NREL PV Module Reliability Workshop (Feb 24, 2015)

Adhesion - Considerations, Testing and Interpretation

Presenter

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3M headquarters in St. Paul, MN, USA; Chemical Engineer B.S. degree from Iowa State University, 1985; 28 years at 3M Company in various divisions; experience with PSA tapes, epoxies, urethanes and fluoroelastomers; ~20 years of Experience with Adhesives; 6 years of tapes and adhesives experience related to the solar industry.

Topics:

1. Adhesion and Testing
    - Failure Modes
    - Types of Forces
    - Types of testing

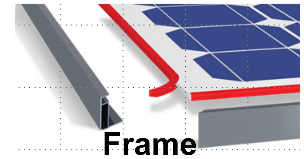
2. Material & Adhesive Characteristics
    - Perform differently – Difficult to compare materials

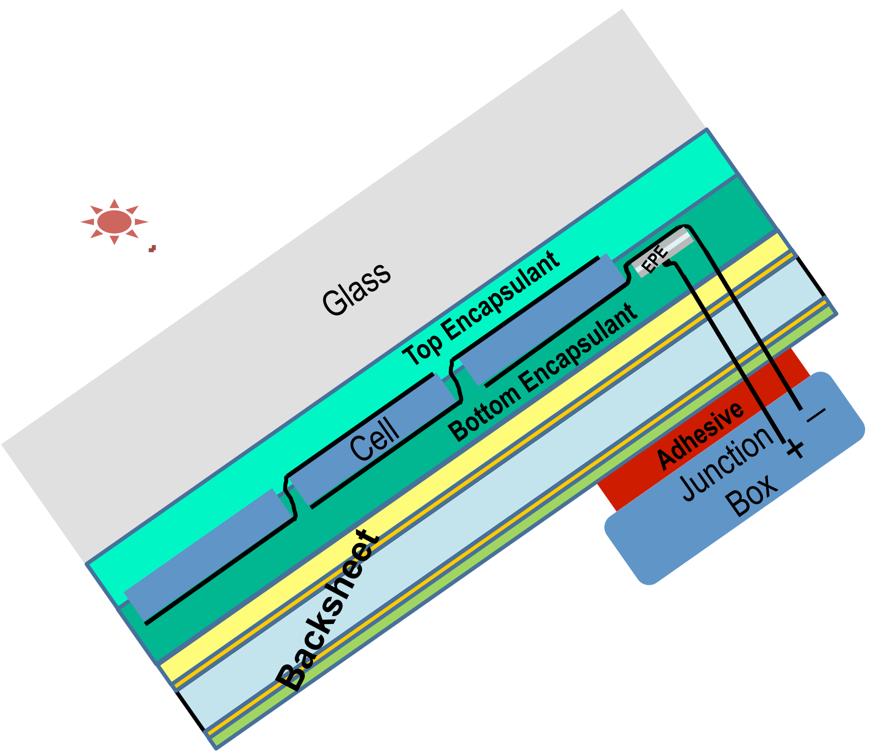
3. Many Variables Impact Test Results and Performance
    - Material types
    - Time & Temperature
    - Environmental
    - Aging (outside scope of this discussion)

4. Rigid PV Module Application
    - Relevant Forces & Testing

Why is Adhesion Important In PV Modules?

Many Adhesion Areas in a Module Can Fail



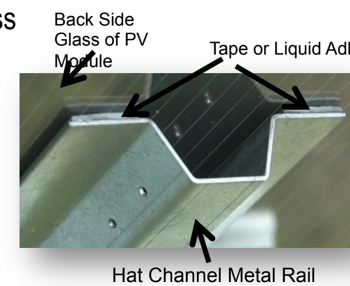


Bulk (with-in a material)

- Each material has its own bulk characteristics
- Some materials (e.g. Backsheets, EPEs) have layers within the material that may have additional Interfacial adhesion issues as well as different bulk characteristics

Interfaces

- Front Glass to Encapsulant
- Encapsulant to Cells and Ribbons
- Encapsulant to Backsheet or Backside Glass
- J.Box to Backsheet
- Rails to Backsheets or Backside Glass
- Frames to Backsheets or Backside Glass
- Edge Seals – Glass/Glass Thin Film



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Adhesion

- Molecular attraction that holds material together (Single material or multiple layers)
- Does it stick together? Is it resistant to de-bonding?

Modes of Failure (De-bonding)

- Cohesive Failure (CO) – Bulk layer
- Adhesion Failure (AF) - Interface between layers

Is CO failure required or is a high force to failure sufficient?

Not Always easy to identify failure mode

- Mixed failure modes (Some CO & some AF)
- Thin bulk layer surface failure (Can be difficult to see)

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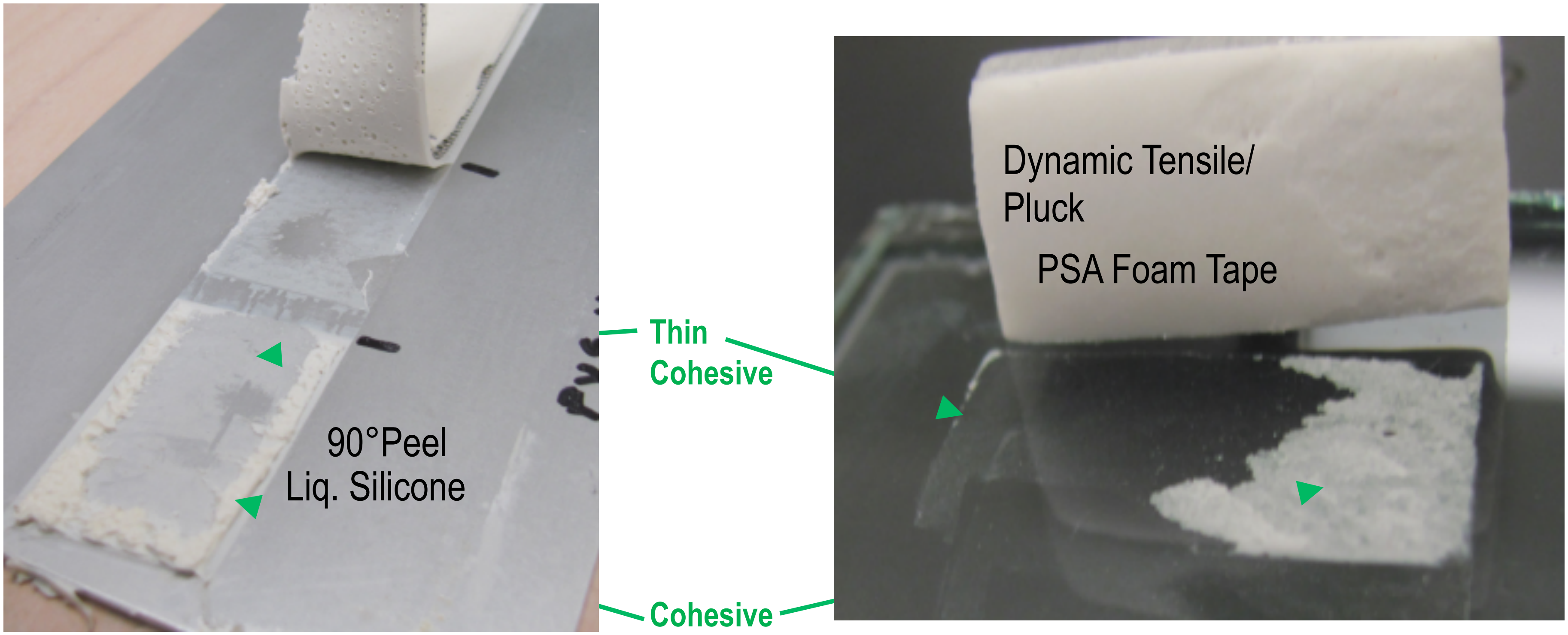
Can Be Difficult To Say If Cohesive (CO) or Adhesion (AF) Failure Some Times



