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Thermal Stress in a glass/metal bond with PR 1578 adhesive

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ABSTRACT

PR 1578 adhesive is often used for bonding a glass mirror to its mounting flexures (Invar or Aluminum) when the mirror assembly is designed to operate in a low temperature environment. PR 1578 is used because it has high strength and remains elastic at low temperature. Several tests conducted at Itek, however, show that the thermal stress induced in the bond may cause fracture of the glass near the bond at cryogenic temperature. This paper examines the reason of fracture and the effects of flexure material, adhesive thickness, and size of bonding.

A finite element model is developed for simulating the bonding of flexure, adhesive, and glass. Temperature dependent material properties are used in the analysis. Good correlation between the analysis and the test is obtained.

1. INTRODUCTION

Structural adhesives are being used increasingly in optical instruments; as a result there is a need to gain a better understanding of all aspects of their behaviors, particularly for bonding a metal to a fragile optical glass. The stress, developed from different thermal expansions of the materials, often impairs the integrity of the bond. An in-depth understanding of how the stresses are developed can guide a designer to make optimal selections on the adhesive material, the adhesive thickness, and the bonding area. Hence, the number of cases to be tested for verification can be minimized.

PR 1578 polyurethane adhesive[1] is often used for bonding a glass mirror to its mounting flexures when the mirror assembly is designed to operate in a low temperature environment. PR1578 has a tensile strength more than 23 ksi and retains 7 to 8% elongation at 80 kelvin. This provides an excellent compliance for the thermal mismatch between the glass and the metal. However, several tests conducted at Itek show that the thermal stress induced in the bond may cause fracture of the glass near the bond at cryogenic temperature. This paper describes two experiments and then examines their test results by a finite element analysis on the reason of fracture and the effects of flexure material, adhesive thickness, and size of bonding.

2. EXPERIMENTS

2.1 SIRTF Experiment[2]

One of the important goals of the SIRTF mirror experiment is to demonstrate that the mirror mount design is suitable for use with a fused silica mirror in an aluminum telescope structure at a temperature of 80 kelvin or less. The mount design is a conventional tangent flexure which consists of a flexure pivot and a flexure leaf (Fig. 1).

A first breadboard of fused silica boss, aluminum flexure pivot, and aluminum flexure leaf was assembled with PR 1578 adhesive. The aluminum pivot was slightly decentered from the silica boss so that the adhesive layers of .003, .006, and .009 inches were present in the test assembly. The assembly was cooled down slowly to 80K by holding in the cold vapor of liquid nitrogen for one hour and then immersing into the nitrogen. After the first immersion, a pair of localized fractures on the silica were found under each of the four feet of the flexure pivot, at the pivot-silica bond as shown in Figure 1. It appears that the severity of the fracture is less for the thicker adhesive layers.

A second breadboard of fused silica boss, invar flexure pivot and aluminum flexure leaf was assembled with PR 1578 adhesive. Again the invar pivot was slightly decentered from the silica boss so that the adhesive layers of .003, .006, and .009 inches were present in the assembly. The assembly was cooled down slowly to 80K by liquid nitrogen as in the previous test. After five cycles, no evidence of fracture or debonding was observed.

2.2 OSG Experiment

The Optical Scene Generator (OSG) developed in Itek recently has a fused silica mirror mounted on an aluminum structure with an aluminum finger flextube mount. This mirror is expected to experience a temperature of 160K. In order to find out whether the PR 1578 adhesive can be used for bonding the aluminum flexure fingers to the mirror at 160K, a test breadboard as shown in Figure 2 is fabricated. The breadboard consists of two aluminum flexure fingers, a fused silica bar and an aluminum bar. Two aluminum flexures are bonded on the two ends of the fused silica bar with PR 1578 adhesive; while the bases of the flexures are tied to the aluminum bar with screws. The dimensions are tailored so that the adhesive layer thicknesses are .003 inches at one end and .006 inches at the other.

The assembly was installed in an environmental chamber with a thermocouple attached to the aluminum bar for temperature readout. Tests were conducted for three different soak down temperatures. First, the assembly was cooled down from room temperature to 210K in two hours and then warmed up to room temperature. The same temperature cycle was repeated once more. Visual inspection was performed after each cycle. Next the same test was repeated for a temperature down to 160K and finally repeated for a temperature down to 80K. There was no fracture or debonding observed after the first two tests. However, after the first 80K cycle the .003 adhesive joint was observed to be broken due to the fracture of the silica and the similar fracture occurred in the .006 adhesive joint after the second cycle.

