Lifetime Prediction of Plastic Parts - Case Studies

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ABSTRACT

Lifetime prediction of plastics is a very difficult proposition, but one that is becoming increasingly important as plastics are used in more demanding and critical applications. The lifetime of a plastic part is influenced greatly by many factors including the type of plastic, stress level, temperature, type of loading, and environmental conditions. All these factors make absolute lifetime prediction a nearly impossible task. However, by understanding how these factors influence plastics over time, one can begin to make educated predictions with some level of accuracy. This paper will discuss techniques that can be used to predict the lifetime of a part. Case studies are given that show the application of lifetime prediction of two industrial applications.

INTRODUCTION

Plastic parts fail through a variety of mechanisms including stress overload, chemical attack, environmental stress cracking, fatigue, and creep. Many of these failures can be avoided by understanding how the specific plastic being used behaves under a certain load at the expected environmental conditions. Lifetime prediction or predicting when a failure will occur can be a powerful method to understand why a part failed. The true benefit of lifetime prediction is using it to prevent failures from taking place. This paper will focus on predicting plastic failures that occur through creep.

Polymer creep, along with variances of it, is a leading mechanism of failure. Figure 1 illustrates the stress versus time to creep rupture of various materials [1]. The y-axis (time = 0.0) represents the properties obtained from classical stress-strain testing following ASTM D 638 [2]. This graph clearly illustrates that the strength of a plastic sample decreases over time. For instance, if one follows the plot for polyacetal (POM) one can see that the stress required to induce failure decreases from approximately 70 MPa to 35 MPa at room temperature. This graph also illustrates an important concept with plastics: one cannot predict the behavior over time with simple single point data/testing, e.g. ASTM D 638. Multipoint data or data taken over time and/or temperature is needed to make these types of predictions. Many engineers that are not familiar with designing with plastics are very surprised by this concept and may not truly appreciate it until a failure occurs because of it.

MATERIAL DATABASES

There are numerous sources of multipoint data including books [3] and electronic databases on the internet [4]. Much of the data in these resources follow ASTM D 2990 “Standard Methods for Tensile, Compressive, and Flexural Creep and Creep Rupture of Plastics” [5] where the tests are performed over an extended period of time, e.g. 1,000 to 10,000 hours. This data can be very useful, if it is available for the temperature and the intended lifetime at which the plastic part will be used. If prediction is needed at an unavailable temperature, extrapolation of the available data can be difficult.

Case Study: Analysis of an Electrical Connector

Figure 2 shows a part made of poly(butylene terephthalate) (PBT) that was found to be cracking at an outer corner. The failure was taking place between the time the part was shipped and received by the original equipment manufacturer (OEM). The fracture surface was extremely smooth with very little evidence of ductility. The manufacturer stated the stress at break for this material was 55 MPa and finite element analysis was performed showing the highest stress in the part, which was at the location of failure, was 45 MPa. The conclusion of the manufacturer’s study was that since the load on the part was markedly lower than the maximum stress, the part should have no issues, Figure 3. From the graph shown in Fig. 1 it should be clear that this statement is extremely dangerous and incorrect.

Using multipoint data from the CAMPUS® materials database [4], one can predict the cracking that took place. Figure 4 shows the strain of the plastic material over time at various stresses. The stress the part was exposed to, as calculated with the finite element analysis, is higher than any of the tests shown in the CAMPUS data. However, one can see that at the maximum stress of 30 MPa, the part is shown breaking after approximately 1000 hours. Though this timeframe is longer than the failure time of approximately one to two weeks, it does illustrate that this material will have trouble with the applied load when used at room temperature. Thus, using data that is readily available from the internet one may be able to quickly determine if this part will have issues.

Creep testing of materials following ASTM D 2990 can be expensive and will take a relatively long time. For this reason creep data are rare and what is available is typically at room temperature and tested for short periods of time.

DYNAMIC MECHANICAL ANALYSIS (DMA)

A method that can overcome the deficiency of requiring long periods of testing at each temperature of interest utilizes a technique called dynamic mechanical analysis (DMA). This technique is used to evaluate the viscoelastic response of a material to a dynamic and typically oscillatory load. Variables such as stress, strain, frequency, and temperature can be controlled in order to examine the material's response. Different DMA instruments are specifically designed to accurately control and monitor specific variables. For example, some units are strain-controlled allowing the system to accurately control the amount of strain applied to a sample. Similarly, stress-controlled units will accurately control an applied stress. Most strain-and-stress controlled instruments will also have the capability of applying a constant strain or stress to a sample, respectively.

