INTRODUCTION TO ADHESIVE BONDING
- PART I -

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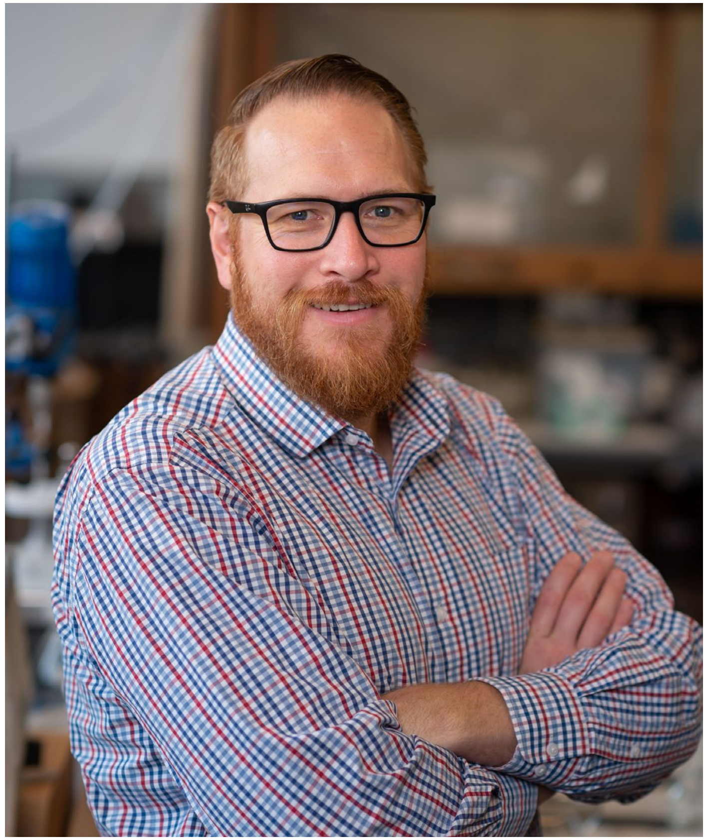

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Assistant Professor of Teaching, University of British Columbia
Director of Knowledge in Practice Centre, CKN

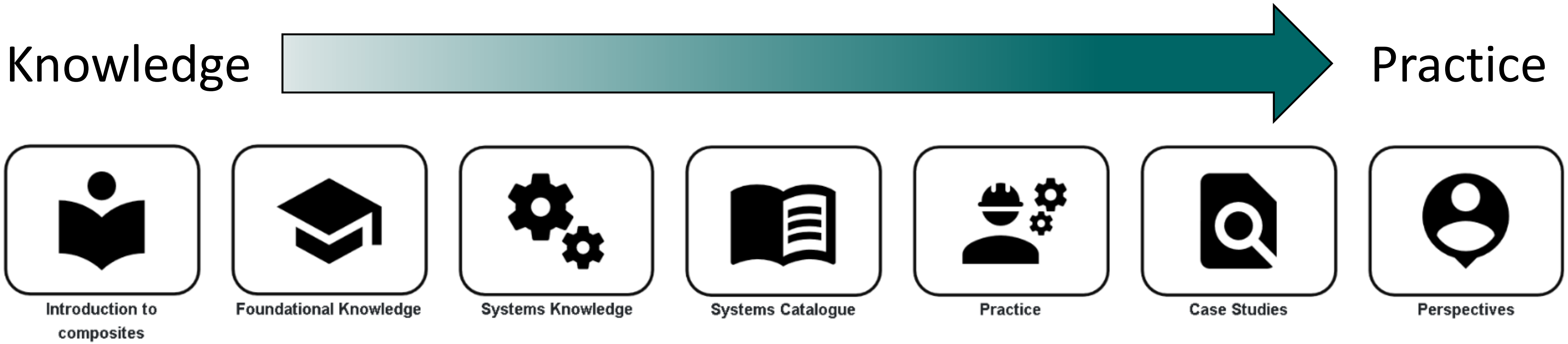
- Ph.D. and M.A.Sc. in Composite Materials Engineering
- Over 15 years experience in industry and academia working on polymer matrix composites in aerospace, automotive, marine, energy, recreation and others
- Experience working with over 150 companies from SME to major international corporations
- Expertise in liquid composite moulding and thermal management

KNOWLEDGE IN PRACTICE CENTRE (KPC)

- A freely available online resource for composite materials engineering:

  compositeskn.org/KPC

- Focus on practice, guided by foundational knowledge and a systems-based approach to thinking about composites manufacturing



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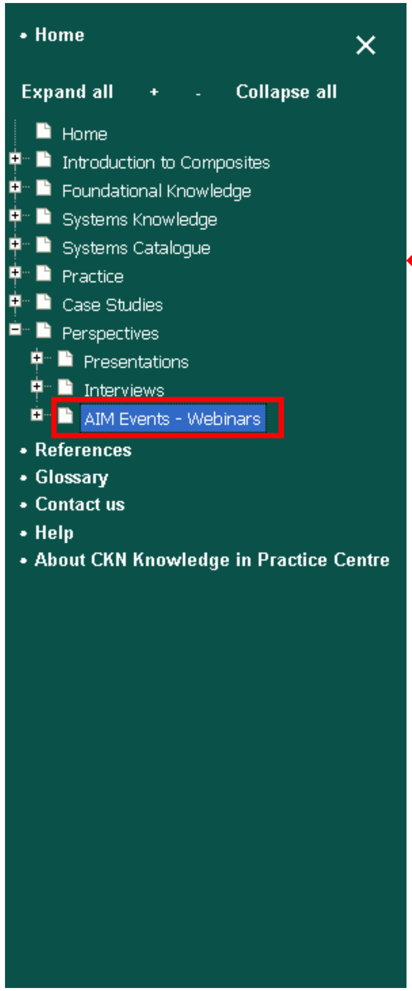