- Not To Hard -But Some May Say Mostly AF
- But Really Thin CO Film

- Difficult – Most would Say Mostly Mixed with 35% CO and 65% AF to Glass
- But Really CO – 35% CO & 65% Thin CO Film

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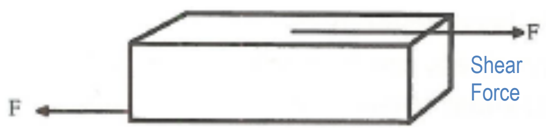
Types of Forces

1. Shear



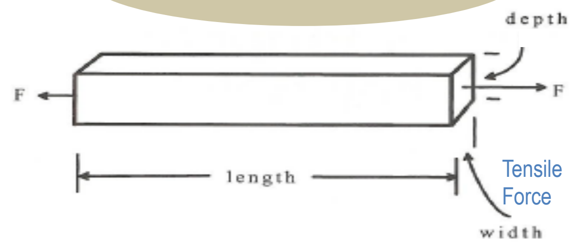
$$Stress = Force/Area$$

Force is Parallel to Bond area

Shear
Force

Area

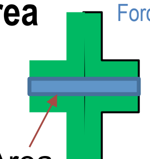
2. Tensile/Pluck



$$Stress = Force/Area$$

Force is Perpendicular to Bond area

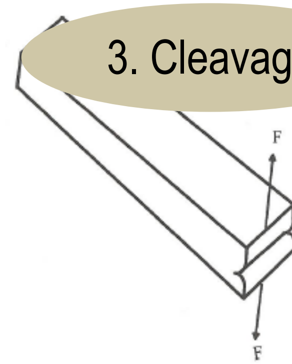
Tensile
Force



Area

Force

3. Cleavage

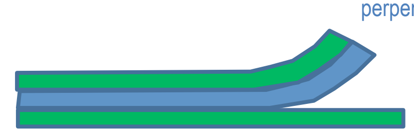


$$Force/Width = Energy/Area$$

Fracture Mechanics

Fracture Energy to propagate a crack

Tensile Force applied
perpendicular to an edge



More complex to understand what cleavage results mean.

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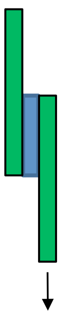
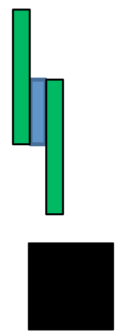
Force Applied In Different Test Modes

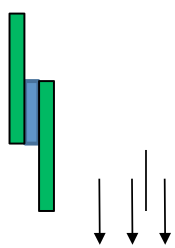
a. Constant Rate - Displacement (or Force)



b. Constant - Force (or Displacement)

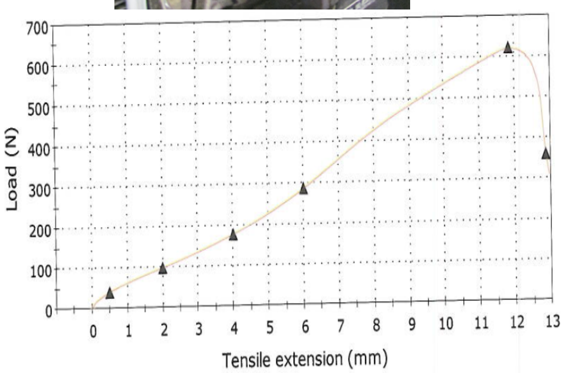


c. Cyclic – Displacement or Force goes up and down

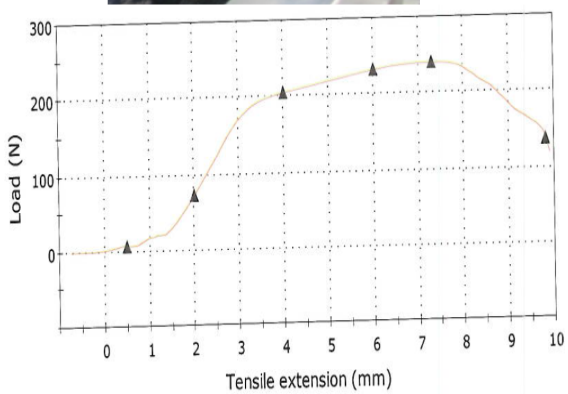


Constant Rate Displacement Lab Test Examples

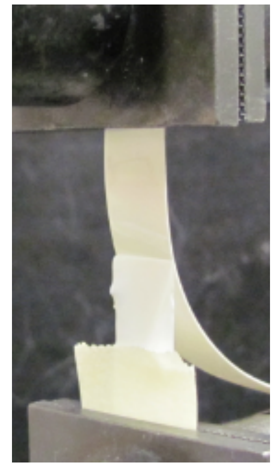
Overlap Shear

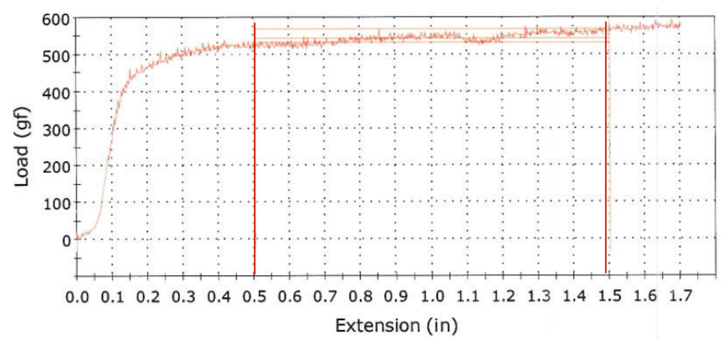


T Block Tensile/pluck



Peel





Williams and Kauzlaurich, *Strain*, **47**(5), 439-448, 2011

Comments on Peel Testing

- Peel is a special class of a cleavage test
- Easy to run
- Complex with regards to understanding what it means relative to performance in an application; Fracture Energy
- **Many variables impact results – Difficult to compare materials unless identical:**
  - Configurations of Peel Test (e.g. 90°,180°,T-Peel, various fixtures, …….)
  - Pull speed (Rate)
  - Temperature
  - Humidity
  - Dwell time
  - Adhesive (Material Characteristics, thickness)
  - Substrates (Material Characteristics, thickness)
  - **Backing (Material Characteristics, thickness) - Can have large Impact**

$$G_a = \frac{P}{b}\left(1+\varepsilon_a - \cos\theta\right) - h\int_0^{\varepsilon_a} \sigma \cdot d\varepsilon - G_{db}$$

fracture energy | Total work done | Energy used to stretch peeling arm material | Energy dissipated in plastic bending of peeling arm