It is known that viscoelastic materials show an equivalency of time and temperature. The response that the material will have to an applied stress or strain at a lower temperature is equivalent to the behavior of the material when subjected to that stress or strain during shorter time scales. Correspondingly, higher temperatures are equivalent to longer time scales. Based on this equivalency, the behavior of a material at very long or very short time scales that are impractical or impossible to test with current equipment can be examined. This equivalency is known as the time-temperature superposition (TTS) and is a technique that can be used concurrently with DMA to characterize a polymeric material. This technique can be applied to examine material behavior under constant stress (creep-TTS) or under constant strain (stress-relaxation-TTS). Additionally, since frequency is the inverse of time, isothermal frequency sweeps (frequency-TTS) can also be used to evaluate the short and long-term behavior of a polymeric material.

Utilizing creep-TTS [6], this instrument can be used to generate what is called a master creep curve, which gives the apparent modulus of the material over a long period of time at the temperature selected. Figure 5 shows the apparent modulus at various temperatures of an exemplar material. The time required for each test takes minutes instead of hours or years. After all runs are completed the reference temperature is selected, which is typically the temperature at which the plastic will be used in the field. A master curve is then generated with the data for the reference representing the actual test time for this sample. The plots representing the apparent modulus at the other temperatures are then horizontally shifted over and aligned to create the master creep curve, Fig. 5. Depending on the material and testing conditions, different models such as WLF and Arrhenius [7] are used to determine shift factors that will aid in the generation of the master curve. With this information the strain over time at a specified load can be calculated. Performing a classical stress-strain test following ASTM D 638 the equivalent strain at yield can be determined and the failure criterion established, Fig. 6. To evaluate the part's lifetime, the stress on the part needs to be determined. This is typically done by structural analysis using the finite element method. This step in the analysis is not trivial, but can give good insight to where stresses are highest and the effect of changing geometry to reduce stress.

Case Study: Analysis of an Industrial Fan

The need to reduce noise emitted by an industrial fan was the driving factor behind a switch from metal to plastic. Design flexibility allowed the company to modify the shape of the blades to give optimal air movement with reduced noise, Fig. 7. The fan measured approximately 760 mm in diameter and a depth of 95 mm. To ensure product performance, injection molded glass reinforced polypropylene fans were endurance tested at elevated temperatures during the development stage. Cracking developed in a number of the test fans after 9 to 11 weeks of continuous operational testing. All cracks occurred at the outer support between the fan blades and coincided with a knitline, Fig. 8. Analysis of the crack surface using the scanning electron microscope showed the crack initiated at the outer peripheral and propagated through dynamic fatigue, Figs. 9 and 10. Good bonding between the fiber and polymer was observed, but most fibers were oriented in the same plane as the knitline, Fig. 9. Strength of the part at the knitline reduces for most plastics and is a common location for failure. Glass reinforced polypropylene is a material that experiences a significant decline in strength at the knitline, Table 1. The table shows that the reduction in material strength reduces to the point where a part without glass reinforcement may produce a stronger part than with glass. The table also shows the material properties for unreinforced and glass reinforced nylon 6/6. There is a reduction in material strength at the knitline; however, the percent loss is significantly less. Properties at the knitline of the glass reinforced nylon 6/6 are much higher than the glass reinforced polypropylene.

Table 1 – Effect of Knitline on Mechanical Properties [8].

Material	Reinforcement	Full Fiber	Knitline	% Retained
Polypropylene	None	5,400	4,650	86
Polypropylene	30% Glass	9,800	3,330	34
Polypropylene	40% Glass	13,700	4,700	34
Nylon 6/6	None	11,500	11,170	97
Nylon 6/6	30% Glass	24,200	14,760	61
Nylon 6/6	40% Glass	28,830	14,990	52

Fourier transformation infrared spectroscopy (FTIR) was conducted to ensure the material was polypropylene and that degradation from oxidation had not taken place, Fig. 11. Molding trials showed the knitline that formed was severe and very little could be done to improve flow, Fig. 12.

Though the failure mechanism was determined to be dynamic fatigue, this mode of failure is closely related to creep [9] and it was concluded that DMA could be used during the product development of the fan to:

- evaluate when failure would occur with glass reinforced polypropylene;
- analyze the effect of the knitline;
- identify an alternate material that would perform at elevated temperatures at the knitline for a long period of time.

