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Recommendation for Mechanical Specifications for Adhesive Bond between Bias Circuit and Silicon Detector Ladders

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Abstract

The conductive bonds between silicon detector ladders and the rest of the GLAST tracker trays are subject to high thermal stresses because of thermal expansion mismatch between the silicon and the rest of the tray and payload assembly. This note is an initial attempt at evaluating the level of shear stress in those bonds and deriving *mechanical* requirements for the adhesive.

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1. Definitions

- CTE or α: Coefficient of thermal expansion
- RTV: room temperature vulcanizing silicone rubber, a compliant adhesive
- *E, G: Young's and shear modulus*
- *t:* thickness
- QI: Quasi-isotropic
- GFRP: graphite fiber reinforced plastic
- GLAST: Gamma ray Large Area Space Telescope
- SSD: silicon strip detector

2. Scope, Introduction, and Assumptions

This notes attempts to set preliminary mechanical requirements for the electrically conductive adhesive bond between SSD ladders and bias circuit for the GLAST trackers. This bond is clearly a critical link in the tracker assembly. Although there is hardly any directly applied mechanical loads to this bond, there is a potential for relatively severe thermal stresses due to temperature excursions.

Because the bond is required to be electrically conductive and because most commercially available electrically conductive adhesives have poor mechanical properties (high stiffness and low adhesion[1]), the selection of that adhesive must be done carefully.

In an attempt to evaluate the required mechanical strength of the bond, we considered two cases of silicon ladders bonded to different substrates:

1. ladders bonded to a baseline payload, i.e. 318μm QI GFRP + bias circuit, rigidly bonded together. The converter layer is not included because, in a standard tray (2.5%RL lead converter) it actually reduces the thermal stress levels, and in a SuperGLAST tray we assume that decoupling layers and/or low CTE converters will be used.
2. ladders bonded to bias circuit only (assuming that the bias circuit is decoupled from the face sheet and converters).

In addition, these calculations are is based on very simplistic bond calculations which are based on the following assumptions:

- no out-of-plane deflections; everything stays flat
- thermal stresses only, no applied mechanical loads of any sort
- shear lag analysis, assumes stiffness and CTE contributions from the adhesive layer itself are negligible (i.e. $E_{bond} \times t_{bond} << E \times t$ of adherents).
- assumed that the lowest test temperature (-30ºC[3]) is the driving condition because of stiffening of the adhesive and the large temperature excursion from the assumed 21ºC assembly temperature (ΔT=-51ºC).

[1] the poor mechanical properties are largely due to high volume fractions of conductive particles used to bring the volume resistivity in the 10^{-3}Ωcm range; note that the resistivity requirement for GLAST is much less severe, with a maximum allowable volume resitivity of the order of 100 Ωcm).

- bond length assumed equal to ladder length (i.e. ignoring segmentation of the bond in the ladder direction). Note that for "stiff" bonds (G>1GPa), the assumed bond length has NO effect on maximum shear stress, unless that length is less than about 5mm (the stress transfer region near the edge of the bond is only about 2mm wide or less). For compliant bonds, however, segmentation in the ladder direction will produce higher shear stresses than predicted here.
- Any relaxation/unloading effects due to creep and/or plastic deformations were ignored.

Based on the predicted stresses, we used the following, conservative safety factor approach to derive requirement on shear modulus and lap shear strength of adhesive:

- ignored shear stress concentration near edges of bond in a lap shear test, i.e. assumed that lap shear strength is a true measure of bond shear strength (conservative).
- assumed that infinite life is required under temperature cycling conditions in the -30 to +50 deg test range[3]. This led us to apply a (conservative) factor of 1:5 between single-cycle static bond strength and endurance limit for stiff adhesives. For softer adhesives such as RTV, which should be less susceptible to fatigue at reasonable strain levels, that factor was reduced to 1:3.
- applied a 1.4 safety factor on top of it all based on NASA specification[2] for bonded joints, assuming they will be qualified by prototyping and qualification testing.
- total explicit safety factor to lap shear strength:
    - for rigid adhesives: $5 \times 1.4 = 7$.
    - for compliant adhesives: $3 \times 1.4 = 4.2$.

3. Recommendation for Mechanical Specification

3.1 Adhesive types

Using a single adhesive for the entire bonding pattern would simplify assembly and reduce the design problem to the selection of a single adhesive type. It also guarantees a more predictable shear stress distribution in the bonds. If using two types (one conductive, the other not), stresses will tend to concentrate in the stiffer of the two, which because of the particulate loading will usually be the conductive type. If two types of adhesives are used, it may be prudent to select them such that their shear modulus is as close as possible, across the temperature range of interest.