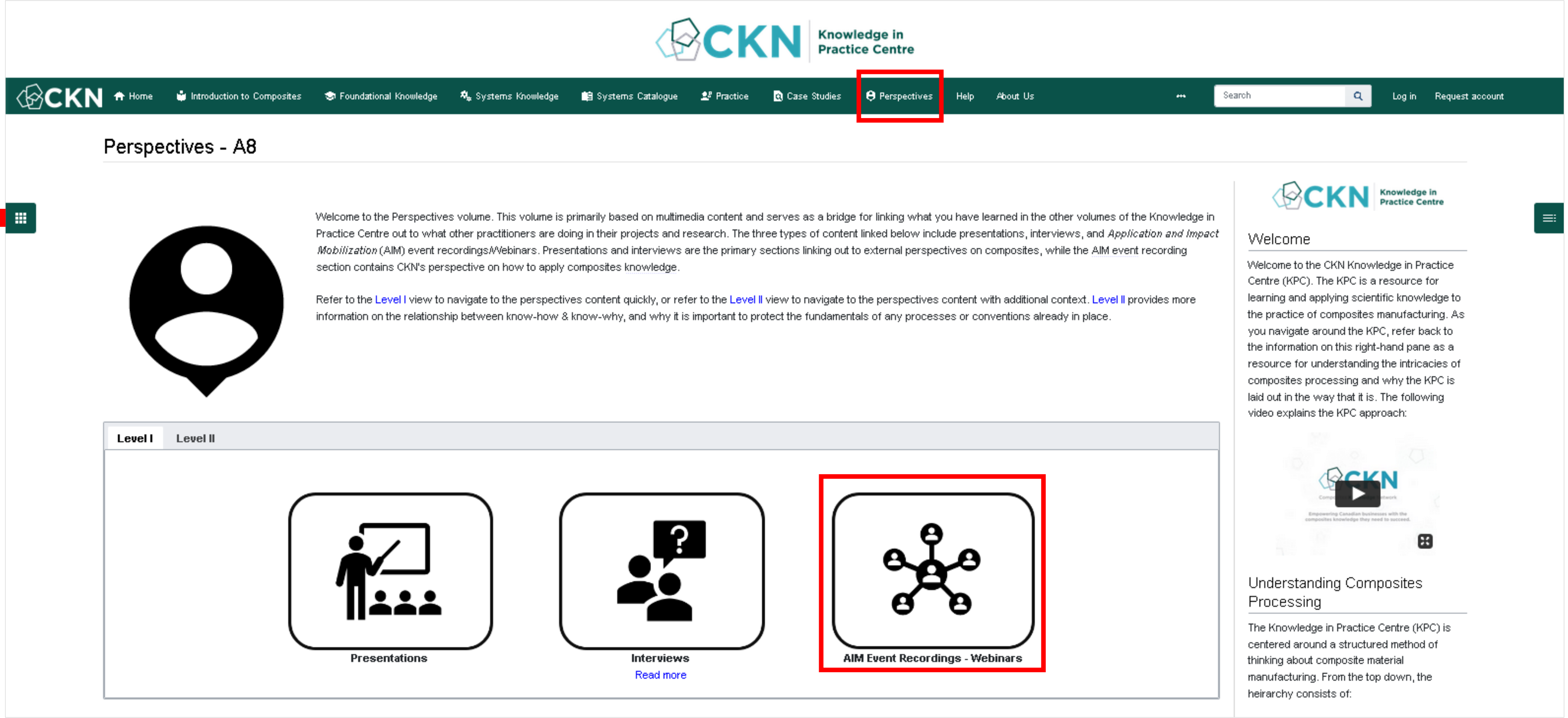

Today's Webinar will be posted at:

https://compositeskn.org/KPC/A354

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TODAY'S TOPIC:

Introduction to Adhesive Bonding - Part I -

OUTLINE

- Advantages/challenges
- Terminology
- Adhesive types (chemistries) and forms
- Surface preparation

- … Part II will focus on applying this information

ADVANTAGES OF ADHESIVE BONDING

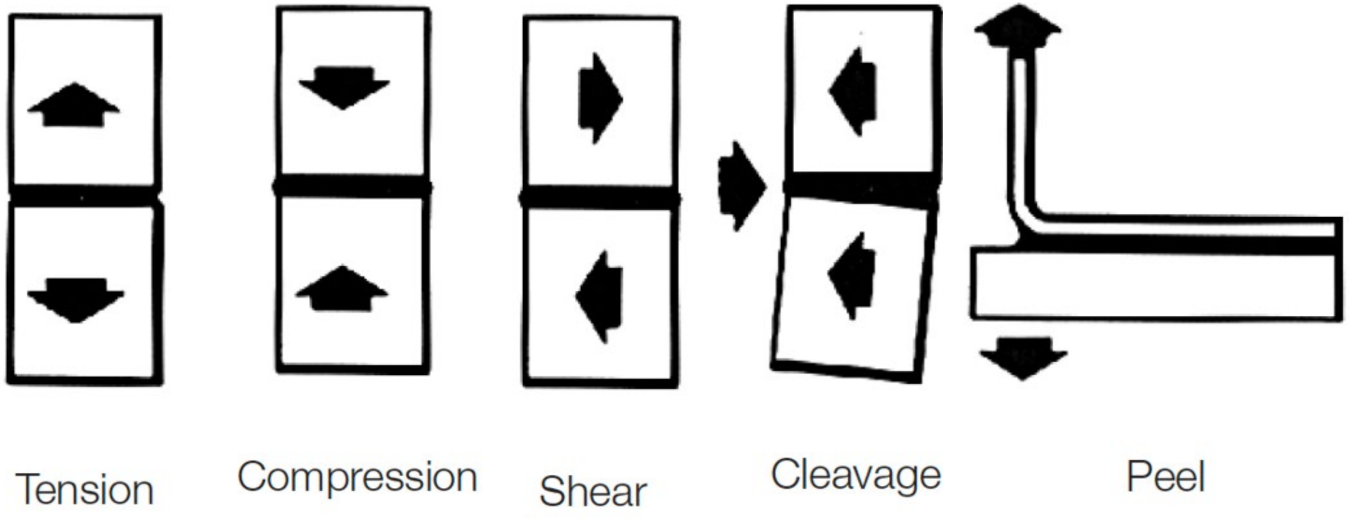
- Continuous bond – uniform stress distribution
- Potential for more discrete appearance
- Can join complex assemblies and simplify the assembly process
- Acts as a sealant
- Can conduct or insulate electric charge
- Damp vibration
- Reduced cost and time

CHALLENGES AND LIMITATIONS OF ADHESIVE BONDING

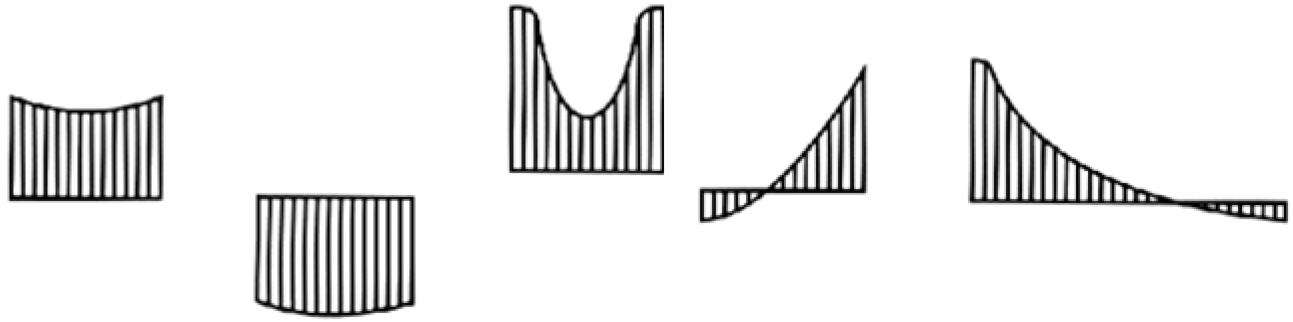
- Temperature sensitivity
- Chemical resistance
- Cure time – not always instant bonding
- Ensuring consistency requires process control
- Can be challenging to inspect
- Typically not easily disassembled for service
- Fit-up considerations

TYPES OF LOADING IN ADHESIVE JOINTS

- Five basic loading conditions in an adhesive joint
  - Usually a combination of two or more in reality
- Cleavage and peel should be minimized due to large stress concentrations



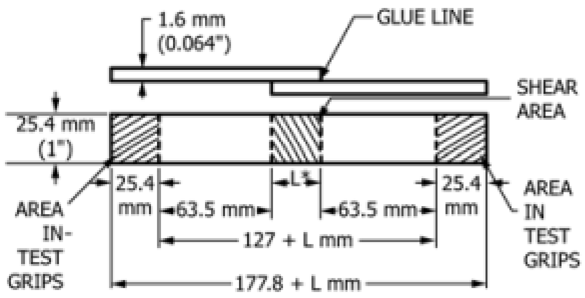
Stress distribution:



https://www.freemansupply.com/datasheets/adhesivesguide.pdf

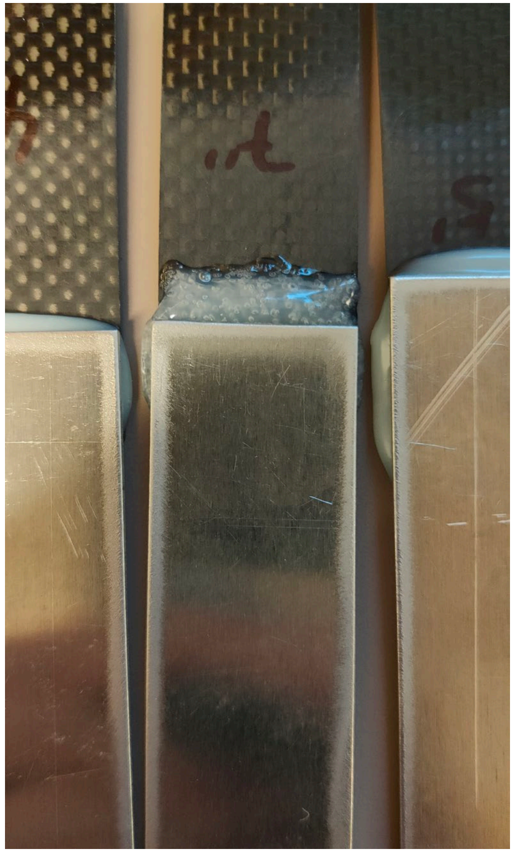
SINGLE LAP JOINT

- A basic adhesive joint where the substrates overlap each other
  - Often used for mechanical testing of the adhesive
  - ASTM D1002: metal-to-metal
  - ASTM D3163: plastic adherends
  - ASTM D5868: composite adherends



