Adhesive Bonding of Composites

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Composite Bonding Definitions:

- **Co-curing**: The act of curing a composite laminate and simultaneously bonding it to some other uncured material, or to a core material such as balsa, honeycomb, or foam core
  - All resins & adhesives are cured during the same process
- **Co-bonding**: The curing together of two or more elements, of which at least one is fully cured and at least one is uncured
  - Requires careful surface preparation of the previously- cured substrate
  - Additional adhesive may be required at interface

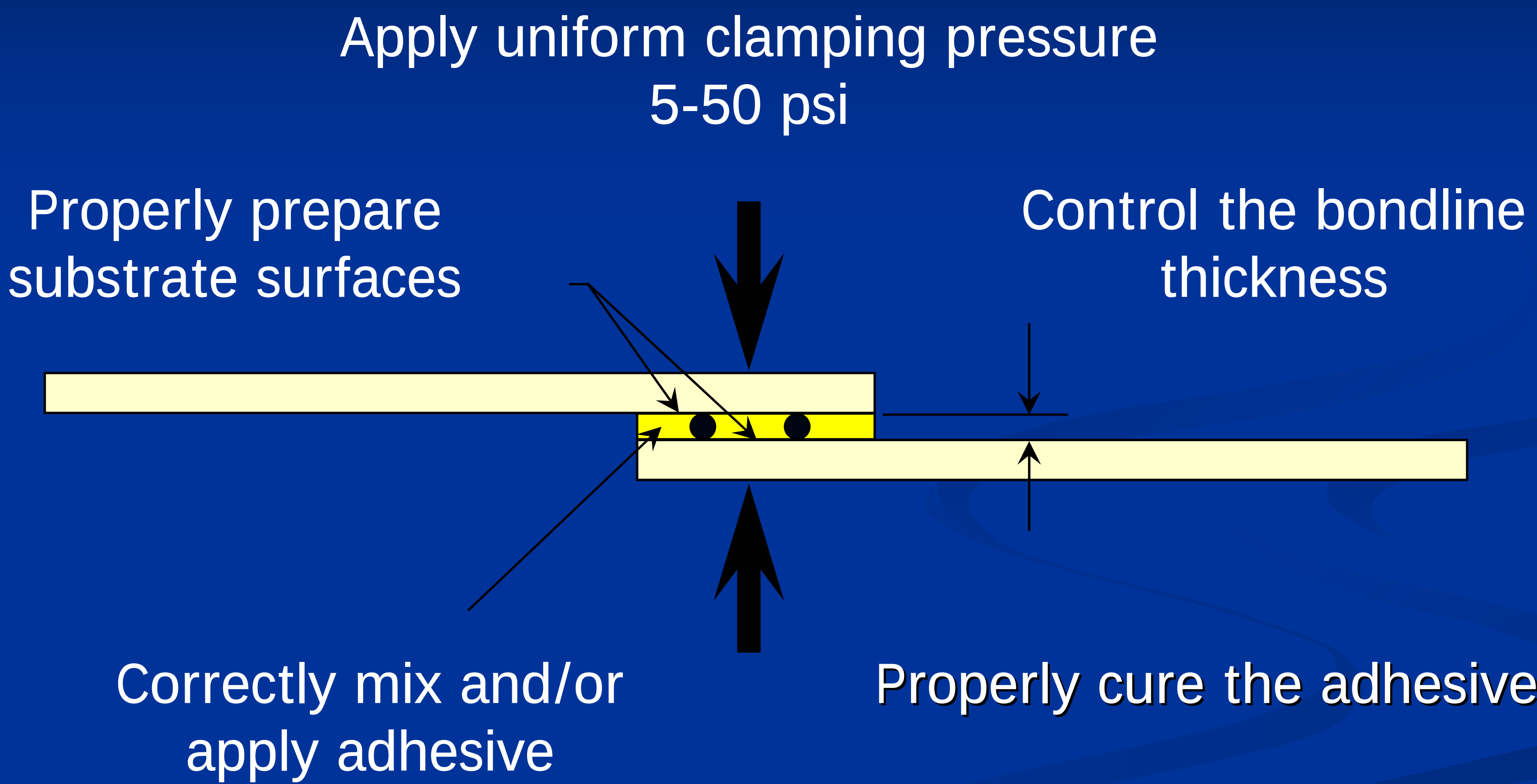
Composite Bonding Definitions:

- **<u>Secondary Bonding</u>**: The joining together, by the process of adhesive bonding, two or more pre-cured composite parts, during which the only chemical or thermal reaction occurring is the curing of the adhesive itself
  - Requires careful preparation of each previously cured substrate at the bonding surfaces
  - Usually requires well designed fixturing to align & clamp parts during processing
  - Re-heating previously cured substrates can be risky

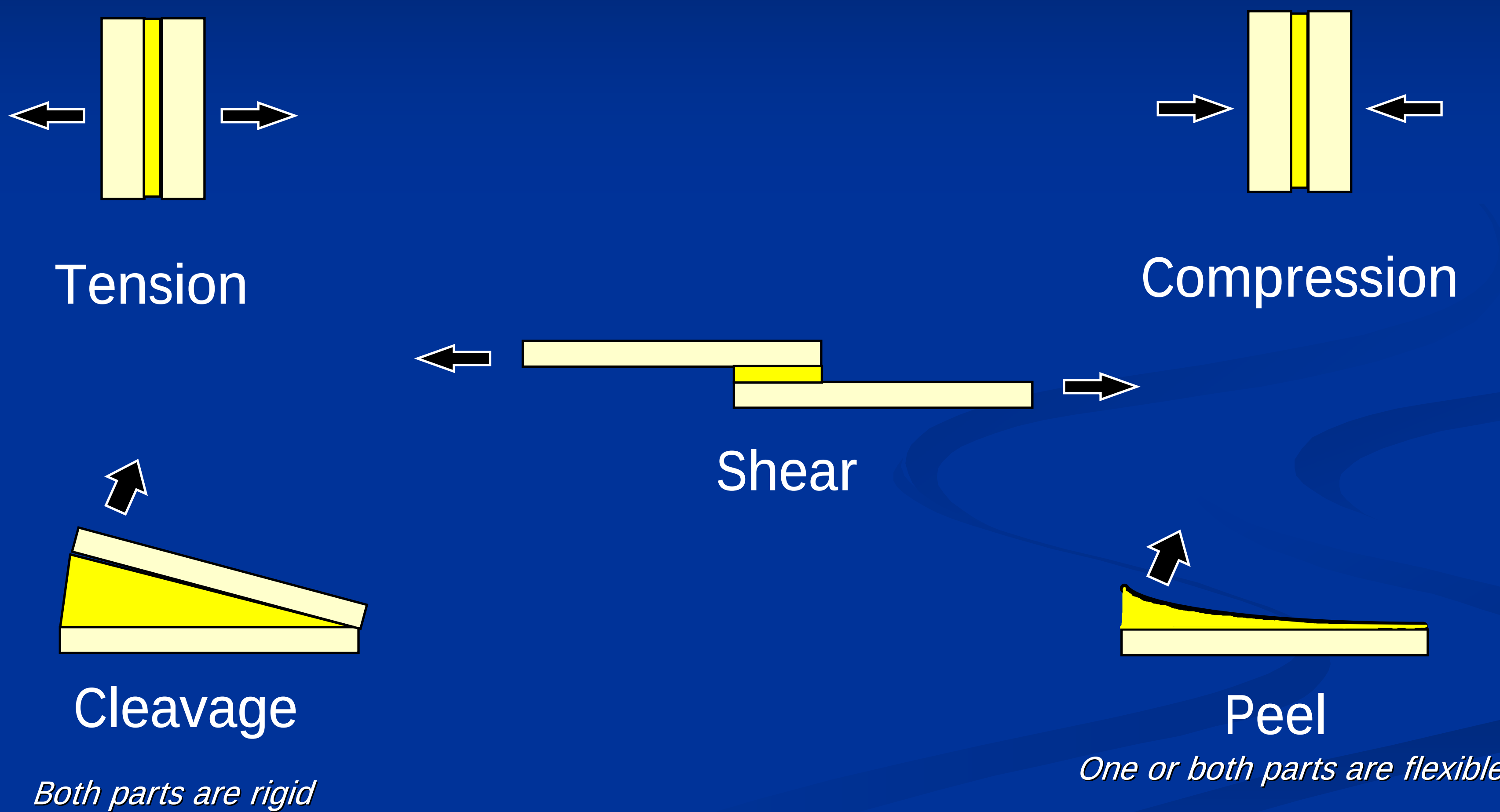
Metal Bonding

- **<u>Metal Bonding</u>**: The same as secondary bonding except with metal substrates instead of cured composite substrates.
- Sometimes metals are bonded directly to composites using one or more processes
  - Metals require very stringent surface preparation including application of corrosion inhibiting primer prior to bonding to obtain long term bond-durability at the metallic interface
  - Care must be taken when bonding metal to carbon as galvanic corrosion can occur in the metal substrate