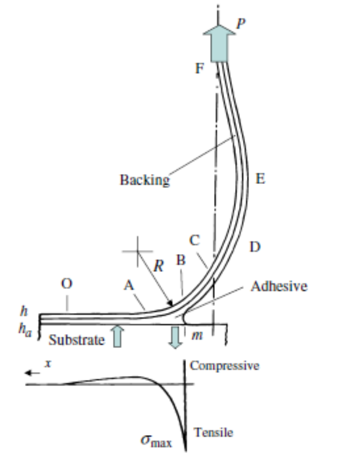


Figure 1: Fixed arm peeling with $\theta = 90°$. The backing of thickness h is attached to the rigid substrate by an adhesive layer of thickness h_a. The peel force P is equilibrated by a distribution of normal stress conveyed by the adhesive to the substrate which is tensile at the point of separation but is compressive at larger values of coordinate x. Dimension R represents the root radius

Effect of Backing Thickness in Conventional Peel Test

Williams and Kauzlaurich, *Strain*, **47**(5), 439-448, 2011

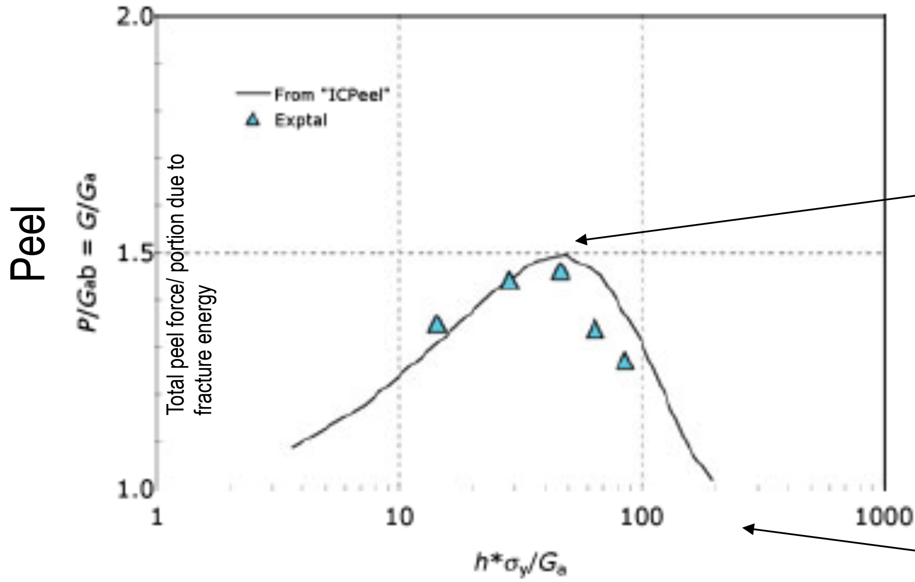


Figure 14: Plot of ratio of total peel energy to de-adhesion energy G/G_a to $h\sigma_y/G_a$ for Mylar backing and 200MP adhesive. Solid line form *ICPeel*

Peel can be 50% higher due to backing effects

- Same adhesive
- Same backing except thickness

Backing thickness range: 75 to 350 µm

Comments on Peel Testing (Continued)

- Peel may not be the best test to use to simulate the forces of PV module applications
- Be cautious in the interpretation of peel data; conclusions can be misleading

Only thing worse than no data is "bad" or misleading data !

When to use peel:

1. Understanding the impact of dwell on adhesion build – How much time should you give something to reach its best interfacial adhesion?
2. QC tests during manufacturing of an adhesive or identical construction - Are things changing?
3. If application is in a peel mode

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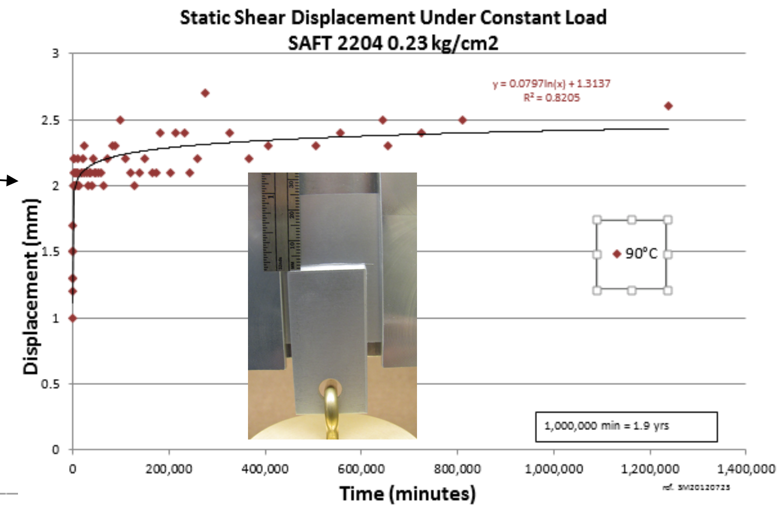
Example Of Constant Load Lab Tests

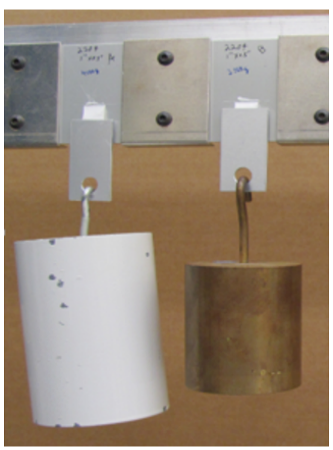
One Condition

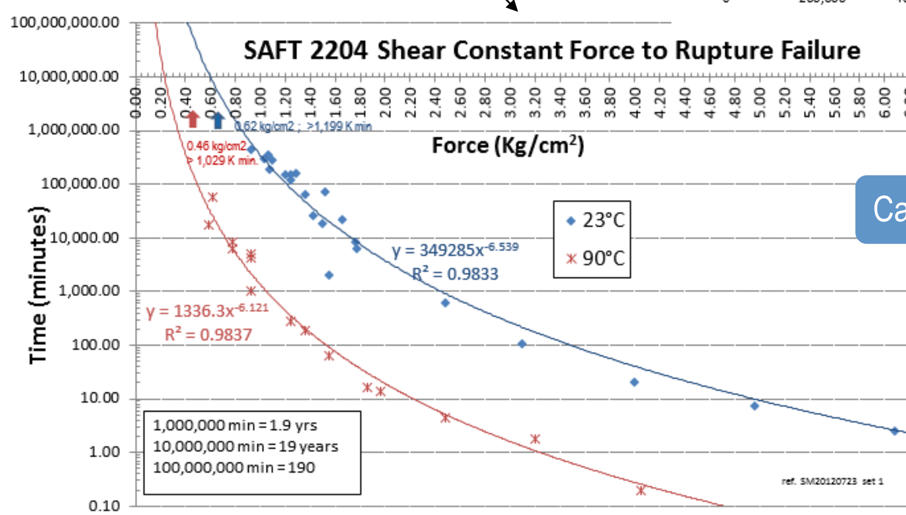
- Pass/Fail
- Measure Displacement as a f(time).



