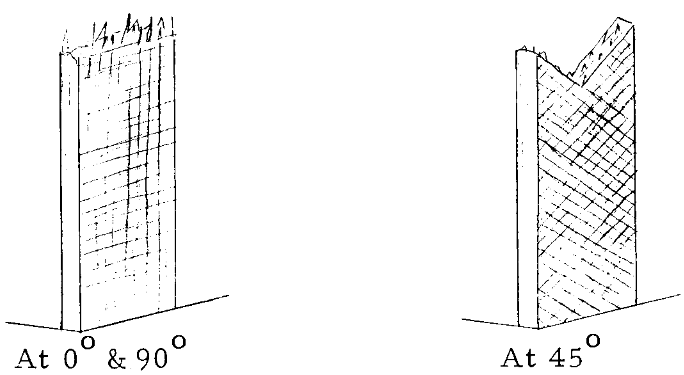
Figure 5. Effect of varying the angle between the direction of stress and warp for unidirectional laminates (Chambers, 1966).



Stress vs. strain at various angles.

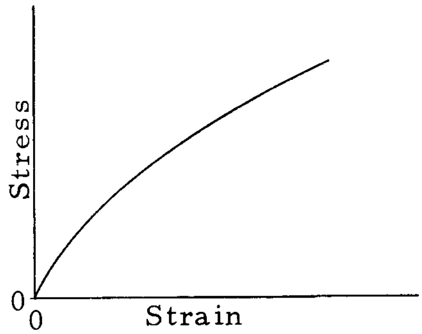


Variations in properties with angle to warp.

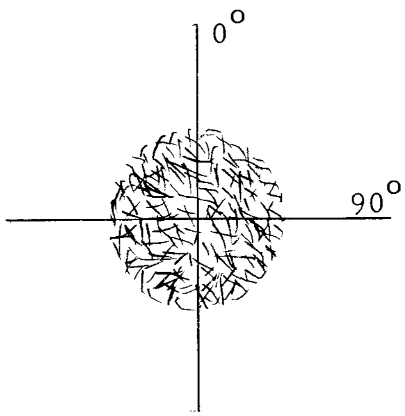


Tensile fracture characteristics.

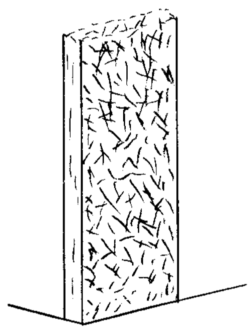
Figure 6. Effect of varying the angle between the direction of stress and warp for bidirectional laminates (Chambers, 1966).



Stress vs. strain at any angle.



Properties independent of angle of stress.



At any angle

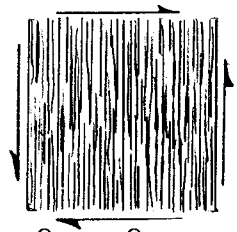
Tensile fracture characteristics.

Figure 7. Effect of varying the angle between the direction of stress and warp for isotropic laminates (Chambers, 1966).

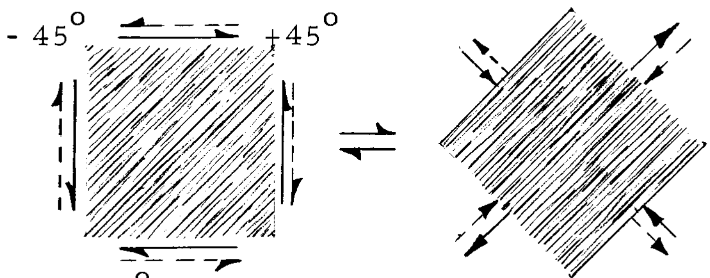
qualities as those in tension. Often the modulus in flexure is given as lower than either the compression or tensile modulus. But Chambers (1966) states that he has proven this phenomenon to be a reflection of the test method (ASTM or Military) and that the actual flexural modulus is the average of the tensile and compression moduli. He goes on to state that the low modulus of flexure usually reported neglects a shear deflection in the test member that can and should be accounted for. This shear deformation can be conservatively accounted for, according to Chambers, by conventional shear formulas using the shear modulus of the resin.

Shear characteristics of a composite are very important and are often critical in a structure. Yet it is a subject seldom considered in the literature. Shear, as discussed in this thesis, is defined as that shear which exists in the plane of the laminate. Similar to tensile and compression characteristics, shear properties also vary according to the direction and placement of reinforcement. It is therefore important when designing a reinforced plastic structure to consider the relationship between applied shear stresses and the direction of reinforcement. The diagrams on the following pages summarize Chambers' (1966) work in this area for unidirectional, bidirectional, and isotropic laminates.

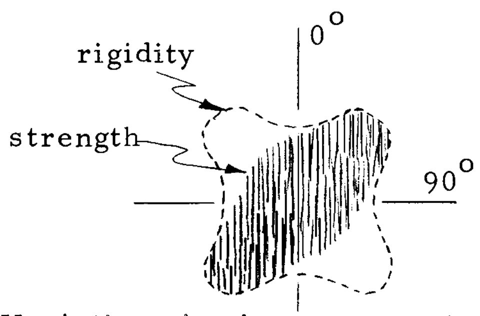
Knowing now that shear effects must be considered when designing, one beings to examine the quality of shear strength data available



Shear at 0° & 90° permits sliding parallel to warp.

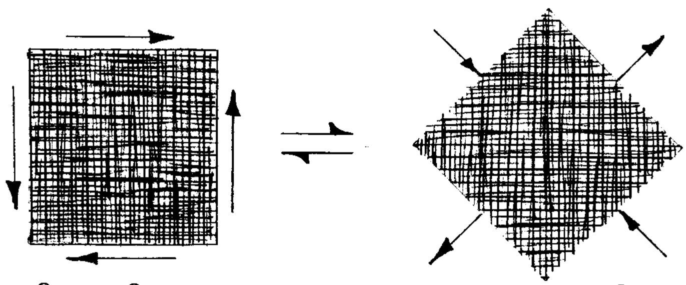


Shear at + 45° causes compression across grain.
Shear at - 45° causes tension across grain.

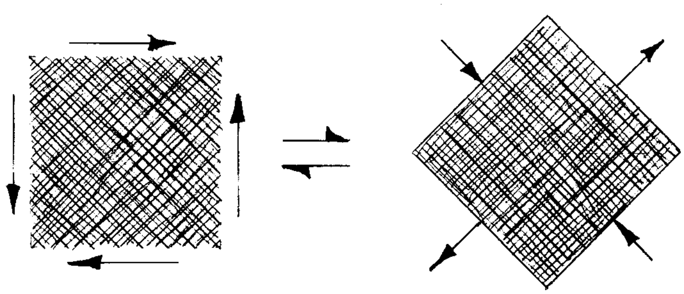


Variations in shear properties with angle to warp.