Basic Bonding Requirements

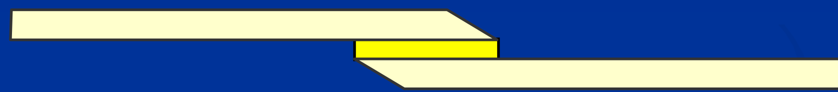


Loads on Adhesive Bonded Joints

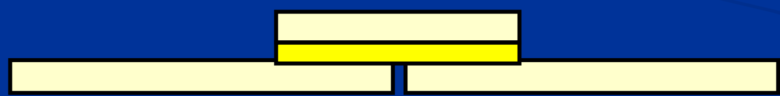


Common Joint Designs

Single Lap

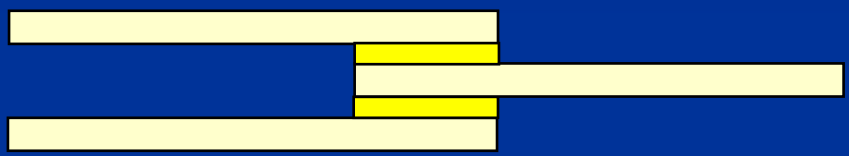


Tapered Single Lap

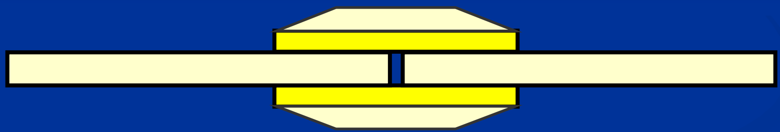


Single Strap Lap

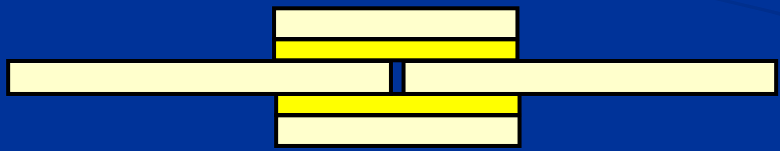
Common Joint Designs



Double Lap

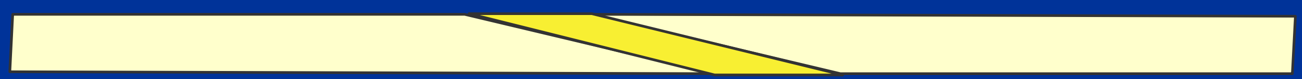


Double Tapered Strap Lap



Double Strap Lap

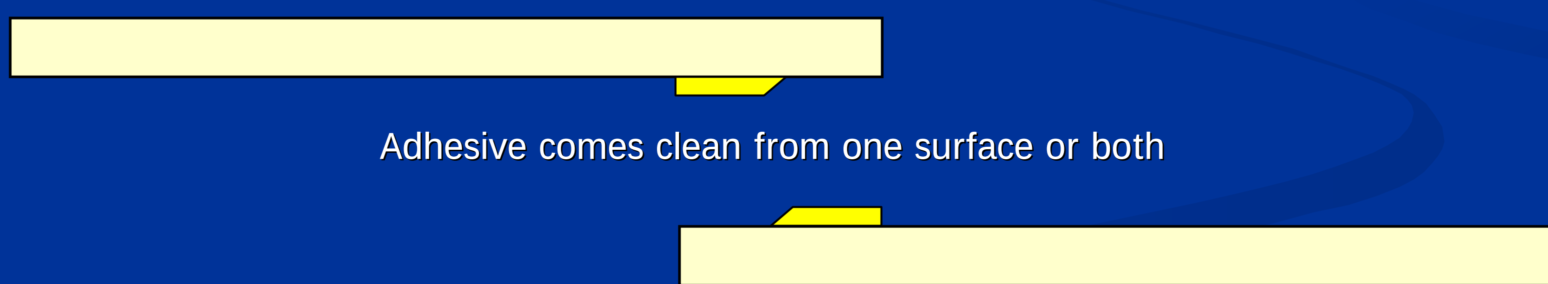
Common Joint Designs



Tapered Scarf Joint

Failure Modes in Adhesive Bonds

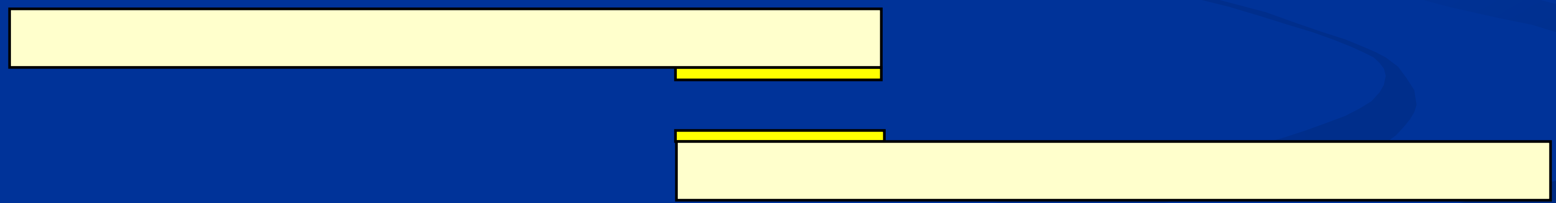
- **Adhesive** Failure: Failure of a bonded joint between the adhesive and the substrate
  - Primarily due to a lack of chemical bonding between the adhesive and the bonding substrate
    - Can be indicative of poor surface preparation or contamination
    - Or, incorrect adhesive selection for the substrate materials



Adhesive Failure

Failure Modes in Adhesive Bonds

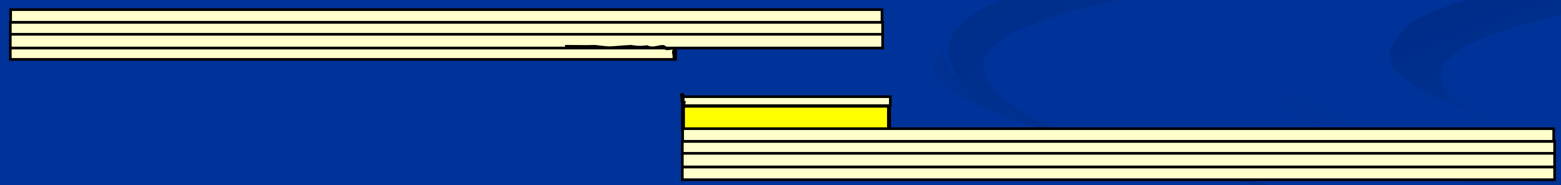
- **<u>Cohesive</u>** failure: Failure of an adhesive joint occurring primarily in the adhesive layer
  - Optimum type of failure in an adhesive bonded joint when failure occurs at predicted loads
    - Lower failure loads are indicative of poorly cured adhesive or moisture or other contaminants present in the adhesive



Cohesive Failure

Failure Modes in Adhesive Bonds

- **<u>Substrate</u>** failure: Interlaminar fracture in composite structures, usually between the first and second plies adjacent to the bondline; can be common in composite laminates especially those with brittle epoxies.



Substrate Failure

Aerospace Structural Adhesives

- Epoxies
  - Wide range of high-strength adhesives available with a variety of curing & service temperatures
- Bismaleimide (BMI)
  - High temperature cure/service (up to 600°F)
- Cyanate Ester
  - Good dielectric properties
  - Low Coefficient of Thermal expansion (C.T.E.)
- Hybrids

Automotive & Industrial Adhesives

- Modified Acrylics/Methacrylates
  - High strength *and* elongation properties
  - Bonds to Thermoplastics!
- Polyurethanes
  - Tough/abrasion resistant
  - Good low-temperature adhesion properties
- Silicones
  - Useful for bonding to glass, plastics, & other rubbers

Marine Adhesives

- Polyester
  - Polyester is less expensive than epoxy and is widely used in marine and other industrial applications
    - Putty joints and fillets are used in many marine designs
  - Polyester is a chemically weak adhesive Vs. epoxy
    - High degree of shrink inherent to polyester resin
- Vinyl Ester
  - Higher strength, modulus, and elongation than polyesters
    - Both polyesters & vinyl esters are co-polymerized with polystyrene and release high levels of volatile organic compounds (VOC's)

Liquids, Pastes, & Film Adhesives

- Liquids:
  - Viscosities typically range between 100-6000 cps
  - Generally works best in thinner bondlines and provide for a higher degree of direct load transfer than pastes
    - Effective thickness range: .002-.010 inch
    - Can run out of thicker bondlines with too low of a viscosity
  - Liquids tend to be more brittle and less resistant to peel and cleavage loads than pastes or films
  - Often “liquid” adhesives are categorized as “pastes” without distinction by the various adhesive manufacturers