3.2 Bond Pattern

Continuous bonds across the entire surface of the ladders are not practical as they make it very difficult to control the amount of adhesive, avoid squeeze-out near the edges, and prevent the formation of trapped air volumes. A set of distributed, circular or oval bond patches is a more practical alternative. It can be achieved easily by applying measured drops of adhesive and squeezing them to a controlled bond thickness. As long as the bond thickness is adequately controlled, there is little risk of squeeze-out at the edges or formation of trapped air pockets. Bond thickness control could be achieved with permanent or removable shims, or by mixing a small percentage of calibrated glass beads in the adhesive.

Using discrete bonding patches however, reduces the total effective width of the bond and therefore increases the shear stresses. To minimize that increase, a bonding pattern with maximum linear coverage near the edges is preferable (see Figure 1 which shows a couple of suggested patterns). The calculations in this note are based on 50% linear coverage near the edges (see figure); this might corresponds to around 20-30% areal coverage.

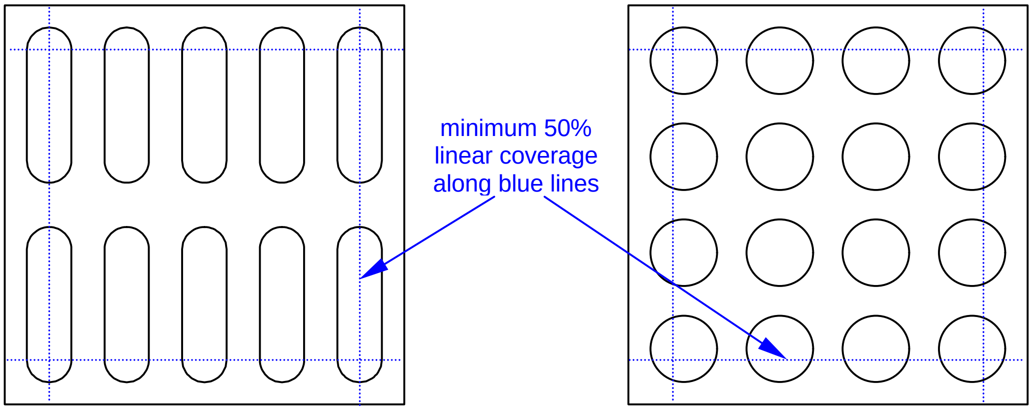

Figure 1: suggested patterns for glue application between SSD and bias circuit; all or only a few of the bonds must be electrically conductive; a 50% linear coverage along the outer edges is assumed in calculations.

Another issue that affects the choice of bond pattern is dynamic response of the SSDs. Earlier studies of the dynamic response of the tray to random vibrations (or acoustic inputs) have shown that, in addition to the overall tray response (drum mode) of the tray, silicon detectors can "flap" with troubling amplitudes unless they are somewhat uniformly bonded to the tray. To avoid this, we would recommend the following initial (and somewhat arbitrary) guideline on the bonding pattern:

- longest unsupported length of silicon between bonds < 20 mm
- widest unsupported overhang of silicon at edges < 10 mm

3.3 Bond Thickness

A minimum bond thickness of 100µm (0.004") was assumed as a baseline. This is a typical and easy to achieve value for a structural bond with epoxy adhesives. However, RTV bond thicknesses tend to be larger, so for those cases, alternate bond thicknesses of 0.008" and 0.0016" are also included. Note that the uniformity of the bond thickness can also be a factor in bond strength as variations can induce stress concentrations.

3.4 Surface Preparation

In researching adhesive properties in manufacturer's literature, it is crucial to recognize that bond strength is very strongly dependant on surface preparation technique. Manufacturers will always list lap shear strengths for the best possible surface preparation approach, which typically involves some combination of thorough degreasing with aggressive solvents, mechanical abrasion, acid etching, and completion of the bond within minutes of the surface preparation. Such aggressive surface preparation procedures are clearly not indicated for this case, so that listed bond strength must be taken with considerable suspicion, and tests specific to this application must be performed as soon as practical.

As an illustration of the strong effect of surface preparation technique on bond strength, Figure 2 lists the measured lap shear strength of aluminum alloy to aluminum alloy bonds performed with an industrial 2-component epoxy adhesive, for increasing levels of surface preparation[1]. The range covers almost an order of magnitude, and the difference between a simple vapor degrease step and an acid etch is more than a factor 3. The manufacturer would likely claim a lap shear strength for this adhesive of 2800+ psi.