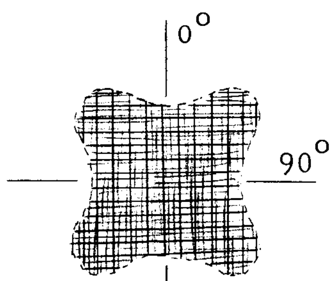
Figure 8. Effect of varying the angle between the direction of in-plane shear stress and warp for unidirectional laminates (Chambers, 1966).



Shear at 0° & 90° causes direct stresses at 45° to act on bias.

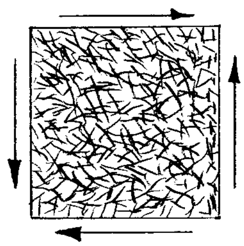


Shear at 45° causes direct stresses to act in direction of fibers.

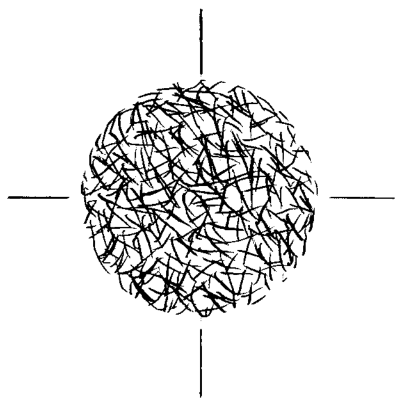


Variations in shear properties with angle to warp.

Figure 9. Effect of varying the angle between the direction of in-plane shear stress and warp for bidirectional laminates (Chambers, 1966).



Random fibers are effective at any angle.



Shear properties do not vary with angle of stress.

Figure 10. Effect of varying the angle between the direction of in-plane shear stress and warp for isotropic laminates (Chambers, 1966).

for the material in question. A word of warning here. Many of the more accurate shear tests are also complicated and tedious. As a result, some agencies, including ASTM, use a punching type of shear test which is simply not representative of the shear found in flexural members.

Chambers (1966) claims that there is substantial evidence that shear strength can be calculated from tensile test data, thus eliminating the difficult shear test. He presents the following formula:

$$\frac{1}{F_{\alpha\beta}^2} = \frac{4}{F_x^2} - \frac{1}{F_\alpha^2} - \frac{1}{F_\beta^2}$$

where

$F_{\alpha\beta}$ = shear strength with shear stress applied parallel and perpendicular to the warp.

F_x = tensile strength at 45° to warp.

F_α = tensile strength parallel to warp.

F_β = tensile strength perpendicular to warp.

The information gained from this formula can be used in place of the shear test.

It should be noted at this point that fiberglass-reinforced plastics are not overly sensitive to stress concentrations. This fact may be surprising in view of the brittle nature of the stress-strain diagram, but it can be explained by the occurrence of local microfracture.

That is, at the tip of a propagating crack, local microfracture of the glass fibers takes place. The energy absorbed by the breaking of these fibers allows stress concentrations to redistribute. Of course, in planes of little or no reinforcement, stress concentrations can do severe damage to the resin matrix.

This completes a brief discussion on some of the points to watch for when designing fiber-reinforced plastics. Several aspects of actual design have been mentioned, but thus far there has been little mention made of the serious problem of obtaining reliable test data for design. It is this problem that has led so many designers in the past to produce unsuitable plastic parts, and as a direct result, plastics have a poor reputation.

Difficulty of Obtaining Reliable Test Data

Tests in common use today for determination of the properties of plastics under load are simply not adequate. Often the tests used are the same tests as are used for metals; but plastics are a much more complicated material than metals. The behavior of plastic composite as well as the condition of actual stress in the plastic is extremely complex; and it is this complex nature that makes simple traditional tests inadequate. Rather, all tests should consider the effects of time, temperature, and rate of loading. Efforts should be made to measure rigidity, and creep tests should be made rather than stress-strain tests. There should be a greater effort to match the test conditions with the end use of the product. Also there is a great need for more control over fabricating variables. For example, the rate of cooling can affect the degree of crystallinity, and variation in temperature, pressure, or type of molding can affect degree of cure. "Often a manufacturer can produce a thousand good items from a mold and from the next plastic shipment, he cannot produce one satisfactory one" (Millard, 1967). When asked what was the major difficulty of producing structural plastics for Boeing's airplanes, Bud Cole (1967) said "quality control". There were no major problems with the plastic itself; rather, the problems stemmed from errors made by people in the hand-lay-up operations. One suggestion (Frados, 1966) is to use specific gravity measurements to control such fabrication variables. Finally, there is a need for greater standardization of test procedure.

The tests in use today consist of mechanical, thermal, optical, permanence, analytical, and electrical tests. Of these, the mechanical tests, which provide critical strength data, are probably the poorest. For example, an elastic modulus and ultimate fiber stress for a material are derived from traditional engineering formulas and a flexural test consisting of a bar loaded symmetrically as a simple beam. Such a test neglects creep effects and the fact that such engineering formulas are valid only for small strains.

Compression tests are conducted, but the results depend greatly upon the geometry of the test specimen. And of course, the time-honored tensile tests are conducted.

From these tensile tests, rigidity is supposedly measured by the slope of the stress-strain curve; strength is measured as the yield point; ductility is measured as the strain at rupture; and the energy required to break the specimen is measured as the area under the stress-strain curve. Yet all of these tests neglect the viscoelastic properties of the plastic and the many factors that have been discussed, such as temperature and strain rate, which affect these properties.

Also consider the mechanical testing of resistance to impact. This is extremely difficult to test accurately because it is affected by such matters as the existence of stress concentrations at corners and defects, the geometry of the striker, the thickness of the test specimen, the shape of the specimen with respect to the location of impact, and the sensitivity of specimens to the fabrication variables that have been mentioned. But in spite of these difficulties, impact resistance is supposedly measured by one or more of several different tests: the Izod impact test, the drop test, the drop weight test, the tensile impact test, or the high speed stressing test. Of these, the Izod pendulum test is the most common and perhaps the poorest.

