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Fatigue of Teflon Bladder Materials

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Synopsis

The fatigue properties of Teflon laminates employed in the fabrication of liquid propellant expulsion bladders were studied by cyclically stretching specimens to constant load in order to achieve a correlation of cycles to failure versus the maximum stress amplitude. This approach provides a useful technique for evaluating the resistance of bladder materials to fatigue failure which could be caused by vibration-induced cyclic loadings during ground testing and launch. Further, the data provides for a direct comparison of the relative fatigue properties of Teflon laminates and, in particular for those which were studied, the relative fatigue properties correlated with their ultimate breaking stresses. This observation, which suggests a simple and rapid method for evaluating relative fatigue behavior of candidate Teflon laminates, is discussed along with the effect of delamination on the fatigue properties observed for one laminate.

INTRODUCTION

Bladders prepared from a standard Teflon film laminate and employed as liquid propellant expulsion devices were failing from the formation of tears and cracks near an aluminum seal ring which forms the mouth of the bladder (Fig. 1). The failures were occurring when the bladders were filled with Freon-TF and isopropyl alcohol, employed as substitute fuels, and then vibrated during a simulated launch test. From a consideration of the conditions imposed on the bladders during test, four factors believed most critical in contributing to the failures were identified for study: (1) fatigue, (2) biaxial stresses, (3) solvent sensitivity, and (4) crystallinity. The results of that study demonstrated that the primary cause for failure of standard laminate was its sensitivity to solvent stress cracking[1,2] and that the bladders failed for that reason. A new material designated codispersion laminate was found to be insensitive to solvent stress cracking and has since replaced the standard laminate material used in construction of JPL Teflon bladders. This article describes the fatigue properties which were generated during the overall failure investigation for both standard and codispersion laminate materials.

BACKGROUND

Fatigue was included for study because it was recognized early in the failure experience that during the vibration testing, the material in the neck

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region of the bladders was being cyclically stressed by action of the sloshing fluid. Further, peak stresses in the neck were estimated to be in excess of the Teflon yield stress which is near 1240 N/cm^2 (1800 psi), a conclusion which was additionally substantiated by the appearance of white marbeling characteristic of yielded Teflon.

A limited amount of fatigue data relating cycles to failure as a function of stress had been found for Teflon[3] and is reproduced in Figure 2. These data, for flexural fatigue rather than the desired cyclic tensile fatigue,

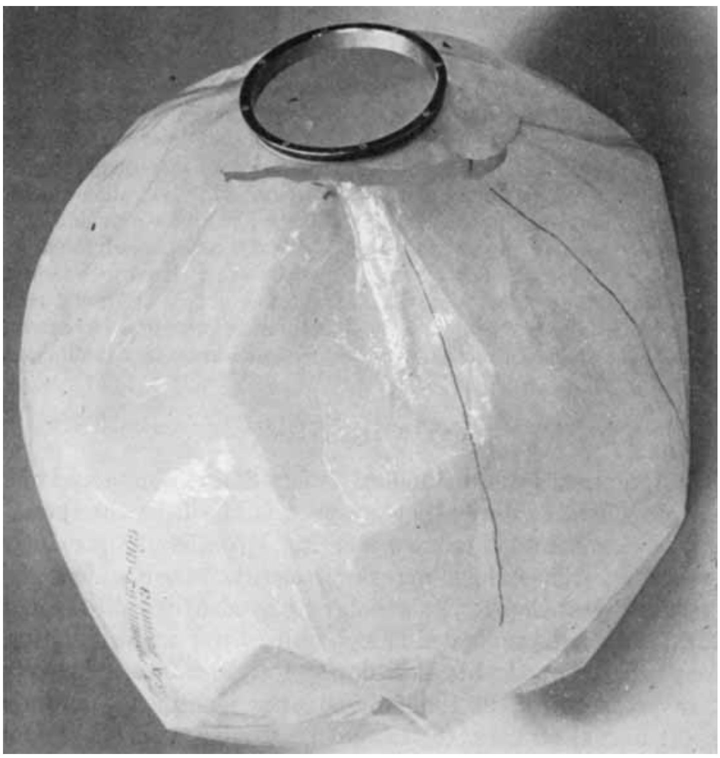

Fig. 1. Liquid-propellant expulsion bladder which has failed from tears and cracks near the aluminum seal ring.

demonstrated that for stresses above 965 N/cm^2 (1400 psi), the fatigue resistance of Teflon dropped dramatically from near 10^7 cycles to less than 1000 cycles at 1034 N/cm^2 (1500 psi) and clearly suggested even lower cycles to failure would be encountered at the higher stresses experienced by the bladders.