Dimensions of the joint (ASTM D1002)

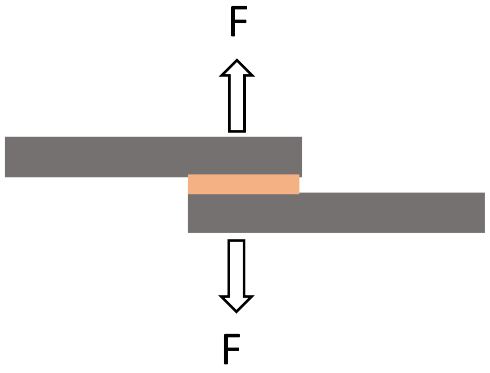
Side view of the single lap joint

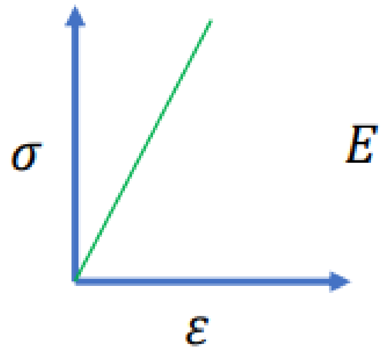


Top view of a single lap joint

TENSILE AND SHEAR PROPERTIES

In a single lap adhesive joint:

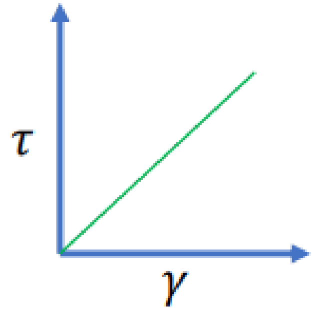




$$E = \frac{\sigma}{\varepsilon}$$

E: Tensile (elastic) modulus

- Ratio of tensile stress to strain



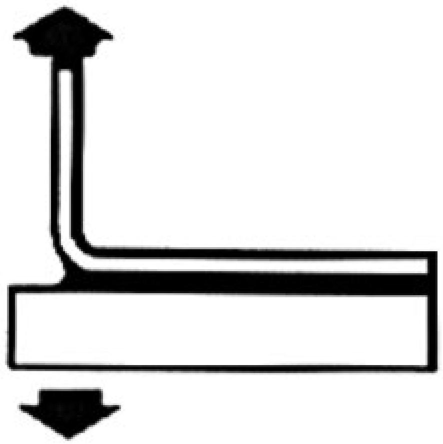
$$G = \frac{\tau}{\gamma}$$

G: Shear modulus

- Ratio of shear stress to strain

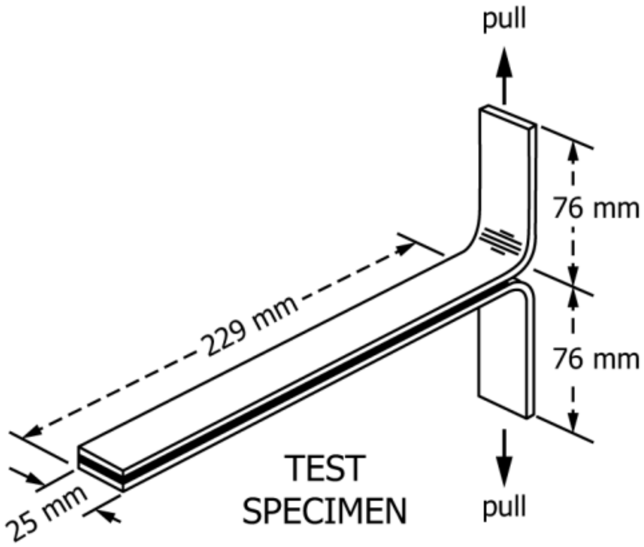
PEEL STRENGTH

- Defined as: "average load per unit width of bondline required to separate progressively a flexible member from a rigid member or another flexible member" – ASTM D1876
- Generally significantly weaker than shear and tensile strengths due to stress concentration on the edge of adhesive



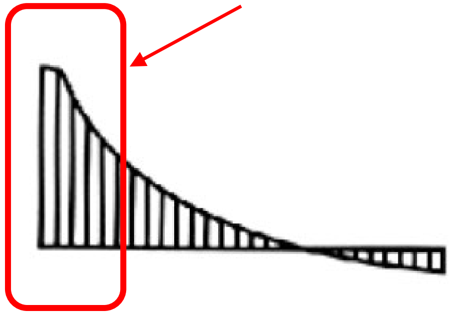
$$P_s = \frac{F_{average}}{b}$$

$F_{average}$ = average peel force [N]
b = adhesive width [mm]



T-peel test specimen (ASTM D1876)

Stress at edge of adhesive

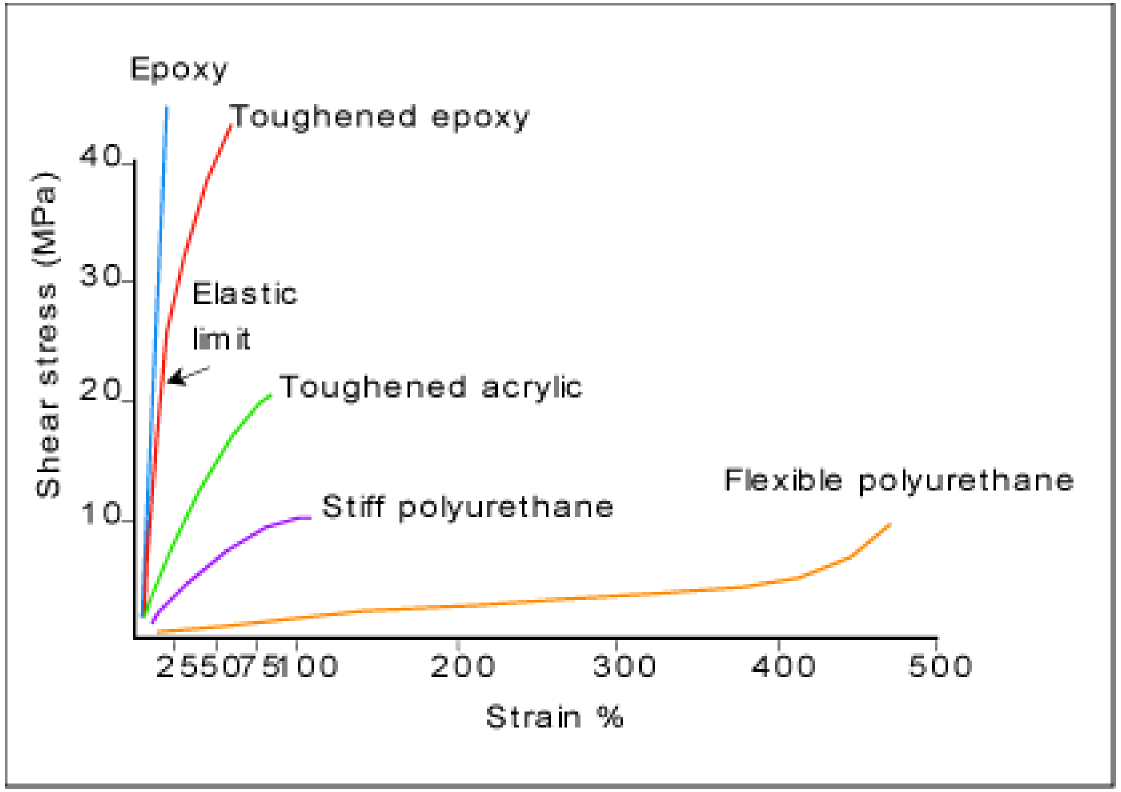


Stress distribution

TOUGHNESS

- Energy absorbed by material before fracture
  - Calculated as area under stress-strain curve until fracture

- Toughened adhesives typically contain elastomeric fillers which increases the ductility and impact resistance



