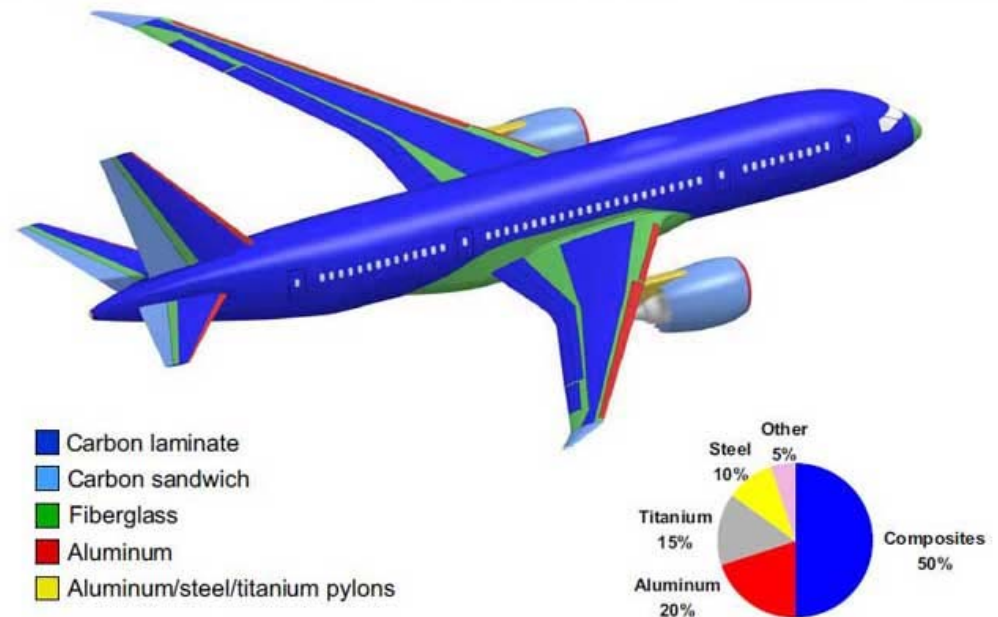


Types of Joining Methods

- **Mechanically Fastened Joints**
 - Cylindrical Rods: bolt, rivet, pin, or staple
 - Primary load bearing
 - The load transfer through the fastener is localized
- **Adhesively Bonded Joints**
 - Structural Adhesives
 - Primary load bearing
- **Welded Joints**
- **Friction Joints**



Joining Methods

Joint Type	Advantages	Disadvantages
Mechanically Fastened	Straightforward Design Inspectable Repairable No Thickness Restrictions Can be disassembled	Many Parts Stress Concentrations/Weak Fatigue, fretting Prone Prone to corrosion Must be sealed
Adhesive Bonding	Few Parts, Full Load Transfer Repairable, Fatigue Resistant Sealing, Stiff Connection Light-Weight, Smooth Contour, corrosion resistant No Stress Concentrations	Difficult to Inspect, Surface Prep Environmental effects, design Required Skill, Thickness limited Residual Stresses No Disassembly Shear Loading Only
Welding	Permanent, Inspectable Load Transfer, Continuous	Permanent, Microstructural change Residual Stresses, Trade Skill
Friction	Simple	Friction Dependent

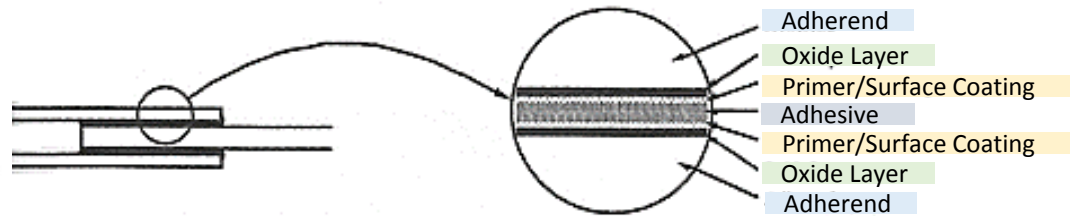
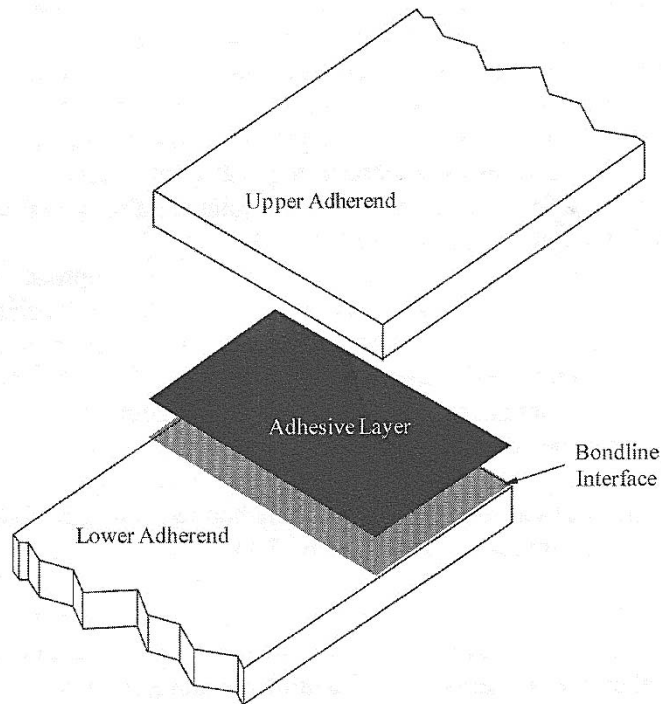
Adhesively Bonded Joint Outline

- **Adhesive Joint Overview**
- **Adhesive Properties**
- **Adhesive Joint Strength**
- **Design of Adhesive Joints**
- **Experimental Evaluation**
 - **Adhesives**
 - **Adhesive Joints**

Joint Design Considerations

- **Joint Geometry**
 - plate width, plate thickness
- **Ply Fiber Orientation and Ply Stacking Sequence**
- **Moisture and Temperature Conditions**
- **Applied Stress**
- **Type of Adhesive**
 - Brittle
 - Ductile

Anatomy of an Adhesive Joint



Typical Bonded Joint Configurations

Simple Lap Joint

- Good



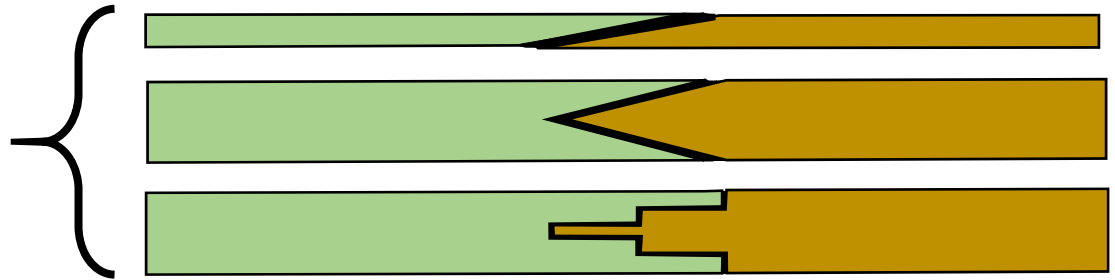
Tapered Lap Joint

- Very Good



Scarf/Stepped Scarf Joints

- Excellent



Stepped Lap Joint

- Very Good



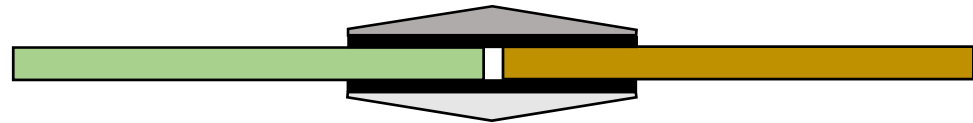
Double Strap Joint/ Double Lap Joint

- Very Good



Tapered Double Strap Joint

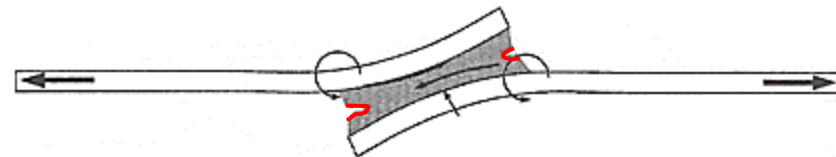
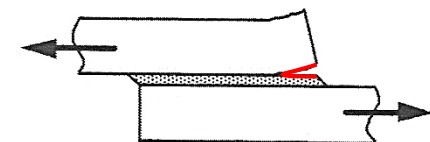
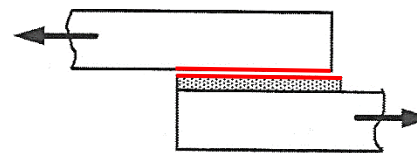
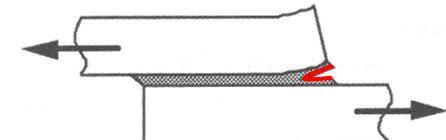
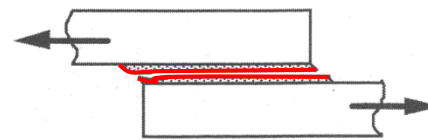
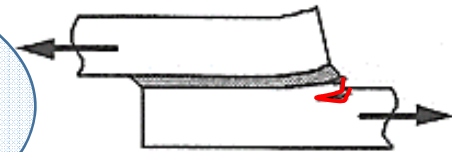
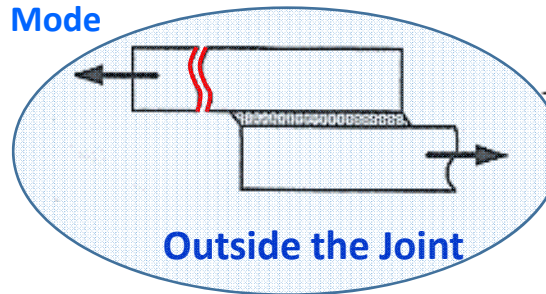
- Excellent



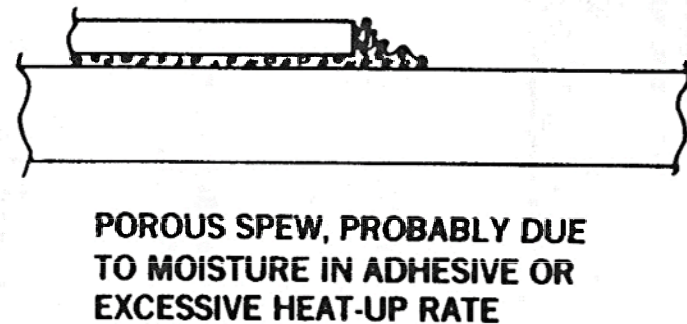
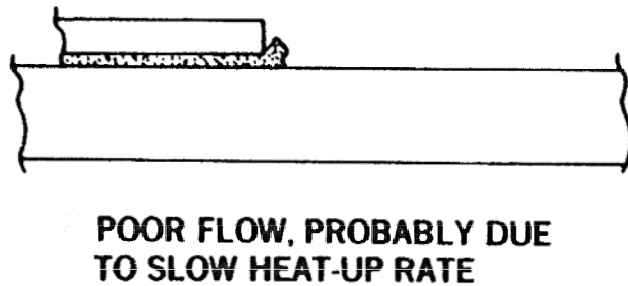
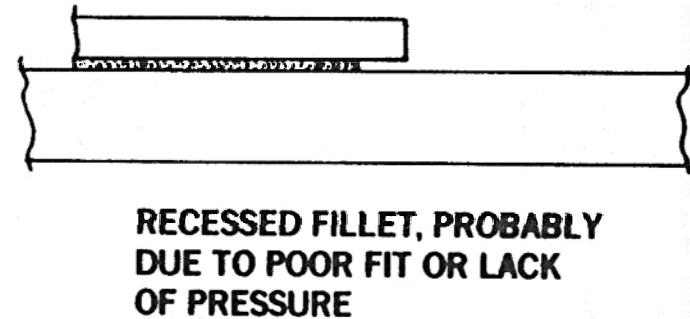
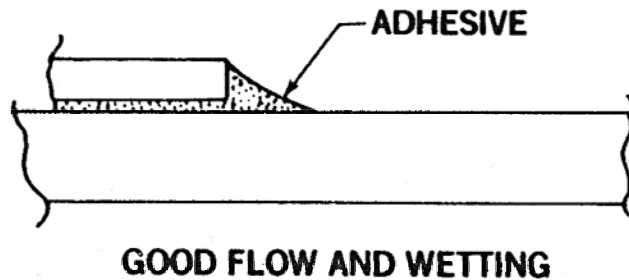
Adhesive Joint Failure Modes

- Adherend Failures
- Cohesive Failures
- Adhesive Failures

Desired Failure Mode

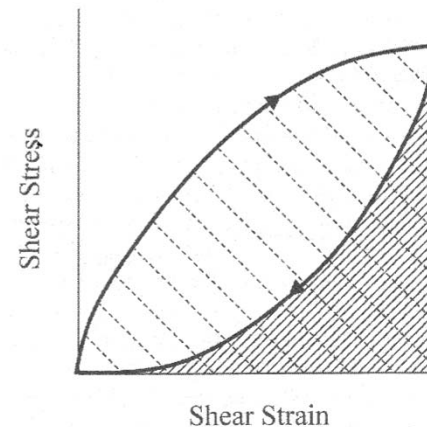
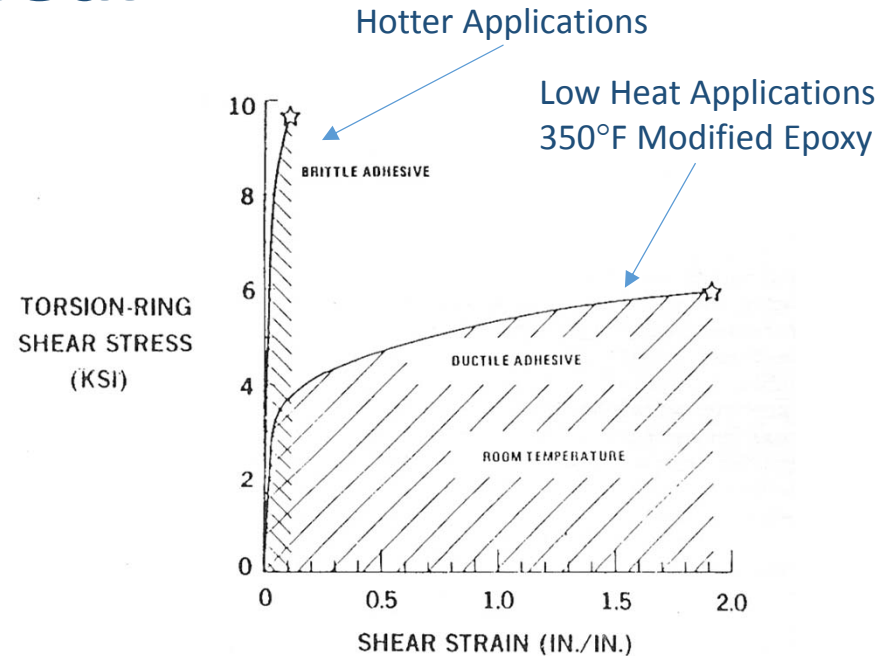


Good and Bad Adhesive Fillets



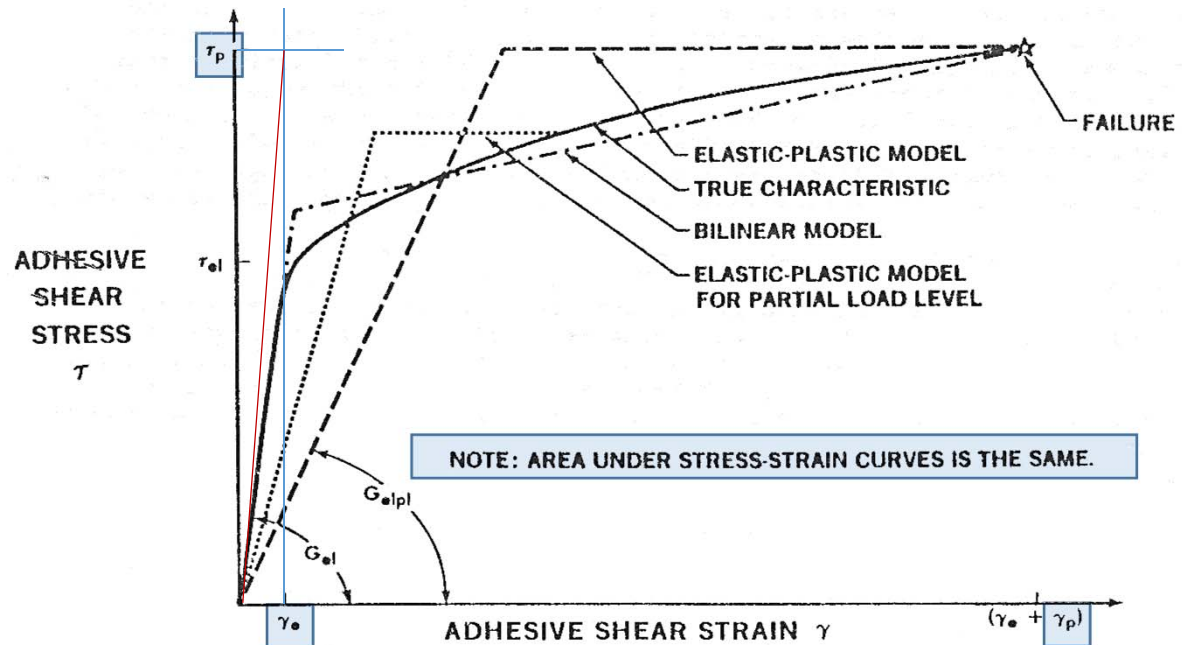
Brittle and Ductile Adhesive Stress-Strain Curves in Shear

- Material Properties Range from Brittle to Ductile Behavior
- Shear Properties more Viscoelastic than Elastic-Plastic
- Viscoelastic Properties Difficult to Model
 - Results in Complex Stress Analysis
 - Simplified approaches taken
- **ANAYLSIS BASED ON ELASTIC-PLASTIC NON-LINEAR STRESS-STRAIN CURVES**
 - Typical Thickness 0.005 in.
 - Joint Strength Defined by the Area Under the Stress-Strain Curve



Adhesive Shear Stress-Strain Curves and Mathematical Models

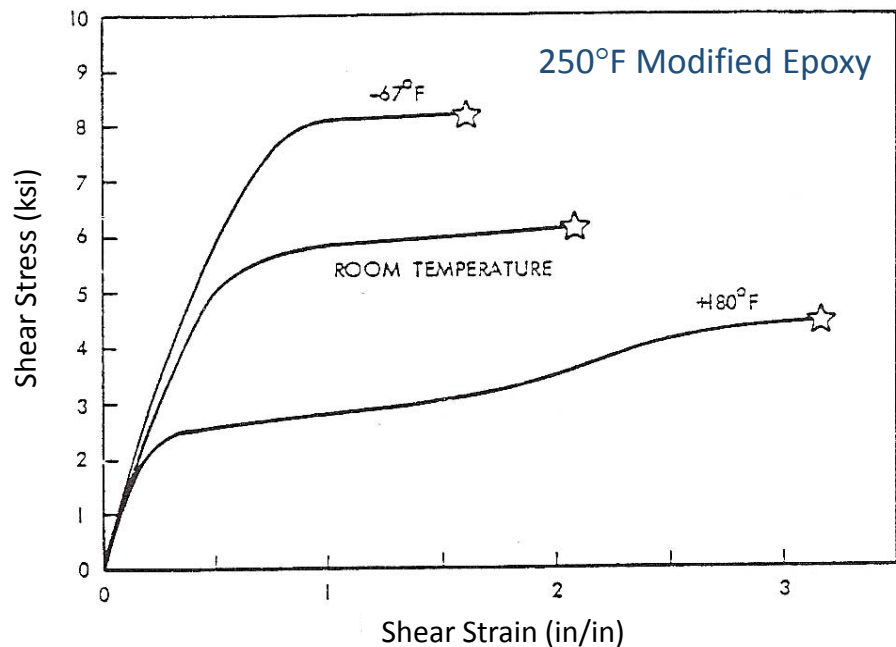
- Current approaches to Modeling
 - Shear Energy Absorbed
- Area Under **ALL** Curves is the same.
 - Failure Stress τ_p and Strain $\gamma_e + \gamma_p$ are all the same.
- Parameters used to Characterize Adhesive Properties
 - Elastic Shear Stress (max. shear stress) τ_p
 - Elastic Shear Strain γ_e
 - Plastic Shear Strain γ_p
- Initial Shear Stiffness G



$$G = \text{Tan}^{-1} \left(\frac{\tau_p}{\gamma_e} \right)$$

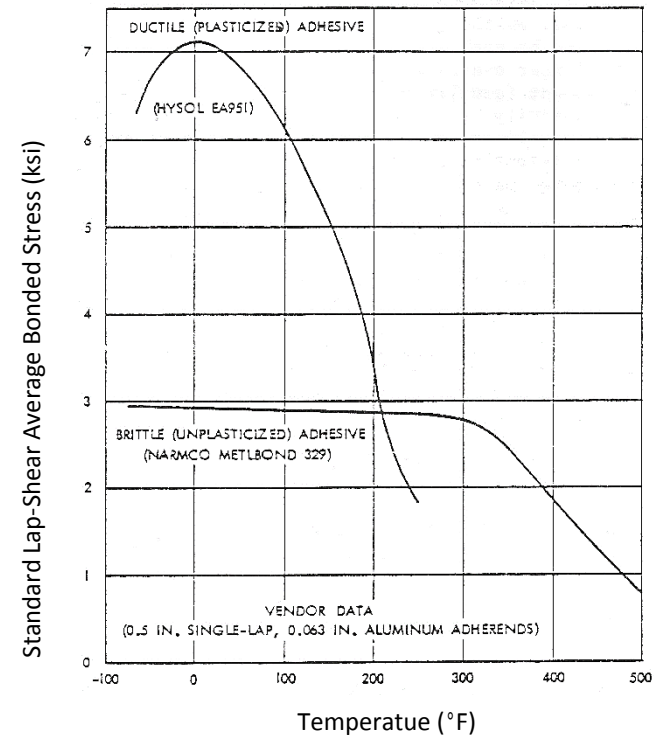
Temperature Dependence on Stress-Strain Characteristics of Adhesive Film in Shear

- **Property Variation**
 - Initial Modulus, G_{init}
 - Stress at the knee, τ_{knee}
 - Failure Stress, τ_p
 - Failure Strain, $\gamma_e + \gamma_p$
- **Area Under Curves the Similar**
 - Strength of a properly proportioned joint insensitive to temperature in the range
 - Joint proportions (maximum overlap) based on environment (Hot/Wet)
 - Does not take into account T_g



Temperature Dependence on Stress-Strain Characteristics of Adhesive Film in Shear

- Above T_g
 - Adhesives undergoes a change of state from glassy to rubbery
 - Pronounced drop-off in shear strength
 - Adhesive becomes unsuitable for use.
- Brittle versus Ductile adhesives
 - Brittle adhesives have **lower shear strength** than Ductile adhesives
 - Brittle adhesives **retain their shear strength** at high temperatures
 - More suitable for high temperature applications
 - Brittle materials become quite Ductile at high temperatures



Note: Values shown bear no relation to torsion-ring or thick-adherend stress-strain curves

From Vendor Data Adhesive Properties Need to be Extracted

- Maximum Shear Strength

- τ_p

- Maximum Shear Strain

- γ_{max}

- Initial Shear Modulus

- G_{init}

- Knee Point Shear Stress and Strain

- τ_{knee} & γ_{knee}

- Tensile Modulus-Bulk

- E_c

- Tensile Strength-Bulk

- σ_c

Typical Vendor Data

Material Property	FM 300 ⁽¹⁾	FM 73 ⁽¹⁾	Ductile Adhesive	Brittle Adhesive
Ultimate Shear Strength, MPa (ksi)	35 (5)	50 (7)	41 (6)	62 (9)
Thickness, μm (in)	0.127 (0.005)	0.127 (0.005)	0.127 (0.005)	0.127 (0.005)
Elastic Strain	0.09	0.1	0.1	0.048
Plastic Strain	0.33	0.45	2.0	0.072
Effective Tensile Modulus, GPa (ksi)	6.9 (1000)	8.3 (1200)	3.4 (500)	10.3 (1500)
Effective Tensile Strength, MPa (ksi)	90 (13)	103 (15)	69 (10)	117 (17)

(1) High Strength Epoxy Based Film Adhesives

Vendor Data Sheets Do Not Always Provide The Needed Data

1. Effective Slope, ϕ

$$\phi = \tan^{-1}(G_{init})$$

2. Final Slope, β
□ if not zero

$$\beta = \tan^{-1}(G_{final})$$

3. Knee Point Bisector Angle, α

$$\alpha = \frac{\pi - \phi + \beta}{2}$$

4. Knee Strain, γ_{knee}

□ Calculate Knee Stress, τ_{knee}

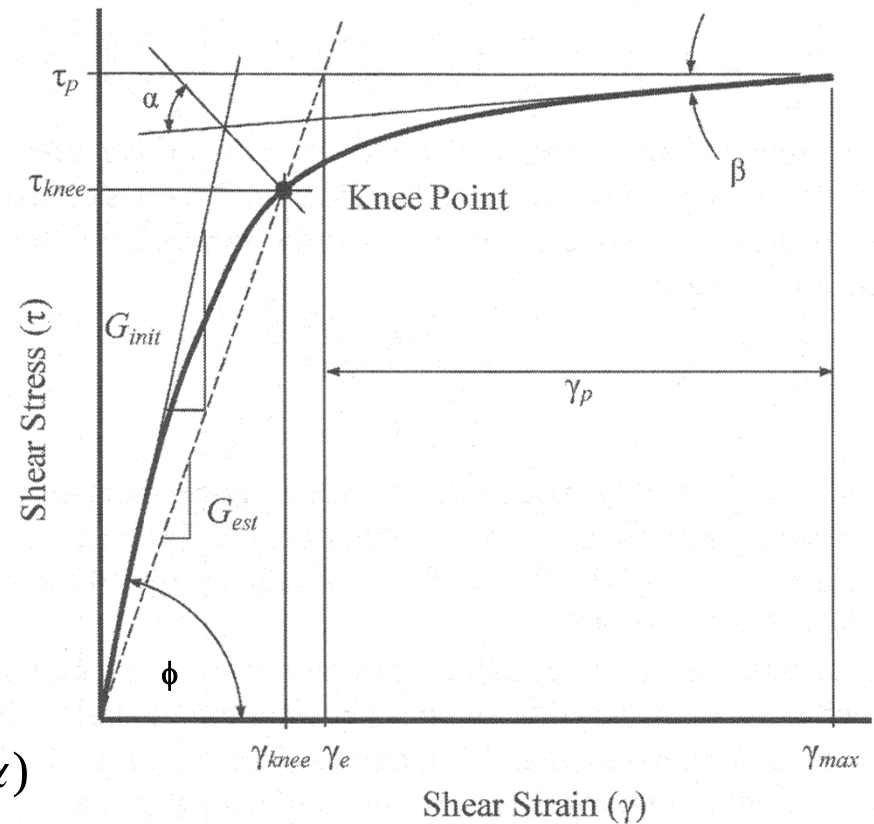
$$\tau_{knee} = \tau_p - \left(\gamma_{knee} - \frac{\tau_p}{G_{init}} \right) \cdot \tan(\alpha)$$

5. Elastic Shear Modulus, G_{est}

$$G_{est} = \frac{\tau_{knee}}{\gamma_{knee}}$$

6. Elastic Shear Strain, γ_e ,
and Plastic Shear Strain, γ_p

$$\gamma_e = \frac{\tau_p}{G_{est}}, \quad \gamma_p = \gamma_{max} - \gamma_e$$



7. Shear Strain Energy, A

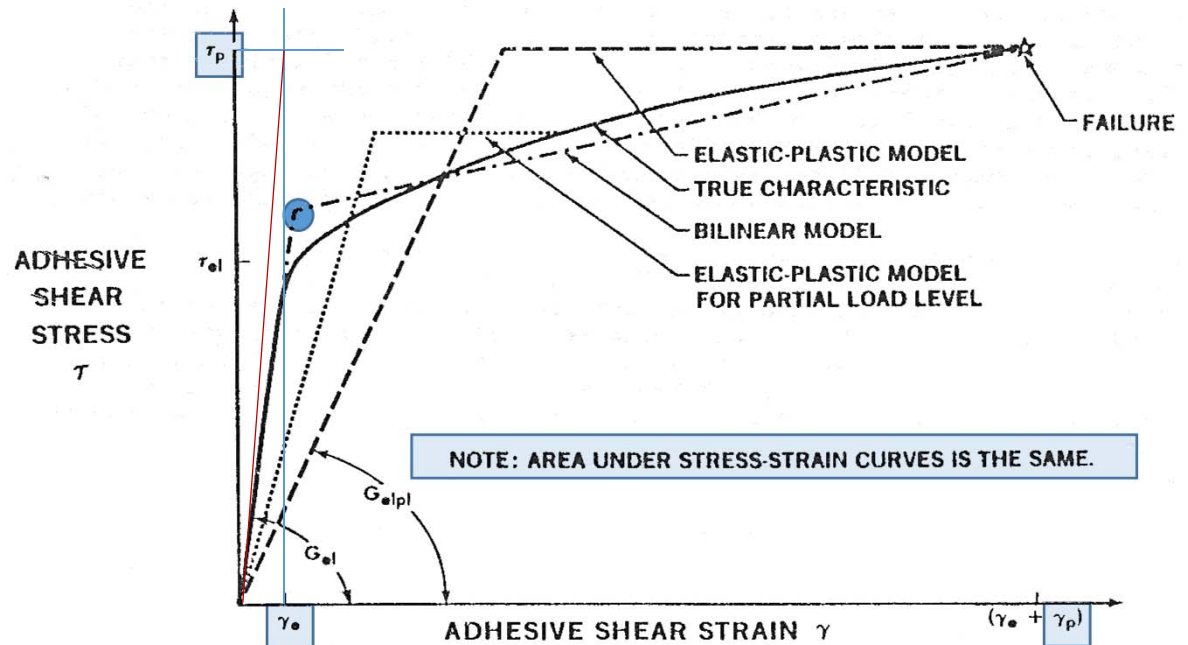
$$A = \tau_p \cdot \left(\gamma_p - \frac{\gamma_e}{2} \right)$$

8. Adhesive Ductile Parameter, ADP

$$ADP = \frac{\gamma_p}{\gamma_e}$$

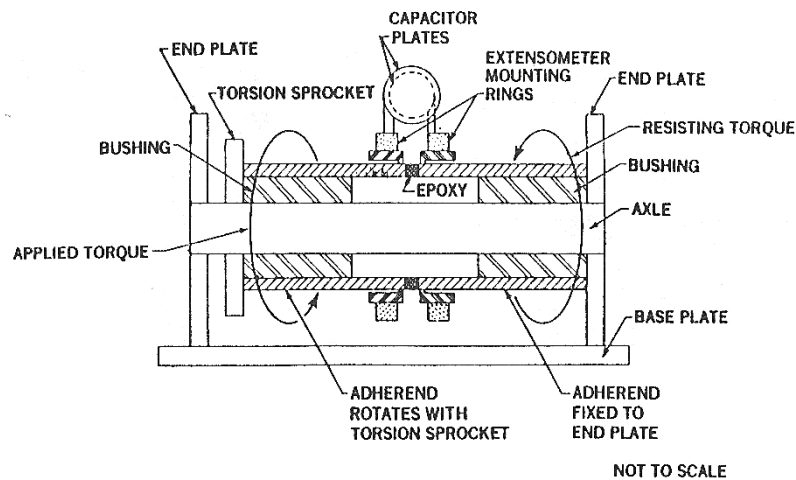
GOOD DESIGN PRACTICE

- Design Below the for Stress Below the Knee
- Plastic region reserved for
 - Redistribution Around Flaws
 - Overloads
 - Damage Tolerance
- Not doing so could make the **Adhesive the Weak Link**

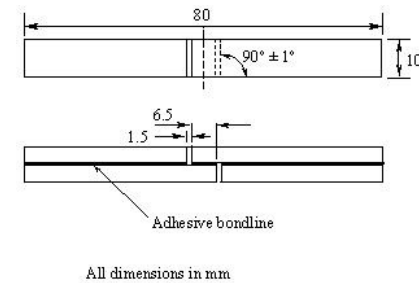


Adhesive Properties Determined Using Standard Test Methods

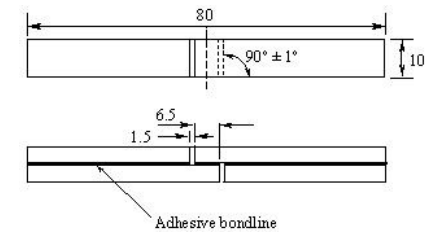
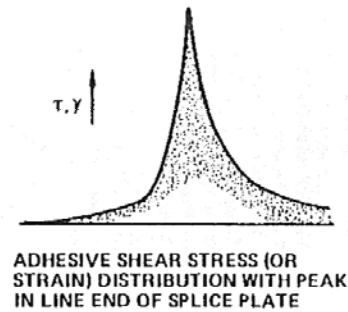
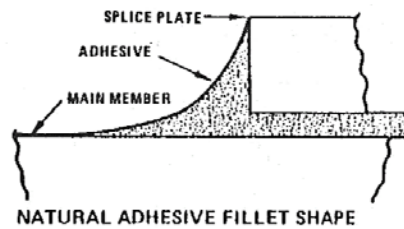
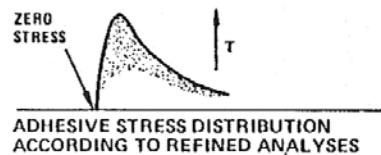
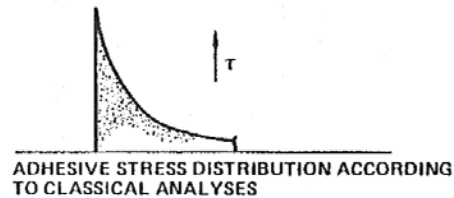
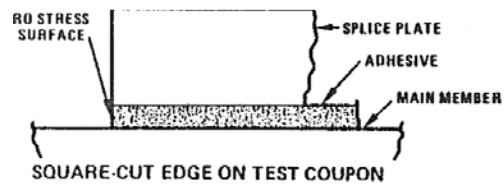
NAPKIN-RING



