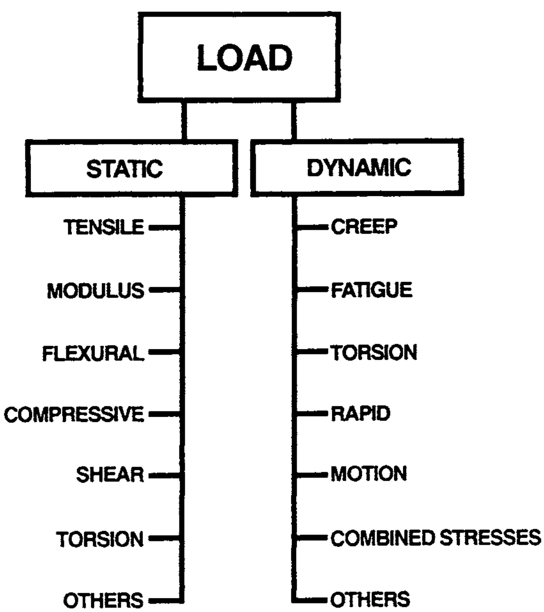
[1] D. Rosato, D. Rosato. Design parameter (Chapter 3), in: D. Rosato, D. Rosato (Eds.) Plastics Engineered Product Design, Elsevier Science, Amsterdam. 2003, pp. 161-197.

3 DESIGN PARAMETER

Load Determination

Loads on a fabricated product can produce different types of stresses within the material. There are basically static and dynamic stresses (Fig. 3.1). The magnitude of these stresses depends on many factors such as applied forces/loads, angle of loads, rate and point of application of each load, geometry of the structure, manner in which the structure is supported, and time at temperature. The behavior of the material in response to these induced stresses determines the performance of the structure.

Figure 3.1 Examples of stresses due to loads (Courtesy of Plastics FALLO)



The behavior of materials (plastics, steels, etc.) under dynamic loads is important in certain mechanical analyses of design problems. Unfortunately, sometimes the engineering design is based on the static loading properties of the material rather than dynamic properties. Quite often this means over-design at best or incorrect design resulting in failure of the product in the worst case.

The complex nature of the dynamic behavior problem can be seen from Fig. 3.1, which depicts a wide range of interaction of dynamic loads that occurs with various materials (metals, plastics, etc.). Ideally, it would be desirable to know the mechanical response to the full range of dynamic loads for each material under all types of conditions. However, certain load-material interactions have more relative importance for engineering design, and significant as well as sufficient work on them exists already. The mechanical engineers, civil engineers, and metallurgical engineers have always found materials (includes plastic, steel, aluminum, etc.) to be most attractive to study. Even so, there is a great deal that we do not understand about these materials in spite of voluminous scientific literature existing worldwide. Each type of load response, e.g., creep, fatigue/vibratory, or impact, is a major field in itself. Data on each response is available. However there is always a desire to obtain more data.

The nature and complexity of applied loads as well as the shape requires the usual engineering calculations. For a simple engineering form like a plate, beam, or box structure the standard design formulas can be used with appropriate parameters relating to the factors of short- and long-time loadings, creep, fatigue, impact, and applying the viscoelastic plastic material behavior (Chapter 2). The term engineering formulas refers to those equations in engineering handbooks by which the stress analysis can be accomplished.

In a product load analysis the structure as a whole and each of its elements together are in a state of equilibrium. There are no unbalanced forces of tension, compression, flexure, or shear acting on the structure at any point. All the forces counteract one another, which results in equilibrium. When all the forces acting on a given element in the same direction are summed up algebraically, the net effect is no load. However the product does respond to the various forces internally.

These forces could deform the product due to internal stresses of varying types and magnitudes. This action could be immediate or to some time-temperature period based on its viscoelastic behavior and underestimating potential internal stresses. To overcome this situation different approaches are used, as explained in the engineering books.

An example is when the cross-sectional area of a product increases for a given load, the internal stresses are reduced, so make it thicker. Design is concerned with determining the stresses for a given shape and subsequently adjusting the shape until the stresses are neither high enough to risk fracture nor low enough to suggest that material is being wasted (costly).

The stress analysis design involves various factors. It requires the descriptions of the product's geometry, the applied loads and displacements, and the material's properties including its viscoelastic behavior. The result is to obtain numerical expressions for internal stresses as a function of the stress's position within the product and as a function of time-temperature as well.

With the more complex shapes the component's geometry complicates the design analysis for plastics (and other materials) and may make it necessary to carry out a direct analysis, possibly using finite element analysis (FEA) followed with prototype testing (Chapter 5).

Loads applied on products induce tension, compression, flexure, torsion, and/or shear, as well as distributing the loading modes. The product's particular shape will control the type of materials data required for analyzing it. The location and magnitude of the applied loads in regard to the position and nature of such other constraints as holes, attachment points, and ribs are important considerations that influences its shape. Also influencing the design decision will be the method of fabricating the product (Chapter 1).

Loads will generally fall into one of two categories, directly applied loads and strain-induced loads (Chapter 2. Isolator). Directly applied loads are usually easy to understand. They are defined loads that are applied to defined areas of the product, whether they are concentrated at a point, line, or boundary or distributed over an area. The magnitude and direction of these loads are known or can easily be determined. An example of a strain-induced load is when it is required that a product be deflected. The load developed is directly related to the strain that occurs. Unlike directly applied loads, strain-induced loads are dependent on the modulus of elasticity; when comparing TPs with TSs, the TPs will generally decrease quicker in magnitude over time. Many assembly and thermal stresses could be the result of these strain-induced loads.

Time-dependent applied loading effects the materials viscoelasticity (Chapter 2). Loads applied for short times and at normal rate cause material response that is essentially elastic in character. However, under sustained load plastics, particularly TPs, tend to creep, a factor that is

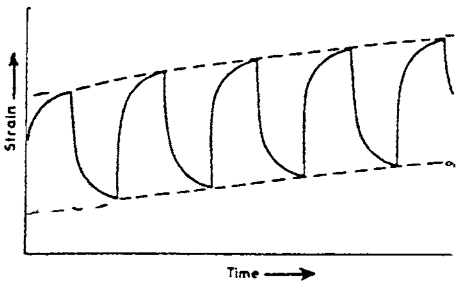


Figure 3.2 Example of intermittent loading

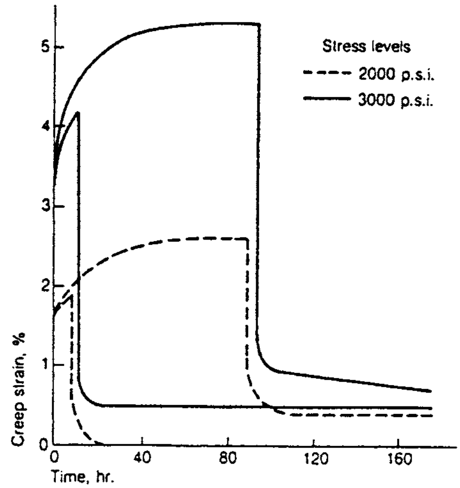


Figure 3.3 Loading and unloading examples of creep changes for engineering TPs

included in the design analysis.

Intermittent loading can involve creep and recovery over relatively long time periods. Creep deformation during one loading can be partly recovered in the unloading cycle, leading to a progressive accumulation of creep strain as the continuous intermittent load action continues (Figs. 3.2 and 3.3). This action in an improperly designed product will probably result in creep rupture. An analogue of creep behavior is the stress-relaxation cycle that can occur under constant strain. This behavior is particularly relevant with push-fit assemblies and bolted joints that rely on maintaining their load under constant strain. Special design features or analysis may be required to counteract excessive stress-relaxation.

There are intermittent or dynamic loads that occur over short time periods that can cause failure due to creep and possibly fatigue. This type loading condition applies to products such as motion control isolators, engine mounts, and other antivibration products; panels that vibrate and transmit noise; chairs; and road surface-induced loads carried to vehicle wheels and suspension systems. Plastics' relevant properties in this regard are material stiffness and internal damping, the latter of which can often be used to advantage in design (Chapter 2). Both properties depend on the frequency of the applied loads or vibrations, a dependence that must be allowed for in the design analysis. Design engineers unfamiliar with plastics' behavior will be able to apply the information contained in this book to applicable equations that involve such analysis as multiple and complex stress concentrations. The various machine-design texts and mechanical engineering handbooks review this subject.

Products can be stressed in a manner that is more complex than simple tension, compression, flexure, or shear. Because yielding will also occur under complex stress conditions, a yield criterion can be specified that will apply in all stress states. Any complex stress state can be resolved into the usual engineering three normal components acting along three mutually perpendicular (X, Y, Z) axes and into three shear components along the three planes of those axes. By making a proper choice it is possible to find a set of three axes along which the shear stresses will be zero. These are the principal axes, with the normal stresses along them being called the principal stresses.

Design analysis process

The nature of design analysis obviously depends on having product-performance requirements. The product's level of technical sophistication and the consequent level of analysis that can be justified costwise basically control these requirements. The analysis also depends on the design criteria for a particular product. If the design is strength limited, to avoid component failure or damage, or to satisfy safety requirements, it is possible to confine the design analysis simply to a stress analysis. However, if a plastic product is stiffness limited, to avoid excessive deformation from buckling, a full stress-strain analysis will likely be required. Even though many potential factors can influence a design analysis, each application fortunately usually involves only a few factors. For example, TPs' properties are dominated by the viscoelasticity relevant to the applied load. Anisotropy usually dominates the behavior of long-fiber RPs and so on.