Multiple Conditions

- *Constant Force To Rupture* (CFTR) Failure Analysis
  - Creates projections on expected failure point
  - Time Temperature Superposition





Can be Done in Shear or Tensile

Adhesive Types

Adhesive State Changes – During Bonding

- Curing Liquids
  - forms bond in liquid (unreacted) state; Crosslinks during cure
  - e.g. epoxies, reactive polyurethanes
  - Some may become glassy (e.g. structural epoxy & acrylics)
- Hot Melt Adhesives (thermoplastics)
  - melt crystals to form bond; solidifies on cooling to give strength
  - Can have crosslinking (e.g. encapsulants)
  - e.g. polyamides, thermoplastic polyurethanes, polyolefins

No Change in Adhesive State – During Bonding

- Pressure Sensitive Adhesives (PSA)
  - forms bond with contact time and pressure
  - relies on viscoelasticity to provide resistance to debonding

Many Variables Impact Adhesion Performance

- Environmental Aging
  - No Change
  - Crosslinking
  - Degradation (Breaking Molecular Bonds)

- Dwell Time
  - Time to each optimal performance - Surface wet out & chemical reactions
  - Be careful, Dwell can cause issues when comparing if not allowed to reach optimal performance

- Adhesive, Substrate, & Backing
  - Bulk Characteristics
  - Surface Chemistry
  - Thickness

- Rate and Temperature
  - Different for different material classes

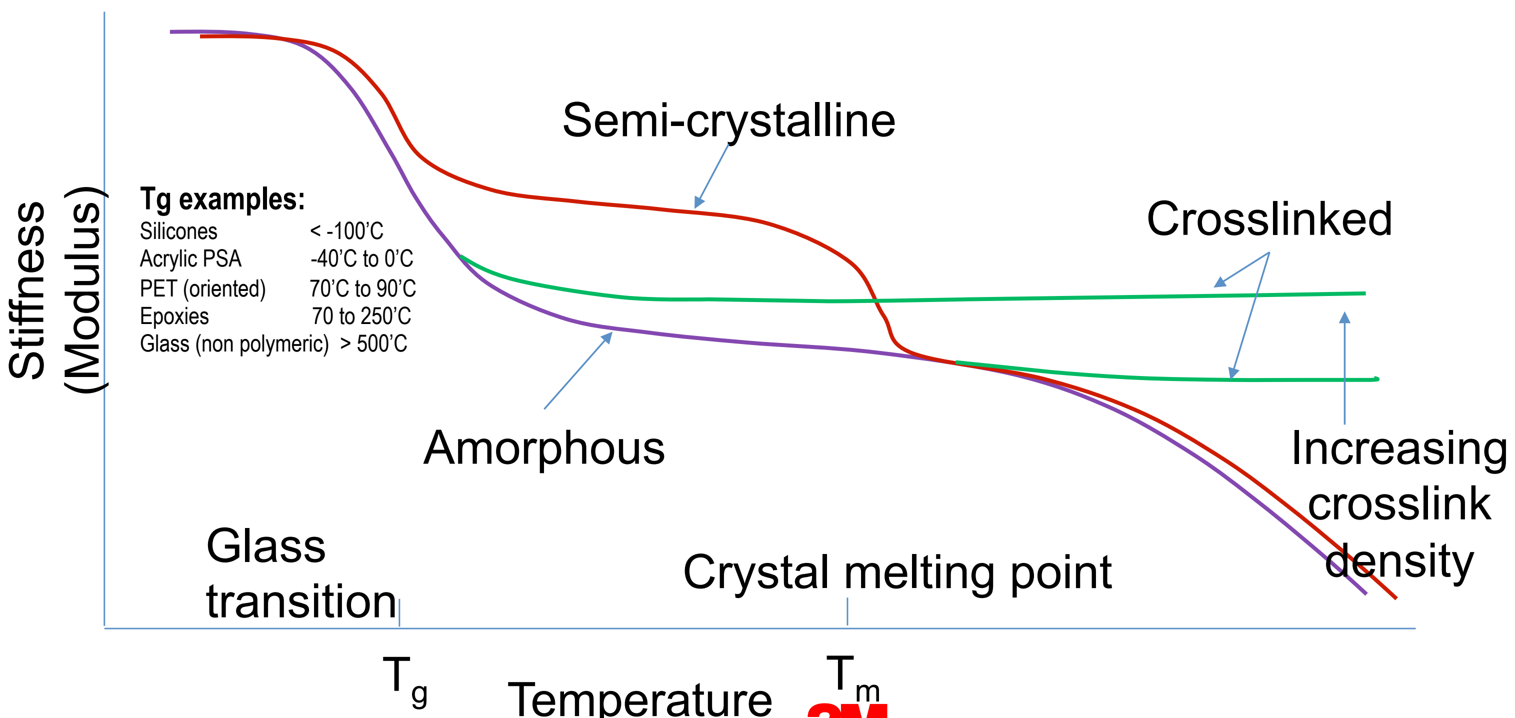
Adhesive and Substrate Properties

Stiffness Dependence on Temperature for Polymers

- Stiffness is impacted by Temperature
- Stiffness is also impacted by Rate (Speed)

Tm examples:

Silicones	Amorphous
Acrylic PSA	Amorphous
PET (oriented)	260'C
EVA (40%-9%)	50'C to 100'C
Glass	Amorphous



