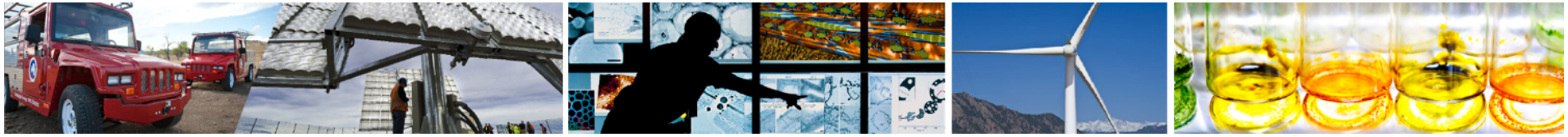
A Fracture Mechanics Based Approach for Adhesion Testing in the PV Module Laminate



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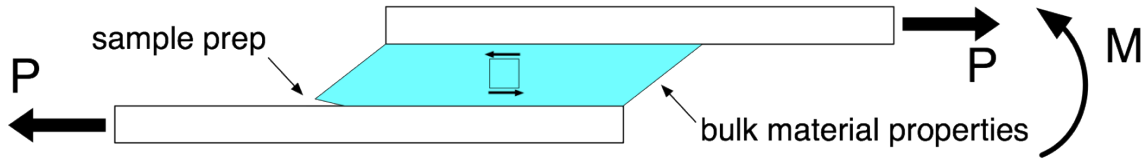
NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

overview

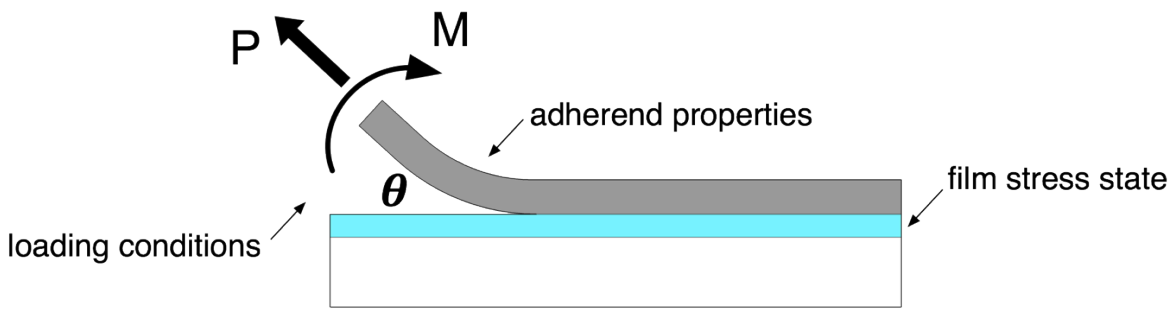
- Short review of common PV adhesion tests
- Introduction of the fracture mechanics based approach to adhesion testing
- Applications of this approach to PV laminate materials at both the coupon and module level
- Extension of these measurements for lifetime prediction of adhesive systems
- Review and Direction