The design analysis processes for metals, plastics, and RPs are essentially the same, However due to a certain degree of differences, they sometimes appear to be drastically different. Experience of design analysis can be misleading if applied without consideration to plastics and RPs behaviors. The design analysis process is composed essentially of the three main steps: (a) assessment of stress and strain levels in the proposed design; (b) comparison of critical stress and/or deformation values with design criteria to ensure that the proposed design will satisfy product requirements and materials limitations; and (c) modification of the proposed design to obtain optimum satisfaction of product requirement.

For metallic materials, component design is usually strength limited so that the design criteria in step (b) are often defined in terms of materials strength values, that is, in terms of a maximum permissible stress. Even when the design criterion is avoidance of plastic flow, rather than avoidance of material failure, the criterion is specified by the limiting yield stress. In these cases, step (a) is only required to provide an analysis of the stress distribution in the component, and the strain and deformation distributions are of little practical interest. These conclusions are a consequence of the relatively high stiffness of metals, and the principal exception is the deformation of thin sections that may lead to buckling.

A further simplification can often arise if the stress analysis problem required in step (a) is statically determinate. In particular, this requires that the externally applied constraints (or boundary conditions) can all be expressed in the form of applied loads and not in terms of imposed relative displacements. The stress distribution depends on the applied loads and on the component geometry, but not on the material stiffness properties. Thus, it is identical for all materials, whether they be elastic, rigid, or any other form, provided only that the material is sufficiently stiff for satisfaction of the assumption that the applied loads can be considered to be applied to the undeformed, rather than deformed, component geometry.

Thus, for metallic materials in many idealized practical situations, the design process is simplified to a stress (but not strain or displacement) analysis followed by comparison and optimization with critical stress values. When the problem is not statically determinate, the stress analysis requires specification of material stiffness values, but the associated strain and deformation values are usually not required. Since the material behavior is usually represented adequately by linear isotropic elasticity, the stress analysis can be limited to that form, and there are many standard formulae available to aid the designer.

For plastics (unreinforced), the emphasis is somewhat different. Due to their relatively low stiffness, component deformations under load may be much higher than for metals, and the design criteria in step (b) are often defined in terms of maximum acceptable deflections. Thus, for example, a metal panel subjected to a transverse load may be limited by the stresses leading to yield and to a permanent dent. Whereas a plastics panel may be limited by a maximum acceptable transverse deflection even though the panel may recover without permanent damage upon removal of the loads. Even when the design is limited by material failure, it is usual to specify the materials criterion in terms of a critical failure strain rather than a failure stress. Thus, it is evident that strain and deformation play a much more important role for plastics than they do for metals. As a consequence, step (a) is usually required to provide a full stress/strain/deformation analysis and, because of the viscoelastic nature of plastics, this can pose a more difficult problem than for metals.

A particular distinction between the mechanical behaviors of metals and plastics is explained in order to avoid a possible confusion that could have arisen from the preliminary review. A typical stress/strain curve for a metal, exhibits a linear elastic region followed by yield at the yield stress, plastic flow, and ultimately failure at the failure stress. Yield and failure occur at corresponding strains, and one could define yield and failure in terms of these critical strains. This is not common practice because it is simpler in many cases to restrict step (a) to a stress analysis alone. By comparison, it may appear strange that it was stated above that plastics failure criteria are usually defined in terms of a critical strain (rather than stress) and, by comparison with the metals case, switching back from strain to stress may appear to be a minor operation.

Explanation of this apparent fallacy depends on recognition of the fact that stress and strain are not as intimately related for plastics as they are for metals. This is demonstrated by a set of stress/strain curves for a typical plastic where their loading rates increase. This emphasizes that the stress/strain curve for a plastic is not unique, but depends on the loading type, that is, also on time, frequency, or rate. For example, the stress/strain curves obtained at different loading rates and for metals these curves would essentially coincident. However, the behavior of plastics can be very different at low and high rates, and there is no unique relation between stress and strain since this depends on the loading rate too. It is evident that characterization of failure through a unique failure strain cannot be valid in general, but it can be a good approximation in certain classes of situations such as, for example, at high rates or under creep conditions.

Reinforced Plastic Analysis

For RPs, the emphasis and difficulty in the design analysis depends on the nature of the RPs. For a thermoplastic reinforced with short fibers, the viscoelastic nature of the matrix remains an important factor, and the discussion given above for unreinforced plastics is relevant. In addition, there may be a significant degree of anisotropy and/or inhomogeneity due to processing that could further complicate the analysis (Chapter 2). For thermosets reinforced with short fibers (for example, BMC; Chapter 1) there may be only a low level of visco-elasticity, anisotropy, and inhomogeneity, and metals-type design analysis may be a reasonable approximation. However, thermosets reinforced with long fibers can have a high degree of anisotropy (depends on lay up of reinforcement), and this must be taken into account in the design analysis. When thermoplastics are reinforced with long fibers there may be significant anisotropy and viscoelasticity, and this creates a potentially complex design analysis situation. In all cases, RPs failure characteristics may be specified in terms of a critical strain, and this requires the design analysis to be performed for stress and strain.

Long-fiber materials can often be tailored to the product requirements, and therefore materials design analysis and component design analysis interact strongly. If the component design analysis is statically determinate (stresses independent of materials properties) then this can be carried out first, and then the material can be designed to carry the stresses in the most efficient manner. However, if the analysis is not statically determinate, then the component stresses depend on material anisotropy, and material and product design have to be carried out and optimized at the same time. This is also the case if component shape is regarded as one of the variable design parameters.

In summary, it can be seen that plastics and RPs design analysis follows the same three steps (a) to (c) as that for metals, but there are some differences of emphasis and difficulty. In particular, step (a) is usually more substantial for the newer materials, partly because a full stress/strain/deformation analysis is required and partly because of the need to take account of viscoelasticity, inhomogeneity, and/or anisotropy. For long fiber materials, the component design analysis may need to contain the associated material design analysis.

Stress Analysis

Different nondestructive techniques are used to evaluate the stress level in products. They can predict or relate to potential problems. There is the popular electrical resistance strain gauges bonded on the surface of the product. This method identifies external and internal stresses. The various configurations of gauges are made to identify stresses in different directions. This technique has been extensively used for over half a century on very small to very large products such as toys to airplanes and missiles.

There is the optical strain measurement system that is based on the principles of optical interference. It uses Moire, laser, or holographic interferometry. Another very popular method is using solvents that actually attack the product. It works only with those plastics that can be attacked by a specific solvent. Immersed products in a temperature controlled solvent for a specific time period identifies external and internal stresses. After longer time periods products will self-destruct. Stress and crack formations can be calibrated using different samples subjected to different loads.

With the brittle coating system that is applied on the surface of a product one identifies conditions such as stressed levels, cracks, etc. A lacquer coating is applied, usually sprayed on the surface of the product. It provides experimental quantitative stress-strain measurement data. As the product is subjected to a load simulating the load that would be encountered in service, cracks begin to appear in the coating. The extent of cracks is noted for each increment of load. Prior to this action, the coating is calibrated by applying the coating on a simple beam and observing the strain at which cracks appear and relating them to the stress behavior of the beam.

Photoelastic measurement is a popular and useful method for identifying stress in transparent plastics. Quantitative stress measurement is possible with a polarimeter equipped with a calibrated compensator. It makes stresses visible. The optical property of the index of refraction will change with the level of stress (strain). When the photoelastic material is stressed, the plastic becomes birefringent identifying the different levels of stress via color patterns.

This photoelastic stress analysis is a technique for the nondestructive determination of stress and strain components at any point in a stressed product by viewing a transparent plastic product. If not transparent, a plastic coating is used such as certain epoxy, polycarbonate, or acrylic plastics. This test method measures residual strains using an automated electro-optical system.

The photoelastic technique relates to the Brewster's Constant law. It states that the index of refraction in a strained material becomes directional, and the change of the index is proportional to the magnitude of the strain present. Thus a polarized beam in a clear plastic splits into two wave fronts (X and Y directions) that contain vibrations oriented along the directions of principal strains. The index of refraction in these directions is different and the difference (or birefringence) is proportional to the stress level. Result is the colorful patterns seen when stressed plastic are placed between two polarized filters providing qualitative analysis. Observed colors correspond to different levels of retardation at that point, which in turn correspond to stress levels.

Stress-strain behavior

The information presented throughout this book is used in different loading equations. As an example stress-strain data may guide the designer in the initial selection of a material. Such data also permit a designer to specify either design stresses or strains safely within the proportional/elastic limit of the material. However for certain products such as a vessel that is being designed to fail at a specified internal pressure, the designer may choose to use the tensile yield stress of the material in the design calculations.

Designers of most structures specify material stresses and strains well within the proportional/elastic limit. Where required (with no or limited experience on a particular type product materialwise and/or processwise) this practice builds in a margin of safety to accommodate the effects of improper material processing conditions and/or unforeseen loads and environmental factors. This practice also allows the designer to use design equations based on the assumptions of small deformation and purely elastic material behavior. Other important properties derived from stress-strain data that are used include modulus of elasticity and tensile strength.