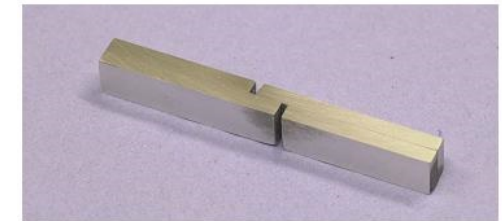
THICK ADHEREND



Thick Adherend Data is Conservative

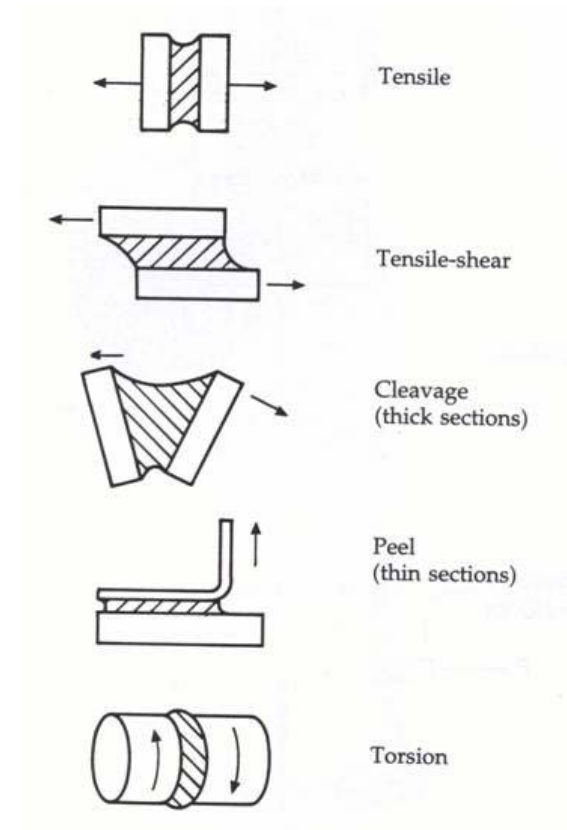


All dimensions in mm



TEST METHODS for Adhesive Materials

- **Two types of Test Methods**
 - Provide Mechanical Properties → Adhesive Selection
 - Determine Quality of Adhesively Bonded Structures → Design Process
- **Use of Test Methods**
 - Qualitative Measurement → Ranking of Adhesive Formulations
 - Determination of Mechanical Properties → Structural Integrity
- **Standardization Organizations**
 - American Society for Testing and Materials (ASTM)
 - British Standards Institution (BS series)
 - International Standards Organization (ISO)



Stress Analysis Requires Basic Properties

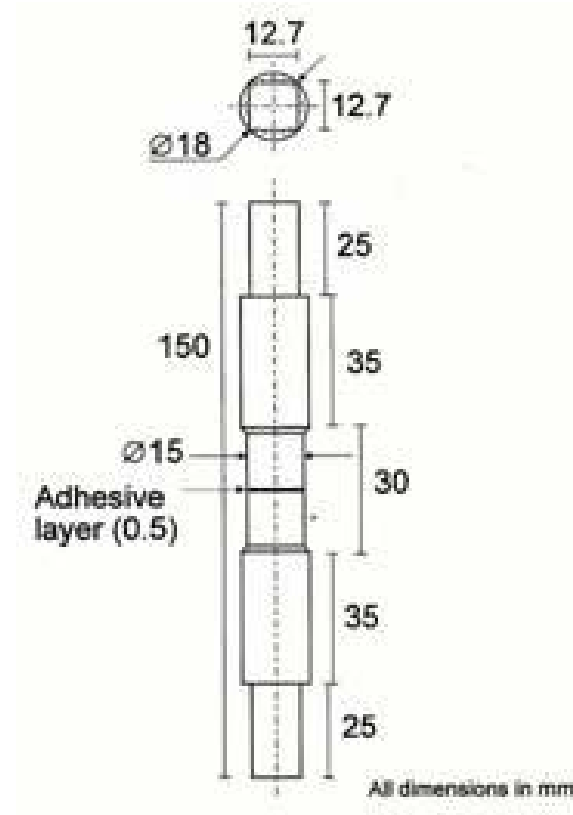
- **Adhesive** shear modulus
- **Adhesive** elastic tensile or compressive modulus
- Effective **adhesive** transverse modulus
- Characteristic **adhesive** shear strength
- Characteristic **adhesive** tensile or compressive strength
- **Adhesive** and **adherend** elastic/plastic shear stress and strain
- **Adherend** tensile or compressive modulus
- **Adherend** Poisson's ratio
- Characteristic **adherend** through-thickness tensile strength
- **Adhesive layer thickness**
- **Thickness of adherends**

Tensile and Peel Test Methods

Test Method	Tensile Butt Joint	T-Peel	Climbing Drum	Floating Roller Method
Mechanical Properties	Tensile strength/modulus	Peel strength	Peel strength/skin stiffness	Peel strength
Material Quantity Requirements per specimen	Low	Low	High	Low
Typical Specimen Dimensions (mm)	Diameter 15–25 Adherend (t) 12–15	Bond length 150 Width 25 Adherend (t) 0.5–1.0 Arm length 50	Long adherend 300 Short adherend 240 Width 25 Adherend (t) 0.5–5.0	Flexible adherend 250 Rigid adherend 200 Width 25 Adherend (t) 0.5–1.6
Materials Suitable for Testing	All	Flexible-flexible adherend	Flexible-rigid adherend Sandwich structures	Flexible-rigid adherend 1–6
Fatigue performance	Limited	unsuitable	Unsuitable	Unsuitable
Creep Performance	Suitable	Possibly	Unsuitable	Unsuitable
Environmental suitability	Suitable	Suitable	Unsuitable	Unsuitable
Standard Test Methods Available	ASTM D 897 ASTM D 2095 BS EN 26922	ISO 8510: Part 2 ISO 11339 ASTM 1876	BS 5350: Part C13 ASTM D 3167	ASTM D 3167

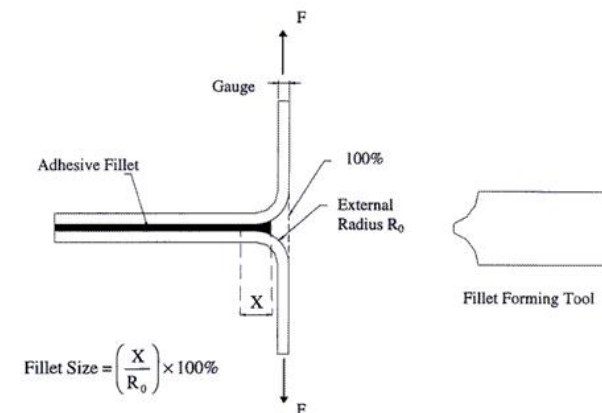
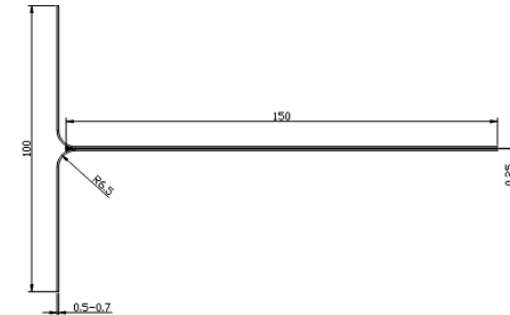
Tensile Butt Joint

Advantages	Disadvantages
Yields tension, torsion and compression • Stiffness/strength	Qualitative adhesive property data only
Straightforward/economic • Specimen fabrication • Testing	Strain measurements difficult
Data reduction	High shear and peel stresses at bondline edges
Standards • BS EN 26922 • ASTM D 897 • ASTM D 2095	Strength sensitive to spew fillet
Suitable for cyclic/environmental testing (QA only)	Sensitive to specimen misalignment
	Limited to thick and rigid adherends
	Failure attributed to peel stresses
	Special bonding fixture required



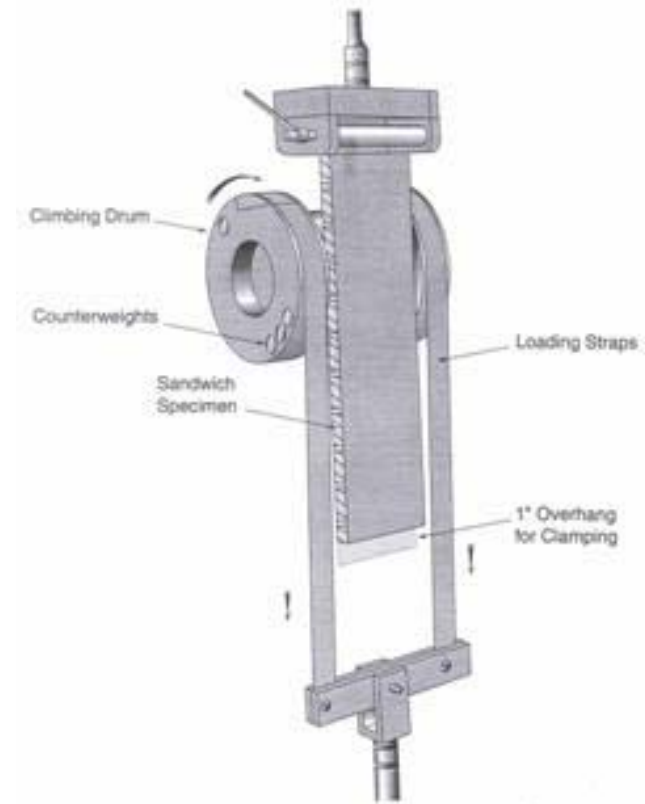
T-Peel Test Method

Advantages	Disadvantages
Yields peel strength	Limited to thin flexible adherends
Straightforward/economic • Specimen fabrication • Testing • Data reduction	Not suitable for generating design data
Discriminates between surface treatments/adhesives	Large uncertainties in measurements
Standards • ISO 8510: Part 2 • ISO 11339 • ASTM D 1876	No allowance for large adherend deformation
Suitable for in-situ environmental testing (QA only)	Sensitive to fillet dimensions
Suitable for fatigue testing	



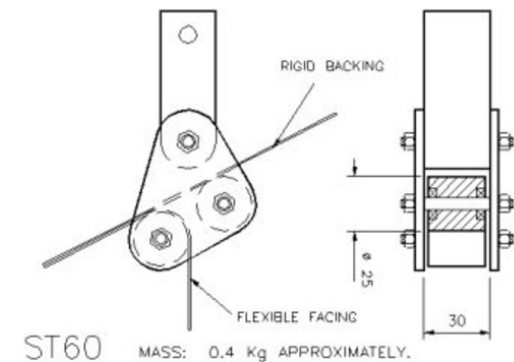
Climbing Drum Peel Test Method

Advantages	Disadvantages
Yields • Peel torque • Skin (facing) stiffness of honeycomb sandwiches	Special test fixture required
Laminated or honeycomb sandwich structures	Limited to
	Laminated or honeycomb sandwich structures
Straightforward/economic	Low stiffness skins (facings)
• Testing • Data reduction	Large and expensive specimens
Standards • BS 5350: Part C13 • ASTM D 3167	Comparative data/service correlation unknown
	Unsuitable for in-situ environmental testing
	Unsuitable for fatigue testing



Floating Roller Test Method

Advantages	Disadvantages
Yields peel strength	Special test fixture required
Compatible with metals and PMCs	Limited to rigid-to-flexible adherends
Straightforward/economic	No allowance for large adherend deformation
• Specimen fabrication (moderate cost) • Testing • Data reduction	Comparative data/service correlation unknown
Standards	Unsuitable for fatigue testing
• DD ENV 1967: 1996 • ASTM D 3167	Unsuitable for in-situ environmental testing

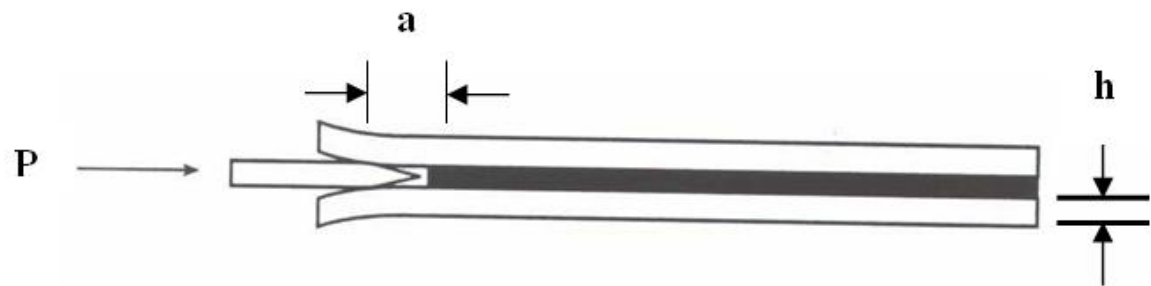


Cleavage and Mode I Fracture Toughness Testing

Test Method	Wedge Cleavage	Compact Tension	DCB	TDCB
Mechanical Properties	Fracture energy	Cleavage strength	Mode I fracture toughness	Mode I fracture toughness
Material Quantity Requirements per specimen	Low	high	Low	High
Typical Specimen Dimensions (mm)	Length 200 Width 25 Adherend (t) 2	Length 25 Width 25 Adherend (t) 12	Length 356 Width 25 Adherend (t) 6.35	Length 240 Width 25 Adherend (t) 12.8
Materials Suitable for Testing				
Fatigue performance	Not suitable	Suitable	Suitable	Suitable
Creep Performance	Possibly	Suitable	Unsuitable	Unsuitable
Environmental suitability	Suitable	Suitable	Suitable	Suitable
Standard Test Methods Available	ASTM D 3762	BS 5350: Part C1 ASTM D 1062	BS 7991 ASTM D 3433	BS 7991 ASTM D 3433

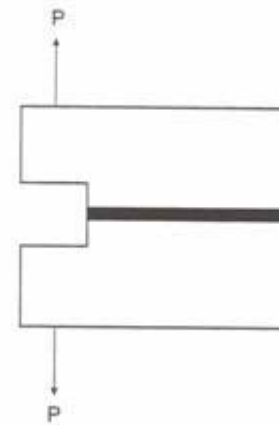
Wedge Cleavage Test Method

Advantages	Disadvantages
Self-stressed	Limited to rigid materials
Yields fracture strength	Not suitable for generating design data
Straightforward/economic • Specimen fabrication • Testing • Data reduction	Limited to rigid adherends
Accurate and highly reproducible data	No allowance for large adherend deformation
Sensitive to environmental effects	Unsuitable for cyclic loading
Standard • ASTM D 3762	
Suitable for environmental testing (QA only)	



Cleavage Strength (Compact Tension) Test Method

Advantages	Disadvantages
Yields fracture strength	Special test fixture required (moderate cost)
Compatible with metals and PMCs	Special bonding fixture required
Straightforward/economic • Specimen fabrication (moderate cost) • Testing • Data reduction	Limited to rigid adherends
Standard • BS 5350: Part C1 • ASTM D 1062	Not suitable for generating design data
Suitable for environmental/fatigue testing (QA only)	



Double Cantilever Beam (DCB) Test Method

Advantages

Yields Mode I fracture toughness

Compatible with metals and PMCs

Straightforward/economic

- Specimen fabrication
- Testing
- Data reduction

Standard

- BS 7991
- ASTM D 3433

Suitable for cyclic/environmental testing

Disadvantages

Limited to rigid adherends

Loading tabs and test fixture required

Limited ability for generating design data

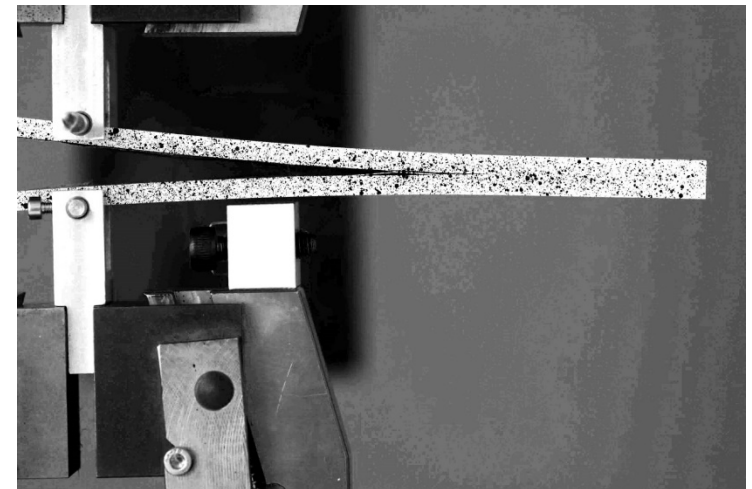
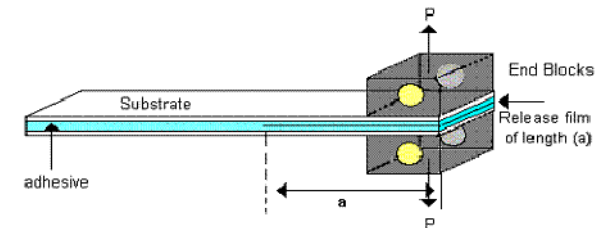
Analysis required to account for

- End (loading) block tilting
- Large beam deflection

Non-linear load-displacement

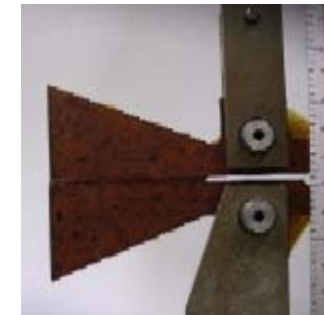
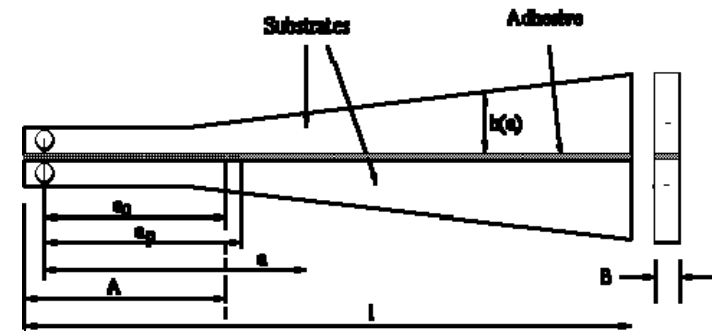
Crack extension measurements difficult

Moderate to large uncertainties in measurements



Tapered Double-Cantilever Beam (TDCB) Test Method

Advantages	Disadvantages
Yields Mode I fracture toughness	Limited to rigid adherends
Compatible with metals	Large specimens required
Adaptable to thin adherends	Special test fixture required
Constant compliance	Limited ability for generating design data
Straightforward/economic • Specimen fabrication • Testing • Data reduction	Special bonding fixture required
Standard • BS 7991 • ASTM D 3433	Analysis required to account for • Root-rotation • Initial beam profile
Suitable for cyclic/environmental testing	Moderate to large uncertainties in measurements

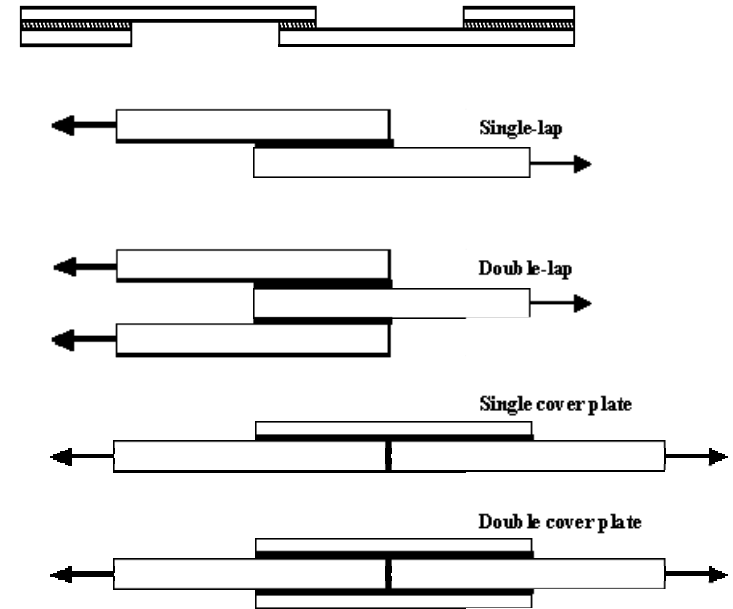


Shear Test Methods

Test Method	Single-Lap	Double-Lap	V-Notched Beam	Arcan
Mechanical Properties	Shear strength	Shear strength	Shear strength/modulus	Shear strength/modulus
Material Quantity Requirements per specimen	Low	Low	Low	Low
Typical Specimen Dimensions (mm)	Length 100 Width 25 Adherend (t) 2 Overlap length 25	Length 100 Width 25 Adherend (t) 12 Overlap length 25	Length 76 Width 20 Notch width 12 Adherend (t) 5	Length 52 Width 40 Notch width 12 Adherend (t) 6
Materials Suitable for Testing				
Fatigue performance	Limited	Suitable	Unsuitable	Suitable
Creep Performance	Suitable	Possibly	Unsuitable	Unsuitable
Environmental suitability	Suitable	Suitable	Suitable	Suitable
Standard Test Methods Available	BS 5350: Part C5 BS EN 1465 BS EN ISO 9664 ASTM D 1002 ASTM D 3166	BS 5350: Part C5 BS EN ISO 9664 ASTM D 1002 ASTM D 3166	No adhesive standard ASTM D 5379—PMCs	None

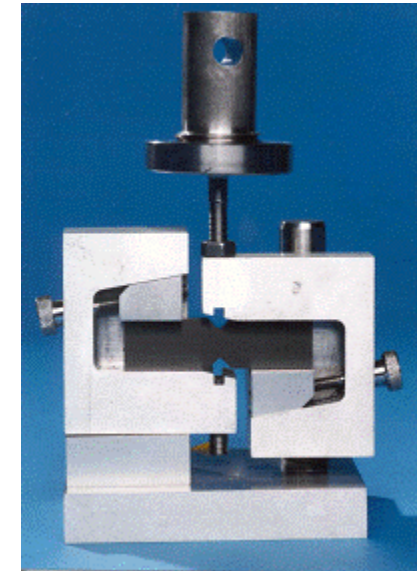
Lap Joint Test Method

Advantages	Disadvantages
Yields “apparent” shear strength	Geometry dependent
Compatible with metals, plastics and PMCs	Limited to rigid adherends
Straightforward/economic • Specimen fabrication • Testing • Data reduction	Not suitable for generating design data
Standards • BS EN 1465 • BS 5350: Part C5 • ASTM D 1002 • ASTM D 3166	Elevated shear and peel stresses at bondline ends
Suitable for cyclic/environmental testing (QA only)	Moderate to high bending moments
	Failure attributed to peel stresses
	Special bonding fixture required
	Large uncertainties in measurements



V-Notched Beam Test Method

Advantages	Disadvantages
<u>Bulk Resin</u> • Shear modulus attainable for all polymeric materials • Shear strength attainable for thermoplastics <u>Adhesive Joints</u> • Yields shear modulus and strength <u>Additional Points</u> • Low material requirements • Data reduction is straightforward • Suitable for use under environmental conditions • Suitable for creep testing • ASTM D 5379—composites • Suitable for cyclic/environmental testing	<u>Bulk Resin</u> • Strain gauges (2 biaxial rosettes) required • Brittle polymers—tensile failure occurs <u>Adhesive Joints</u> • Special bonding fixture required • Interfacial tensile failure occurs • Non-uniform shear stress state <u>Additional Points</u> • Accurate specimen machining required • Special test fixture required • Unsuitable for use under cyclic loading conditions



Arcan Test Method

Advantages

Bulk Resin

- Shear modulus attainable for all polymeric materials
- Shear strength attainable for thermoplastics

Adhesive Joints

- Yields shear modulus and strength
- Suitable for compliant adhesives

Additional Points

- Low material requirements
- Data reduction is straightforward
- Suitable for use under environmental conditions
- Suitable for creep testing

Disadvantages

Bulk Resin

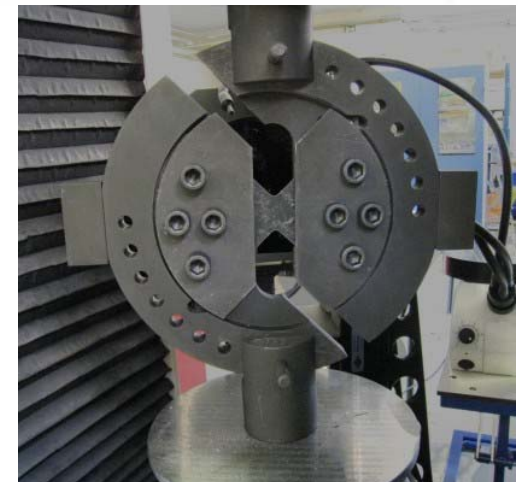
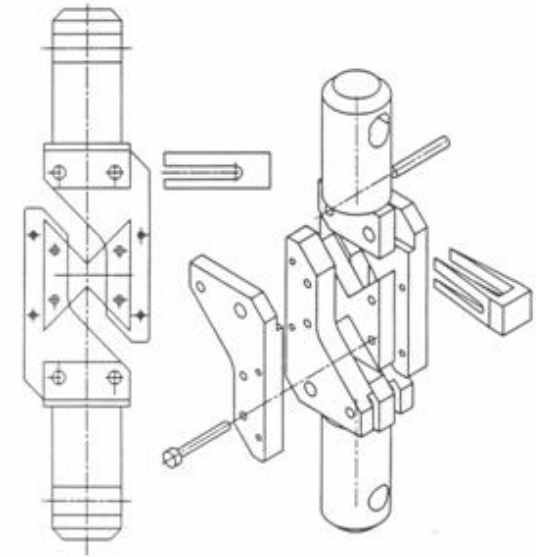
- Strain gauges/extensometer required
- Brittle polymers—tensile failure

Adhesive Joints

- Special bonding fixture required
- Interfacial tensile failure occurs
- Non-uniform shear stress state

Additional Points

- Accurate specimen machining required
- Special test fixture required
- Unsuitable for use under cyclic loading conditions
- No existing national or international standards



Shear Test & Mode II Fracture Toughness Methods

Test Method	Thick Adherend	Torsion Butt Joint	Napkin Ring	ENF
Mechanical Properties	Shear strength/modulus	Shear strength/modulus	Shear strength	Mode II fracture energies
Material Quantity Requirements per specimen	Low	Low	Low	Low
Typical Specimen Dimensions (mm)	Length 110 Width 5 Adherend (t) 26 Overlap length 5	Diameter 15–25 Adherend (t) 12–15	Length 356 Width 25 Adherend (t) 6	
Materials Suitable for Testing				
Fatigue performance	Not suitable	Suitable	Suitable	Suitable
Creep Performance	Possibly	Suitable	Unsuitable	Unsuitable
Environmental suitability	Suitable	Suitable	Suitable	Suitable
Standard Test Methods Available	ISO 11003 ASTM D 3165	None	ASTM E 229	ASTM D 7905

Thick Adherend Test Method

Advantages

Yields shear strength and shear modulus

Compatible with all metals, plastics and PMCs

Stress state relatively uniform over bondline

Straightforward/economic

- Specimen fabrication (moderate cost)
- Testing
- Data reduction

Tension standards

- ISO 11003–2
- ASTM D 695

Compression—NPL draft procedure

Suitable for environmental testing

Disadvantages

Complex/expensive extensometers (2 off) required

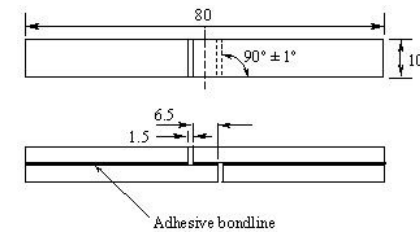
Special bonding fixture required

Accurate specimen machining required

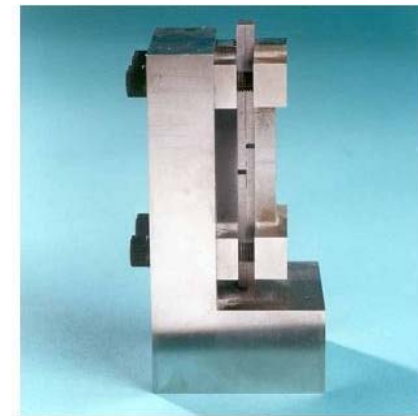
Stress concentrations present at bondline ends

Stress analysis difficult

Limited fatigue capability



All dimensions in mm



Torsion Butt Joint Test Method

Advantages

Bulk Resin

- Shear modulus attainable
- Shear strength attainable for thermoplastics

Adhesive Joints

- Yields shear strength and shear modulus
- Compatible with metals and composites

Additional Points

- Suitable for use under environmental conditions
- Suitable for cyclic/creep testing

Disadvantages

Bulk Resin

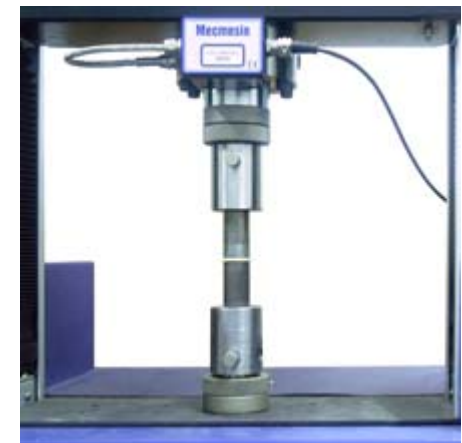
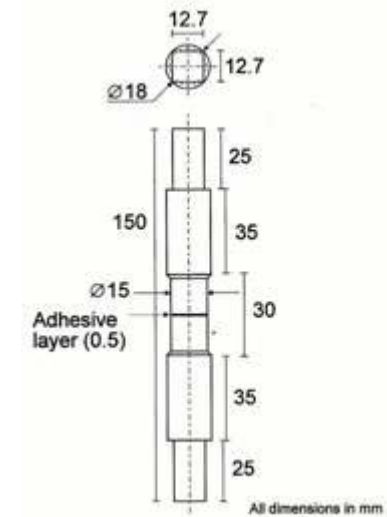
- Strain gauges/extensometers required
- Brittle polymers—tensile failure occurs
- Axial strains need to be monitored

Adhesive Joints

- Special bonding fixture required
- Non-uniform shear stress state
- Small strains—difficult to measure accurately

Additional Points

- Accurate specimen machining required
- Torsion facility required
- Stress concentrations present at end grips
- Complex data reduction (non-linear stress/strain)
- No existing national or international standards



Napkin Ring Test Method

Advantages

Yields shear strength and shear modulus

Compatible with all metals and PMCs

Stress state relatively uniform over bondline

Straightforward/economic

- Specimen fabrication (moderate cost)
- Testing
- Data reduction

Suitable for environmental testing

Disadvantages

Extensometers required

Special bonding fixture required

Accurate specimen machining required

Small strains difficult to measure

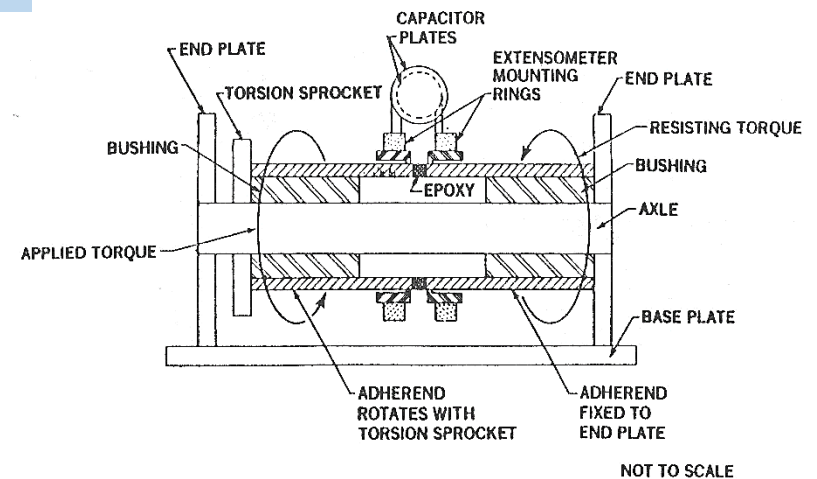
Stress concentrations present at bondline ends

Bondline thickness difficult to control

Stress analysis difficult (non-linear stress/strain)

No existing national or international standards

Limited fatigue capability



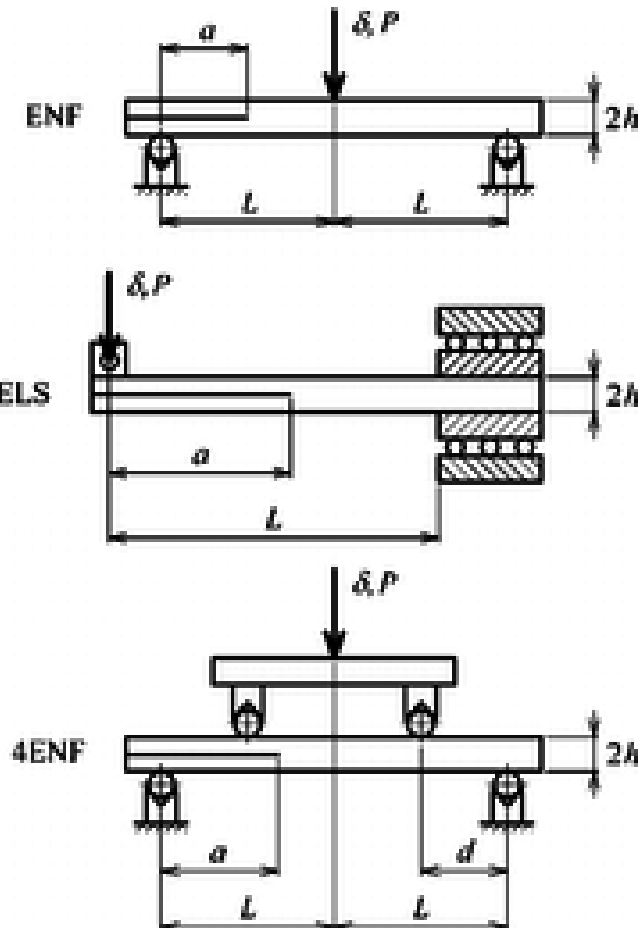
End Notch Flecture (ENF) Test Method

Advantages

- Yields Mode II fracture toughness
- Compatible with metals and PMCs
- Straightforward/economic
 - Specimen fabrication
 - Testing
 - Data reduction
- Standard for Composite
 - D7905
- Suitable for cyclic/environmental testing (QA only)

Disadvantages

- Limited to rigid adherends and brittle adhesives
- Flexural test fixture required
- Unsuitable for generating design data
- Analysis required to account for
 - Shear deformation
 - Large beam deflection
- Non-linear load-displacement
- Pre-cracking difficult
- Crack extension measurements difficult
- Moderate to large uncertainties in measurements



Types of Adhesives

Epoxies

- Relatively inexpensive
- Very good moisture resistance
- Good temperature range
- Poor peel
- Relatively brittle

Acrylics

- Reasonably inexpensive
- Good moisture resistance
- Reasonable temperature range
- Reasonable peel
- Difficult to bond to

Cyanoacrylates

- Inexpensive
- Poor moisture resistance
- Small temperature range
- Very poor peel

Anaerobics

- Reasonably inexpensive
- Low moisture resistance
- Low temperature range
- Poor peel

Principal Properties of Adhesives

Adhesive	(1)Type	(2)Cure	Shear Str MPa (ksi)	Peel Str N/m (lb/in)	(3)Impact Resistance	(3)Solvent Resistance	(3)Moisture Resistance	Relative Price	Temp Range (°C)	Substrate Bonded
Epoxies	1 2 FT	H RTH HP	15.4 (2.2)	< 525 (< 3)	Poor	Excellent	Excellent	Low	-50/100	Most
Modified Acrylics	1	RTH	25.9 (3.7)	5,250 (30)	Good	Good	Good	Moderate	-75/100	Most, Smooth, & non-Porous
Cyanoacrylates	1	M	18.9 (2.7)	< 525 (< 3)	Poor	Good	Poor	Moderate to High	-25/75	Non-Porous metals & Plastics
Anaerobics	1	NO	17.5 (2.5)	1,750 (10)	Fair	Excellent	Good	Moderate	+200	Metals, glass, & thermoplastics

(1) 1: One Component, 2: Two Components, FT: Film and tape

(2) H: Heat, RTH: Room Temp and Heat, HP: Heat and Pressure, M: Moisture, NO: No Oxygen

(3) Basis of this column is the **Environmental Performance Selection Criteria**.

