Proc. of SPIE Vol. 1998, Optomechanical Design, ed. D Vukobratovich, P R Yoder, V L Genberg (Sep 1993) Copyright SPIE

Analysis of adhesive bonds in optics

Alson E. Hatheway

Alson E. Hatheway Inc.
Suite 400
595 East Colorado Boulevard
Pasadena, California 91101

INTRODUCTION

Adhesive bonds are difficult to analyze for a number of reasons: first, the properties of the materials are often difficult to find in the desired form; second, the actual properties often appear to be quite different from the advertised or published values; and third, comprehensive analyses of adhesive bonds are often prohibitively expensive because of the size of such models based upon the small dimension of the adhesive bond itself.

All of these problems may be alleviated somewhat by an understanding of the basic behavior of the adhesive as a solid, i. e., through solid mechanics. A brief review of the properties of isotropic materials is presented (especially as it pertains to the adhesives), some technique are discussed to minimize the size of adhesive models and the results are applied to a family of sample problems to explain the discrepancy between the apparent behavior of adhesives and the anticipated (or published) behavior. Suggestions are offered to designers to assist them in realizing the "published behavior" in addition to the analysis suggestions for the engineer.

MATERIAL PROPERTIES

In evaluating the strength and elastic behavior of an adhesive it is usually treated as a uniform isotropic material (i. e., one having the same properties in all directions at all points in the material). The theory of elasticity tells us that such materials may be fully characterized by two constants or properties. In practice several properties that are commonly used, Young's modulus, the shear modulus (modulus of rigidity), Poisson's ratio and the bulk modulus are a few of them. Any two such properties are sufficient to describe the elastic behavior of the material and it follows that knowing two properties one may derive all of the others.

For structural engineering materials it is common to find Young's modulus and the shear modulus offered among lists of material properties. If we define,

Young's modulus = E = longitudinal stress/longitudinal strain

and

shear modulus = G = shear stress/shear strain,

we may define all of the other properties in terms of E and G. For many other material one may find the Young's modulus and Poisson's ratio offered and, similarly, it is possible to define all the other properties in terms of these two if we choose.

Poisson's ratio is the negative ratio of the lateral strain to the longitudinal strain caused by longitudinal loading of a slender bar (contractions are considered negative strains and extensions are considered positive strains so the negative ratio of the two causes Poisson's ratio to be positive, usually):

Poisson's ratio = P = -(lateral strain)/(longitudinal strain).

From considerations of the geometry of a solid body it may be shown that Poisson's ratio must be between 0.0 and 0.5. The prior value indicates a material that has no lateral extension or contraction when loaded while the latter indicates a material whose lateral strains are just sufficient to maintain a constant volume in the material. It is theoretically impossible for a real material to achieve either of these extreme values but many come very close; cork, sponge and foam materials have very low Poisson's ratios, perhaps 0.001 or lower; rubbers and elastomers have very high Poisson's ratios, perhaps .499 or higher. Common structural materials (and some uncommon ones such as ceramics, glasses, and beryllium) may have Poisson's ratios ranging from about .15 to .35.

It is often useful to express all the other elastic properties in terms of the Poisson's ratio and Young's modulus. For the shear modulus:

$$G = E / 2(1 + P).$$

Since the value of Poisson's ratio is limited to values between 0.0 and 0.5, the values of G are similarly limited,

$$E/3 < G < E/2.$$

For the bulk modulus:

$$B = E / 3(1 - 2P),$$

and the bulk modulus is limited by the value of P,

$$E/3 < B < \text{infinity}.$$

There are other elastic properties but these are the ones of principal concern here.

Now, since there are two equations presented in four unknowns (P, G, E, B) it is necessary (and sufficient) to know two of these values in order to calculate the other two (or any of the others that may be of interest).

In some fields of engineering it is possible to analyze the behavior of structures using only one elastic property, usually Young's modulus. However, in adhesives it is essential to account for the complete three dimensional behavior of the material and two elastic constants are necessary. Furthermore, many adhesives have very high Poisson's ratios and these materials, when constrained in thin layers (an adhesive bond) may have apparent behavior very different than that described by their Young's moduli.