Rigidity (EI)

Tensile modulus of elasticity (E) is one of the two factors that determine the stiffness or rigidity (EI) of structures comprised of a material. The other is the moment of inertia (I) of the appropriate cross section, a purely geometric property of the structure. In identical products, the higher the modulus of elasticity of the material, the greater the rigidity; doubling the modulus of elasticity doubles the rigidity of the product. The greater the rigidity of a structure, the more force must be applied to produce a given deformation.

It is appropriate to use E to determine the short-term rigidity of structures subjected to elongation, bending, or compression. It may be more appropriate to use the flexural modulus to determine the short-term rigidity of structures subjected to bending, particularly if the material comprising the structure is non-homogeneous, as foamed or fiber-reinforced materials tend to be. Also, if a reliable compressive modulus of elasticity is available, it can be used to determine short-term compressive rigidity, particularly if the material comprising a structure is fiber-reinforced. The room temperature E for several plastics and some other materials are presented in Chapter 2.

Hysteresis Effect

Hysteresis relates to the relation of the initial load applied to a material and its recovery rate when the load is released. There can be a time lapse that depends on the nature of the material and the magnitude of the stresses involved. This plastic behavior is typically nonlinear and history dependent. This incomplete recovery of strain in a material subjected to a stress during its unloading cycle is due to energy consumption. Upon unloading, complete recovery of energy does not occur. During a static test this phenomenon is called elastic hysteresis; for vibratory stresses it is called damping. The area of this hysteresis loop, representing the energy dissipated per cycle, is a measure of the damping properties of the material. Under vibratory conditions the energy dissipated varies approximately as the cube of the stress.

This energy is converted from mechanical to frictional energy (heat). It can represent the difference in a measurement signal for a given process property value when approached first from a zero load and then from a full scale as shown in Figs. 3.4 and 3.5. They provide examples of recovery to near zero strain. It shows that material can withstand stress beyond its proportional limit for a short time, resulting in different degrees of the hysteresis effect.

The hysteresis heating failure occurs more commonly in plastic members subject to dynamic loads. An example is a plastic gear. With the gear teeth under load once per revolution, it is subjected to a bending load that transmits the power from one gear to another. Another example is a link that is used to move a paper sheet in a copier or in an accounting machine

Figure 3.4 Hysteresis recovery effects

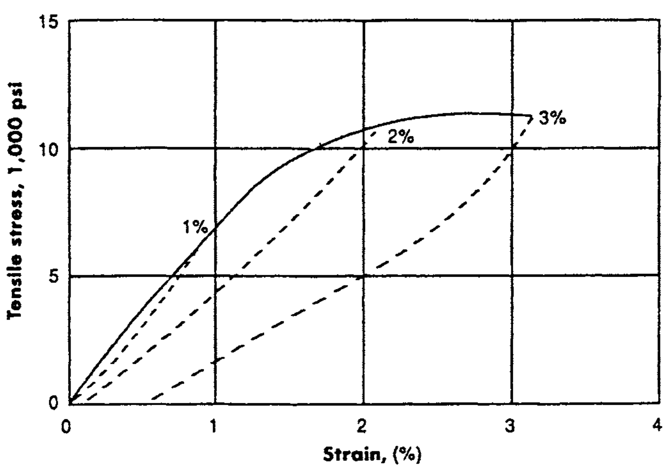
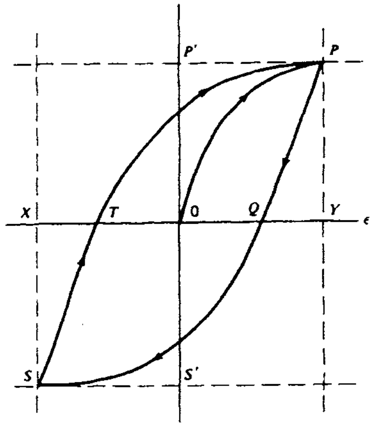


Figure 3.5 Hysteresis loop related to cyclic loading



from one operation to the next. The load may be simple tensile or compressive stresses, but more commonly it is a bending load.

Poisson's Ratio

Poisson's ratio is a required constant in engineering analysis for determining the stress and deflection properties of materials (plastics, metals, etc.). It is a constant for determining the stress and deflection properties of structures such as beams, plates, shells, and rotating discs. With plastics when temperature changes, the magnitude of stresses and strains, and the direction of loading all have their effects on Poisson's ratio. However, these factors usually do not alter the typical range of values enough to affect most practical calculations, where this constant is frequently of only secondary importance. The application of Poisson's ratio is frequently required in the design of structures that are markedly 2-D or 3-D, rather than 1-D like a beam. For example, it is needed to calculate the so-called plate constant for flat plates that will be subjected to bending loads in use. The higher Poisson's ratio, the greater the plate constant and the more rigid the plate.

When a material is stretched, it's cross-sectional area changes as well as its length. Poisson's ratio (ν) is the constant relating these changes in dimensions. It is defined as the ratio of the change in lateral width per unit width to change in axial length per unit length caused by the axial stretching or stressing of a material. The ratio of transverse strain to the corresponding axial strain below the tensile proportional limits.

For plastics the ratio falls within the range of 0 to 0.5. With a 0 ration there is no reduction in diameter or contraction laterally during the elongation but would undergo a reduction in density. A value of 0.5 would indicate that the specimen's volume would remain constant during elongation or as the diameter decreases such as with elastomeric or rubbery material. Plastic range is usually from about 0.2 to 0.4; natural rubber is at 0.5 and reinforced TPs at 0.1 to 0.4. In mathematical terms, Poisson's ratio is the diameter of the test specimen before and after elongation divided by the length of the specimen before and after elongation. Poisson's ratio will have more than one value if the material is not isotropic. (Table 3.1)

Table 3.1 Poisson's ratios (and shear data) for different thermoplastics

Plastic	*Poisson's ratio*	*Shear modulus MPa*	*Shear stress MPa*
ABS	0.35	965	51.2
	0.36	660	30.0
Acetal homopolymer	0.35	1340	65.5
Acetal copolymer	0.35	1000	53.0
Nylon (0.2 wt%)	0.34–0.43		66.4
Polycarbonate	0.37	785	41.5
Polymethyl methacrylate	0.35		44.6

Brittleness

Brittleness identifies material easily broken, damaged, disrupted, cracked, and/or snapped. Brittleness can result from different conditions such as from drying, plasticizer migration, etc. Brittle materials exhibit tensile S-S behaviors different from the usual S-S curves. Specimens of such materials fracture without appreciable material yielding. They lack toughness. Their brittle point is the highest temperature at which a plastic or elastomer fractures in a prescribed impact test procedure.

Plastics that are brittle frequently have lower impact strength and higher stiffness properties. A major exception is reinforced plastics. The tensile S-S curves of brittle materials often show relatively little deviation from the initial linearity, relatively low strain at failure, and no point of zero slope. Different materials may exhibit significantly different tensile S-S behavior when exposed to different factors such as the same temperature and strain rate or at different temperatures.

A brittleness temperature value is used. It is the temperature statistically calculated where 50% of the specimens would probably fail 95% of the time when a stated minimum number are tested. The 50% failure temperature may be determined by statistical calculations.

There is a Griffith design failure theory. It expresses the strength of a material in terms of crack length and fracture surface energy. Brittle fracture is based on the idea that the presence of cracks determines the brittle strength and crack propagation occurs. It results in fracture rate of decreased elastically stored energy that at least equals the rate of formation of the fracture surface energy due to the creation of new surfaces.

Ductile

Ductility is the amount of strain that a material can withstand before fracture. In turn the fracture behavior of plastics, especially microscopically brittle plastics, is governed by the microscopic mechanisms operating in a heterogeneous zone at their crack or stress tip because of internal or external forces. In TPs, craze zones can develop that are important microscopic features around a crack tip governing strength behavior. Fracture is preceded by the formation of a craze zone, which is a wedge shaped region spanned by oriented microfilms. Methods of craze zone measurements include optical emission spectroscopy, diffraction techniques, scanning electron beam microscopy, and transmission electron microscopy.

Fig. 3.6 is an example of the ductile plastic tensile stress-strain curve. This curve identifies behavior so that as the strain increases, stress initially increases approximately proportionately (from point 0 to point A). Point A is called the proportional limit. From point 0 to point B, the behavior of the material is purely elastic/stretches; but beyond point B, the material exhibits an increasing degree of permanent deformation/stretch. Point B is the elastic limit of the material. At point C the material is yielding and so its coordinates are called the yield strain and stress (strength) of the material. Point D relates to the S-S elongation at break/failure. Table 3.2 provides these type data at room temperature for different materials.

Temperature influences the S-S curve. With a decrease in temperature the yield stress and strain usually decreases or the strain rate decreases. Point D corresponds to specimen fracture/failure. It represents the maximum elongation of the material specimen; its coordinates are called the ultimate, or failure strain and stress. As temperature decreases the ultimate elongation usually decreases or the strain rate increases.

