# Synopsis of Technical Report

## "Analysis of Adhesive Bonds in Optics"


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## Introduction

This paper documents methods to analyze adhesive bonds, particularly in optical applications. Analysis of bonded joints can be challenging for a number of reasons. It is often difficult to obtain the material properties to analyze the bond. When properties are published, it is often found that the adhesive behaves differently when used in thin layers. Additionally, modeling bond joints can be difficult due to the size of the computer model needed to accurately represent the behavior of the bonded joint.

The information presented in this paper is useful for engineers, scientists, and technicians that are involved in designing or analyzing optics bonds. The paper helps one understand the mechanisms in which adhesive bonds behave, suggestions for modeling adhesive bonds, and advice on how to ensure a bonded joint's performance is predicted reliably.

## Material Properties

The paper begins by providing an overview of the elastic behavior of materials as it pertains to adhesives. It is common to treat an adhesive as a uniform isotropic material when evaluating strength and elastic behavior. From the theory of elasticity, two of any of the following properties are sufficient to describe the behavior: Young's Modulus (E), Shear Modulus (G), Poisson's ratio (v), and Bulk Modulus (B). The others can be calculated from the two known properties. It is most common for Young's Modulus and Poisson's ratio to be provided in material property data. The author includes equations to determine the other properties based on these.

Shear Modulus: $G = \frac{E}{2(1+v)}$

Bulk Modulus: $B = \frac{E}{3(1-2v)}$

The author emphasizes the necessity to account for the complete three dimensional behavior of the material (thereby using two elastic constants) when analyzing adhesive bonds. When adhesives are used in thin layers, their apparent behavior may be quite different than that described by their Young's Modulus due to their very high Poisson's ratios. Recall that Poisson's ratio is the negative ratio of the lateral strain to the longitudinal strain caused by longitudinal loading of a slender member. The maximum theoretical Poisson's ratio is 0.5 which corresponds to the material undergoing zero volume change during loading. Since the Poisson ratio of adhesives is often near 0.5, they behave as shown in Figure 1 (scale exaggerated). When the substrates are compressed, the bond thickness is reduced so the adhesive must bulge out to maintain nearly the same volume. The opposite is true for the tensile case.

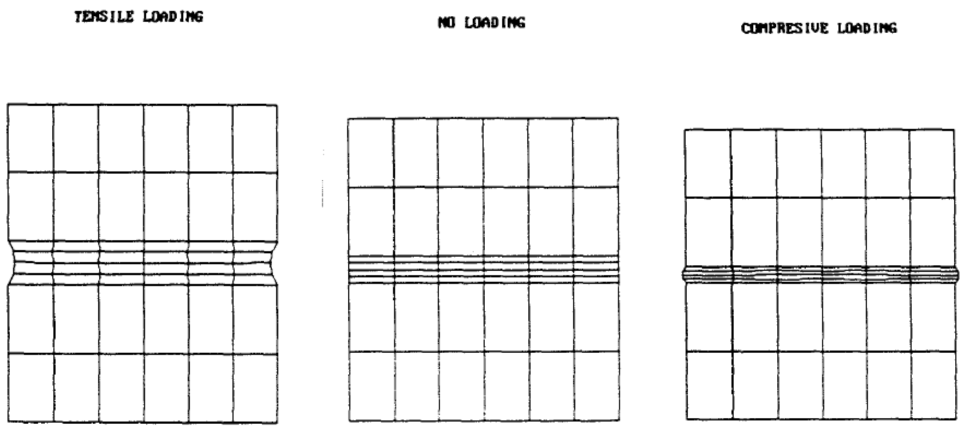


Figure 1. The behavior of an adhesive bond between two substrates

## Finite Element Modeling

The author states that using FEA can be very effective at modeling the behavior of adhesives bonds, if done properly. The analysis can be computationally expensive due to the extensive number of elements to accurately model the bond behavior. At least three to five elements must be used to represent the thickness of the adhesive layer to allow for the elastic response (lateral movement of adhesive as shown in Figure 1).

Adhesives usually have much lower Young's modulus than the substrates to which they are bonded (on the orders of 1,000 psi for the adhesive and 10,000,000 psi for the substrates). This means that the strains and distortions of the adhesive will be much higher than that of the substrates. FEA programs are susceptible to numerical ill conditioning of the equations which is caused by very stiff elements being joined to very soft elements. This can cause a significant reduction in the precision of the calculations. The author advises a method to mitigate this by isolating the adhesive from the substrates in the FEA model. Replace the substrates with rigid boundary conditions at the adhesive interface rather than modeling the substrate itself. Figure 2 is similar to Figure 1 except the substrates are replaced with rigid boundary conditions. The left side of the model in Figure 2 is the center of symmetry.

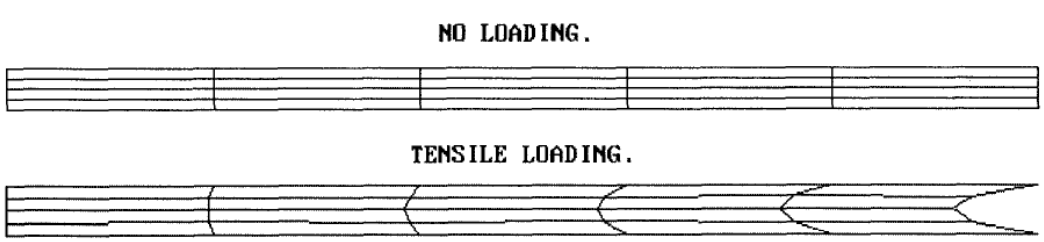


Figure 2. One half of an adhesive bond with the substrates simulated as rigid elements

The author also warns against letting the ratio of the element sides exceed 1:10, which can be challenging considering how small the elements through the thickness must be. This supports the author's previous suggestion to model the bond joint separately from the rest of the structure. Having elements that are sufficiently small to represent an adhesive bond used over a large structure would result in an excessive number of elements.