One of the alternative materials investigated was nylon 6/6 with 30% (wt) glass loading.

To understand the stress level in the fan, a structural analysis study was performed using the finite element method, Fig. 13. Location of the highest stress correlated well with the crack initiation site. The maximum stress was calculated to be 5.5 MPa [800 psi].

Samples (polypropylene and nylon) were removed from the part at the knitline (denoted as "knitline" samples) and away from the knitline (denoted as "full fiber" samples) for the DMA testing and to establish the failure criteria. The failure criteria were established utilizing ASTM D 638 at an elevated temperature that equaled the maximum service temperature. Table 2 shows the equivalent strain at yield selected as the failure criterion.

Table 2 – Equivalent Strain at Yield (% Strain).

Material	Full Fiber	Knitline
Polypropylene	1.25	1.25
Nylon 6/6 - Dry	1.50	1.70
Nylon 6/6 - Conditioned	2.00	2.40

Testing with the DMA, was completed at the elevated service temperature and progressively higher temperatures, and the modulus curves were shifted relative to the elevated service temperature result to give the creep master curves, Figs. 14 and 15. The nylon samples were run in a dry and conditioned state. With the apparent modulus over time and the applied stress known, the strain of the polymer was calculated following Hooke's law, Figs. 16 and 17. Using the failure criterion established earlier, the time to failure was predicted, which was calculated to be approximately 7 weeks, Fig. 16. This was in line with the failure time experienced with the tests fans of 9 to 11 weeks. Failure was not predicted to occur at the full fiber regions with glass reinforced polypropylene in the timeframe tested. More importantly, failure was also predicted not to occur for any of the nylon samples, including those at the knitline, Fig. 17.

This investigation showed that creep-TTS via DMA was able to predict time to failure quite accurately. Further, this technique was able to show that using 30% glass filled nylon 6/6 will work for this application. The manufacturer of the fan performed continuous long-term testing to confirm that nylon material would not fail. Additionally, the nylon fan has been successfully used since the product was launched.

CONCLUSIONS

Lifetime prediction of a plastic part is one method that can be used to prevent failure. Other techniques commonly used are over designing the part, employing rules of thumb, and utilizing experience with a similar part and material. If a failure does occur, lifetime prediction can be an important technique to help determine the cause.

The change of properties over time leading to creep is a primary cause of failure and one that cannot be predicted using traditional single point material property data. The ability to predict the lifetime of a plastic product is becoming more important as plastics are used in more demanding applications where failure can lead to personal injury or large monetary losses. Some multipoint data exist in online databases that can help assess the long-term behavior of plastics. A case study was given showing how a failure could have been prevented by using this type of information. However, extrapolation of data to longer times than what was tested and to other temperatures is difficult. This paper showed how dynamic mechanical analysis can be used to perform short-term testing along with time-temperature superposition for predicting long-term material behavior. A case study showed how this technique was successfully applied to predict failure and then used to choose an alternate material. This material has been successfully used in the field since the product was launched. More importantly, it gave the manufacturer confidence that the part will perform as expected at extreme conditions for the lifetime of the unit.

It is important to note that using creep-TTS or other techniques to predict failure should be used with caution. There are numerous variables that contribute to the behavior of the plastic that are not evaluated when performing lifetime prediction. The real usefulness of these techniques is not to predict the actual time to failure, but for comparing the performance of materials to one another.

REFERENCES

[1] ASM International, Engineering Plastics, Volume 2, Engineered Materials Handbook (1988).
[2] ASTM D 638, "Standard Method for Tensile Properties of Plastics."
[3] Domininghaus, H., Plastics for Engineers, Hanser Publishers (1993).
[4] www.materialdatacenter.com, CAMPUS® materials database.
[5] ASTM D 2990 "Standard Methods for Tensile, Compressive, and Flexural Creep and Creep Rupture of Plastics"
[6] Sepe, M., "The Materials Analyst: Part 67," A matter of time-Part 2, Injection Molding Magazine.
[7] Osswald, T.A. and G. Menges, Material Science of Polymers for Engineers, Hanser, (1995).
[8] LNP Clouw, McDowell & Gerakaris, Plastics Technology, Aug. 1976.
[9] Hertzberg, R., Manson, J., Fatigue of Engineering Plastics, Academic Press (1980).