limitations of common adhesion tests

lap shear



peel test



fracture mechanics

fracture toughness

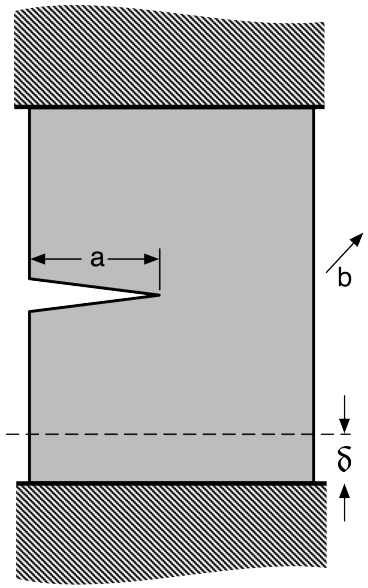
$$G_c = \frac{dW_s}{dA}$$

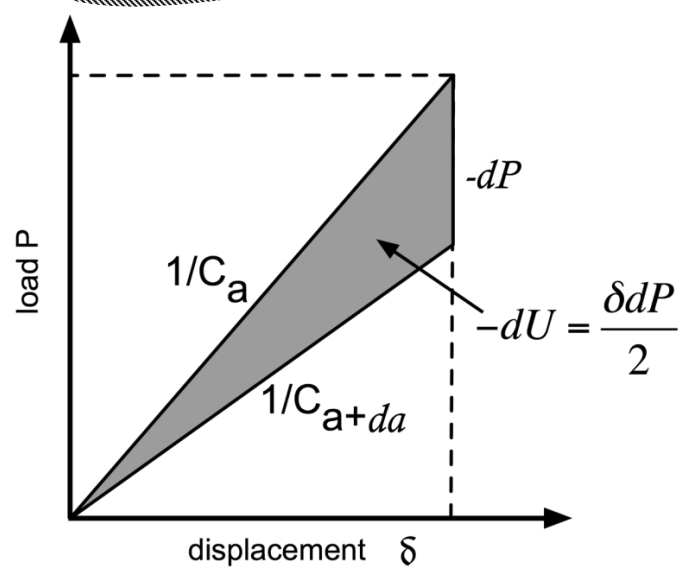
compliance

$$C = \frac{\delta}{P}$$

energy release rate
toughness
adhesion
debond energy

$$G = \frac{P^2}{2b}\frac{dC}{da}$$





figures inspired by: T.L. Anderson, "Fracture Mechanics" CRC Press, Boca Raton, FL 1995