Accordingly, a study of the tensile fatigue properties of the Teflon bladder materials was carried out by measuring the cycles to failure as a function of the maximum stress amplitude in tension. The intention of the study was (1) to confirm that tensile fatigue would behave similar to flexural fatigue,

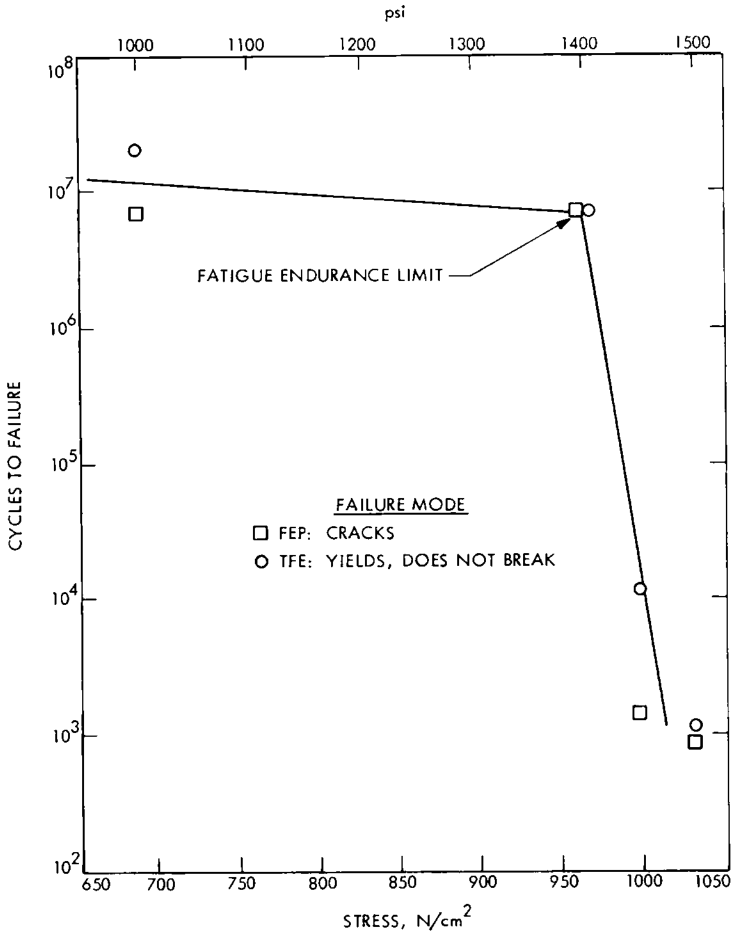

Fig. 2. Flexural fatigue of TFE (Teflon) and FEP (fluorinated ethylene-propylene copolymer) (reproduced from data in ref. 3).

(2) to evaluate tensile fatigue as the causitive mechanism of bladder failure, and (3) to develop, if possible, a simple technique for assessing comparative fatigue properties of candidate bladder materials.

BLADDER CONSTRUCTION

The construction of the bladders is detailed in Figure 3. Standard laminate is constructed in two plies, one of FEP 120 (fluorinated ethylene–propylene copolymer, du Pont) and the other of TFE 30 (Teflon, du Pont). Codispersion laminate is constructed in three plies; an inner ply consists of FEP 9511 while the two outer plies are formed from a codispersion of 80% TFE and 20% FEP 9511.

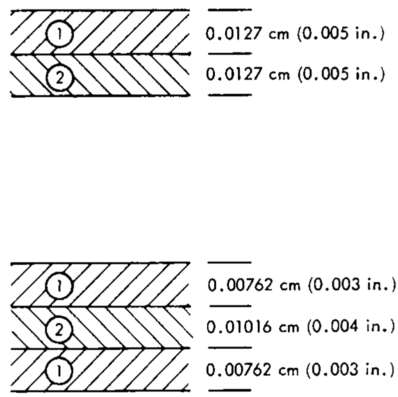

Fig. 3. Bladder construction details: (a) standard laminate—① FEP 120; ② TFE 30; (b) codispersion laminate—① codispersion 80% TFE 30/20% FEP 9511; ② FEP 9511.