Crazing

Crazing is also called hairline craze. They can be fine, thin, tiny type cracks that may extend in an unreinforced or reinforced plastic network

Figure 3.6 Tensile stress-strain behavior of ductile plastics

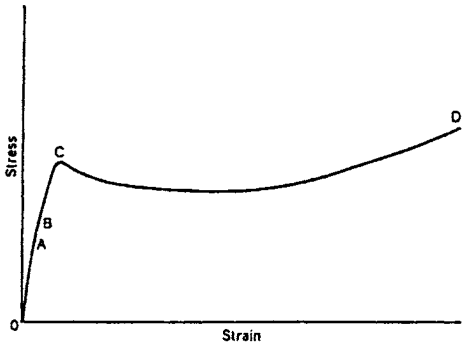


Table 3.2 Tensile data

Plastic	*Modulus MPa*	*Yield stress MPa*	*Elongation at yield, %*	*Elongation at break, %*
ABS	2,700	55	2.5	75
Acetal homopolymer	3,100	69	12	75
Acetal copolymer	2,800	61	12	60
Acrylic	3,000	72		5.4
Nylon	2,400	82	5	60
Phenolic	19,300	62	8	90
Polyethylene	1,200	30	20	600
Polypropylene	1,400	35	12	400
Polystyrene	3,100	25	8	60
Polysulfone	2,500	70	6	100

on or under the surface or through a layer of a plastic material. Different conditions and effects occur depending on the type plastic, load conditions, and environment. The formation of crazes are like cracks in that they are wedge shaped and formed perpendicular to the applied stress. They differ from cracks by containing plastic that is stretched in a highly oriented manner perpendicular to the plane of the craze. They are parallel to the applied stress direction. Another major distinguishing feature is that unlike cracks, crazes are able to support stress.

With the application of static loading, the strain at which crazes start to form decreases as the applied stress decreases. In constant strain-rate testing crazes always start to form at a well-defined stress level. Crazes start sooner under high stress levels. When tensile stress is applied to an amorphous (Chapter 1) plastic such as acrylics, PVCs, PS, and PCs, crazing may occur before fracturing. Crazing occurs in crystalline plastics, but in those its onset is not readily visible. It also occurs in most fiber-reinforced plastics, at the time-dependent knee in the stress-strain curve.

Environmental stress cracking is the cracking of certain plastic products that becomes exposed to a chemical agent while it is under stress. This effect may be caused by exposure to such agents as cleaners or solvents. The susceptibility of affected plastics to stress cracking by a particular chemical agent varies considerably among plastics, particularly the TPs.

The resistance of a given plastic to attack may be evaluated by using either constant-deflection or constant-stress tests in which specimens are usually coated with the chemical or immersed in the chemical agent. After a specified time the degree of chemical attack is assessed by measuring such properties as those of tensile, flexural, and impacts. The results are then compared to specimens not yet exposed to the chemical. In addition to chemical agents and the environment for testing may also require such other factors as thermal or other energy-intensive conditions.

It is possible with solvents of a particular composition to determine quantitatively the level of stress existing in certain TP products where undesirable or limited fabricated-in stresses exist. The stresses can be residual (internal) stresses resulting from the molding, extrusion, or other process that was used to fabricate the plastic product. Stresses can also be applied such as bending the product. As it has been done for over a half century, the product is immersed in the solution that attacks the plastic for various time periods. Any initial cracks or surface imperfections provide information that stresses exist. Other tests conducted can be related to the stress-time information. Information on the solvent mixtures suitable for this type of test and how to interrupt them are available from plastic material suppliers or can be determined from industry test data which show solvents that effect the specific plastic to be evaluated.

TP cracking develops under certain conditions of stress and environment sometimes on a microscale. Because there are no fibrils to connect surfaces in the fracture plane (except possibly at the crack tip), cracks do not transmit stress across their plane. Cracks result from embrittlement, which is promoted by sustained elevated temperatures and ultraviolet, thermal, chemical, and other environments.

For the designer it is not important whether cracking develops upon exposure to a benign or an aggressive medium. The important considerations are the embrittlement itself and the fact that apparently benign environments can cause serious brittle fractures when imposed on a product that is under sustained stress and strain, which is true of certain plastics.

Crazing or stress whiting is damage that can occur when a TP is stretched near its yield point. The surface takes on a whitish appearance in regions that are under high stress. Crazing is usually associated with yielding. For practical purposes stress whiting is the result of the formation of microcracks or crazes, which is another form of damage. Crazes are not true fractures, because they contain strings of highly oriented plastic that connect the two flat faces of the crack. These fibrils are surrounded by air voids. Because they are filled with highly oriented fibrils, crazes are capable of carrying stress, unlike true fractures. As a result, a heavily crazed product can still carry significant stress, even though it may appear to be fractured.

It is important to note that crazes, microcracking, and stress whiting represent irreversible first damage to a material, which could ultimately cause failure. This damage usually lowers the impact strength and other properties of a material compared to those of undamaged plastics. One reason is that it exposes the interior of the plastic to attack and subsequent deterioration by aggressive fluids. In the total design evaluation, the formation of stress cracking or crazing damage should be a criterion for failure, based on the stress applied.

Stress Whitening

It is the appearance of white regions in a TP when it is stressed. A stress-whitening zone may be a sign of crazing in some plastics where individual fine crazes may be difficult to detect. Stress whitening occurs fairly late in the rupture stage, just prior to yielding. The surface takes on a whitish appearance in regions that are under high stress. It is usually associated with yielding. For practical purposes, stress whiting is the result of the formation of microcracks or crazes that is a form of damage.

Combined stresses

In the direct design procedure the assumption is made that no abrupt changes occur in cross-section, discontinuities in the surface, or holes through the member. This is not the case in most structural parts. The stresses produced at these discontinuities are different in magnitude from those calculated by various design methods. The effect of the localized increase in stress, such as that caused by a notch, fillet, hole, or similar stress raiser, depends mainly on the type of loading, the geometry of the product, and the material. As a result, it is necessary to consider a stress-concentration factor. In general it will have to be determined by the methods of experimental stress analysis or the theory of elasticity, and by a simple theory without taking into account the variations in stress conditions caused by geometrical discontinuities such as holes, grooves, and fillets. For ductile materials it is not customary to apply stress-concentration factors to members under static loading. For brittle materials, however, stress concentration is serious and should be considered.

There are conditions of loading a product that is subjected to a combination of tensile, compressive, and/or shear stresses. For example, a shaft that is simultaneously bent and twisted is subjected to combined stresses, namely, longitudinal tension and compression, and torsional shear. For the purposes of analysis it is convenient to reduce such systems of combined stresses to a basic system of stress coordinates known as principal stresses. These stresses act on axes that differ in general from the axes along which the applied stresses are acting and represent the maximum and minimum values of the normal stresses for the particular point considered. There are different theories that relate to these stresses. They include Mohr's Circle, Rankine's, Saint Venant, Guest, Hencky-Von Mises, and Strain-Energy.

Surface Stresses and Deformations

It can be said that the design of a product involves analytical, empirical, and/or experimental techniques to predict and thus control mechanical stresses. Strength is the ability of a material to bear both static (sustained) and dynamic (time-varying) loads without significant permanent deformation. Many non-ferrous materials suffer permanent deformation under sustained loads (creep). Ductile materials withstand dynamic loads better than brittle materials that may fracture under sudden load application. As reviewed, materials such as plastics often exhibit significant changes in material properties over the temperature range encountered by a product.

There are examples where control of deflection or deformation during service may be required. Such structural elements are designed for stiffness to control deflection but must be checked to assure that strength criteria are reached. A product can be viewed as a collection of individual elements interconnected to achieve an overall systems function. Each element may be individually modeled; however, the model becomes complex when the elements are interconnected.

The static or dynamic response of one element becomes the input or forcing function for elements adjacent or mounted to it. An example is the concept of mechanical impedance that applies to dynamic environments and refers to the reaction between a structural element or component and its mounting points over a range of excitation frequencies. The reaction force at the structural interface or mounting point is a function of the resonance response of an element and may have an amplifying or damping effect on the mounting structure, depending on the spectrum of the excitation. Mechanical impedance design involves control of element resonance and structure resonance, providing compatible impedance for interconnected structural and component elements.

As an example view a 3-D product that has a balanced system of forces acting on it, F_1 through F_5 in Fig. 3.7, such that the product is at rest. A product subjected to external forces develops internal forces to transfer and distribute the external load. Imagine that the product in

Figure 3.7 Example of stresses in a product

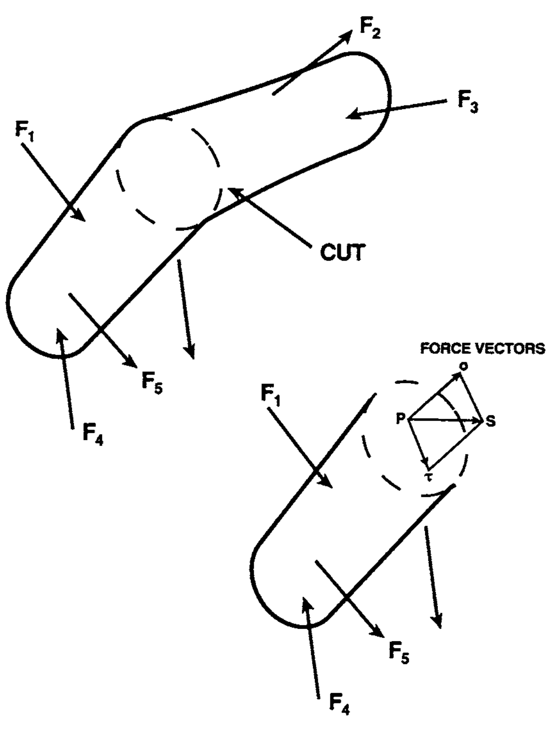


Fig. 3.7 is cut at an arbitrary cross-section and one part removed. To keep the body at rest there must be a system of forces acting on the cut surface to balance the external forces. These same systems of forces exist within the uncut body and are called stresses. Stresses must be described with both a magnitude and a direction. Consider an arbitrary point, P, on the cut surface in the figure where the stress, S, is as indicated. For analysis, it is more convenient to resolve the stress, S, into two stress components. One acts perpendicular to the surface and is called a normal or direct stress, σ. The second stress acts parallel to the surface and is called a shear stress, τ.