3. ANALYSIS

3.1 Finite Element Model

To calculate the thermal stress in the bond and to understand the reason why the glass fractures at 80K, a NASTRAN finite element model is developed to simulate the bonding of the flexure pivot, the adhesive, and the glass boss of the SIRTF test sample. In view of the symmetric conditions, only a quarter of the bond is modeled as shown in Figure 3. The flexure is represented by 180 plate elements (CQUAD4), the adhesive is represented by three layers of solid elements (CHEXA), 180 elements in each layer; and the glass boss is represented by six layers of solid elements, 210 elements in each layer. The symmetric conditions are used for the grids in the x-z plane and in the y-z plane. A portion of the glass boss is excluded from the model because including that or not makes little difference to the results of interests. A constraint in Z is imposed on the grids located at the end of the glass boss, i.e., grids in the plane of $z = -.144$ inches.

3.2 Material Properties

The thermal stress in the bond depends on the material properties of thermal expansion coefficient, α, young modulus, E, and poison ratio, ν as well as the temperature change. The α and E of PR 1578 vary largely in the temperature range of 80K to 293K. They are shown in figures 4 and 5[1,3]. The α of fused silica, invar, and aluminum also depends on the temperature as shown in Figures 6 and 7; while the E and ν of these materials remain nearly constant in the temperature range of interest. The values used in the analysis are summarized in Table 1:

Material	α	ν	E
PR 1578	Figure 4	.495	Figure 5
Fused Silica	Figure 6	.17	10.5×10^6 psi
Invar	Figure 6	.3	21×10^6 psi
Aluminum	Figure 7	.3	10.6×10^6 psi

Table 1 - Material Properties

The poison ratio of PR 1578 is nearly .5. A value of .495 is used in the analysis to avoid any possible numerical error. Examination of a typical case under study here was done with $\nu = .49$, .495 and .499. The results of maximum stress have 2.5% deviation between .49 and .495, and .5% deviation between .495 and .499.

3.3 Analysis approach

To account for the temperature dependent material property, the thermal stress is calculated by the following approach:

- Divide the total temperature range into several increments, $\Delta T = \sum_{i}^{n} \Delta Ti$
- Use the effective $\bar{\alpha}_i$ and $\bar{E}_i$ in each increment as defined by $\bar{\alpha}_i = \int^{\Delta Ti} \alpha dT/\Delta T_i$ and $\bar{E}_i = \int^{\Delta Ti} E\alpha dT/\Delta T_i\bar{\alpha}_i$
- Obtain the stress at any particular point from $\sigma = \sum_{i}^{n} \sigma_i$

The number of increments required for obtaining accurate results depend on how the material property varies with the temperature. Table 2 shows the maximum thermal stress obtained from different number of increments for a typical case under study (aluminum flexure with .009 inch thick adhesive). It is seen that the maximum stress obtained from one increment approximation yields only about 9% error. Six increments are used in all of the following predictions.

n	ΔTi (K)	Maximum Von-Mises Stress (psi)	% error
1	213	3475	9
3	71	3938	3
6	35	3819	0.1
12	18	3822	0

Table 2 - Error Due To Analysis Approximation

3.4 Stress prediction and discussion

Based on the above analysis approach, calculations were carried out for various adhesive thicknesses and different flexure materials. A typical stress distribution in the glass at the interface is shown in Figure 8. The maximum stress is located near the corner of the bonding. Here the VonMises stress is used because it is consistent with the principle stress for the stress of interest. Also it is an invariant in the stress field and can be summed algebraically among all the temperature increments used in the analysis. The maximum VonMises stress in the glass at 80K versus the adhesive thickness is plotted in Figure 9. It shows that the stress is much higher in the case with aluminum flexure than in the one with invar flexure. The stress with aluminum flexure is very sensitive to the thickness of the adhesive and increases exponentially as the adhesive thickness decreases. The stress with invar flexure appears insensitive to the adhesive thickness and is slightly lower in the case with the thinner adhesive. This prediction clearly explains the SIRTF test results that the glass boss fractures in the test sample with aluminum flexure and not in the one with invar flexure. Also the fracture is less severe in the glass with the thicker adhesive layer. Figure 10 shows the maximum stress in glass versus soak down temperature for the case with aluminum flexure. It shows that the stress is less than 1000 psi at 160K and higher than 4000 psi at 80K. This explains the OSG test results why the glass fractures at 80K and not at 160K.