FIGURES

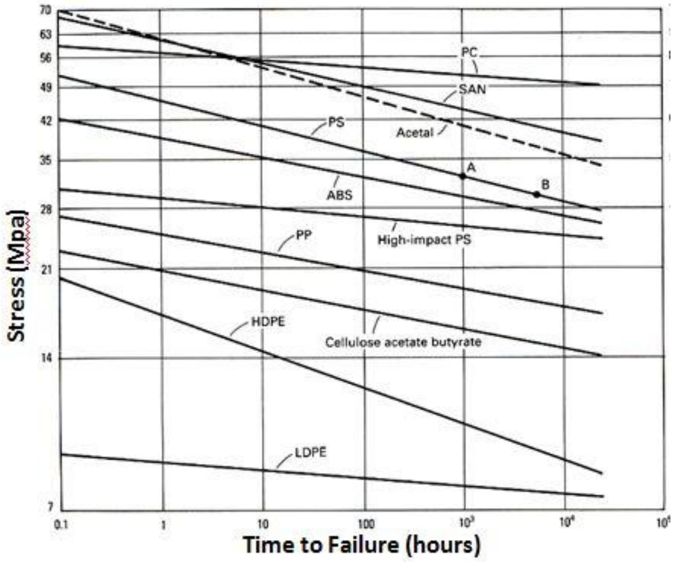
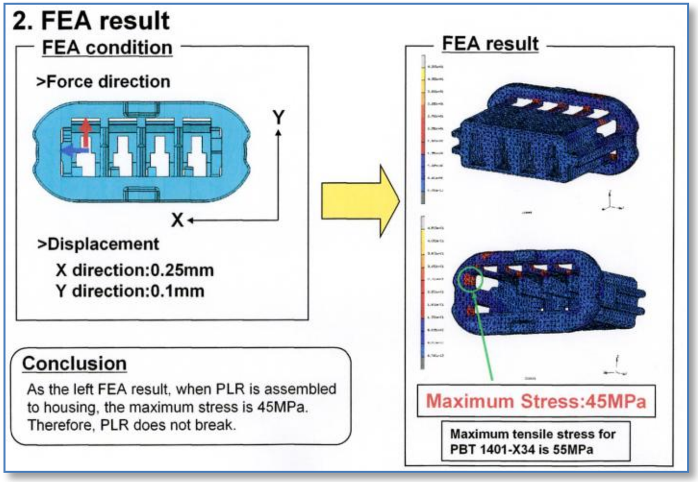


Figure 1 – Creep rupture stress of several polymers at 20°C [1].

Figure 2 – Cracking of a poly(butylene terephthalate) (PBT) part that took place between the part manufacturer and the OEM.



2. FEA result

FEA condition

>Force direction

>Displacement

X direction:0.25mm
Y direction:0.1mm

Conclusion

As the left FEA result, when PLR is assembled to housing, the maximum stress is 45MPa. Therefore, PLR does not break.

FEA result

Maximum Stress:45MPa

Maximum tensile stress for PBT 1401-X34 is 55MPa

Figure 3 – Finite element results show the high stress at the area of cracking and the conclusion by the manufacturer was that the part should not fail.

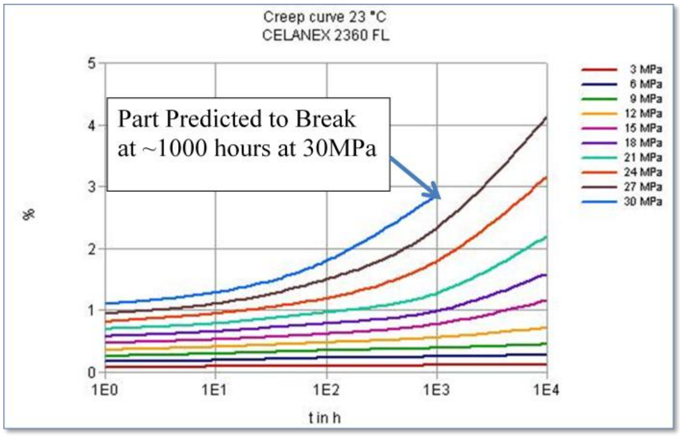


Figure 4 – Strain versus time of a poly(butylene terephthalate) (PBT) at various stresses at room temperature [4].