Liquids, Pastes, & Film Adhesives

- Pastes
  - Paste adhesive viscosities typically are > 8000 cps
  - Generally works better in slightly thicker bondlines
    - Effective thickness range: .005-.020 inch
    - Thicker shim or gap filling applications are not necessarily considered structural – sometimes used with fasteners
  - Different fillers offer a wide range of properties
    - Minerals, rubbers, thermoplastics, & metals are common
  - Pastes usually do not wet-out as well on the substrate as liquids due to the influence of the added filler

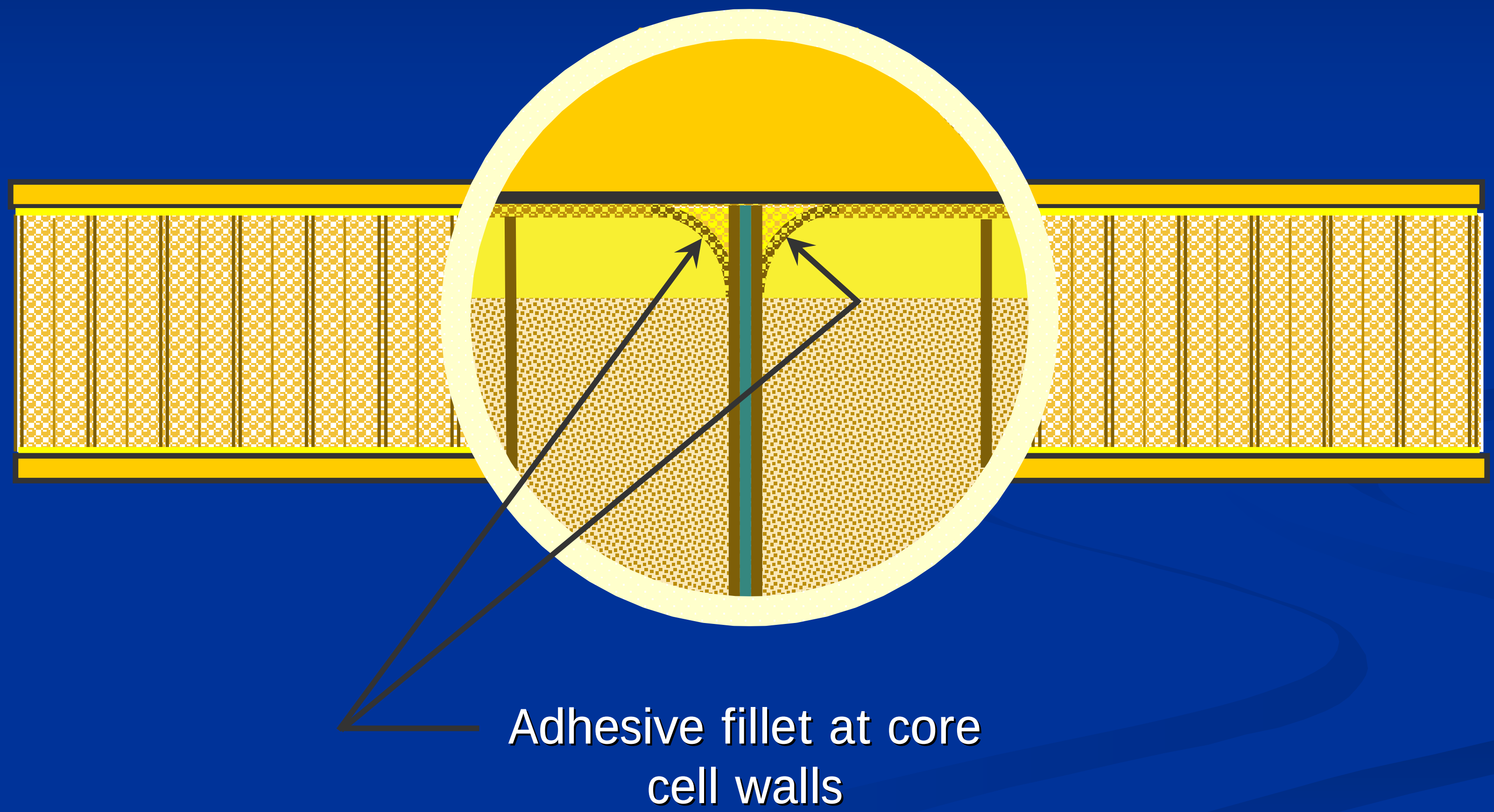
Liquids, Pastes & Film Adhesives

- Film Adhesives
  - High-performance structural prepreg film adhesives
    - Stored frozen & thawed to room temperature before use
    - Requires an elevated temperature cure cycle
  - Different carriers for maintaining bondline thickness control
    - Woven scrim cloth
    - Knit carrier
    - Non-woven (mat)
      - Typically carriers are made of treated Polyester or Nylon fibers

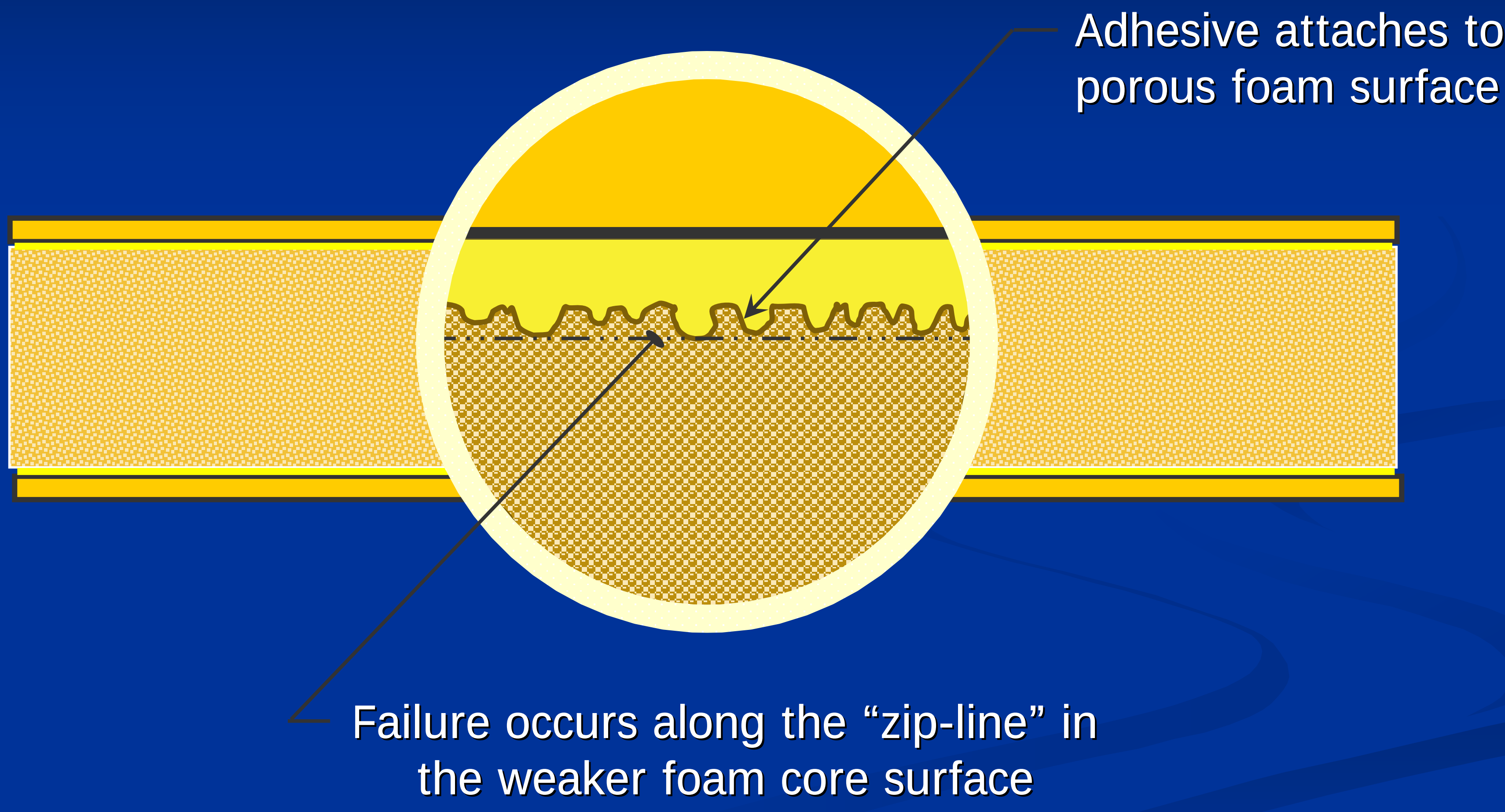
Reticulation

- Reticulating film adhesives
  - Bonding to honeycomb core
    - Heating an unsupported or knit supported film adhesive, causing the adhesive to flow and fillet the core cell ends
  - Reticulating perforated skins in acoustic panels
    - Heating an unsupported film adhesive, causing the adhesive to flow away from the small holes in the acoustic skin prior to bonding it to a honeycomb or other open cell core material