Observe in Figure 1 the cusping and bulging of the free surfac of a typical adhesive. These effects are greatly exaggerated in

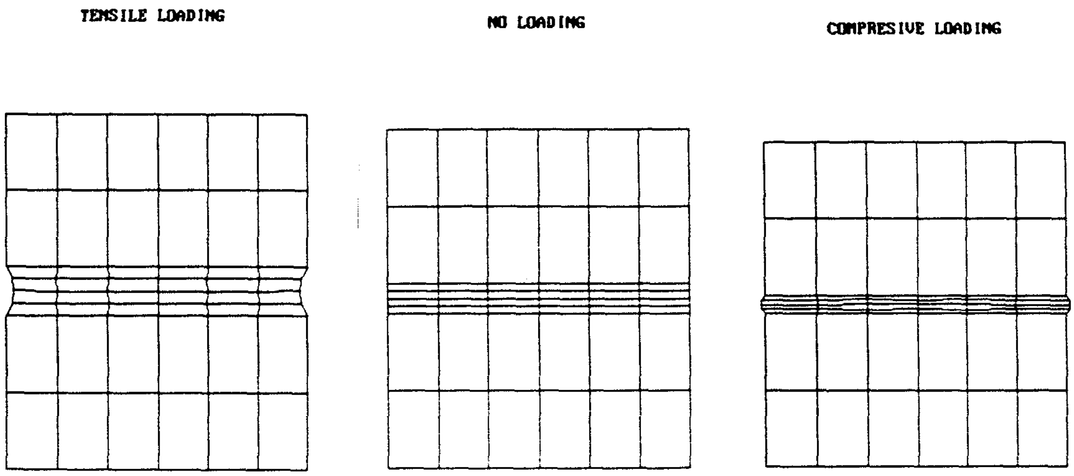

Figure 1. The behavior of an adhesive bond between two substrates.

order to be visible in the plots of the structural model but one may observe the same effects by stretching and compressing a simple rubber eraser. When the bond is put into compression the adhesive thickness is slightly reduced but since it has a high Poisson's ratio its volume must be nearly unchanged. The only place for the material to go is to bulge out at the free edges. Similar reasoning accounts for the cusping at the free surface of the adhesive under tension.

FINITE ELEMENT MODELING

Finite element analysis of adhesive bond joints is a very effective way to understand their behavior. Because they are usually very small features of an assembly they require many elements to describe them. The resulting analyses are often time consuming because of the large number of degrees of freedom required in the model.

A model of an adhesive bond needs to be at least three elements through its thickness (for coarse work) or five elements (for more accurate work). Models of single element thickness cannot allow for the elastic response in the adhesive. In response to compressive and tensile loading in the bond line, the adhesive expands and contracts laterally (in the plane of the bond). These lateral strains arise from the adhesive having a high Poisson's ratio and are very important in the elastic behavior of the adhesive. A single layer of elements cannot allow the adhesive to independently expand and contact because all of the grid points are also connected to the substrates: the adhesive cannot expand and contract without distorting the substrates as well.

Figure 1 shows a finite element model of an adhesive bond between two substrates. One characteristic of adhesive bonds is that the adhesive usually has a much lower Young's modulus than the substrates; under 1,000 psi. for the adhesive and over 10,000,000 psi. for the substrates. Consequently, the strains and distortions in the adhesive are expected to be much larger than in the substrates. In figure 1a the adhesive is in tension as can be observed from the inward cusping at the free edges of the adhesive. In Figure 1c the adhesive is in compression and the free edges of the adhesive bulge outward. Finite element models of adhesives need to have several layers of elements through the thickness of the adhesive in order to permit the bulging and cusping of the free edges.

The cusping and bulging of the adhesive observed in Figure 1 is a result of the fact that when the bond changes thickness under compression or tension, the adhesive material has to go somewhere, and that can only be in one or both of the lateral directions.

Although the model in Figure 1 gives qualitative indications of the nature of the distortions in adhesives it may not be giving accurate numerical results. This is because of the great difference in the elastic properties of the substrate and the adhesive. This difference can lead to numerical ill conditioning of the equations which is caused by very stiff elements being joined to very soft elements. The addition and subtraction of these largely different numbers can lead to a significant loss in precision of the calculations.

