TECHNICAL BULLETIN: PLASTICS PARTS DESIGN

*This article is a free adaptation of the entitled article "**Distinguishing Features of the Mechanical Design of Plastic Parts. Commentaries for the Undergraduate Student**". S.I. Krishnamachari, Pioneer Technologies, Inc. Naperville, IL.*

The creation of new technologies and materials in plastic industry has allowed the ongoing replacement of other materials such as metal, paper and ceramic in several industrial applications. Less weight, less costs and better appearance are some of the reasons that have allowed the growth on uses of plastic products worldwide. Unfortunately, the design criteria for plastic materials have followed the guidelines for more rigid materials design.

The process needed to achieve an efficient product design under such conditions involves two basic stages: the product and its individual elements design (such as reinforcement ribs, holes, edges, etc.), and stress analysis depending on the final product application.

The most important design parameters that must be considered in order to manufacture plastic parts are presented below. The purpose is that readers can learn about design criteria of different materials depending on final application, as well as minimal required conditions that will ensure both manufacturers and consumers a good-quality part.

1 Stress Analysis in Plastic Parts Mechanical Design

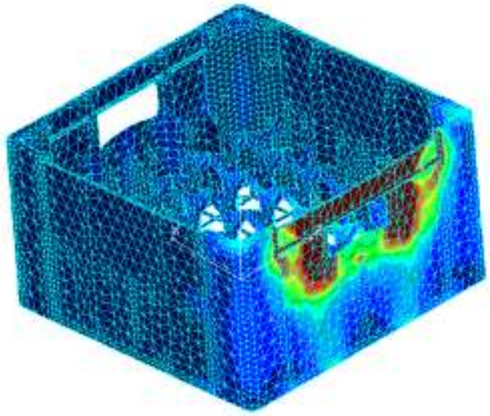
A stress analysis of load conditions that a part will undergo is essential when designing a product with certain mechanical requirements. This analysis is based on basic properties of plastic materials, as well as on different load conditions (stockpiling, stretching, bending, etc.), that product could undergo. Improper use of product could also be analyzed in order to prevent failures, or suggest modes of use.

The design factor that involves such features is called **Safety Factor** (**SF**), which is an *unknown factor*. SF ensures that the design fulfills all application´s mechanical requirements, even if there is a large difference between real life and results theoretically obtained from analysis of idealized models; considering that the design can be affected by much unquantifiable elements.

The chosen SF must reflect aspects such as material behavior, use, service conditions, among others. Therefore, a SF could be chosen in different ways for different products, materials, and specific material failure modes. Table 1 (at the end of this bulletin) shows some SF recommendations for different conditions of use. Other different use criteria are described herein below:

2 Static Resistance and Stiffness

Static strength and stiffness are the most demanded features for plastic parts. However, when both features are required in unfilled materials, stiffness requirements must be predominant. These parameters depend on the short-term strength and tensile module, respectively. Most technical products data sheets show these values.

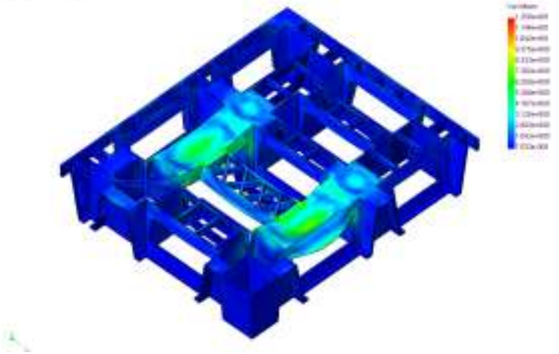


Usually, it is considered that a SF of 1.5 to avoid yielding and maximum allowable displacement provides a proper protection in order to achieve desired static strength and stiffness. This SF value is a traditional value that has been successfully used in metal and nowadays in plastics.

Historically, this SF was set when there was not a detailed knowledge of material resistance, and when stress concentration theory was not developed yet; therefore, a SF of 1.5 was used in order to avoid stress concentration and yielding. Now it is known that in many cases, depending on product application, this value tends to be very high and it results in excess of material, high-cycle times and generally a higher cost per part.

In displacement case, it is also necessary to apply this SF value, because long-term accumulative effects must be considered. Deformation could be unacceptable in long term and it could even fail at low stress levels

On the other hand, the use of this SF is extremely important under permanent load conditions, since most unfilled plastics tend to undergo creep[*] during early stages of static load.



Let's take the case of a 210-liter container that must be stockpiled in 3 or 4 levels. If this part is not properly designed, its bottom zone may suffer the "elephant leg" effect due to creep.

Even if this effect does not cause a catastrophic failure of the part, or spilling of its contents; this is not a desired situation as the container cannot be stockpiled due to its new shape. Therefore, short-term deformations must be restricted in a better way.