The fracture stress of a glass depends highly on the surface finish. A stress release operation by either fine grinding or acid etch is required for the bonding surface. The SIRTF glass boss was generated with a 150-grit diamond wheel and etched in hydroflouric acid to remove approximately .005 inch from the surface. The OSG glass had stress relieved with a 400-grit diamond wheel after the initial surface generation.

To understand the effect of the bonding area on this thermal interface stress, calculations were carried out for cases with shorter bondline along Y. The results of maximum VonMises stress versus the length of bondline are plotted in Figure 11. It shows that the shorter the bondline is, the smaller the stress is. Analyses were also done for the cases having the bondline breaking at the middle (Y= 0) or at the one third point (Y = 1/3L). The results, however, show almost no difference on the maximum stress among all three cases.

Based on all the analyses done in this study, it is found that the primary driver of this interface stress in the glass is due to the shrinkage of the adhesive and the thermal mismatch between the glass boss and the metal flexure. For the case shown in Figure 8, the maximum stress has about 1867 psi contributed from the shrinkage of the adhesive (based on an analysis with a glass flexure) and the remaining 1955 psi contributed from the glass/aluminum mismatch. This explains why the bond has a higher stress in the glass with the aluminum flexure and a lower stress with the invar flexure; since the former has a relatively larger mismatch than the latter. It is also evident that this interface stress is proportional to the stiffness of the adhesive in the case with aluminum flexure. When the adhesive thickness decreases, its stiffness increases exponentially and the stress increases as shown in Figure 9. Similarly the stress increases exponentially when the temperature decreases as shown in Figure 10. Finally, breaking the bondline does not reduce the glass/aluminum mismatch and the stress induced from the adhesive shrinkage is a local nature. Therefore, there is no effect on the maximum stress by breaking the bondline into several smaller sections.

4. CONCLUSION

When a glass/metal bond with PR 1578 adhesive is cooled down to a cryogenic temperature, the thermal shrinkage of the adhesive and the flexure yields a large stress between the adhesive and the glass interface. At 80K this stress exceeds the fracture stress of the glass for the bond with high CTE aluminum flexure, but not for the bond with low CTE invar flexure. The adhesive thickness plays an important role for the bond with aluminum flexure but not for the bond with invar flexure. This interface stress is lower for a smaller bonding area. However, there is no effect on the maximum stress by breaking the bondline into several smaller sections.

5. REFERENCES

1. Products Research and Chemical Corporation, Laboratory Product Report on PR-1578, December 1976.
2. William P. Barnes Jr., "Fused Silica Mirror Development for SIRTF", *Itek Tech. Report NAS2-10869*, July 1983.
3. Thermophysical Properties of Matter, Vol. 13, IFI/PLENUM, 1977.