Group Treatment	lb/in²
1. As received	444
2. Vapor degrease	837
3. Vapor degrease, 15 percent NaOH	1671
4. Solvent wipe, sand (not wet and dry), 120 grit	1329
5. Vapor degrease, wet and dry sand, wipe off with sandpaper	1726
6. Unsealed anodized	1935
7. Vapor degrease, $Na_2Cr_2O_7$-H_2SO_4, tap water rinse	2756
8. Vapor degrease, alkaline clean, $Na_2Cr_2O_7$-H_2SO_4, tap water rinse	2826
9. Vapor degrease, grit blast 90-mesh grit, alkaline clean, $Na_2Cr_2O_7$-H_2SO_4, distilled water rinse	3091

Figure 2: effect of surface preparation technique on the shear strength of an aluminum-aluminum bond with industrial 2-component epoxy[1].

3.5 Mechanical Properties of the Adhesive

Clearly, to minimize the maximum shear stress in the bond, a softer adhesive is preferable. However, softer adhesives are also typically weaker, so a compromize must be found.

Because the shear stress peaks near the edges of the bonds are a strong function of the shear modulus of the adhesive, it is not possible to establish a single number shear strength requirement for all adhesives that may be considered. Softer, more compliant adhesives will significantly reduce the shear strength requirement on the bond by reducing the sharpness of the stress peaks near the edges. To account for this effect, the minimum required lap shear strength of the adhesive must be a function of the shear modulus of the adhesive.

A few remarks must be made about this requirement. First, lap shear strength is a very strong function of the adherent materials, surface preparation, cure schedule, and the temperature during the test. Manufacturers typically only list lap shear strength for:

- aluminum alloy/aluminum alloy bonds
- the best surface preparation technique (i.e. a careful, multiple step procedure of degreasing, alkaline bath, aggressive acid etching, and rinses, performed within 1 hour of bonding).

- a specified cure schedule (often an elevated temperature cure, which almost always produces stronger bonds than room temperature cures)
- room temperature testing.

The adherents in this application are a pure aluminum layer on the backside of the SSD, pure gold plated layer at the electrical contact areas of the bias circuit, and Kapton-like material everywhere else. Before any final engineering judgment can be made about the chance of survival of those bonds, actual lap or circumferential (better) shear test data will need to be gathered that duplicates:

- the exact material pairs (aluminum-gold and aluminum-Kapton)
- the same handling, surface preparation, bonding procedures, and cure schedule as planned for flight hardware

The operating temperature cannot be matched in bond strength tests because of thermal stress buildup. Because of this, actual temperature cycling test on flight-like assemblies will be an essential part of the development and certainly the qualification of the design.

Second, lap shear

Finally, manufacturers do not often provide very extensive data on shear modulus of their adhesives. At best, a shear modulus or durometer value may be provided for room temperature use. Because the modulus is a very steep function of temperature, large safety factors must be used or preferably data must be obtained for the modulus at the low end of the temperature range.

3.6 Bond analysis and Requirement for Compliant Adhesive (RTV-like, 30 to 250 psi shear modulus).

Refer to the introduction for an explanation of the assumptions used. In summary:

- 3 bond thicknesses considered: 4, 8, and 16 mil (100, 200, and 400 microns)
- factor of safety of 4.2 included in lap shear strength requirement
- assumed 50% linear coverage near the edges of the ladder
- to be conservative, the shear modulus in the figure should be interpreted as the shear modulus of the adhesive at a temperature of -30degC.
- the shear strength requirement should be interpreted as the true shear strength of a bond between gold/Kapton and a SSD, following the surface preparation and cure schedule prescribed for GLAST.

3.6.1 Case 1: standard tray, top payload assembly

In this case, the silicon ladder is bonded to the top side of a baseline tray (318 micron face sheet, and bias circuit rigidly bonded to it). The CTE mismatch is small; the effective CTE of the face sheet/bias circuit assembly is estimated at $0.8\times10^{-6}/^{o}C$. However, the face sheet stiffness is very high.

Figure 3 shows the minimum required shear strength of the bond (safety factor included) as a function of the shear modulus of the adhesive, for the three different bond thicknesses. As expected, the strength requirement is more severe for thinner bonds.

Figure 4 shows the effect of the adhesive's modulus on the thermal stress in the silicon. Because of the low CTE mismatch, these soft adhesives are able to decouple the silicon to some extent.