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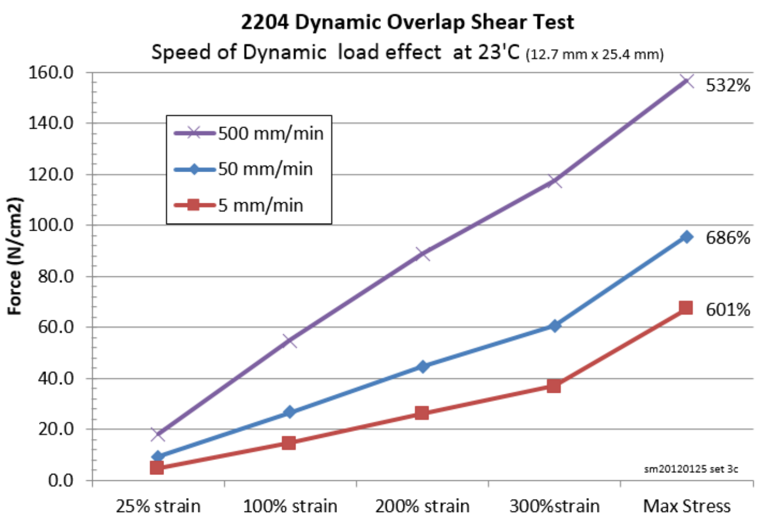
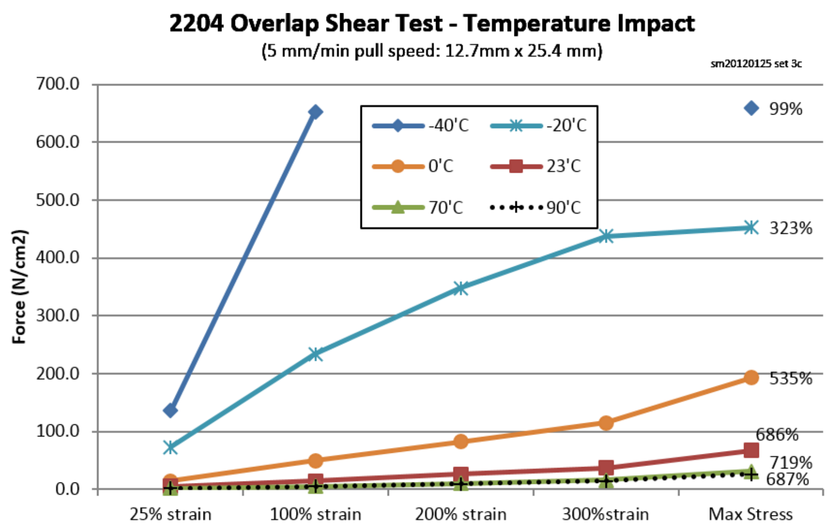
Temperature & Test Rate - Significant Impact On An Adhesive

- Some material are influenced more by this than others…..e.g.silicone versus acrylic PSA
- Need to ask what is important in the application

Effect of Rate on Adhesive Strength

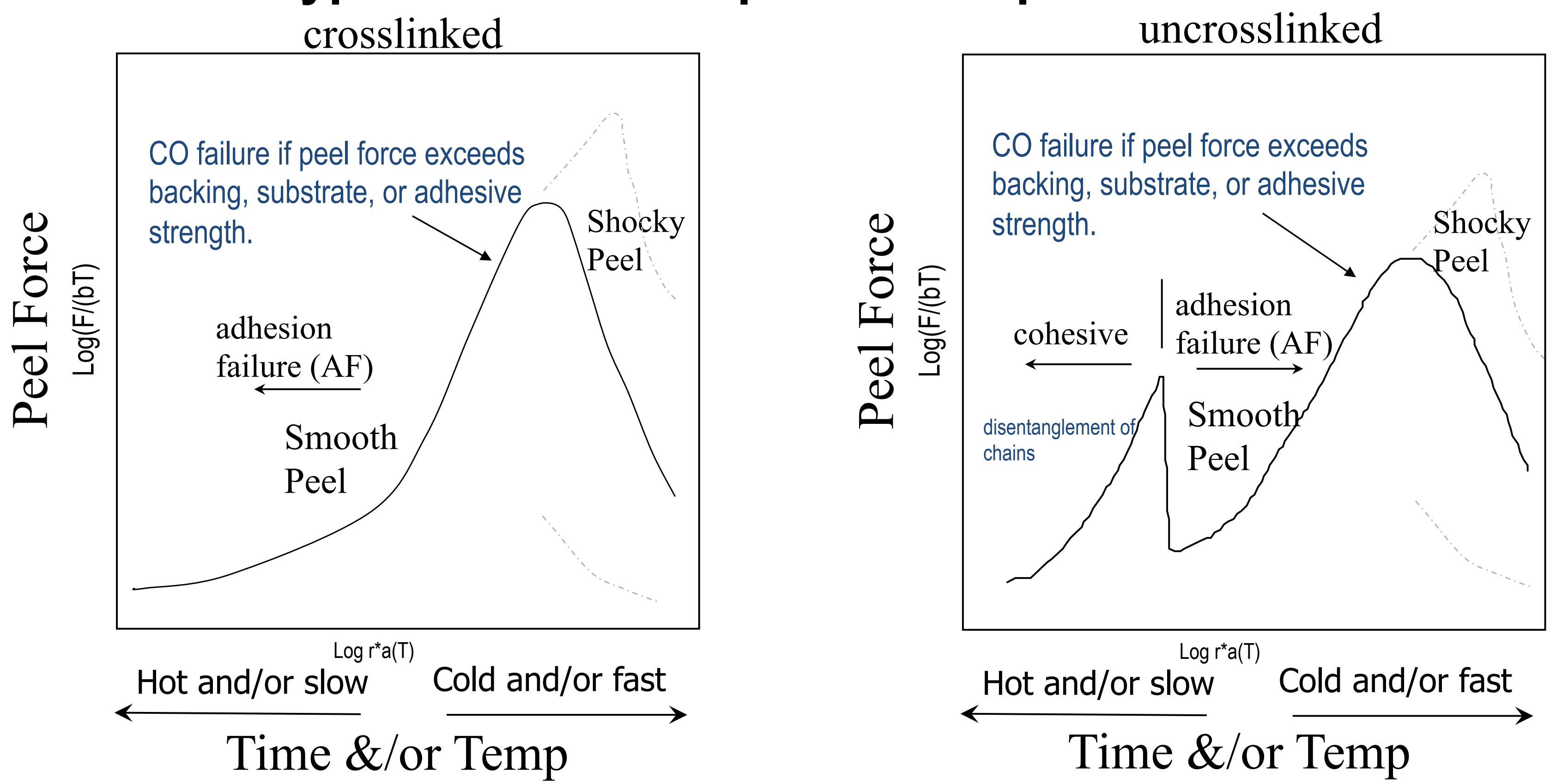


Effect of Temperature on Adh. Strength



Technique that can be used to relate time & temperature
– time temperature super-positioning (hot is like slow; cold is like fast) → Master curve

Typical Rate & Temperature Impact On Peel



What is the temperature and rate that should be used to represent the application?