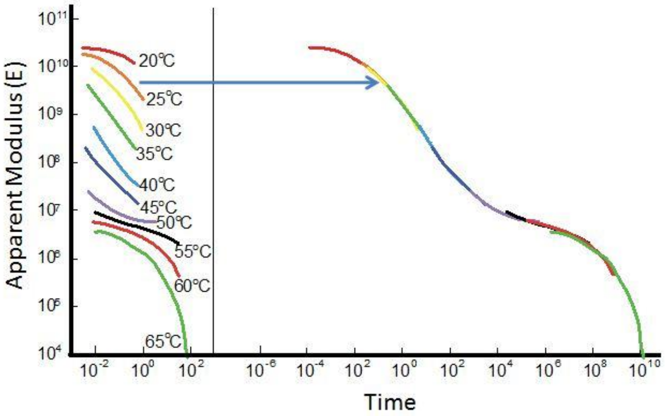


Figure 5 - Apparent modulus at various temperatures of an exemplar material and the creep master curve at 25°C.

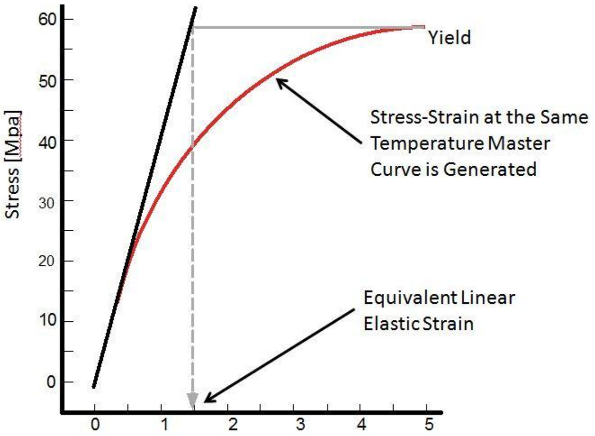


Figure 6 – Stress-strain plot of exemplar material showing the equivalent strain at yield.

[redacted]

Figure 7 – Industrial fan analyzed with DMA for lifetime prediction.

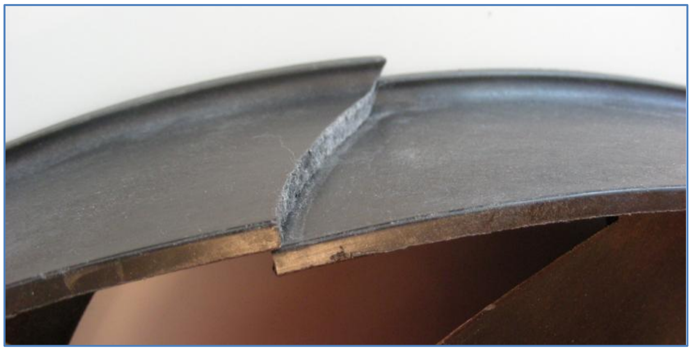


Figure 8 – Close-up of crack at knitline.

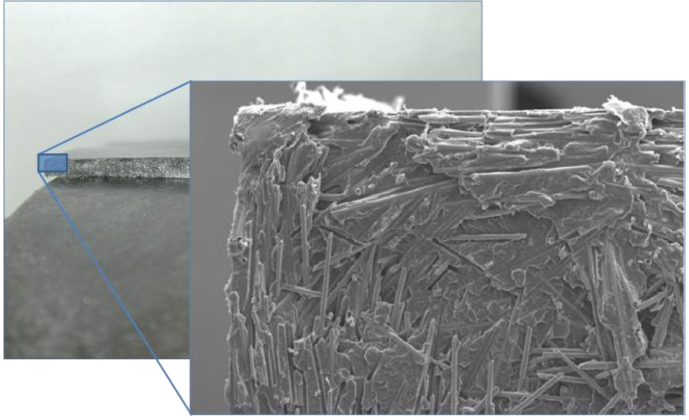


Figure 9 – SEM of crack initiation site.

