Showcase on

Virginia Fiber-Reinforced Polymer Composites: Materials, Design, and Construction

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Polymers and Adhesives for the Infrastructure

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Outline

- **Polymer Fundamentals**
  - **Polymers, Resins, and Adhesives**
  - **Material Behavior of Polymers**

- **Adhesion Mechanics**
  - **Adhesion/Adhesive Testing**
  - **Mechanical Analysis of Adhesive Bonds**
  - **Design of Adhesively Bonded Joints**

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Chemical Composition of Polymers

Polymer: compound consisting of up to millions (**poly-**) of repeated linked units **(-mer**)
Monomer: molecule combine with others to form a polymer

Homopolymer ~~~A-A-A-A-A-A-A-A-A-A-A-A-A-A-A-A~~~

Random copolymer ~~~A-A-B-A-B-B-B-A-B-B-A-B-B-B-A~~~

Block copolymer ~~~ A-A-A-A-A-A-A-A-B-B-B-B-B-B-B-A-A-A-A-A-A-A-A~~~

Graft copolymer

```
A-A-A-A-A-A-A-A-A-A-A-A-A-A-A-A-
      |           |
      B           B
      |           |
      B           B
      |           |
      B           B
      |           |
      B           B
      |           |
      B           B
```


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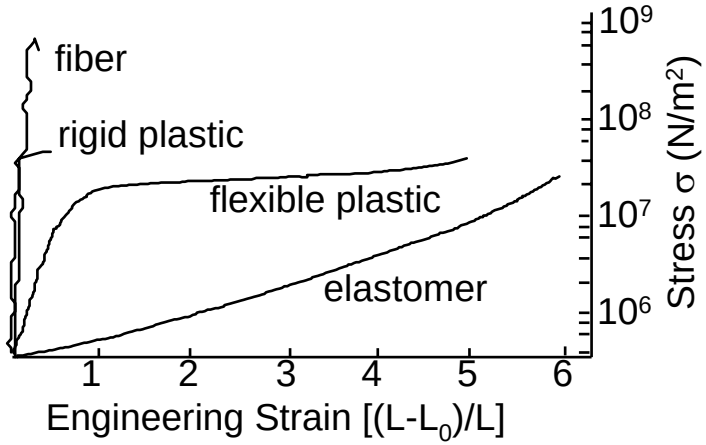
Classes of Polymers



Some Common Elastomers, Plastics, and Fibers

Elastomers	Plastics	Fibers
polyisoprene	polyethylene	
polyisobutylene	polytetrafluoroethylene	
polybutadiene	polystyrene	
	poly(methyl methacrylate)	
	phenol-formaldehyde	
	urea-formaldehyde	
← poly(vinyl chloride)	→	
← polyurethanes	→	
	← polyamide	→
	← polyester	→
	← polypropylene	→

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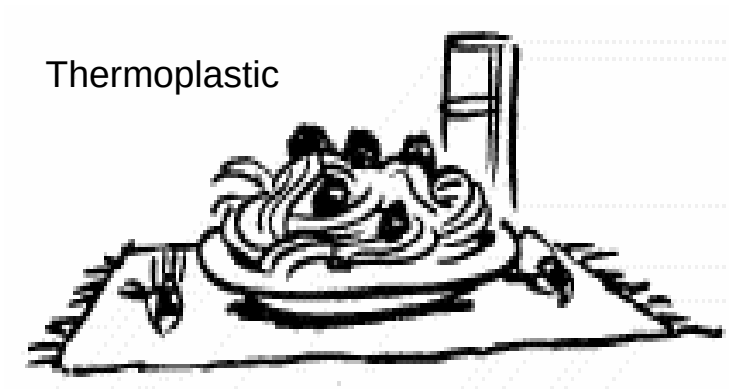
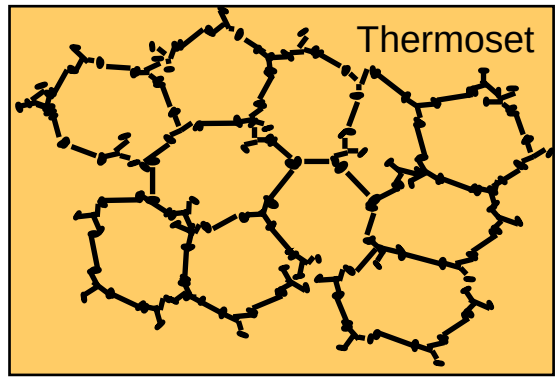
Polymers as Resins & Adhesives

Thermoplastics: like metals, soften with heating and eventually melt, hardening again with cooling. Softening can be repeated. (*flexible plastic*)

Thermosets: formed from a chemical reaction, the resin and catalyst are mixed and then undergo a non-reversible chemical reaction to form a hard, infusible product. (*rigid plastic*)

The majority of FRP structural parts are made with thermosets: **polyester**, **vinyl ester, epoxy, and phenolic resins**.





Desirable properties: Good adhesive properties
Allow certain plastic deformation
Good toughness properties
Good resistance to environmental attacks

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Advantages/Disadvantages of Typical Resins

	Advantages	Disadvantages
Polyesters	Easy to use Lowest cost of resins available (£1-2/kg)	Only moderate mechanical properties High styrene emissions in open moulds High cure shrinkage Limited range of working times
Vinylesters	Very high chemical/environmental resistance Higher mechanical properties than polyesters	Postcure generally required for high properties High styrene content Higher cost than polyesters (£2-4/kg) High cure shrinkage
Epoxies	High mechanical and thermal properties High water resistance Long working times available Temperature resistance can be up to 140°C wet / 220°C dry Low cure shrinkage	More expensive than vinylesters (£3-15/kg) Critical mixing Corrosive handling

SP Composite Guide
(www.spsystems.com)

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Advantages/Limitations of Typical Structural Adhesives

Adhesive	Advantages	Limitations
Epoxy	High strength, good resistance at elevated temperatures, relatively low cost	Exothermic reaction, short pot life
Polyurethane	Excellent flexibility even at low temperatures, moderate cost	Moisture sensitive, poor resistance at elevated temperatures, short pot life
Acrylic	Good flexibility, good peel and shear strength, bonding of dirty surfaces possible, moderate cost	Low strength at elevated temperatures, toxic, flammable, limited open time

EDCH (Clarke 1996)

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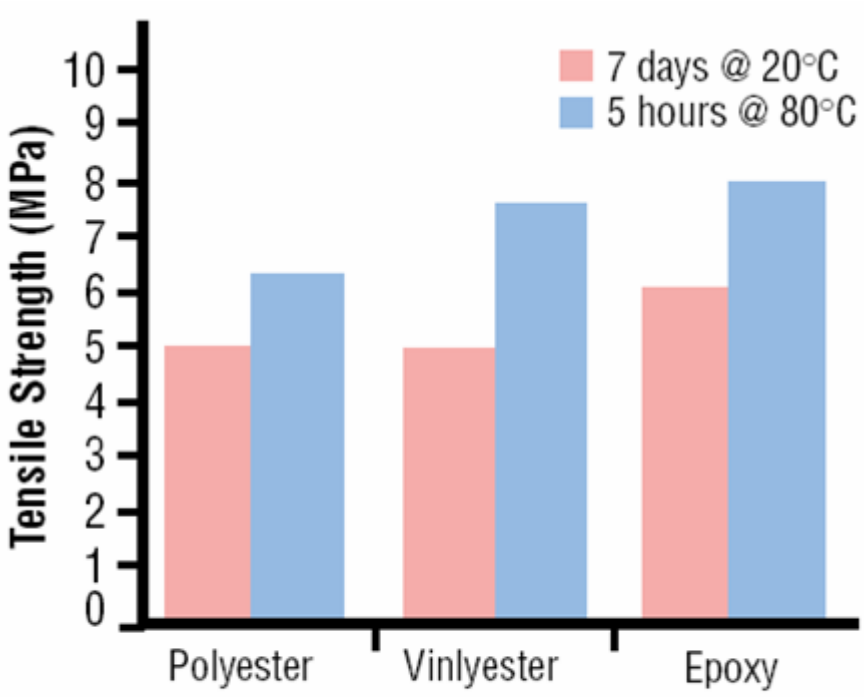
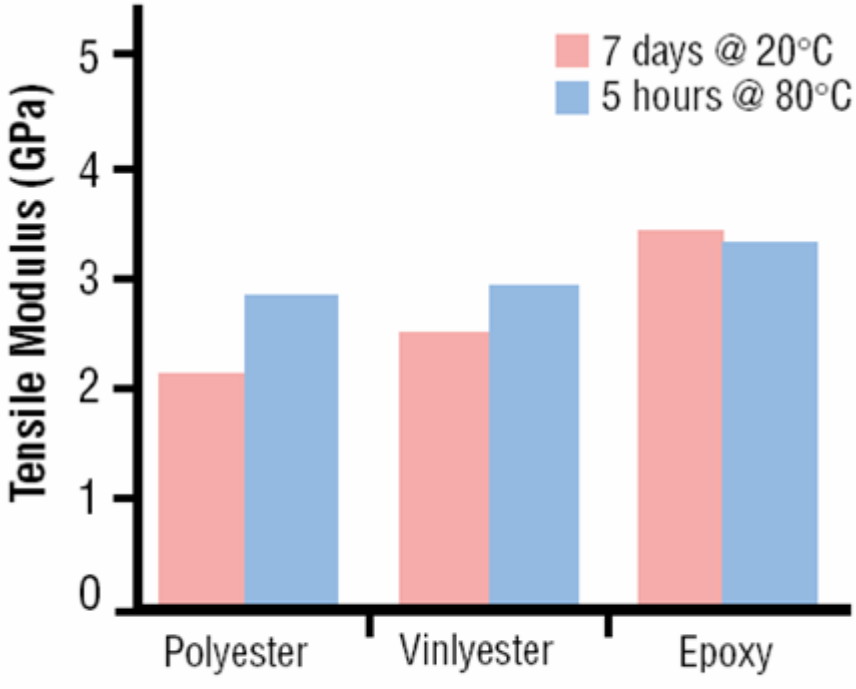
Mechanical Properties of Typical Resins



