Adhesives

We use adhesives to hold things together.

For optical applications, we can define several classes of adhesives:

**Optical adhesives**
Transparent. Optical qualities are important.

**Structural adhesives**
Strength is most important

**Elastomers**
Use rubbery properties for sealing and to provide compliance

**Cyanoacrylates**
Superglue
Quick staking,
Beware: outgassing can ruin coatings

**Issues:**
- Choice of materials, bond thickness, bond area
- Strength of the bond
- Stability
- Stiffness
- Thermal stresses
  - Can thermal effects cause the bond to fail?
  - Can thermal effects cause distortion in the optics
- Ease of assembly
  - Surface preparation
  - Primers
- Ease of disassembly
  - Solvents
  - Mechanical cutting
Elastomeric bonds

Rubber and RTV (ν ≈ 0.5) behave strangely as an elastic material.

- \( G \) (Shear modulus) \( \approx 100 \text{ psi} \) (~1 MPa)
- \( E_0 \) (Young's modulus) \( \approx 3 \times 100 = 300 \text{ psi} \) (~3 MPa)
- \( E_B \) (Bulk modulus) \( \approx 100,000 \text{ psi} \) (~1000 MPa)

Shear stiffness, where thickness < width

Shear stiffness \( K_s \) is

\[
K_s = \frac{\delta F_{\text{shear}}}{\delta y} = \frac{GA}{t}
\]

Very compliant

Axial stiffness, for tensile elongation where axial length >> width

Axial stiffness \( K_1 \)

\[
K_1 = \frac{\delta F_{\text{axial}}}{\delta z} = \frac{E_0 A}{L}
\]

Very compliant

In compression, this buckles and behaves non-linearly
For thin rubber, thickness << width, transverse strain is constrained, use the bulk modulus

\[ K_2 = \frac{\delta F_{axial}}{\delta z} = \frac{E_B A}{t} \]

Very stiff!

What about compression for a more general case?

The dominant axial compliance for this case is due to shape change, not material strain.

Axial stiffness – depends on shape

\[ K_z = \frac{\delta F_{axial}}{\delta z} = \frac{E_C A}{t} \]

Where \( E_C \) is the compression modulus, which depends on geometry

\[ E_C = E_0 \left( 1 + \phi S^2 \right) \]

\( E_0 = \) Young’s modulus
\( S = \) Shape factor
\( \phi = \) material compressibility coefficient (=0.64 for RTV)
The shape factor $S$ is defined as

$$S = \frac{\text{Load area}}{\text{Bulge area}} = \frac{A}{\text{perimeter} \times \text{thickness}} = \frac{l \times w}{(2w + 2l) \times t}$$

<table>
<thead>
<tr>
<th>Shear modulus, $G$ (kPa)</th>
<th>Young's modulus, $E_0$ (kPa)</th>
<th>Bulk modulus, $E_b$ (MPa)</th>
<th>Material compressibility coefficient, $\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>296</td>
<td>896</td>
<td>979</td>
<td>0.93</td>
</tr>
<tr>
<td>365</td>
<td>1158</td>
<td>979</td>
<td>0.89</td>
</tr>
<tr>
<td>441</td>
<td>1469</td>
<td>979</td>
<td>0.85</td>
</tr>
<tr>
<td>524</td>
<td>1765</td>
<td>979</td>
<td>0.80</td>
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<tr>
<td>621</td>
<td>2137</td>
<td>1,007</td>
<td>0.73</td>
</tr>
<tr>
<td>793</td>
<td>3172</td>
<td>1,062</td>
<td>0.64</td>
</tr>
<tr>
<td>1034</td>
<td>4344</td>
<td>1,124</td>
<td>0.57</td>
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<tr>
<td>1344</td>
<td>5723</td>
<td>1,179</td>
<td>0.54</td>
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<tr>
<td>1689</td>
<td>7170</td>
<td>1,241</td>
<td>0.53</td>
</tr>
<tr>
<td>2186</td>
<td>9239</td>
<td>1,303</td>
<td>0.52</td>
</tr>
</tbody>
</table>

For small $S$, $E_C = E_0$ as above

For large $S$, $E_c$ would blow up according to the relationship above. Take the maximum value of $E_c$ to be the bulk modulus $E_b$

For 2 mm thick RTV pad 20 x 20 mm

$E_0 = 3\text{MPa}$

$G = 1\text{MPa}$

$\phi = 0.64$

$S = \frac{(20\times20)}{4\times(2\times20)} = 2.5$

$E_C = 3\text{MPa} \left(1 + 0.64 \times 2.5^2\right) = 15\text{MPa}$

$K_Z = \frac{E_C A}{t} = 3000\text{N/mm}$

$K_S = \frac{GA}{t} = 200\text{N/mm}$

$K_{ax}/K_s = 15$ : 15 times stiffer axially than in shear.