A better way to model adhesives is to isolate the adhesive from the substrates, which are simulated by rigid elements and rigid boundary constraints. The rigid members are removed from the equations before solution begins and therefore the numerical ill conditioning is avoided. Figure 2 is a model similar to Figure 1 with the substrates replaced by rigid members (which

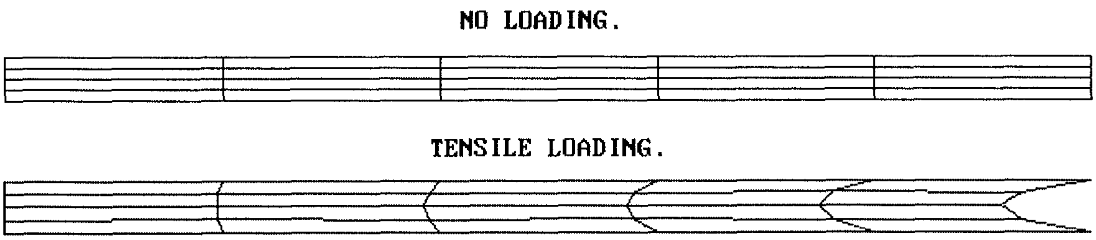

Figure 2. One half of an adhesive bond with the substrates simulated as rigid elements.

are not visible in the figure). The left side of the model in the figure represents the center of symmetry for the circular model, the free edge being on the right side in the figure. In the figure one may see that tension is accompanied by sizable shear strains as the adhesive material in the center attempts to move laterally but is being resisted by the fixed surfaces at the substrates. Compressive loads are accompanied by similar shear strains, of opposite sense, as the adhesive bulges at the free edge.

The need to model several layers of elements establishes the size of elements that can be used in a model. If an adhesive bond is .005 inches thick and five element are needed to model its thickness then .001 inch is the maximum thickness of the elements in the model.

As a rule of thumb one should not expect to use elements that have a ratio of their sides greater than about 1:10. Some analysis codes will issue warning messages if a predetermined ratio is exceeded. But even without the warning messages, very slender elements have computational problems and may give bad answers. If the adhesive bond (above) is .250 inches wide and 3 inches long and one observes the 1:10 rule, it will require 25 elements across the width of the bond and 300 elements along the length of the bond; a total of 37,500 elements to model just the adhesive. Adhesive bonds are rarely included in a system model, even though they may be very important structural features.

Usually, adhesive bonds are modeled separately and include just enough surrounding structural detail to obtain the desired displacements and stresses if ill conditioning can be avoided.

The model in Figure 2 was constructed along these lines with the additional requirement that the thickness of the adhesive layer should be variable over two orders of magnitude in order to study the influence of adhesive thickness on the elastic stiffness of the assembly. The model represents two circular substrates with an adhesive between. The adhesive thickness may be varied and one may determine the effect of a high Poisson's ratio on the tensile stiffness of the adhesive assembly. The substrates are assigned properties typical of glass or aluminum and the adhesive is assigned properties of a common silicon rubber. The rubber properties are,

Young's modulus = 507 psi.
Poisson's ratio = .49947.

These are measured properties and are typical of cured silicone rubber resins.

The model was used for some computer-experiments. One substrate was held fixed and the other was given a fixed tensile displacement. The strain in the adhesive was calculated as,

strain = fixed displacement / initial thickness of adhesive.

The forces necessary to maintain the fixed displacement were calculated by the finite element routine (MSC/pal2, a product of MacNeal-Schwendler Copr. Los Angeles, California)[1] and the resulting stress was calculated as,

stress = sum of forces / area of adhesive.

An "apparent modulus" was calculated from the stress and strain the same way Young's modulus is calculated,

apparent modulus = stress / strain.

A number of calculations were made with adhesive thickness from about .001 inch to about 10.0 inches. The results are plotted in Figure 3. The thickness has been divided by the diameter of the analytical model in order to remove the dimensionality of the model from the results. The analytical data are identified as "Transition Behavior" in the figure. The Young's modulus and the bulk modulus are included for reference.