Figure 5 illustrates that point further by showing the shear stress distribution in the bond, from one end of the ladder to the other. The very progressive transition from zero stress at the center of the bond to a maximum at the edge is typical of a compliant bond.

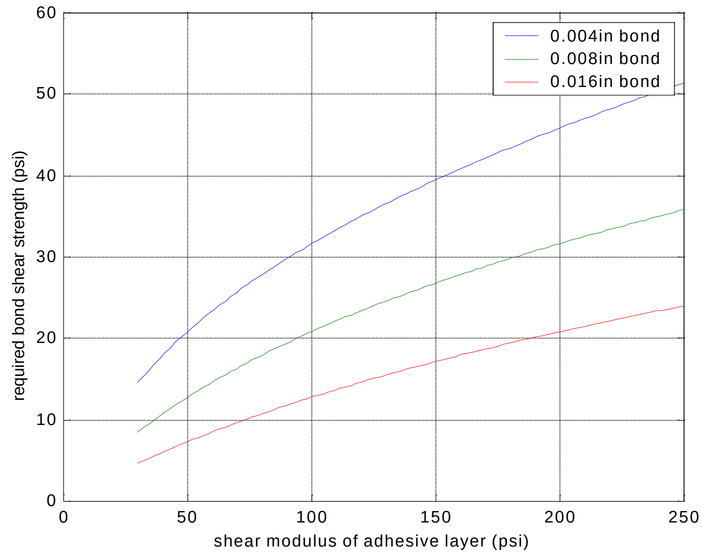

Figure 3: case 1, bond shear strength requirements for soft adhesive as a function of adhesive modulus and bond thickness.

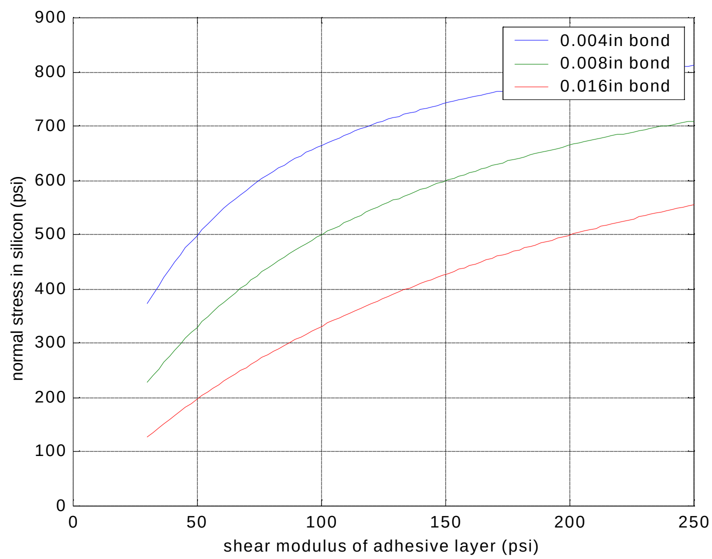

Figure 4: case 1: effect of shear modulus of adhesive on stress level in silicon (soft adhesives).

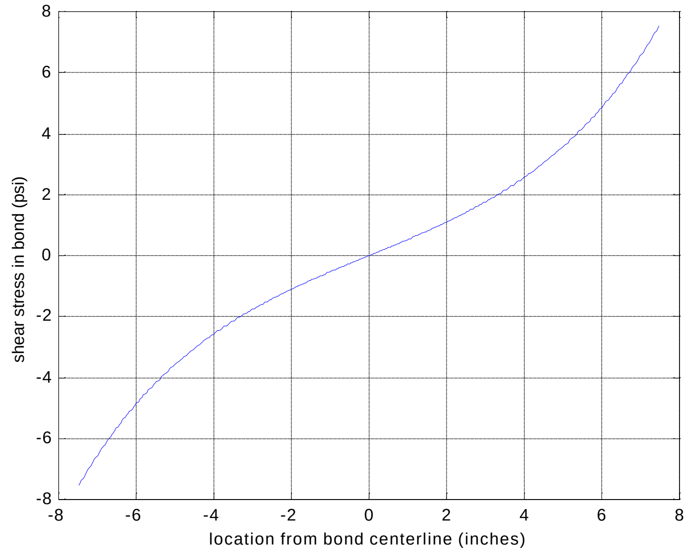

Figure 5: case 1, shear stress distribution from one end of the ladder to the other (assuming continuous bond in that direction), for a 0.004" bond with a shear modulus of 100psi.