Comparative Tensile Strength of Resins



Comparative Stiffness of Resins

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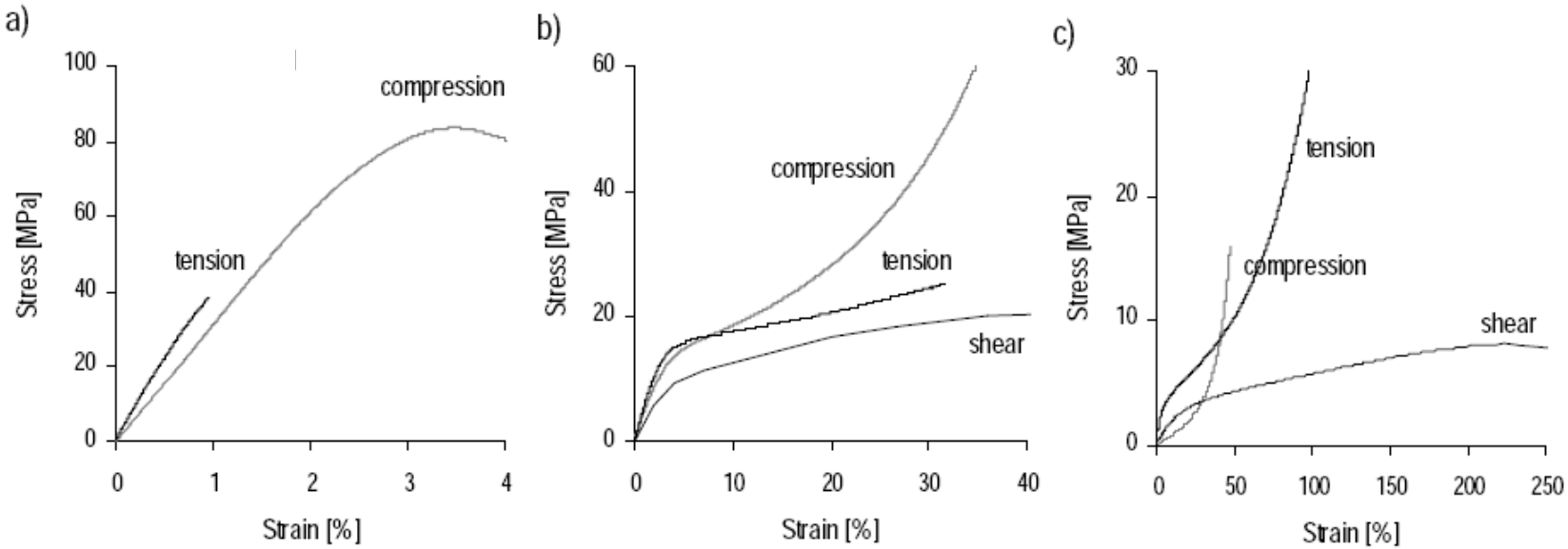
Mechanical Properties of Typical Adhesives



Epoxy Polyurethane Acrylic

Tested in normal lab condition

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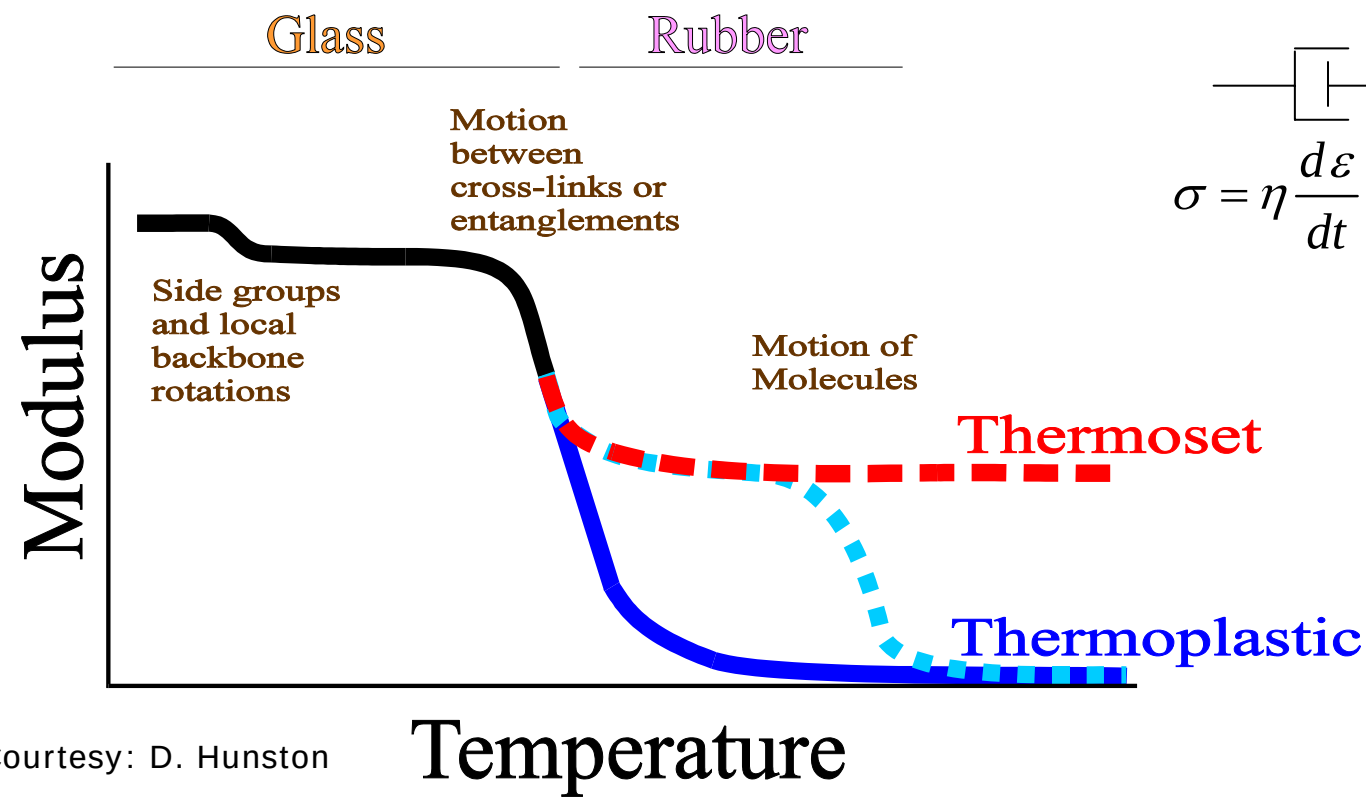
Viscoelastic Polymer Behavior



$$\sigma = \eta \frac{d\varepsilon}{dt} = \eta \dot{\varepsilon}$$

Courtesy: D. Hunston

Once cured, thermosets will not become liquid again if heated, although above a certain temperature their mechanical properties will change significantly. This temperature is known as the **Glass Transition Temperature** (Tg).

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Challenges in Testing Adhesive Bonds

- **Test of a material system**
  - Strength, fracture, and durability tests should be performed on the actual **material system**, consisting of adherends, surface treatment, primer, adhesive, etc.

- **Test of a structure**
  - Every test of an adhesive joint is a test of a **structure**, having complex stress distributions and requiring mechanics analysis.