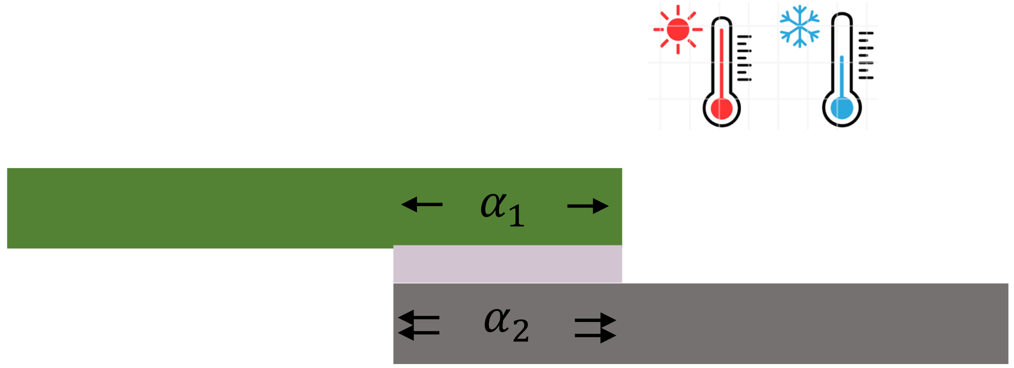
Stress-strain curves of various adhesives [1]

[1] https://www.twi-global.com/technical-knowledge/faqs/faq-what-stress-strain-behaviour-can-i-expect-adhesives-to-have

COEFFICIENT OF THERMAL EXPANSION (CTE)

- Differences in CTE of substrates will create a thermal strain when temperature changes

Thermal strain can be calculated by: $\varepsilon_{thermal} = \Delta L/L_0 = \alpha \Delta T$	
In a CFRP-Aluminum bond, assuming $\Delta T = 65$	$\alpha_{Al} = 22 \times 10^{-6} \frac{m}{m°C}$
	$\alpha_{CFRP,quasi-isotropic} \cong 0$
$\varepsilon_{thermal} \cong 0.14\%$ (thermal strain)	
If $G_{adhesive} \cong 2.76\ GPa$,	
$\tau_{thermal} = 3.86\ MPa$ (**shear stress caused by thermal effects**)	
If $\tau_{adhesive} = 30.3\ MPa$ (**shear strength of adhesive**)	
Around ***12%*** of adhesive shear strength is lost due to thermal effects	



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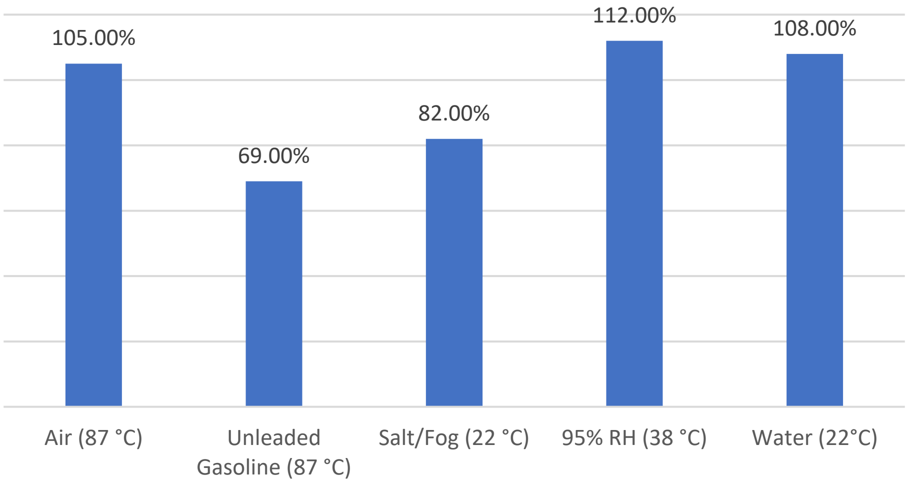
ENVIRONMENTAL FACTORS

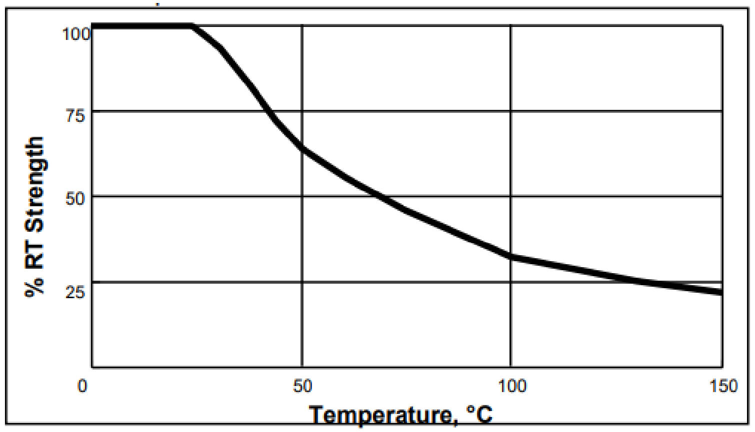
- Depending on the formulation, adhesives can gain/lose strength due to temperature/humidity changes
- Polymers will experience a drop in Tg when exposed to humidity, which effects MOL

For more details on effect of environmental factor on mechanical properties, see “Effect of cure on mechanical properties of a composite (Part 2 of 2)” A320



% initial strength after 1000 hr exposure (tested at 22 °C)

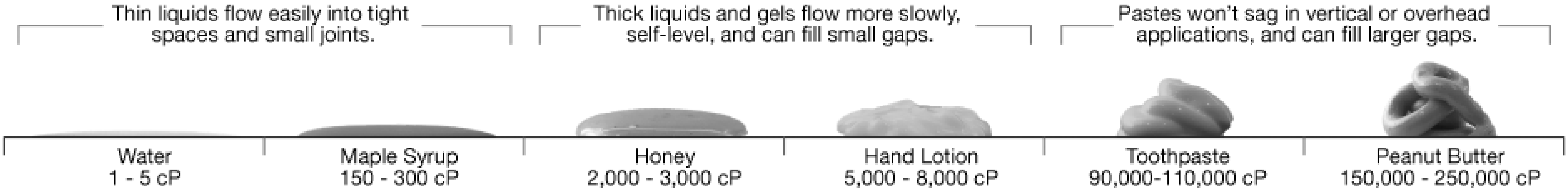
The same urethane adhesive gains strength after being exposed to moisture *(adopted from Loctite UK U-05FL datasheet)*



An urethane adhesive loses strength at higher temperatures
(Loctite UK U-05FL datasheet)

VISCOSITY

- "The resistance to flow expressed as the ratio of the applied shear stress to the resulting rate of shearing strain" - ASTM D907
  - Viscosity affects how well the adhesive flows during application and gap filling capability
  - Thixotropy: "shear-thinning" adhesives can prevent sagging during application on vertical surfaces



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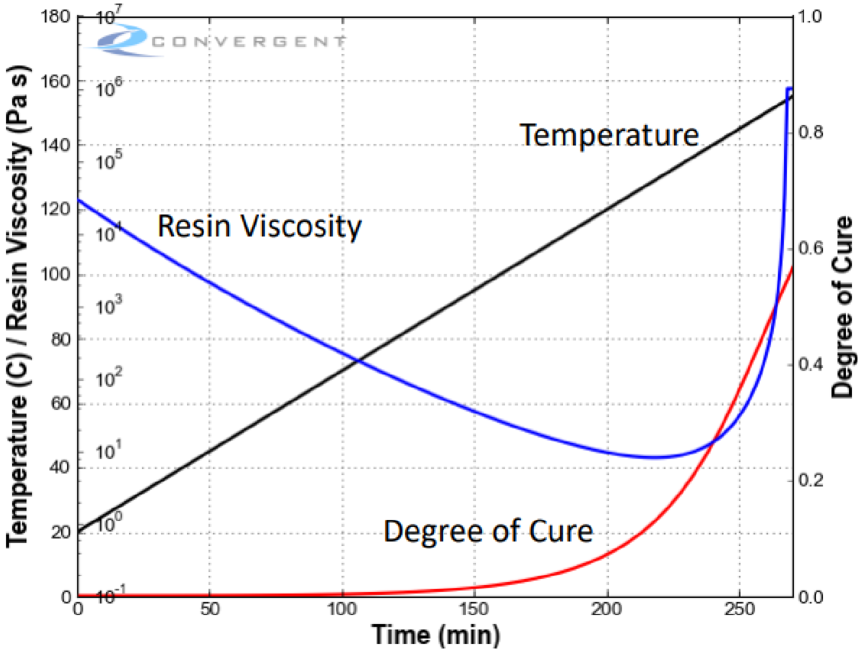