3.6.2 Case 2: SSD ladder bonded to bias circuit only

Here we assume that the silicon ladder is bonded to the bias circuit only. Designs with very effective decoupling between the bias circuit and the face sheet or converters may come close to this situation. In this case, because Kapton and copper both have high CTE, the CTE mismatch is much larger; the effective CTE of the bias circuit is estimated at $20.9\times10^{-6}/^{o}C$. However, the bias circuit is also very thin and soft, so that it will tend to stretch to accommodate the silicon, thereby relaxing the stresses in the bond. This is evident in Figure 8, where the shear stress distribution looks more like that of a rigid bond, with sharp shear stress concentrations near the edges. One could say that even RTV behaves very much like a rigid adhesive when bonding a thin and flexible bias circuit.

Figure 6 and Figure 7 show the minimum required shear strength of the bond (safety factor included) and the stress level in the Silicon detectors, as a function of the shear modulus of the adhesive, for the three different bond thicknesses.

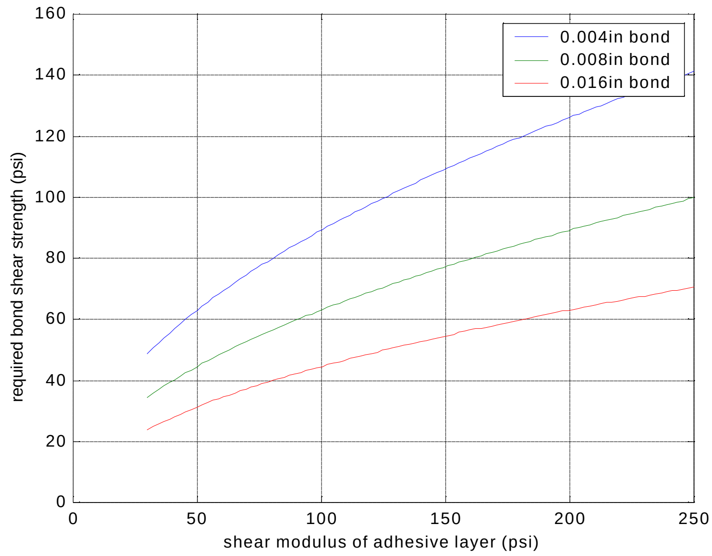

Figure 6: case 2, bond shear strength requirements for soft adhesive as a function of adhesive modulus and bond thickness.

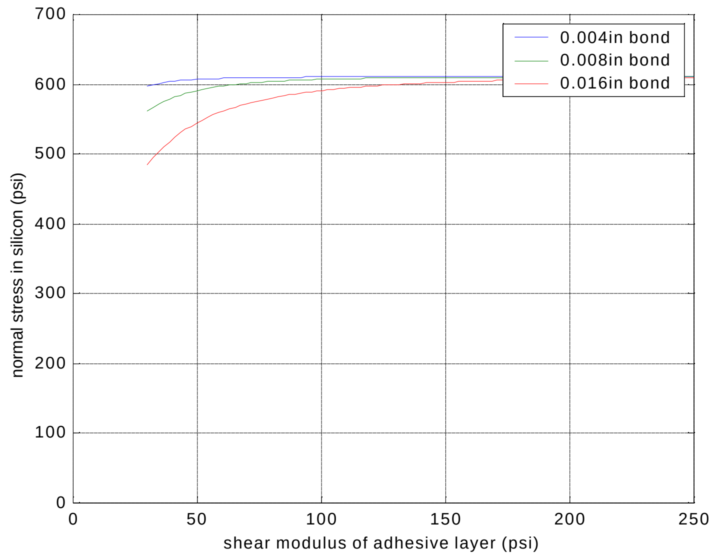

Figure 7: case 2: effect of shear modulus of adhesive on stress level in silicon (soft adhesives).

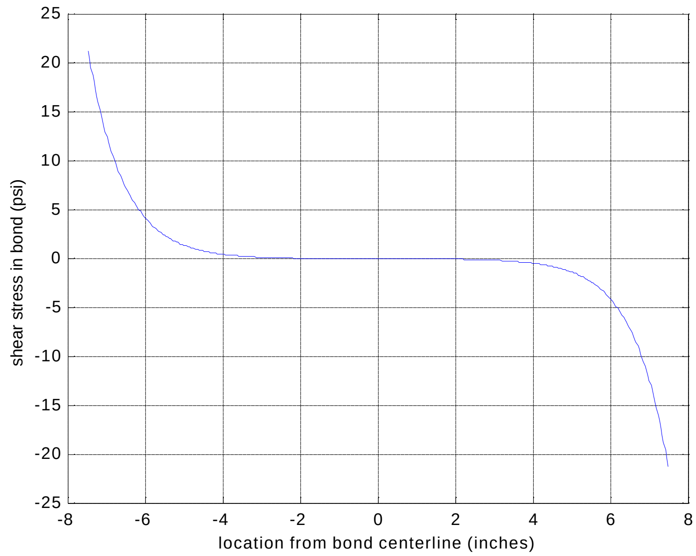

Figure 8: case 2, shear stress distribution from one end of the ladder to the other (assuming continuous bond in that direction), for an adhesive with a shear modulus of 100psi.