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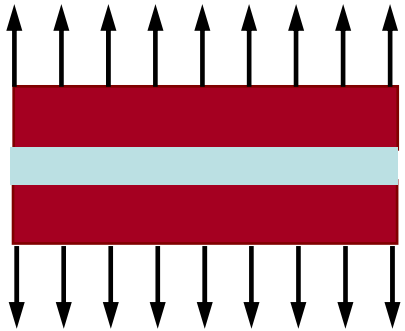
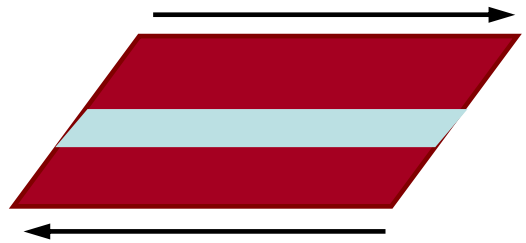
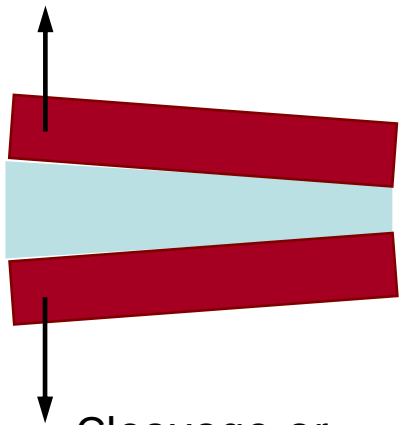
Joint Loading



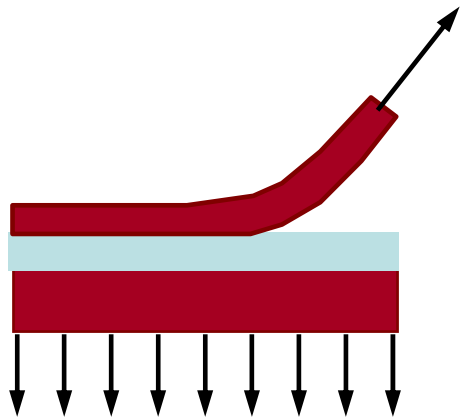
Butt or Normal Load



Shear Load



Cleavage or
Eccentrically Loaded



Peel

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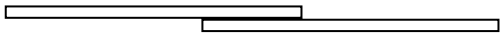
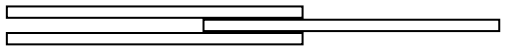
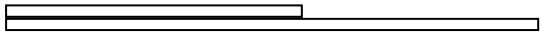
Basic Joint Geometries



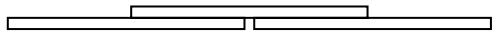
(a) Single-Lap Joint



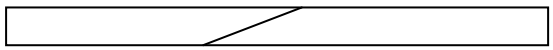
(b) Double-Lap Joint



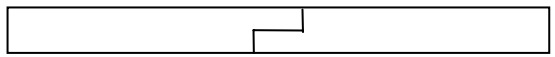
(c) Lap-Strap Joint



(d) Single-Strap Joint

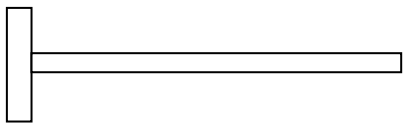


(e) Scarf Joint



(f) Stepped Joint

(g) Butt Joint



(h) Tee Joint

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Testing Standards for Adhesives and Bonded Joints

Measured Property	Recommended Testing Standard
Adhesive Characterization	
Standard Terminology	ASTM D907-05, D4800-94(2005)
Physical Properties	ASTM D1084-97(2005), D7149-05, D2556-93a(2005)
Strength and Shear Modulus	ASTM D3983-98(2004), D4027-98(2004), D905-03, D4896-01
Bonding Characteristics	ASTM D5868-01
Environmental Aging	ASTM D1183-03
Joint Characterization	
Laminate Surface Preparation	ASTM D2093-03
Failure Mode Classification	D5573-99(2005)
Tensile Shear Loading	ASTM D5868-01, D3163-01, D3164-03, D3165-00; ISO 4587:2003 ASTM D897-01, D2095-96(2002); ISO 6922: 1987
Tensile Loading (Butt-Joint)	ASTM D1781-98(2004), D1876-01, D3167-03a(2004), D903-98(2004)
Peel Loading	ASTM D1184-98(2004)
Flexural Loading	ASTM D5041-98(2004), D950-03, D1062-02, D3433-99(2005), D3807-98(2004)
Cleavage Loading	ASTM D1780-05, D2293-96(2002), D2294-96(2002)
Creep	ASTM D3166-99(2005)
Fatigue and Durability	ASTM D1151-00, D1828-01e1, D2918-99(2005), D2919-01e1, D3762-03, D3632-98(2004), D1144-99(2005), D904-99(2005), D896-04

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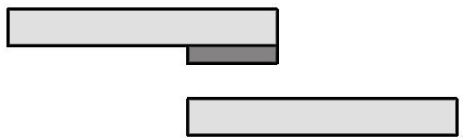
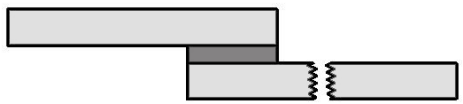
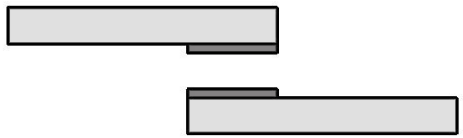
Failure Modes in Adhesively Bonded Joints



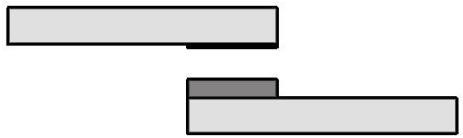
Adhesive failure



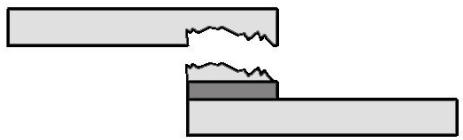
Stock-break failure



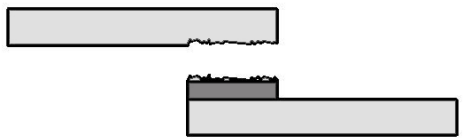
Cohesive failure



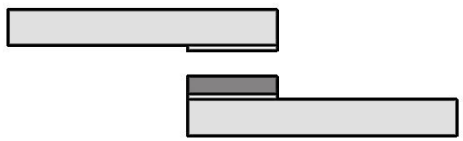
Thin-layer cohesive failure



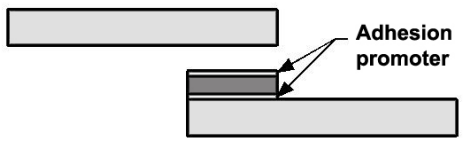
Fiber-tear failure



Light-fiber-tear failure



Adhesive to adhesion promoter



Adhesion promoter to substrate

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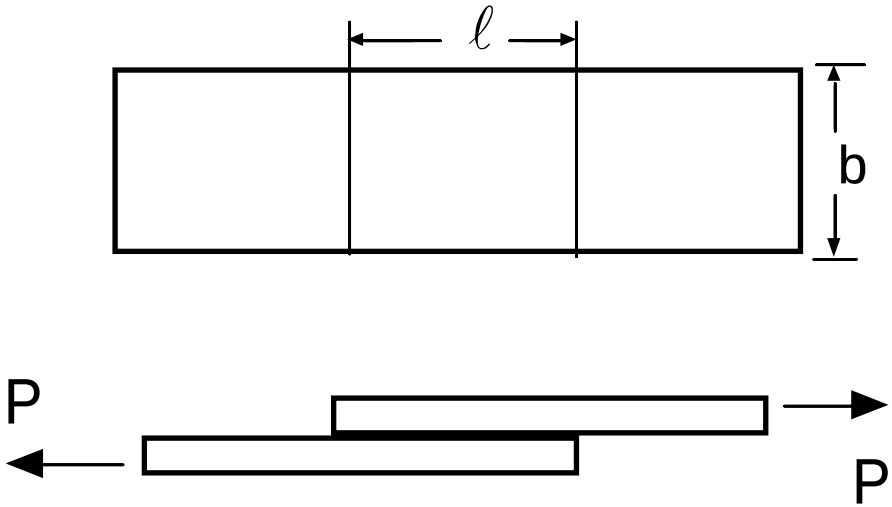
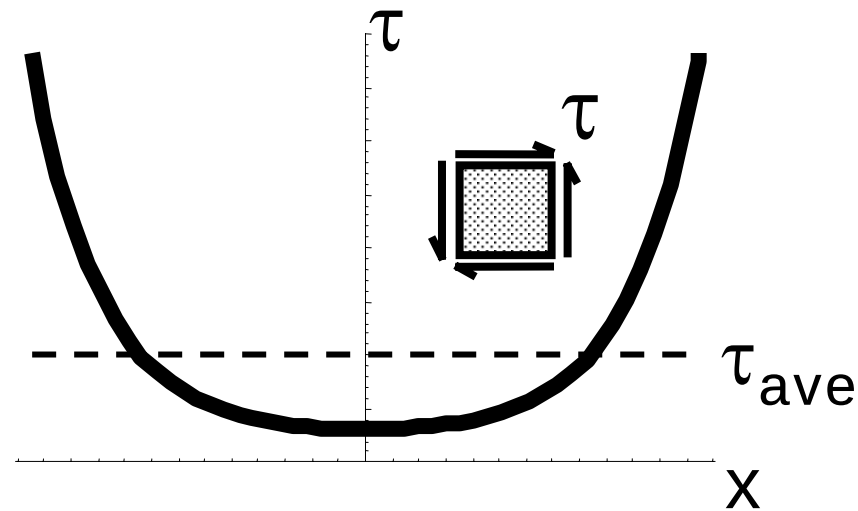
Simplest Lap Joint Analysis





$$\tau \neq \frac{P}{A} = \frac{P}{b\ell}$$

$$\tau_{ave} = \frac{P}{A} = \frac{P}{b\ell}$$

Common expression true only in an average sense.