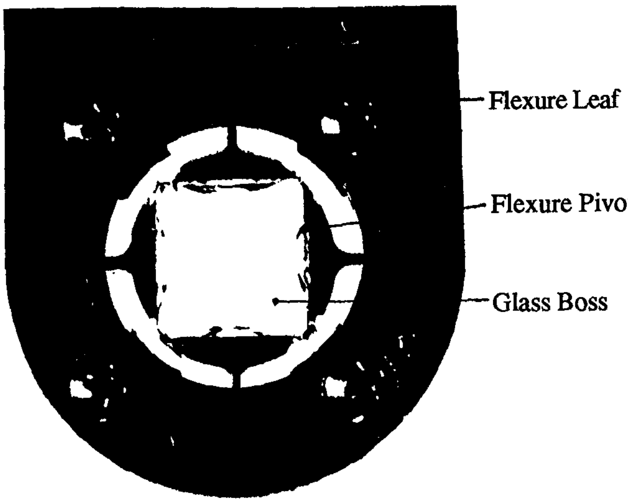

Figure 1. SIRTF Test Sample

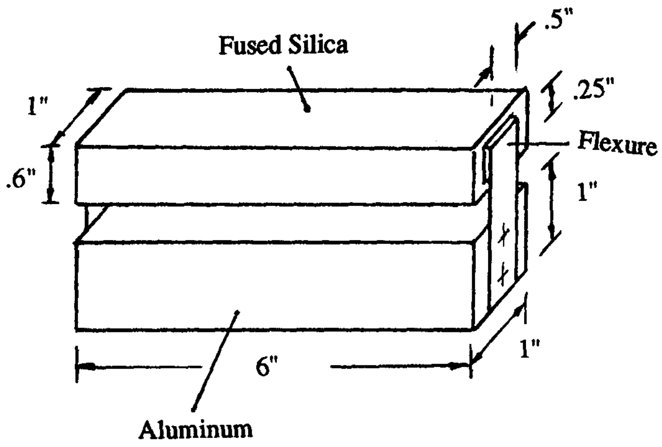

Figure 2. OSG Test Sample

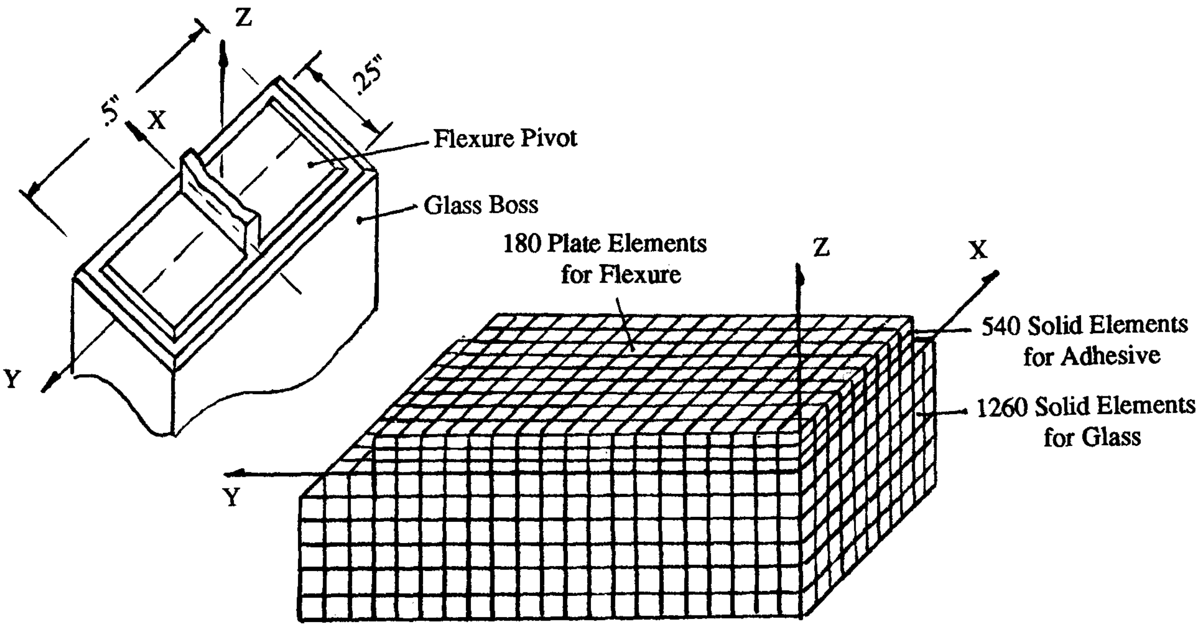

Figure 3. Finite Element Model

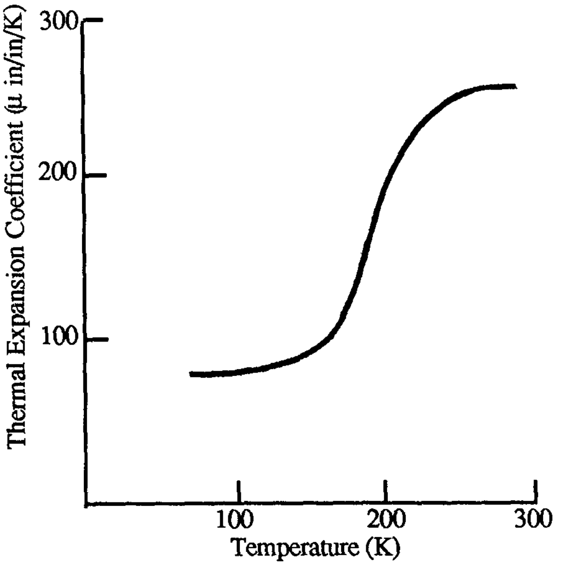

Figure 4 - Thermal Expansion Coefficient of PR1578

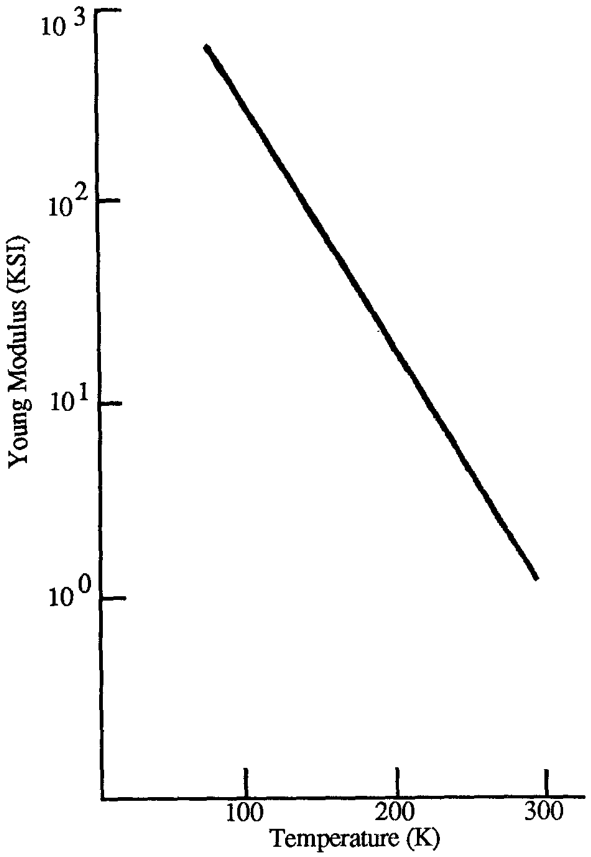

Figure 5 - Young Modulus of PR1578