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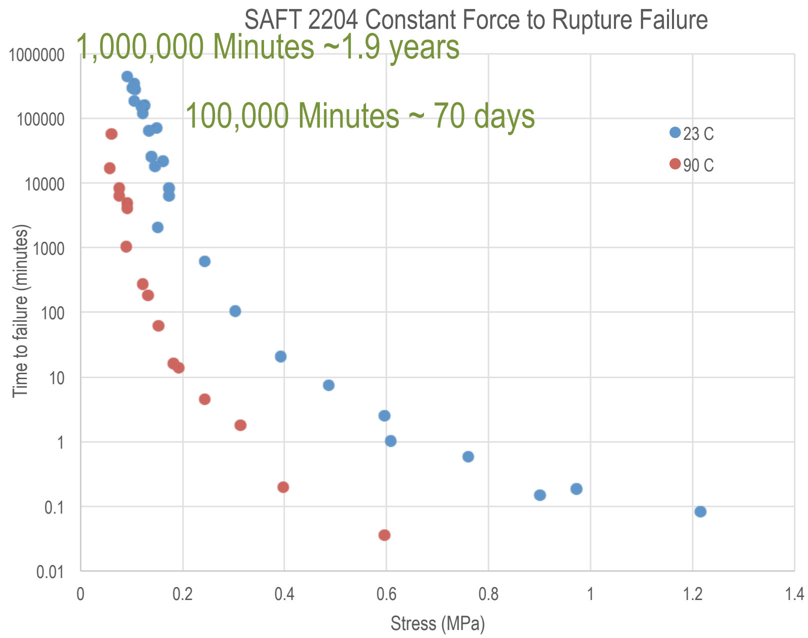
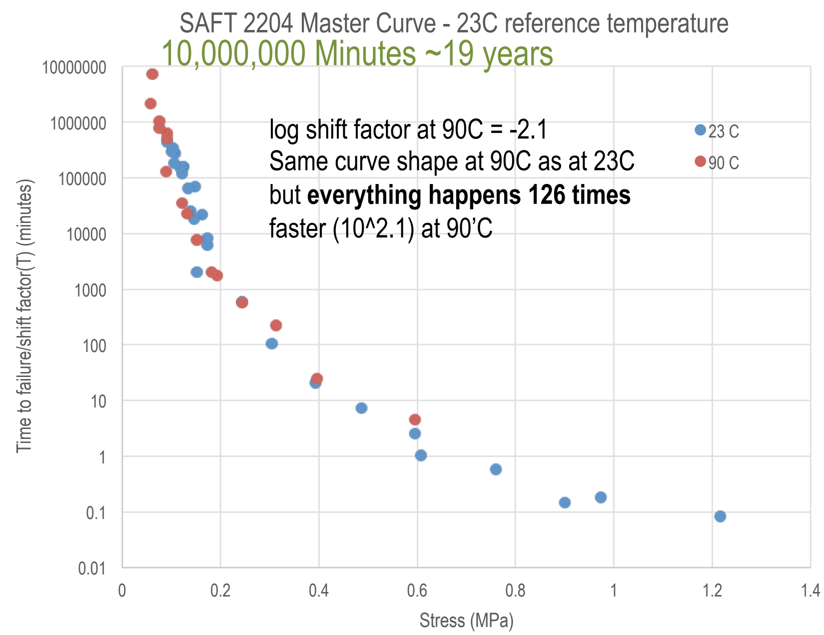
Time Temperature Super-postitioning Shear CFTR Example

Time and temperature dependence - failure times in constant shear load of 2204 foam tape

Time-temperature superposition





Time Temperature Super-posititioning – When It Doesn't Work

When does time-temperature superposition not work?

- Semi-crystalline materials
  - Not work with materials that are Crystalline - melting of crystal phase produces softening that will not be seen below T_m regardless of time scale of test
- Multi-phase materials
  - different phases have different sensitivity to temperature
- Temperature causes irreversible changes/degradation of material

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Each Application is Unique - Need to ask the following

- **What are the critical forces that can cause failure?**
  - Type - Shear, Tensile, Cleavage
  - Mode - Constant Load, Constant Rate, cyclic
  - Limit - maximum forces requirement

- **What are reasonable tests that can be run to help get a perspective on performance?**
  - Usually have to make compromises to do the best you can on a small scale
  - Need to validate &/or correlation with field results

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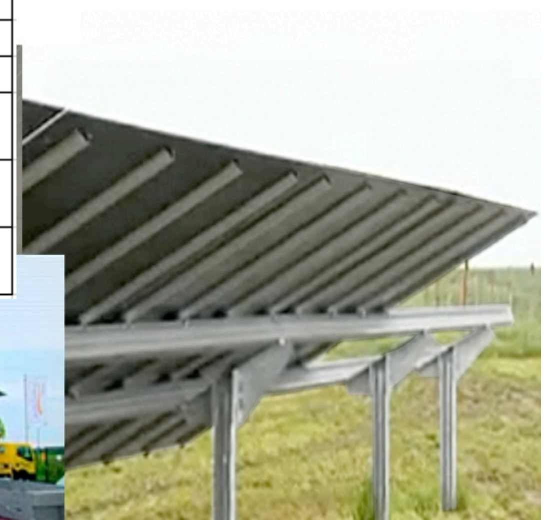
PV Example - Rail Bonding Adhesives In Rigid PV Modules

What are the type of forces on this adhesive?

What are test methods that simulate the forces?

			Type of Lab Test						
			Tensile/Pluck			Shear			Cleavage
			Constant Rate Displacement		Constant Load	Constant Rate Displacement		Constant Load	peel
			Slow	Fast		Slow	Fast		
application characteristics	***Forces***	importance							
Ability to handle stress from an adhesion perspective Does It stick?	***gravity***	***9***				1		9	
	wind gusts	***9***		9	1		9	1	
	Installation/Handling	***9***		9	1		9	1	1
	Thermal variations (CTE mismatch)	***3***				3			3
	Snow Loads	***3***				1 (cold)		9 (cold)	
	IEC& UL Mechanical Load Test				9				

- **Fast Tensile/Pluck**
- **Fast Shear**
- **Constant Load Shear**



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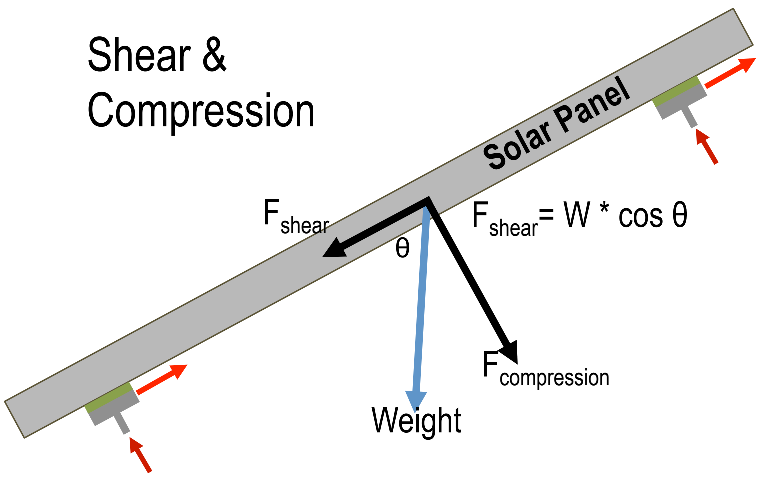
Example of Forces on Rail Bonding Adhesives In Rigid PV Modules

- **Gravity**

  Panel Weight – Above Ambient Temperatures
  Long time Scale – 25+ years
  Snow Load – Cold Temperatures

What are the type of forces on this adhesive?

Shear & Compression



What are test methods that simulate the forces?