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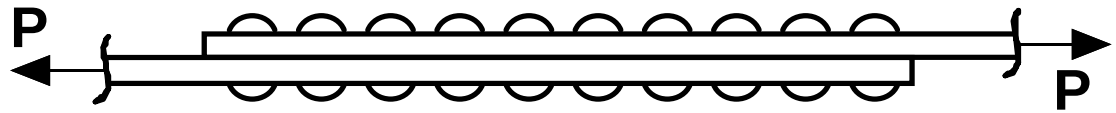
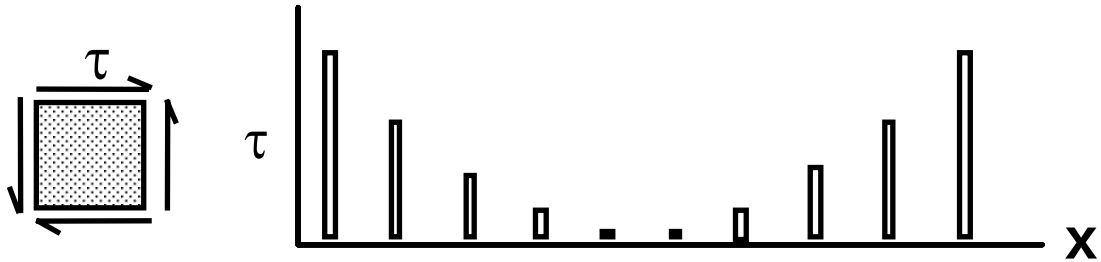
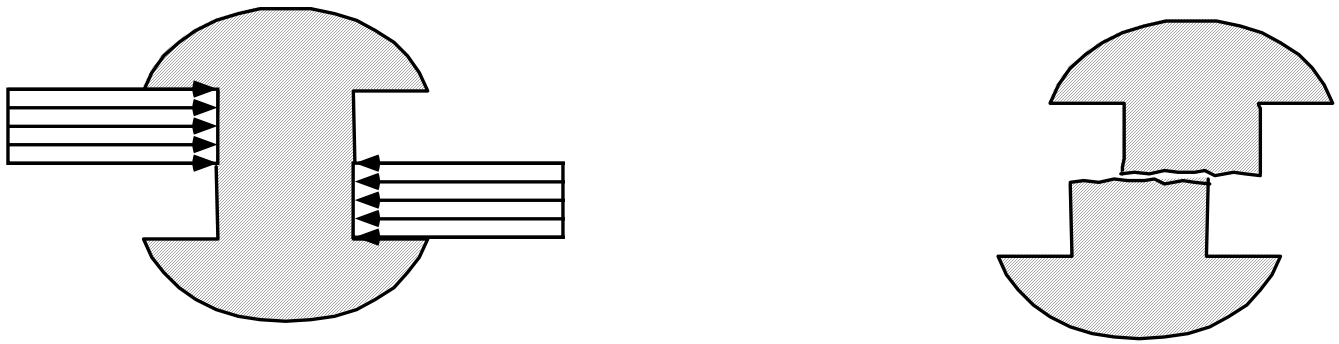
The Rivet Problem Analogy



End rivets carry the load.





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Volkersen Shear Lag Analysis

- **O. Volkersen, *Luftfahrtforschung*, 15, 41, 1938.**

- **Assumptions:**
  - Adhesive deforms in shear and offers no axial stiffness
  - Adherends extend, but do not shear
  - Adherends and adhesive are linear elastic

- **Completely ignores:**
  - Load eccentricity, adherend bending, moment equilibrium
  - Peel stresses
  - Singular stresses, spew details

For additional reading: Adams et al., *Structural Adhesive Joints in Engineering*, 2nd ed., Chapman & Hall, 1997.)

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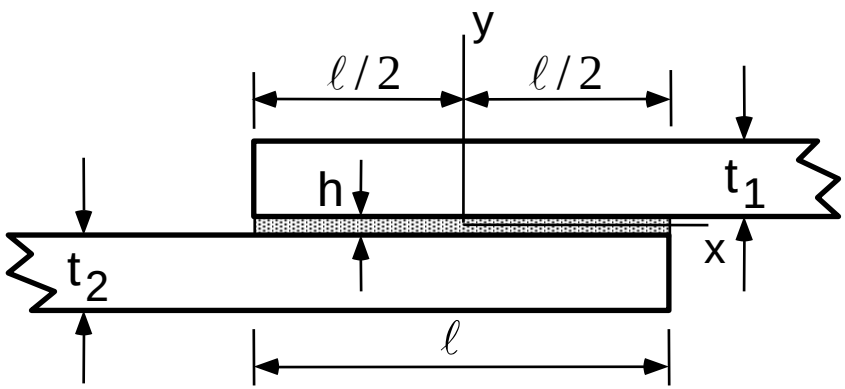
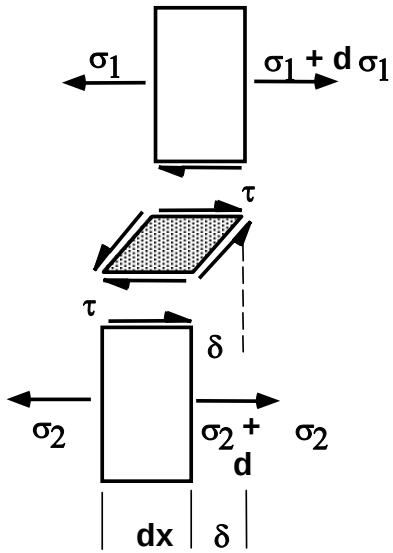
Volkersen Shear Lag Equation





$$\tau(x) = \frac{P\omega}{2\sinh\left(\frac{\omega\ell}{2}\right)}\cosh\omega x + \frac{P\omega}{2\cosh\left(\frac{\omega\ell}{2}\right)}\left(\frac{E_2t_2 - E_1t_1}{E_1t_1 + E_2t_2}\right)\sinh\omega x$$

$$\omega = \sqrt{\frac{G}{h}\left(\frac{E_1t_1 + E_2t_2}{E_1t_1E_2t_2}\right)}$$

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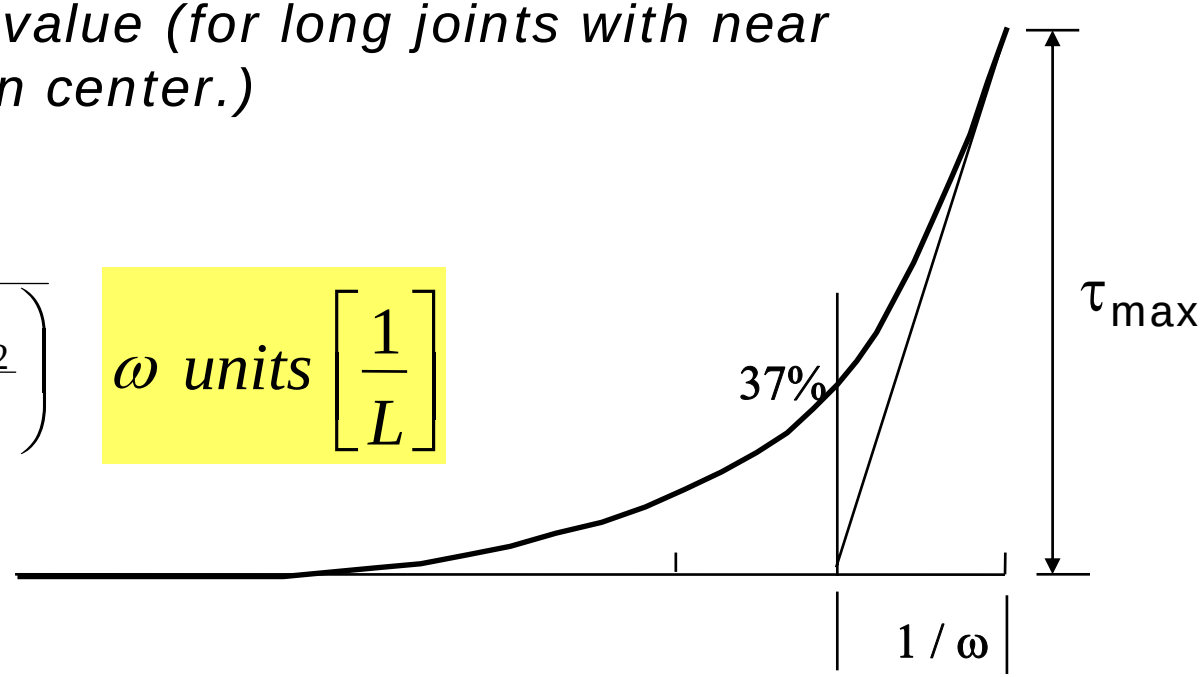
Concept of Shear Lag

Shear Lag - Refers to the finite distance required to transfer axial load from one adherend to the other. There is a spatial "lag" before the normal axial stresses equilibrate to share the load within the adherends.