3 Non-Linear Stress - Deformation Behavior

The relationship between stress (applied load) and loaded part deformation when deformation and/or stress are low, tends to be proportional, elastic, and recoverable. They are inter-related through the Elastic Modulus (E) that can be measured by various methods. In most cases, it is desired that stresses in a plastic product were located at this zone because of deformations are recoverable when load ceases. However, sometimes it is necessary to perform an analysis where loads or deformations exceed such status. A simple elastic-linear analysis can be used in order to calculate stress or deformation of any part that shows a non-linear elastic behavior. It is only necessary to adjust SF by using the relationship between tangent modulus and secant modulus. This SF is given then by: $SF=1.5\cdot[E_{tan}/E_{sec}]$[†]

This SF value is chosen because of displacement increases by a factor of $[E_{tan}/E_{sec}]$ for non-linear behavior materials. Therefore, stiffness problems are solved using this factor.

Material resistance is usually measured by a permissible deformation. In stress concentration areas, it is reasonable to assume that stress can be read from load-displacement curves, without using advanced methods such as computer simulation. However, the established SF value is too conservative, so proper simulations might be required as an alternative to analyze part deflection, where SF modification is not necessary at all.

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[*] *Creep* is a slow yielding or material deformation when it is under loads during long periods of time. Thermoplastic materials are more sensitive to creep than metal, glass or even wood.

[†] For further information about the different methods of modulus measurement, please contact your seller or the Marketing Management of Polinter.

4 Fatigue

Fatigue is understood as part failure under cyclic stress. One of the most representative examples is the "flip-top" cap of a toothpaste tube.

Structures undergoing cyclic load require a very high SF value according to load cycles number. It is recommended a SF of 10 when considering number of cycles, or a SF of 2 when preventing failure by stress level. For example, for a part that requires over 50,000 load cycles, with a yield stress of 25 MPa (3,226 psi), the recommendation can be the following:

- Find the stress corresponding to 500,000 cycles (by using a SF of 10 in number of cycles) and change design to limit the stress in concentration areas to this value. This determination might be complex if there is a lack of proper laboratory equipment.
- Change the design to limit the stress in concentration areas to 12.5 MPa -1813 psi - (means to use a SF of 2 to prevent stress). In this case, traditional stress analysis methods or static load simulations should be used.

At this point, SF is high because failure related to fatigue is very sensitive to microscopic local imperfections in critical areas, depending on several variables that are difficult to control, either by the resin supplier, or the product manufacturer. It is also very common that imperfections and high stress appears simultaneously in the same place, and such vulnerabilities cannot be quantitatively considered in the design, therefore a high SF must be used. It is important to mention that all the failure modes must be considered, and not fatigue cases only.

Results obtained from fatigue curves can be very scattered because of high sensitivity of failure modes to local defects. Fatigue simulations required a deep knowledge of the problem and material behavior, even if it is performed with specialized software programs.

It is important to highlight that fatigue stress evaluation must include stress concentration analysis that occurs in corners, reinforcement ribs, etc. On the other hand, as plastic parts generally undergo under fatigue stress with low deformation but high cycle frequency, a linear stress analysis could be precise enough.

5 Creep

Creep is a common phenomenon in plastic parts, and usually a deformation creep limit is set for a plastic product. This deformation (ε_{all}) must be less than break deformation at the end of service life (T). A very conservative protection can be reached by selecting a proper design stress, defined as:

$$\sigma = \text{Min}\,(\sigma_1, \sigma_2, \sigma_3),$$

where:

σ_1= (stress at ε_{all} deformation at the end of life, T) / (SF=10)[‡].

σ_2: (stress caused by cracks at the end of time, T) / (SF=1.0)

σ_3: (rupture stress at the end of time, T) / (SF=1.5).

Short-term deformation variable and stress criteria are implicit in these expressions. Short or long-term stress analysis requires more sophisticated tools such as simulation programs.

A SF of 1.0 for σ_1 and σ_2 can be used when part failure will not be catastrophically once it reached the allowed deformation; in this case, the product may be retired without any damage. However, creep failure is usually catastrophic and in such cases a SF of 1.5 is necessary.

It is important to mention that crack growing and fracture are found in high stress concentration areas. Thus, product design must fulfill these requirements in order to keep stress and concentration effects lower than σ. These criteria are used in local design elements, such as reinforcement ribs, interfaces with metal inserts,

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[‡] Usually, this is the criteria applied on the design of containers by the technical staff of Polinter as support of its customers.

and other features where the fracture mechanism will probably start.