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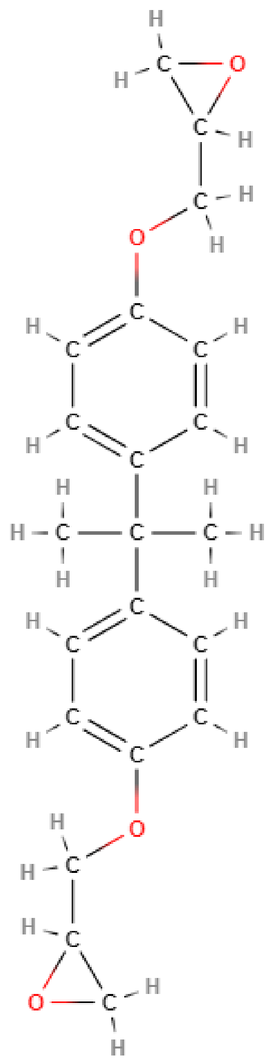
ADHESIVE FORMATS

- Adhesives are available in different formats
- Thick or thin liquid
- Paste
- Gels
  - Can be light- or UV-curable
- Putty
- Film
  - One-part adhesives that are dry to the touch and are faster and easier to apply than two-part adhesives
  - Can be conductive and replace soldering
  - Similar to prepreg but without the fibre

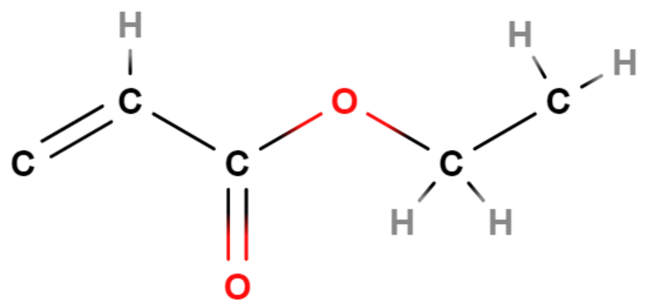
ADHESIVE TYPES

- Epoxy
  - Two-part or single-part (heat-activated)
  - Wide range of formulations
  - Toughened epoxy
    - Contains elastomeric fillers for impact resistance
  - Suitable for elevated temperatures and environments
  - High shear and peel strength
  - Suitable for bonding dissimilar materials

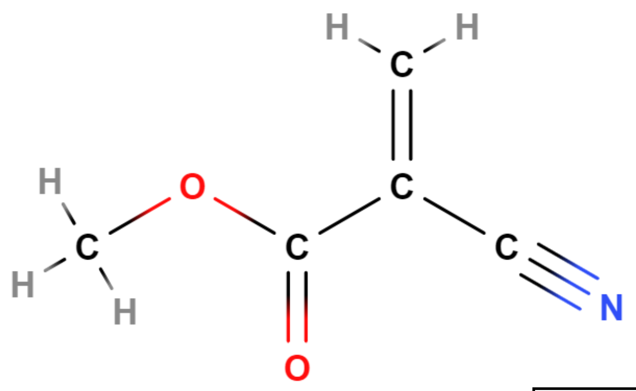


ADHESIVE TYPES

- Acrylic
  - Known as anaerobic adhesives and can cure in the absence of air
    - Two-part or UV-cured
  - Can be either thermoplastic or thermosetting
  - Typically fast-curing at room temperature
  - Low viscosity
  - Low shrinkage during cure
  - Can potentially bond to oily or poorly prepared surfaces, and generally resistant to oils and fluids



- Cyanoacrylate
  - E.g. “super glue”
  - Specific type of acrylic activated by moisture
  - Need close fit
  - Low shear strength, so not good for structural
  - ‘Instant bond’



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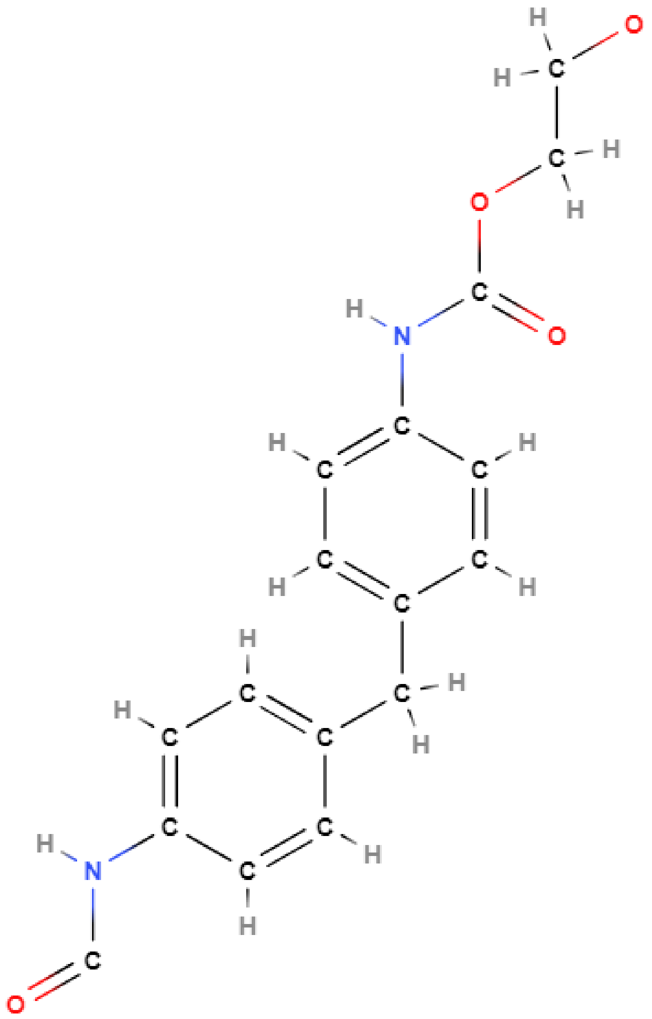
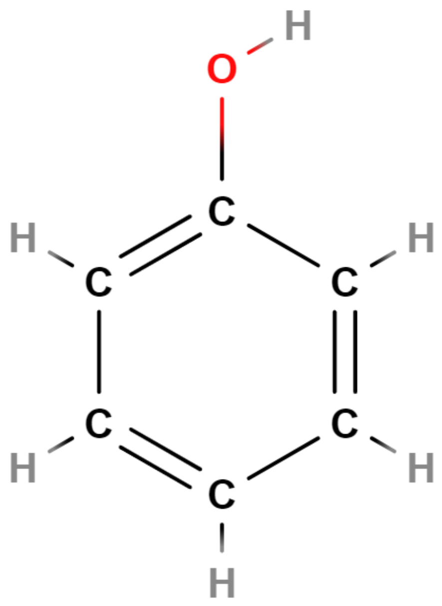
Adhesive Types

- Urethane
  - Two part or moisture-activated
  - Expands as it hardens, so it is efficient for cavity filling
  - Non-toxic
  - Flexible, due to lightly crosslinked thermoset structure
    - High peel strength and impact resistance
  - High strength at cryogenic conditions