FATIGUE PROPERTIES

Experiment. The fatigue properties of the Teflon materials were measured by cyclically stretching specimens on an Instron test machine to constant load in order to achieve a correlation of cycles to failure with the maximum applied stress. Because the Teflon materials underwent a permanent set and a reduction in area when stretched, the cross-sectional area employed for the stress calculation was determined after five cycles. A minimum of three specimens were tested at each stress condition. For this study, dumbbell specimens of 0.0254-cm (0.010-in.) thickness, 0.635-cm (0.250-in.) width, and 3.175-cm (1.25-in.) gauge length were tested on the Instron operating at a cross-head speed of 0.423 cm/sec (10 in./min). (where applicable, the International System of Units is stated first, followed by the customary units in parentheses. In each case, the value in parentheses represents the measured or calculated unit.)

Results. The fatigue data for both standard and codispersion laminate materials are plotted in Figure 4 as the log of cycles to failure versus the maximum stress applied during the fatigue test. For both materials, the upper portions of their fatigue curves were extrapolated to the "fatigue endurance limit" which was observed in the flexural fatigue data. This was done because of the increasing experimental time required to obtain fatigue data as the stress levels were decreased; and hence, the fatigue testing for each laminate was only continued until it became evident that the experimental data were approaching a common convergence at this "fatigue endurance limit."

At the higher stress levels, both fatigue curves intercepted the axis for one cycle at a stress which corresponds to their ultimate breaking stress (Fig. 5). The data curve for the codispersion laminate is linear while curvature and a plateau are observed for the standard laminate. This departure from lin-

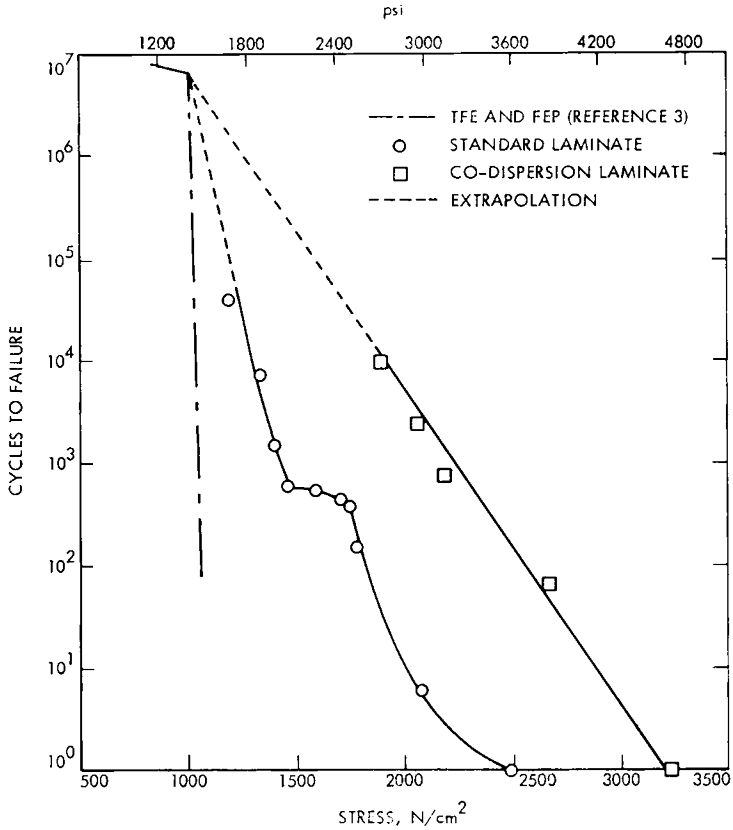

Fig. 4. Fatigue properties of Teflon bladder materials.

earity is believed to be caused by the tendency of standard laminate to delaminate during the fatigue testing. This point will be discussed later.