The Izod test consists simply of a falling pendulum which reaches a maximum velocity of 800 inches per minute at the bottom of its swing just prior to impact. The impact resistance of the specimen is measured by the height of swing following impact. Such a test has the following limitations: it is a single speed test, it allows plastics to fail in a great variety of ways, and it favors materials that are soft and ductile or fibrous in nature. For such ductile or fibrous materials, the energy of the pendulum is consumed in stretching the material or tearing loose fibers after failure. The materials which break cleanly are penalized by such a test. That is, a material that breaks cleanly may have an Izod impact resistance rating of 1.0 ft. lb. per inch of notch whereas a fibrous or ductile material may have the superior rating of 1.5 ft. lb. per inch even though the fibrous material may have failed structurally, for all practical purposes, after consuming only 0.9 ft. lb. per inch of energy. The Izod test, therefore, should not be considered a reliable indicator of impact strength when comparing one plastic with another. Rather, the test is only useful when comparing the impact resistance of several grades of a particular plastic or when determining the notch sensitivity of a plastic.

Probably the best of the impact tests is the high speed stressing type of test, since impact resistance is actually a measure of the ability of a material to absorb energy at high speeds of stressing. It has advantages in being able to control the testing speed and produce data in the form of stress versus time graphs. It has disadvantages in that it is an expensive test and that many plastics are sensitive to a particular loading rate. One may say, in general, that although impact resistance can be given to plastics, it cannot be adequately measured as yet.

Consider next the difficulty of obtaining adequate shear strength data. The writer has mentioned the poor nature of punch type tests and the use of a formula to calculate the shear stress from tensile test data for laminates, but Goldenberg, Arcan, and Nicolau (1959) have devised a more suitable method of shear testing. These men felt that the problem with conventional shear testing consisted of four parts: one could not be certain that the deformation occurring during testing was due exclusively to shear forces; one did not know that the system of stresses resulted in pure shear at the required cross section; the shear may not be uniformly distributed over the cross section, resulting in stress concentrations; and the test may not give results that can be equally well interpreted in all practical cases in which the material is subjected to shear stress. Also, the shape of the proposed specimen must allow the shearing stress to be distributed uniformly across the failure plane by loading with two equal and opposite forces in such a manner that a third stabilizing force is not required. Goldenberg, Arcan, and Nicolau (1959) devised several excellent shapes, but one of the best was the "S" shape. This was loaded at the rate of 150 mm per minute and found to have good results. It should be noted that their tests resulted in 20 percent higher stresses than the standard ASTM shear test for the same material. The "S" shape test has at least four advantages over the standard ASTM test: at the failure cross-section, nearly pure shear occurs; the stresses are uniformly distributed across the failure zone; the shape is easily made and tested in standard machines; and the test specimens can be quickly tested. The following page presents a sketch of the isostatic lines for such a test. The sketch was made of a photograph from the article by Goldenberg, Arcan, and Nicolau (1959).

Considering some of the faults mentioned for present day methods of testing, one is somewhat discouraged with the poor quality of data available. But considering the complexity of the material, the data is not too poor. For instance, one would expect that before a meaningful test is derived, a thorough knowledge of the failure mechanism should be obtained. Yet for plastics, specifically reinforced plastics, this is not available, according to Victor G. Grinius, senior research engineer for Whittaker Corportation.

> The prediction of tensile strength and mode of failure for a fiber reinforced composite appears to be a simple problem at first. However, reported theoretical studies have not been completely successful in describing the behavior of even the simplest, unidirectionally reinforced composite configurations (S.P.I. R.P.D., 1967).

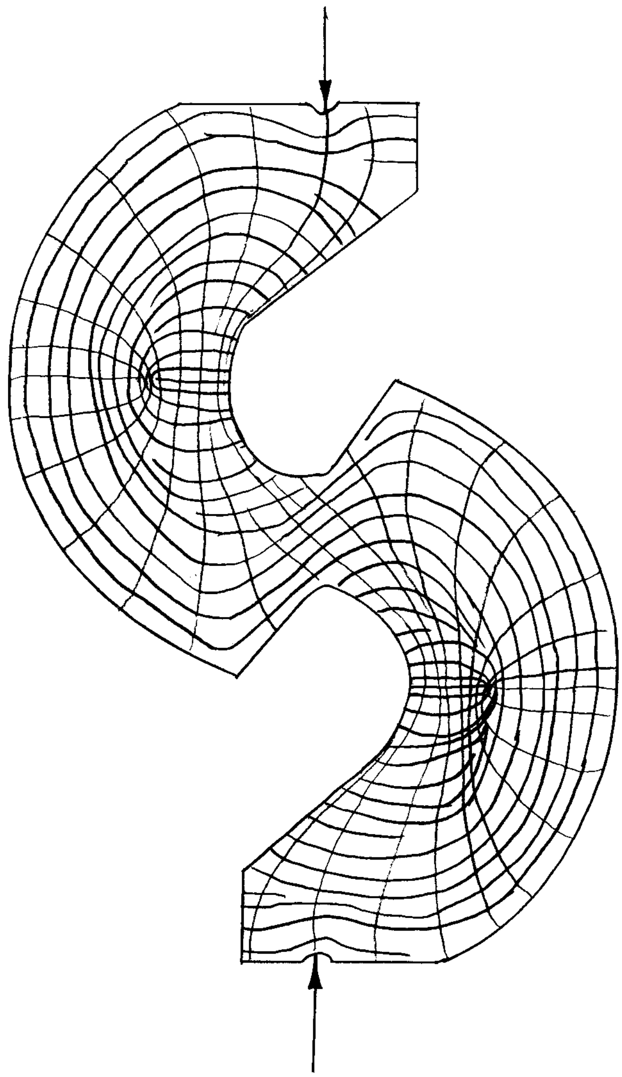


Figure 11. Pattern of isostatic lines showing 45 degree intersection in shearing zone (Goldenberg, Arcan, and Nicolau, 1959).

For reinforced plastics, the problem of determining the failure mechanism stems from the complicated nature of the combined failure of reinforcement and resin matrix. For unreinforced plastics, the problem would not seem as great; yet, due to the anisotropic nature of extruded, formed, or molded plastics, the validity of test data is still in question. For example, consider a plastic part formed by injection molding. As the polymer is injected into the mold cavity through a restricted opening, the molecules are subjected to shearing stresses which tend to orient them. With the long-chain molecules oriented, the strength properties become highly dependent upon the attitude of stress with respect to molecular orientation (Högberg, 1959). Hilding Högberg, head of the plastics laboratory for the research division of L.M. Ericson Co., Stockhom, Sweden, has conducted some interesting tests in this area. Although the problem exists mainly in non-structural thermoplastics, it is interesting to note that residual stresses from the molding operation can cause creep problems with no externally applied loads. Also, if some plastics with significant residual stresses are etched with mild acids, they can literally explode when the strength of the plastic has been eroded to the point where it can no longer support the "frozen-in" stresses.