$1/\omega$ is the characteristic "lag" distance at which the shear stress has decreased to only 37% of the maximum value (for long joints with near zero stresses in center.)

$$\omega = \sqrt{\frac{G}{h}\left(\frac{E_1 t_1 + E_2 t_2}{E_1 t_1 E_2 t_2}\right)}$$

$$\omega \text{ units } \left[\frac{1}{L}\right]$$



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Use of Volkersen Shear Lag Approach

- Based on simple **shear lag** concept
- Ignores peel stresses, bending, etc.
  - (more appropriate for double than single lap joints)
- Ignores singularities, material nonlinearity
- Simple model offers insights into many practical bonding problems
  - All members of lap joint family
  - Residual thermal stresses due to adherend CTE mismatch
  - Matrix cracking in composites
  - Fiber pull-out (related solution)
  - …

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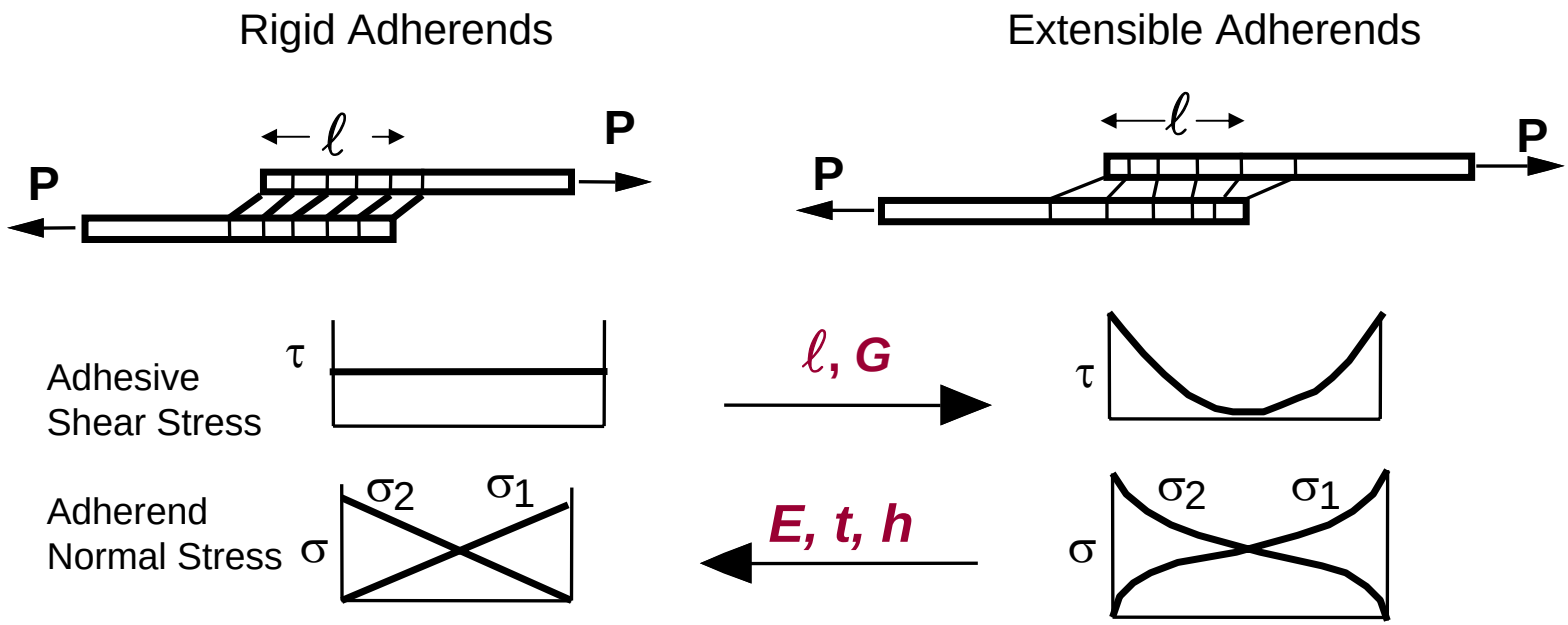
Volkersen's Five Parameters



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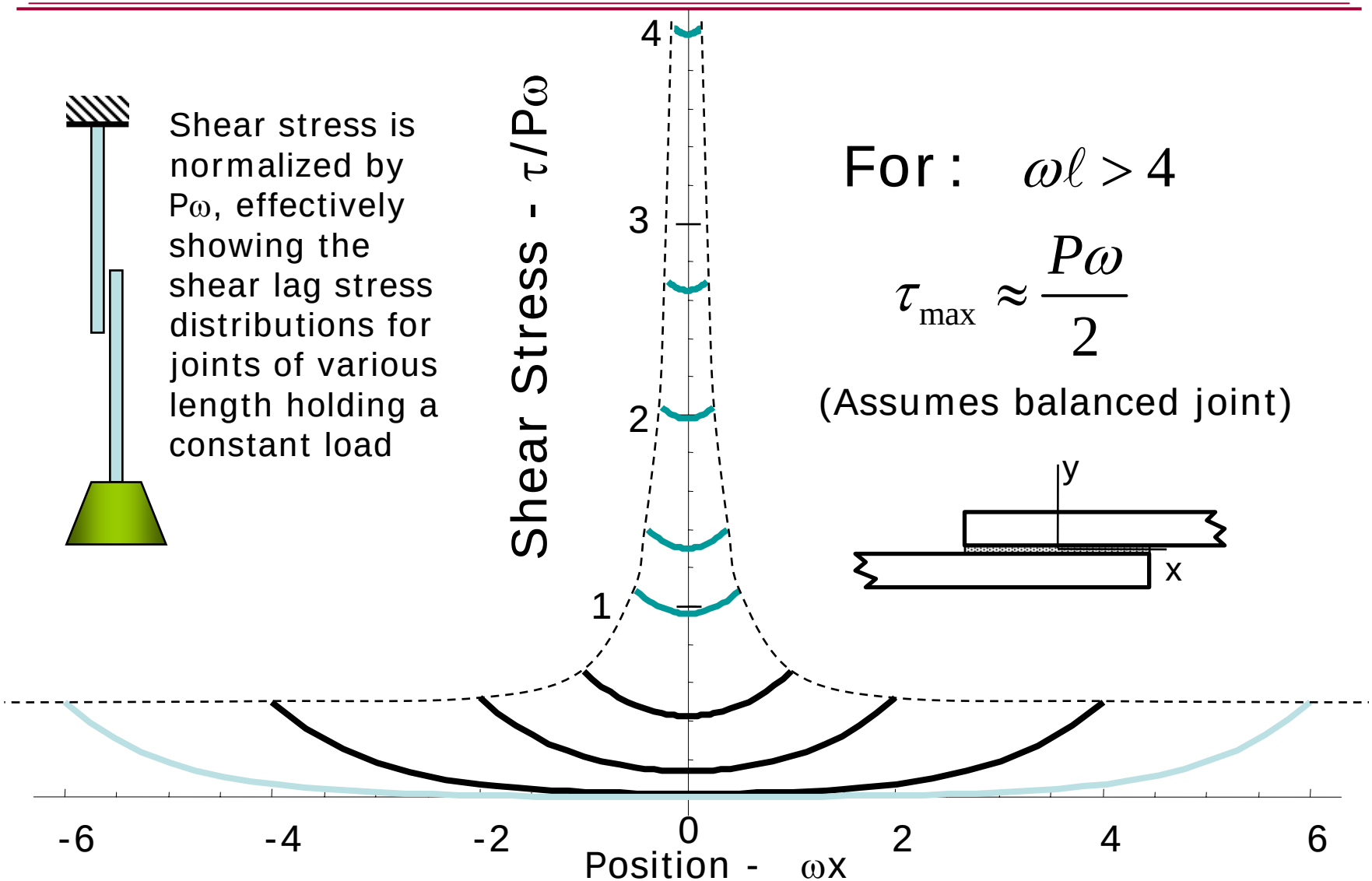
Effect of Joint Length at Fixed Load

Shear stress is normalized by Pω, effectively showing the shear lag stress distributions for joints of various length holding a constant load



For : $\omega\ell > 4$

$$\tau_{\max} \approx \frac{P\omega}{2}$$

(Assumes balanced joint)