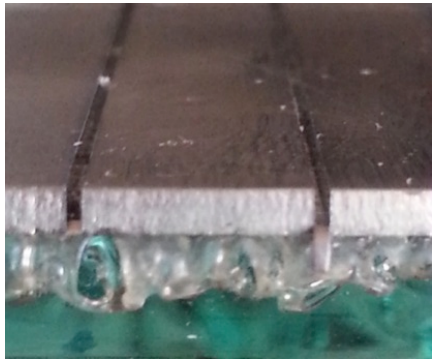
sample modification

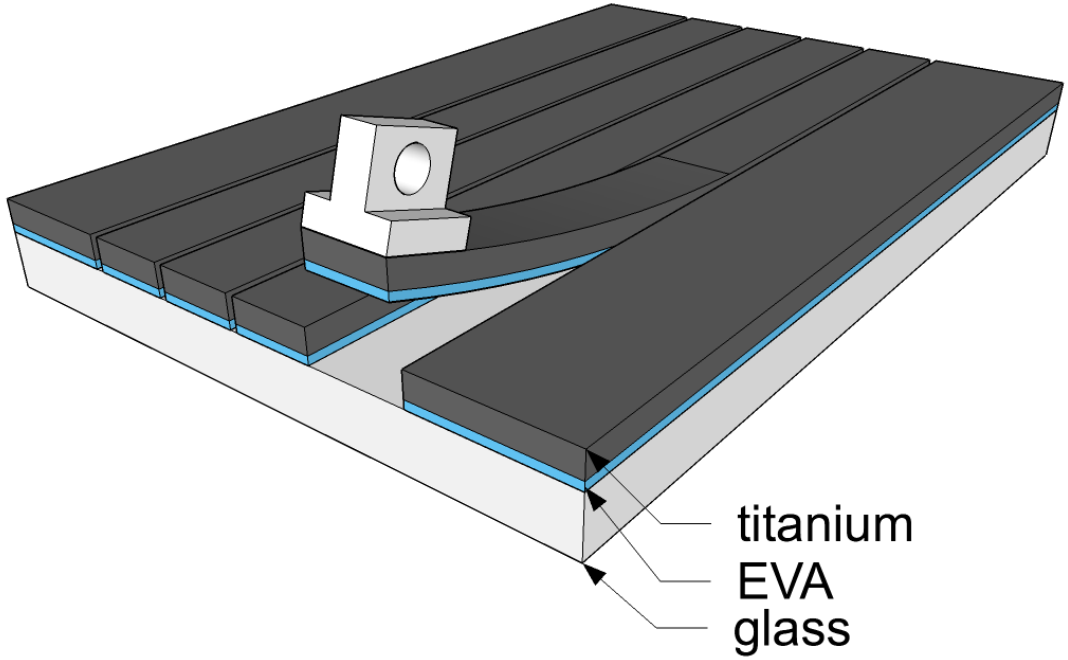
peel test

cantilever beam

single cantilever beam

glass/EVA





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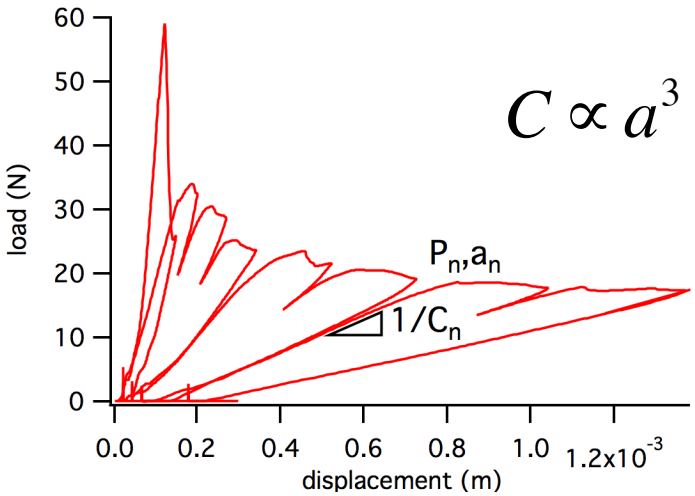
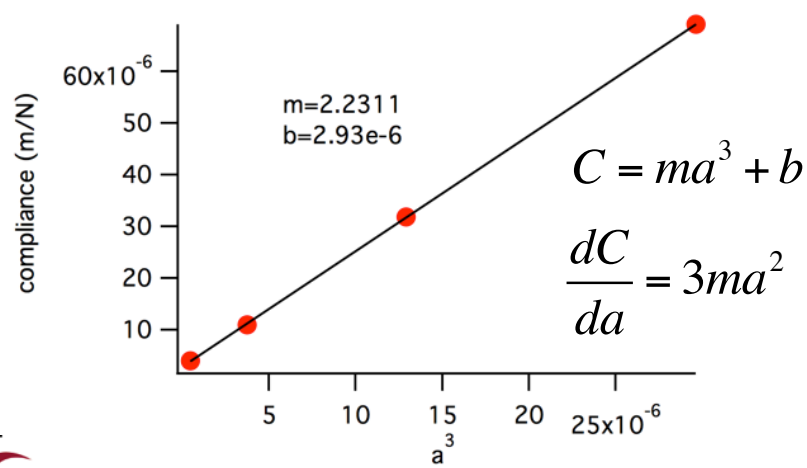
single cantilever beam

0% silane





- Load reversals to measure compliance with crack extension
- produce linear fit of compliance with crack extension
- Evaluate toughness at each crack length

$$G = \frac{P^2}{2b}\frac{dC}{da} = \boxed{\frac{P_n^2}{2b}3ma_n^2}$$

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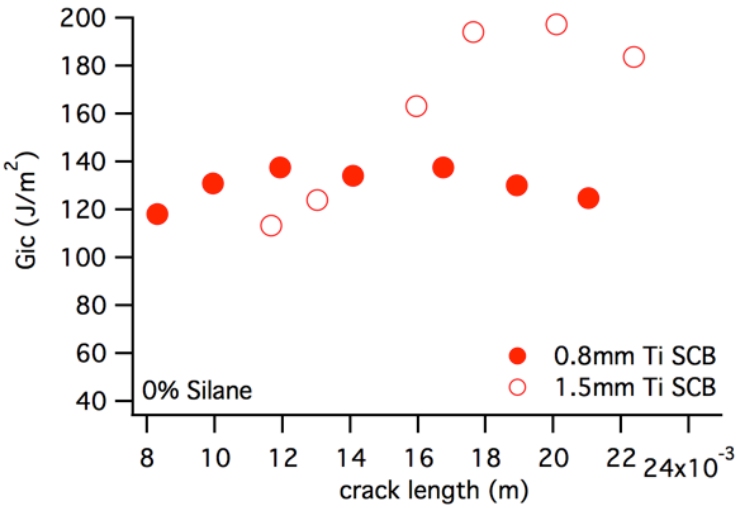
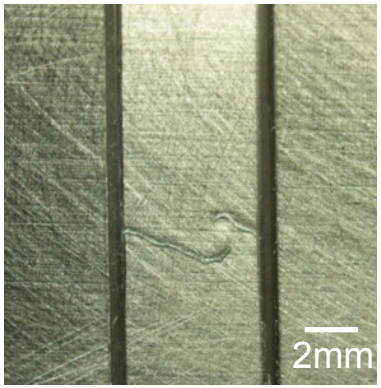
single cantilever beam, coupon level