Bonding to Honeycomb Core



Bonding to Foam Core



Surface Preparation of Metals

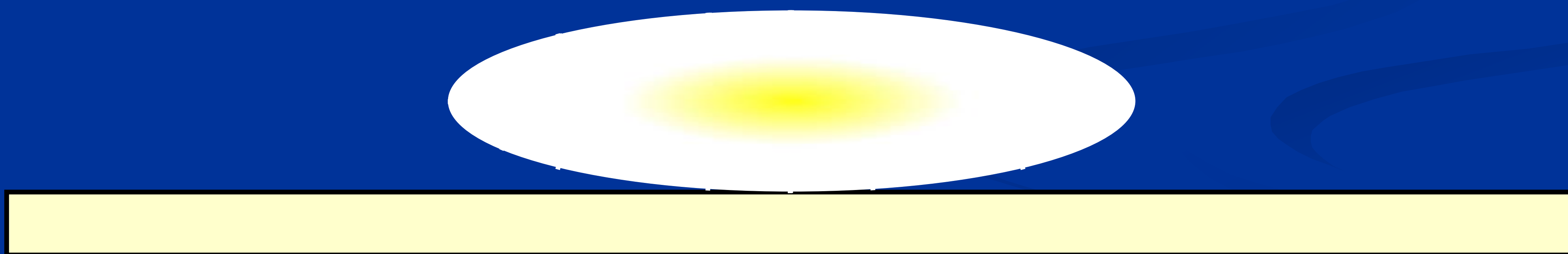
- Clean Metal Surfaces
  - Vapor or solvent degrease
- Increase Surface Morphology
  - Chemical or acid-etch bonding surfaces
    - Phosphoric Acid Anodization (PAA) for aluminum
- Chemical Coupler Surface Treatment
  - Sol-Gel technology
- Corrosion Resistant Primer
  - Primer is necessary to preserve the freshly treated surface
  - Provide resistance to hydrolysis
    - *Cytec BR 127 or BR 6747-1

Surface Preparation of Composites

- Goal:
  - Raise the surface-free energy of the composite substrate to enhance wetting of the surface and to facilitate molecular cross-linking
    - Raise surface energy without damaging fibers in the laminate
      - Ref: Armstrong & Allen; Surface Tension/Surface Energy
- Methods:
  - ScotchBrite or sandpaper abrasion
  - Grit-blast with alumina, silica, or other abrasive media
    - High risk method - somewhat operator dependent

Surface Free-Energy Exchange

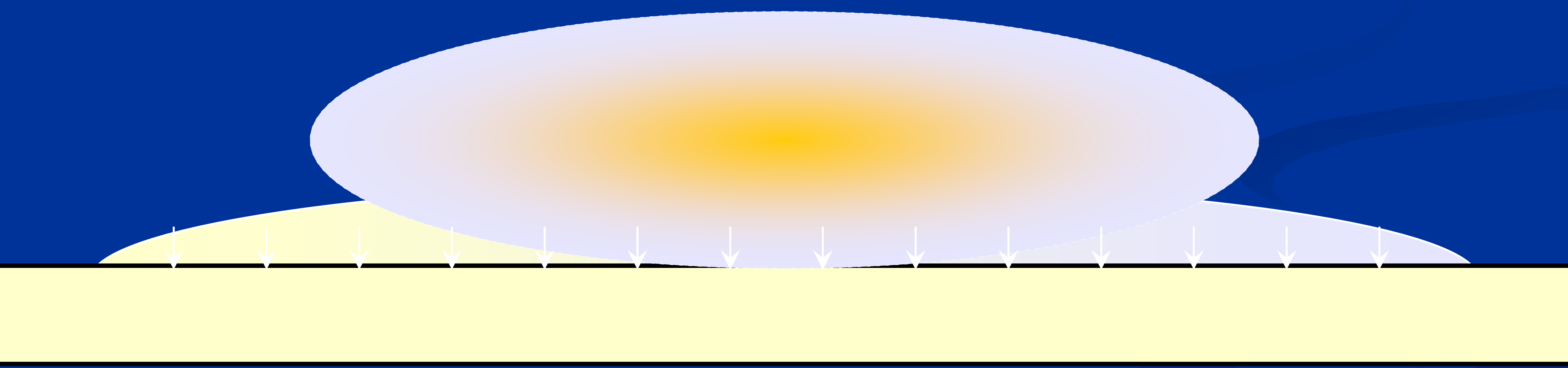
If the surface tension value of the liquid is greater than the surface-free energy value of the substrate the liquid molecules stay bound together



Poor wetting means a poor bond!

Surface Free-Energy Exchange

When the surface free energy value of the substrate is higher than that of the liquid it allows the liquid to uniformly wet the surface



This is important to achieving a good bond

Clean the Freshly Energized Composite Surface

- Objective: Remove dust and debris from bonding surface without inducing contamination
- *Solvent wipe* with clean cheesecloth or approved wipes
  - Double wipe method often specified: Use a solvent saturated wipe followed with a clean dry wipe to pick-up residual contaminants
  - High risk of inducing moisture or other contaminants onto freshly energized/slightly porous composite surface
- What effect does wiping with solvent have on the surface-free energy of the freshly prepared composite surface?
- Alternative: *Dry wipe* with clean cheesecloth or approved wipes
  - Multiple wipes may be required to remove dust sufficiently
  - Low risk of inducing moisture or other contaminants

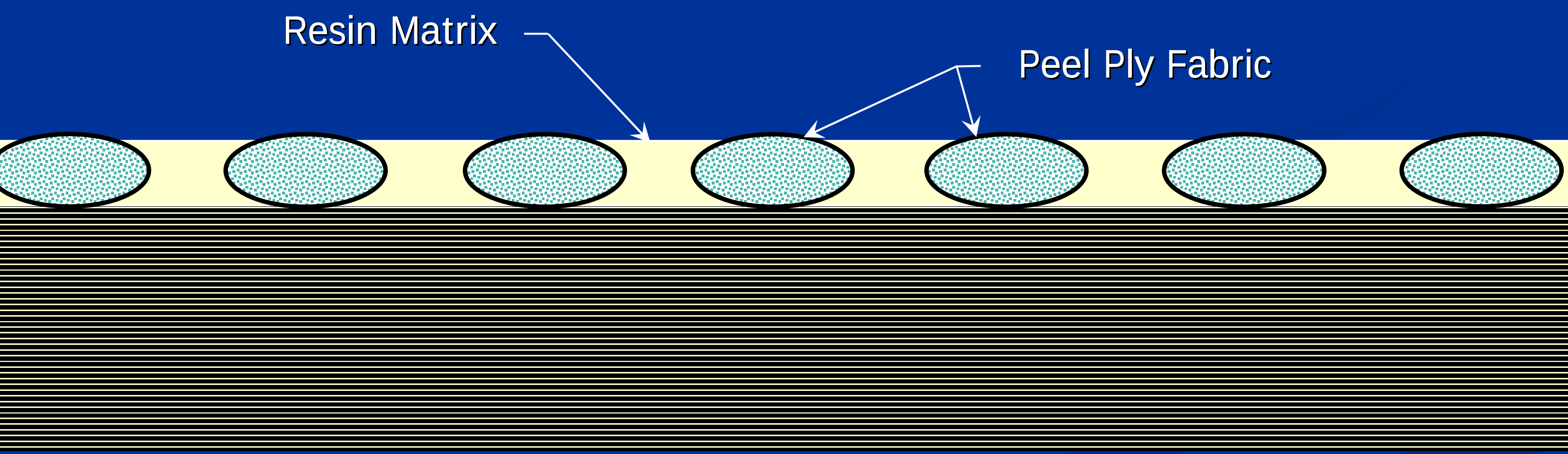
Water-Break Test on CFRP Panel

Water-break testing is not recommended for actual panels to be bonded

What About Peel-Ply Surfaces?