3.7 Bond Analysis and Requirement for Rigid Adhesive (epoxy-like, 50 to 1000 ksi shear modulus).

This section applies to "rigid" adhesives, i.e. those whose shear modulus is high enough that there is no decoupling between the substrates, or equivalently, no significant shear strain in the adhesive layer. In this case, we are in particular considering two component, room-temperature-cure, electrically conductive epoxy adhesives, with shear moduli assumed in the 50 to 1000 ksi range (room temperature shear moduli of unloaded epoxies typically range from 50 to 250 ksi). Note again that the shear modulus at low temperature could be substantially higher than at room temperature.

Refer to the introduction for an explanation of the assumptions used. In summary:

- bond thickness is assumed to be 4 mil (100 microns)
- factor of safety of 7.0 included in lap shear strength requirement.
- assumed 50% linear coverage near the edges of the ladder
- to be conservative, the shear modulus in the figure should be interpreted as the shear modulus of the adhesive at a temperature of -30degC.
- the shear strength requirement should be interpreted as the true shear strength of a bond between Kapton/gold and a SSD, following the surface preparation and cure schedule prescribed for GLAST.

3.7.1 Case 1: standard tray, top payload assembly

Refer to Section 3.6.1. In this case, the silicon is bonded with a rigid adhesive to the rest of the payload. Figure 9 shows the required bond strength as a function of shear modulus of the adhesive. Note that the required strength numbers are very high: the lap shear strength of the better industrial epoxies, cured at high temperatures, on etched aluminum samples rarely exceed 2 to 3 ksi (3M2216, an industrial standard for aerospace applications, typically fails at 1850 to 2500psi on etched aluminum). Conductive adhesives are much weaker and stiffer: Tra-Duct

2902, which was used on the beam test trays, fails at 700psi on etched aluminum. Within the assumptions and safety factors used in this study, this essentially disqualifies rigid conductive epoxies for this application.

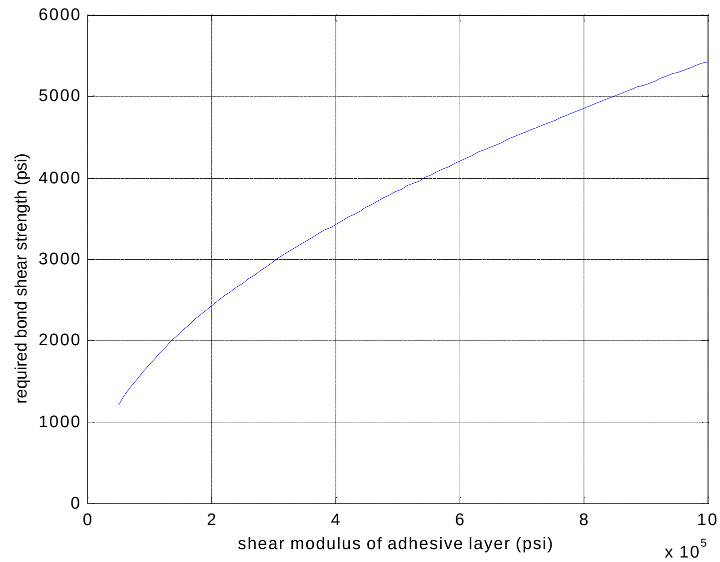

Figure 9: case 1, bond shear strength requirements for rigid adhesive as a function of adhesive modulus and bond thickness.

Figure 10 and Figure 11 show the thermal stress in the silicon and the shear stress distribution along the bond, for a 200ksi shear modulus. Notice the very sharp shear stress concentration near the edge, typical of a rigid bond. Also, in this range of modulus, the shear coupling is complete so that changes in the shear modulus of the adhesive have no effect on the stress level in the substrates.