The writer has spent some time discussing the properties of plastics, and the reader should now have some idea of the complexity of design. Indeed, the field of design is very new to plastics and has a long way to go, but the writer will now mention some of the design methods being currently used and some recent contributions to this field.

DESIGN AS IT IS DONE TODAY

Code Problem

Any article written about engineering design in the U.S.A. must also include a section on building codes, for the codes in the U.S.A. have a reputation of being conservative and limiting design freedom. Their strict nature has often hindered and even prohibited true engineering design. For plastics, this is especially true, as all U.S.A. building codes have traditionally been specification type codes. Such codes often prohibit the introduction of new materials that may prove to perform adequately.

Until the mid-fifties, the plastics industry was not producing enough structural plastics to cause concern. But shortly thereafter, the industry found it was restricted by code barriers. Sometimes a plastics producer would confront the local code officials and have his product approved. Then another producer would approach the same officials with an entirely different type of plastic for approval. Soon the building officials were completely confused, and understandably so.

In 1955 the SPI Code Advisory Committee was formed. Until this time, the Basic Building Code of the Building Officials Conference of America was the only principal building code that even mentioned plastics and it did not offer significant help.

In 1956 the SPI Code Advisory Committee, in conjuction with the Plastics in Building Committee of the Manufacturing Chemists Association, produced a booklet entitled "A Model Chapter on Plastics for Inclusion in a Building Code." From this time on, in their treatment of plastics, the codes have been slowly changing from specification to performance type codes.

Below, are the four main reference codes in America with their sponsors (Perrine, 1966).

1. National Board of Fire Underwriters (NBFU) - National Building Code (NBC).
2. International Conference of Building Officials (ICBO), formerly Pacific Coast Building Officials Conference - Uniform Building Code (UBC).
3. Building Officials Conference of America (BOCA) - Basic Building Code and Abridged Building Code (BBC) and (ABC).
4. Southern Building Code Congress (SBCC) - Southern Standard Building Code (SSBC).

As a result of the slow development of these codes in comparison to the development of plastics, most of the outstanding achievements in the plastics field have occurred either in countries outside the U.S.A. or in regions bounded by very local, liberal, and temporary codes such as existed at the World Fair Sites.

Commonly Used Methods of Design

As a result of inadequate building codes, the newness of the plastics industry, the scarce and confused condition of design data, the complex nature of proper design techniques, and the often misleading results obtained from available design data, there is very little true engineering design of plastics being done today.

The writer interviewed five plastics producers or users none of which attempted to design plastics accurately. When asked how he handled the time-dependent nature of the elastic modulus of plastics, Jud Brummond, plastics engineer for Tektronix Inc. of Beaverton, replied that he usually raised the factor of safety and used conventional design equations. He stated that his company felt that the resulting decrease in material cost was not worth the time and expense of accurate design. Similarly, Bud A. Cole, general supervisor of the fiberglass development group for Boeing Aircraft Co., stated that when designing plastic parts for airplanes, even the much publicized SST, they used design stresses so low that the plastics behaved as an elastic material and there were no creep problems. Of course, prototypes were made and tested and if they performed poorly, the design could be changed.

Actually there is quite a lot of evidence that although not a precise method of design when applied to plastics, traditional design, with large factors of safety, provides completely adequate structures. Take, for example, the Monsanto House of the Future at Disneyland, California. This is a futuristic all-plastic dwelling. It was designed in the following manner: the designers selected a value of elastic modulus of 2×10^6 psi. This value was chosen "because values less than this would incur penalities with respect to weight, thickness of laminates, and fabricating operations" (Dietz, Heger, and McGavy, 1957). For reinforcement, 181 glass fabric was chosen. Then full size models were designed and fabricated according to traditional methods. These models were then tested. It was decided that although the models were structurally sound, the 181 fabric caused difficulties in lay-up and handling problems. So a woven roving fabric was chosen; models were constructed and tested; and the house was built. Today, about ten years later, the house is performing satisfactorily. There are now many all plastic experimental houses throughout the U.S.A., but each was built just as the Monsanto House, by traditional design methods with high safety factors, model testing, and finally actual construction. Such testing is expensive, but this, along with more lenient building codes, is how England built two 22 story and two 24 story buildings with extensive use of plastic wall panels[8] (Griffin, Teviotdale, and Smith, 1967).

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[8]The use of plastics reportedly resulted in a 50 percent savings in foundation costs.

There have also been many articles written in support of designing plastics according to conventional design equations, but all are based on numerous faulty assumptions. R. Darvas (1964) derives formulas for the design of foam core sandwich laminates assuming "that the materials are homogeneous and elastic, following Hooke's Law, and that Young's moduli...are known."

T.T. Chiao, head of engineering and development for Rock Island Fiber Glass Products Co. (1966) explains design procedures for filament wound structures. But he only considers one type of failure, that due to excessive internal pressure, and uses the low design stress value of $S = 200,000$ psi and the large factor of safety of $C = 12$. "The high value of C and the low value of S is to take into account the loss of glass fiber strength due to various handling and for long term performance" (Chiao, 1966).

M.E. Kenny (1966) presented extensive equation derivation with supporting test data on the "design and stress analysis for reinforced plastic road and rail transport tanks." He considered four types of failure: failure due to internal pressure; failure due to bending; failure due to torsion, twisting, or racking; and a composite failure of bending and torsion. His work involved deriving equations for theoretical stresses under an assumed loading, designing and fabricating a tank, and subjecting the tank to destructive testing. It should be noted that his equations were derived upon the following assumptions: "a layer of fiberglass is elastic and homogeneous"; "a layer of fiberglass is orthotropic and has different strength properties perpendicular to two orthotropic axes, which are the neutral axes of the material"; and "layers of a fiberglass laminate are connected by a material with infinite shear rigidity so that the dimensions of the fiberglass laminate are such that buckling will be eliminated." His results from testing did not quite agree with his design values and he concludes:

> The error between theoretical and experimental results can be attributed to errors in strain gauge readings and creep. But, probably, the largest error must be attributed to the fact that all theoretical calculations were carried out assuming normal elastic theories when in fact at such high stress readings the laminates were past the elastic limit and no account has been taken for stress distribution in the plasticity region (Kenny, 1966).

The writer could go on explaining methods for design of reinforced plastic shell structures (Heger, 1966) or reinforced plastic beams (Reitman, 1966, 1967). But the examples given of current methods of design of plastics indicate the general method in common use. That is, it is a method not for plastics at all, but for traditional materials that are homogeneous, isotropic, and elastic. Obviously, information obtained from such design methods, when applied to plastics, cannot be expected to yield reliable results but rather must be considered as useful approximations. Actually, homogeneous, isotropic, and elastic design procedure is fairly accurate for a large range of stresses when applied to some of the more rigid reinforced thermosetting materials, but are extremely poor for most thermoplastics.