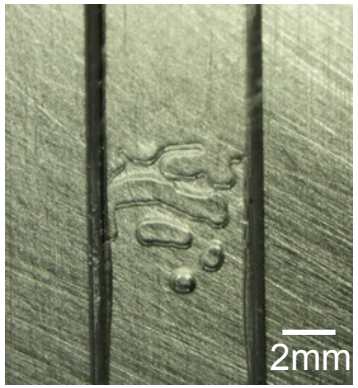
0% silane



Calculate fracture toughness for each crack extension



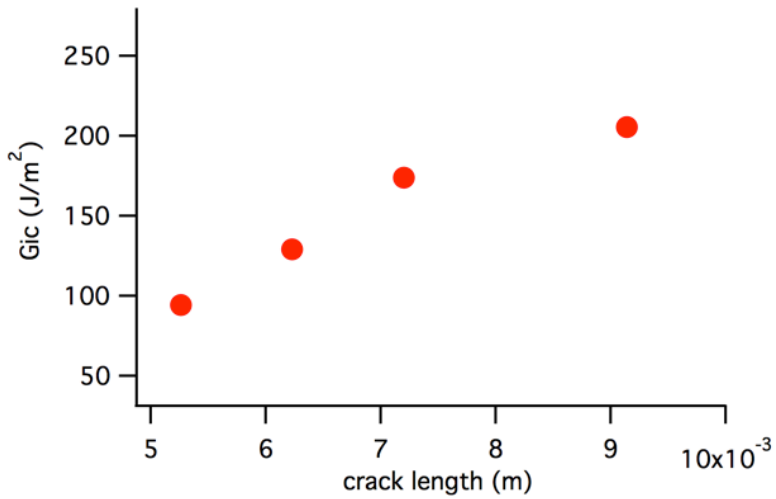
0.8 mm Ti beam