ADHESIVE TYPES

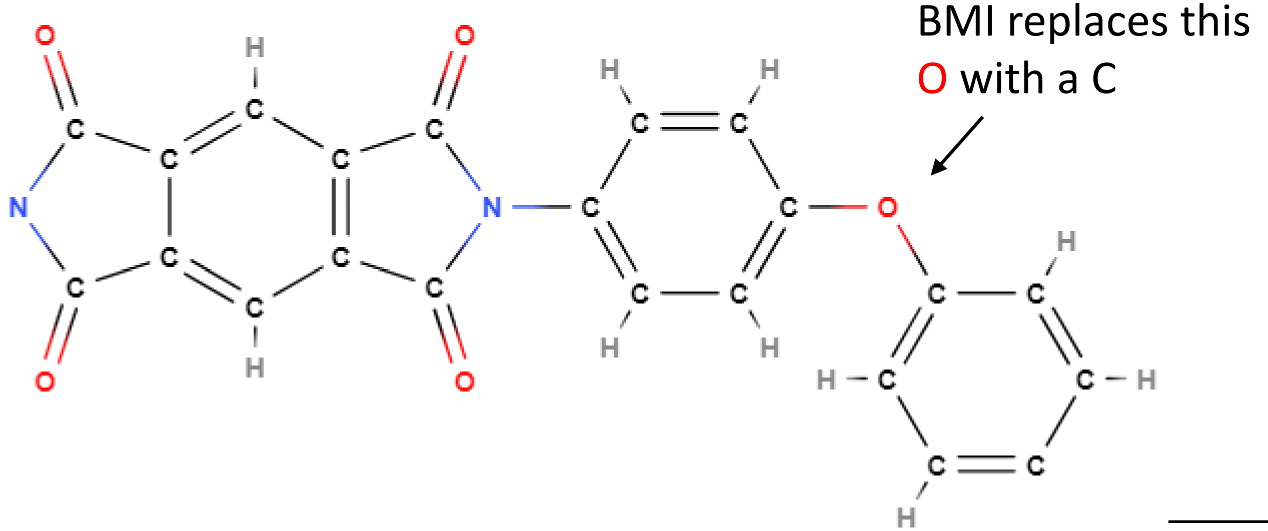
- Modified Phenolic
  - Usually alloyed with another chemical group to combine properties
    - E.g. epoxy-phenolic, vinyl-phenolic, nitrile-phenolic
  - Heat and pressure cured
  - Available as liquids and film adhesives
  - Can be expensive
  - Typically used in high performance applications
  - Often used for non-metallic honeycomb core production



S. Ebnesajjad and A. H. Landrock, “Chapter 4 - Classification of Adhesives and Compounds,” in *Adhesives Technology Handbook (Third Edition)*, S. Ebnesajjad and A. H. Landrock, Eds., Boston: William Andrew Publishing, 2015, pp. 67–83.

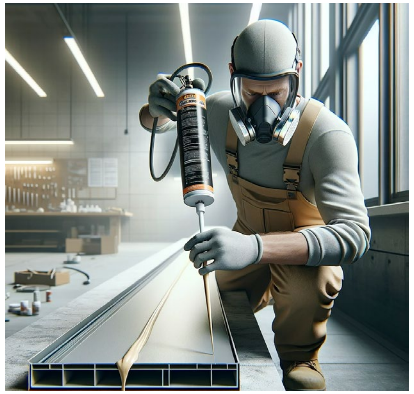
ADHESIVE TYPES

- Polyimide
  - E.g. bismaleimide (BMI)
  - Cured at high temperatures
  - Resistant to high temperatures, up to 500 ^{o}C
  - Can be used as thermoplastic and thermoset
  - Often used in film adhesives and honeycombs

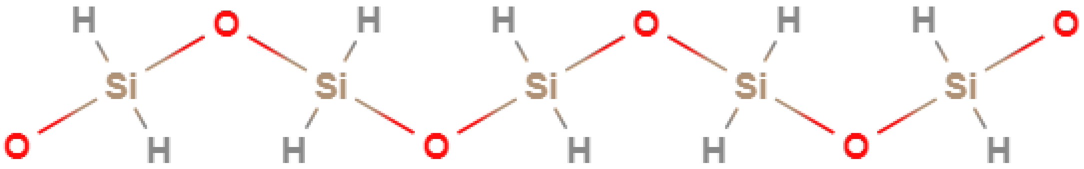


F. C. Campbell, "Chapter 8 - Adhesive Bonding and Integrally Cocured Structure: A Way to Reduce Assembly Costs through Parts Integration," in *Manufacturing Processes for Advanced Composites*, F. C. Campbell, Ed., Amsterdam: Elsevier Science, 2004, pp. 241–301.

ADHESIVE TYPES



- Silicones
  - Often used as sealant (room-temperature vulcanizing or RTV)
  - Relatively slow curing
  - Thermally and chemically stable
  - Flexible bond, allowing for even transmission of weight
  - Sometimes used for semi-permanent bonds, as silicone can be separated after curing
  - NOTE: Silicone can cause epoxies to not bond by forming a thin layer on the bonding surface, avoid cross contamination.



SURFACE PREPARATION

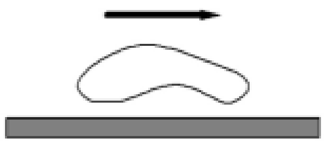
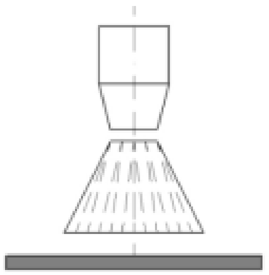
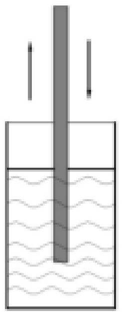
- Surface preparation can be used to enhance the bond and make it more reliable
- Surface preparation can increase the surface energy of the substrate, which improves the ability of the surface to absorb substances (wettability)
- Several methods can be used to prepare substrate surface for bonding:
  - Degreasing
  - Abrasion
  - Chemical treatment
  - Flame or plasma treatment

- Abrading the surface of substrate removes pre-existing deposits and increases the surface area, which increases mechanical adhesion

https://www.mcmaster.com/products/adhesives/

DEGREASING

- Degreasing removes dirt and other contaminants from the surface of substrates
- Solvents such as acetone, methyl ethyl ketone, or isopropyl alcohol are common for degreasing
- Degreaser is applied and allowed to dry a number of times to remove dirt and any residual solvent

Method	Schematic design
Rubbing	
Spraying	
Immersion	

Various methods of degreasing

ABRASION

- Mechanical abrasion removes heavy deposits such as oxide layers and other contaminants and increases the surface area for bonding
- Common mechanical abrasion methods include
  - Abrasion with sandpaper
  - Sandblasting
  - Wire brushing

- The surfaces must be cleaned before and after abrasion
- Some abrasion techniques may pose health hazards
- Grit blasting may cause deformation on thin laminates

CHEMICAL TREATMENT

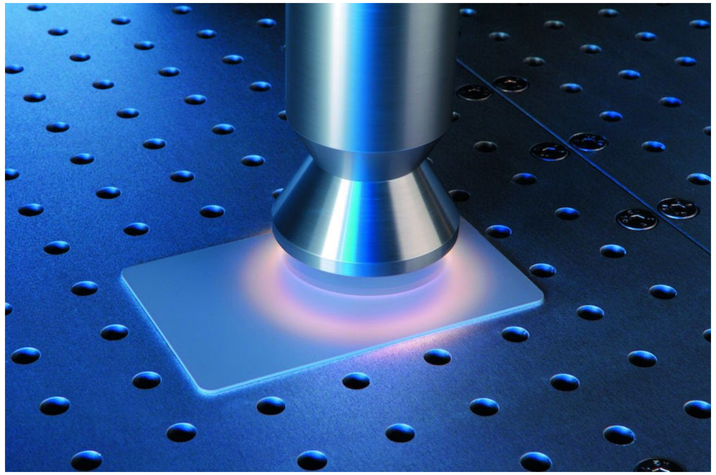
- Chemical treatment techniques change the physical and chemical properties of the surface to improve adhesion
  - Eg: etching
- Recipes are available in the literature for different substrate materials which optimizes the bonding capabilities

FLAME TREATMENT

- Chemical treatment or mechanical abrasion is not effective for some materials, such as nylon
- Techniques such as flame treatment change the surface's reactivity and improves adhesion
- With flame treatment, the surface is exposed to a gas flame for a few seconds which oxidizes the surface and increases the surface energy
- Flame treatment might cause warping of the surface