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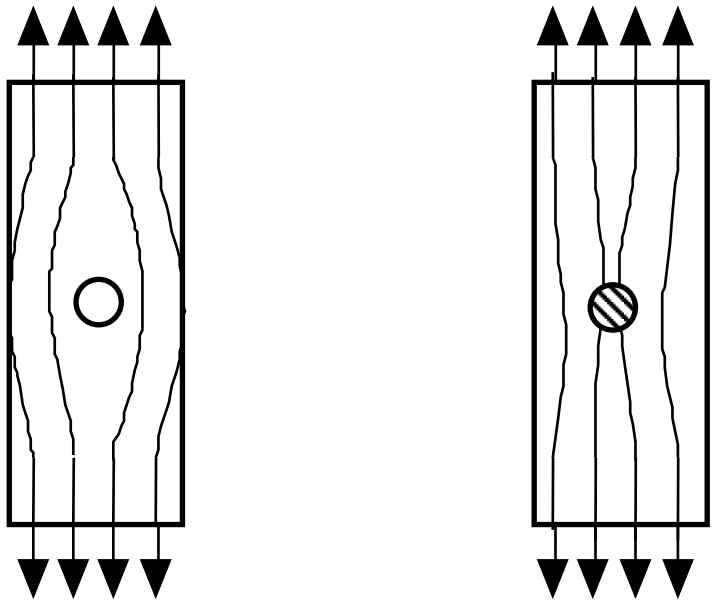
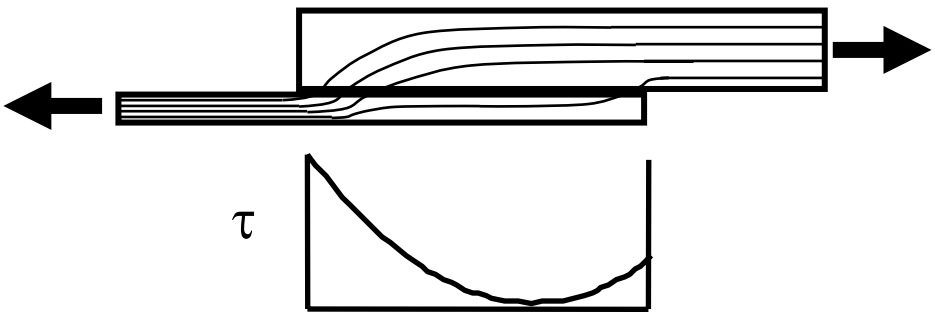
Stress “Seeks” Stiffest Path



open hole

filled hole

Stresses always concentrate in <u>stiffer</u> regions (seek stiffest path).



Shear stresses are higher at the end of the <u>stiffer</u> adherend.

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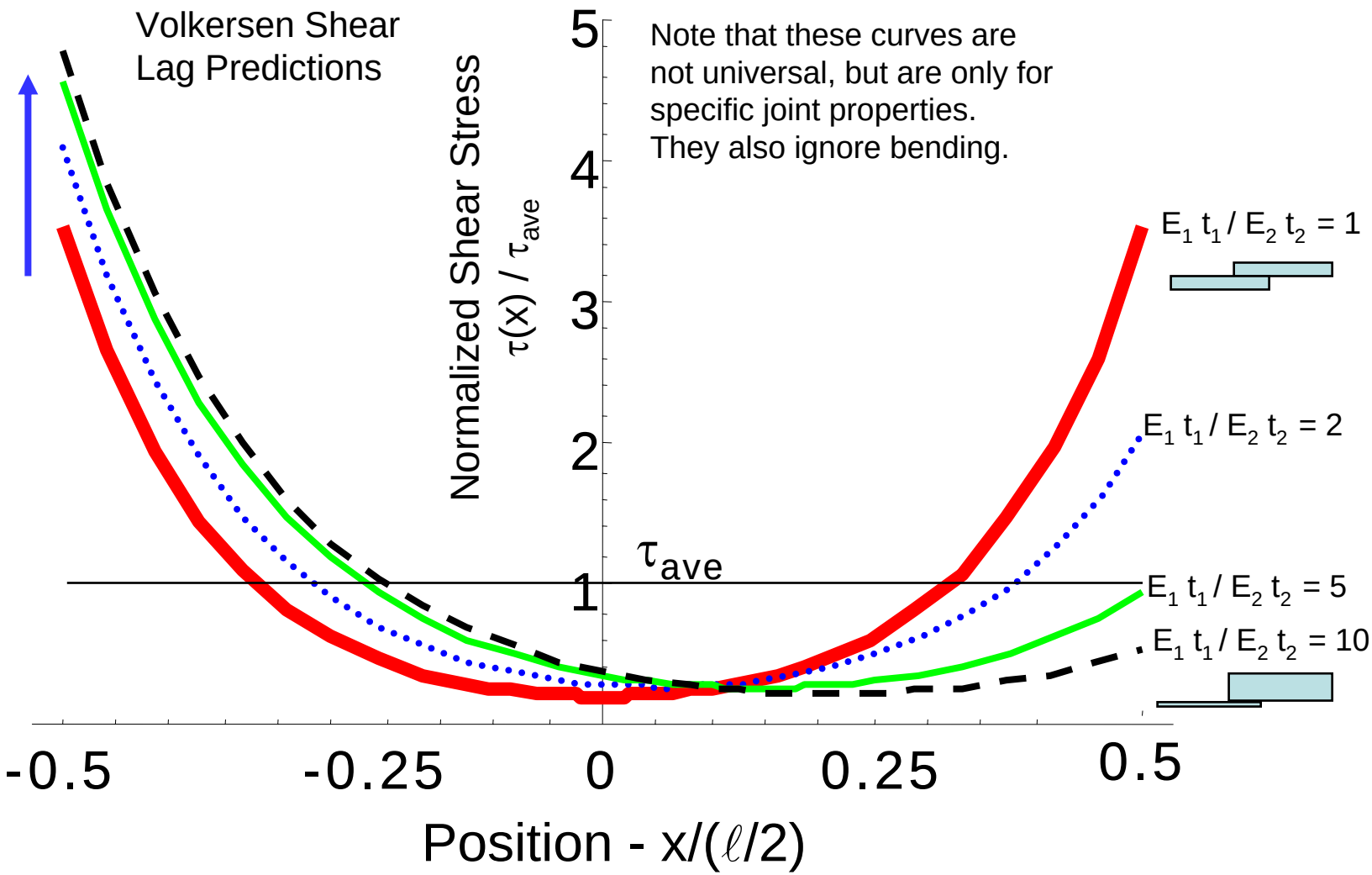
Effect of Adherend Mismatch



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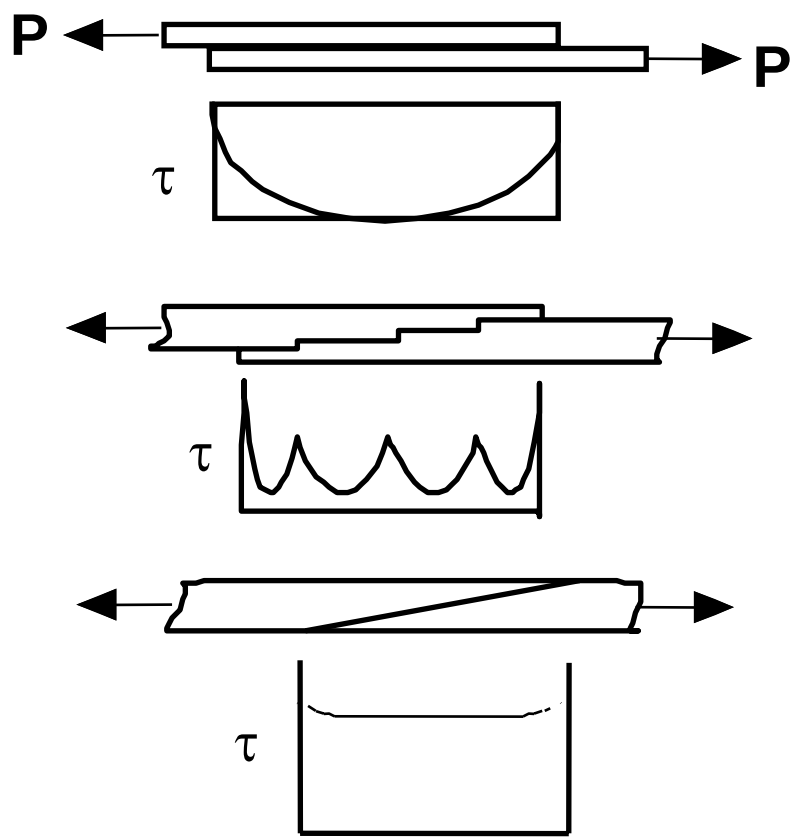
Shear Lag and Adherend Stiffness Change

Shear stresses are required anywhere there is a relative change in stiffness between the adherends. Abrupt changes in relative stiffness lead to large shear stress peaks; gradual changes result in more uniform stress stress distributions.