One may observe that for thick adhesives, i. e., the thickness is greater than the diameter, the apparent modulus approaches the Young's modulus. However, at adhesive thickness less than the diameter the apparent modulus begins to rise rapidly. For a thickness equal to 1/10th the diameter the apparent modulus is about an order of magnitude larger than the Young's modulus. For thickness less than about 1/100th of the diameter the data begin to flatten again and approach a new asymptotic value, the value of the bulk modulus.

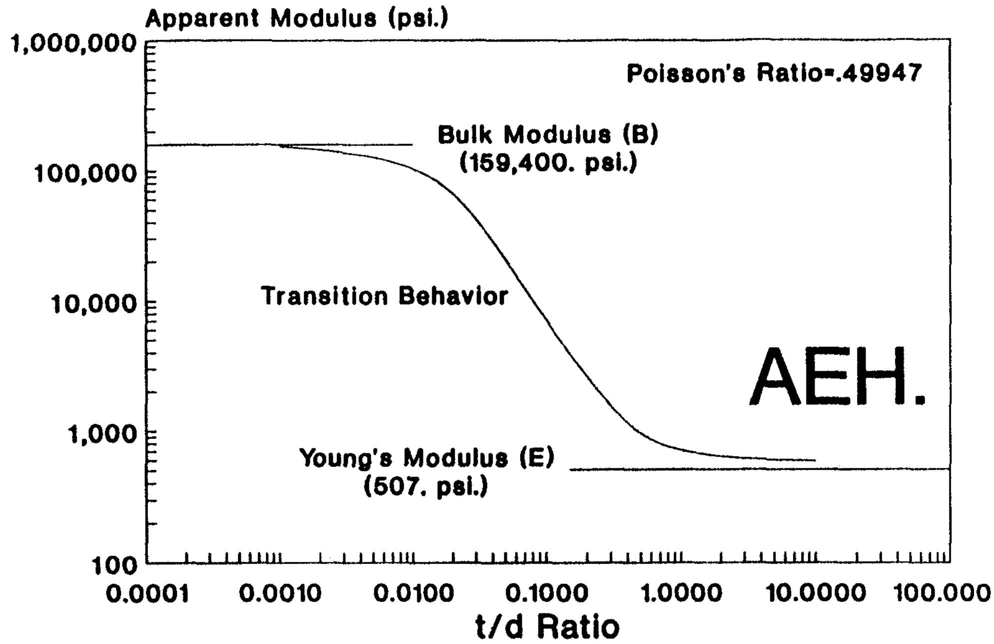

Figure 3. The apparent stiffening of an elastomer in thin bonds.

Figure 4 shows the same data but the value of the apparent modulus has been divided by the Young's modulus to determine a "Multiple of E," that is, the factor that one would apply to the Young's modulus to determine the apparent modulus at a