The author parameterized the adhesive thickness for the model shown in Figure 2 in order to study the effect of the adhesive thickness on its elastic behavior. One substrate was held fixed while the other was subjected to a tensile load. The thickness was varied from .001" to about 10". The "apparent modulus" was calculated for each case as stress/strain. The data is plotted in Figure 3. The apparent stiffness of the adhesive is a strong function of the adhesive thickness. For thick bonds, the apparent stiffness is close to Young's Modulus. For thin bonds, the apparent stiffness is close to the Bulk Modulus. At common adhesive thicknesses (not very thick), the apparent stiffness can be two hundred times greater than Young's Modulus.

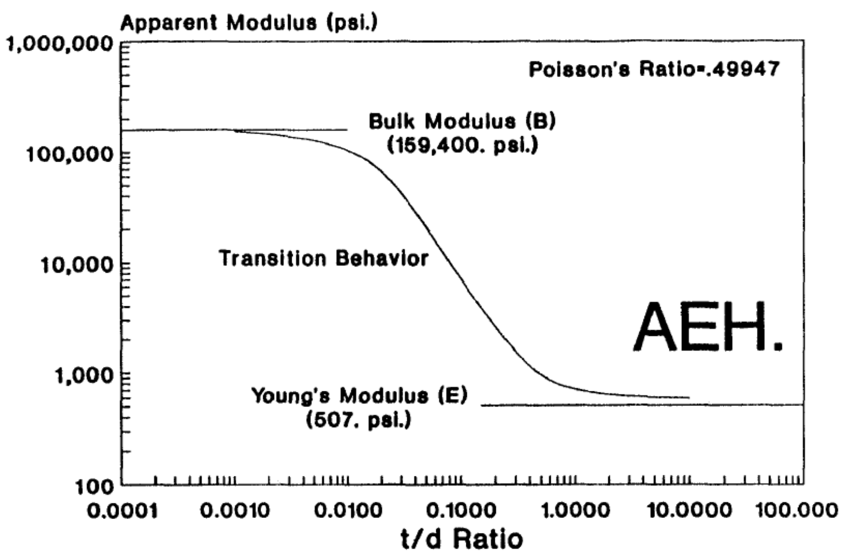


**Figure 3. The apparent stiffening of an elastomer in thin bonds**

The author notes that the above discussion about the apparent properties only applies to the tensile/compressive properties, not to shear properties (e.g. shear modulus). This is because shear strains are naturally constant volume processes and don't cause material flow.

## Design Implications

The author closes out the paper giving some design suggestions and reiterating some important points.

Adhesives can become much stiffer than their Young's moduli indicate when used in thin layers (as is most common). The designer should avoid over-constraining the bonded optic (e.g. bonding a prism to housing by applying adhesive to opposing surfaces). Unless the structure has some flexible sections to allow stress relief, the optic could undergo high stresses from dynamic inputs or temperature changes. Use of kinematic mounting principles can aid in preventing this.

When using FEA to model an adhesive bond, the engineer should use the apparent stiffness (see Figure 3) in place of Young's modulus and the published shear modulus as the two elastic properties. These will be inconsistent for isotropic materials and some software codes will issue warnings or refuse to run because of this.

The primary takeaways from this article are listed below for convenience:

1. Understand theory of elasticity and make sure to account for three dimensional behavior of adhesive (use two elastic properties instead of just Young's Modulus).
2. Model bond joint separately than rest of structure when doing FEA to prevent excessive computation time.
3. Use at least three to five elements through the thickness of an adhesive layer.
4. Replace substrates with rigid boundary conditions to avoid numerical ill conditioning in FEA models.
5. The "apparent stiffness" of an adhesive is a strong function of the adhesive thickness. For thick bonds, the apparent stiffness is close to Young's Modulus. For thin bonds, the apparent stiffness is close to the Bulk Modulus.
6. When using FEA to model an adhesive bond, the engineer should use the apparent stiffness (see Figure 3) in place of Young's modulus and the published shear modulus as the two elastic properties.

Vukobratovich's "Intro to Optomechanical Design" course notes offer additional information on bonding optics. One particularly useful equation is that to determine the stress developed from bonding two materials with different CTEs over a temperature change (provided in Figure 4). The derivation of this equation, along with a detailed analysis, is presented in "Thermal Stress in Bonded Joints" by Chen and Nelson (1979).

$$\tau_{\max} = \frac{(\alpha_1 - \alpha_2) \quad \Delta T \; G \tanh(\beta L)}{\beta \; h_r}$$

$$\beta = \left[ \frac{G}{h_r} \left( \frac{1}{E_1 h_1} + \frac{1}{E_2 h_2} \right) \right]^{\frac{1}{2}}$$

Where:

| | |
|---|---|
| $\tau_{MAX}$ | Is the maximum shear stress due to the difference in thermal coefficient of expansion |
| $\alpha_1 \alpha_2$ | Are the thermal coefficient of expansion of materials 1 and 2. |
| $\Delta T$ | Is the change in temperature |
| G | Is the shear modulus of the adhesive |
| L | Is the size (radius) of the adhesive bond |
| $h_r$ | Is the thickness of the adhesive bond |
| $E_1 E_2$ | Are the elastic modulii of materials 1 and 2 |
| $h_1 h_2$ | Are the thickness of materials 1 and 2 |

**Figure 4. Stress produced by bonding two materials with different thermal coefficients of expansion (Vukobratovich course notes)**