Types of Adhesives, Continued

Urethanes

- Reasonably inexpensive
- Good moisture resistance
- Low temperature range
- Good peel

Silicones

- Generally inexpensive
- Reasonable moisture resistance
- Good temperature range
- Low peel

Hot Melts

- Reasonably Inexpensive
- Poor moisture resistance
- Limited temperature range
- Reasonable poor peel

Phenolics

- Reasonably inexpensive
- Good moisture resistance
- Good temperature range
- Poor peel

Principal Properties of Adhesives, Cont.

Adhesive	⁽¹⁾ Type	⁽²⁾ Cure	Shear Str MPa (ksi)	Peel Str N/m (lb/in)	⁽³⁾ Impact Resistance	⁽³⁾ Solvent Resistance	⁽³⁾ Moisture Resistance	Relative Price	Temp Range (°C)	Substrate Bonded
PolyUrethanes	1 1 2	H M RTH	15.4 (2.2)	1400 (80)	Excellent	Good	Fair	Moderate	-75/100	Most, Smooth, & non-Porous
Silicones	1	M	3.4 (0.25)	612 (3.5)	Good	Good	Excellent	High	-50/275	Most
Hot Melts	1	H	4.3 (0.6)	?	Fair	Fair	Good	Moderate to High	+100	Thermoplastics & Metals
Phenolics	1 2 FT	H H HP	20 (3)	8,000 (45)	Fair	Good	Good	Low	-40/250	Metals
High Temperature	1 FT	H HP	14 (2)	1,200 (7)	Fair	Fair	Poor	High	-40/350	Thermoplastics & Metals

(1) 1: One Component, 2: Two Components, FT: Film and tape

(2) H: Heat, RTH: Room Temp and Heat, HP: Heat and Pressure, M: Moisture, NO: No Oxygen

(3) Basis of this column is the **Environmental Performance Selection Criteria**.

Causes of Nonuniform Adhesive Shear Load Transfer in Bonded Joints

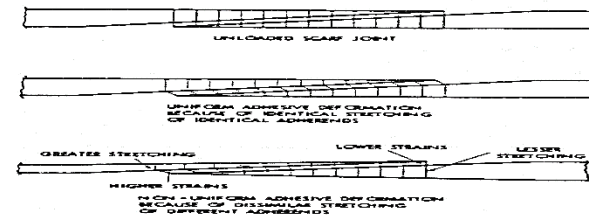
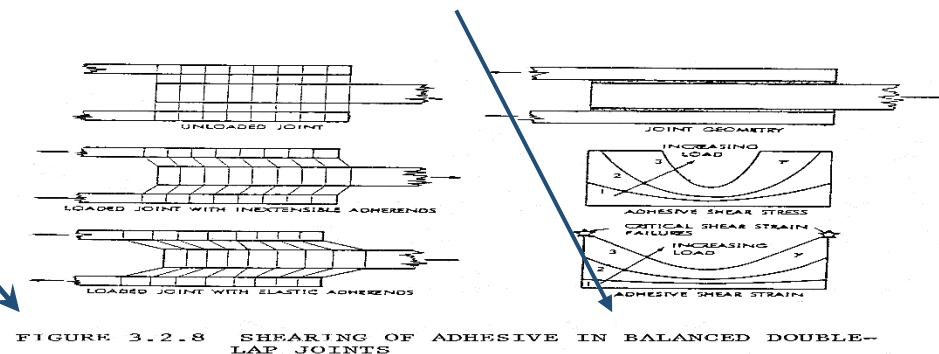
1. The **adherend extensibility** in a balanced joint.
 - a. Necessity for long-life joints
2. The influence of **adherend stiffness imbalances**, from one end of the joint to the other.
 - a. True Inefficiency should be minimized or eliminated
3. **Adherend thermal mismatch**, as between dissimilar materials
 - a. True Inefficiency should be minimized or eliminated

Effect of Adherend Extensibility in a Balanced Double-Lap Joint

- **Stiffer Adherends** promote a more uniformly loaded joint
- **Flexible Adherends** have little load transfer in middle of joint
- **Joint Strength** is defined by the load at which the adhesive shear strain attains the maximum allowable value

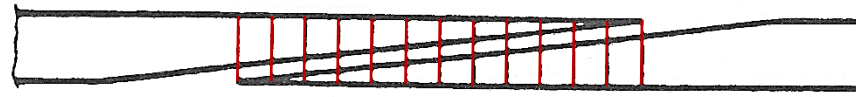
Plastic Zone Load Transfer

- More energy absorbed

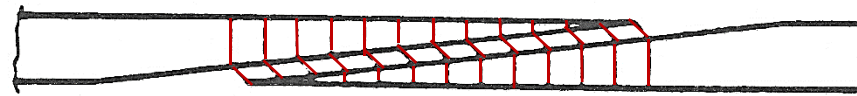


3-13

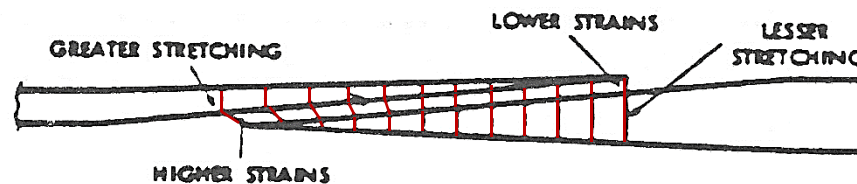
Shearing of Adhesive in Balanced and Unbalanced Scarf Joints



Unloaded Scarf Joint



Uniform Adhesive Deformation Because
Of Identical Stretching of Identical Adherends



Non-Uniform Adhesive Deformation Because
Of Dissimilar Stretching of Different Adherends

Adhesive-Bonded Joint Loaded by In-Plane Shear

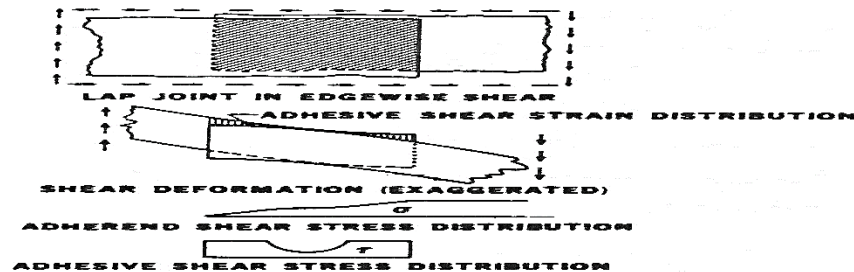


FIGURE 3.2.10 ADHESIVE-BONDED JOINT LOADED BY IN-PLANE SHEAR

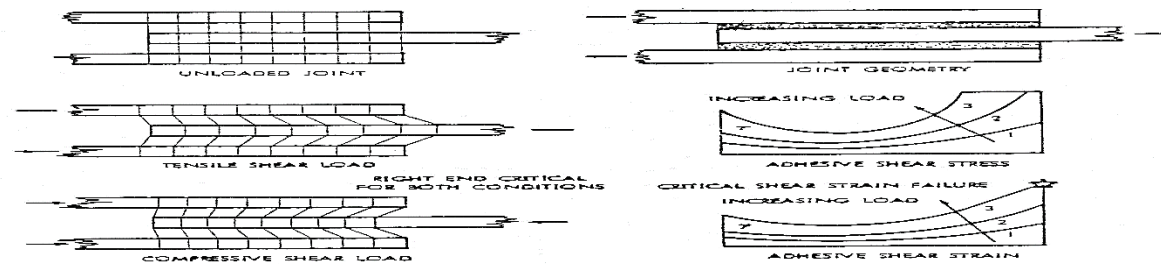
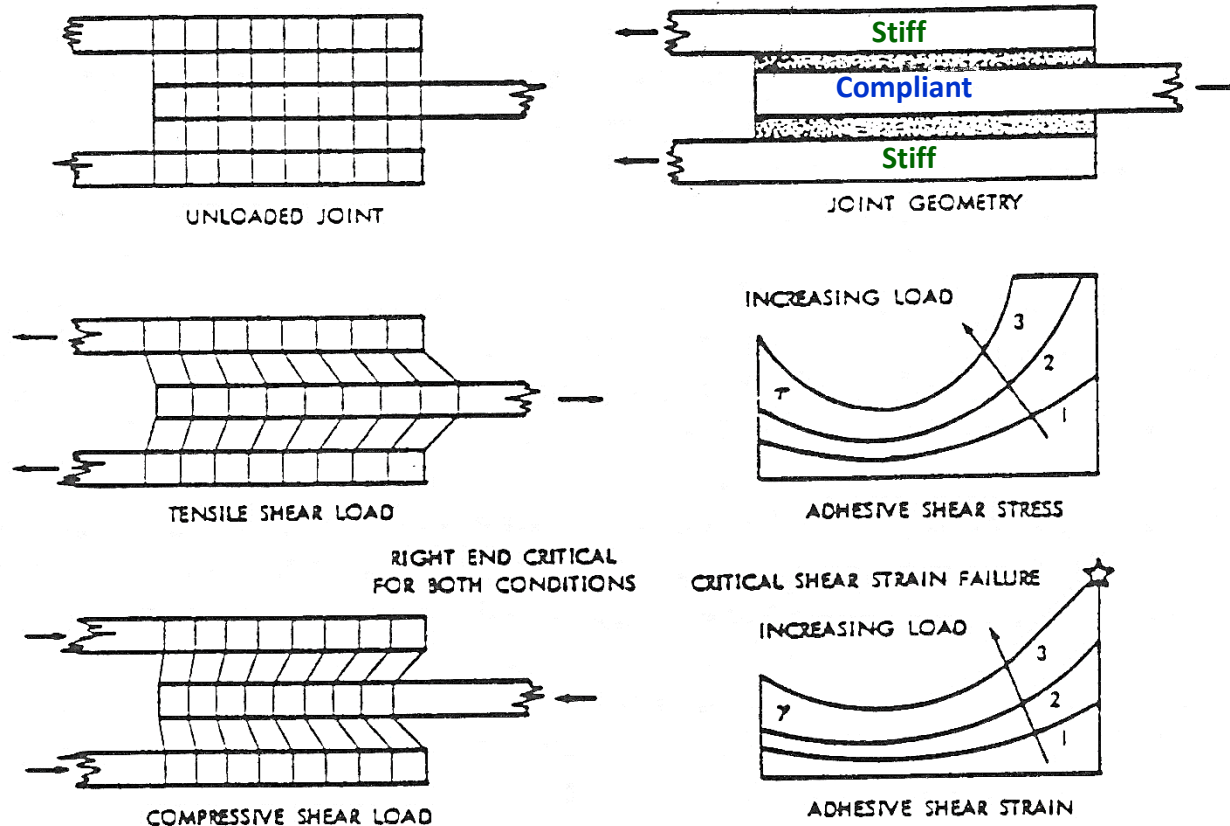
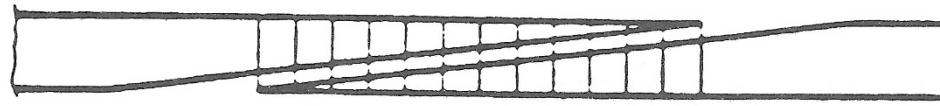


FIGURE 3.2.11 DEFORMATIONS AND ADHESIVE SHEAR STRAINS IN STIFFNESS-UNBALANCED BONDED JOINTS

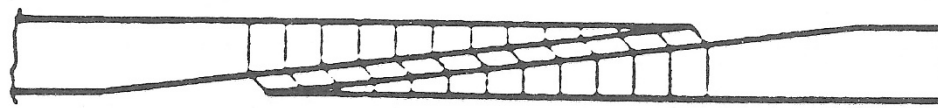
Deformation and Adhesive Shear Strains in Stiffness-Unbalanced Joints



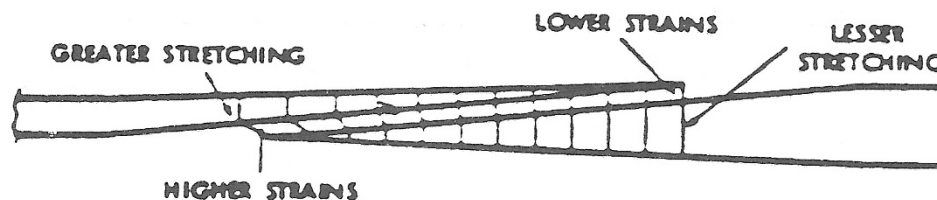
Shearing of Adhesive in Balanced and Unbalanced Scarf Joint



Unloaded Scarf Joint



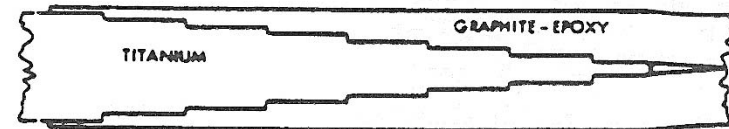
Uniform Adhesive Deformation Because of Identical Stretching of Identical Adherends



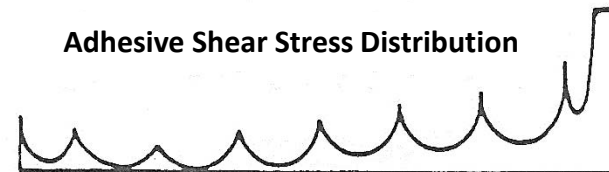
Non-Uniform Adhesive Deformation Because of Dissimilar Stretching of Different Adherends

Extreme Stiffness Balanced and Unbalanced Stepped-Lap Joints

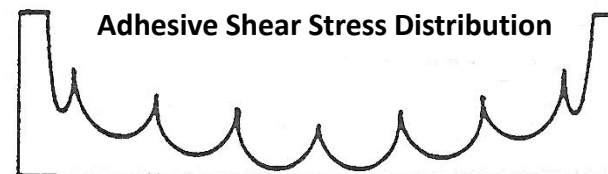
- This type of joint used for high load transfer
- Titanium Step Plate should be significantly thinner than the composite
- **Titanium elastic modulus twice as large as typical composite elastic modulus**



Constant Thickness Stiffness-Unbalanced Joint

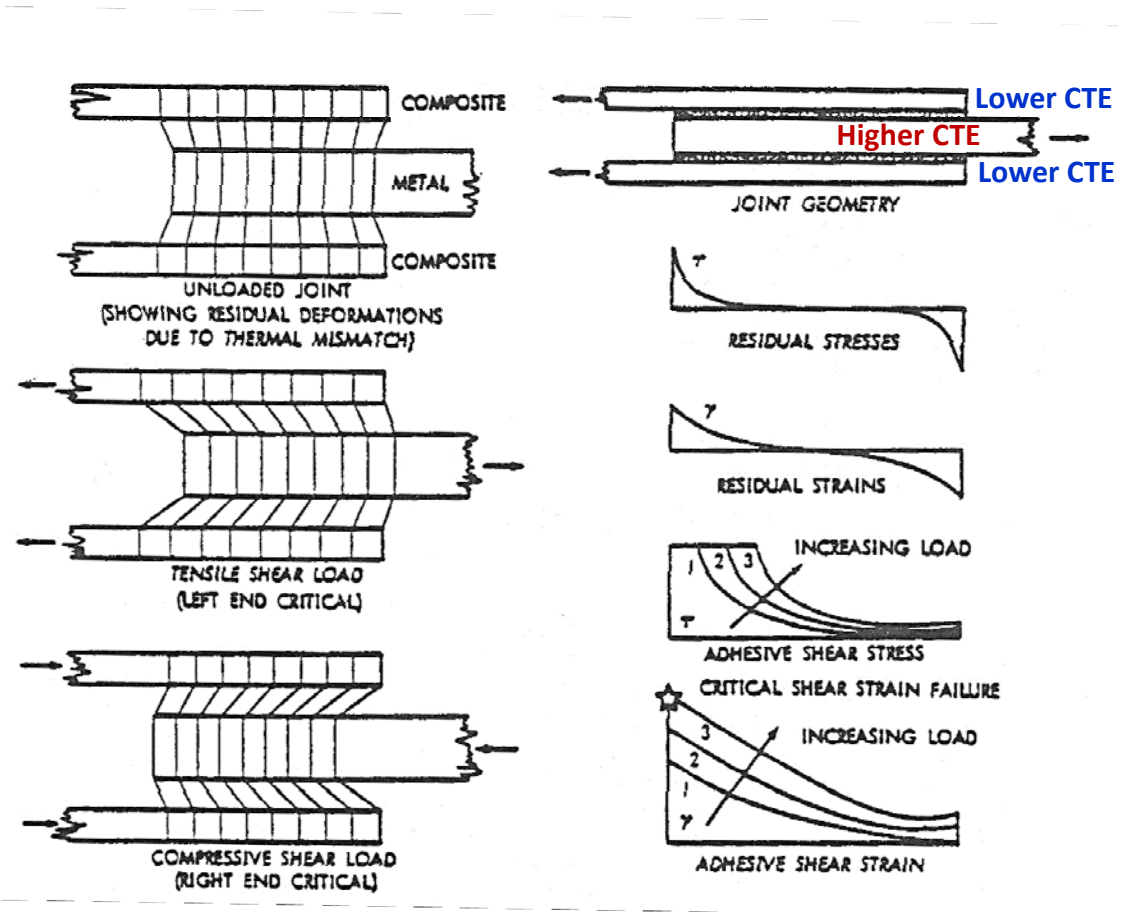


Constant (Variable Thickness) Joint

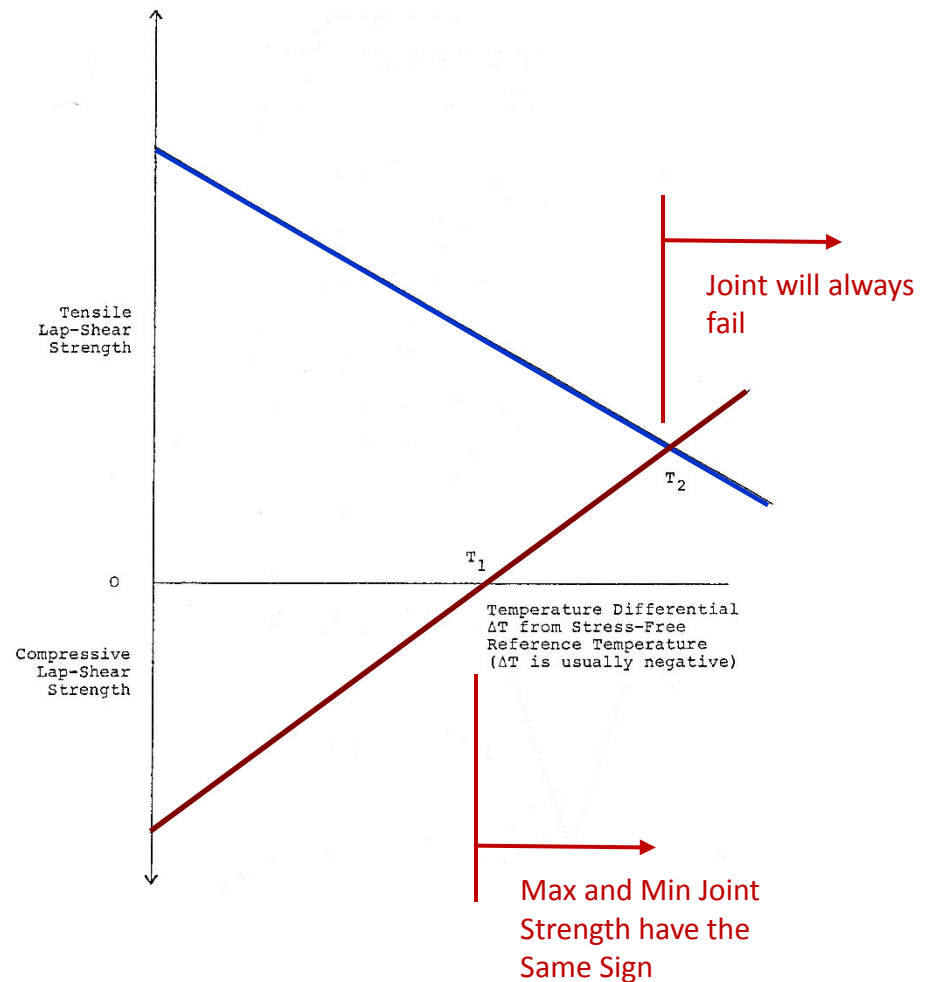
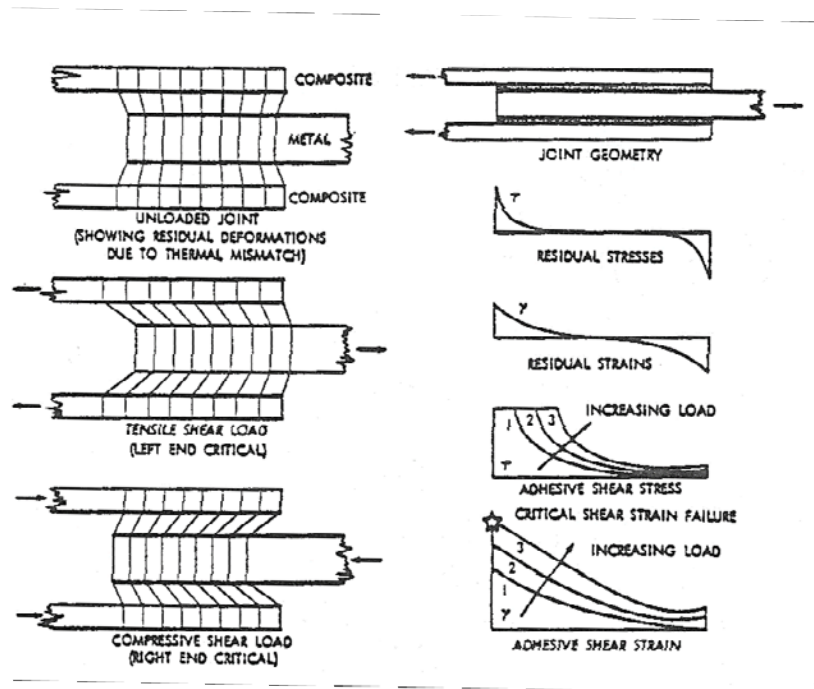


Deformations and Adhesive Shear Strains in Thermally-Mismatched Bonded Joints

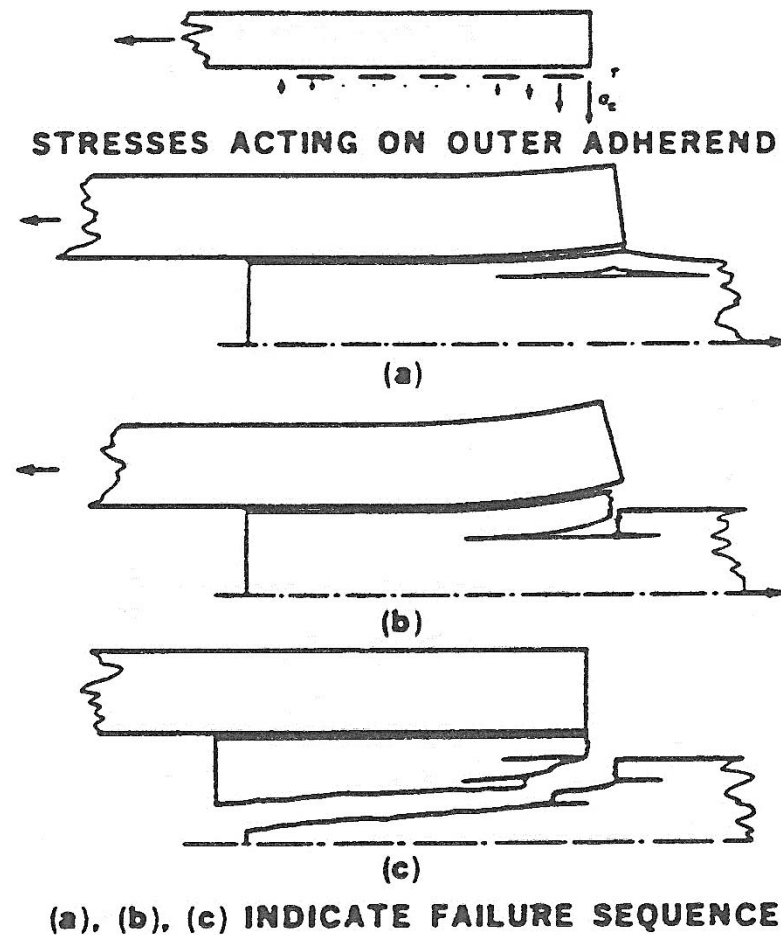
- High strength adhesives are customarily cured at temperatures far above their operating temperatures
- Some assemblies are so large as to preclude RT cured adhesives
- **Effort should be made to avoid inducing residual stresses**
- In **Short Overlaps** adhesive creep can eliminate or minimize problem



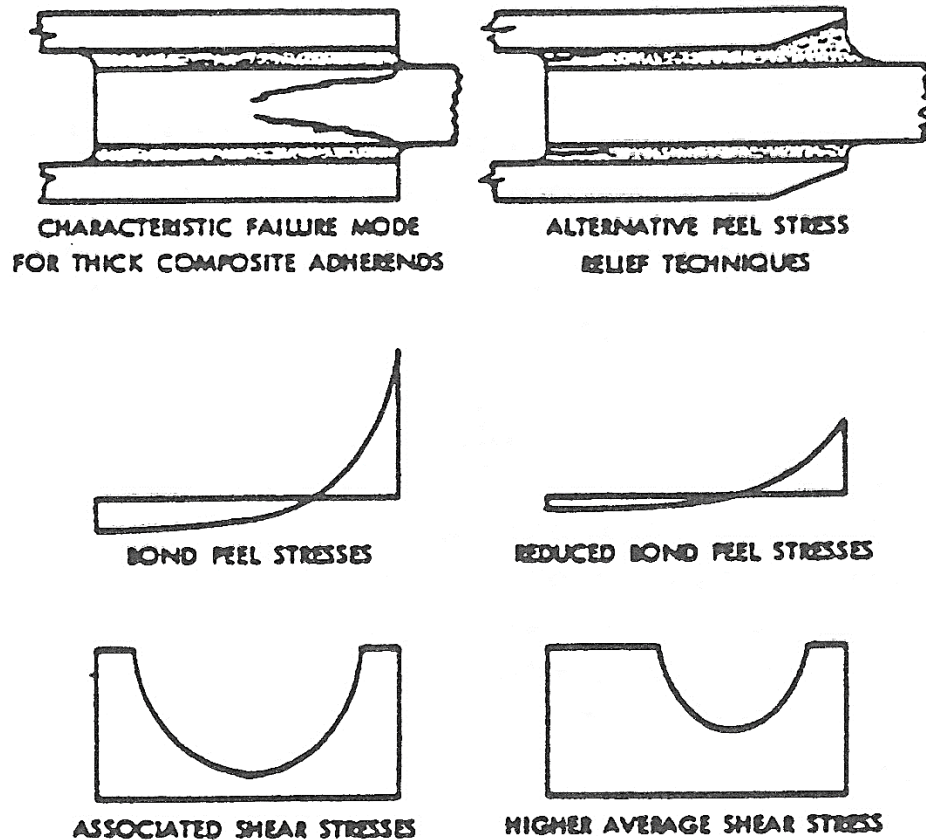
Effect of Temperature Differential: Simultaneous Stiffness and Temp Mismatch



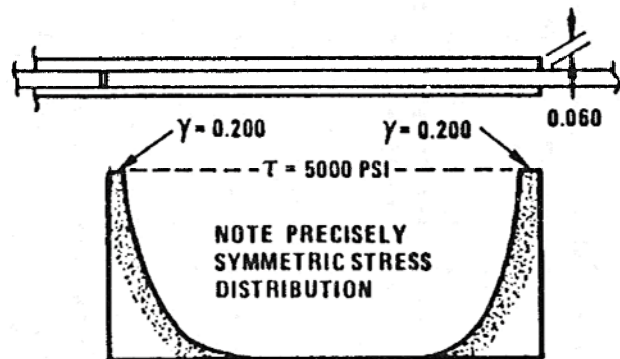
Peel Stress Failure Sequence for a Thick Composite Joint



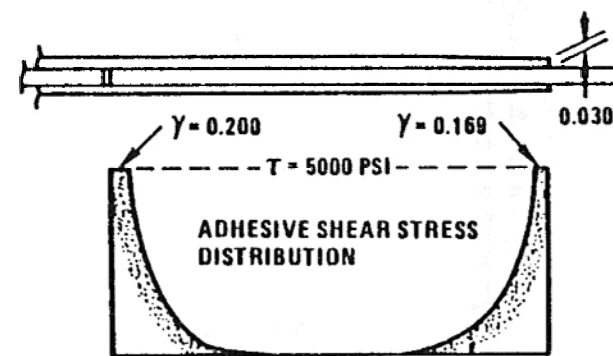
Alleviation of Adhesive Peel Stress



Insensitivity of Adhesive-Bonded Joint Strength to Modifications at the End of the Joint Only – Sufficiently Long Overlap