These results in Figure 4 suggest the existence of a correlation between fatigue properties and stress–strain behavior, as well as a method for assessing expected fatigue behavior of Teflon materials when cyclically stressed in excess of the "fatigue endurance limit."

Examination of the stress–strain curves in Figure 5 reveals that the "fatigue endurance limit" actually corresponds to that location on the stress–strain curves where departure from linearity occurs. This stress level at two-thirds of the yield stress is defined as the elastic limit; and it is above this stress value, not the yield stress, at which the fatigue resistance of Teflon falls off significantly. For stresses within the linear portion of the stress–strain curve, fatigue failure occurs at about 10^7 cycles. But for stresses exceeding those for linear behavior, i.e., in excess of the "fatigue endurance limit" or elastic limit, the number of cycles to failure decreases with increasing stress and the curves terminate at one cycle with a stress corresponding to the ultimate breaking stress. It is this latter observation

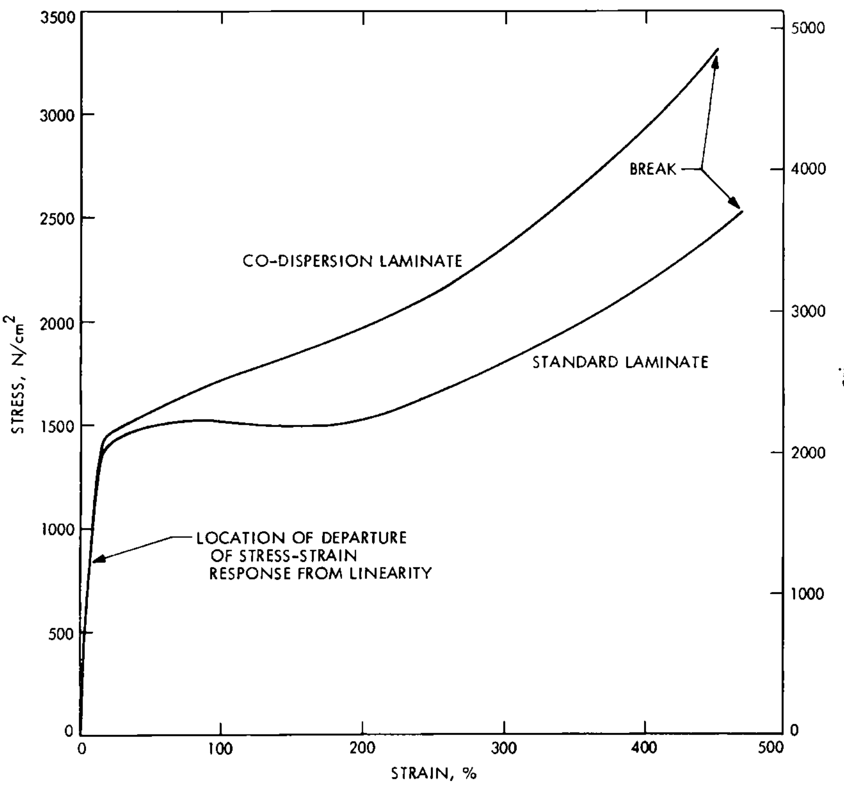

Fig. 5. Stress–strain curves.

which can provide a simple and rapid method for comparing expected fatigue behavior of Teflon materials. If the "fatigue endurance limit" is common for all Teflon materials, and their fatigue curves can be expected to decrease monotonically with increasing stress, then a comparison of the ultimate breaking stresses of the Teflon materials will give a comparison of the expected fatigue behavior. This idea may have extension to other systems having stress–strain behavior similar to that of Teflon.

DELAMINATION OF STANDARD LAMINATE

All specimens of standard material delaminated during the fatigue testing, with the extent of delamination reflected in the behavior of the data curve. For the cycle region above the plateau, substantial delamination was observed, while negligible delamination was observed in the cycle region below the plateau. The plateau occurs as the result of a transition from extensive delamination at high cycles to negligible and no delamination at low cycles. It is believed that delamination not only accounts for the departure of the standard laminate fatigue curve from linearity as observed for codispersion, but also results in a substantial reduction in resistance to fatigue failure. This can be seen in Figure 6, where the fatigue curve is reproduced for this material along with the linear relationship expected for the absence of delamination.