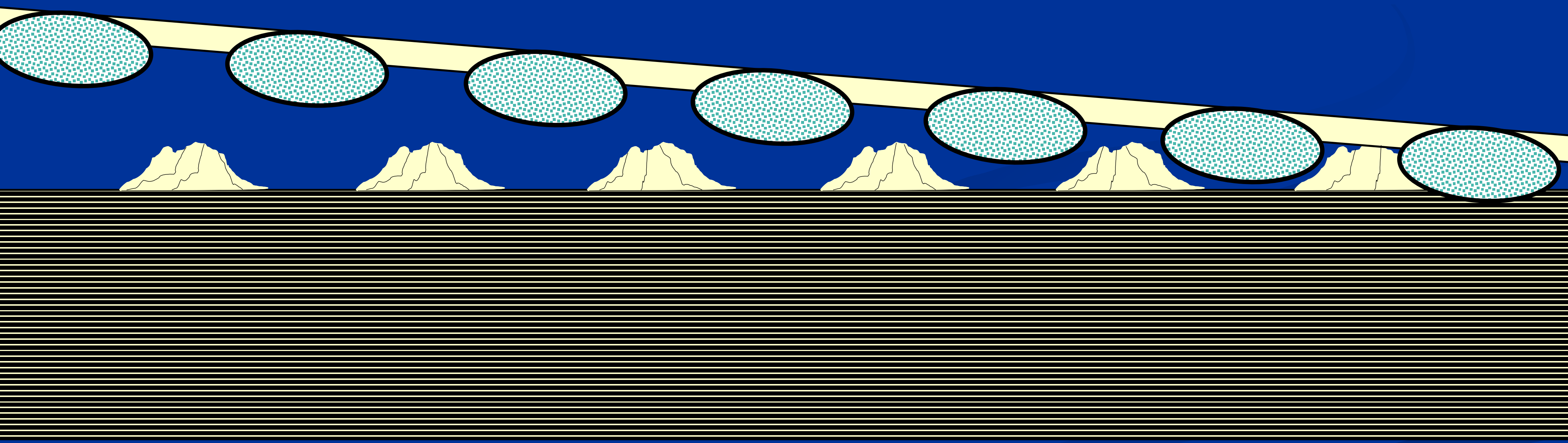
- Non-coated Nylon or polyester fabrics
  - Leaves no trace contaminates on part surface
  - Does not always peel off easy
- Release treated Nylon or polyester fabrics
  - Can transfer release agent to part surface
- P.T.F.E. Coated Glass Fabrics
  - Easy to remove from part surface with low risk of damage to part
  - Produces a fairly low-energy surface on the composite

Effect of Peel Ply on Surface



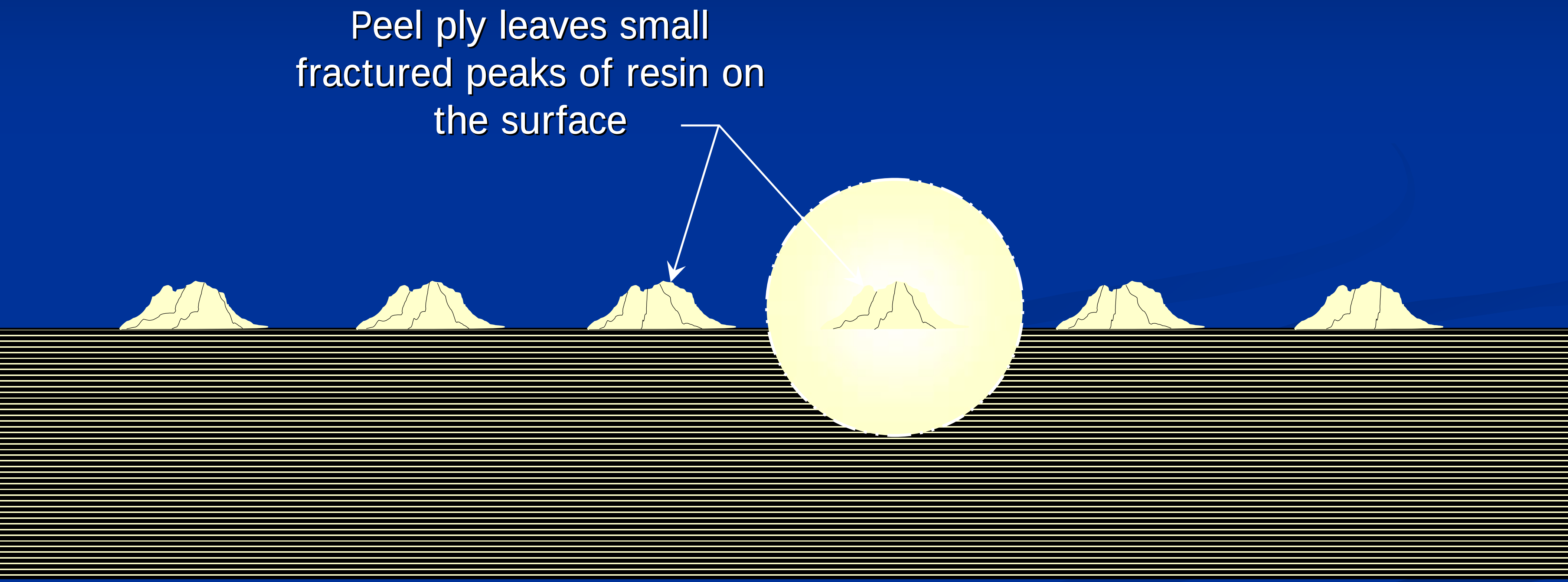
Cross-section through peel ply on surface of laminate

Effect of Peel Ply on Surface



Remove the peel ply from the surface

Effect of Peel Ply on Surface

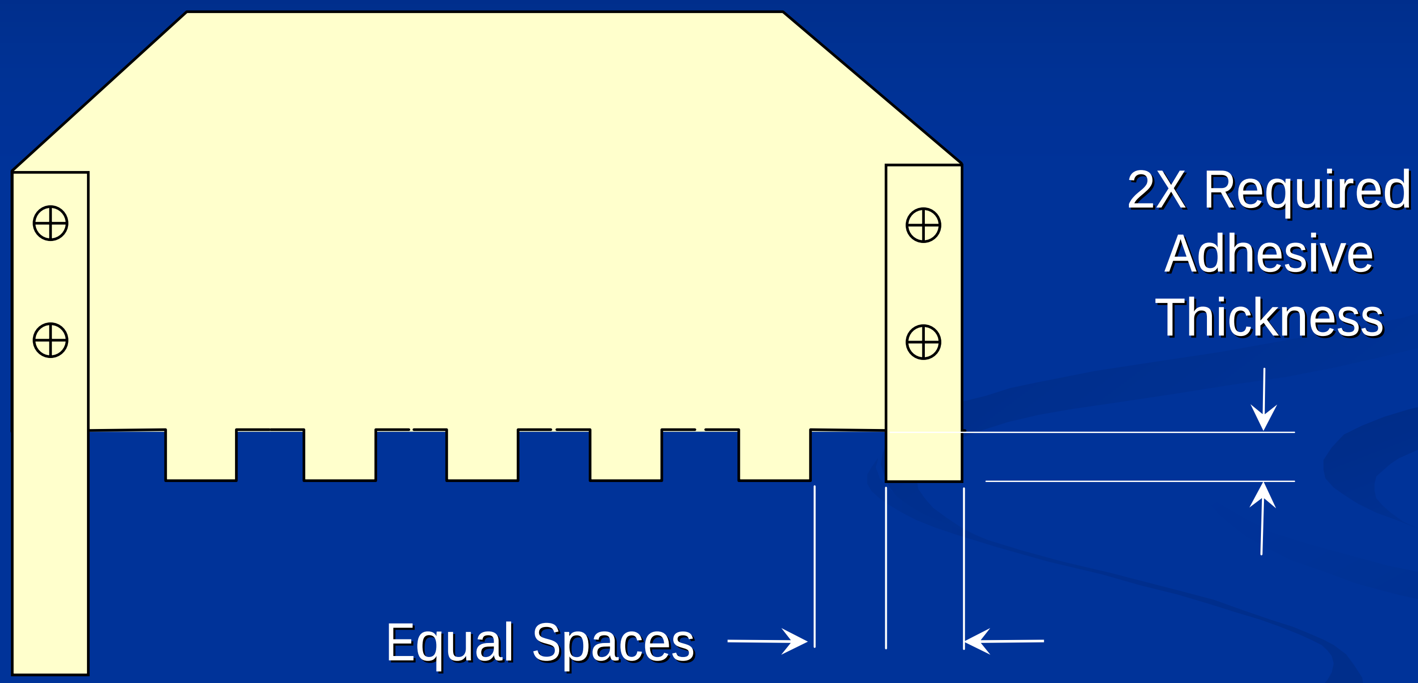


Would you want to bond to this surface?