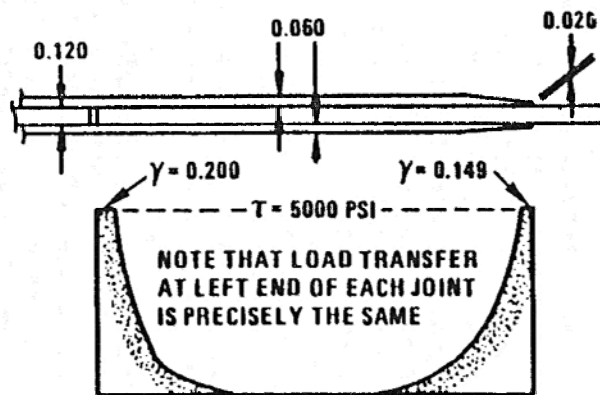


A. BASELINE JOINT – NO ADHEREND TAPER

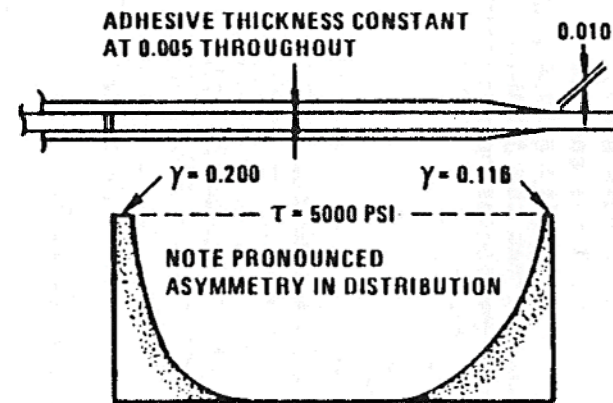


B. SLIGHT ADHEREND TAPER

ALL DIMENSIONS IN INCHES)



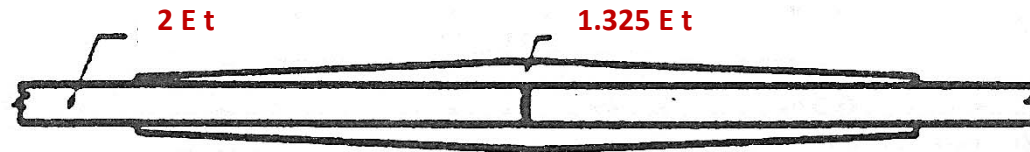
C. MODERATE ADHEREND TAPER



D. SEVERE ADHEREND TAPER

ADHESIVE STRAIN AT RIGHT END OF JOINT DECREASES WITH MORE TAPER

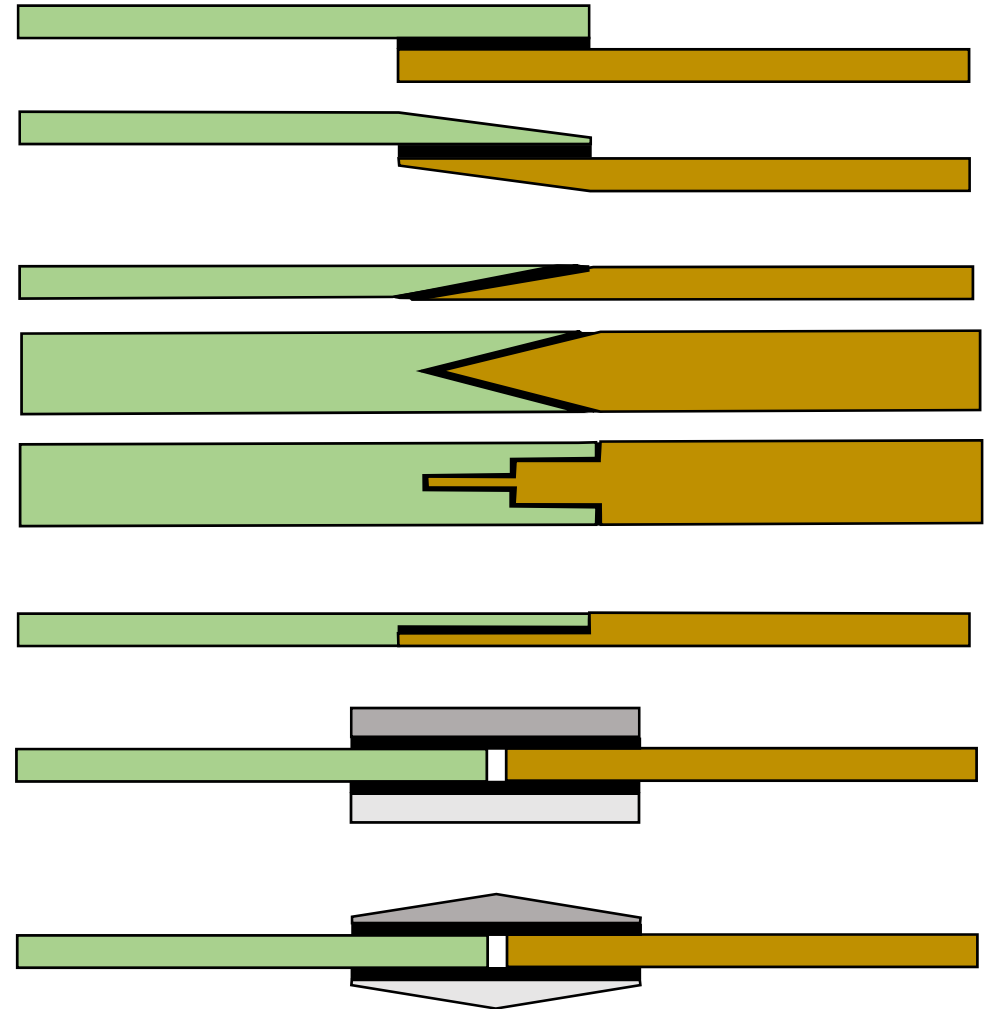
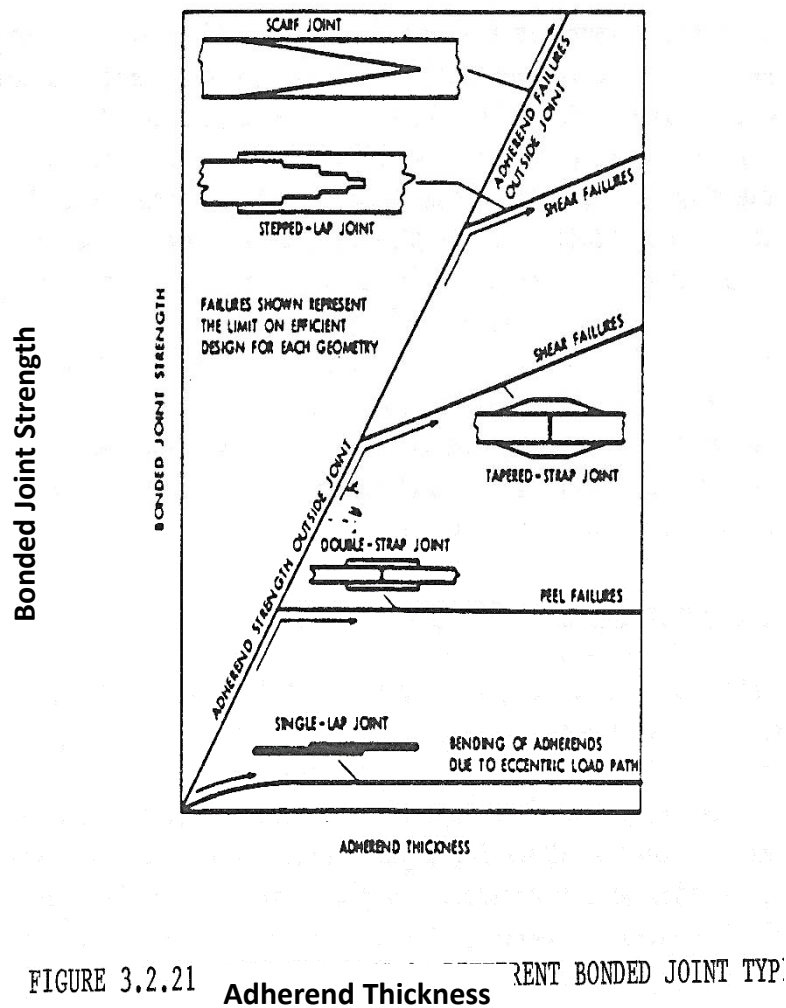
Tapered-Strap Bonded Joints to Improve Strength



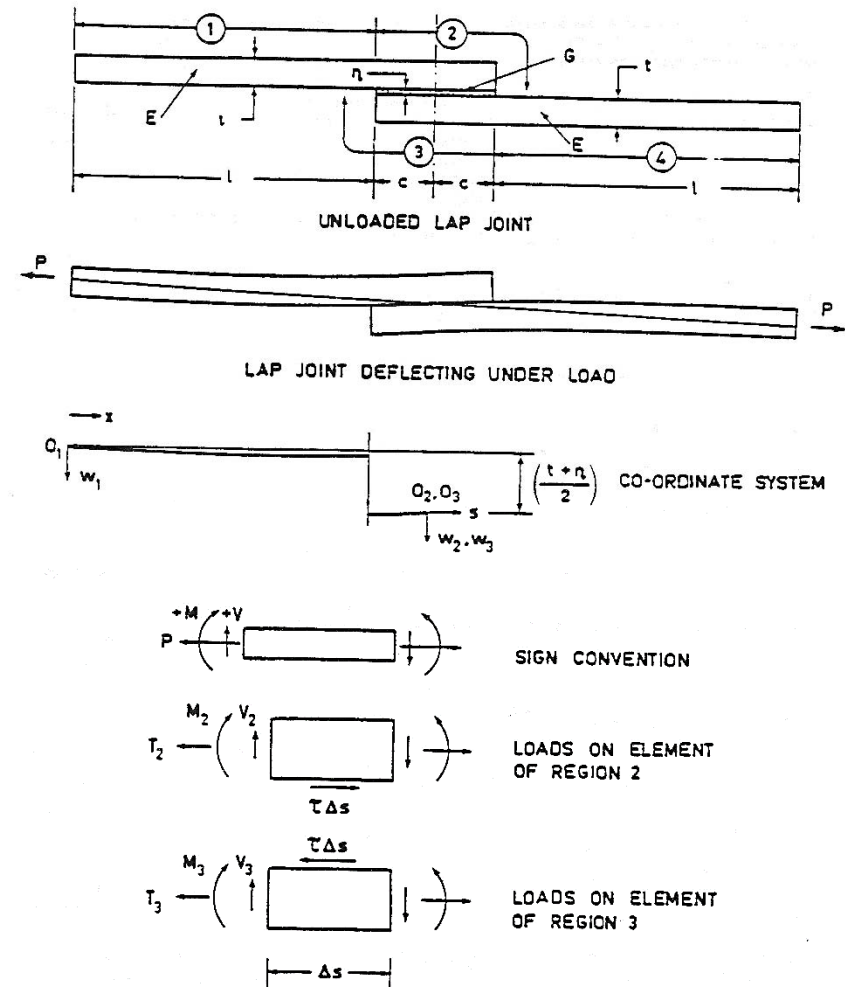
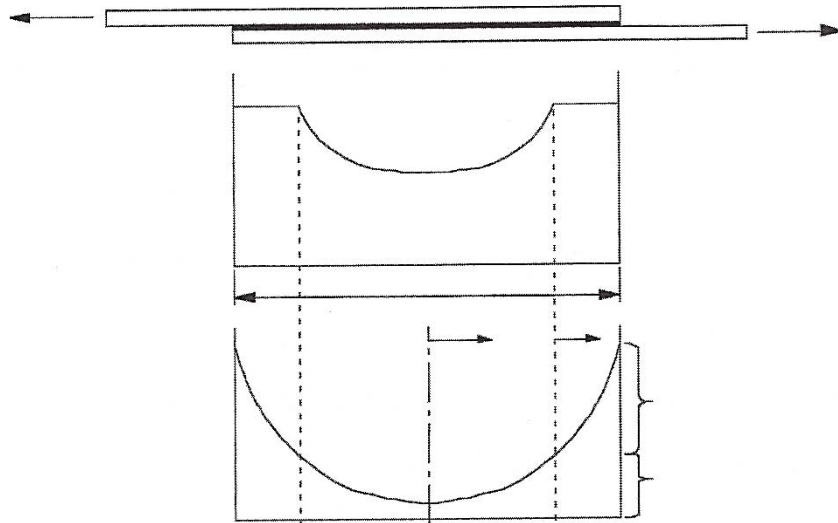
**Shear Strength of Adhesive 24% greater
Than Uniform Balanced Joint Below**



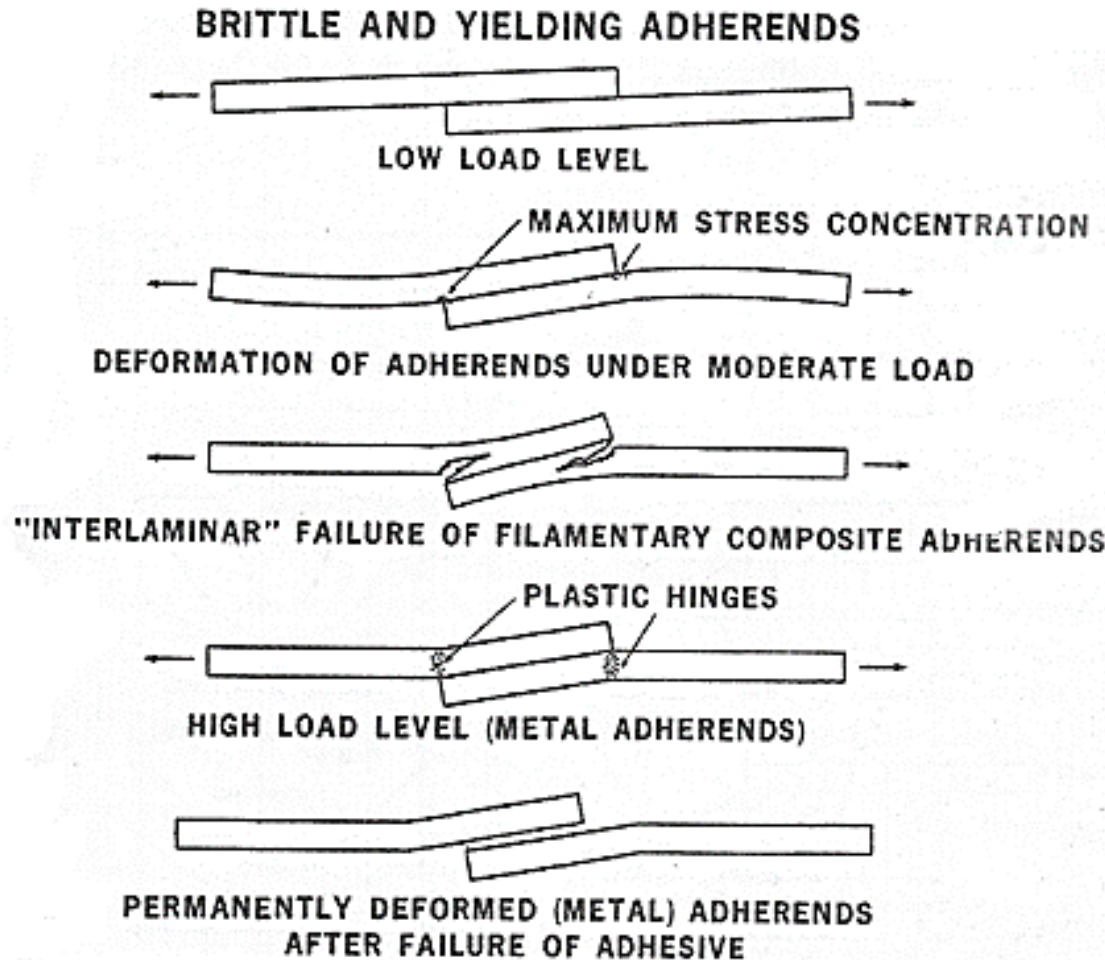
Typical Bonded Joint Configurations



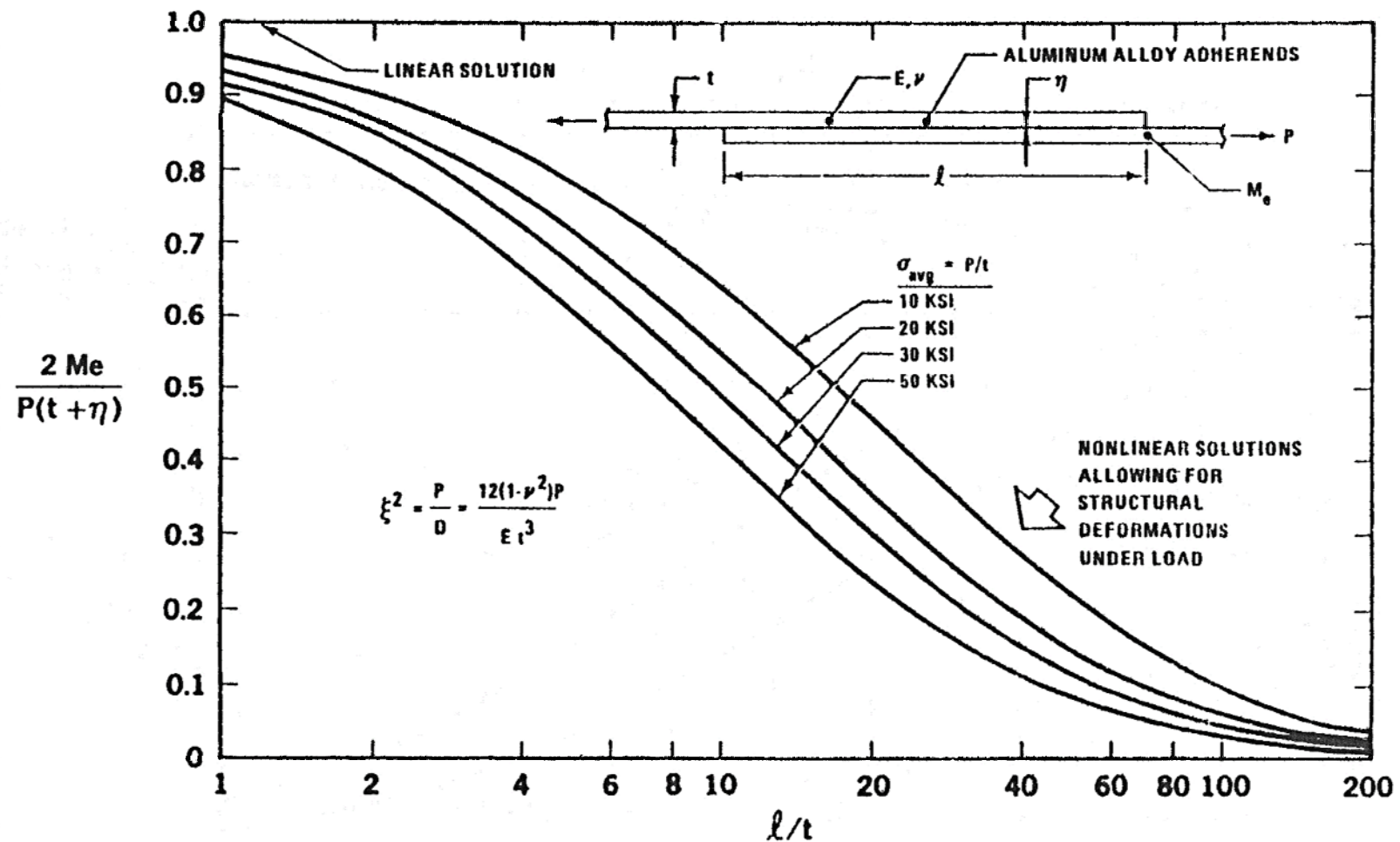
SINGLE LAP JOINT



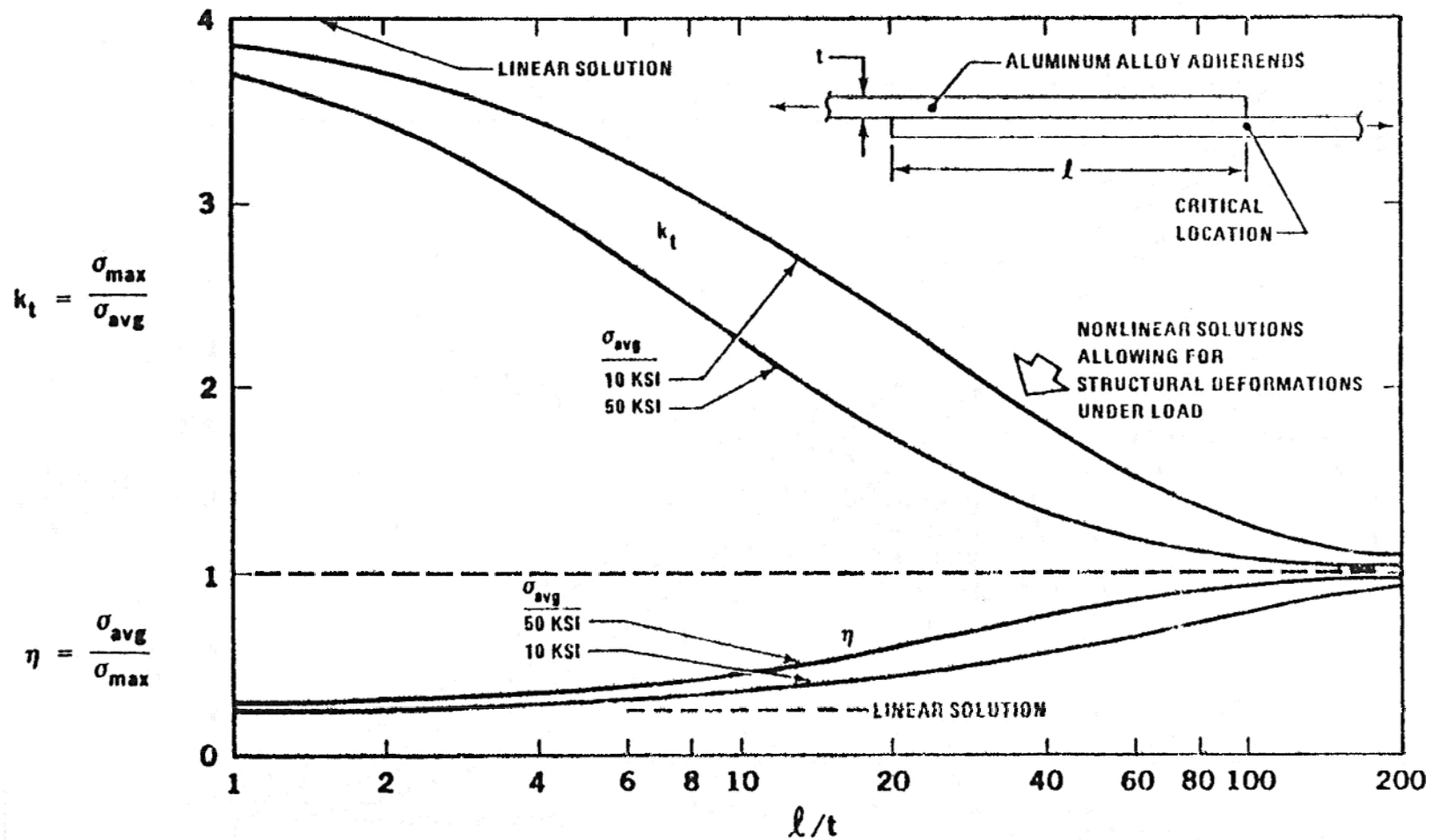
Failure of Single-Lap Bonded Joints with Brittle and with Yielding of Adherends



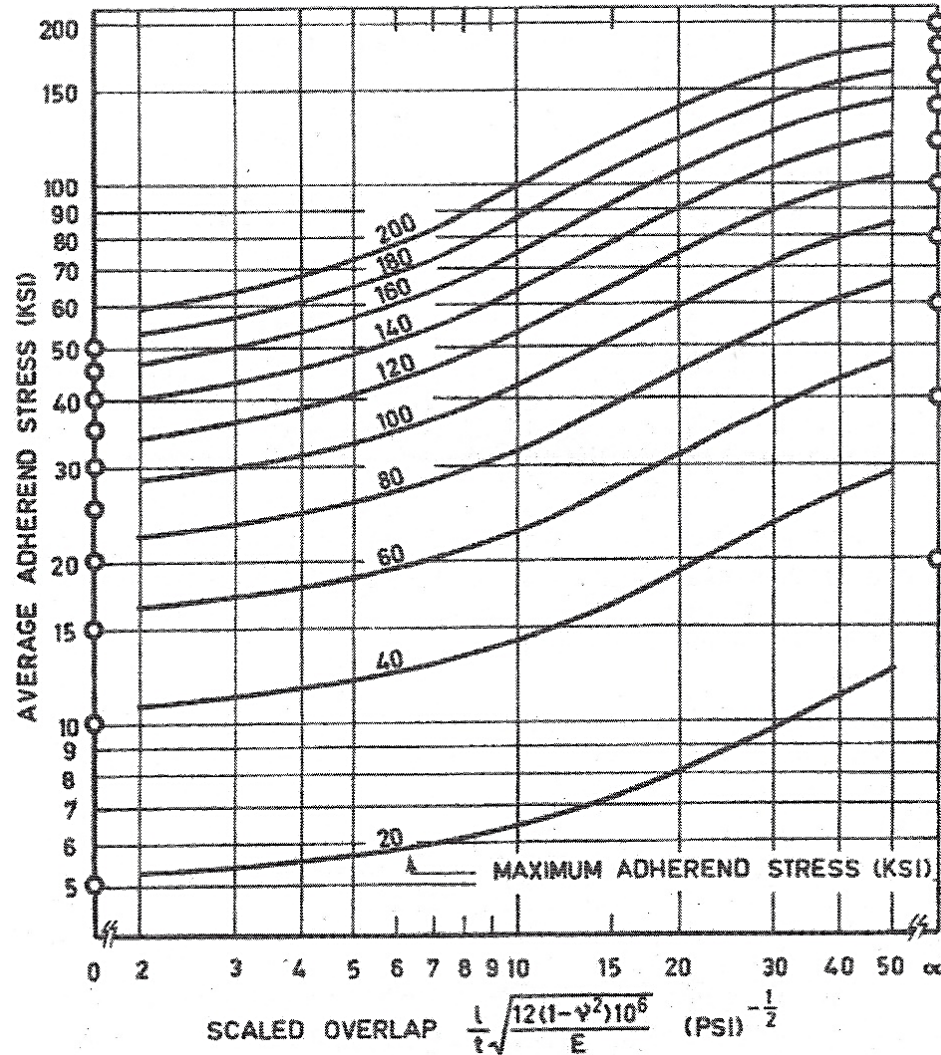
Non-Dimensional Adherend Bending Moment in Single-Lab Joints



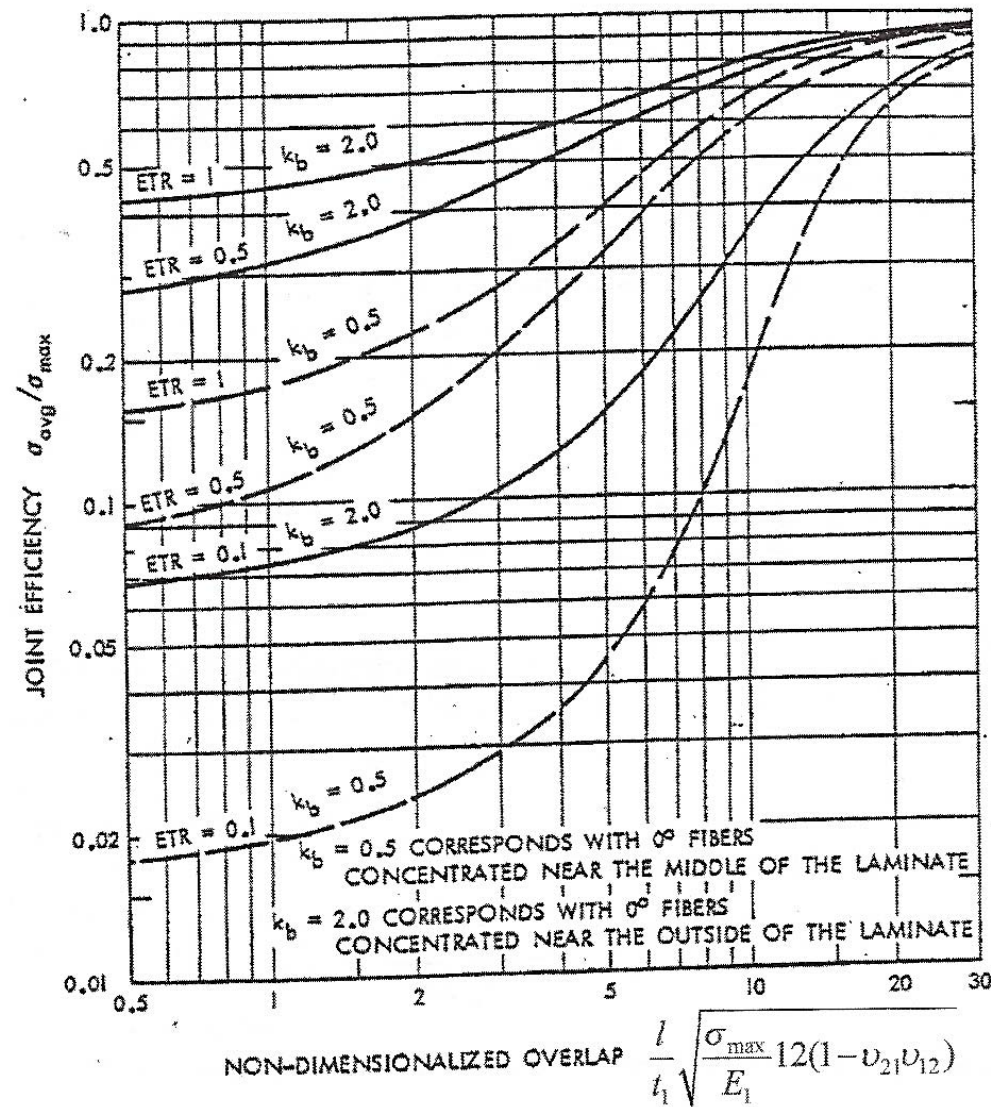
Adherend Stress Concentration and Joint Efficiency of Single-Lap Joints



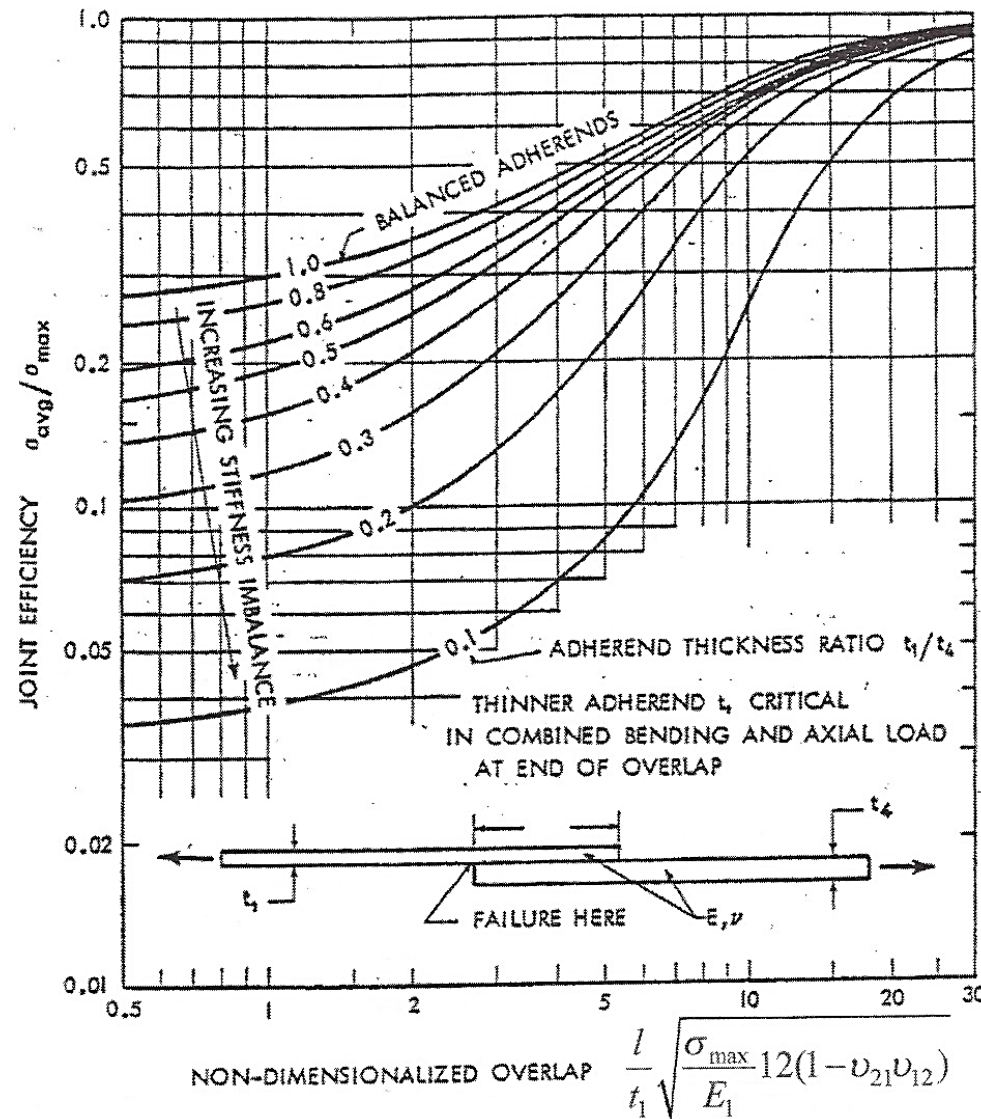
Adherend Average Stresses in Elastically Balanced Single-Lap Joint