CORONA AND PLASMA TREATMENT

- Corona treatment involves generating discharge by ionizing the air between two closely spaced electrodes
- The discharge interacts with substrate surfaces to form free radicals, which rapidly react with oxygen and increase the substrate surface energy
- Plasma treatment is usually carried out under partial vacuum
- Plasma treatments often provide better stability than the previously discussed methods



SURFACE PREPARATION - CFRP

- Common procedure:
  - Wipe with acetone, sand with medium-grit, wipe with a clean dry cloth, then repeat acetone wipe at room temperature
  - Sources, including ASTM D2093*, Lees (1984)**, Davies (2021)***, generally agree on: degrease before and after one type of sanding (either medium or fine grit)

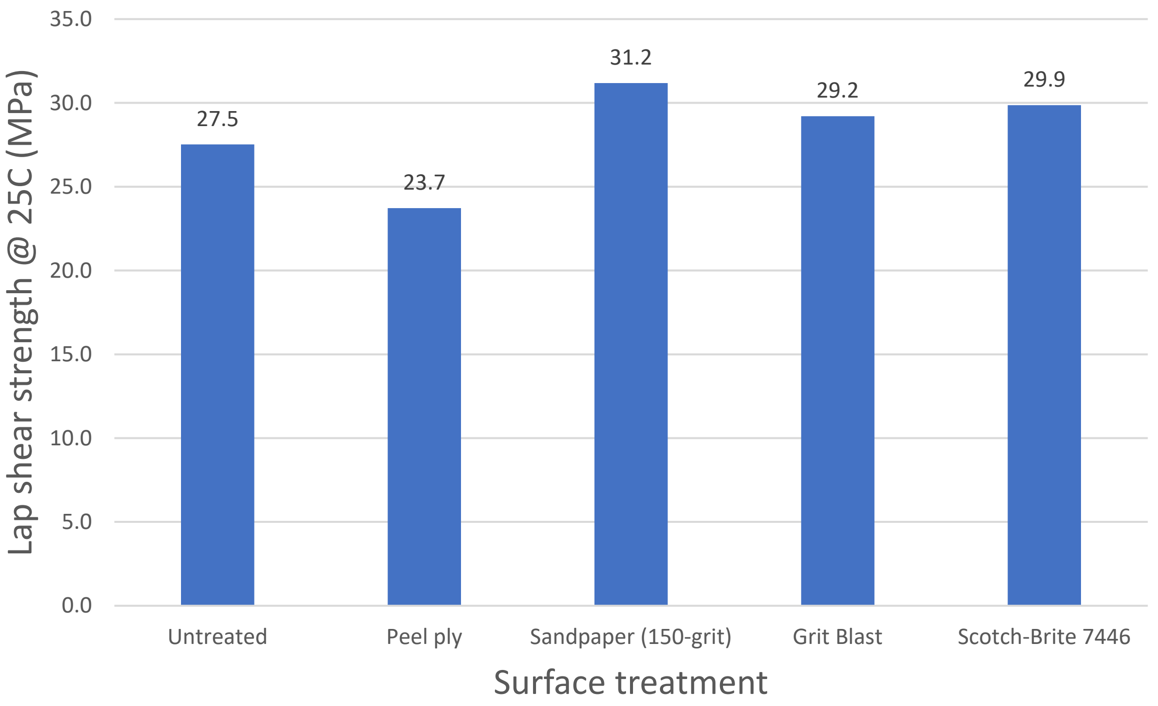
*"Standard Practice for Preparation of Surfaces of Plastics Prior to Adhesive Bonding." Accessed: Nov. 14, 2023. [Online]. Available: https://www.astm.org/d2093-03r17.html

**W. A. Lees, "Surface preparation," in Adhesives in Engineering Design, W. A. Lees, Ed., Berlin, Heidelberg: Springer, 1984, pp. 81–91. doi: 10.1007/978-3-662-11032-4_4.

***P. Davies, "16 - Adhesive bonding of composites," in Adhesive Bonding (Second Edition), R. D. Adams, Ed., in Woodhead Publishing Series in Welding and Other Joining Technologies. , Woodhead Publishing, 2021, pp. 499–524. doi: 10.1016/B978-0-12-819954-1.00007-1.

SURFACE PREPARATION EXAMPLE WITH CFRP

- Sanding can offer better strength than some peel plies
  - Note: some peel plies are treated with PTFE or silicone which may leave contaminants that compromises the adhesion



Lap shear strength vs surface treatment

[1] Adopted from A. V. Pocius, *"Adhesion and Adhesives Technology - An Introduction (4th Edition),"* 2021, [Online]. Available: https://app.knovel.com/hotlink/toc/id:kpAATAIE11/adhesion-adhesives-technology/adhesion-adhesives-technology

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SURFACE PREPARATION - CFRP

- Internal diameter grit blaster example
- Uses aluminum oxide or glass beads as blast media
- Possible considerations:
  - Typically designed for pipes, so within a rectangular profile, the abrasion might not be uniform
  - Therefore, optimum parameters for grit blasting have to be determined experimentally

"Internal Pipe Blasting Equipment - Mod-u-blast." Accessed: Nov. 09, 2023. [Online]. Available: https://www.modublast.com/newpage1

C. Li, S. Viswanathan-Chettiar, F. Sun, Z. Shi, and B. Blackman, "Effect of CFRP surface topography on the adhesion and strength of composite-composite and composite-metal joints," *Composites Part A: Applied Science and Manufacturing*, 2023

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SURFACE PREPARATION - NYLON

- Common procedure:
  - Wipe with acetone, sand with medium-grit, wipe with a clean dry cloth, then repeat acetone wipe at room temperature
    - Sources, including ASTM D2093, Wegman and van Twisk (2013)[1], and others agree on degreasing before and after some kind of sanding (either medium or fine grit)
- Consider mechanical locking features
- Corona/plasma treatment improves the adhesion of thermoplastics (e.g. Nylon) significantly[2]

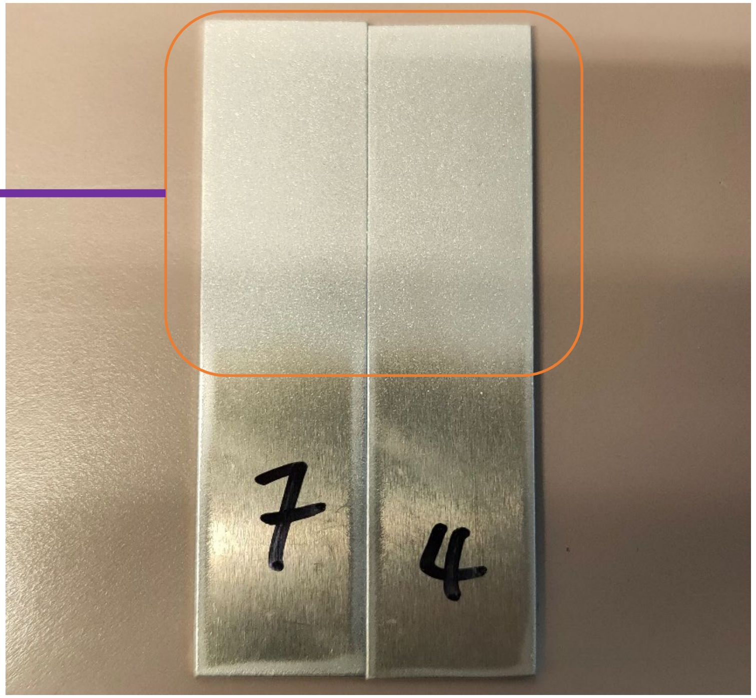
[1] R. F. Wegman and J. Van Twisk, "8 - Plastics," in *Surface Preparation Techniques for Adhesive Bonding (Second Edition)*, R. F. Wegman and J. Van Twisk, Eds., William Andrew Publishing, 2013