Current Advancements in Design Procedure

In spite of the rather primitive state of current design methods, there are improvements constantly being made. The writer has already mentioned the use of the apparent modulus. This modulus should be used in design rather than an elastic modulus. But more recently, R. L. Alexander (1966) has presented a new concept in designing with materials that creep.

Basically, he stated that elastic materials are of two types, those that are linear and those that are non-linear. Likewise, viscoelastic materials can behave either linearly or non-linearly. This concept of linear and non-linear viscoelasticity can be explained in the following manner. Consider a material subjected to a specific stress, loading time, and temperature; it will deflect or deform a certain amount during the loading time. If the material is then subjected to the same conditions except that its stress is doubled, and the resulting deformation in the given time is also doubled, then the material is behaving linearly. If, on the other hand, the deflection were not exactly doubled, the material would be considered non-linear. Linear elastic materials are designed according to Young's modulus. R.L. Alexander maintains that linear viscoelastic materials should be designed with a modulus he calls the Boltzmann modulus. This modulus is explained by the graphs on the following page taken from Alexander's article. As can be seen, creep tests are run for various stress levels. Then modulus versus time is plotted for each stress level just as was done for the apparent modulus. For the stress levels of tests A, B, and C, the material is seen to behave linearly as their modulus versus time plots coincide. But for tests D and E, the material is non-linear. The graph of modulus versus time for tests A, B, and C defines the Boltzmann moduli. Using these moduli, one can design exactly as was done in the writer's example of design with the apparent modulus. The difference between the apparent and Boltzmann moduli is that the Boltzmann moduli are restricted to the linear regions of behavior. The apparent modulus, on the other hand, is not restricted to the linear stress zone, but is restricted to an arbitrarily set "modulus accuracy limit."

Obviously, the limits of linear behavior must be established for the Boltzmann moduli. Alexander does this by plotting isochronal lines, at various times, from the creep test data and developing an envelope of linear viscoelastic behavior.

Freund and Silvergleit (1966) have made a valuable advancement for design techniques in the field of fatigue. Generally, fatigue testing, which has not been done much in the past, is performed by

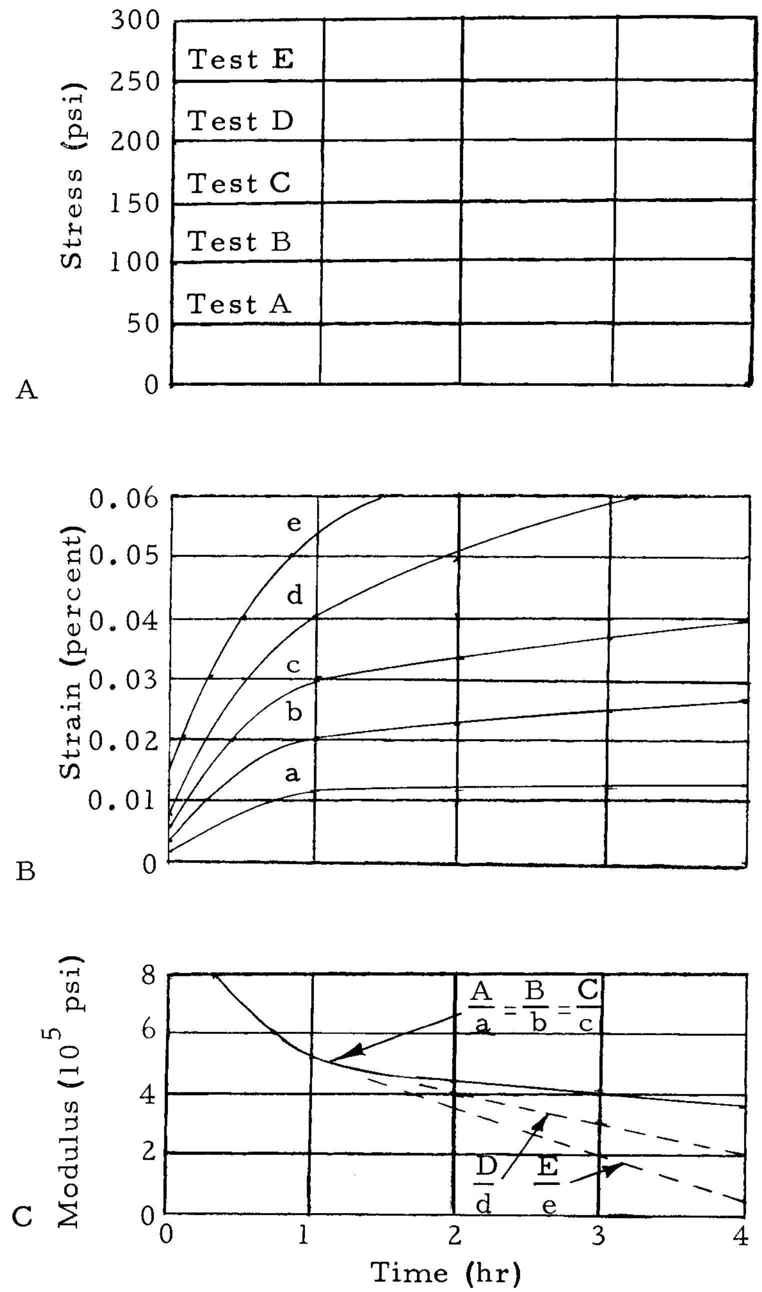

Figure 12. One method of determining the linear timedependent behavior of a material--a Boltzmann modulus--is to run several tests at various creep stresses. The common time-dependent moduli in creep (solid line in c) define a Boltzmann modulus (Alexander, 1966).

generating what are called S-N curves. These are curves of stress versus the log of the number of cycles to failure. Often it is possible to evaluate parameters such as frequency and fabrication variables by their effect on the S-N curves. Also, S-N curves make it possible to determine whether a material has an endurance limit. "The endurance limit is defined as the stress level below which a specimen will withstand cyclic stress indefinitely" (Frados, 1966).