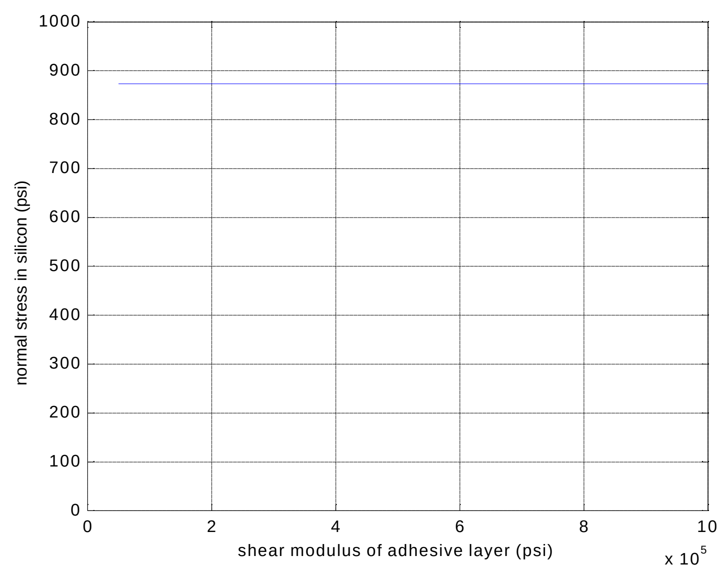

Figure 10: case 1: effect of shear modulus of adhesive on stress level in silicon (rigid adhesives).

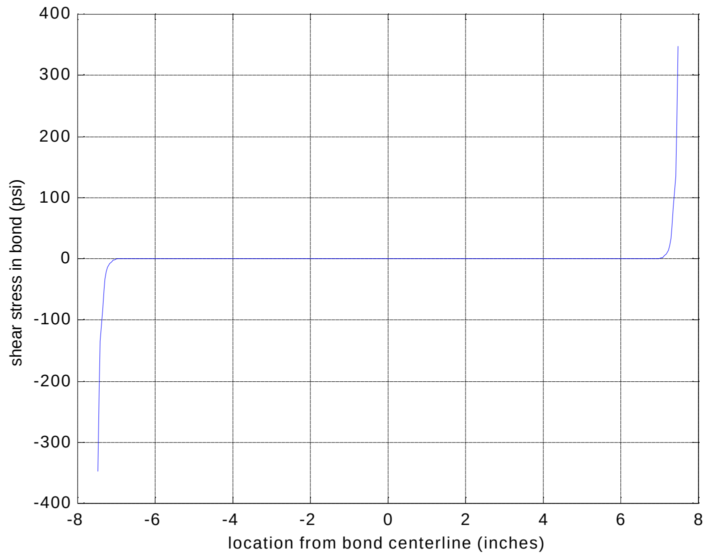

Figure 11: case 1, shear stress distribution from one end of the ladder to the other (assuming continuous bond in that direction), for an adhesive with a shear modulus of 200ksi.

3.7.2 Case 2: SSD ladder bonded to bias circuit only

In this case, the situation is very similar to the previous case: the bond is behaving entirely rigid, causing large stress concentrations at the edges. The required strength is higher than for case 1 and pretty clearly excludes the use of rigid adhesives. See Figures Figure 12, Figure 13, and Figure 14 for results.

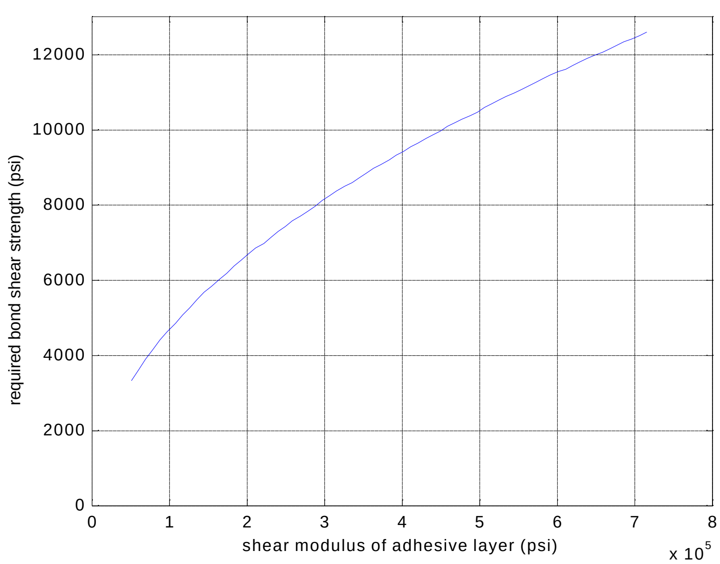

Figure 12: case 2, bond shear strength requirements for rigid adhesive as a function of adhesive modulus and bond thickness.