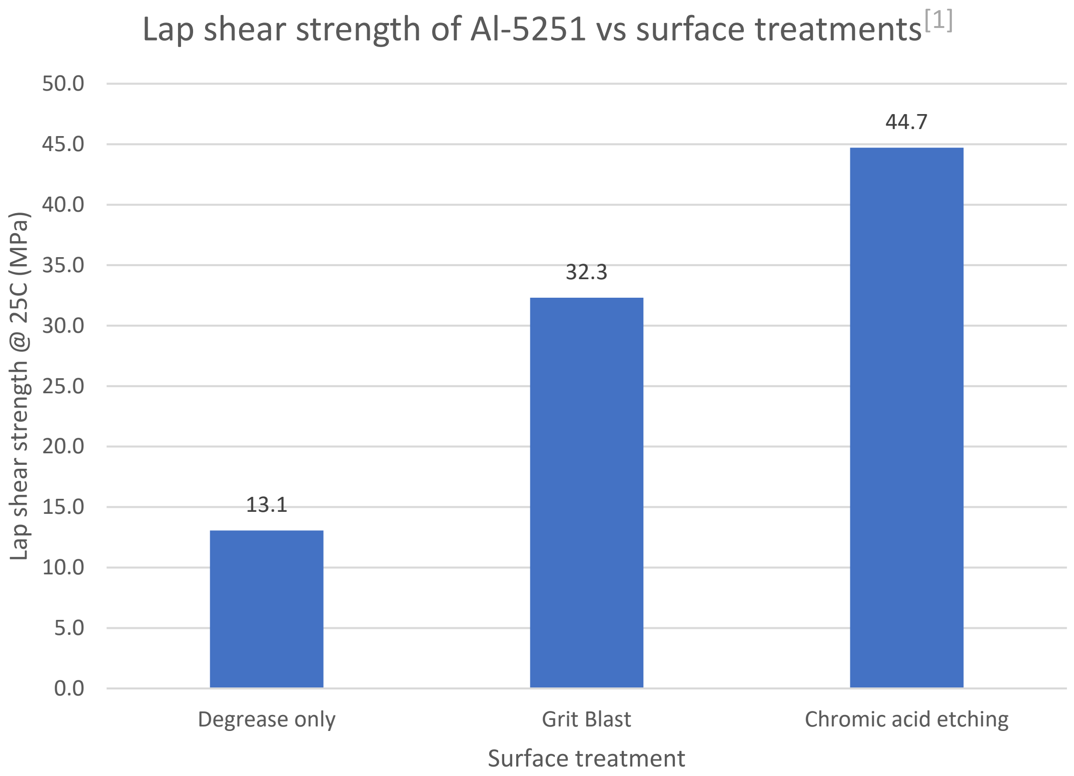
[2] G. A. Wade and W. J. Cantwell, "Adhesive bonding and wettability of plasma treated, glass fiber-reinforced nylon-6,6 composites," *Journal of Materials Science Letters*, 2000

SURFACE PREPARATION EXAMPLE WITH ALUMINUM

- Grit blasting is a viable method
  - Results in weaker bond than chemical etching
  - However, significantly better than only degreasing
  - Silane primer can be used shortly after the surface preparation to protect from contaminations and promote adhesion*

Grit-blasted area





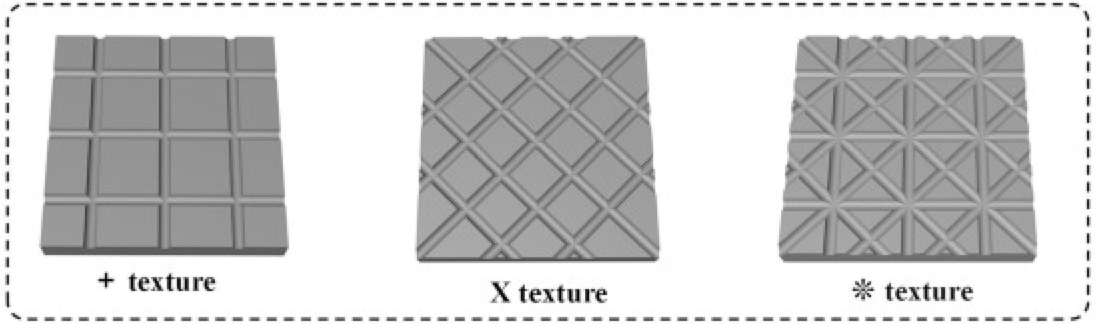
[1] Adopted from G. W. Critchlow, “4 - Surface pretreatments for optimised adhesive bonding,” in Adhesive Bonding (Second Edition), R. D. Adams, Ed., in Woodhead Publishing Series in Welding and Other Joining Technologies. , Woodhead Publishing, 2021, pp. 109–132.

SURFACE PREPARATION – ALUMINUM AND CFRP

- Generally not recommended to bond Al directly to CFRP due to significant difference in CTE and possibility of galvanic corrosion
- Non-conductive adhesive and uniform bond line thickness creates a barrier which prevents galvanic corrosion
- More compliant adhesive (such as urethane) can reduce thermal stresses caused by difference in CTEs between adherends
- A ply of glass fibre is commonly used between Al and CFRP

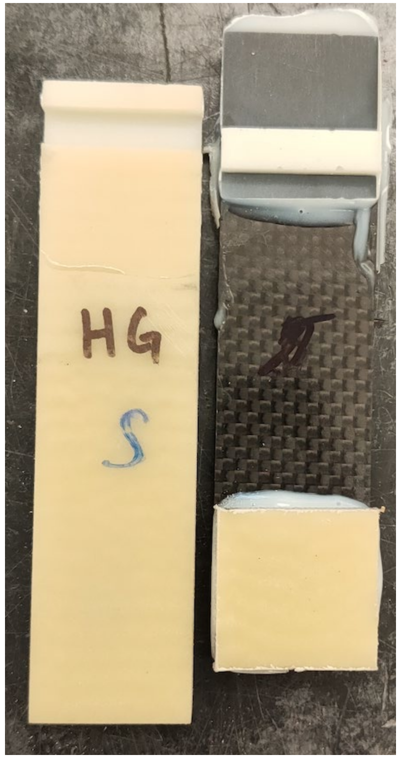
MECHANICAL LOCKING

- Varying the geometry of the grooves can lead to differing lap shear strengths



Examples of laser etched surfaces [1]

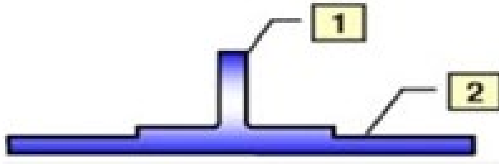
Vertical groove



Horizontal groove

[1] https://www.sciencedirect.com/science/article/pii/S0263823123007152

TYPES OF PROCESSING OF BONDED JOINTS

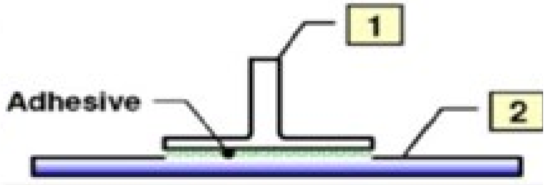


Co-Curing

Components cured together

- Both components uncured

May include additional adhesive and/or continuous structural plies common to both components

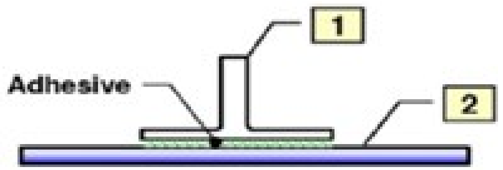


Secondary Bonding
(Structural Bonding)

Components bonded together with separate bonding operation

- Component 1 cured*
- Component 2 cured*

* Or metal



Co-Bonding
(Structural Bonding)

Components bonded together during cure of one of the components

- Component 1 cured*
- Component 2 uncured

OR

- Component 1 uncured
- Component 2 cured*

*Or Metal

May not include additional adhesive

NOTE: Different companies in different industries may have different interpretation of these terms

Adapted from: https://www.sto.nato.int/publications/STO%20Meeting%20Proceedings/STO-MP-AVT-266/MP-AVT-266-06.pdf

Thank you for joining us!

Keep an eye out for upcoming AIM events:

Introduction to Adhesive Bonding – Part II
Hosted by Dr. Casey Keulen
February 28, 2024
https://compositeskn.org/KPC/A355

And don't forget to visit the KPC for more information:

https://compositeskn.org/KPC

Today's Webinar will be posted at:
https://compositeskn.org/KPC/A354

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