6 Constant Thermal Stress

From a thermal-stress point of view, it is not necessary to add an additional SF in a part design process. It is just necessary to use proper design criteria (such as avoid thermal expansion or contraction). In contrast, it is recommendable to keep thermal and load stresses less than 80% of the short-term yield stress.

SF is not required for thermal stress analysis because, firstly, these thermal stresses are very low in plastic materials, and secondly, these stresses tend to relax along time. The speed of relaxation of thermal stress is approximately equal and opposed to creep rate. Therefore, it is not possible to cause a catastrophic material failure due to the solely action of thermal stresses, either on long or short term.

7 Thermal and Creep Cycles

There are many products that undergo relatively regular load / unload cycles, and in many situations these include thermal cycles. In this way, the part passes through deformation and recovery cycles according to material stress–creep–time–temperature ratio.

Usually, stress occurs at high temperatures, while relaxation occurs at room temperature. This is an interesting situation because creep deformation speed increases at higher temperatures, whereas relaxation speed at room temperature is somewhat slow (just as creep at room temperature). In consequence, creep deformation is not fully recoverable and each cycle accumulates certain amount of residual deformation in those high-stress areas.

The unique limit set for design is $\varepsilon(T) \leq \varepsilon_{all}$, wherein $\varepsilon(T)$ is the accumulated deformation at the end of part lifetime, and ε_{all} is the allowable material deformation. However, stress or accumulated deformation calculation per cycle is not an easy task.

8 Periodical Vibration

Periodical vibration is related with an identifiable excitation force that is usually caused by a rotating machine, such as hand tools. Plastic components under vibration must be stiff enough in a way that its natural frequency (NF) is at least twice than the machine rotating frequency. This value of NF>2 is recommended when stresses in dynamical conditions are less than those in static conditions.

If there is more than one excitation frequency caused by a rotating machine or any other source, it is recommendable to use simulation software programs to obtain more precise values for Safety Factors.

9 Random Vibrations

Random vibrations are those occurring when a wide array of excitation frequencies is present all the time, so it is not possible to design for a particular frequency. The following indicators may be used as a guide for parts design:

- Use high stiffness, proper edges radii, proper methods for parts assembly and control processes, so that residual stresses are minimized. Altogether will reduce stress response.
- Include additional support points or additional mass.
- It is acceptable to ignore ribs as they turn into stress conservative estimations in natural frequency calculation and modal analysis.

A high material resistance will also increase frequency values of resonance; therefore, energy values are lower.

A real random vibration example occurs on car windshields when they are raised. Wind loads are a perfect example of random vibration. As reinforce ribs cannot be added, all the stiffness must come from shell-shaped window, and latch methods as well.

If simulation tools are used to analyze these cases, it is recommended to use highly detailed models in order to detect small sources of stress concentration that might act as failures acceleration elements. However, computer hardware, software programs, and CPU times are expensive.

10 Buckling

Buckling is defined as an instance of lateral bending or bowing of the part due to a compressive load. Buckling occurs when compressive-resulting stresses, combined with a bowing effect, are predominant in certain parts of the component (see figure).

In order to prevent buckling, it is required to increase part stiffness. The three components that provide part stiffness are: material elastic modulus, part thickness, and reinforcement elements.

A SF of 2 is generally applied to buckling critical load, which is also calculated by a non-linear buckling analysis software. In other words, the minimum part buckling resistance must exceed by two the applied load. The ways to achieve this, using the same material, are: increasing part thickness, increment the ribs number and height, as well as increase the supports number. These analyses may be provided by Polinter's Technical Assistance Services.

As plastics are low-stiffness materials, almost all structures are prone to fail due to buckling. Moreover, many plastics processing techniques limit part thickness. In consequence the part will lack stiffness; so reinforcement elements are required to avoid this failure mode.

Other well-known factors, such as load eccentricity, non-uniform properties, thickness variations, and non-linear behavior of the material, tend to reduce part buckling strength. On the other hand, it must be recognized that, for any given material or part, there are no natural effects that increase buckling strength but proper design of elements that can increase such resistance.

Considerations inherent to a stress analysis as stage in the plastic part design process have been reviewed. It is important to keep in mind that all proposed conditions are intended to the designed part **endurance** under certain loads or deformations without failing. In none of the cases, it is required that the part failed or yield in some way. However, there are some design criteria for applications in which the material failure is required, for example, in tamper-evident seals.

11 Thickness Limits and Use of Reinforcing Elements

A special feature of all plastic part designs is that manufacturing process imposes a limit on part thickness. It seems that a maximum universal thickness limit of 15-20 mm is applied to all plastic, regardless of the process. Nevertheless, for most plastic parts, lengths and width are considerably larger than thickness. This is the reason why reinforcement elements are needed and some rules of thumb need to be considered when ribs are designed:

- In order to achieve greater stiffness, it is recommended to place a great deal of shorter, thinner ribs than lesser ribs that are thicker or taller. Because larger ribs generate torsion buckling problems under eccentric loads, besides the greater stresses generation at the ribs tips.