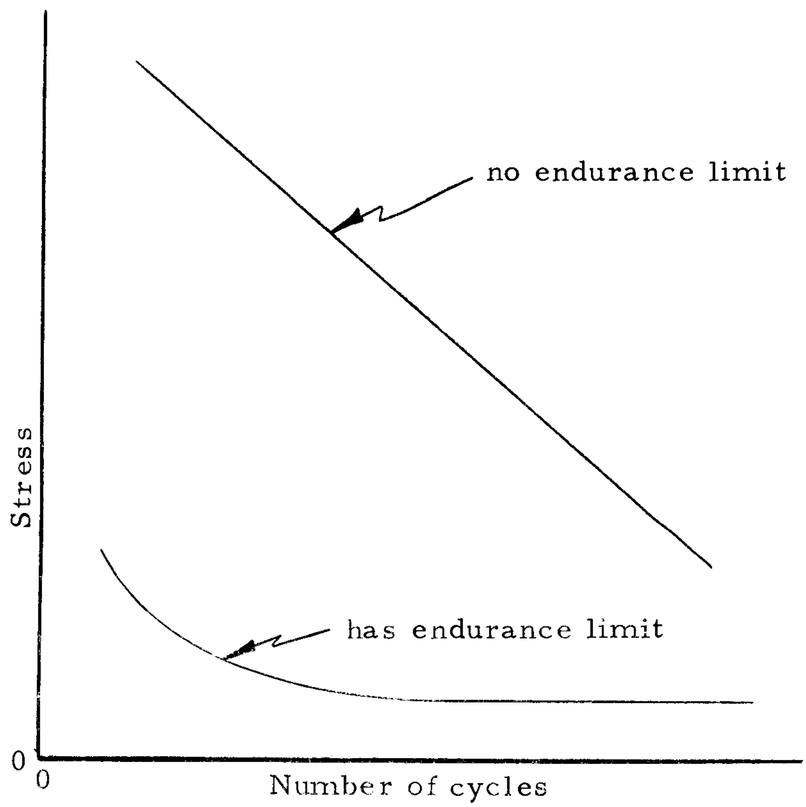

Figure 13. Typical fatigue test of plastic with and without endurance limit.

The work of Freund and Silvergleit is somewhat incomplete, but it may prove to initiate a new field of study. These men say:

> Based on an analysis of existing biaxial and uniaxial compression and shear fatigue data it is concluded that a 'percentage of ultimate' concept exists wherein the applied fatigue stress, as a percentage of true ultimate static stress, can be used in reliably predicting the fatigue life of fiberglass reinforced plastic material (Freund and Silvergleit, 1966).

Basically, this "percentage of ultimate" concept can be observed from the graph on the following page which is one of many such graphs presented by Freund and Silvergleit. Observe that the line drawn through the least number of cycles to failure, for each stress level, results in a rather regular curve. Tests have indicated that the regular nature of this curve exists regardless of the "test method, specimen fabrication, or specimen geometry." If a designer has access to such curves, it is a simple matter to predict a failure cycle for a given stress level. However, Freund and Silvergleit admit that the "predicting method is approximate since the true static stress is difficult to ascertain at present except by destructive testing." It should be noted that the true value of such a "percentage of ultimate" concept may soon be possible as there is current research being conducted on nuclear resonance techniques for nondestructive testing of reinforced plastics (S.P.I. R.P.D., 1967).

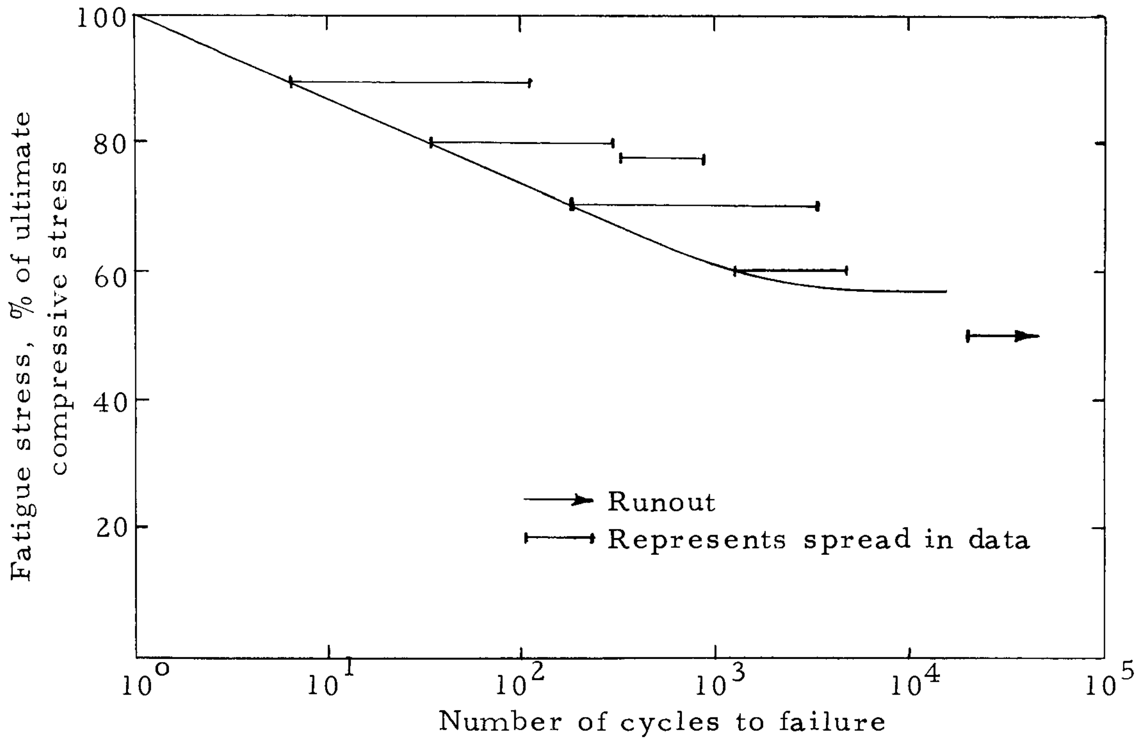

Figure 14. Fatigue stress as a percentage of ultimate uniaxial compressive stress versus number of cycles to failure (Freund and Silvergleit, 1966).

SOME MODERN DIVERSIFIED USES OF PLASTICS[9]

Foams

Thus far in this thesis there has been no mention of plastic foam. Perhaps this is an oversight as foamed plastics find some structural applications, expecially when used in sandwich panel construction. However, the field of foamed plastics is so broad that it cannot be adequately mentioned in a thesis of this scope. Let it suffice to say that foams can be used by cutting slab stock, pouring-in-place, frothing, and spraying; and the foams may be either of an open-celled or closed-celled structure. The most common use of foamed plastics is either for insulation or core material for sandwich construction or a combination of the two.