Poor Efficiency

Better Efficiency

Best Efficiency

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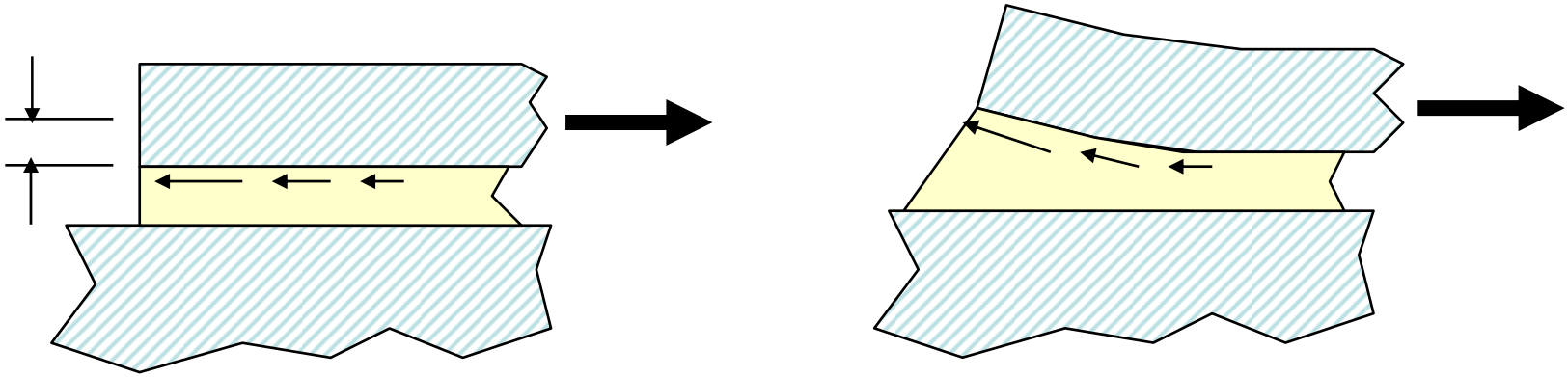
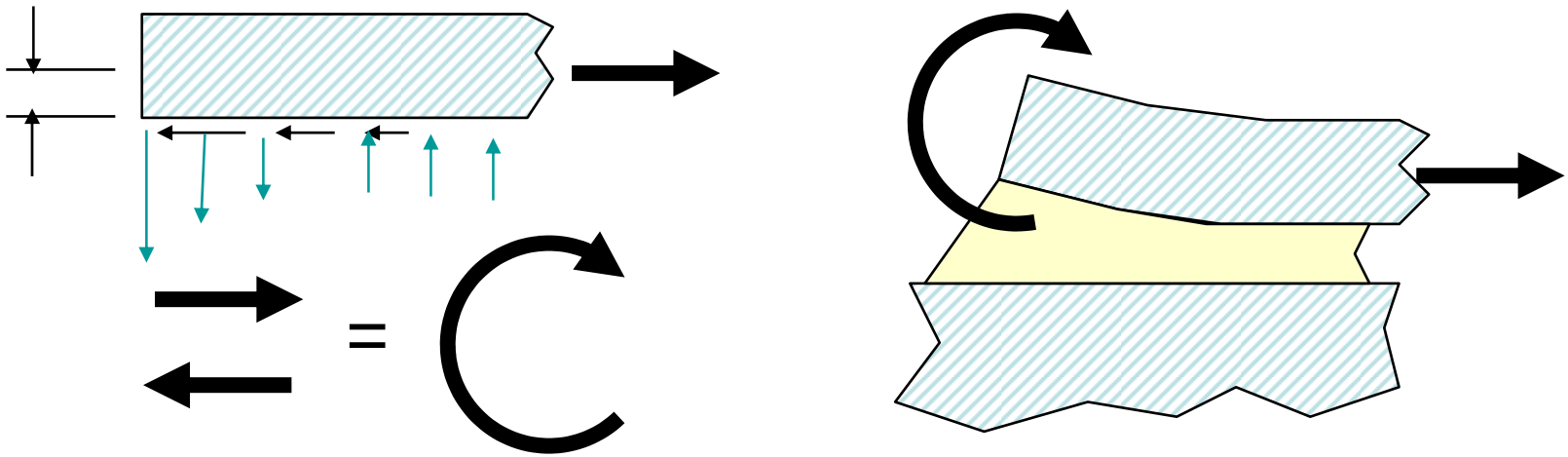
Shear and Peel Coupling



Shear stresses ---> Bending moment ---> Peel stresses



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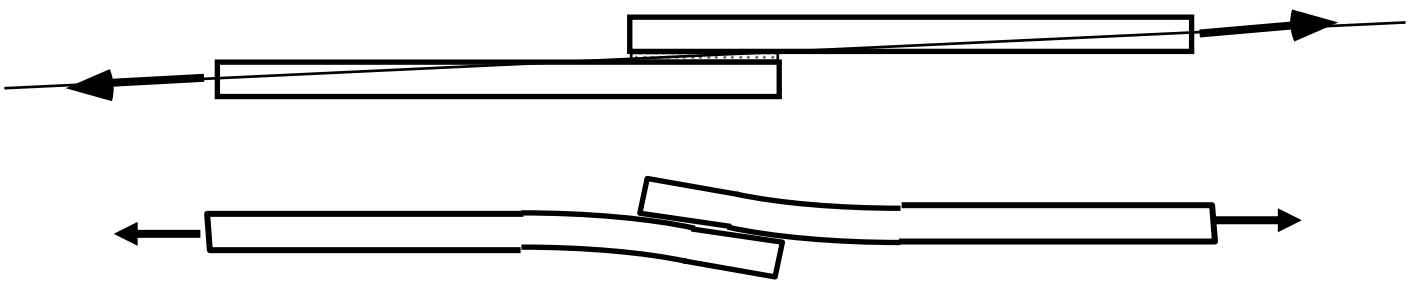
Goland and Reissner Analysis

- Analyze the geometric nonlinear deformations
- Analyze stresses within bonds



M. Goland and E. Reissner, “The Stresses in Cemented Joints”, *J. Appl. Mech, Transactions of ASME*, **77,** 1944.

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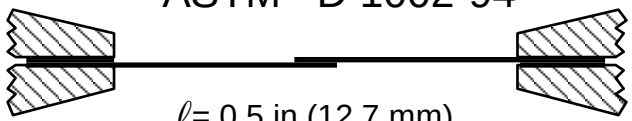
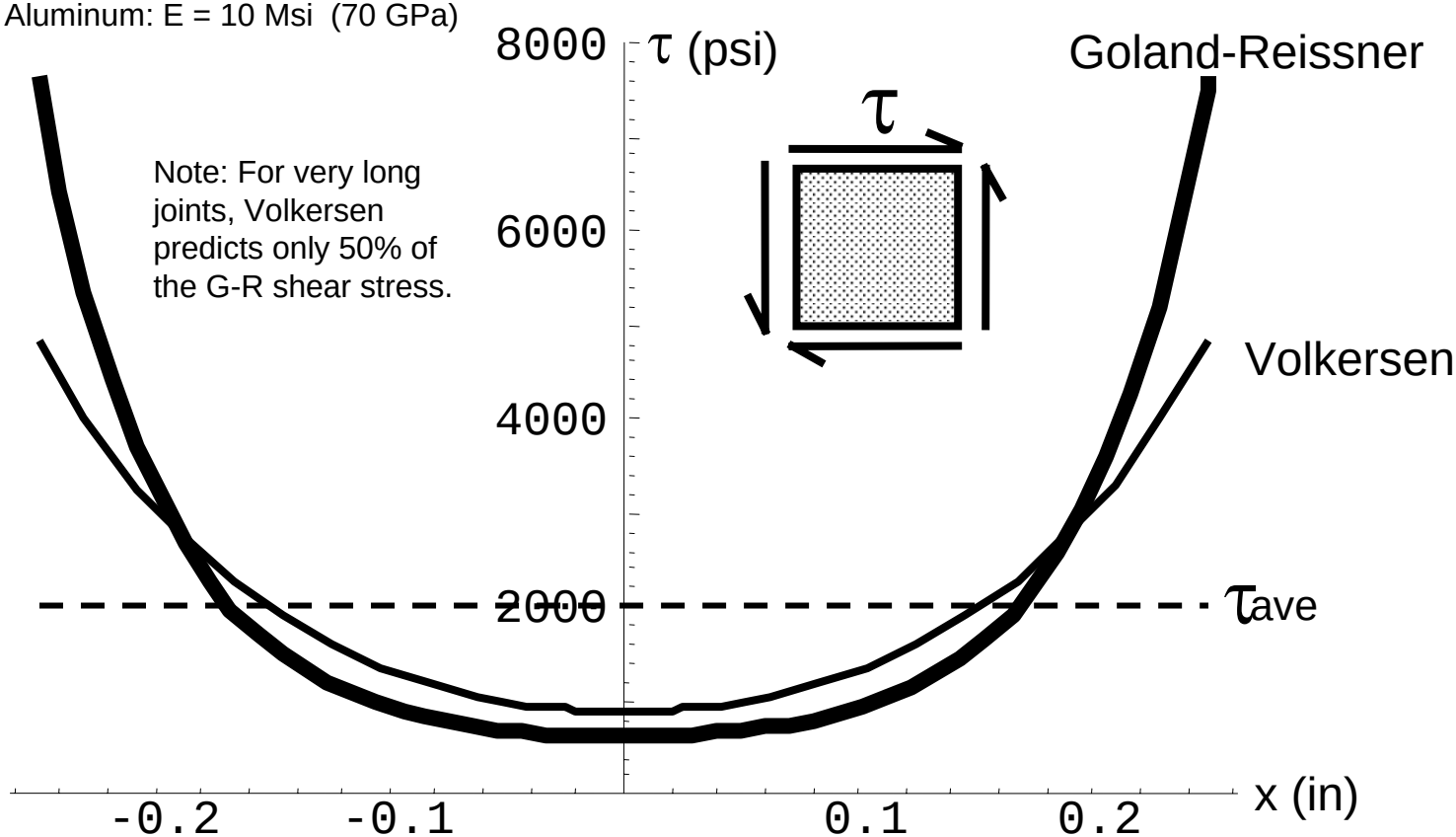
SLJ Shear Stress Distribution