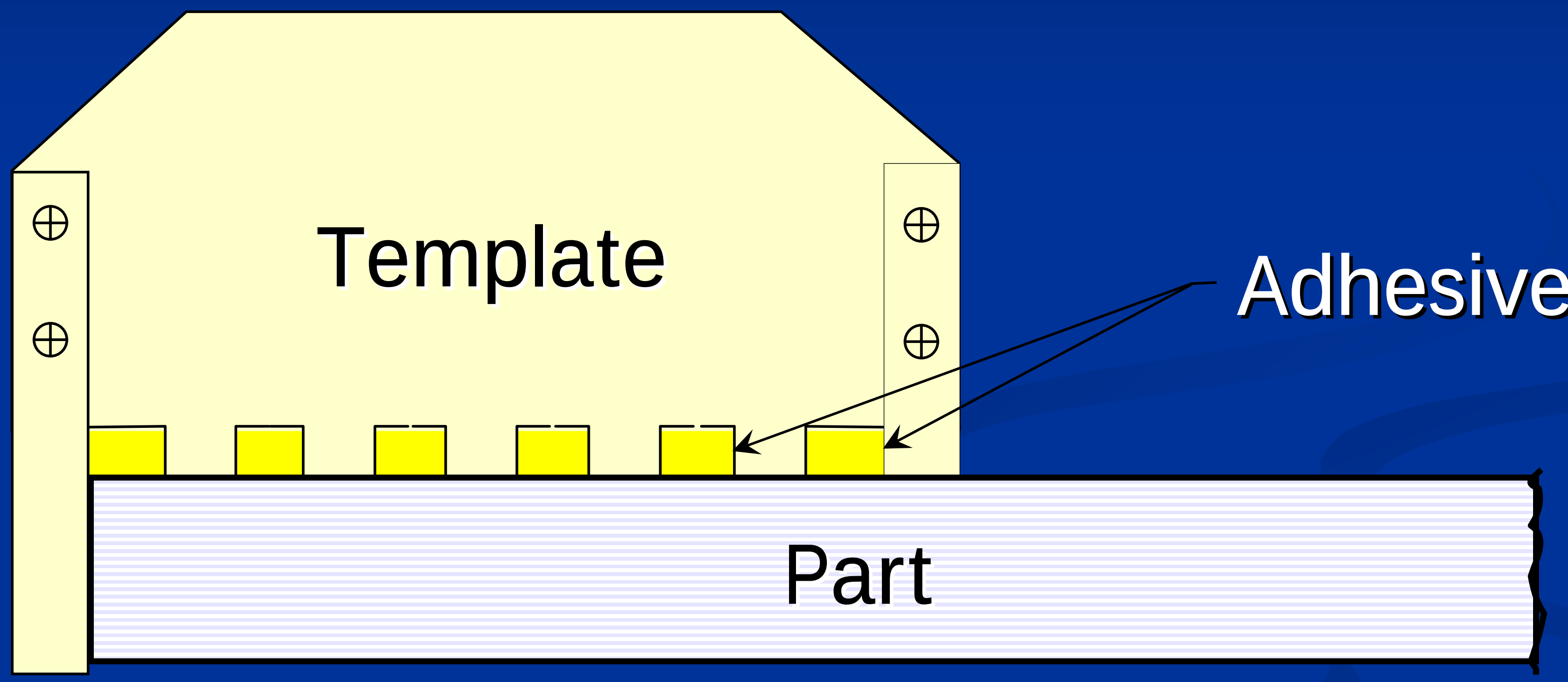
Adhesive Application Issues

- Applying Film Adhesives
  - Simple to apply along the faying surface of one or both substrates that are to be joined
    - Heat may be required to form some films to complex shapes
- Applying Liquid & Paste Adhesives
  - Goal: to apply slightly more adhesive than required and close the joint in a timely fashion
    - Provide enough adhesive along the joint to do the job
      - *Refer to application template design sketch
      - Excess adhesive = excess weight

Application Template Design



Using the Application Template



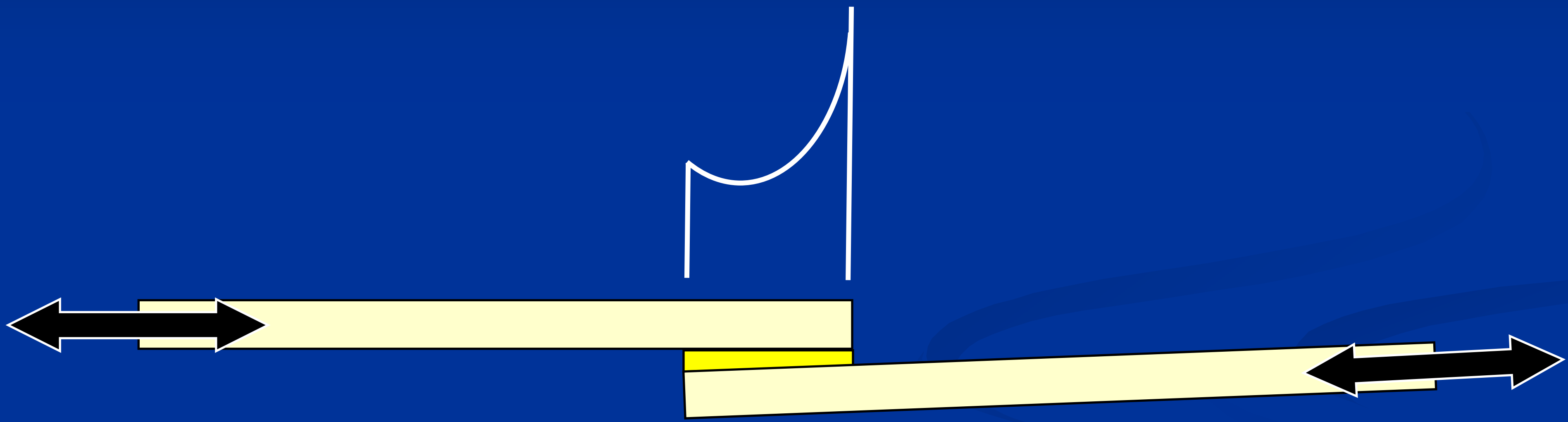
Open Time is the Enemy

- A freshly energized surface will try to stabilize over time and subsequently lose the desired effect
  - The surface takes on H^2O and other contaminants when left exposed to the normal shop/clean-room environment
- Adhesive left open on the surface for extended time may also be affected by the environment (H^2O & CO^2)
  - Amine Carbonate formation can inhibit most room-temperature curing epoxy adhesive systems
    - *Refer to Hysol EA 9394 Open Time Considerations

Bondline Thickness Control

- Consistent bondline thickness of the adhesive layer is critical, without uniform thickness the joint strength is only as good as its weakest point
  - Options for thickness control media:
    - Micro-Beads (mixed in the adhesive)
    - Scrim Cloth
    - Knit Carriers
    - Non-Woven Carriers (Mat)

Bondline Thickness Control



Unequal stress distribution through an unevenly bonded joint

Uniform Clamping Pressure

- Uniform clamping pressure is required to achieve good wet-out and optimum bond strength
  - Added force contributes to free-energy exchange
  - Typical bonding pressures range from 5-50psi
  - Mechanical clamping requires sturdy fixturing
  - Vacuum bagging can provide uniform pressure
    - Vacuum bagging can also cause micro-porosity in the joint due to frothing of the adhesive under vacuum

Curing the Adhesive

- To achieve maximum performance and ultimate structural & thermal properties, the adhesive must be properly cured and/or post-cured
  - Room temperature curing systems usually take several days to achieve good structural properties
    - The standard definition of room temperature is 77° F (25°C)
  - Elevated temperatures lower the adhesive viscosity and enhancing the wet-out (energy exchange) characteristics
  - High performance adhesives usually require an elevated temperature cure and/or post-cure for best performance

Lap Shear Coupons

- Single lap coupon
  - ASTM D1002: Standard Test Method for Lap Shear Adhesion for metallic Bonding
  - ASTM D5868-01**:** Standard Test Method for Lap Shear Adhesion for Fiber Reinforced Plastic (FRP) Bonding
    - Somewhat useful for quality assurance testing of adhesives and surface preparation methodology
  - The varying stiffness of different substrate materials influence the apparent adhesive shear strength in the lap shear test*

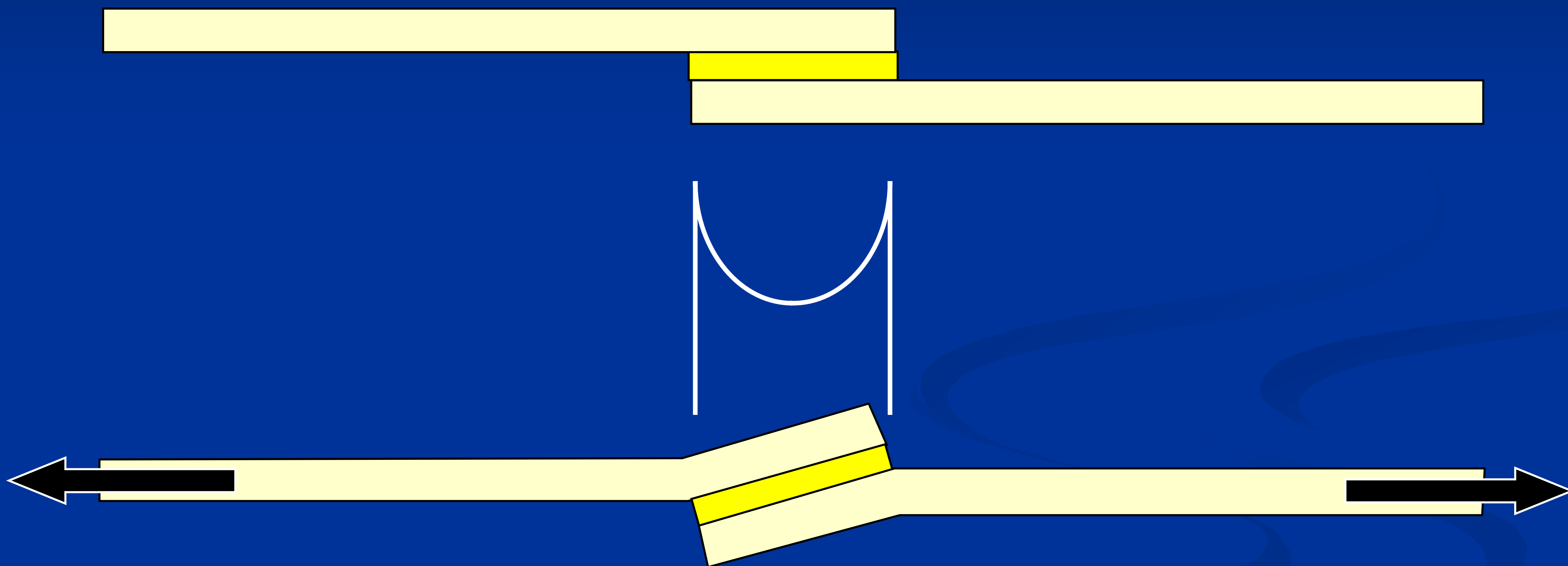
*Ref. L.J. Hart-Smith, *The Bonded Lap Shear Coupon-Useful for Quality Assurance But Dangerously Misleading for Design Data*