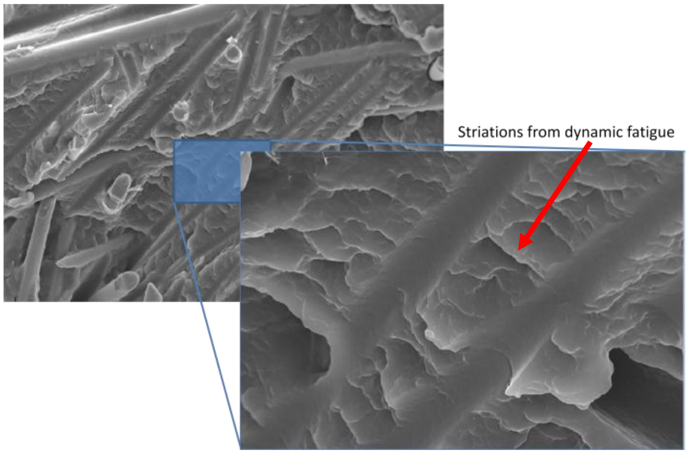


Figure 10 – SEM near crack initiation site.

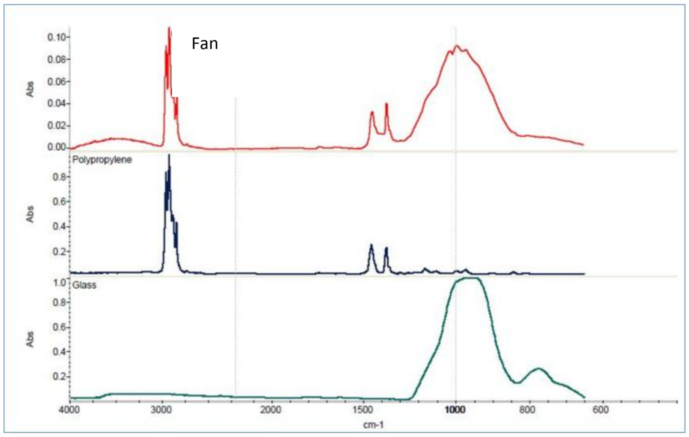


Figure 11 – FTIR of glass reinforced polypropylene fan with library matches.

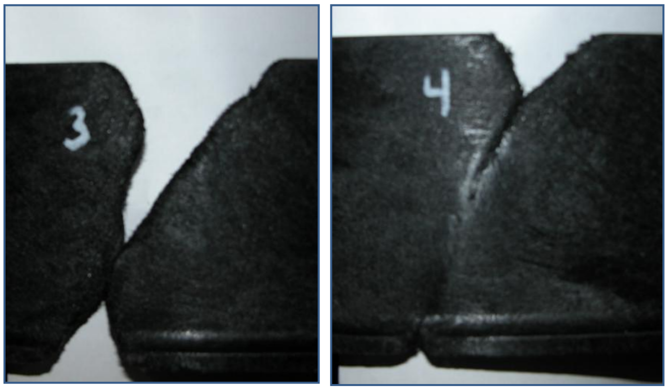


Figure 12 – Mold filling snapshots showing knitline formation.

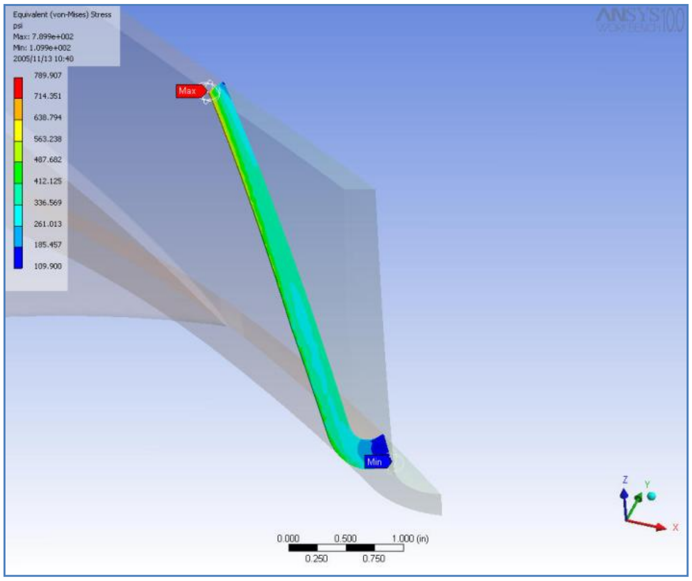


Figure 13 – Structural analysis of fan at failure location.