Creep

Plastic materials subjected to a constant stress can deform continuously with time and the behavior under different conditions such as temperature. This continuous deformation with time is called creep or cold flow. In some applications the permissible creep deformations are critical, in others of no significance. But the existence of creep necessitates information on the creep deformations that may occur during the expected life of the product. Materials such as plastic, RP, zinc, and tin creep at room temperature. Aluminum and magnesium alloys start to creep at around 300°F. Steels above 650°F must be checked for creep.

There are three typical stages. The initial strain takes place almost immediately, consisting of the elastic strain plus a plastic strain near its end, if the deformation extends beyond the yield point. This initial action in the first stage shows a decreasing rate of elongation that can be called strain hardening (as in metals). The action most important to the designer's working area concerns the second stage that is at a minimum strain rate and remains rather constant. In the third stage a rapid increase in the creep rate occurs with severe specimen necking/ thickness reduction and ultimately rupture. It is important for the designer to work in the second stage and not enter the third stage. Thus, after plotting the creep vs. time data of a 1,000 h test, the second stage can be extrapolated out to the number of hours of desired product life.

These test specimens may be loaded in tension or flexure (with some in compression) in a constant temperature environment. With the load kept constant, deflection or strain is recorded at regular intervals of hours, days, weeks, months, or years. Generally, results are obtained at different stress levels.

In conducting a conventional creep test, curves of strain as a function of time are obtained for groups of specimens; each specimen in one group is subjected to a different constant stress, while all of the specimens in the group are tested at one temperature. In this manner families of curves are obtained. Important are the several methods that have been proposed for the interpretation of such data.

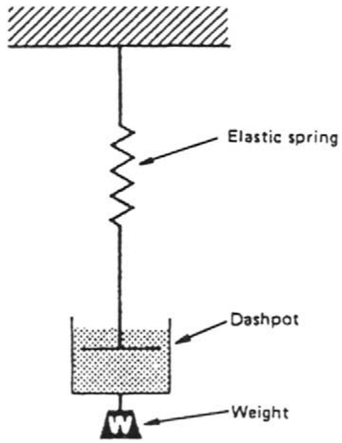
The rate of viscoelastic creep and stress relaxation at a given temperature may vary significantly from one TP to another because of differences in the chemical structure and shape of the plastic molecules (Chapter 1). These differences affect the way the plastic molecules interact with each other. Viscoelastic creep and stress relaxation tests are generally conducted up to 1,000 hours. Time-temperature super-positioning is often used to extrapolate this 1,000 hours of data to approximately 100,000 hours (≈ 12 years). Basically with TPs subjected to heat there is an increase in the rate of creep and stress relaxation. The TSs and particularly reinforced thermosets (RTSs) remains relatively unaffected until a high temperature is encountered.

Usually the strain readings of a creep test can be more accessible if they are presented as a creep modulus that equals stress divided by strain. In the viscoelastic plastic, the strain continues to increase with time while the stress level remains constant. Result is an appearance of a changing modulus. This creep modulus also called the apparent modulus or viscous modulus when graphed on log-log paper, is a straight line and lends itself to extrapolation for longer periods of time.

Plastic viscoelastic nature reacts to a constant creep load over a long period of time by an ever-increasing strain. With the stress being constant, while the strain is increasing, result is a decreasing modulus. This apparent modulus and the data for it are collected from test observations for the purpose of predicting long-term behavior of plastics subjected to a constant stress at selected temperatures.

The creep test method of loading and material constituents influences creep data. Increasing the load on a part increases its creep rate. Particulate fillers provide better creep resistance than unfilled plastics but are less effective than fibrous reinforcements. Additives influence data such as the effect of a flame-retardant additive on the flexural modulus provides an indication of its effect on long-time creep. Increasing the level of reinforcement in a composite increases its resistance to creep. Glass-fiber-reinforced amorphous TP RPs generally has greater creep resistance than glass fiber-reinforced crystalline TP RPs containing the same amount of glass fiber. Carbon-fiber reinforcement is more effective in resisting creep than glass-fiber reinforcement.

Figure 3.8 Mechanical Maxwell model



For the designer there is generally a less-pronounced curvature when creep and relaxation data are plotted log-log. Predictions can be made on creep behavior based on creep and relaxation data. This usual approach makes it easier to extrapolate, particularly with creep modulus and creep-rupture data.

To relate the viscoelastic behavior of plastics with an S-S curve the popular Maxwell model is used, this mechanical model is shown in Fig. 3.8. This model is useful for the representation of stress relaxation and creep with Newtonian flow analysis that can be related to plastic's non-Newtonian flow behavior. It consists of a spring [simulating modulus of elasticity (E)] in series with a dashpot of coefficient of viscosity (η). It is an isostress model (with stress δ), the strain (ε) being the sum of the individual strains in the spring and dashpot.

Based on this mechanical loading system a differential representation of linear viscoelasticity is produced as:

$$d\varepsilon/dt = (1/E)\, d\delta/dt + (\delta/\eta) \qquad (3\text{-}1)$$

When a load is applied to the system the spring will deform. The dashpot will remain stationary under the applied load, but if the same load continues to be applied, the viscous fluid in the dashpot will slowly leak past the piston, causing the dashpot to move. Its movement corresponds to the strain or deformation of the plastic material.

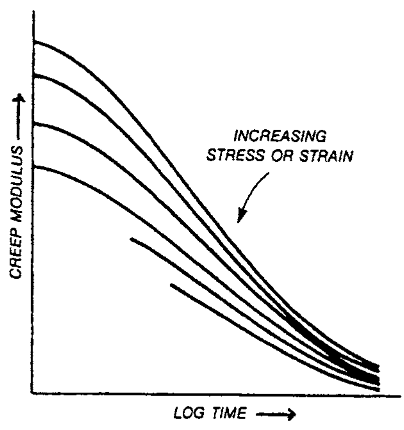
When the stress is removed, the dashpot will not return to its original position, as the spring will return to its original position. The result is a viscoelastic material behavior as having dual actions where one is of an elastic material (spring), and the other like the viscous liquid in the dashpot. The properties of the elastic phase is independent of time, but the properties of the viscous phase are very much a function of time, temperature, and stress (load). A thinner fluid resulting from increased temperature under a higher pressure (stress) will have a higher rate of leakage around the piston of the dashpot during the time period. A greater creep occurs at this higher temperature that caused higher stress levels and strain.

The Maxwell model relates to a viscoelastic plastic's S-S curve. The viscoelasticity of the plastic causes an initial deformation at a specific load and temperature. It is followed by a continuous increase in strain under identical test conditions until the product is either dimensionally out of tolerance or fails in rupture as a result of excessive deformation.

Test data using the apparent creep modulus approach is used as a method for expressing creep. It is a convenient method of expressing creep because it takes into account initial strain for an applied stress plus the deformation or strain that occurs with time. Because parts tend to deform in time at a decreasing rate, the acceptable strain based on service life of the part must be determined. The shorter the duration of load, the higher the apparent modulus and the higher the allowable stress.

When plotted against time, they provide a simplified means of predicting creep at various stress levels. It takes into account the initial strain for an applied stress plus the amount of deformation or strain that occurs over time. Fig. 3.9 shows curves of deformation versus time. Beyond a certain point, creep is small and may safely be neglected for many applications.

Figure 3.9 Apparent creep modulus vs. log time with increased load (Courtesy of Mobay/Bayer)



The acceptable strain based on the desired service life of a product can be determined since they deform under load in time at a decreasing rate. Short duration results in the higher apparent modulus and in turn a higher allowable stress. The apparent modulus is most easily explained with an example. The apparent modulus E_a is calculated in a very simplified approach as:

$$E_a = \mathit{Stress/Initial\ strain} + \mathit{Creep} \tag{3-2}$$

As long as the stress level is below the elastic limit of the material, its E can be obtained from the usual equation:

$$E = \mathit{Stress/Strain} \tag{3-3}$$

If a compressive stress of 10,000 psi (69 MPa) is used, the result is a strain of 0.015 in./in. (0.038 cm/cm) for FEP plastic at 63°F (17°C). Thus:

$$E = 10{,}000/0.015 = 667{,}000 \text{ psi } (4{,}600 \text{ MPa}) \tag{3-4}$$

If this stress level remains for 200 hours, the total strain will be the sum of the initial strain plus the strain due to time. This total strain can be obtained from a creep-data curve. With a total deformation under a tension load for 200 hours of 0.02 in./in., the result is:

$$E = 10{,}000/0.02 = 5{,}000{,}000 \text{ psi } (3{,}500 \text{ MPa}) \tag{3-5}$$

An E can then be determined for one year. Extrapolating from the straight-line creep-data curve gives a deformation of 0.025 in./in. the E becomes:

$$E = 10{,}000/0.025 = 400{,}000 \text{ psi } (2{,}800 \text{ MPa}) \tag{3-6}$$

Different attempts have been used to create meaningful formulas for the apparent modulus change with respect to time. However the factors in the formulas that would fit all conditions are more complicated to use than presenting test data in a graph form and using it as the means for predicting the strain (elongation) at some distant point in time. Log-log test data usually form a straight line and lend themselves to easy extrapolation by the designer. The slope of the straight line depends on the material being tested such as its rigidity and temperature of heat deflection with the amount of stress in relation to tensile strength.