ASTM D 1002-94



ℓ= 0.5 in (12.7 mm)
t = 0.064 in (1.6 mm)
Aluminum: E = 10 Msi (70 GPa)

Stresses shown for an applied load of:
P = 1000 lb. (4.4 kN)



Note: For very long joints, Volkersen predicts only 50% of the G-R shear stress.

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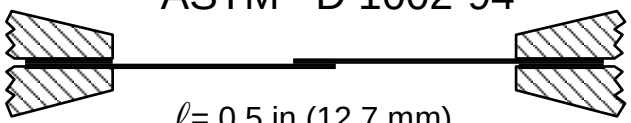
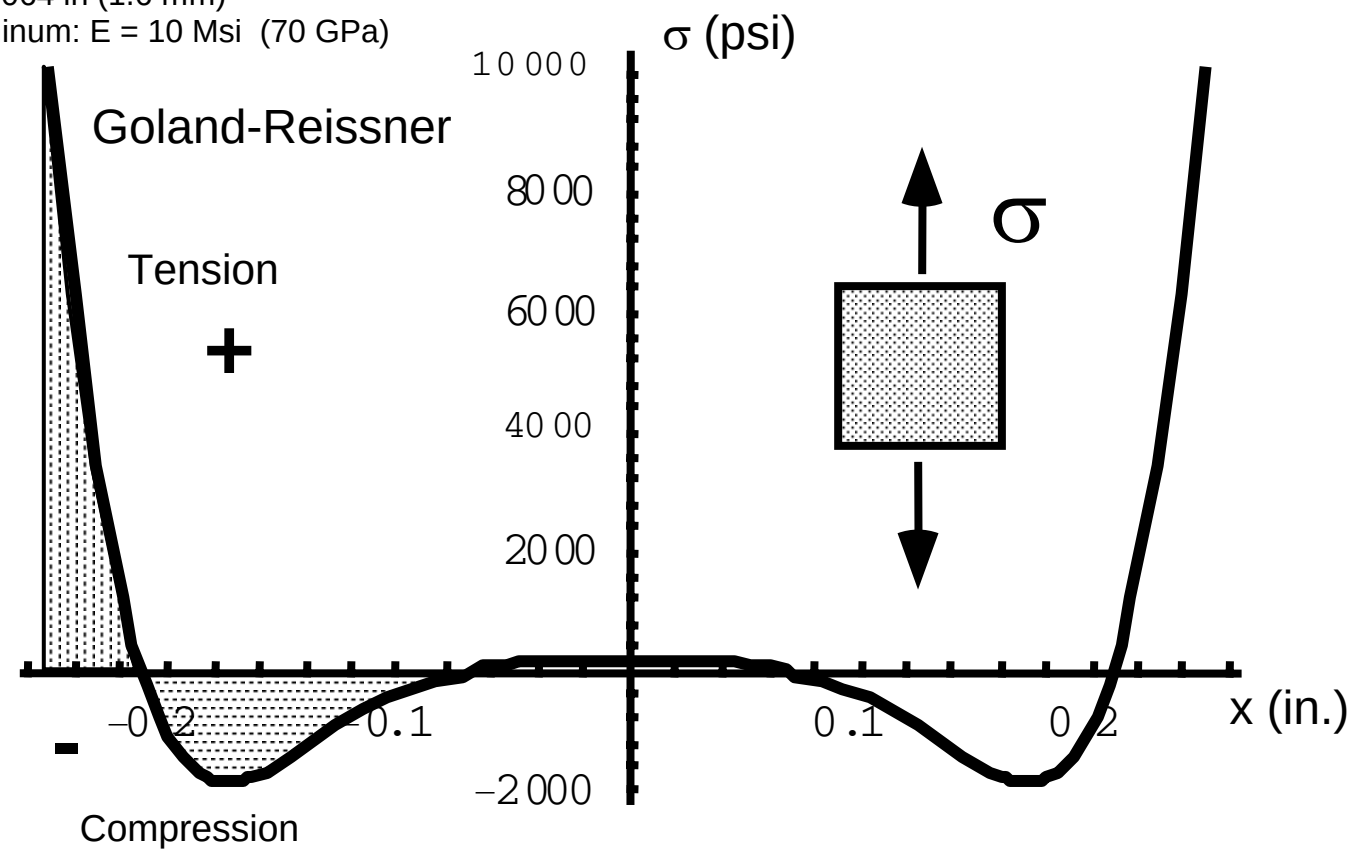
SLJ Peel Stress Distribution

ASTM D 1002-94



ℓ= 0.5 in (12.7 mm)
t = 0.064 in (1.6 mm)
Aluminum: E = 10 Msi (70 GPa)

Stresses shown for an applied load of:
P = 1000 lb. (4.4 kN)



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Outline

- **Polymer Fundamentals**
  - **Polymers, Resins, and Adhesives**
  - **Material Behavior of Polymers**

- **Adhesion Mechanics**
  - **Adhesion/Adhesive Testing**
  - **Mechanical Analysis of Adhesive Bonds**
  - **Design of Adhesively Bonded Joints**

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Joint Design

SPDM (ASCE 1984) & EDCH (Clarke 1996)

Procedures:

- Identify joint design requirements
- Select joint configuration
- Detailed joint design
- Analysis and design verification

Requirements:

- The failure of a joint should occur either in the adhesive or in its adherends but **not in the interfaces**
- Allowable shear stress and peeling stress of adhesive are not exceeded
- Allowable through-thickness tensile stress and out-of-plane shear stress of adherends should not be exceeded

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Design Parameters for Adhesively Bonded Joints

FRP Component	(a) Fiber type and form/architecture/lay-up scheme (b) Resin type (c) Material properties (anisotropy or orthotropy, viscoelasticity, environmental degradation, brittleness, etc.)
Structural Adhesive	(a) Mechanical properties (brittle or ductile, adhesion properties, requirements for primer and surface preparation, pot life) (b) Requirements for curing (c) Resistance to environmental parameters
Joint	(a) Geometry: FRP adherends (thickness, width, length), surface area, bondeline thickness, overlap length (b) Parameters concerning joint type, loading, lifetime, and environment
Fabrication	(a) Preparation before bonding: surface treatment (b) Curing and post-curing: the control of environments, clamping pressure (vacuumed assisted or not).

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Partial Safety Factors for Structural Adhesives

Failure Criteria:

$$\tau_{\max} \le \tau_{allow} \qquad \sigma_{\max} \le \sigma_{allow} \qquad \frac{\sigma_z}{\sigma_{z,allow}} + \frac{\tau_{xz}}{\tau_{xz,allow}} = 1$$

The overall safety factor (γ_m) is the product of four partial safety factors considering the source of adhesive properties ($\gamma_{m,1}$) , the method of adhesive application ($\gamma_{m,2}$), the type of loading ($\gamma_{m,3}$) and environmental conditions ($\gamma_{m,4}$) [EDCH (Clarke 1996)]:

$$\gamma_m = \gamma_{m,1} \times \gamma_{m,2} \times \gamma_{m,3} \times \gamma_{m,4}$$

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Partial Safety Factors for Adhesively Bonded Joints

Source of Adhesive Properties ($\gamma_{m,1}$)	
Typical or textbook values	1.5
Values obtained by testing	1.25
Method of Adhesive Application ($\gamma_{m,2}$)	
Manual application, no adhesive thickness control	1.5
Manual application, adhesive thickness controlled	1.25
Established procedure with controlled parameters	1.0
Type of Loading ($\gamma_{m,3}$)	
Long term loading	1.5
Short-term loading	1.0
Environmental Conditions ($\gamma_{m,4}$)	
Service conditions outside the adhesive test conditions	2.0
Adhesive properties determined for service conditions	1.0

EDCH (Clarke 1996)

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Questions

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