Single Lap Shear Coupon

- Not useful for generating actual design data*:
  - Example: 1 inch wide x ½ inch overlap coupon fails at 3000 lbs breaking loads.
  - Multiply the breaking strength x 2 = 6000 psi.
  - However - with a 1 inch wide by 1 inch overlap the breaking number is significantly less than 6000 lbs.
  - The joint strength is not doubled with the overlap length

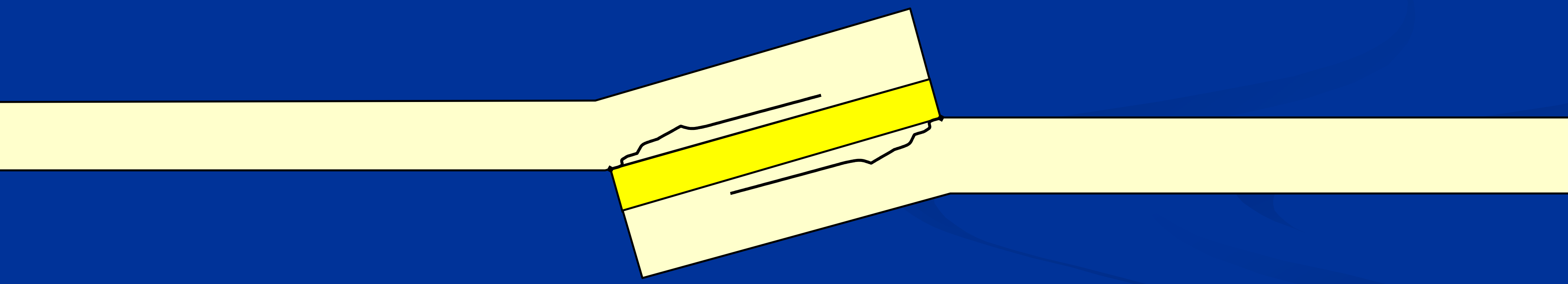
*Ref. L.J. Hart-Smith, *The Bonded Lap Shear Coupon-Useful for Quality Assurance But Dangerously Misleading for Design Data*

Single Lap Shear Coupon



Peak stresses in both shear & peel concentrated at edges of single lap coupon induced by deformation of specimen when loaded

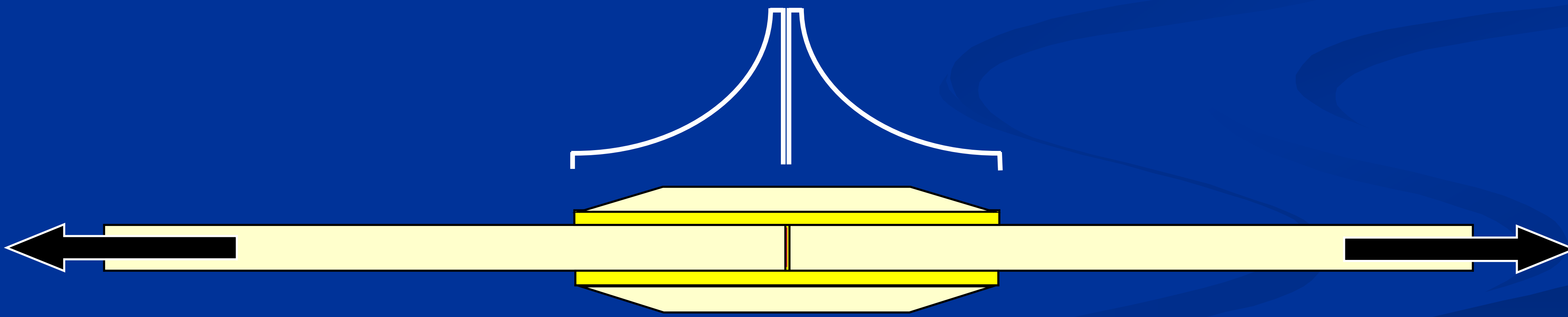
Common Substrate Failure in Composite Lap-Shear Specimens



Failure typically occurs between the first and second plies from the bond surface in one or both substrates

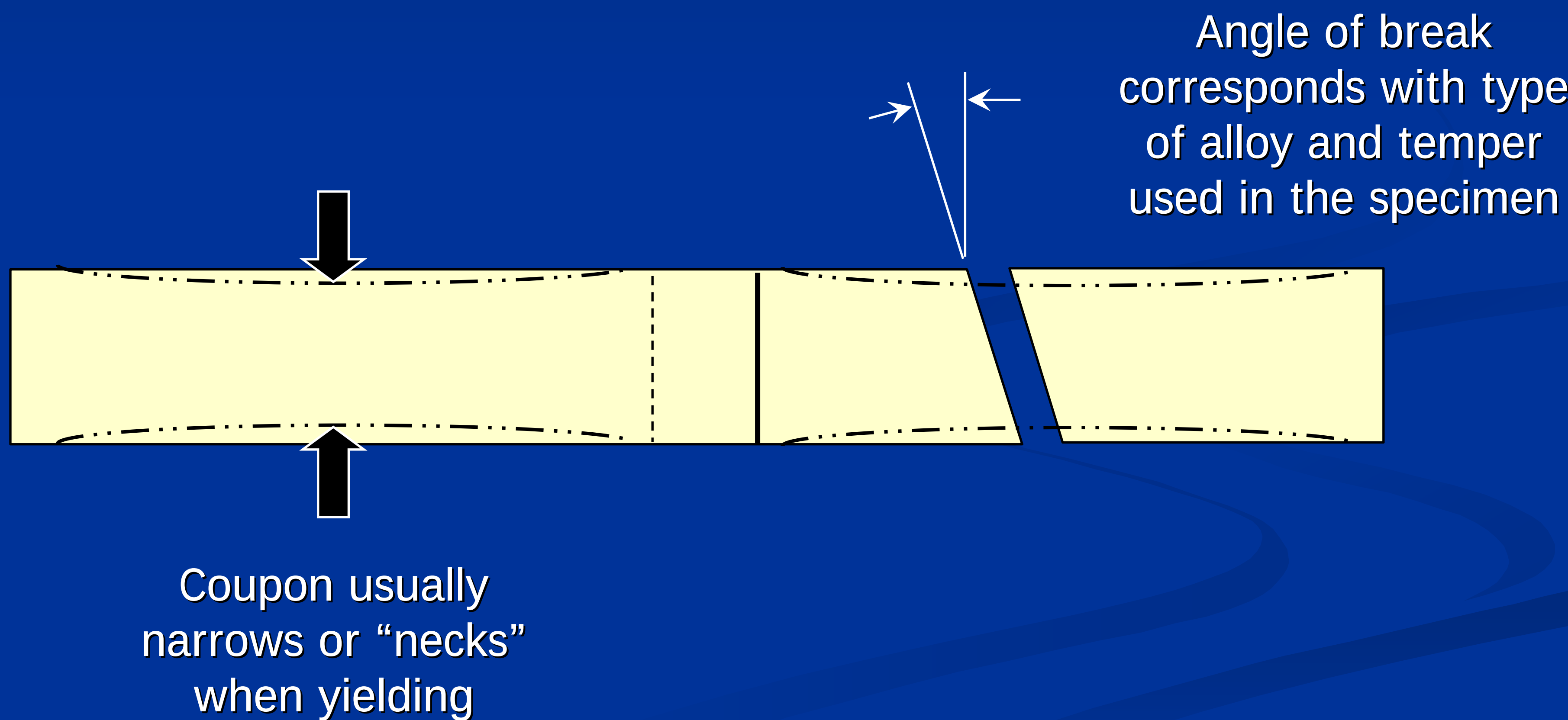
Double Lap Shear Coupons

- Double lap coupon (ASTM D 3528-96)
  - Also useful for quality assurance testing of adhesives although not generally referenced in data sheets from mfr's
  - More useful for generating design data or predicting shear load capabilities through a bonded double-lap joint