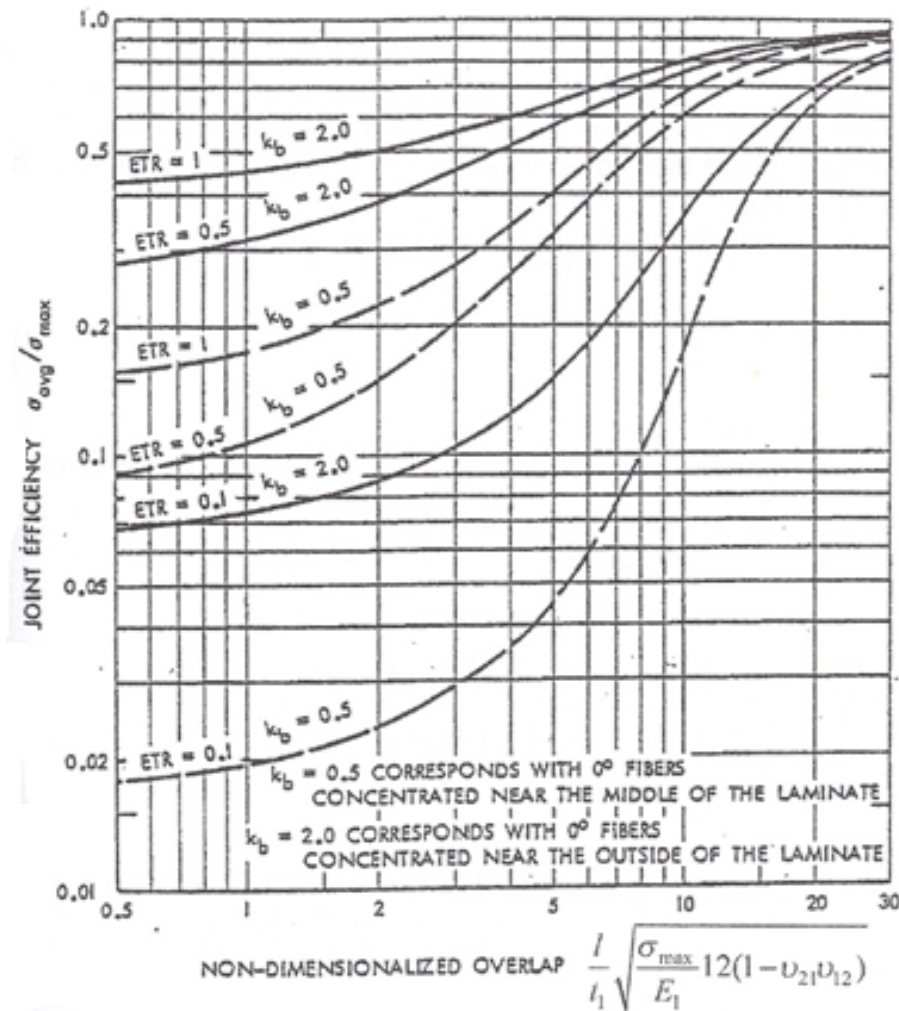
Balanced Single Lap Joint Peel Stresses



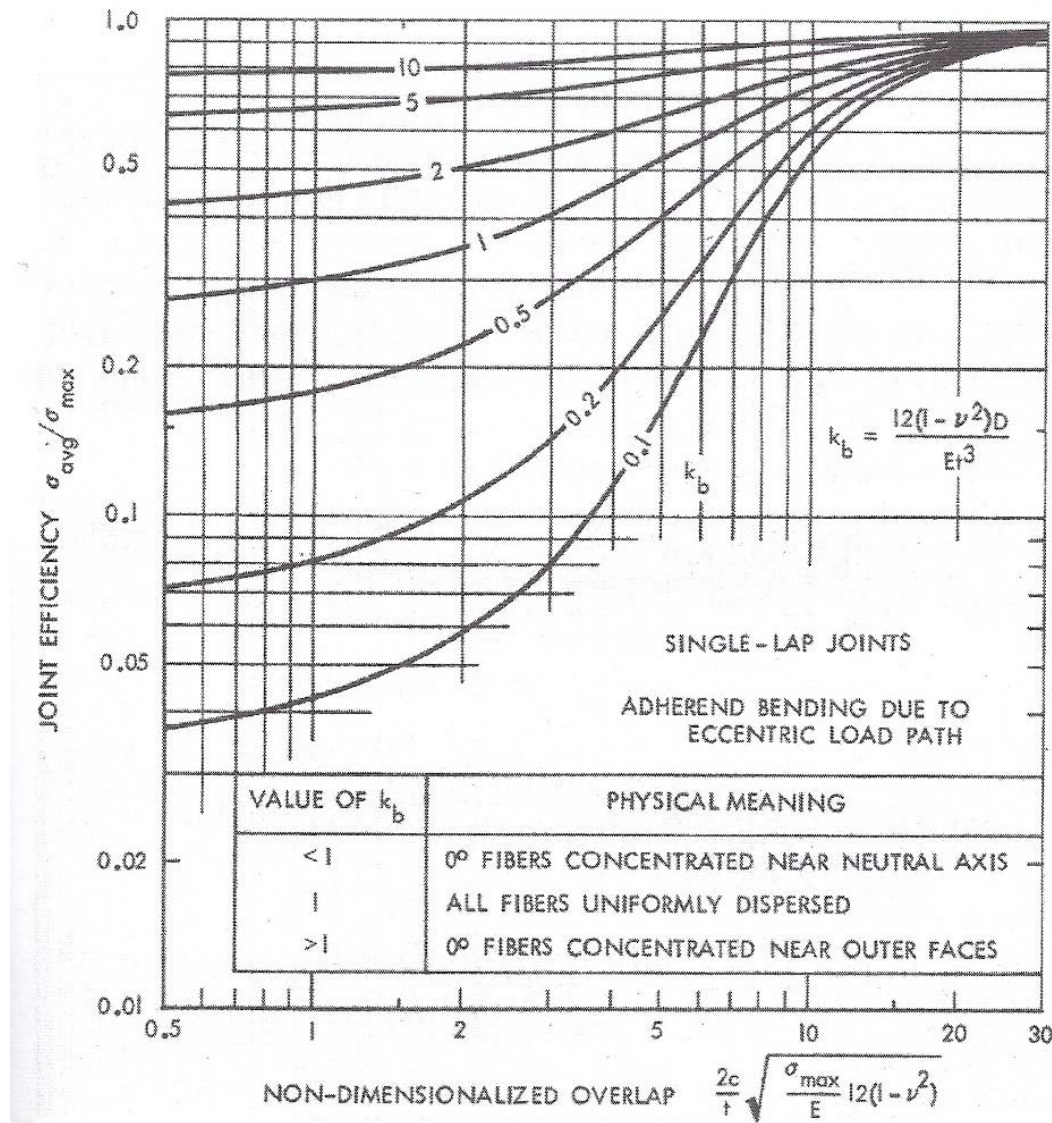
Stiffness Imbalance Effects in Single-Lap Joints with ISOTROPIC Adherends



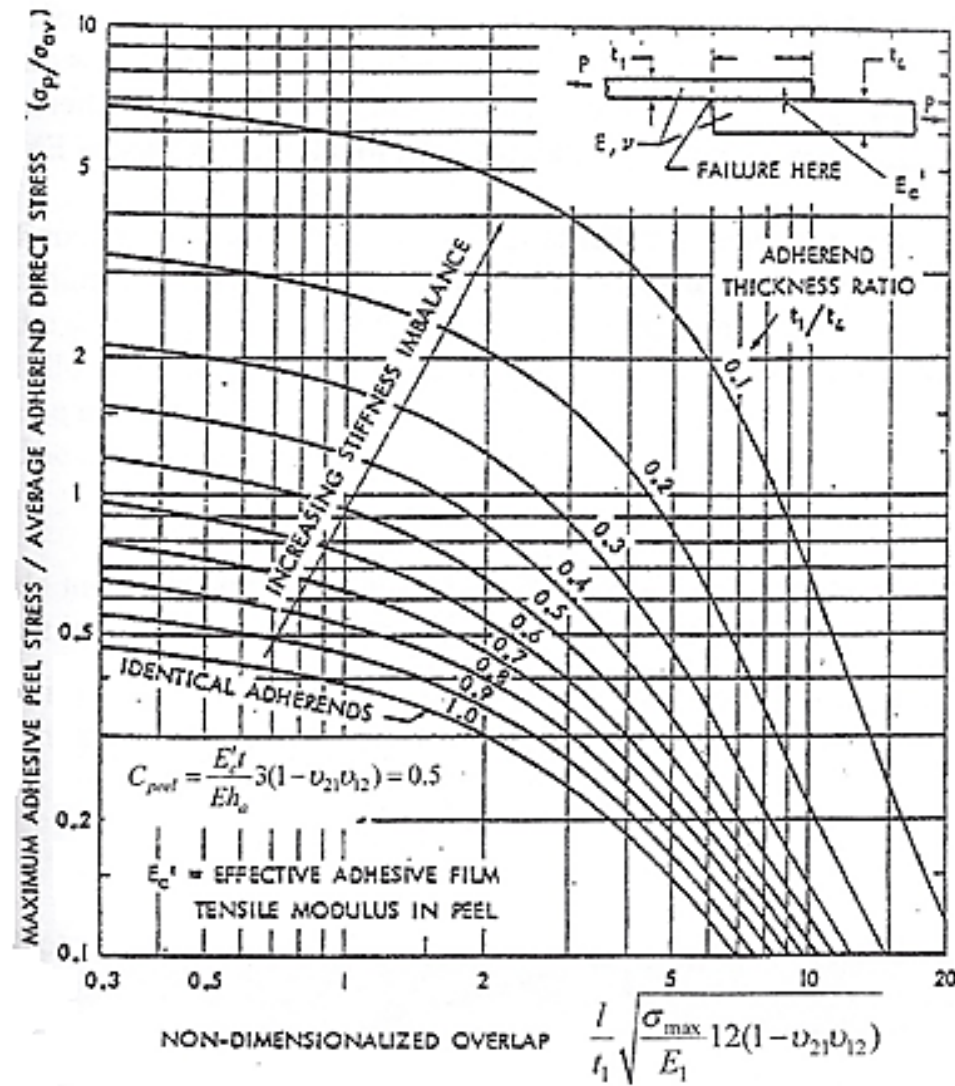
Stiffness Imbalance Effects in Single Lap Joints with COMPOSITE Adherends



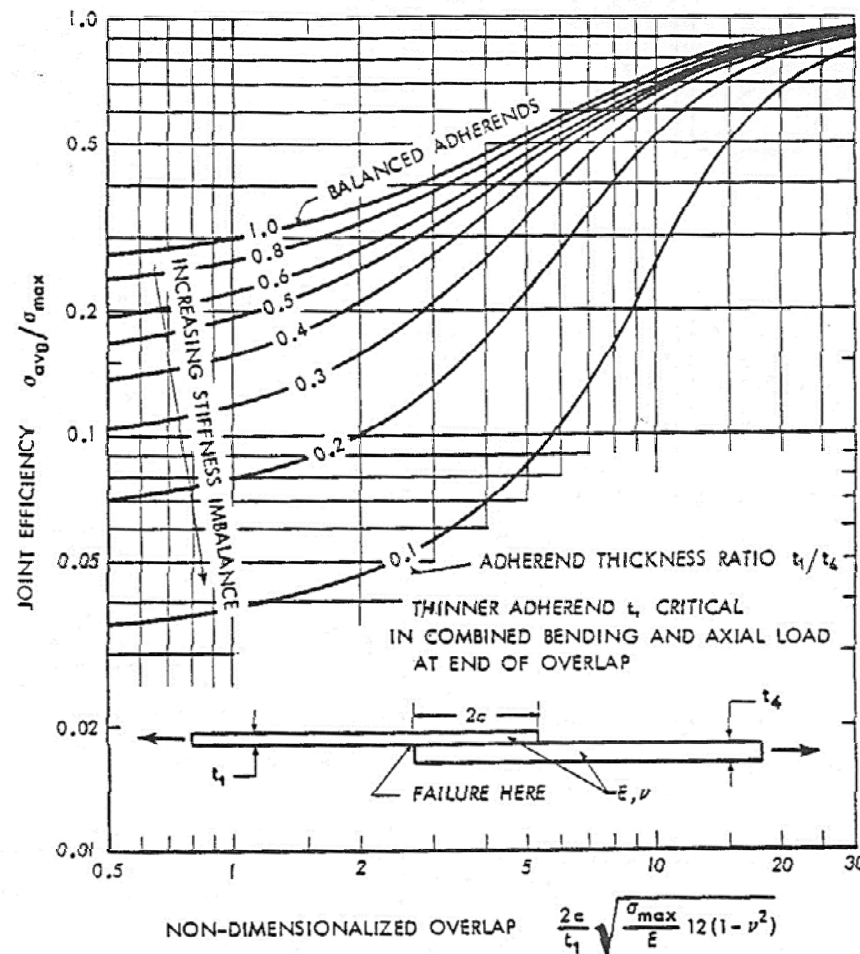
Ply Stacking Effects of the Stress Distribution in COMPOSITE Adherend Single Lap Joints



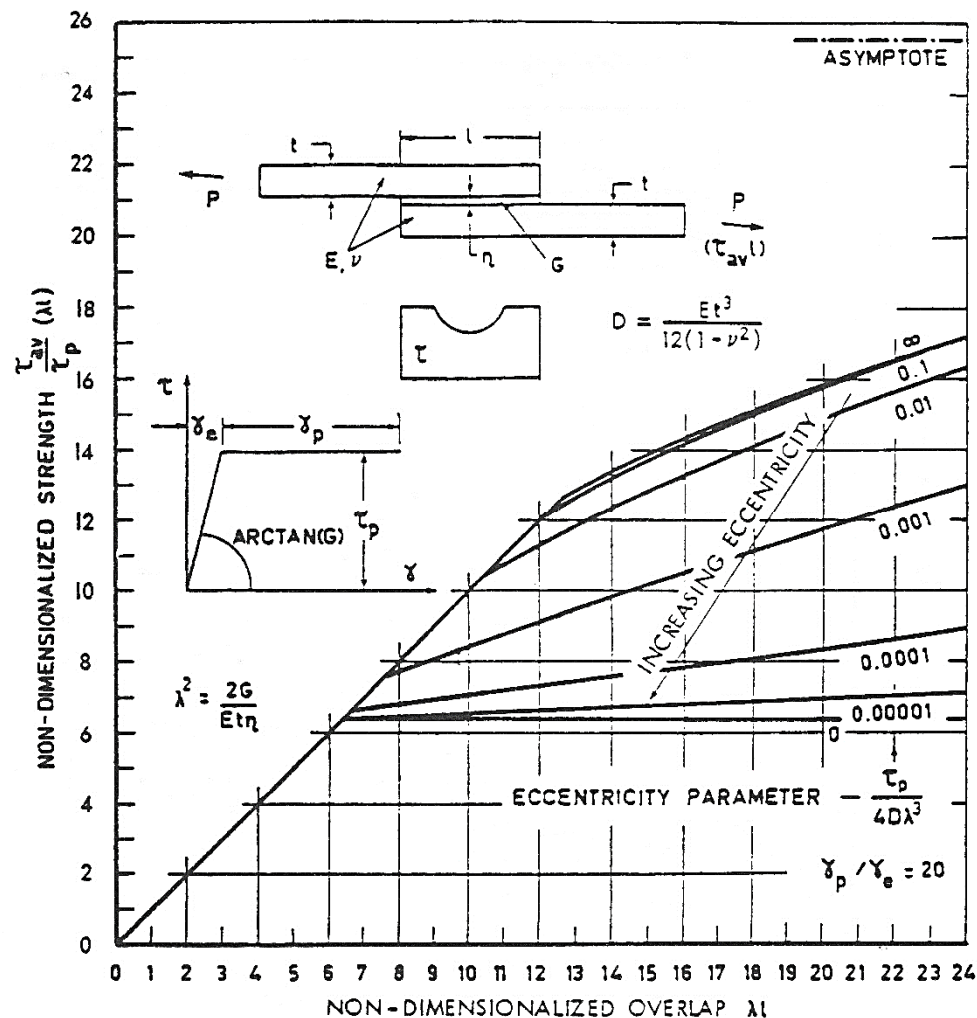
Peel Stress Due to Single Lap Joint Stiffness Imbalance



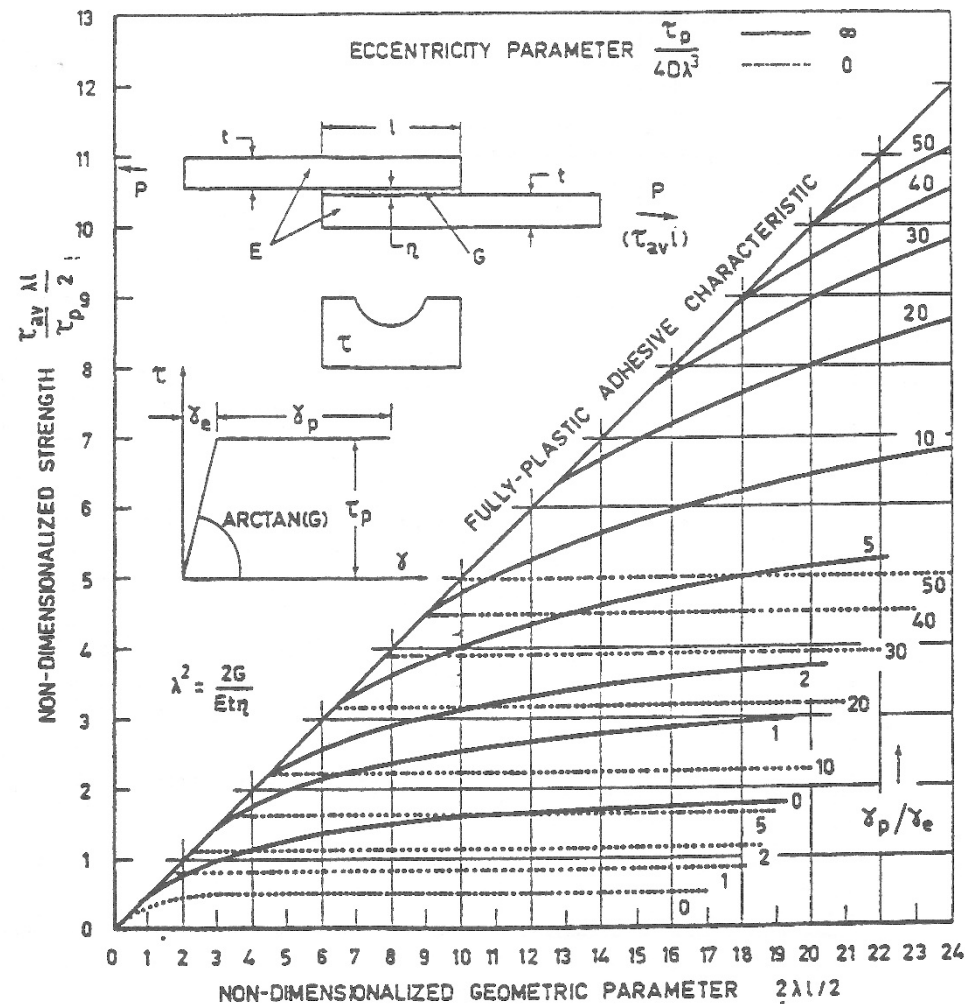
Effect of Adherend Stiffness Imbalance on Adherend Bending Strength of Single-Lap Bonded Joints



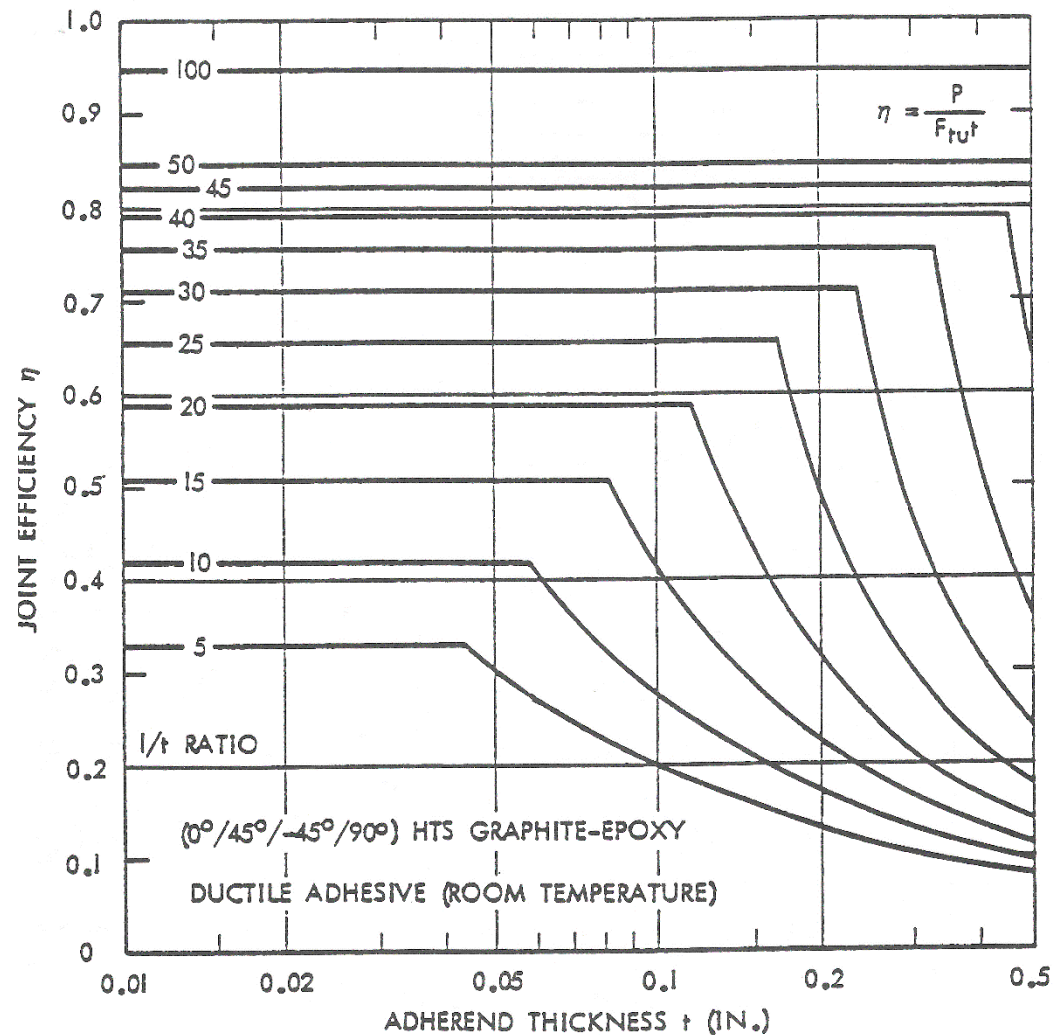
Influence of ADHEREND Properties on Shear Strength of Single-Lap Bonded Joints



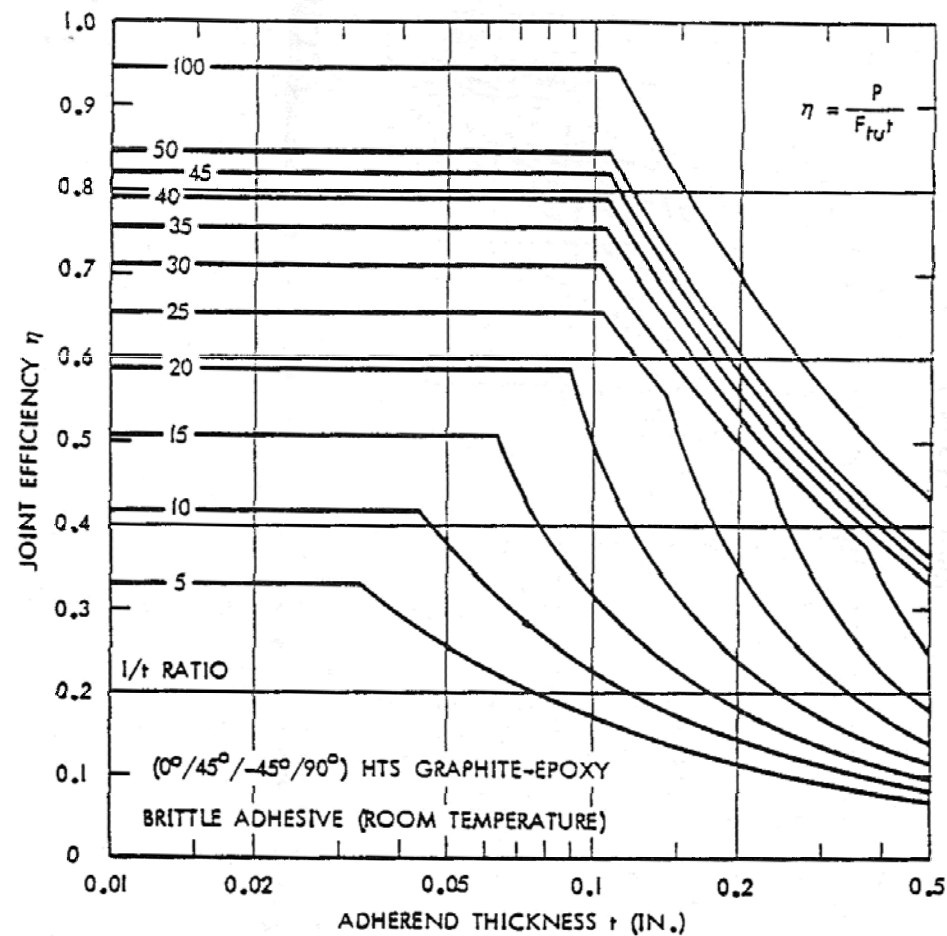
Influence of ADHESIVE Properties on Shear Strength of Single-Lap Bonded Joints



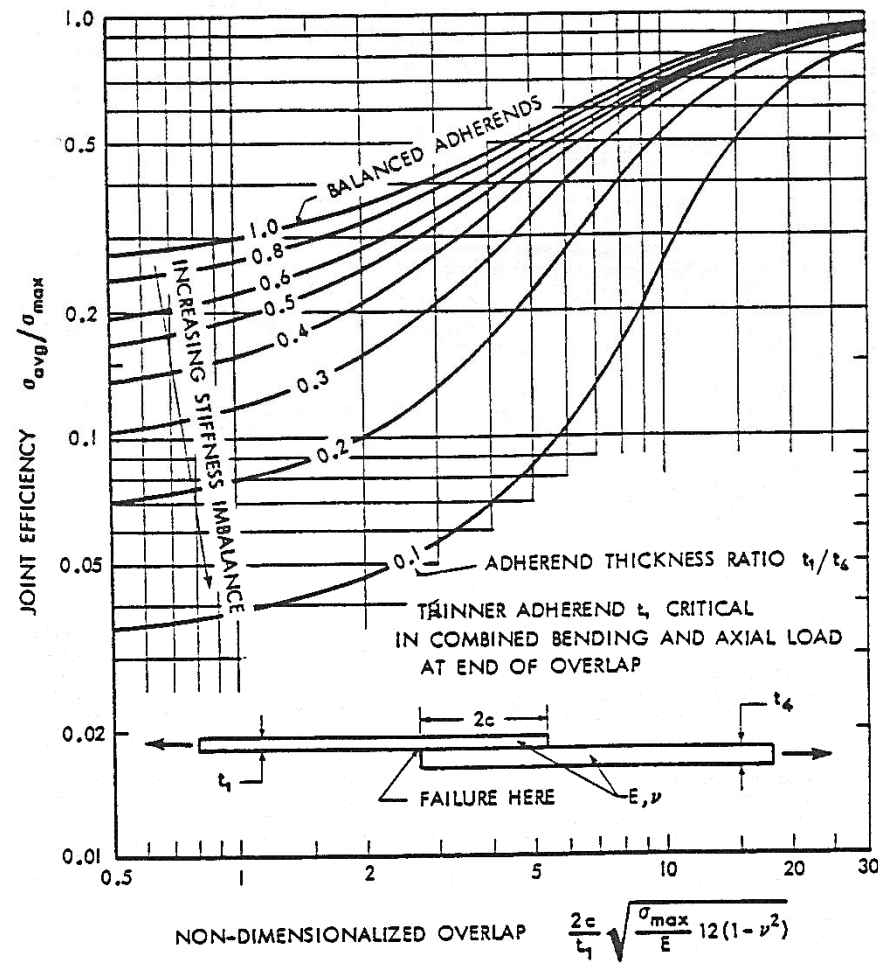
Joint Efficiency Chart for Single-Lap Composite Joints



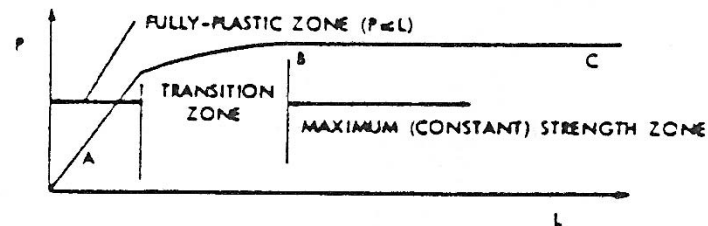
Joint Efficiency Chart for Single-Lap Joint



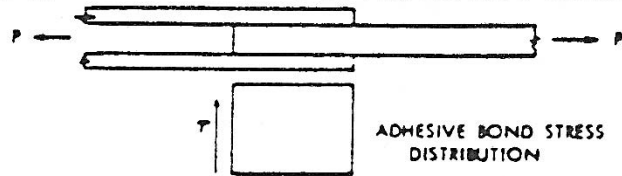
Effect of Adherend Stiffened Imbalance on Adherend Bending Strength in Single-Lap Bonded Joint



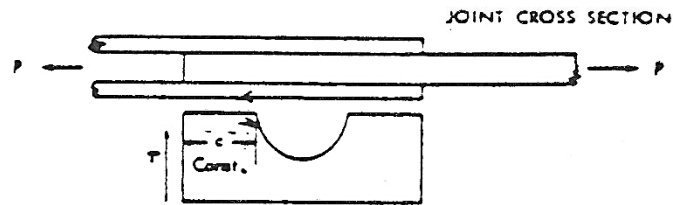
DOUBLE LAB JOINT



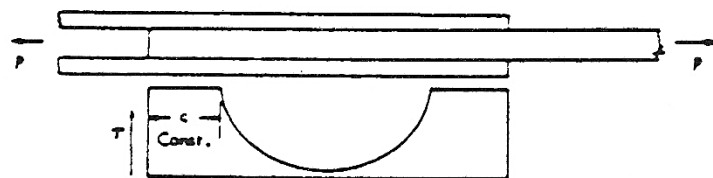
EFFECT OF LAP LENGTH ON ADHESIVE-BONDED JOINT STRENGTH



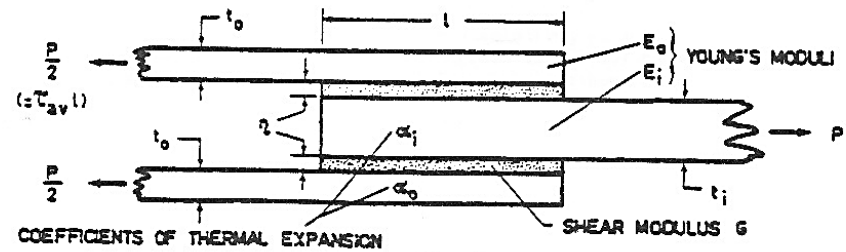
A. SHORT OVERLAP



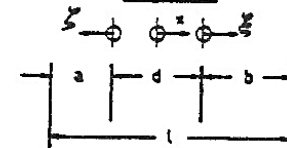
B. INTERMEDIATE OVERLAP



C. LONG OVERLAP



GEOMETRY



ADHESIVE BEHAVIOUR

$$\left(1 + \frac{T_o}{E_o t_o} + \alpha_o \Delta T\right) \Delta x$$

$$\left(1 + \frac{T_i}{E_i t_i} + \alpha_i \Delta T\right) \Delta x$$

$$\Delta x \text{ (REFERENCE)}$$

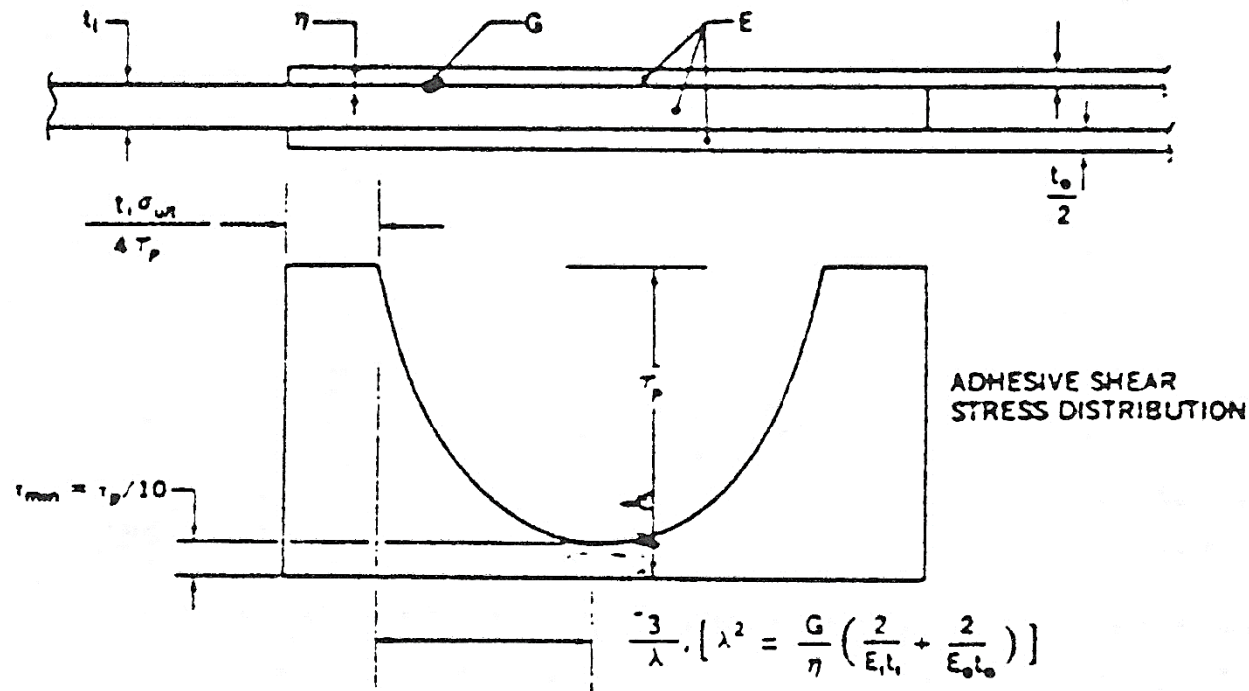
$$\epsilon_o + \left(\frac{d\epsilon_o}{dx}\right) \Delta x$$

$$\epsilon_i + \left(\frac{d\epsilon_i}{dx}\right) \Delta x$$

$$\Delta x \text{ (REFERENCE)}$$

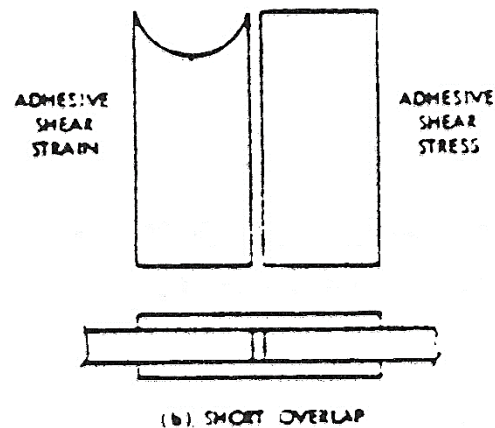
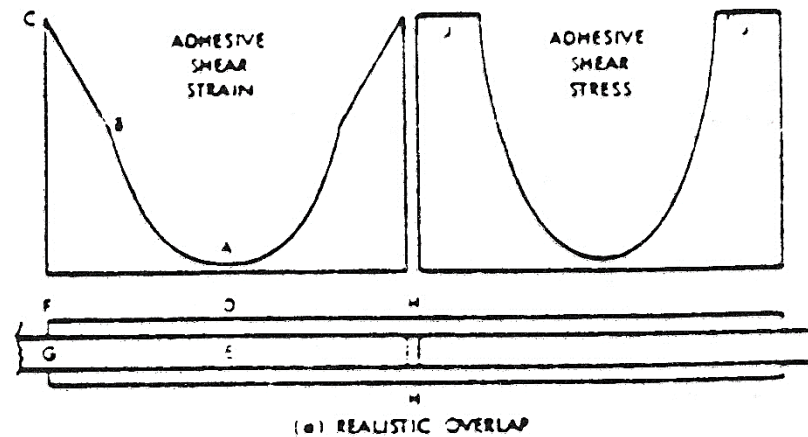
DISPLACEMENTS AND FORCES