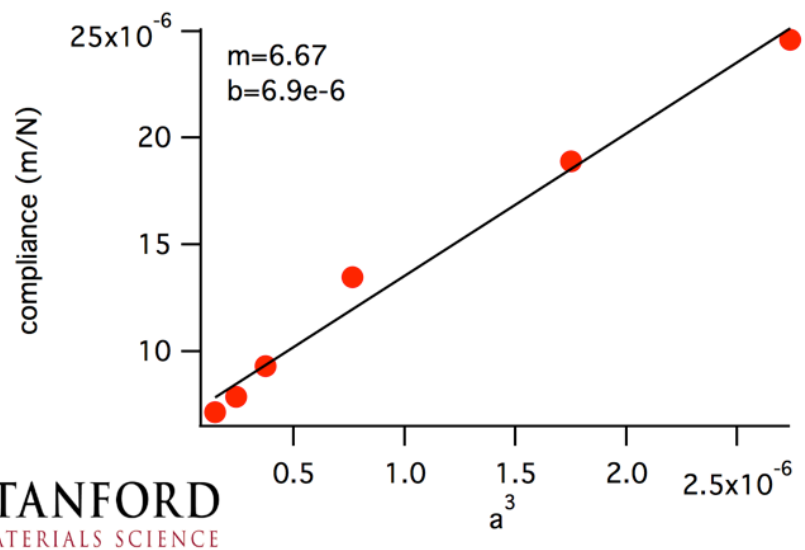


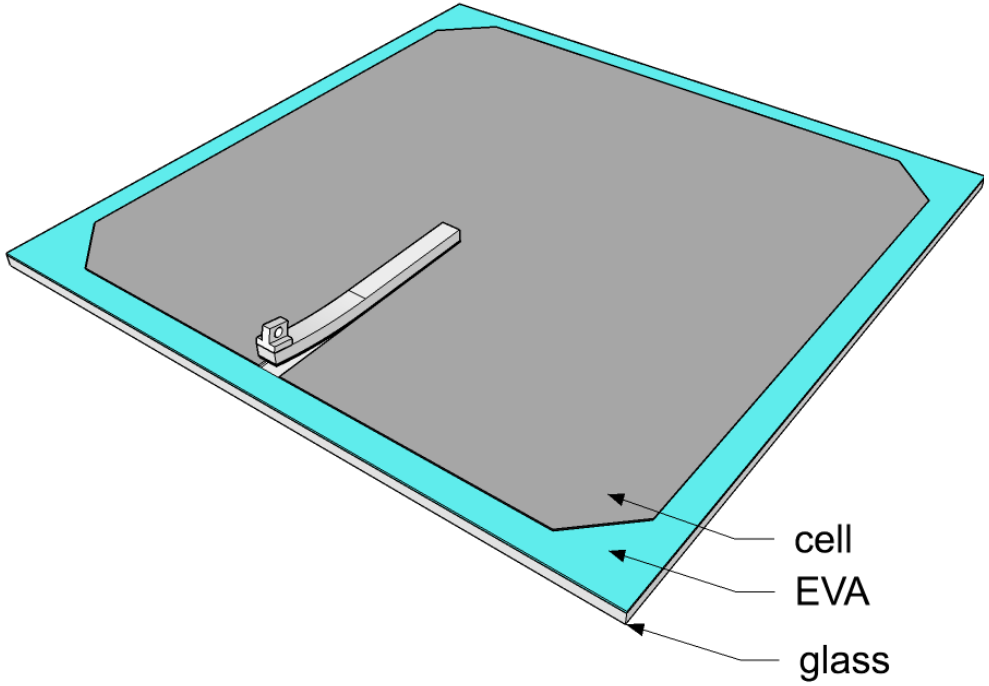
1.5 mm Ti beam

single cantilever beam, module level

0% silane







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