Stress distribution through a double-lap coupon

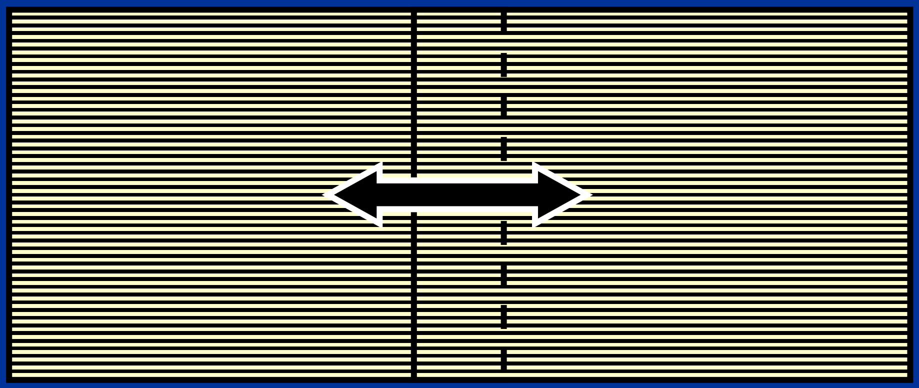
Failure of Metallic Lap Coupon

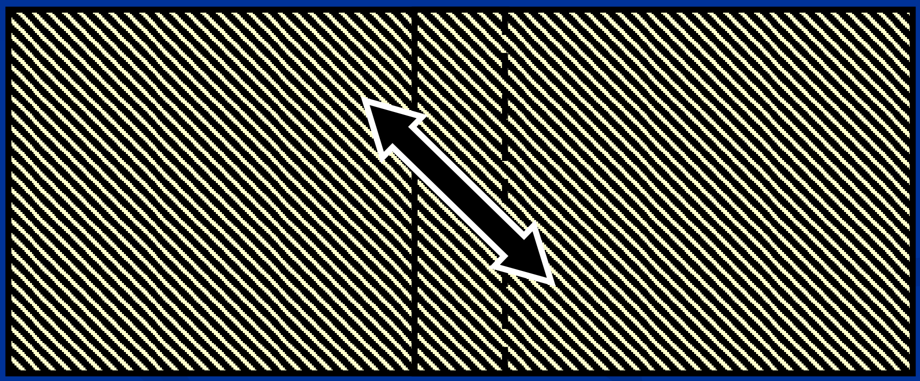


Effect of Different Fiber Forms at the Faying Surfaces in a Bonded Joint

- Uni-directional Tape
  - Should run directly across the joint for best results
    - Normally not recommended as faying layer in joint design
- Bi-directional woven fabrics
  - Plain & Twill weaves
    - Generally good surface materials for faying layer in joint design
  - Harness-satin weaves
    - Warp/fill face orientation dominance must be considered
- Multi-axial stitched fabrics
  - Functions like a unidirectional tape dependent on faying layer orientation
- Non-woven mats
  - Diminished load transfer through mat surface layer

Effect of Different Fiber Forms at the Faying Surfaces in a Bonded Joint

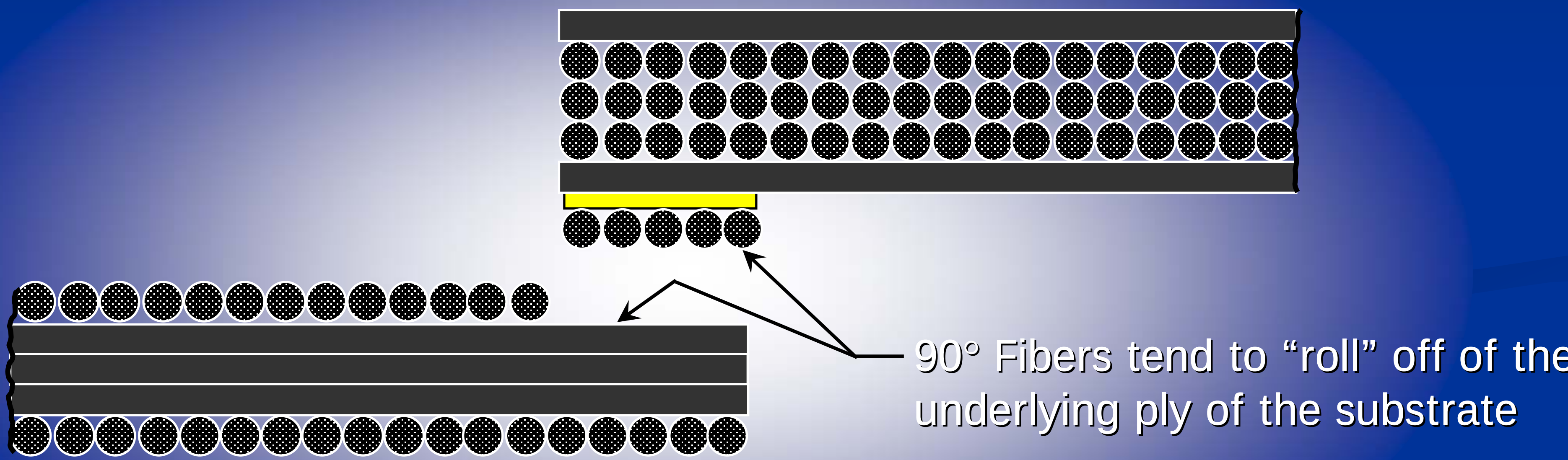




Uni-directional fibers at faying surfaces:

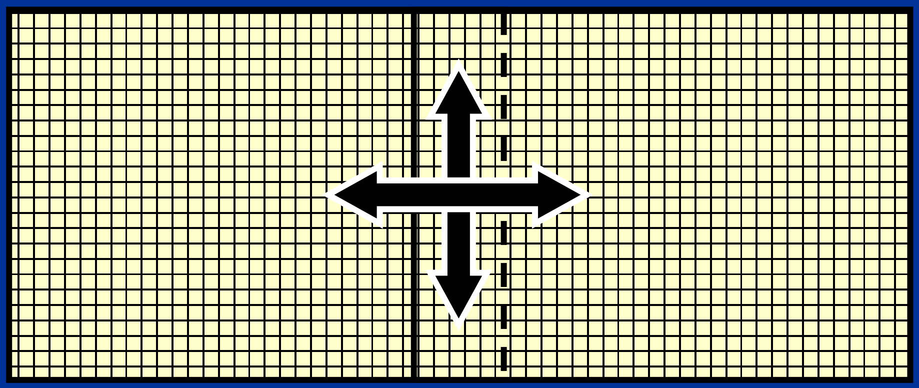
Orient fibers across the bonded joint in primary load direction

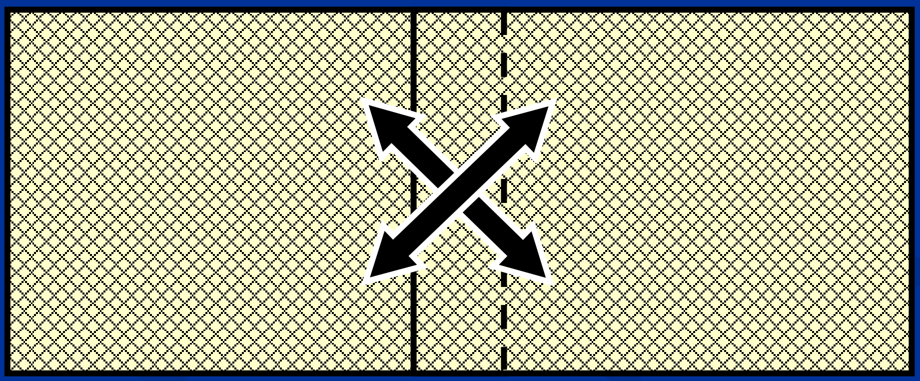
Effect of Different Fiber Forms at the Faying Surfaces in a Bonded Joint



Effect of 90° uni-directional fibers at bond joint

Effect of Different Fiber Forms at the Faying Surfaces in a Bonded Joint





Bi-directional plain-woven fabrics at faying surfaces provide uniform load transfer across bonded joint

Summary

- To achieve an optimum bond with metals:
  - Clean surfaces free of oils & dirt if applicable
  - Refresh oxide layer with suitable process
  - Chemically etch or couple to fresh oxide layer
  - Apply corrosion inhibiting primer (Aluminum)
  - Use appropriate adhesive for the application
  - Provide uniform bondline thickness
  - Provide constant clamping pressure along B/L
  - Cure adhesive to achieve structural properties

Summary

- To achieve an optimum bond with composites:
  - Abrade or energize the surfaces to be bonded
  - Clean surfaces free from dust or debris
  - Use appropriate adhesive for the application
  - Provide uniform bondline thickness
  - Provide constant clamping pressure along bondline
  - Cure adhesive to achieve structural properties