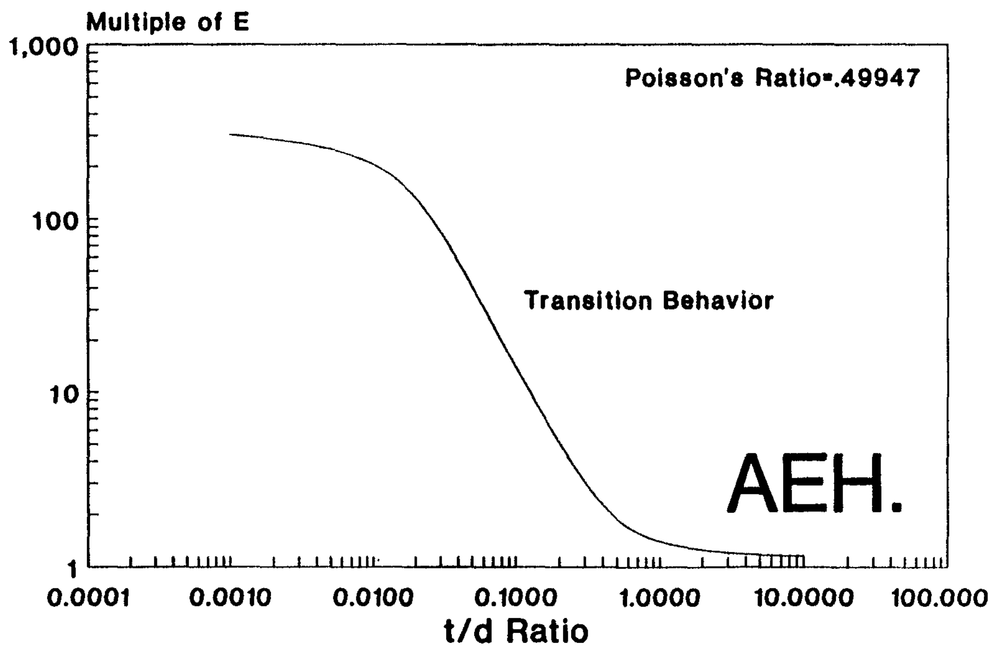

Figure 4. The apparent stiffness as a multiple of Young's modulus (E).

given thickness to diameter ratio. The figure shows that at normal adhesive thickness the tensile stiffness of the adhesive may be two-hundred time greater than the Young's modulus, or even greater.

All of the above discussion about the apparent properties apply only to the tensile/compressive properties. **The shear properties such as the shear modulus remain unchanged.** Shear strains, by their nature are constant volume processes and do not cause complementary material flows. The shear modulus may be used as read from tables of properties or as calculated from the Young's modulus and the Poisson's ratio.

IMPLICATIONS IN DESIGN

Optical elements are often mounted with a resilient adhesive in order to isolate the element from flexure and dimensional changes that may occur in the mounting structure and lens cells. Properly designed these adhesive mounts can be very effective but the designer must understand the behavior of the adhesive in order to design the mounting.

In thin layers the adhesive may become very stiff. This allows the designer to make a very stiff mount for an optical element, which will hold it in place under very severe environments, however, if the element is over-constrained very large stresses may be generated in the element and its mounting structure.

One typical case of over-constraint is in the mounting of prisms. If a prism is bonded into a housing by applying adhesive to opposite flat surfaces, the prism may be over constrained. In such cases the designer must allow for stress relief of the optical element by ensuring some flexible sections in the surrounding structure. If the structure does not provide for this stress relief the adhesive bond mounting may cause very high stresses from dynamic environments and temperature changes. The writer has observed a prism mounted in this way which came free (under thermal cycling) from the casting into which it was bonded. The stresses were sufficiently high to fracture the glass.

Another example of over constraint is in the mounting of lenses into cells. This is often performed with a continuous bead of adhesive around the circumference of the lens and completely filling the space between the lens and the ring. In this geometry the adhesive over constrains the lens around the whole perimeter. Again, temperature changes may cause very large stresses in the lens and the ring of the cell.

In evaluating these types of over constraint one may refer to Figures 3 and 4 for guidance in determining the appropriate apparent modulus for use in the analysis. But one may have to run his own computer-experiments if the material properties are significantly different than the silicone rubber used here as an example. By substituting the apparent modulus for the Young's modulus in the analysis one will have a much more accurate estimate of the performance of the adhesive.

The engineer needs to be aware that the shear modulus is not affected by the constraint of the substrates. In the analysis one wants to use the apparent modulus (in stead of the Young's modulus) and the shear modulus as the two elastic properties that define the adhesive's elastic behavior. These two properties are inconsistent for isotropic materials. Some software codes will issue a warning message and while others may not run at all under these circumstances.

If the design needs a soft mounting the designer must allow sufficient free surface area around the bond and avoid thin sections ($t/d < .10$) entirely. Surface-bonds, spot-bonds and tag- bonds are typical descriptions for adhesive bonds that observe this guidance. In these bonds the material properties are very close to the published values that are for free (unconstrained) specimens.

CONCLUSION

The apparent tensile and compressive properties of adhesives are often considerably different from the published value of Young's modulus. The fact that adhesive bonds are often considerably stiffer than expected is predicted by conventional elastic theory for the material. Full scale finite element models are large and expensive to run while simplified models rarely give the right answers. These problems can be partly overcome by making small models of the adhesive of interest in order to derive an apparent modulus from the data and constructing analytical models using the apparent properties.