On additional observation can also be made from Figure 6. The points above the plateau extrapolate to the one-cycle line at an ultimate breaking

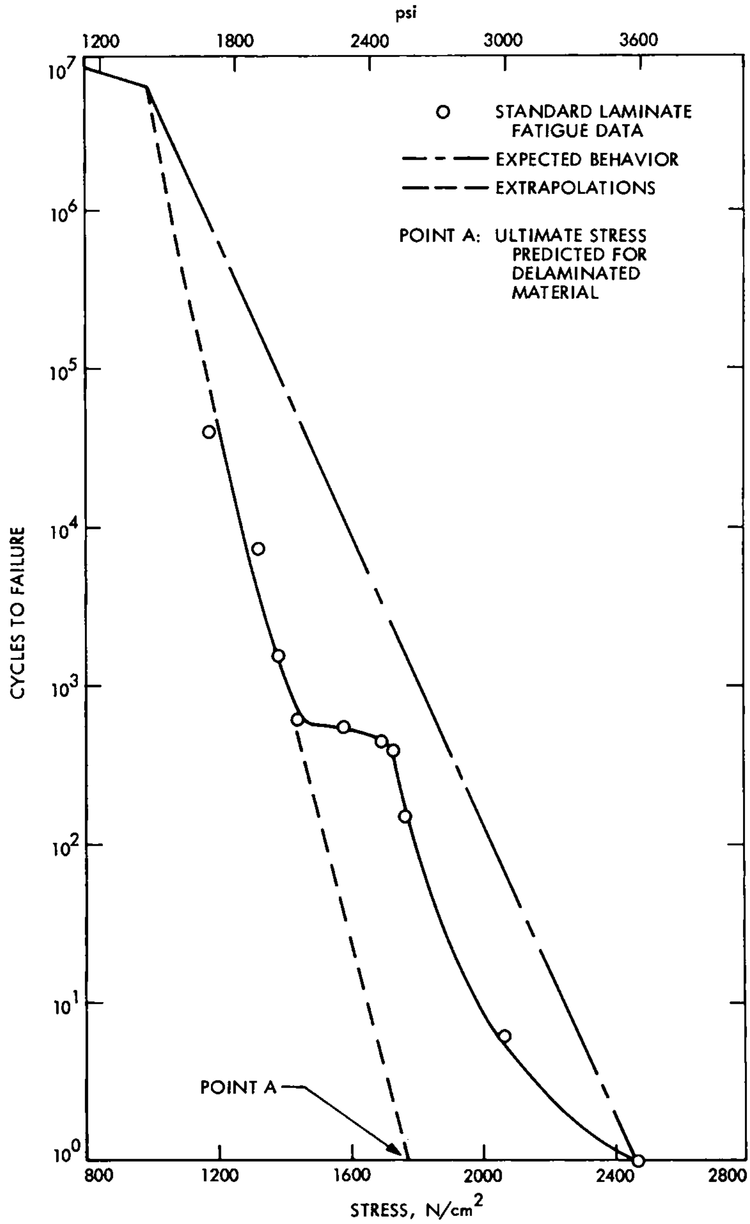

Fig. 6. Comparison of actual standard laminate fatigue data with expected behavior.

stress of 1792 N/cm^2 (2600 psi). This value would presumably be obtained for a standard material delaminating during a uniaxial stress–strain measurement. This same value of ultimate stress was measured for standard materials which were tested while completely immersed in Freon-TF and isopropyl alcohol.[1] This suggests that part of the mechanism contributing to the solvent sensitivity of standard laminate may be a tendency to be delaminated by solvents.

CONCLUSION

The monotonic relationship between fatigue cycles and stress provides a simple method of fatigue analysis for Teflon materials. Given the ultimate breaking stress and the fatigue endurance limit, the fatigue properties can be predicted. Further, since the fatigue endurance limit is apparently common, a rapid assessment of the fatigue behavior of various Teflon materials can be made from only a comparison of the ultimate breaking stresses. Similarly, the effect of environmental or other factors on fatigue properties can be inferred from their effect on the ultimate properties.

These considerations should also be applicable to materials having similar stress–strain characteristics as Teflon. These would include other crystalline polymers, such as polyethylene, and many block and graft copolymers, including segmented urethanes.

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