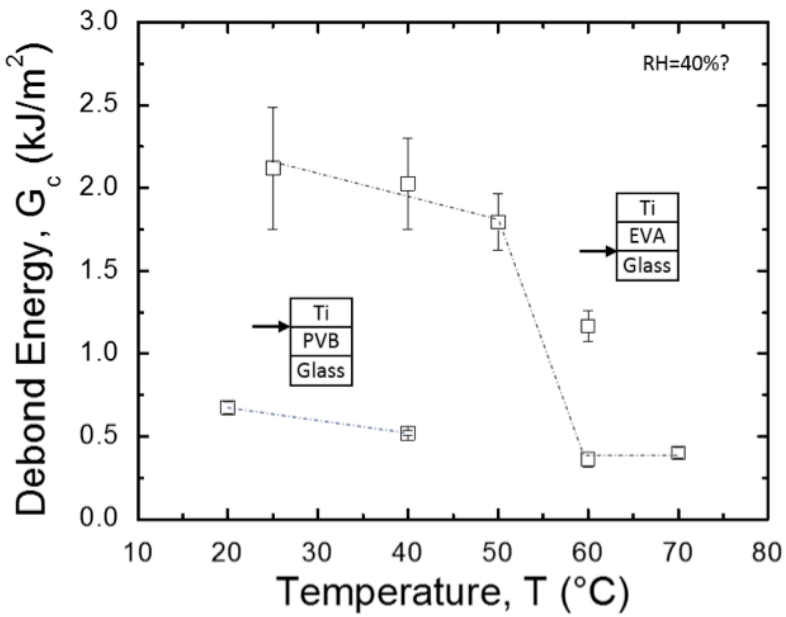
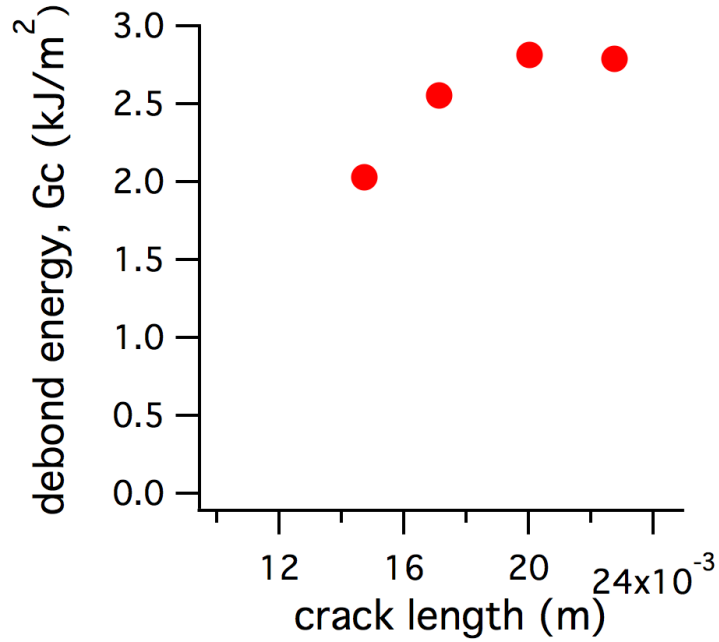
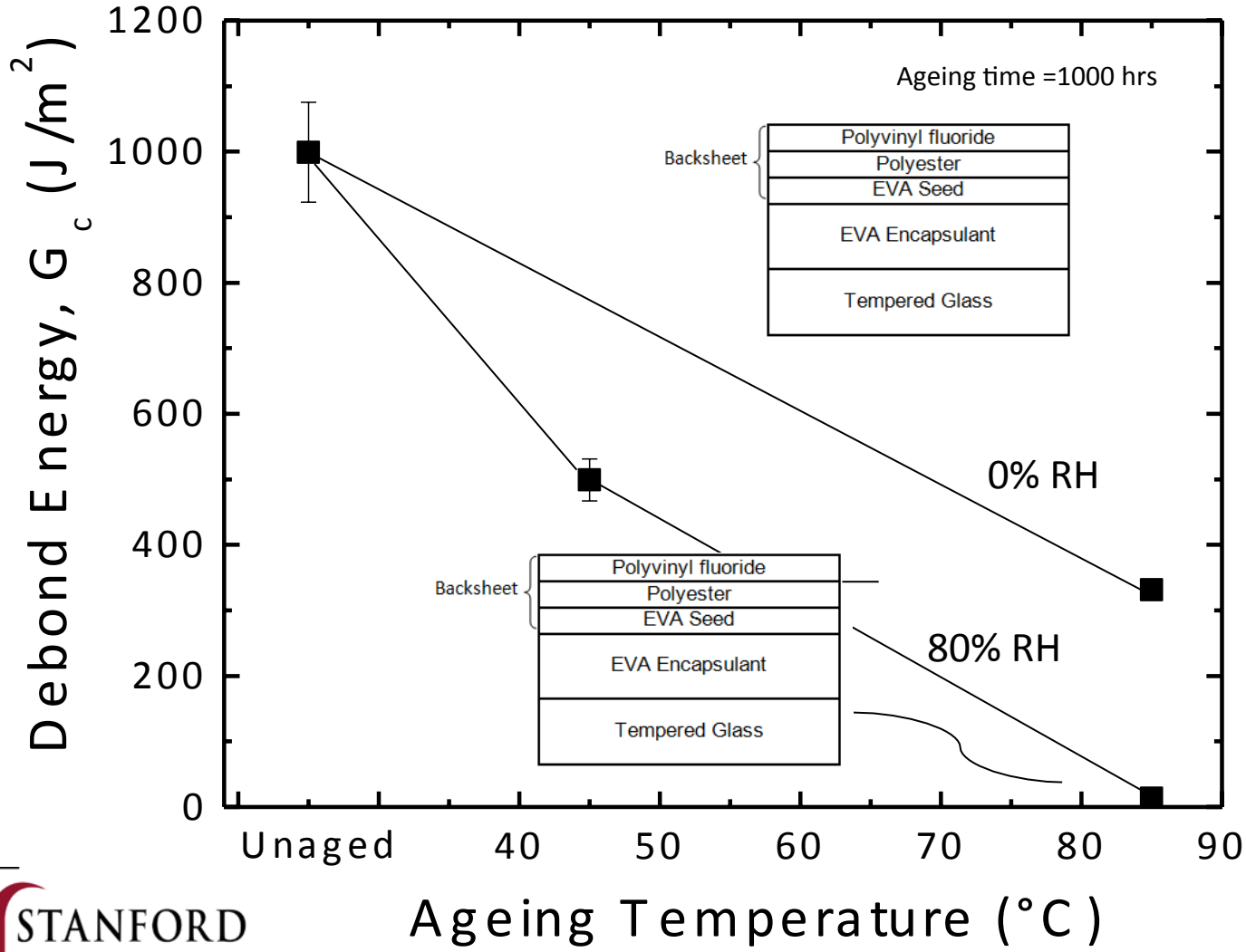
single cantilever beam, EVA