Long term behavior of plastics involves plastic exposure to conditions that include continuous stresses, environment, excessive heat, abrasion, and/or continuous contact with liquids. Tests such as those outlined by ASTM D 2990 that describe in detail the specimen preparations and testing procedure are intended to produce consistency in observations and records by various manufacturers, so that they can be correlated to provide meaningful information to product designers. The procedure under this heading is intended as a recommendation for uniformity of making setup conditions for the test, as well as recording the resulting data. The reason for this move is the time consuming nature of the test (many years' duration), which does not lend itself to routine testing. The test specimen can be round, square, or rectangular and manufactured in any suitable manner meeting certain dimensions. The test is conducted under controlled temperature and atmospheric conditions.

The requirements for consistent results are outlined in detail as far as accuracy of time interval, of readings, etc., in the procedure. Each report of test results should indicate the exact grade of material and its supplier, the specimen's method of manufacture, its original dimensions, type of test (tension, compression, or flexure), temperature of test, stress level, and interval of readings. When a load is initially applied to a specimen, there is an instantaneous strain or elongation. Subsequent to this, there is the time-dependent part of the strain (creep), which results from the continuation of the constant stress at a constant temperature. In terms of design, creep means changing dimensions and deterioration of product strength when the product is subjected to a steady load over a prolonged period of time.

All the mechanical properties described in tests for the conventional data sheet properties represented values of short-term application of forces. In most cases, the data obtained from such tests are used for comparative evaluation or as controlling specifications for quality determination of materials along with short-duration and intermittent-use design requirements. The visualization of the reaction to a load by the dual component interpretation of a material is valuable to the understanding of the creep process, but meaningless for design purposes. For this reason, the designer is interested in actual deformation or part failure over a specific time span. The time segment of the creep test is common to all materials, strains are recorded until the specimen ruptures or the specimen is no longer useful because of yielding. In either case, a point of failure of the test specimen has been reached, this means making observations of the amount of strain at certain time intervals which will make it possible to construct curves that could be extrapolated to longer time periods. The initial readings are 1, 2, 3, 5, 7, 10, and 20 h, followed by readings every 24 h up to 500 h and then readings every 48 h up to 1,000 h.

The strain readings of a creep test can be more convenient to a designer if they are presented as a creep modulus. In a viscoelastic material, strain continues to increase with time while the stress level remains constant.

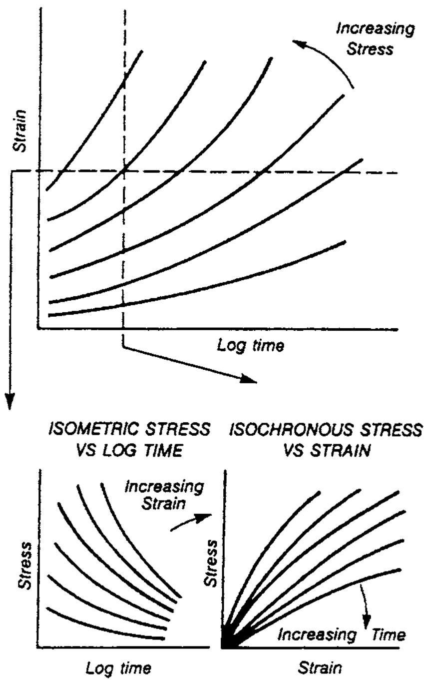
Since the modulus equals stress divided by strain, there is the appearance of a changing modulus.

The method of obtaining creep data and their presentation have been described; however, their application is limited to the exact same material, temperature use, stress level, atmospheric conditions, and type of test (tensile, compression, flexure) with a tolerance of ±10%. Only rarely do product requirement conditions coincide with those of the test or, for that matter, are creep data available for all grades of material. In those cases a creep test of relatively short duration such as 1,000 h can be instigated, and the information can be extrapolated to the long-term needs. It should be noted that reinforced thermoplastics and thermosets display much higher resistance to creep (Chapter 4).

The stress-strain-time data can be plotted as creep curves of strain vs. log time (Fig. 3.10 top view). Different methods are also used to meet specific design requirements. Examples of methods include creep curves at constant times to yield isochronous stress versus strain curves or at a constant strain, giving isometric stress versus log-time curves, as shown in the bottom views in Fig. 3.10.

To date the expected operating life of most plastic products designed to

Figure 3.10 Examples of different formatted creep vs. log time curves (Courtesy of Mobay/Bayer)



withstand creep is usually at least ten to twenty years. Available data at the time of designing will not be available so one uses available creep test-data based on at least 1,000 hours that is the recommended time specified in the ASTM standard. These long-time data have been developed and put to use in designs for over a half-century in designing plastic materials. An example is the engineering design and fabrication of the first all-plastic airplane.

Creep information is not as readily available as that from short-term property data sheets. From a designer's viewpoint, it is important to have creep data available for products subjected to a constant load for prolonged periods of time. The cost of performing or obtaining the test in comparison with other expenditures related to product design would be insignificant when considering the element of safety and confidence it would provide. Furthermore, the proving of product performance could be carried out with a higher degree of favorable expectations as far as plastic material is concerned. Progressive material manufacturers can be expected to supply the needed creep and stress-strain data under specified use conditions when requested by the designer; but, if that is not the case, other means should be utilized to obtain required information.

In conclusion regarding this subject, it can be stated that creep data and a stress-strain diagram indicate whether plain plastic properties can lead to practical product dimensions or whether a RP has to be substituted to keep the design within the desired proportions. For long-term product use under continuous load, plastic materials have to be considered with much greater care than would be the case with metals.

Preparing the important creep rupture data for the designer is similar to that for creep except that higher stresses are used and the time is measured to failure. It is not necessary to record strain. The data are plotted as the log stress vs. log time to failure. In creep-rupture tests it is the material's behavior just prior to the rupture that is of primary interest. In these tests a number of samples are subjected to different levels of constant stress, with the time to failure being determined for each stress level.

The overall behavior is the time-dependent strain at which crazing, stress whitening, and rupture decreases with a decreasing level of sustained stress. The time to develop these defects increases with a decreasing stress level.

Thermoplastic fiber RPs display a degree of creep, and creep rupture compared to RPs with thermoset plastics. TS plastic RPs reinforced with carbon and boron is very resistant to deformation (creep) and failure (creep rupture) under sustained static load when they are loaded in a fiber-dominated direction. The creep and creep rupture behavior of aramid fiber is not as good but still rather high. Creep and creep rupture with RPs has to take into consideration the stresses in matrix-dominated directions. That is fiber oriented directional properties influence the data.

In service products may be subjected to a complex pattern of loading and unloading cycles that is represented by stress relaxation. This variability of intermittent loading can cause design problems in that it would clearly not be feasible to obtain experimental data to cover all possible loading situations, yet to design on the basis of constant loading at maximum stress would not make efficient use of materials or be economical. In such cases it is useful to have methods for predicting the extent of the accumulated strain that will be recovered during the no load periods after cyclic loading.

Tests have been conducted that provide useful stress relaxation data. Plastic products with excessive fixed strains imposed on them for extended periods of time could fail. Data is required in applications such as press fits, bolted assemblies, and some plastic springs. In time, with the strain kept constant the stress level will decrease, from the same internal molecular movement that produces creep. This gradual decay in stress at a constant strain (stress-relaxation) becomes important in these type applications in order to retain preloaded conditions in bolts and springs where there is concern for retaining the load.

The amount of relaxation can be measured by applying a fixed strain to a sample and then measuring the load with time. The resulting data can be presented as a series of curves. A relaxation modulus similar to the creep modulus can also be derived from the relaxation data, it has been shown that using the creep modulus calculated from creep curves can approximate the decrease in load from stress relaxation. From a practical standpoint, creep measurements are generally considered more important than stress-relaxation tests and are also easier to conduct.

The TPs are temperature dependent, especially in the region of the plastics' glass transition temperature (Tg). Many unreinforced amorphous types of plastics at temperatures well below the T_g have a tensile modulus of elasticity of about 3×10^{10} dynes/cm^2 [300 Pa (0.04 psi)] at the beginning of a stress-relaxation test. The modulus decreases gradually with time, but it may take years for the stress to decrease to a value near zero. Crystalline plastics broaden the distribution of the relaxation times and extend the relaxation stress to much longer periods. This pattern holds true at both the higher and low extremes of crystallinity. With some plastics, their degree of crystallinity can change during the course of a stress-relaxation test.