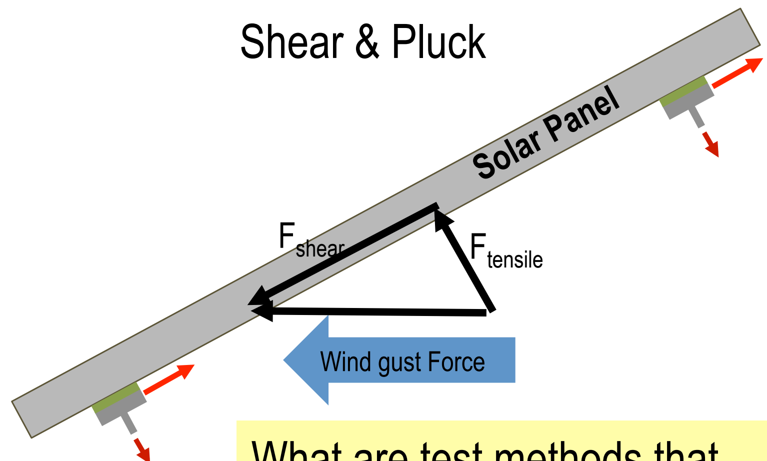
Shear & Compression

- **Wind Gusts**

  (Building codes use 3 second wind gusts)

What are the type of forces on this adhesive?

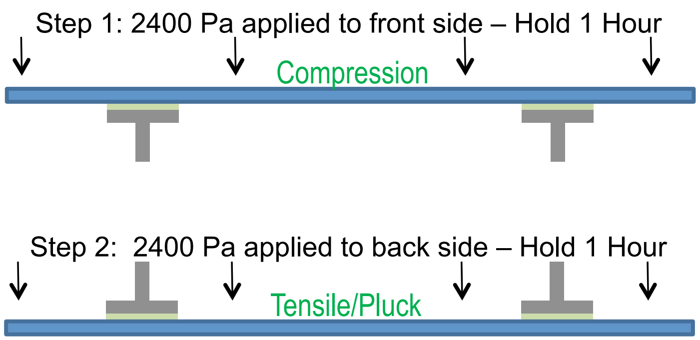
Shear & Pluck



What are test methods that simulate the forces?

Shear & Pluck

Mechanical Load Test - IEC & UL Standard



Repeat steps 1 & 2 three times.
If want heavy snow load approval, replace last front loading with 5400 Pa.

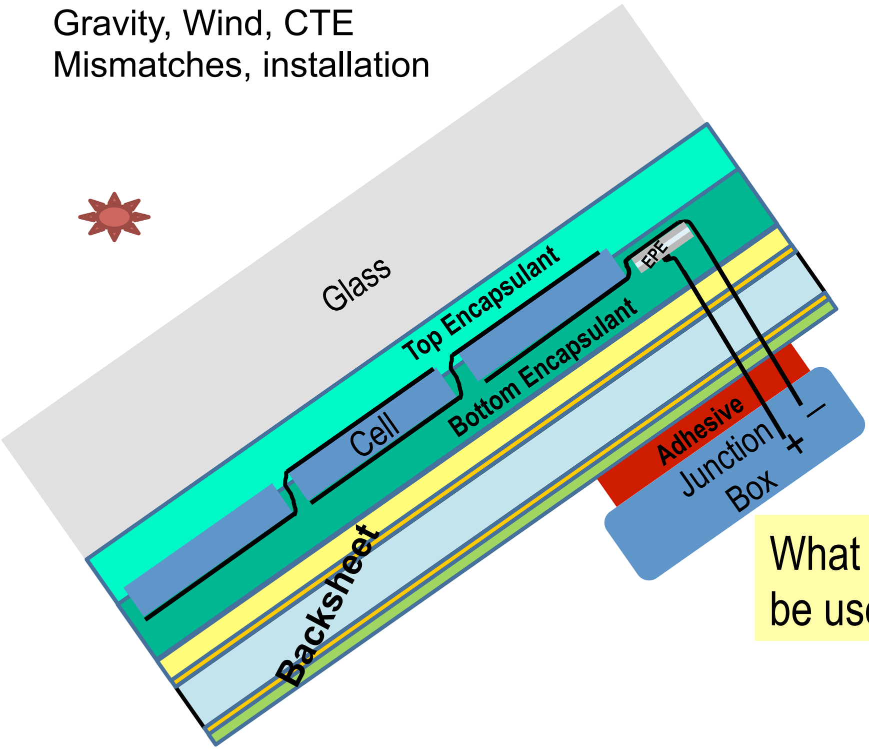
Concerns

- **1 hr load is not representative of a wind gust.**
  - Building codes – 3 second wind Gusts
- **Not representative of snow load because testing:**
  - Does not include shear
  - Is done at room temperature

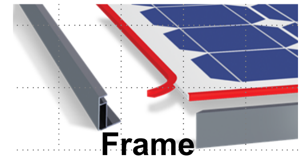
Solar Panel Stack Up – Adhesion Areas in a Module

What are the forces acting on the layers in the module?

Gravity, Wind, CTE Mismatches, installation



Interfacial



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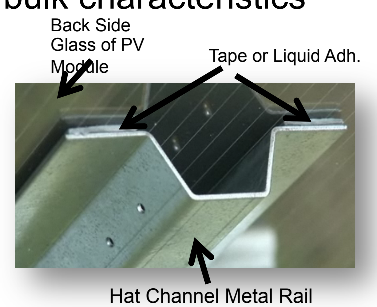
Bulk

- Each material has its own bulk characteristics
- Some materials (e.g. Backsheets, EPEs) have layers within the material that may have additional Interfacial adhesion issues as well as different bulk characteristics

What are test methods that can be used to simulate forces?

Shear, Tensile, Cleavage

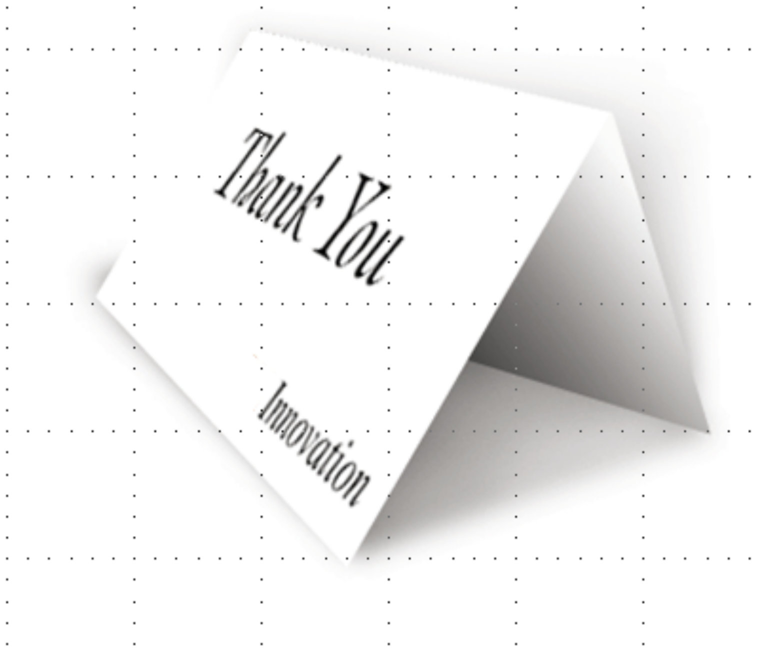


Key Points:

1. Peel
   - Easy to run but complex with regards to understanding what it means relative to performance in an application.
   - Influenced by many variables. (Backing, substrate, angle, stretching,………)
   - May not be the best test to use to simulate the forces of PV module applications