Aircraft

Structural reinforced plastics are now being used extensively in aircraft where their high strength to weight ratio is useful. Of the seven most recent airplanes that Boeing Aircraft Co. has either built or designed, the first, KC - 135, had only 100 square feet of structural sandwich; the next, 707 - 720, each had 200 square feet; then came the 727 and 737 which had 1,800 and 3,500 square feet

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[9] This chapter will mention some of the current structural uses of plastics.

respectively; now they are building the 747 which will have 8,000 square feet; and the proposed super sonic transport airplane, SST, will have approximately 14,000 square feet. These surfaces will compose radomes, fairings, closure panels, rudders, elevators, control tabs, leading wing edges, and wing panels. Each of these is composed of a particular combination of materials which best fit the requirements and then fabricated by a hand-lay-up procedure and cured in an autoclave. Most of the sandwich panels, however, are composed of "S" type fiberglass homeycomb cores impregnated with either epoxy or phenolic resin and covered with fiberglass skins also impregnated with the epoxy or phenolic resin.

The SST, though, will be provided with a highly heat resistant polyimide resin, the development of which was instrumental in allowing Boeing to win the government construction contract. (As a point of interest, the honeycomb glass core impregnated with polyimide resin costs approximately $1500. per cubic foot.) Wing panels for the SST will be constructed with an outer skin of titanium approximately 2.5 mm thick. This skin will be bonded to the fiberglass-polyimide honeycomb core of one inch thickness. The inner skin of the sandwich panel will be composed of a fiberglass fabric impregnated with the polyimide resin.

Plastic Impregnated Wood

There are currently two plants in the U.S.A. that are producing a new product which is essentially a wood-plastic alloy. The rather simple production process requires only an impregnation chamber, a pump, a pressure chamber, and a source of radiation. Actually there are several slightly different methods of obtaining the desired end product, but all are based on the process of impregnating wood with a monomer and then polymerizing the monomer to form immobile chain molecules within the wood fiber. The larger of the two U.S. plants uses radiation from a Cobalt 60 source to accomplish the polymerization (Barrett, 1967). Most of the physical property data are not yet available. However, Dr. Elwood at North Carolina State College and others are conducting research, the results of which will soon become available. In general, this remarkable material will have the following properties, taken from the April, 1966 issue of Plastics Design and Processing:

1. WPC[10] is up to several hundred percent harder than wood but retains the appearance of natural wood.
2. WPC is more mar, abrasion, and scratch resistant.
3. WPC is stronger and more durable than natural wood.

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[10] Wood-plastic composite.

4. WPC absorbs moisture more slowly, and hence is more resistant to warping and swelling.
5. WPC has increased compressive strength, improved static bending, and shear strength.
6. WPC has a hard, beautiful, satin smooth surface that accentuates the wood grain. Finish needs only sanding and buffing.
7. WPC can be sawed, drilled and turned in an ordinary manner.
8. WPC cannot be stained or surface treated except with finishes which adhere to plastic.
9. WPC cannot be nailed.
10. Screws can be used if pilot holes slightly larger than those used with untreated wood are drilled.
11. WPC can be drilled and tapped for machine screws.
12. WPC is heavier than natural wood with one pound of monomer used in every pound of treated wood.

It is easy to visualize this material becoming a very common material as it finds application in flooring, furniture, sporting equipment, house siding, and virtually all uses requiring wood subjected to weathering or abrasion.

Transportation

Plastics are also enjoying a mushrooming growth in the field of transportation where their high strength coupled with low weight is required. Plastics for airplanes have already been mentioned. But reinforced plastics are also being extensively used by automobile, boat, and ship manufacturers.

> Most owners of the glass fiber reinforced polyester Corvette purchased between 1953 and 1958 (in other words, cars 11 to 6 years old at the time of the survey) reported that their vehicles are still in good to excellent condition with only a few bodies in poor shape (Hauck, 1965).

Boats are being made from plastics in sizes ranging from a nine foot by five foot collapsable polypropylene boat to a 600 ton 160 foot cargo ship currently under construction in England. About the only disadvantage of the monster ship being produced in England is that it is estimated to have a ten percent greater cost than an equivalent steel ship. However, it can boast the following advantages: one-half the weight of a steel ship; no corrosion and consequently lower maintenance costs; and military advantages in that it is protected from weapons equipped with magnetic attraction devices. Although the builders are being rather secretive, they say that rigidity is provided by "blocks of a glass-reinforced polyester resin of a honeycomb construction" (Reinforced Plastics Graduate from Boats to Ships, 1967). It is assumed that these blocks are then covered with reinforced plastic skins to form a structural sandwich.

EXCITING NEW AREAS OF RESEARCH

Actually, the areas of promising research in the field of plastics are too numerous and diversified to attempt to mention them all. Rohm and Haas Co., by a process not yet understood, adds Acrylic latex to concrete and improves its tensile strength 300 percent, its flexural strength 200 percent, its adhesion properties 400 percent, and its compressive strength 100 percent (Gallagher, 1967). As already mentioned, Dr. Manuel Ballester has discovered a method of substituting chlorine atoms for hydrogen atoms in polymers. As a result, "a new series of polymer plastics, which among other things are magnetic, act like metals and semiconductors, and withstand temperatures up to 1000°F are within reach" (Magnetic Plastics, 1967). Then too, there is much research being conducted on a new type of foamed plastic called syntactic foam. According to Davis and Johnson, this foam is filled with tiny glass "microbubbles" that greatly lower the density of the foam while increasing its strength (S.P.I. R.P.D., 1967). But the writer feels that the most promising field of research is in the field of new reinforcements for plastics. Such reinforcements include steel; ceramic, boron, and carbon fibers; whiskers; and cobwebs.

Consider first, common fiberglass reinforcement. These fibers are of comparatively large diameter. As a result, there is a statistically great chance of flaws existing in the fibers that will weaken them. Therefore, if one could develop finer and finer fibers there would be a decrease in fiber flaws with a resulting increase in strength. Theoretically, by producing fibers smaller and smaller, their strength should approach that strength holding molecules together. To utilize this greater strength, there would be a correspondingly greater bonding surface. With this goal in mind, whiskers have been developed. These are fibers made up of single crystals growing end to end in chain-like manner. Whiskers have the tiny diameter of 1-30 microns [11] with lengths ranging from 1-10,000 microns. The only disadvantage of whiskers is that a new discontinuous fiber technology must be developed in order to realize their much greater reinforcing potential. Consider the property charts on the following pages most of which were prepared by R. Bacon, A.A. Pallozzi, and S.E. Slosarik of Union Carbide Corporation (Frados, 1966).

Note that for composites prepared from epoxy resin, boron reinforced material has only slightly greater tensile strength than composites made from traditional "S" glass, whereas its elastic modulus is nearly five times as great. Also consider the growth potential for such materials, as Thornel 25 is the best material currently in the beginning stages of production, and yet it is far inferior to some of

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[11] One micron equals 0.0001 centimeter.