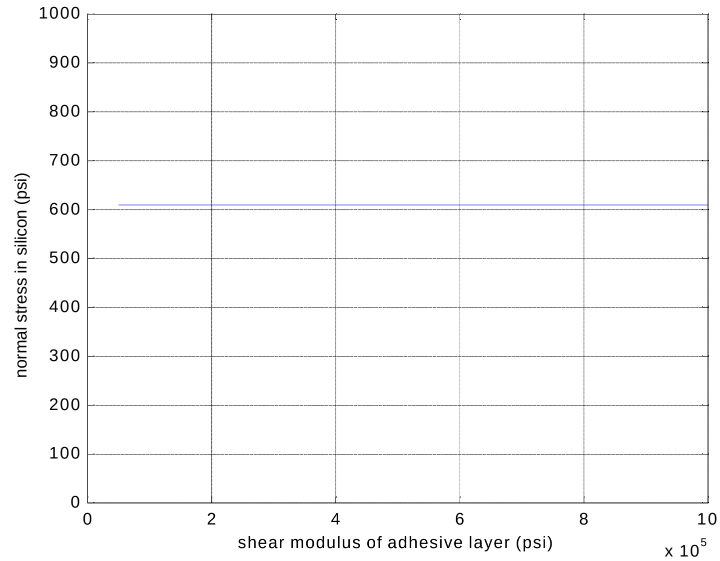

Figure 13: case 2: effect of shear modulus of adhesive on stress level in silicon (rigid adhesives).

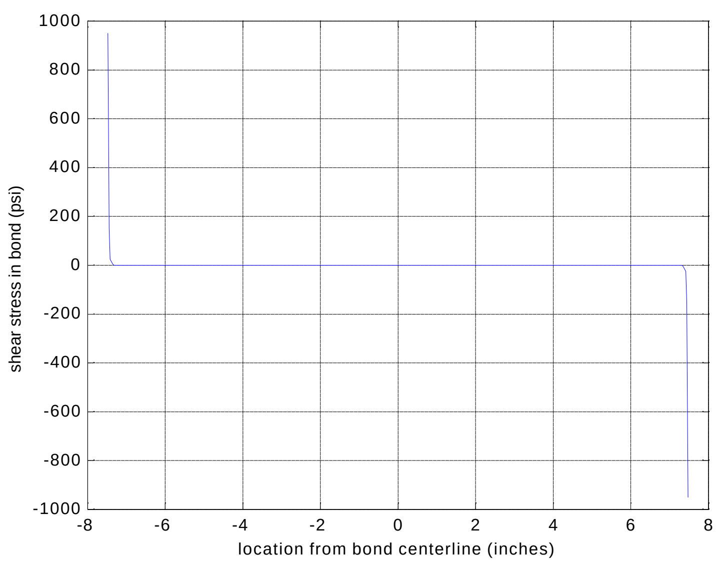

Figure 14: case 2, shear stress distribution from one end of the ladder to the other (assuming continuous bond in that direction), for an adhesive with a shear modulus of 200ksi.

4. Conclusions

Based on simple closed-form 2D shear lag analysis of the bonds between the SSD ladders and the bias circuits for GLAST, a preliminary set of mechanical requirements for the adhesive and bond layout has been derived. Large safety factors have been incorporated in an attempt to produce bond designs with unlimited fatigue life under thermal cycling. Alternatively, these same large safety factors may protect the initial selection of an adhesive from the very large uncertainties in bond modulus and strength. The resulting requirements should help in understanding the trends and issues in this bond design and selecting a few candidate adhesives, which will then have to be tested in realistic conditions. Validation of the simplifying assumptions through more detailed numerical modeling may also be useful.

The calculations also show that rigid adhesives (shear modulus above 50 ksi) should not be considered for this application (whether on regular or SuperGLAST trays) because of the high thermal stress levels induced in the bond. Compliant adhesives on the other hand should be useable in bond thicknesses as small as 100 micron; the required bond strength in that case oscillates beween a 50 psi and a few hundred psi depending on the severity of the CTE mismatch and the bond thickness.

5. References

1. *Adhesives, Sealants, and Primers / Plastic Material Selector*, Edition 6, D.A.T.A. Business Publishing, San Diego, CA, 1991.
2. Structural Design and Test Factors of Safety for Spaceflight Hardware, NASA Technical Standard, NASA-STD-5001, June 21, 1996.
3. Draft thermal requirements for GLAST, Martin Nordby, SLAC, March 31, 2000.