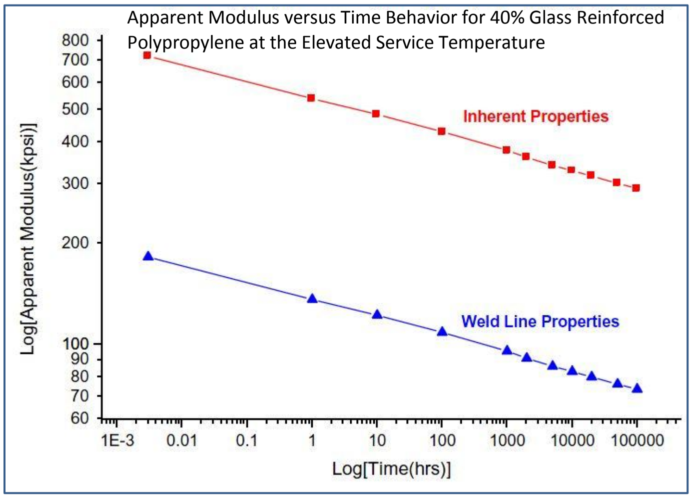


Figure 14 – Creep master curve for glass reinforced polypropylene at the elevated service temperature.

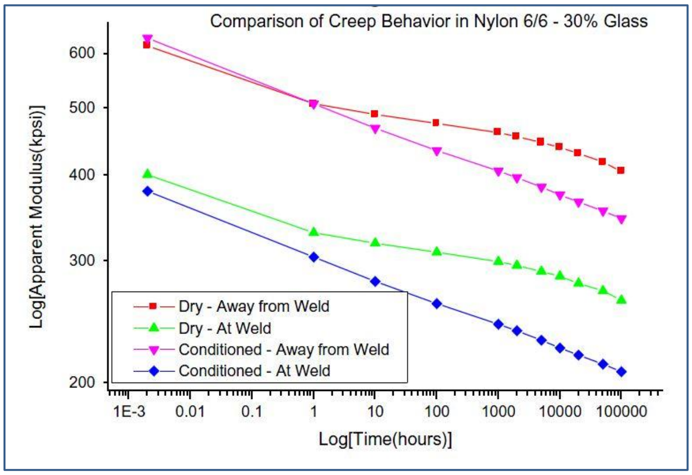


Figure 15 – Creep master curve for glass reinforced nylon 6/6 at the elevated service temperature.

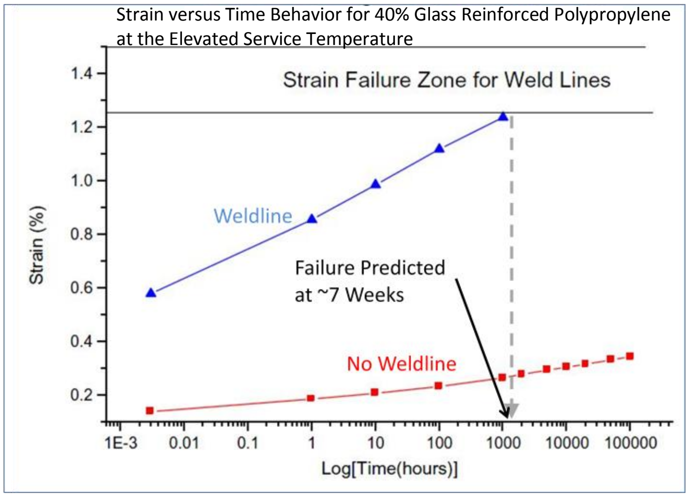


Figure 16 – Creep curve and failure prediction for glass reinforced polypropylene at the elevated service temperature.

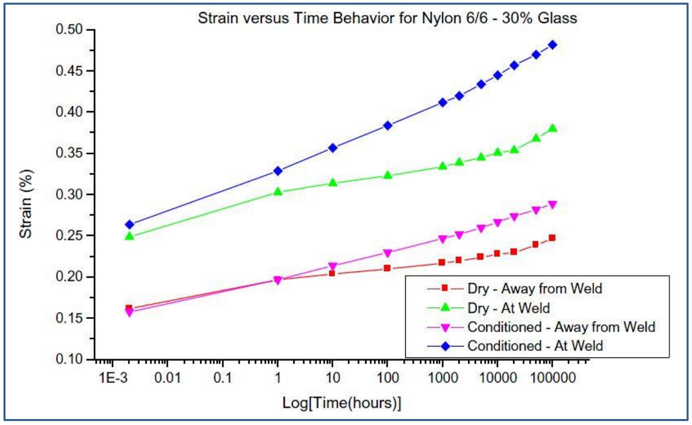


Figure 17 – Creep curve for glass reinforced nylon 6/6 at the elevated service temperature.