Stress-relaxation test data has been generated for the designer. Plastic is deformed by a fixed amount and the stress required maintaining this deformation is measured over a period of time. The maximum stress occurs as soon as the deformation takes place and decreases gradually with time from this value.

Creep data in designing products has been used for over a century; particularly since the 1940s. Unfortunately there is never enough data especially with the new plastics that are produced. However, relationships of the old and new are made successfully with a minor amount of testing.

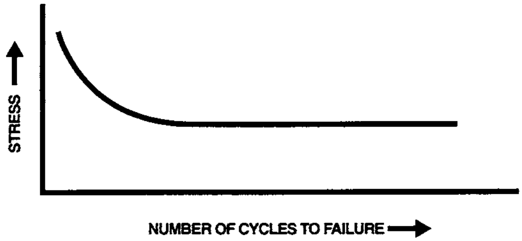
Fatigue

When reviewing fatigue one studies their behaviors of having materials under cyclic loads at levels of stress below their static yield strength. Fatigue test, analogous to static creep tests, provides information on the failure of materials under repeated stresses. The more conventional short-term tests give little indication about the lifetime of an object subjected to vibrations or repeated deformations. When sizing products so that they can be modeled on a computer, the designer needs a starting point until feedback is received from the modeling. The stress level to be obtained should be less than the yield strength. A starting point is to estimate the static load to be carried, to find the level of vibration testing in G levels, to assume that the part vibrates with a magnification of 10, and to multiply these together to get an equivalent static load. The computer design model will permit making design changes within the required limits.

If the loading were applied only once the magnitude of the stresses and strains induced would be so low that they would not be expected to cause failure. With repeated constant load amplitude tests, maximum material stress is fixed, regardless of any decay in the modulus of elasticity of the material. Constant deflection amplitude fatigue testing is less demanding, because any decay in the modulus of elasticity of the material due to hysteretic heating would lead to lower material stress at the fixed maximum specimen deflection.

Material fatigue data are normally presented in constant stress (S) amplitude or constant (s) strain amplitude plotted vs. the number of cycles (N) to specimen failure to produce a fatigue endurance S-N

Figure 3.11 Typical S-N curve



curve for the material (Fig. 3.11). The test frequency for plastics is typically 30 Hz, and test temperature is typically conditioned and tested in an environment of 23°C (73°F). The behavior of viscoelastic materials is very temperature and strain rate dependent. Consequently, both test frequency and test temperature has a significant effect upon the observed fatigue behavior. The fatigue testing of TPs is normally terminated at 10^7 cycles.

S-N curve provides information on the higher the applied material stresses or strains, the fewer cycles the specimen can survive. It also provides the curve that gradually approaches a stress or strain level called the fatigue endurance limit below which the material is much less susceptible to fatigue failure. A curve of stress to failure vs. the number of cycles to this stress level to cause failure is made by testing a large number of representative samples of the material under cyclical stress. Each test made at a progressively lowered stress level. This S-N curve is used in designing for fatigue failure by determining the allowable stress level for a number of stress cycles anticipated for the product. In the case of materials such as metals, this approach is relatively uncomplicated. Unfortunately, in the case of plastics the loading rate, the repetition rate, and the temperature all have a substantial effect on the S-N curve, and it is important that the appropriate tests be conducted.

There is the potential for having a large amount of internal friction generated within the plastics when exposed to fatigue. This action involves the accumulation of hysteretic energy generated during each loading cycle. Because this energy is dissipated mainly in the form of heat, the material experiences an associated temperature increase. When heating takes place the dynamic modulus decreases, which results in a greater degree of heat generation under conditions of constant stress. The greater the loss modulus of the material, the greater the amount of heat generated that can be dissipated. TPs, particularly the crystalline type that are above their glass-transition temperatures (T_g), will be more sensitive to this heating and highly cross-linked plastics or glass-reinforced TS plastics (GRTSs) are less sensitive to the frequency of load.

If the TP's surface area of a product is insufficient to permit the heat to be dissipated, the plastic will become hot enough to soften and melt. The possibility of adversely affecting its mechanical properties by heat generation during cyclic loading must therefore always be considered. The heat generated during cyclic loading can be calculated from the loss modulus or loss tangent of the plastics.

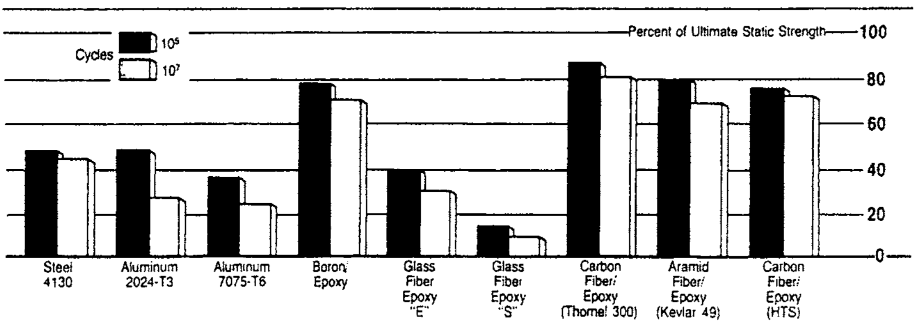
Damping is the loss of energy usually as dissipated heat that results when a material or material system is subjected to fatigue, oscillatory load, or displacement. Perfectly elastic materials have no mechanical damping. Damping reduces vibrations (mechanical and acoustical) and prevents resonance vibrations from building up to dangerous amplitudes. However, high damping is generally an indication of reduced dimensional stability, which can be very undesirable in structures carrying loads for long time periods. Many other mechanical properties are intimately related to damping; these include fatigue life, toughness and impact, wear and coefficient of friction, etc. Measuring damping capacity is equal to the area of the elastic hysteresis loop divided by the deformation energy of a vibrating material. It can be calculated by measuring the rate of decay of vibrations induced in a material.

This dynamic mechanical behavior of plastics is important. The role of mechanical damping is not as well known. Damping is often the most sensitive indicator of all kinds of molecular motions going on in a material. Aside from the purely scientific interest in understanding the molecular motions that can occur, analyzing these motions is of great practical importance in determining the mechanical behavior of plastics. For this reason, the absolute value of a given damping and the temperature and frequency at which the damping peaks occur can be of considerable interest and use.

High damping is sometimes an advantage, sometimes a disadvantage. For instance, in a car tire high damping tends to give better friction with the road surface, but at the same time it causes heat buildup, which makes a tire degrade more rapidly. Damping reduces mechanical and acoustical vibrations and prevents resonance vibrations from building up to dangerous amplitudes. However, the existence of high damping is generally an indication of reduced dimensional stability, which can be undesirable in structures carrying loads for long periods of time.

To improve fatigue performance, as with other properties of other properties use is made of reinforcements. RPs are susceptible to fatigue.

Figure 3.12 High-performance fatigue properties of RPs and other materials



However, they provide high performance when compared to unreinforced plastics and many other materials (Fig. 3.12). With a TP there is a possibility of thermal softening failures at high stresses or high frequencies. However, in general the presence of fibers reduces the hysteretic heating effect, with a reduced tendency toward thermal softening failures. When conditions are chosen to avoid thermal softening, the normal fatigue process takes places as a progressive weakening of the material from crack initiation and propagation.

Plastics reinforced with carbon, graphite, boron, and aramid are stiffer than the glass-reinforced plastics (GRP) and are less vulnerable to fatigue. (E-glass is the most popular type used; S-glass improves both short- and long-term properties.) In short-fiber GRPs cracks tend to develop easily in the matrix, particularly at the interface close to the ends of the fibers. It is not uncommon for cracks to propagate through a TS matrix and destroy the material's integrity before fracturing of the fabricated product occurs. With short-fiber composites fatigue life can be prolonged if the fiber aspect ratio of its length to its diameter is large, such as at least a factor of five, with ten or better for maximum performance.

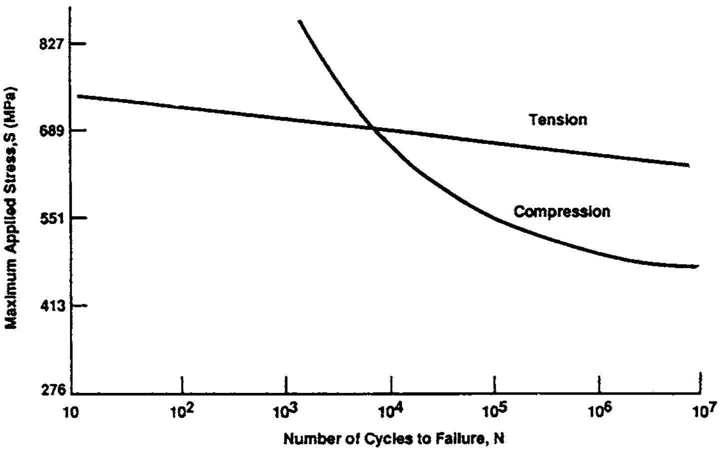
In most GRPs debonding can occur after even a small number of cycles, even at modest load levels. If the material is translucent, the buildup of fatigue damage can be observed. The first signs (for example, with glass-fiber TS polyester) are that the material becomes opaque each time the load is applied. Subsequently, the opacity becomes permanent and more pronounced, as can occur in corrugated RP translucent roofing panels. Eventually, plastic cracks will become visible, but the product will still be capable of bearing the applied load until localized intense damage causes separation in the components. However, the first appearance of matrix cracks may cause sufficient concern, whether for safety or aesthetic reasons, to limit the useful life of the product. Unlike most other materials, GRPs give visual warning of their fatigue failure.