- A reduced number of larger ribs provide stiffness only when stresses are high, and it reduces part weight compared to a larger amount of ribs with less height that provides the same stiffness at a reduced level of stresses, but with a higher part weight.

- It is recommendable to place ribs in two perpendicular directions, even if the design does not strictly require them in the second direction.

The geometrical design of a reinforcement rib is commonly obtained from the extrapolation of previous successful designs, and generally there are no specific rules for a more efficient design. A balance must exist between part thicknesses imposed by the processing method, the rib height imposed by the permissible stress, and the fulfillment of both weight and stiffness requirements as well.

Other physical reasons that make ribs design complex are: (i) generally they are created on curved surfaces; (ii) their height is not constant and the tip might follow a certain contour shape; (iii) it could be partially slotted due to assembly reasons; (iv) they could have a hole for inserts; (v) ribs are spreaded unevenly. It is recommended to exceed the required stiffness in the initial design due to these difficulties and thereafter optimize it by using simulation software tools.

Although ribs and other reinforcements might considerably increase the part stiffness, the geometrical ribs shapes depend on the processing method to be used. Here are some aspects related to the stiffness of the part, depending on the molding technique:

- Injection molded parts might be designed for a desired bending stiffness, but in general they are deficient in terms of torsion stiffness due to the presence of open ribs (visible).

- Gas-assisted process produces hollow ribs that might increase both bending and torsion stiffness. However, the process only allows placing few ribs in pre-selected locations. On the other hand, it must be considered that these hollow ribs cannot intercept each other and the gas assisted injection molding method is used for relatively large-part manufacturing.

- Rotomolding or double layer products, in which two opposed surfaces are designed to be in contact and merged together, have a high bending and torsion stiffness.

- Blow-molded bottles, drums, and containers have high stiffness due to its geometry, which (generally) is round.

12 New Concepts in Plastic Parts Design

Plastics’ low stiffness (compared to metal) is not a disadvantage since new design concepts and elements have been developed depending on this property. Among the newest elements, there are “snap fits” that are used in removable or non-removable packages, and that might be integrated in the part. These elements could not be added in materials such as metal and represent a great advantage with a reasonable cost and less amount of material.

Part consolidation is another new concept. This means the possibility of combining several functions in a single part. In the case of metals, many separated parts had to be joined, which implies more time, costs and production challenges.

Finally, there are new products with a very high impact strength obtained thanks to plastic material´s high capacity deformation and low stiffness.

Considering these aspects, there is an important development of a wide variety of products based on the concept that part must fail under certain loads. The best examples are medical applications and hygienic packages. Lids of dairy products, for example, may protect bottle contents if it falls, but it can be broken easily when the correct load is applied, as when opening the package.

Other unique functions have been achieved with plastics, some of which are:

- Energy-absorbent articles, soundproof panels and vibration dampers that take advantage of the materials viscoelastic properties.
- Support elements widely used in anti-seismic support systems, by using a viscoelastic gel that is forced through small orifices in which a piston is placed and the gel passes through piston at a very low speed, but they clog and solidify if high speed is produced by earthquakes.
- Materials with either high or low friction coefficient, which are widely used in home applications.
- Impact-resistant materials, such as application that stop high speed projectiles.

Table 1. Safety Factor recommendations for different use conditions for plastic parts.

Main characteristic of behavior		Safety Factor (SF)	Applied SF on:
1	Strength, Stiffness	1.5	Yield stress, maximum allowable displacement.
2	Non-linear behavior	1.5 [E_{tan}/E_{sec}]	Yield stress, maximum allowable displacement.
3a	Fatigue	10	Allowable number of cycles
3b	Fatigue	2	Endurance Limit
4	Creep resistance Life = T hours	Apply design stress: =Min(σ_1, σ_2, σ_3), wherein: σ_1: (stress caused by a deformation of ε_{all} at the end of life time T). σ_2: (stress causing crazing at the end of time T). σ_3: (stress caused by the rupture at the end of time T)	
5	Thermal Stress	1.5	Total stress due to mechanical loads and thermal stresses
6	Periodic Vibration	2.5 ~ 3.0	Forced frequency
7	Random Vibration	Hard to predict, it is recommended the use of specialized help if it is the predominant behavior of the part.	
8	Buckling	2.0	Required Buckling Resistance. Use non-linear buckling analysis.
9	Failure Design	≤ 1.0	Detailed analysis by means of simulations. Product Trial.

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