Design of Double-Lap Bonded Joints

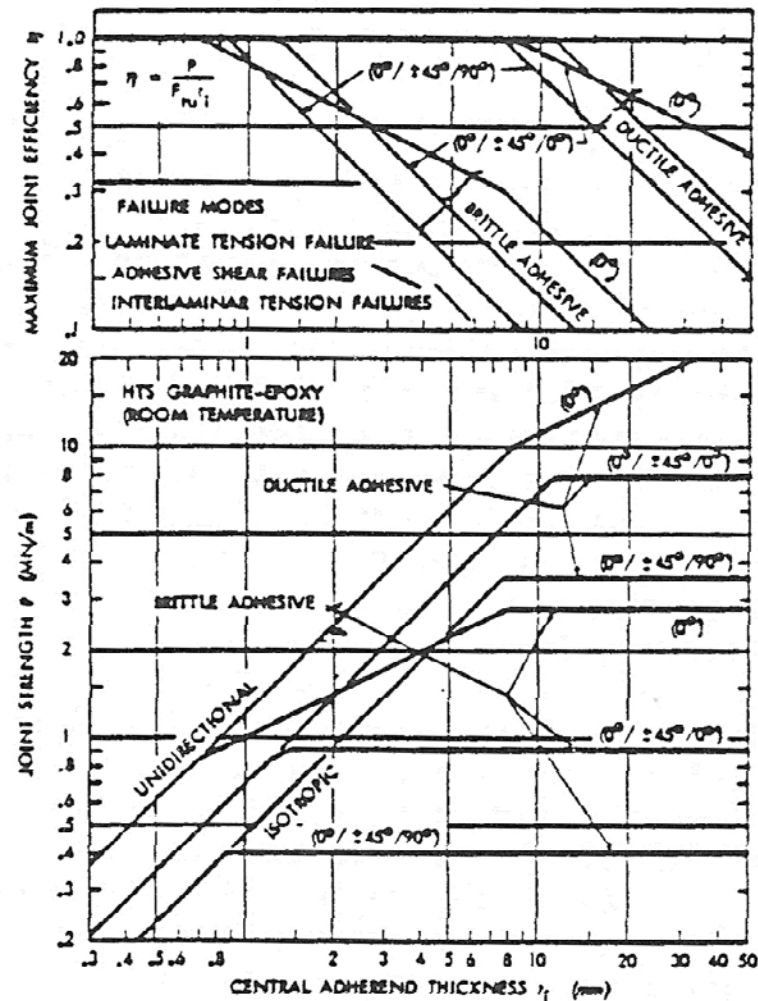


- PLASTIC ZONES LONG ENOUGH FOR ULTIMATE LOAD
- ELASTIC TROUGH WIDE ENOUGH TO PREVENT CREEP AT MIDDLE
- CHECK FOR ADEQUATE STRENGTH

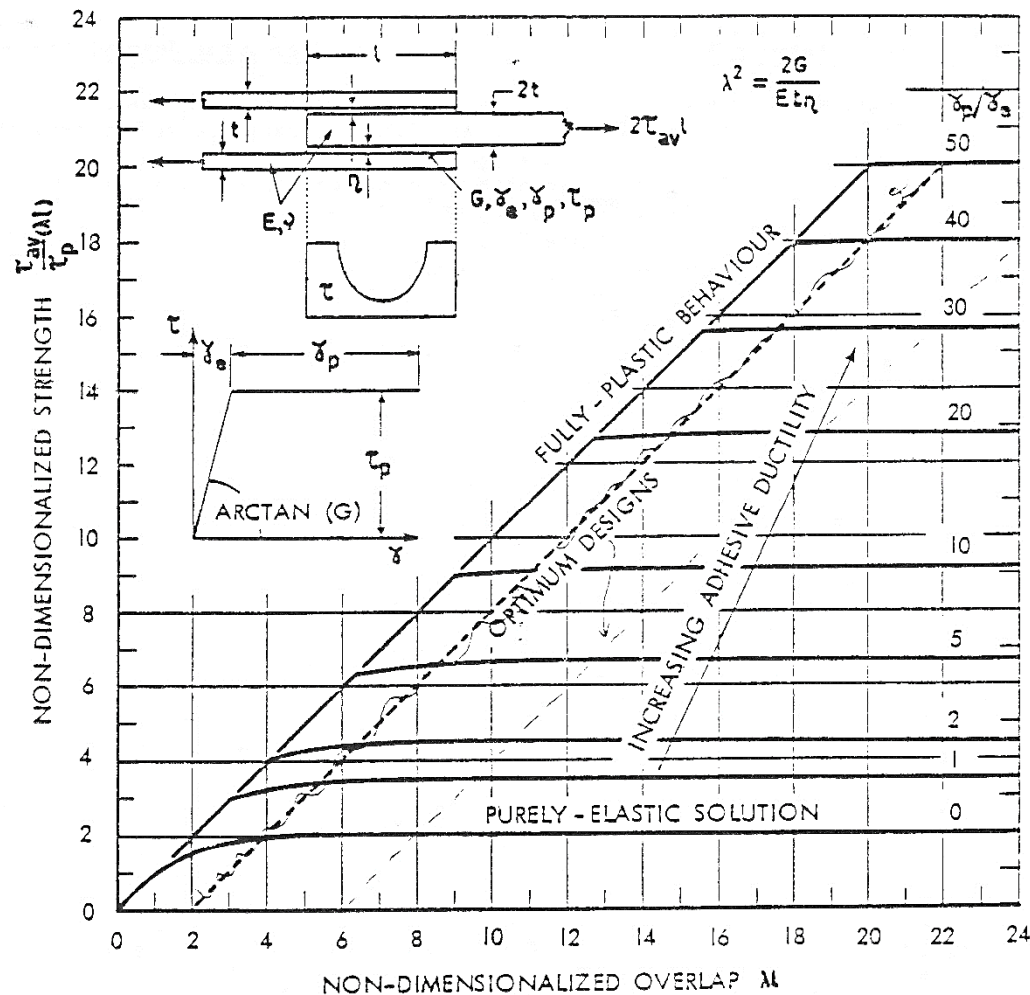
Non-Uniform Stresses and Strains in Bonded Joints



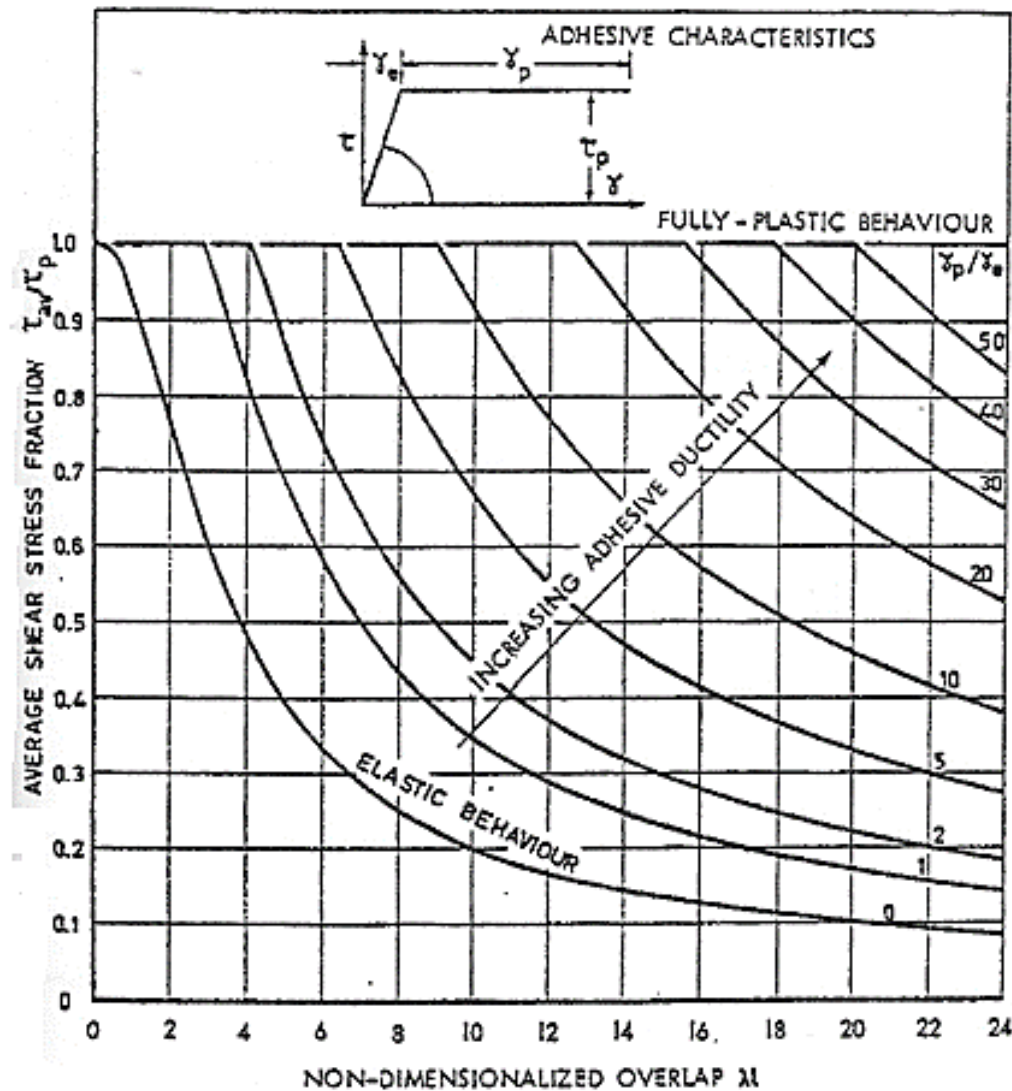
Maximum Efficiency and Joint Strengths for Graphite-Epoxy Double-Lap Joints



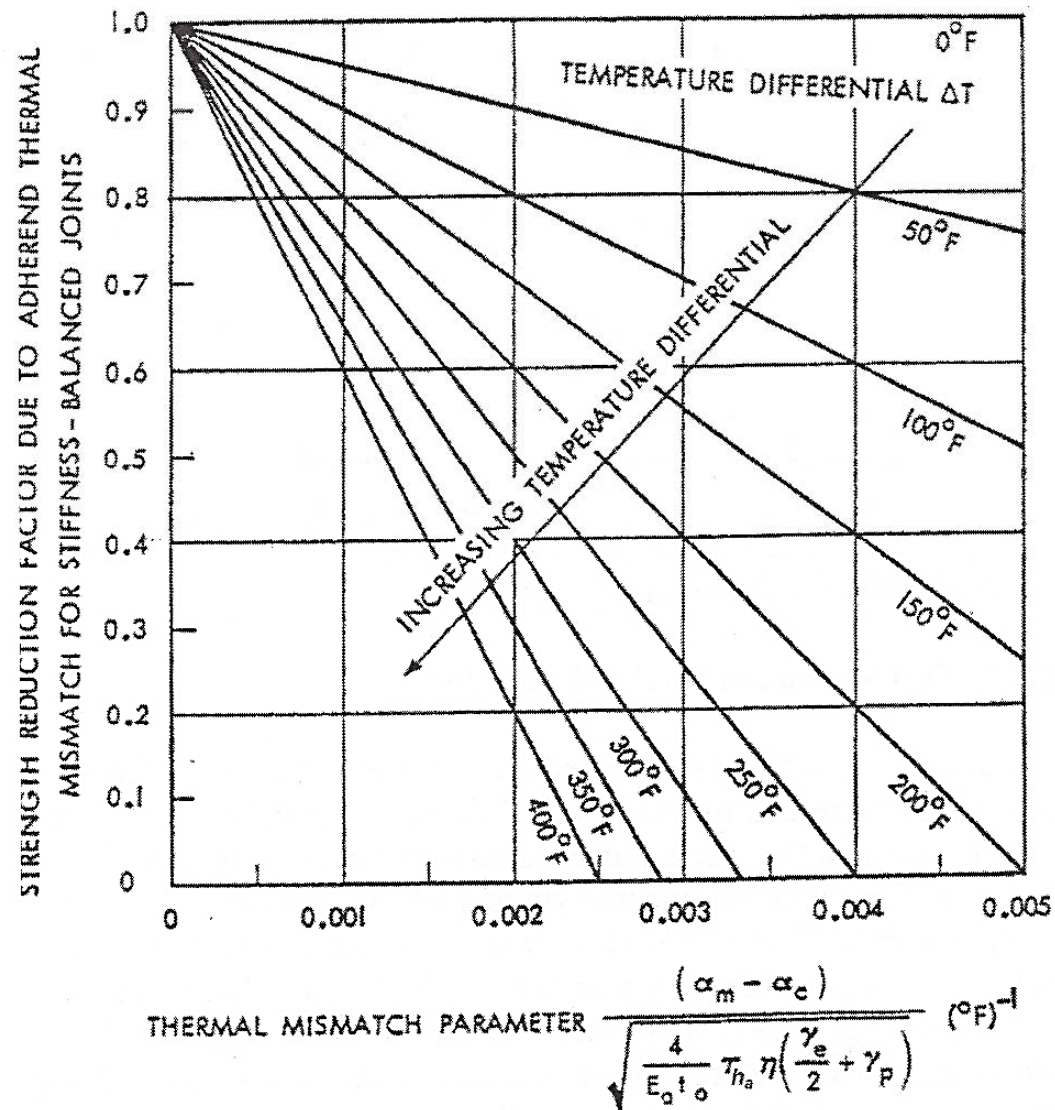
Shear Strength of Double-Lap Bonded Joints



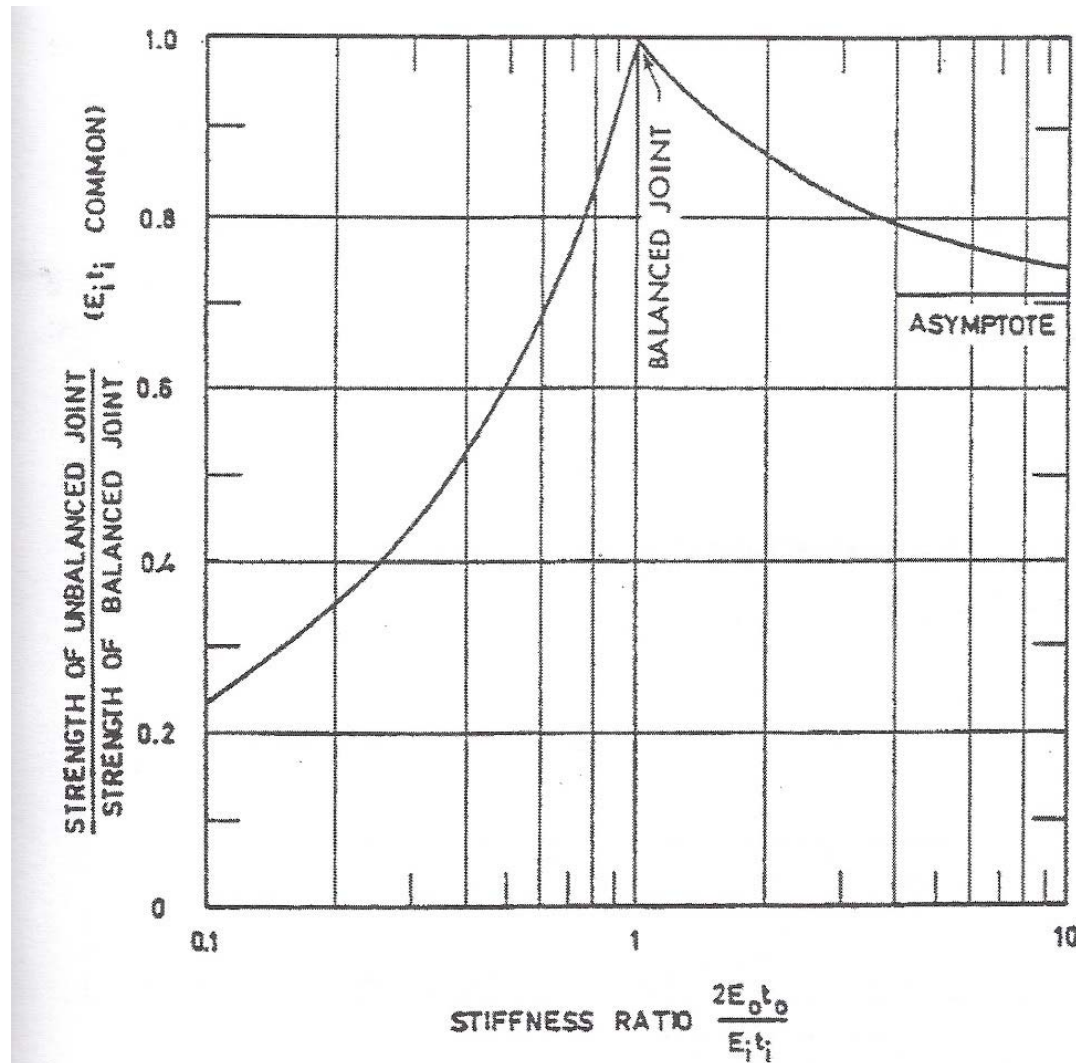
Double Lap Joint Average Shear Stresses



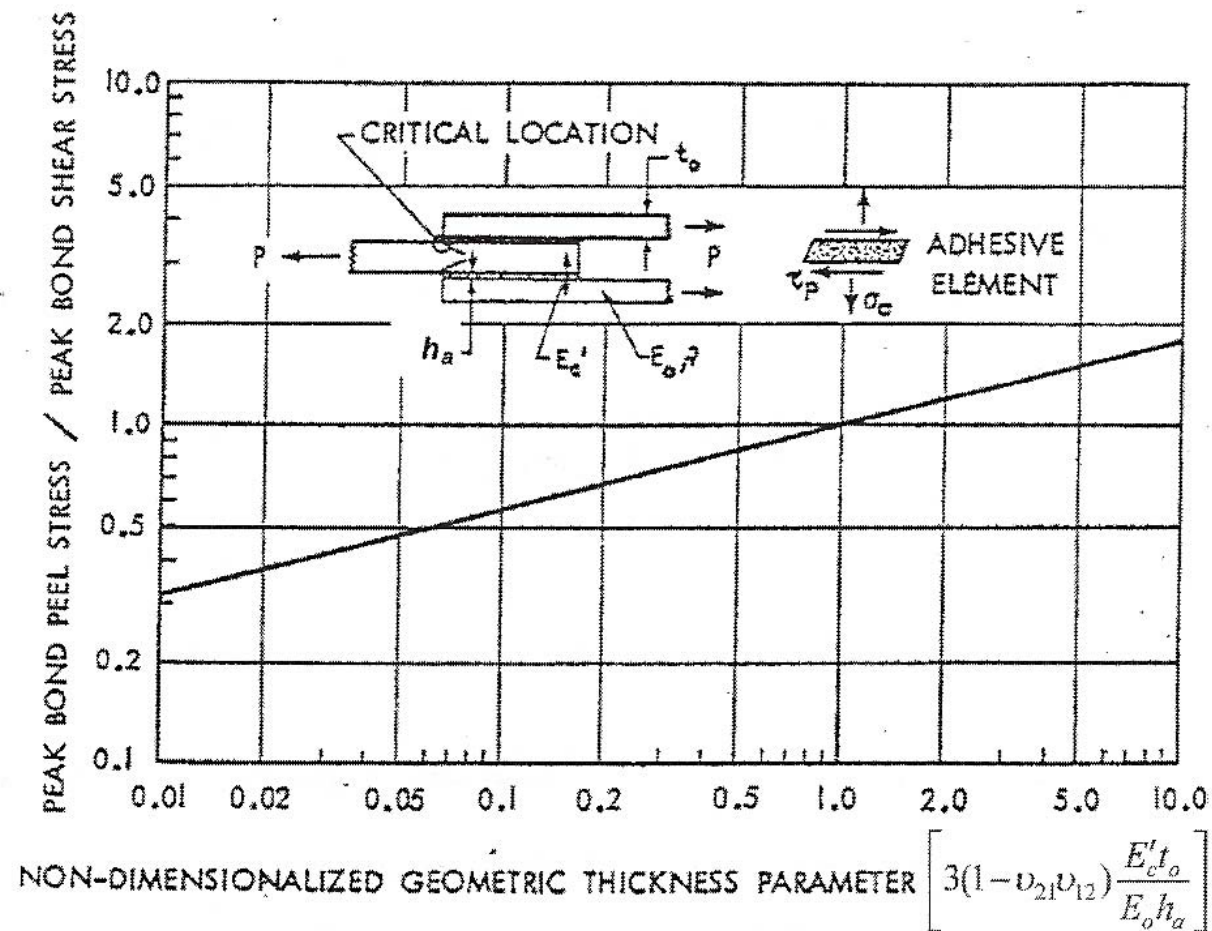
Strength Reduction Factor in Double Lap Bonded Joints with Adherend Thermal Mismatch



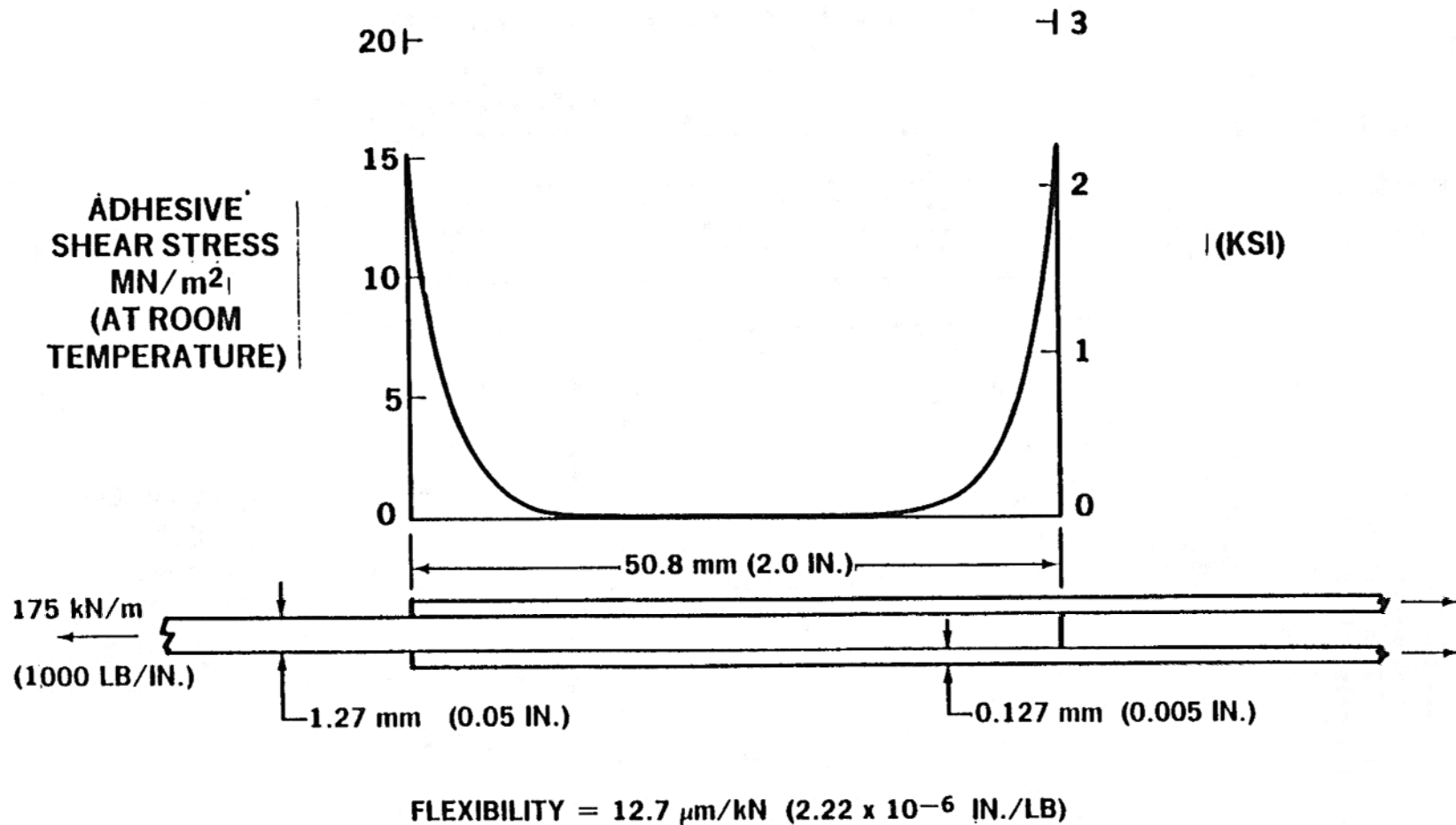
Strength Reduction in Bonded Joints Due to Adherend Stiffness Imbalance



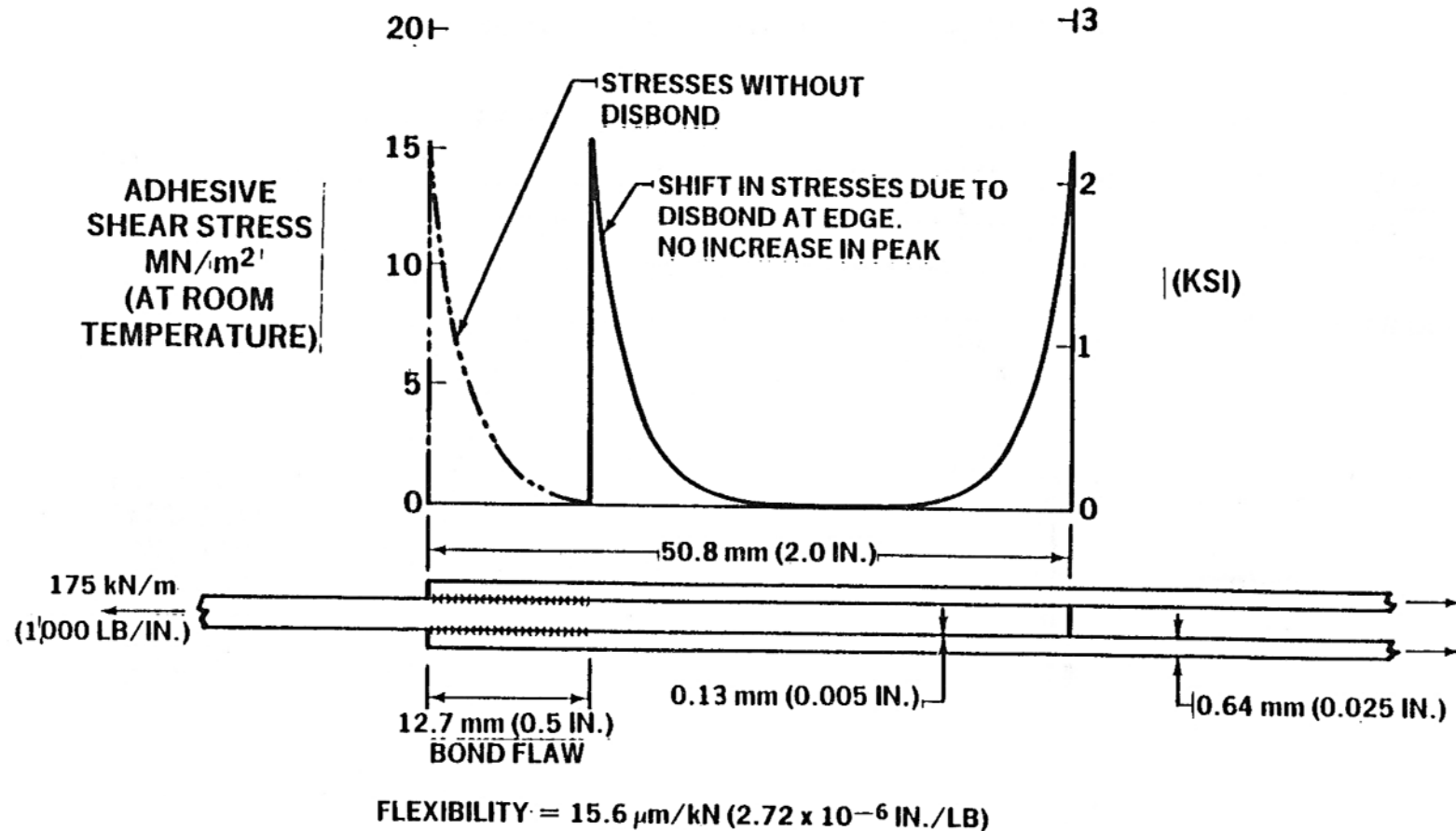
Non-Dimensional Elastic Peel Stresses in Double-Lap Adhesively Bonded Joints



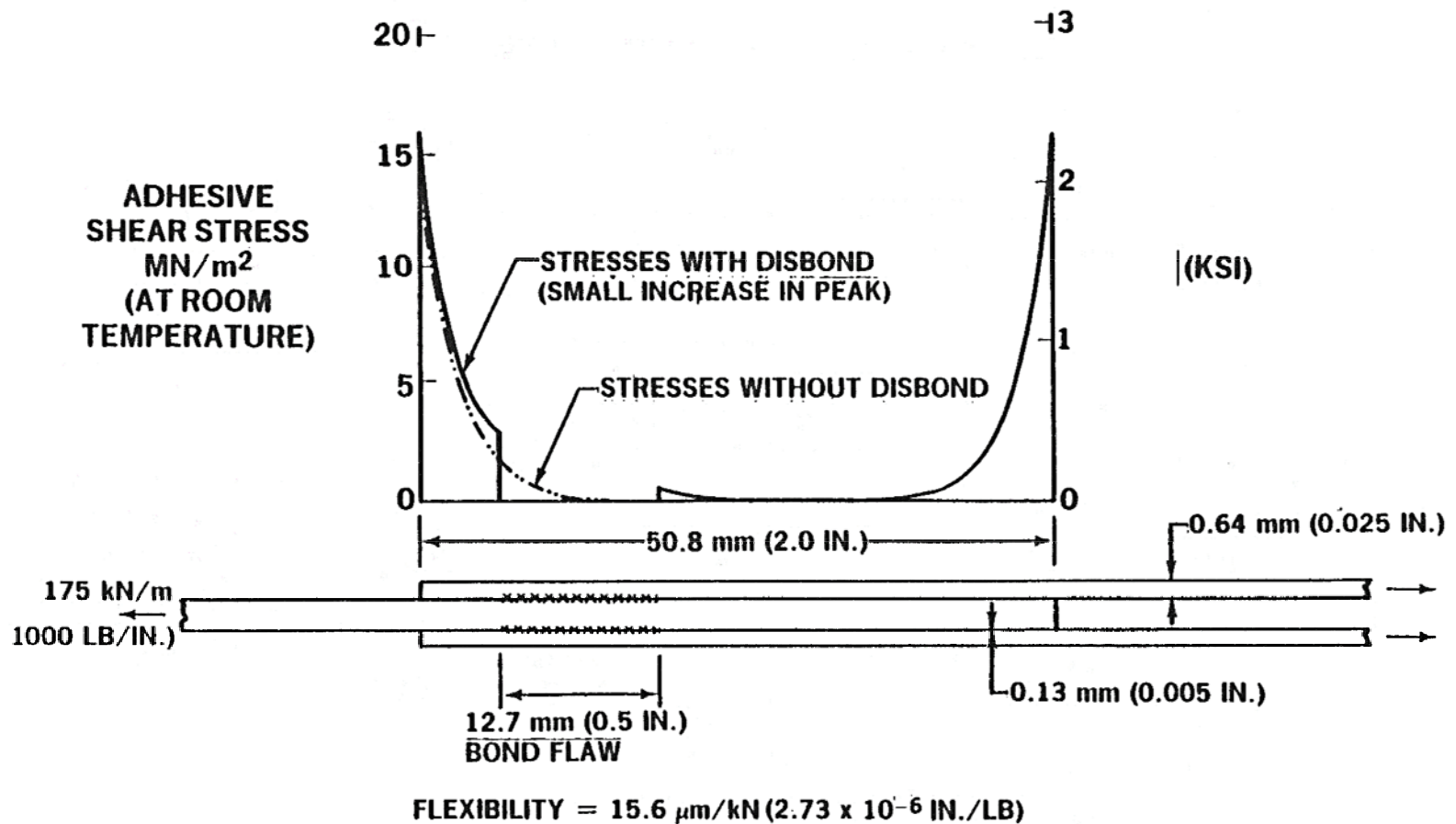
Adhesive Shear Stresses in Bonded Joints