2. Understand application stresses & simulate stress as best as possible to get most relevant information.

3. Various adh. & materials perform differently - makes it difficult to compare application performance.


Thank You
Innovation

Backup Slides

Time & Temperature Have A Significant Impact Failure Mode

Peeling PET film from rubber at differen

Gent and Petrich, Proc. Roy. Soci. A., **310**, 433 (1969)

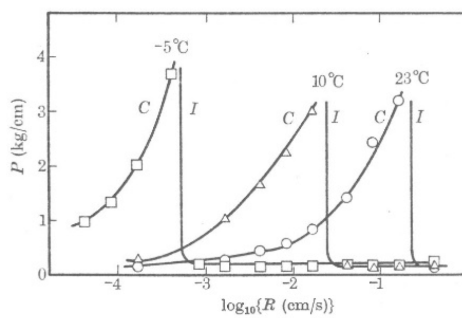


FIGURE 2. Average peel force P against rate of peel R for polymer
C and I denote cohesive and interfacial failure mo

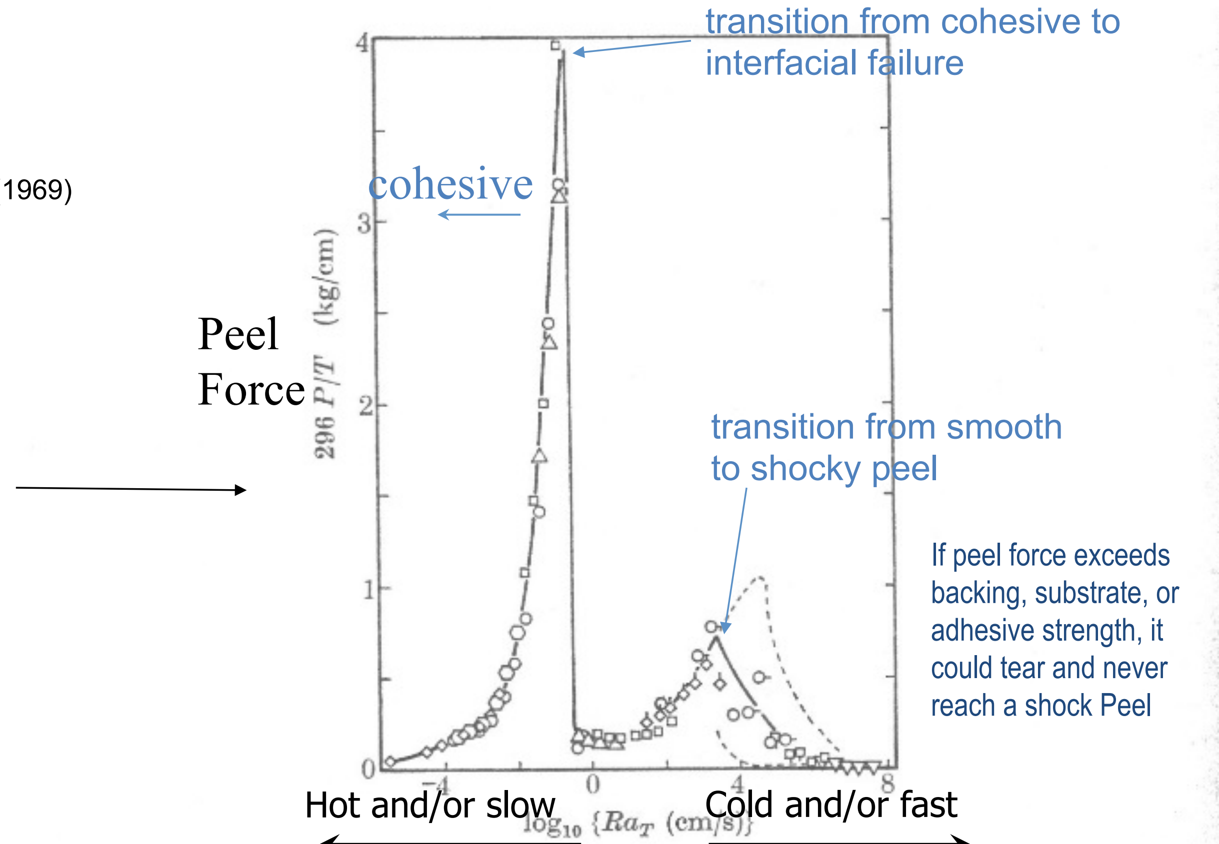
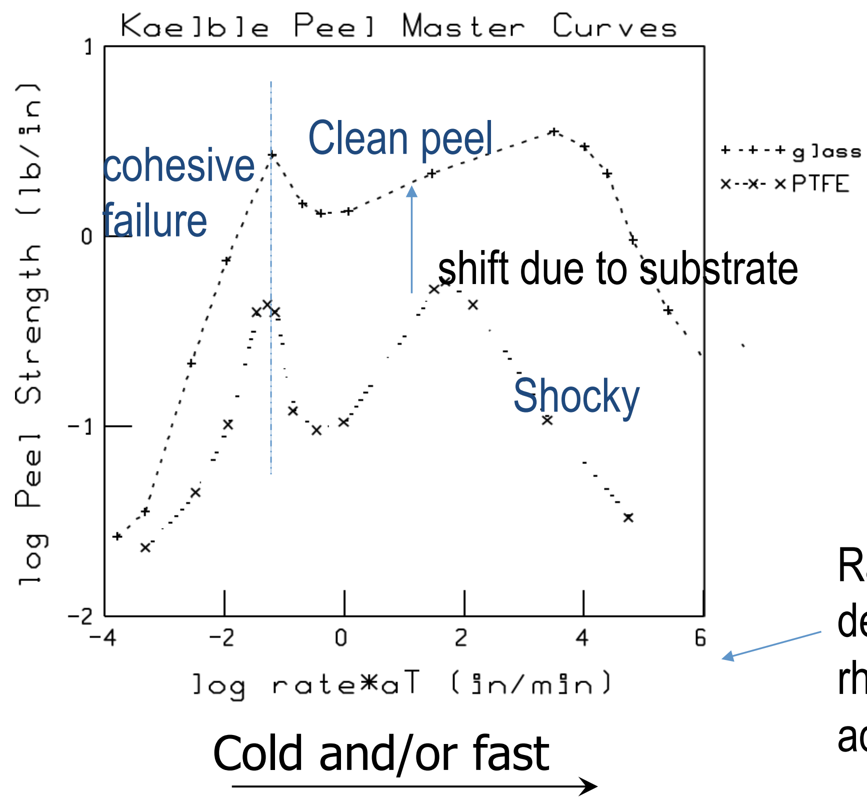


FIGURE 3. Master relation for peel force P against rate of peel R, reduced to 23 °C, for polymer A adhering to Mylar. Broken curves denote the extreme values when stick-slip peeling occurred.

Substrate Type Can Have A Significant Impact Failure Mode

Interaction of interfacial forces and material properties



Rate and temperature dependence comes from rheological properties of the adhesive and backing