Since GRPs can tend not to exhibit a fatigue limit, it is necessary to design for a specific endurance, with safety factors in the region of 3 to 4 being commonly used. Higher fatigue performance is achieved when the data are for tensile loading, with zero mean stress. In other modes of loading, such as flexural, compression, or torsion, the fatigue behavior can be more unfavorable than that in tension due to potential abrasion action between fibers if debonding of fiber and matrix occurs. This is generally thought to be caused by the setting up of shear stresses in sections of the matrix that are unprotected by some method such as having properly aligned fibers that can be applied in certain designs. An approach that has been used successfully in products such as high-performance RP aircraft wing structures, incorporates a very thin, high-heat-resistant film such as Mylar between layers of glass fibers. With GRPs this construction significantly reduces the self-destructive action of glass-to-glass abrasion and significantly increases the fatigue endurance limit.

Fatigue data provides the means to design and fabricate products that are susceptible to fatigue. Ranking fatigue behavior among various plastics should be conducted after an analysis is made of the application and the testing method to be used or being considered. It is necessary to also identify whether the product will be subjected to stress or strain loads. Plastics that exhibit considerable damping may possess low fatigue strength under constant stress amplitude but exhibit a considerably higher ranking in constant deflection amplitude and strain testing. Also needing consideration is the volume of material under stress in the product and its surface area-to-volume ratio. Because plastics are viscoelastic, this ratio is critical in that it influences the temperature that will be reached. At the same stress level, the ratio of stressed volume to area may well be the difference between a thermal short-life failure and a brittle long-life failure, particularly with TPs.

Like in metal and other material in any design books, factors should be eliminated or reduced such as sharp corners or abrupt changes in their cross-sectional geometry or wall thickness should be avoided because they can result in weakened, high-stress areas. The areas of high loading where fatigue requirements are high need more generous radii, combined with optimal material distribution. Radii of ten to twenty times are suggested for extruded parts, and one quarter to one half the wall thickness may be necessary for moldings to distribute stress more uniformly over a large area.

Figure 3.13 Carbon fiber-epoxy RPs fatigue data



In evaluating plastics for a particular cyclic loading condition, the type of material and the fabrication variables are important. As an example, the tension fatigue behavior of unidirectional RPs is one of their great advantages over other plastics and other materials. In general the tension S-N curves (curves of maximum stressed plotted as a function of cycles to failure) of RPs with carbon, boron, and aramid fibers are relatively flat. Glass fiber RPs show a greater reduction in strength with increasing number of cycles. However, RPs with high strength glass fiber are widely used in applications for which fatigue resistance is a critical design consideration, such as helicopter blades.

Fig. 3.13 shows the cycles to failure as a function of maximum stress for carbon fiber-reinforced epoxy laminates subjected to tension and compression fatigue. The laminates have 60% of their layers oriented at 0°, 20% at +45°, and 20% at –45°. They are subjected to a fluctuating load in the 0° direction. The ratios of minimum stress-to-maximum stress for tensile and compressive fatigue are 0.1 and 10, respectively. One observes that the reduction in strength is much greater for compression fatigue. However as an example, the RPs compressive fatigue strength at 10^7 cycles is still considerably greater than the corresponding tensile value for aluminum.

Metals are more likely to fail in fatigue when subjected to fluctuating tensile rather than compressive load. This is because they tend to fail by crack propagation under fatigue loading. However, the failure modes in RPs are very different and more complex. One consequence is that RPs tend to be more susceptible to fatigue failure when loaded in compression.

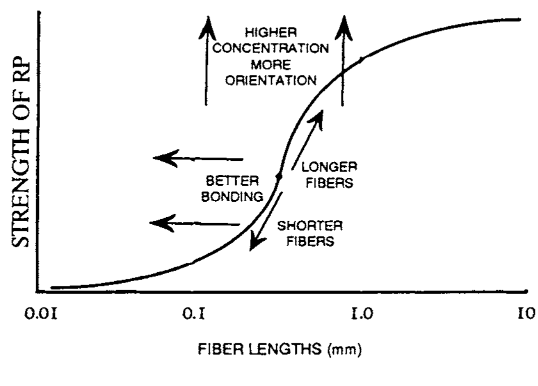
Fiber reinforcement provides significant improvements in fatigue with carbon fibers and graphite and aramid fibers being higher than glass fibers. The effects of moisture in the service environment should also be considered, whenever hygroscopic plastics such as nylon, PCs, and others are to be used. For service involving a large number of fatigue cycles in TPs, crystalline-types offer the potential of more predictable results than those based on amorphous types, because the crystalline ones usually have definite fatigue endurance. Also, for optimum fatigue life in service involving both high-stress and fatigue loading, the reinforced high-temperature performance plastics like PEEK, PES, and Pi are recommended.

Reinforcement performance

Reinforcements can significantly improve the structural characteristics of a TP or TS plastic. They are available in continuous forms (fibers, filaments, woven or non-woven fabrics, tapes, etc.), chopped forms having different lengths (Fig. 3.14), or discontinuous in form (whiskers, flakes, spheres, etc.) to meet different properties and/or processing methods. Glass fiber represents the major material used in RPs worldwide. There are others that provide much higher structural performances, etc. The reinforcements can allow the RP materials to be tailored to the design, or the design tailored to the material.

To be effective, the reinforcement must form a strong adhesive bond with the plastics; for certain reinforcements special cleaning, sizing, finishing, etc. treatments are used to improve bond. Also used alone or in conjunction with fiber surface treatments are bonding additives in the plastic to promote good adhesion of the fiber to the plastic.

Figure 3.14 Fiber strength vs. fiber length (Courtesy of Plastics FALLO)



Applicable to RPs is the aspect ratio of fibers. It is the ratio of length to diameter (L/D) of a fiber. In RP fiber L/D will have a direct influence on the reinforced plastic performance. High values of 5 to 10 provide for good reinforcements. Theoretically, with proper lay-up the highest performance plastics could be obtained when compared to other materials. To maximize strength and modulus of RPs the long fiber approach is used.

Different types of reinforcement construction are used to meet different RP properties and/or simplify reinforcement layup for certain fabricating processes to meet design performance requirements. They include woven, nonwoven, rovings, and others (Table 3.3). These different constructions are used to provide different processing and directional properties.

Table 3.3 Example of E-glass constructions used in TS polyester RPs

	Bulk Molding Compound	*Sheet Molding Compound*	*Chopped Strand Mat*	*Woven Roving*	*Unidirectional Axial*	*Unidirectional Transverse*
Glass content (wt %)	20	30	30	50	70	70
Tensile modulus GPa (Msi)	9 (1.3)	13 (1.9)	7.7 (1.1)	16 (2.3)	42 (6.1)	12 (1.7)
Tensile strength MPa (Ksi)	45 (6.5)	85 (12)	95 (14)	250 (36)	750 (110)	50 (7)

There are certain types of so-called nonwoven fabric that are directly formed from short or chopped fiber as well as continuous filaments. They are produced by loosely compressing together fibers, yarns, rovings, etc. with or without a scrim cloth carrier; assembled by mechanical, chemical, thermal, or solvent methods. Products of this type include melted and spun-bonded fabrics. The nonwoven spun-bonded integrates the spinning, lay-down, consolidation, and bonding of continuous filaments to form fabrics. Felt is the term used to describe nonwoven compressed fabrics, mats, and bats prepared from staple fibers without spinning, weaving, or knitting; made up of fibers interlocked mechanically.

A fibrous material extensively used in RPs are the mat constructions. They consist of different randomly and uniformly oriented products: (1) chopped fibers with or without carrier fibers or binder plastics; (2) short fibers with or without a carrier fabric; (3) swirled filaments loosely held together with a plastic binder; (4) chopped or short fiber with long fibers included in any desired pattern to provided addition mechanical properties in specific directions; (5) and so on.

There are reinforcement preform constructions. A preform is a method of making chopped fiber mats of complex shapes that are to be used as reinforcements in different RP molding fabricating processes (injection, etc.). Oriented patterns can be incorporated in the preforms.

When conventional flat mats are used, they may tear, wrinkle, or give uneven glass distribution when producing complex shapes. To alleviate this problem, it is necessary to take great care in tailoring the mat and in placing it properly in the mold cavity. Otherwise, mats may cause poor products or poor production rates. Preforms are used to overcome these problems. They are slightly more expensive for short production runs. However they are used when mats are considered impractical, or a relatively high production run exists that offsets the higher cost.

Fiber-reinforced plastics differ from many other materials because they combine two essentially different materials of fibers and a plastic into a single plastic composite. In this way they are somewhat analogous to reinforced concrete, that combines concrete and steel. However, in the RPs the fibers are generally much more evenly distributed throughout the mass and the ratio of fibers to plastic is much higher.

In designing fibrous-reinforced plastics it is necessary to take into account the combined actions of the fiber and the plastic. At times the combination can be considered homogeneous, but in most cases homogeneity cannot be assumed (Chapter 2).