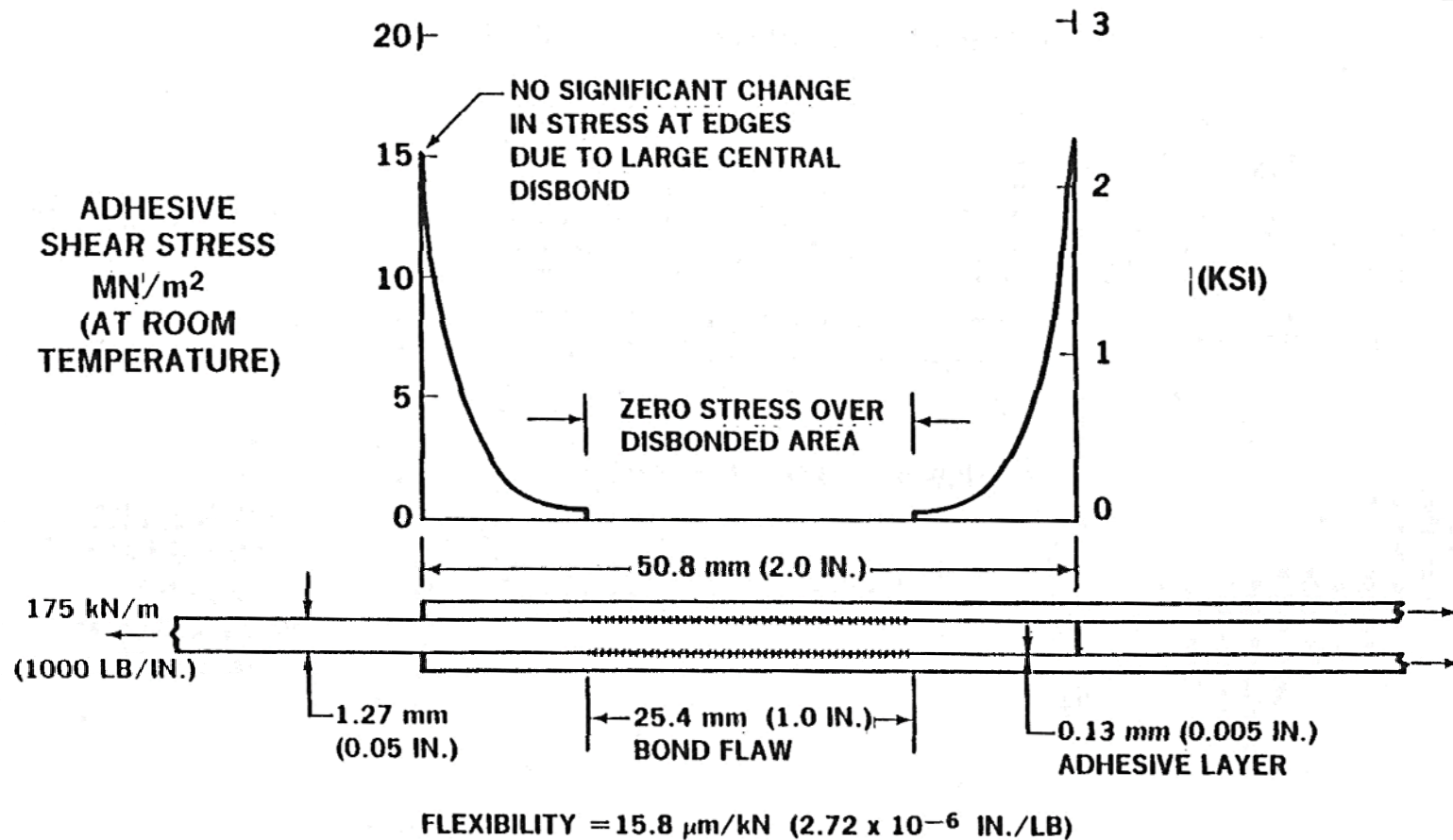
Adhesive Stresses in Flawed Bonded Joints (Without Disbond)



Adhesive Stresses in Flawed Bonded Joints (with Disbond)



Adhesive Stresses in Flawed Bonded Joints (Large Central Disbond)



SCARF JOINT



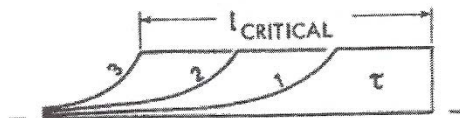
SCARF JOINT BETWEEN DISSIMILAR MATERIALS ($\alpha_1 > \alpha_2$, $E_1 t_1 = E_2 t_2$)



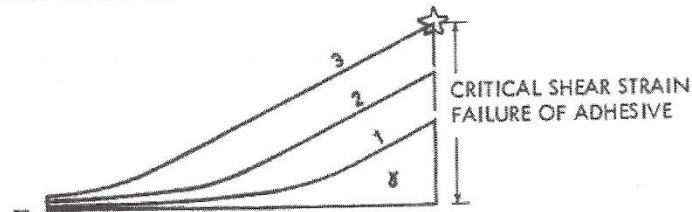
RESIDUAL ADHESIVE SHEAR STRESS



RESIDUAL ADHESIVE SHEAR STRAIN

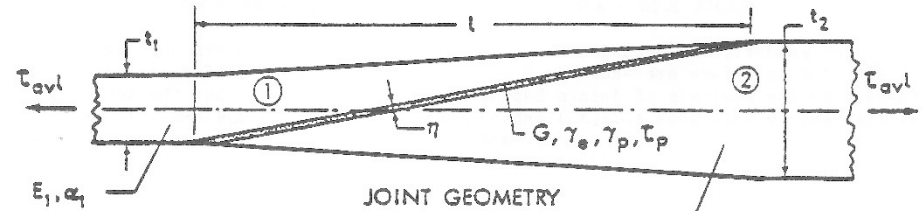


ADHESIVE SHEAR STRESSES
UNDER PROGRESSIVELY INCREASING TENSILE LOADS

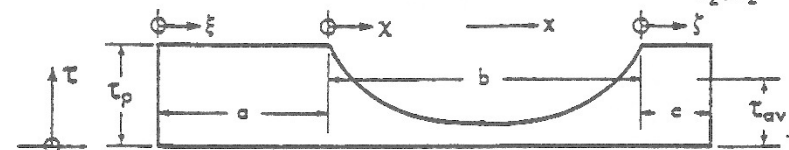


CORRESPONDING ADHESIVE SHEAR STRAINS

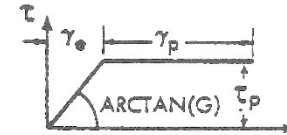
CRITICAL SHEAR STRAIN
FAILURE OF ADHESIVE



JOINT GEOMETRY



ADHESIVE BEHAVIOUR



ADHESIVE SHEAR CHARACTERISTIC

$$(\lambda l)^2 = \frac{G}{\eta} \left(\frac{1}{E_1 t_1} + \frac{1}{E_2 t_2} \right) l^2$$

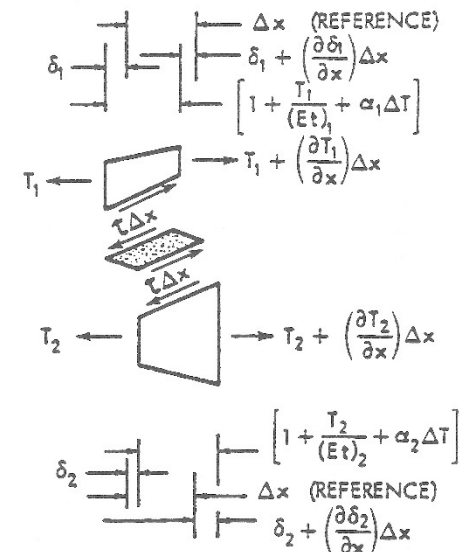
$$ETR(1) = E_1 t_1 / E_2 t_2$$

$$ETR(2) = E_2 t_2 / E_1 t_1$$

$$CTHERM(1) = \frac{(\alpha_2 - \alpha_1) \Delta T \lambda}{\tau_p \left(\frac{1}{E_1 t_1} + \frac{1}{E_2 t_2} \right)}$$

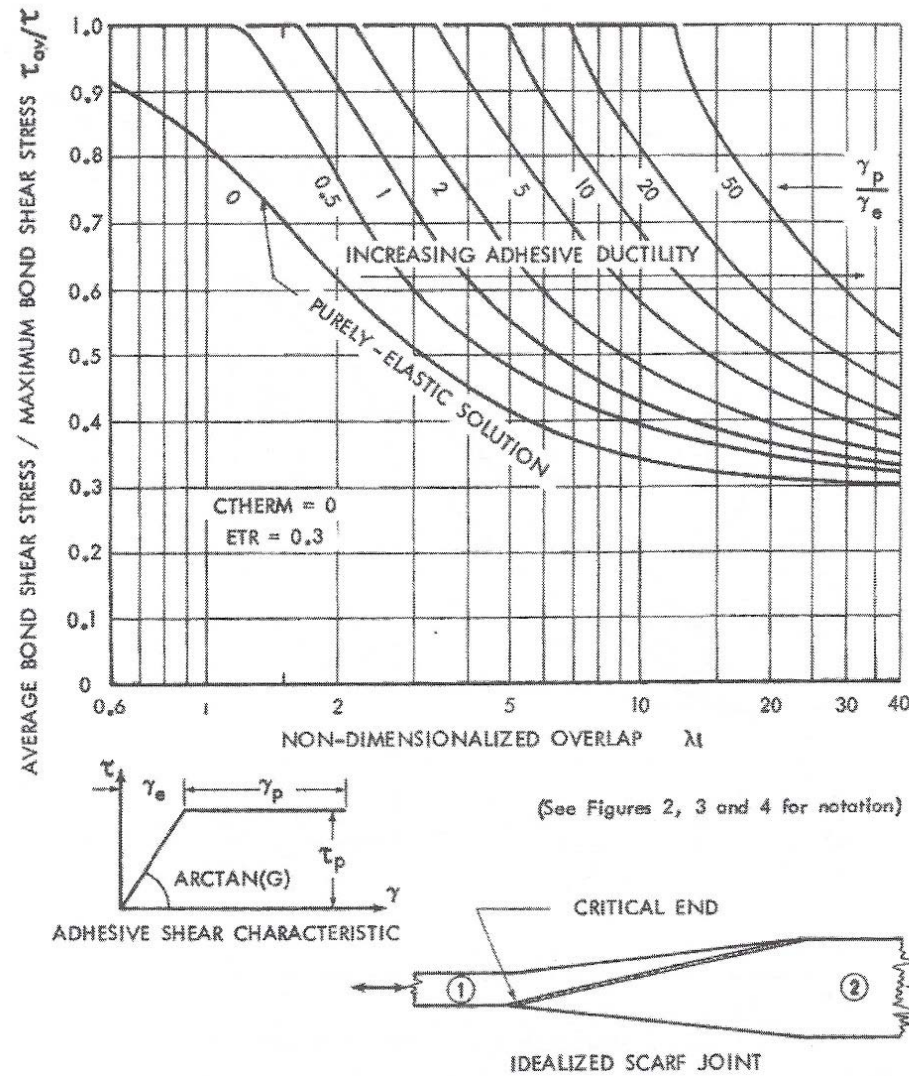
$$CTHERM(2) = \frac{(\alpha_1 - \alpha_2) \Delta T \lambda}{\tau_p \left(\frac{1}{E_1 t_1} + \frac{1}{E_2 t_2} \right)}$$

NON-DIMENSIONALIZED
JOINT PARAMETERS

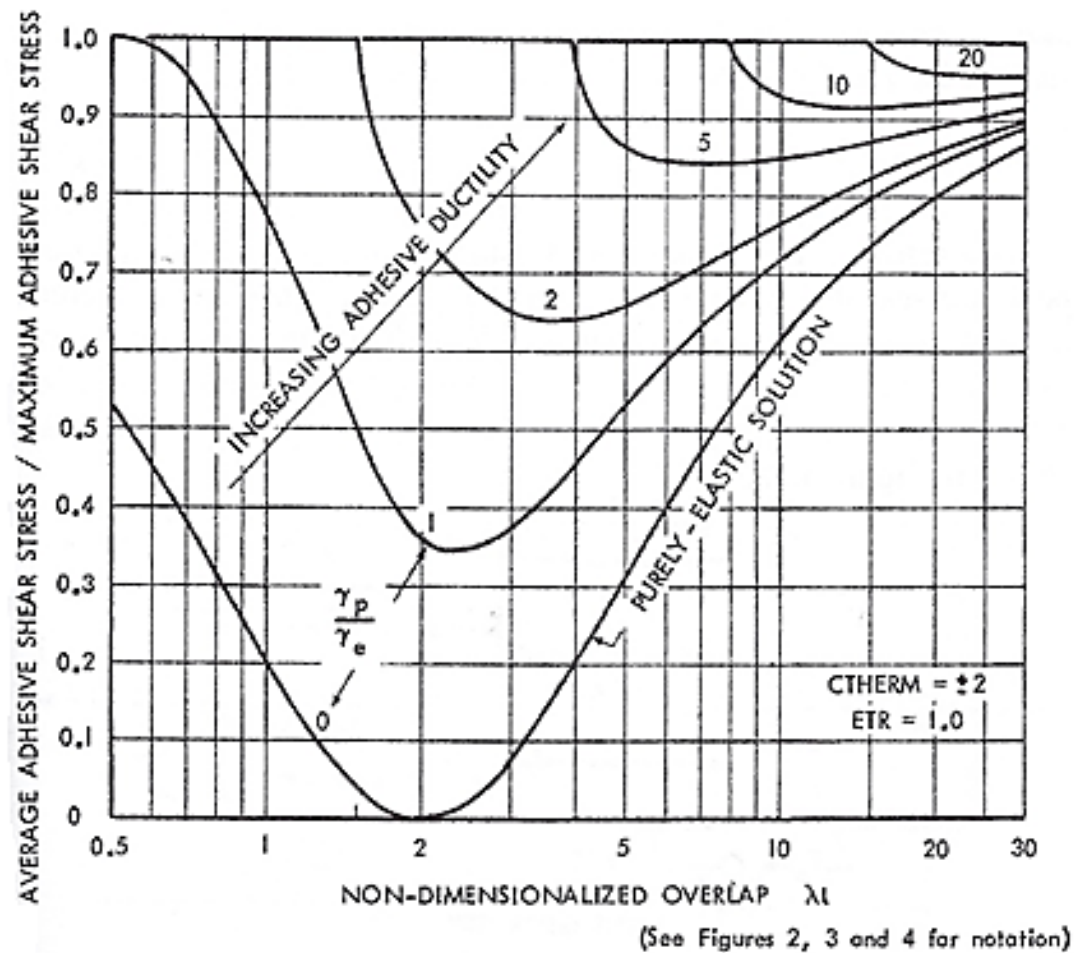


DISPLACEMENTS AND ELEMENT LOADS

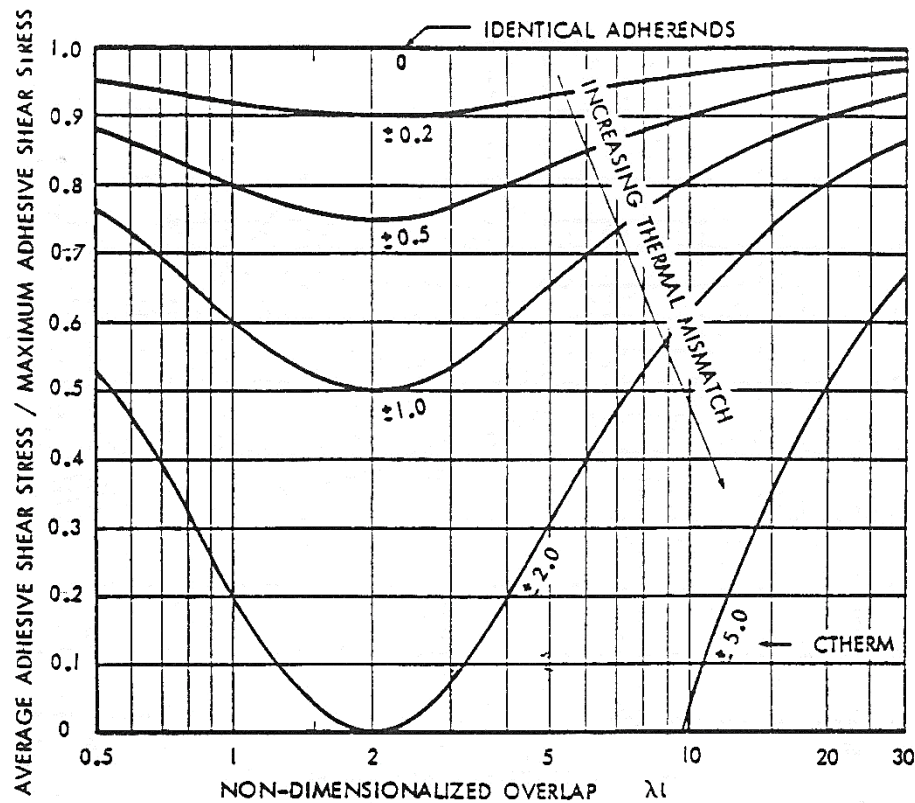
Effect of Adhesive Plasticity with Stiffness Imbalance in Scarf Joints



Effect of Adhesive Plasticity with Thermal Mismatch in Scarf Joints



Effect of Adherend Thermal Mismatch on Elastic Strength of Bonded Scarf Joints



$$\lambda^2 = \frac{G}{\eta} \left[\frac{1}{E_1 t_1} + \frac{1}{E_2 t_2} \right]$$

$$CTHERM = \frac{(\alpha_2 - \alpha_1) \Delta T \lambda}{\tau_p \left(\frac{1}{E_1 t_1} + \frac{1}{E_2 t_2} \right)}, \quad \Delta T = T_{\text{operating}} - T_{\text{stress free}}$$

LOCATION A CRITICAL FOR $CTHERM < 0$ AND $P > 0$
 LOCATION A CRITICAL FOR $CTHERM > 0$ AND $P < 0$
 LOCATION B CRITICAL FOR $CTHERM < 0$ AND $P < 0$
 LOCATION B CRITICAL FOR $CTHERM > 0$ AND $P > 0$

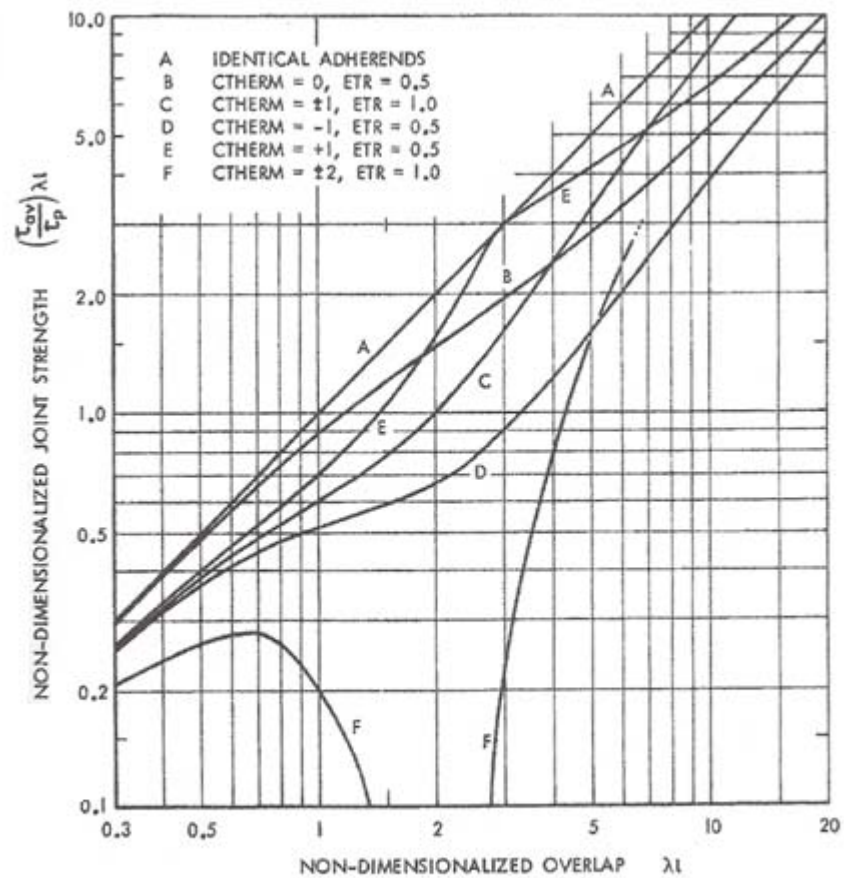
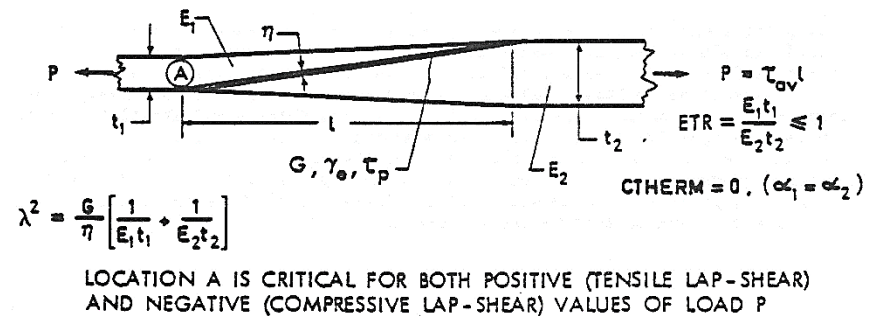
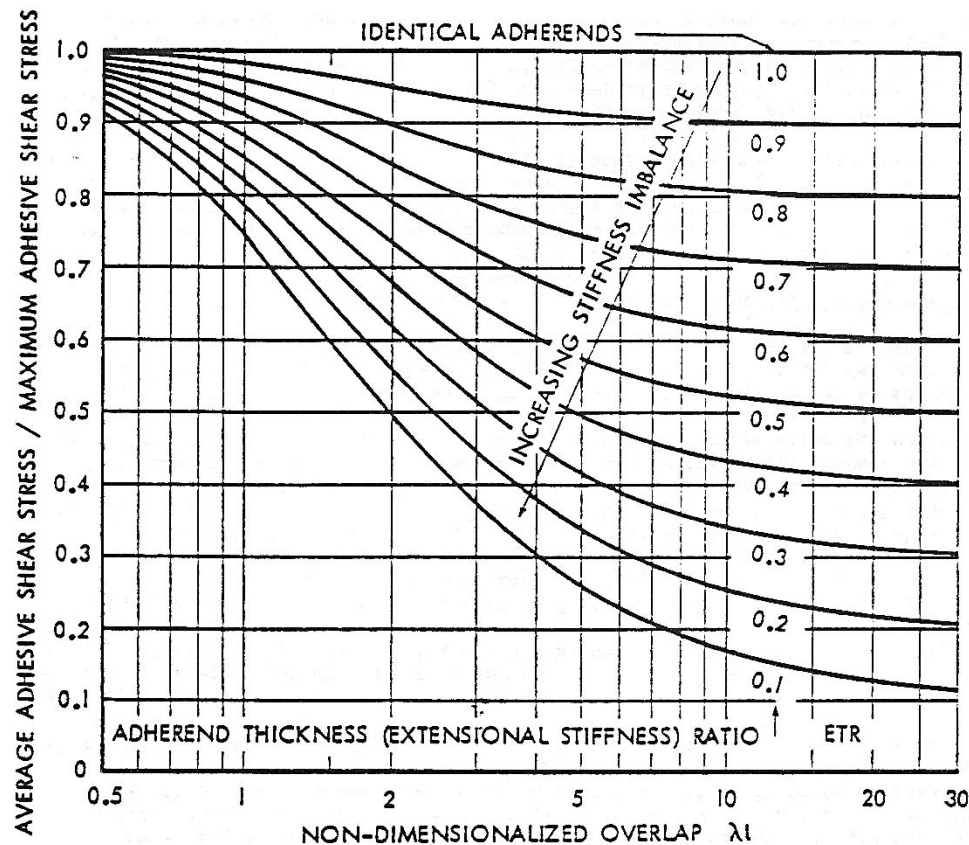
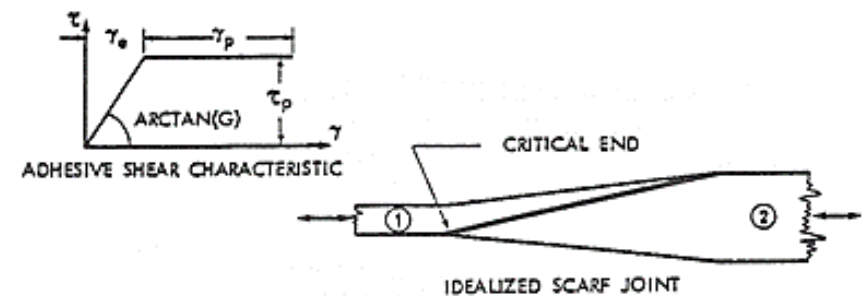
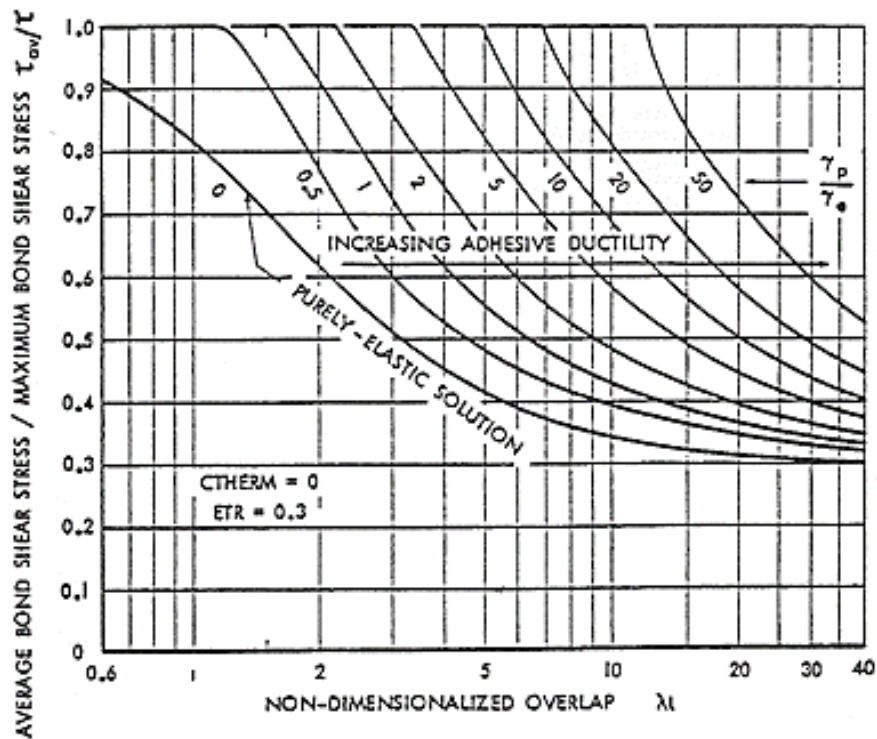


FIGURE 5.48. Scarf Joint Interaction of Stiffness Imbalance and Thermal Mismatch—Elastic Strength (Courtesy L.J. Hart-Smith, NASA CR-112237).