Reference:

Hardness
Defined as resistance to indentation, according to specific tests:

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>APPROXIMATE VISCOSITY (in centipoise)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water @ 70 F</td>
<td>1</td>
</tr>
<tr>
<td>Blood or Kerosene</td>
<td>10</td>
</tr>
<tr>
<td>Anti-Freeze or Ethylene Glycol</td>
<td>15</td>
</tr>
<tr>
<td>Motor Oil SAE10 or Corn Oil</td>
<td>50 to 100</td>
</tr>
<tr>
<td>Motor Oil SAE30 or Maple Syrup</td>
<td>150 to 200</td>
</tr>
<tr>
<td>Motor Oil SAE40 or Castor Oil</td>
<td>250 to 500</td>
</tr>
<tr>
<td>Motor Oil SAE60 or Glycerin</td>
<td>1,000 to 2,000</td>
</tr>
<tr>
<td>Corn Syrup or Honey</td>
<td>2,000 to 3,000</td>
</tr>
<tr>
<td>Molasses</td>
<td>5,000 to 10,000</td>
</tr>
<tr>
<td>Chocolate Syrup</td>
<td>10,000 to 25,000</td>
</tr>
<tr>
<td>Heinz Ketchup or French's Mustard</td>
<td>50,000 to 70,000</td>
</tr>
<tr>
<td>Tomato Paste or Peanut Butter</td>
<td>150,000 to 250,000</td>
</tr>
<tr>
<td>Crisco Shortening or Lard</td>
<td>1,000,000 to 2,000,000</td>
</tr>
<tr>
<td>Caulking Compound</td>
<td>5,000,000 to 10,000,000</td>
</tr>
<tr>
<td>Window Putty</td>
<td>100,000,000</td>
</tr>
</tbody>
</table>

(McMast Carr)

Viscosity
A fluid’s resistance to flow. The “thickness” of the fluid.

10 poise = 1 Pa s
**Thermal stress**

Usually, thermal mismatch is accommodated by the adhesive, because it has most compliance. Also, the thermal expansion of the adhesive is usually less important than that of the substrates.

For bond with dimension $a$, thickness $t$

Adhesive goes into pure shear.

Maximum shear strain, $\gamma$, at distance $a/2$ from center:

$$\gamma = \frac{a}{2} \frac{\alpha_1 \Delta T - \frac{a}{2} \alpha_2 \Delta T}{t} = \frac{a}{2t} (\alpha_1 - \alpha_2) \Delta T$$

Shear stress $\tau$ at distance $a/2$ from center:

$$\tau = G \gamma = \frac{Ga}{2t} (\alpha_1 - \alpha_2) \Delta T$$

This approximation will work most of the time. It is conservative. Actual stress is reduces by additional compliance of substrates. For cases where the substrates are thick compared to the glue:

$$\frac{\text{Substrate compliance}}{\text{Epoxy compliance}} \approx \frac{0.1}{t} \frac{G_{\text{epoxy}}}{E_{\text{substrate}}}$$

For epoxy, $G \approx 150$ ksi.

Bonding metal to glass. Approximation is only valid for size/thickness: $a/t < 100$

A more complete relationship is given in Yoder p.802 and Vukabratovich p 123. (Note $L$ is the bond radius, not the overall size. (Chen and Nelson 1979).
Example
Bond Glass to Aluminum

For 3M 2216,
\[ G = 342 \text{ MPa at } 24^\circ C, \quad 1500 \text{ MPa at } 0^\circ C \]
\[ \text{CTE} = 100 \text{ ppm}/^\circ C \]

Shear strength of 2216 = 2 ksi = 14 MPa

Nominal bond is 0.1 mm thick.
For 5 mm bond, strength @ 14 MPa is 274 N (62 lbs)
for \( \Delta T = 20^\circ C \), \( \Delta a/2 \) is \((20^\circ C)(5 \text{ mm})/2*(23 – 7)\text{ppm}/^\circ C = 0.8 \mu m \)
\[ \gamma = \Delta a/2 / t = 0.8/100 \]
\[ \gamma = 0.008 \]

Using \( G @ 24^\circ C \) of 342 MPa
\[ \tau = 2.8 \text{ MPa} \]
\[ \text{safety factor} = 14/2.8 = 5 \]

If cooled 20°C, use \( G = 1500 \text{ MPa} \)
\[ \tau = 12 \text{ MPa} \]
This is close to the strength of the epoxy

Taking into account deflection of 6 mm thick aluminum, 25 mm thick glass. Use relation on p 125 of Vukabratovich (L is the bond RADIUS) the stress is reduced from 12 MPA to 11 MPA.

To survive this temperature:
1. Use an epoxy with lower modulus at temperature
2. Use thicker adhesive layer
3. Prepare the glass surface (fine ground and acid etched) to provide > 2000 psi (14 MPa) strength. At this point the epoxy is the weakest link.
4. Use smaller bond area
5. Use mechanical design with flexures to allow thermal expansion.