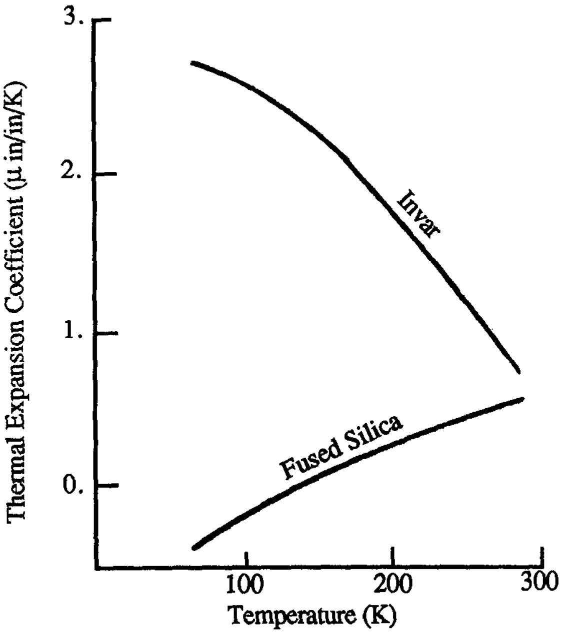

Figure 6 - Thermal Expansion Coefficient
of Fused Silica and Invar

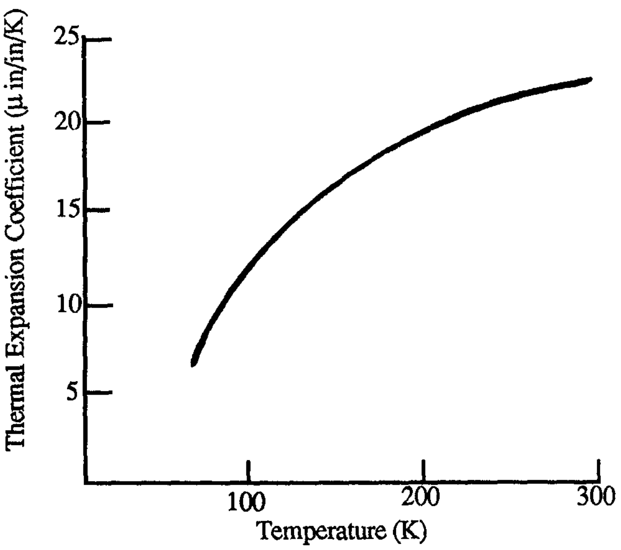

Figure 7 - Thermal Expansion Coefficient
of Aluminum

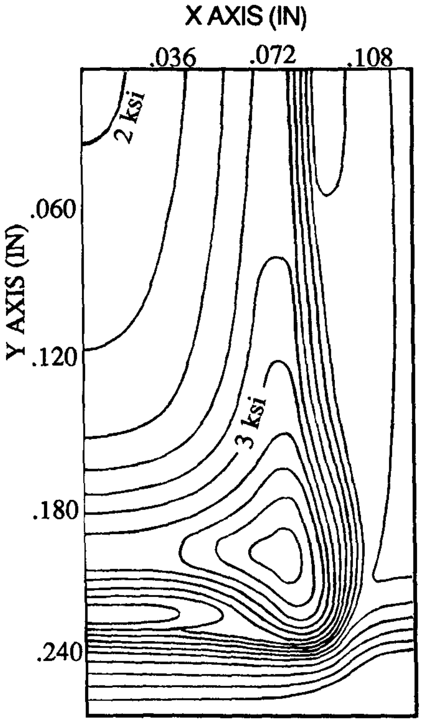

Figure 8- Stress Distribution in Glass at 80K for Case with Aluminum Flexure and .009 Inch Thick Adhesive

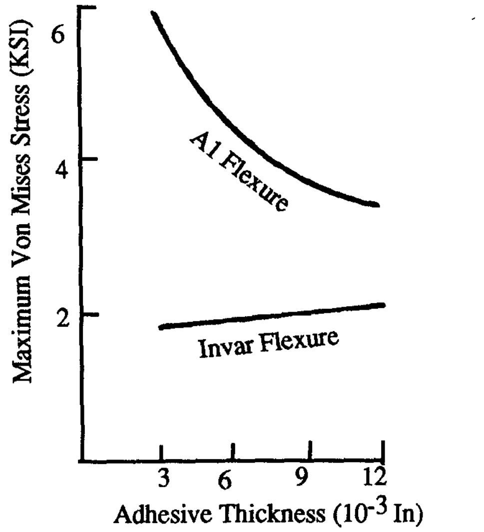