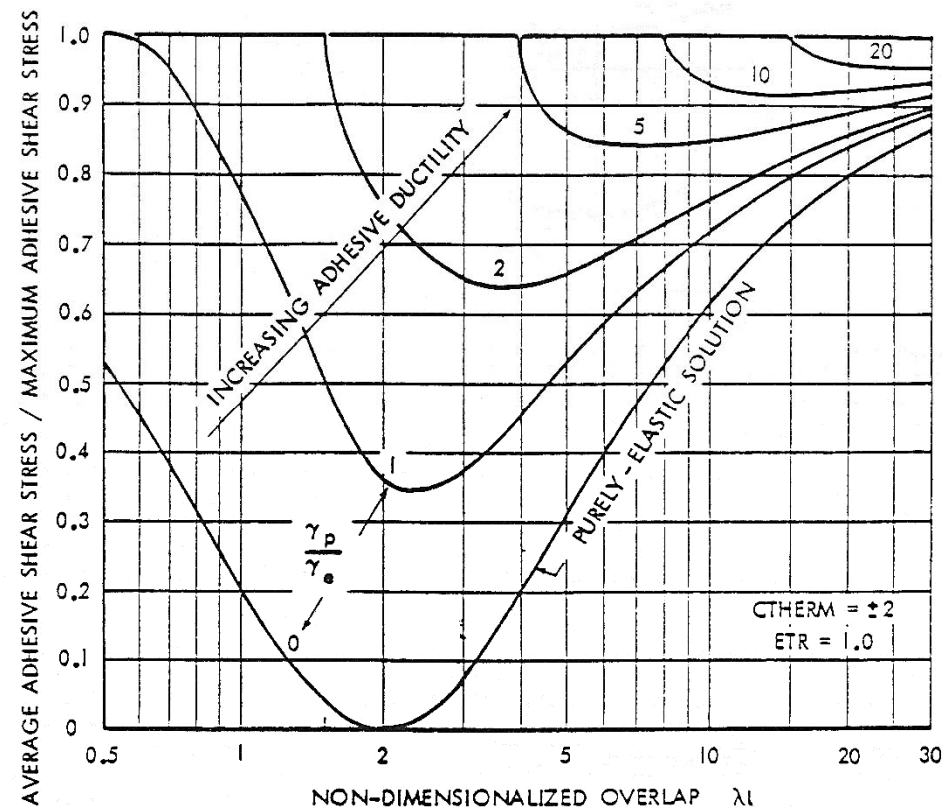
Effect of Adherend Stiffness Imbalance on Elastic Strength of Bonded Scarf Joints



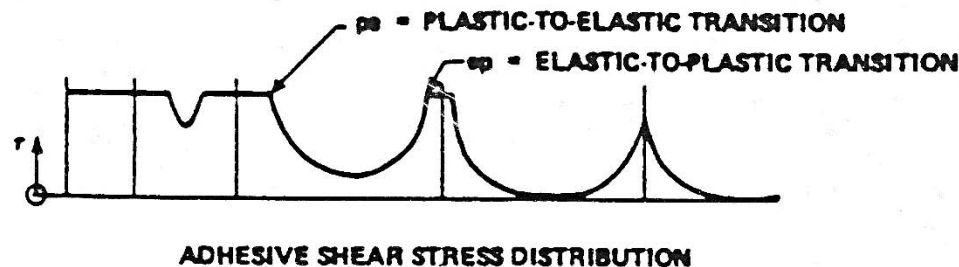
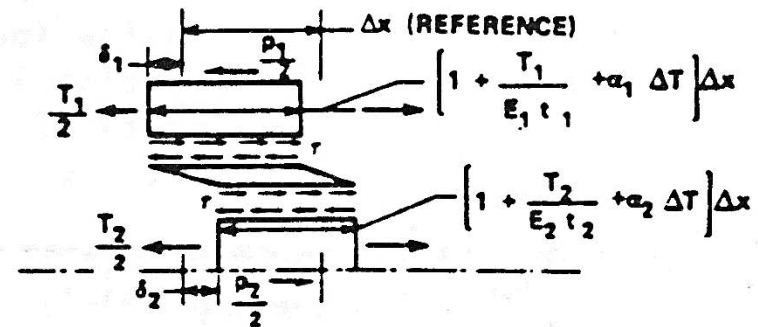
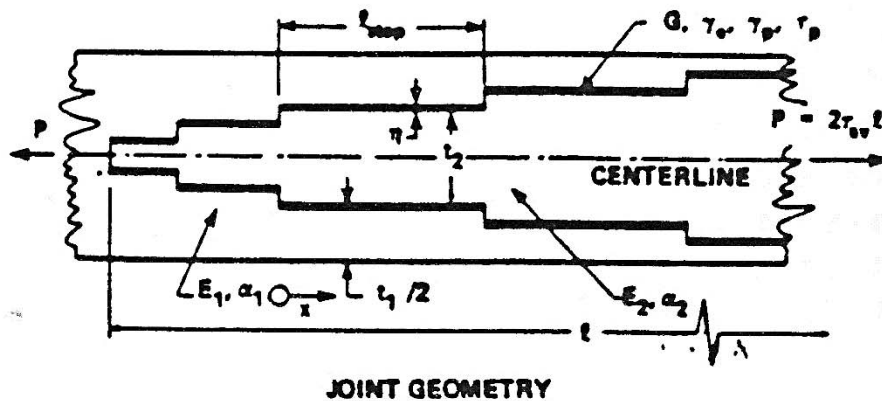
Effect of Adhesive Plascity in Reducing Strength Loss Due to Adherend Stiffness Imbalance for Bonded Scarf Joints



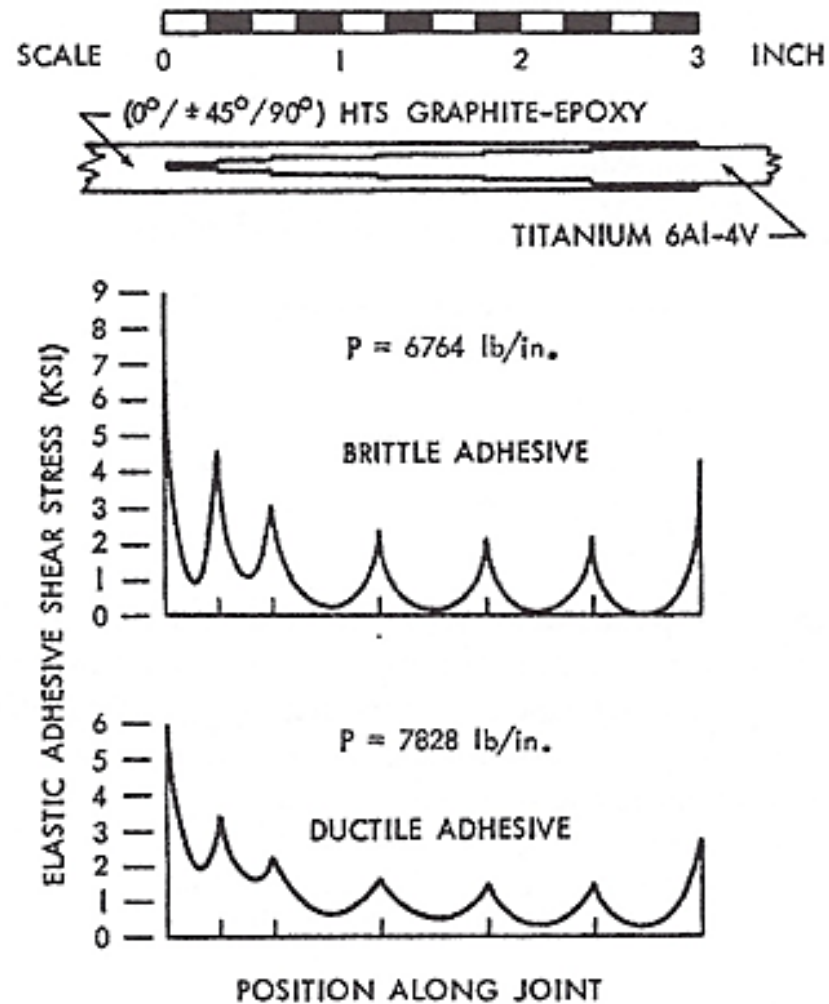
Effect of Adhesive Plasticity in Reducing Strength Loss Due to Adherend Thermal Mismatch for Bonded Scarf Joints



Notation and Geometry for Adhesive-Bonded Stepped-Lap Joint Analysis

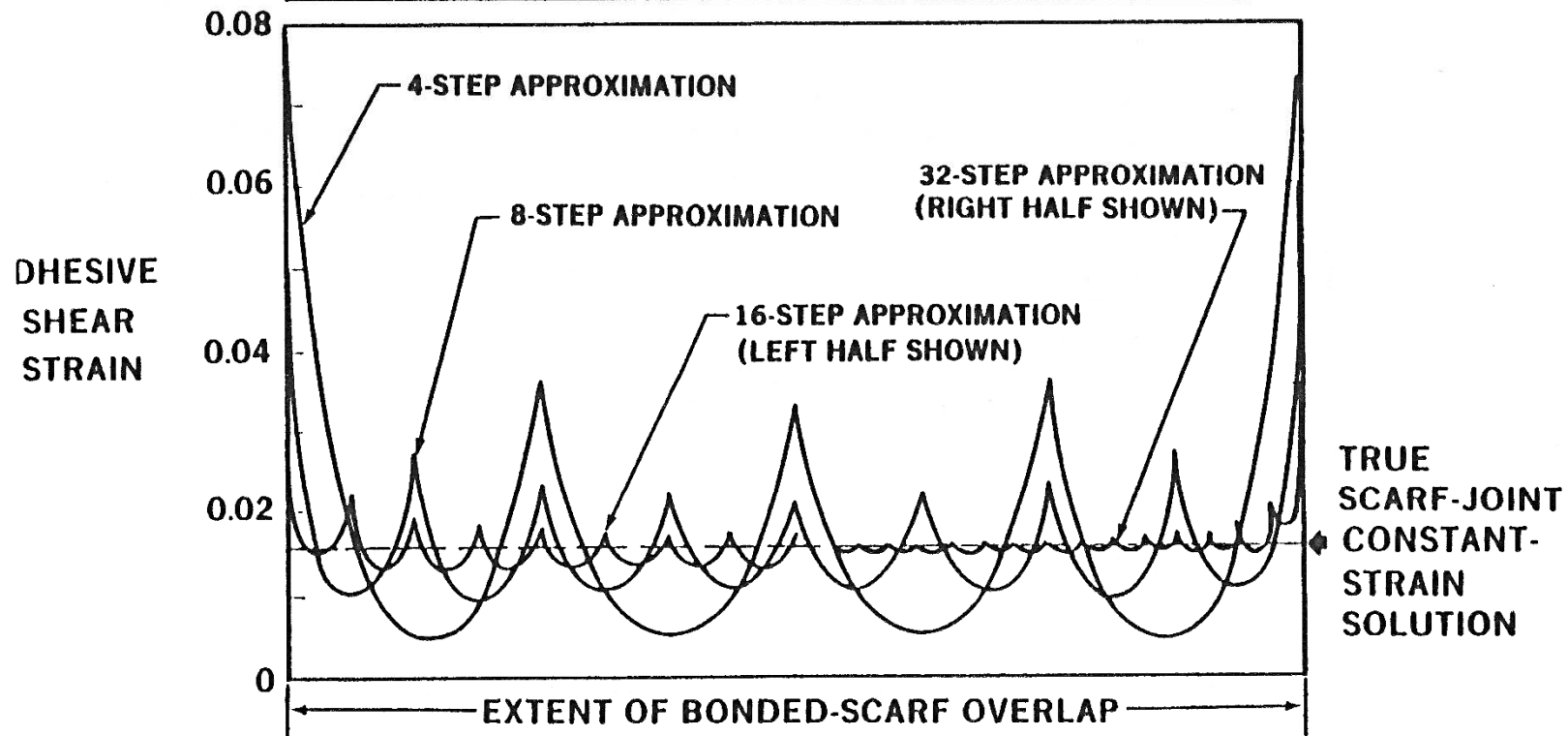


Elastic Shear Stress Distribution



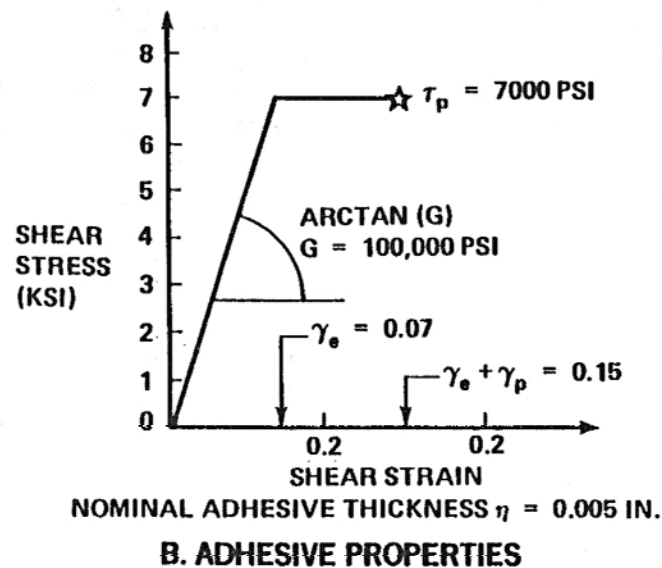
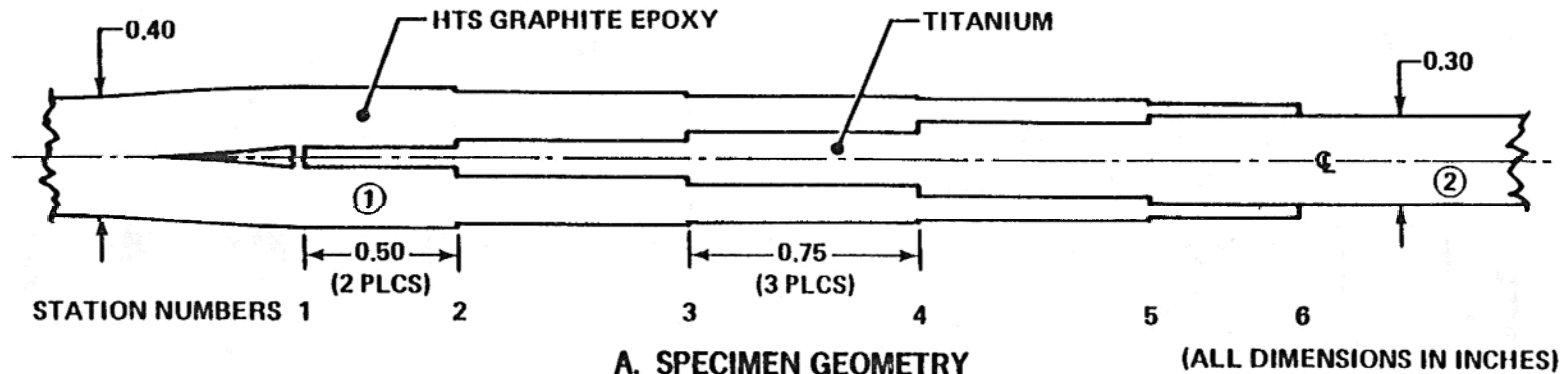
Influence of Precision of Modeling on Analysis of Scarf Joint

STEPS IN APPROXIMATION	4	8	16	32
PEAK SHEAR STRAIN COMPUTED	0.079	0.060	0.045	0.035
ACTUAL SHEAR STRAIN, UNIFORM THROUGHOUT	0.0156			



NOTE: BEST ANSWERS FOR A GIVEN TOTAL NUMBER OF STEPS ARE ACHIEVED WITH A VERY FINE GRID NEAR THE ENDS AND A COARSER GRID IN THE INTERIOR

Typical Stepped-Lap Adhesive-Bonded Joint

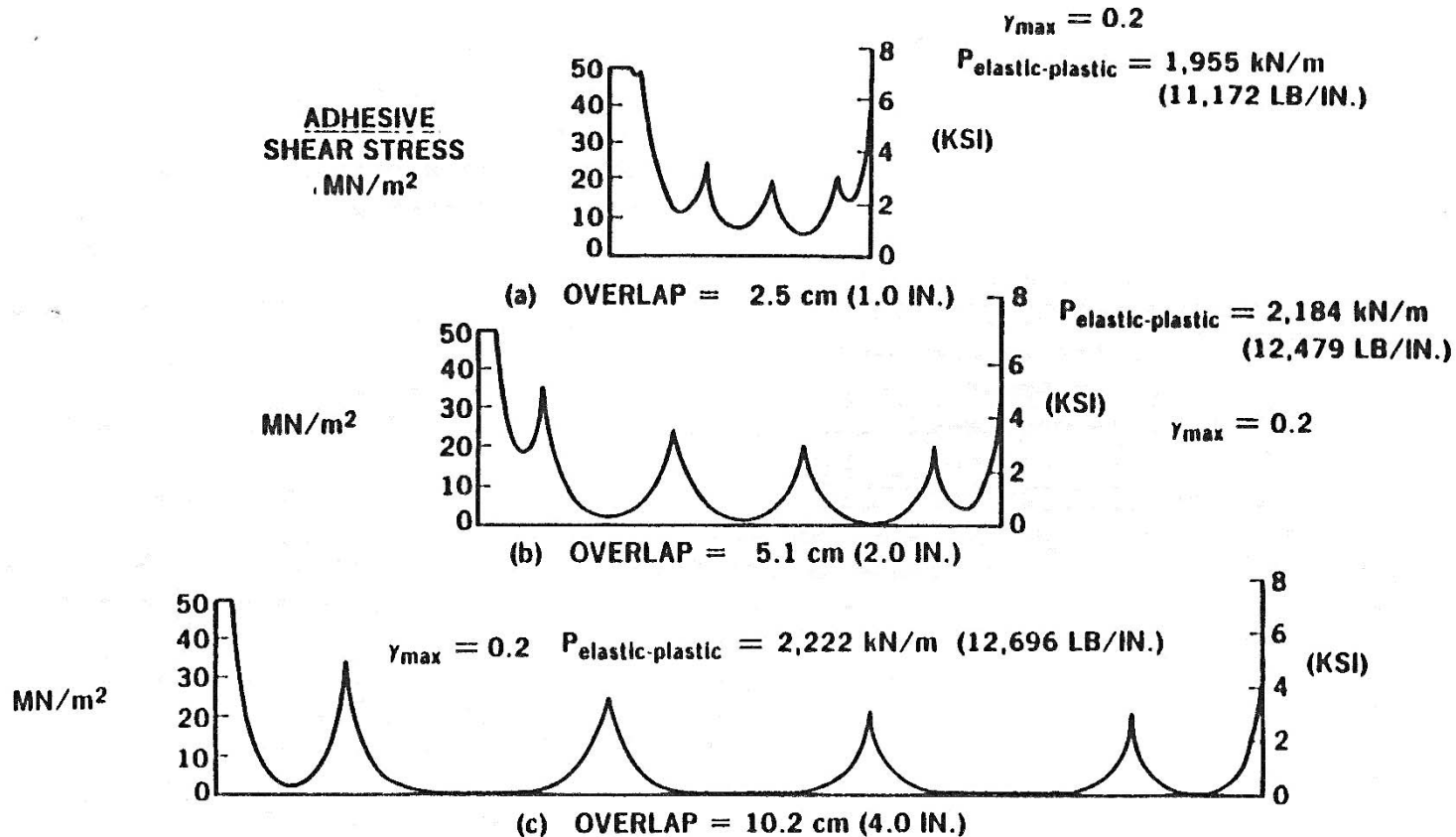


ADHERENDS "1"
MATERIAL: TITANIUM
 $E = 12 \times 10^6$ PSI
 $F_{tu} = 120$ KSI
 $\alpha = 0$

ADHERENDS "2"
MATERIAL: TITANIUM
 $E = 16 \times 10^6$ PSI
 $F_{tu} = 130$ KSI
 $\alpha = 0.000006/^{\circ}\text{F}$

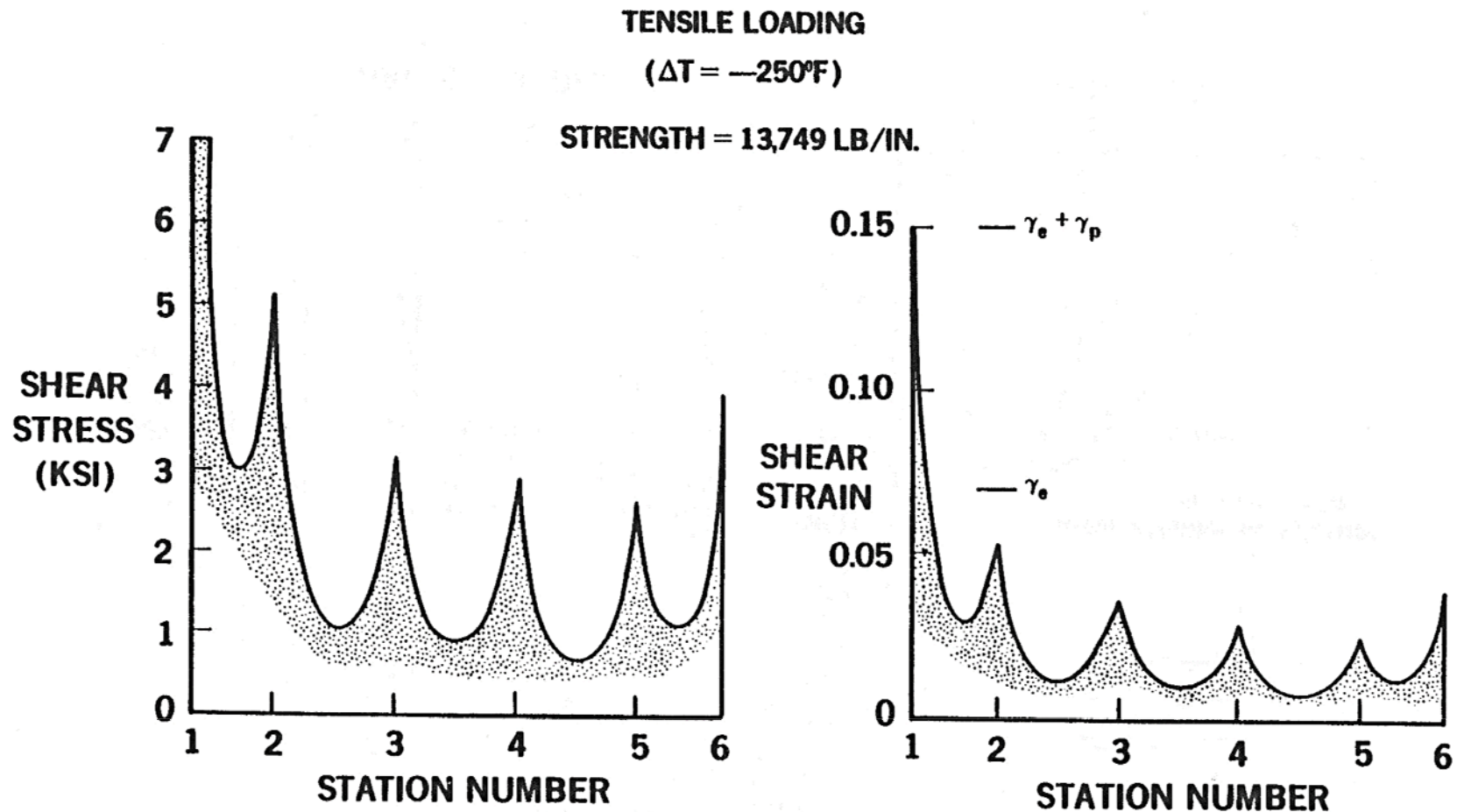
C. ADHEREND PROPERTIES

Limited Effect of Overlap on Strength on Strength of Stepped-Lap Bonded Joints

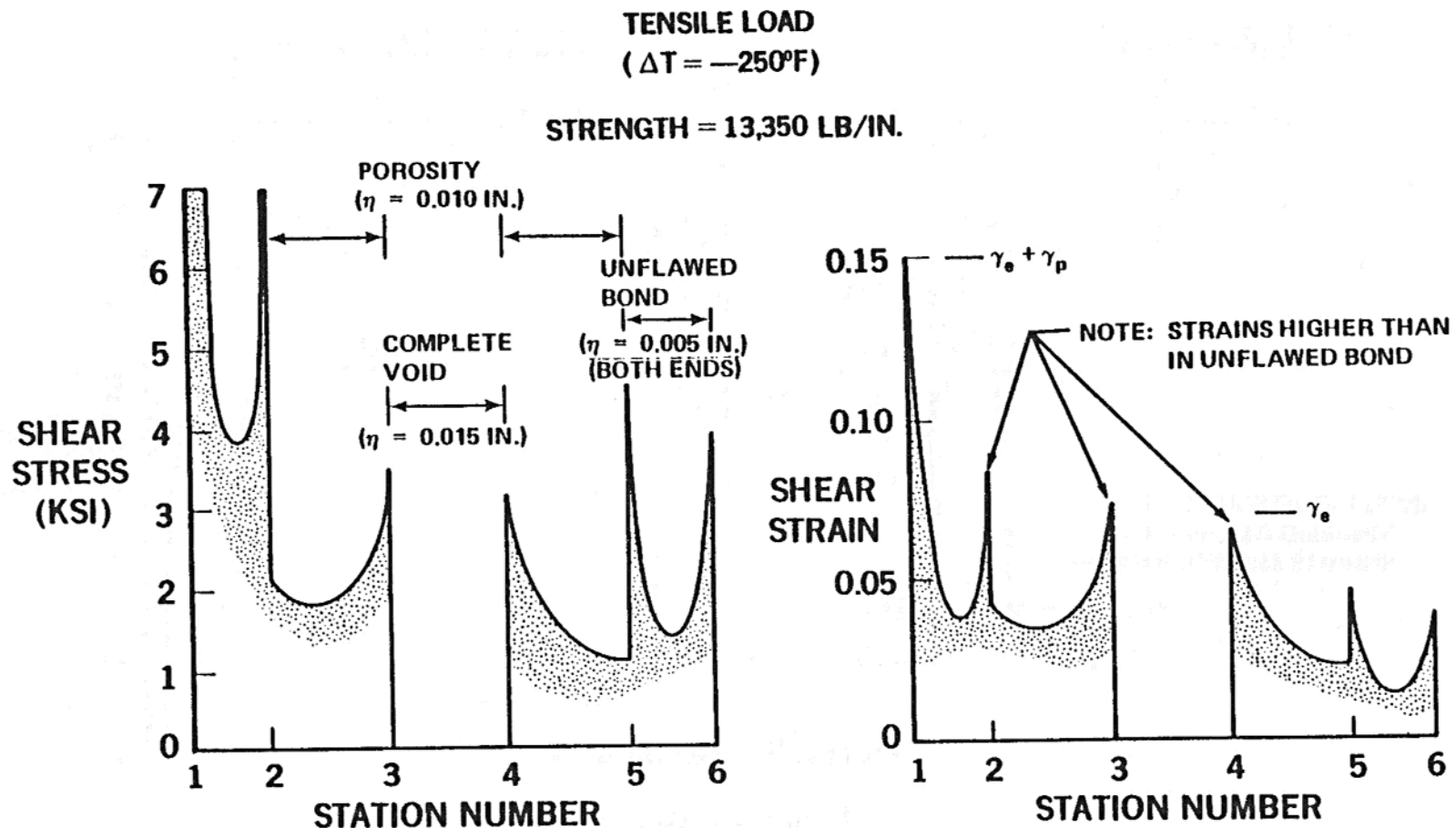


Note: All Cross Sections Identical and all Step Lengths Proportional

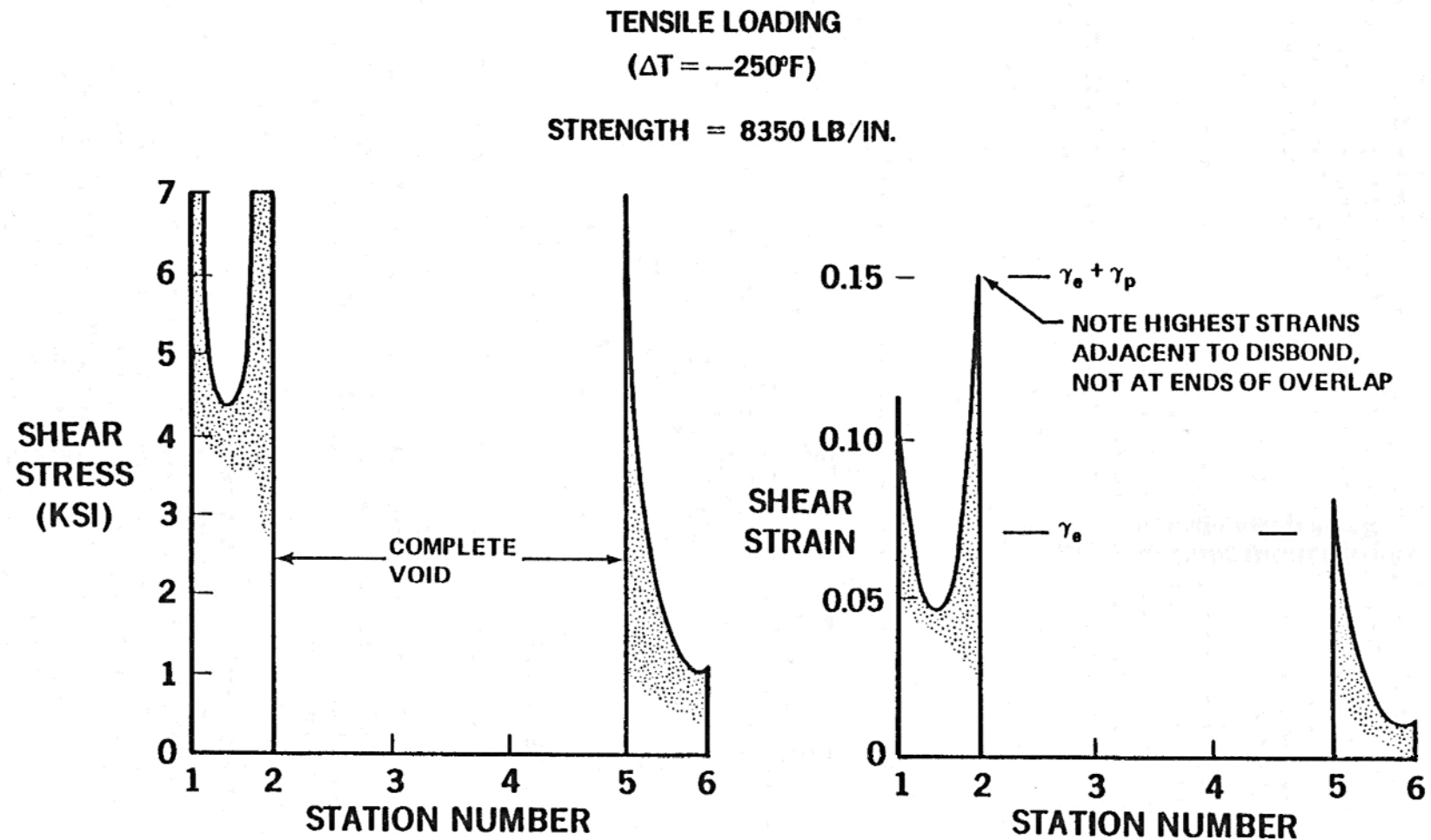
Adhesive Shear Stresses and Strains in Unflawed Joint



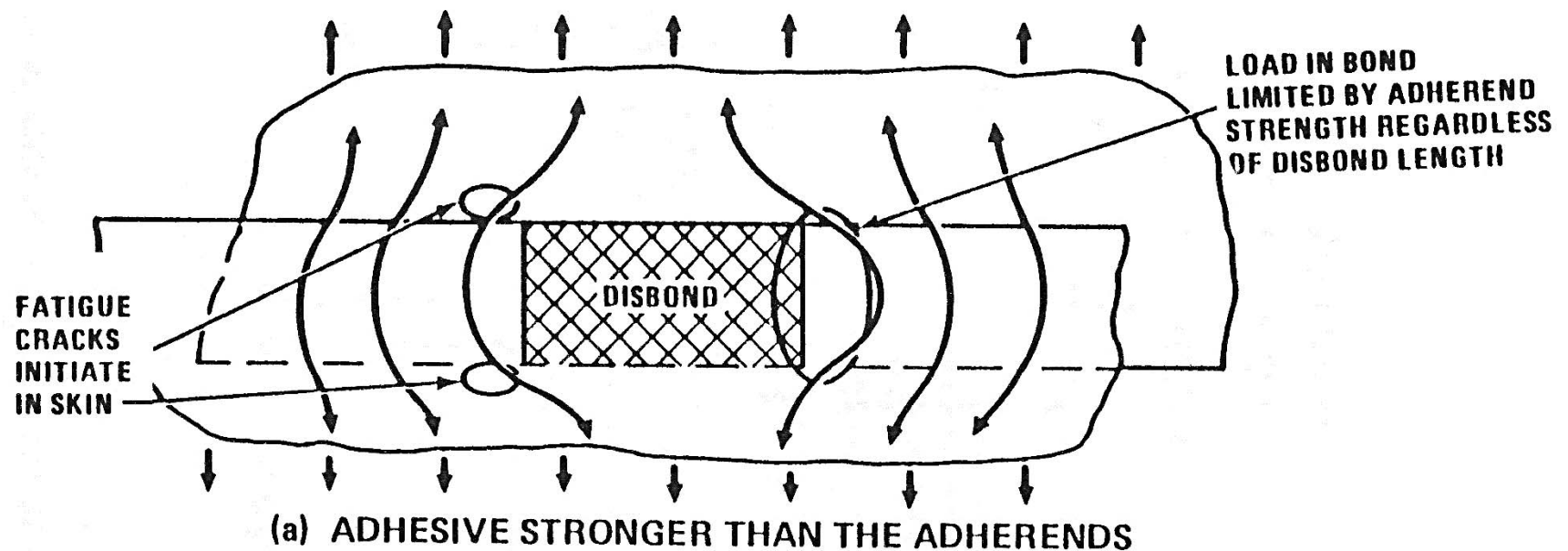
Shear Stresses and Strains in Flawed, Porous Bonded Joint



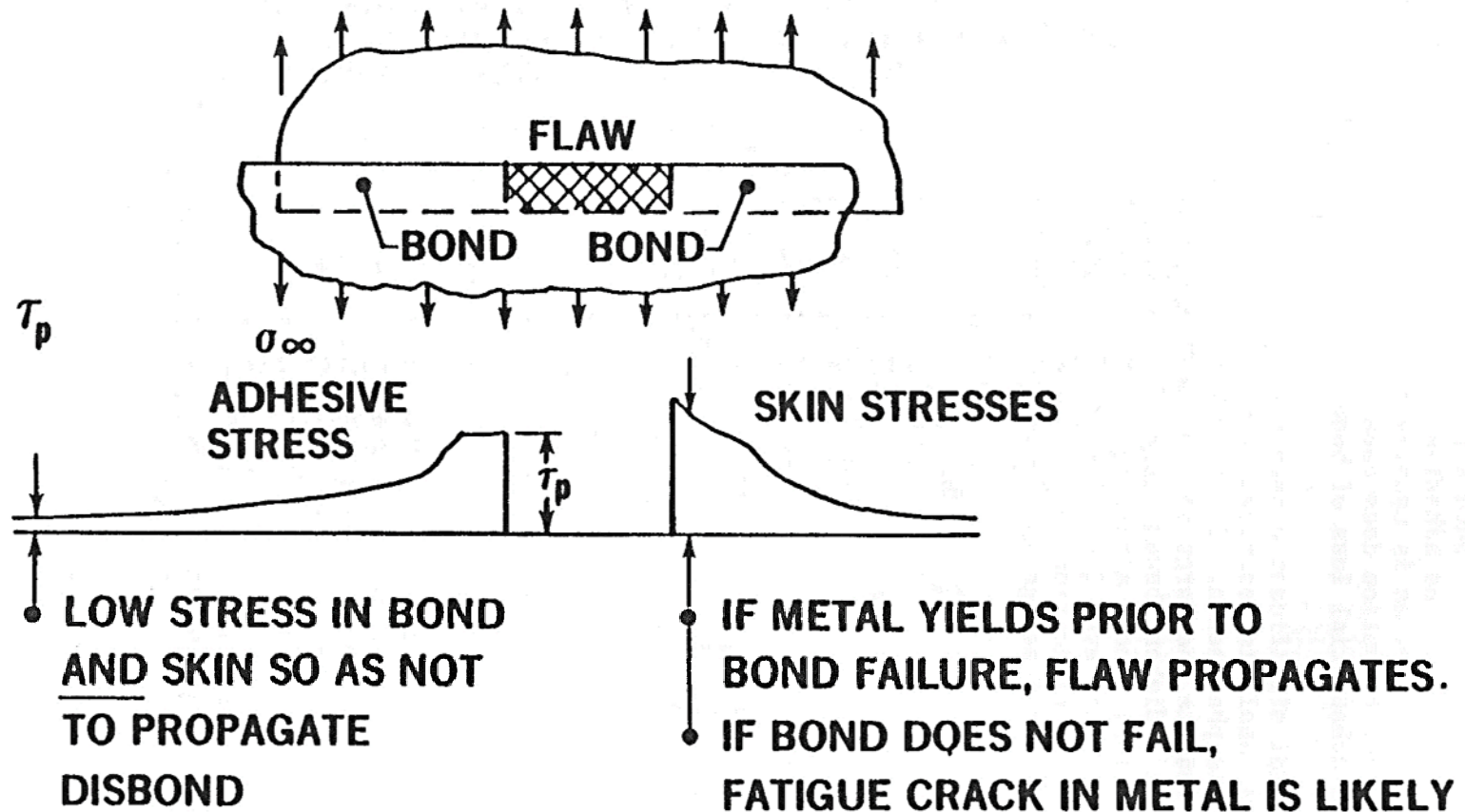
Shear Stresses and Strains in Flawed Adhesive-Bonded Joints



Load Redistribution Around Two-Dimensional Adhesive-Bond Flaws



Redistribution of Load at Flaws in Bond



Load Redistribution Around Two-Dimensional Adhesive-Bond Flaws