Table 2. Properties for composites with 30 percent epoxy resin by volume (Frados, 1966).

Property	Boron	"S" Glass
density (lb/in^3)	0.074	0.074
specific gravity	2.05	2.05
ultimate tensile strength (10^3 psi)	320.0	260.0
E (10^6 psi)	36.0	7.6

Table 3. Tensile strength and modulus of elasticity for several forms of carbon (Frados, 1966).

Carbon form	Tensile strength (psi)	E (10^6 psi)
single crystal	---	140
graphite whiskers	3,000,000	100
pyrolytic graphite filaments	600,000	92
pyrolytic graphite	95,000	100
graphite filaments	400,000	50
Thornel 25 graphite yarn (pilot production)	200,000	20-30
carbon filaments VYB (current production)	180,000	6
ZTA (bulk graphite)	5,000	7
ATJ (bulk graphite)	3,000	2.5

Table 4. Mechanical strength of carbon reinforced epoxy composite (Frados, 1966).

Property	Grade VYB	Grade WYB	Thornel 25
NOL tensile strength (10^3 psi)	79.8	64.5	95.9
tensile E (10^6 psi)	3.1	3.16	9.0
NOL compressive strength (10^3 psi)	133.6	60.1	56.5
compressive E (10^6 psi)	3.5	3.6	15.4
NOL flexural strength (10^3 psi)	107.4	83.3	68.9
bending E (10^6 psi)	3.3	3.3	15.3
NOL horizontal shear strength (10^3 psi)	11.3	3.6	2.3
density, H_20 (gm/cc)	1.42	1.24	1.4
resin content, percent by volume	38.0	30.0	28.0

Table 5. Material comparisons (Frados, 1966).

Material	Density (lb/in^3)	Tensile Strength (10^3 psi)	Tensile Strength/ Density (in)	E (10^6 psi)	E/ Density (10^6 in)
Graphite	0.054	400	7.40	50.0	910.0
Boron	0.090	500	5.55	60.0	666.0
"S" glass	0.072	650	9.00	12.5	174.0
Titanium	0.160	113	1.81	16.2	101.2
Maraging steel	0.260	319	1.10	27.0	93.2

the graphite whiskers and single crystals. Indeed, such materials of the future will find unlimited application where high performance is critical. Consider the following statement by Shyne and Milewski:

> With the advent of commercial production, whiskers will be used as a universal reinforcement in all types of materials and will find their way into many commonplace products. For example, whisker-reinforced plastics will be used extensively for body and basic structures in the automotive industry where they will have three times the strength of steel of equivalent modulus, and about one-third the weight.
>
> The potentialities of whisker reinforcements are by no means limited to plastics composites. Thus, whisker additions to aluminum will allow development of fully cast submarines, for example, with hulls having the strength of steel, the modulus of titanium and a density of only slightly higher than that of aluminum. Whisker-reinforced concrete will require a whole new approach to design in the construction industry. Whisker reinforcements will replace large portions of sand and gravel, assuring phenomenal tensile strength and crack resistance in structures having extremely thin sections.
>
> The future of fine-fiber technology is foreshadowed by new experimental fibers called cobweb sapphire. These fibers are so small that they cannot be resolved with the best optical equipment; they are seen only as a blue cloud formed by light refraction similar to that which causes the sky to appear blue. Electron micrographs at 200,000 X show the fibers to be 200 Angstroms[12] in diameter. Their strength can only be guessed at from extrapolated data. Theoretically, by growing them smaller and smaller and hence more perfect, we can produce crystals having atomic strengths in the range of 50 million psi, and bring a new order of reinforcing strength to materials and design (Frados, 1966).

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[12]One Angstrom equals 0.0001 micron or 0.00000001 centimeter.

CONCLUSIONS

In conclusion, one can say that the present status of plastics as an engineering material is very dynamic. There is much that is not known about even the most obsolete plastics; in fact there have not been adequate design procedures formulated. Yet, the industry is rapidly forging ahead into new areas before the old are understood. As a result, the engineer attempting to design a plastic structure is in a sorry state indeed. He has no accurate design technology for plastics; and even if he did, he would have to choose from a myriad of resin matrix as well as reinforcement types with only scant and misleading property data to guide him. Even these poor data are not readily available, but must be sought from handbooks, producers, and researchers among a multitude of confusing trade names. Today's engineer must soon find that his best method for design is an expensive method of plastic selection, trial design, construction, testing, and redesign. And perhaps, even after a satisfactory structure has been decided upon, he will find local building code restrictions.

Therefore, it is evident that plastics have a long way to go before they are accepted as an engineering material equal in importance to metals. Yet the potential is there; the present growth of the structural plastics industry is phenomenal.

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APPENDICES

APPENDIX I

List of Symbols and Abbreviations

E_{app} - apparent modulus of elasticity

Tg - glass transition temperature

S - design stress

C - factor of safety

ASTM - American Society for Testing and Materials

SPI - The Society of the Plastics Industry, Inc.

WPC - wood-plastic composite

APPENDIX II

Empirical Method for Accounting for Time Effects on Strength Derived from the Linear Nature of Stress vs. Time on a Semi-log Plot

(Chambers, 1966)

$\sigma_R = \sigma_O - M \log t$ σ_R = stress psi that can be maintained for a given time interval.

t = time in hours.

σ_O, M = constants from stress rupture plot.

$\epsilon_t = \epsilon_O \sinh\frac{\sigma}{\sigma_m} + m' t^n \sinh\frac{\sigma}{\sigma_m}$ t = time of stress application (hours).

ϵ_t = strain occurring in time t (in/in).

σ = stress level (psi) that is applied for time t.

σ_O, σ_m, m', n = empirical constants from strain/time/stress plot.

Weave type	For stress rupture		For strain/time/stress			
	σ_O (psi)	M (psi)	ϵ_O (in/in)	m' (in/in)	σ_m (psi)	n
181 fabric	27,700	3,050	0.033	0.00017	13,000	0.210
181 fabric (FR)[13]	26,300	3,300	---	---	---	---
10 ounce fabric	22,500	2,620	0.280	0.00011	6,500	0.190
Woven roving	17,700	1,800	0.206	0.01460	40,000	0.230
Mat[14]	6,400	275	0.0067	0.00110	8,500	0.190

[13] FR indicates general purpose resin with ten percent flexibilizer all other materials are based on general-purpose polyester resins.

[14] Mat laminates were tested dry; all other materials were stressed while submersed in water.