Figure 9 - Maximum Stress in Glass at 80K versus Adhesive Thickness

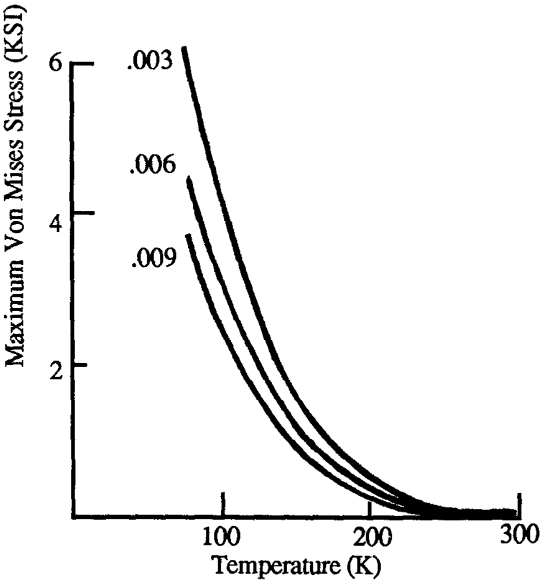

Figure 10 - Maximum Stress in Glass versus Soak down Temperature for Case with Aluminum Flexure

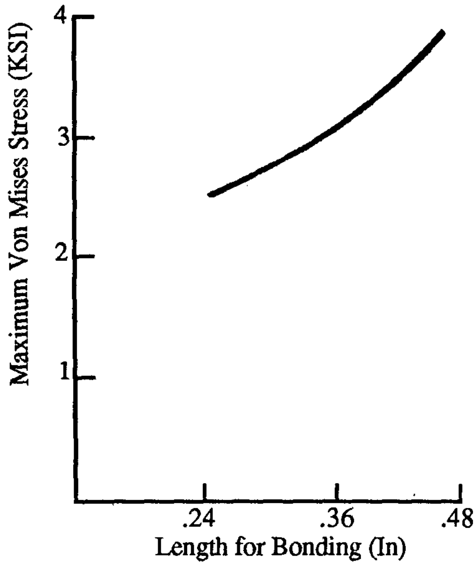

Figure 11 - Maximum Stress in Glass at 80K versus Various Lengths of Bondline for Case With Aluminum Flexure and .009 Inch Thick Adhesive