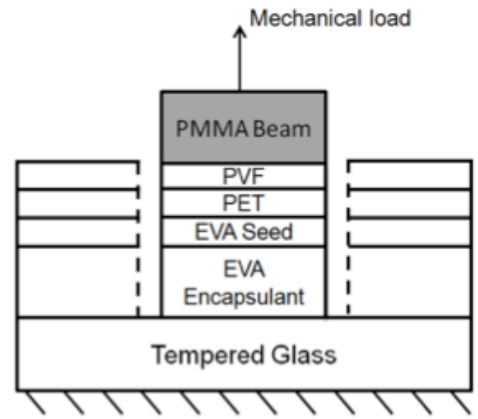


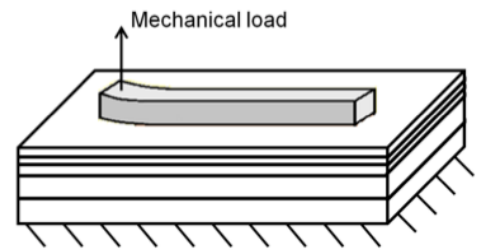


single cantilever beam, backsheet

Debond Energy decreased with aging temperature and RH







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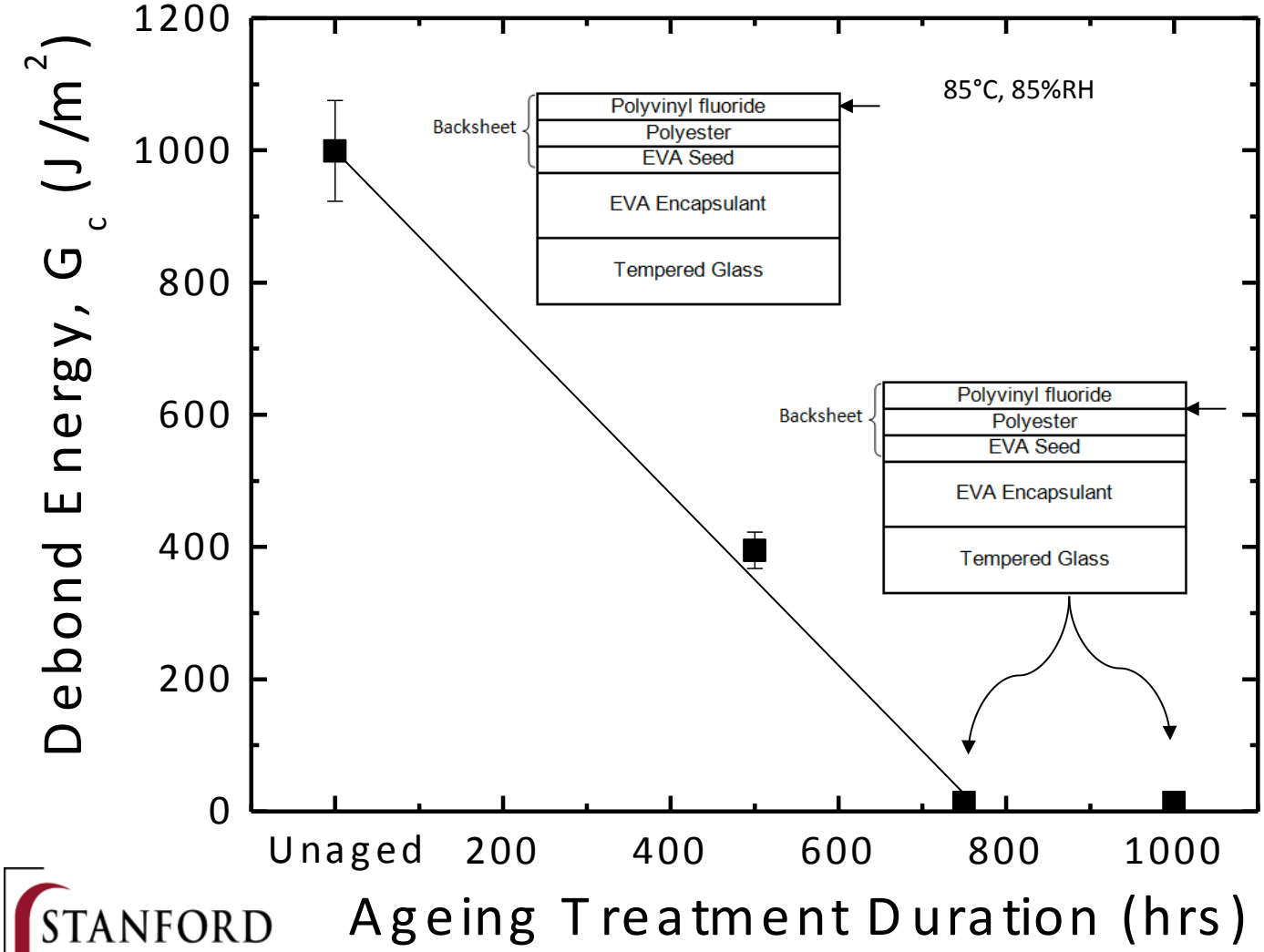
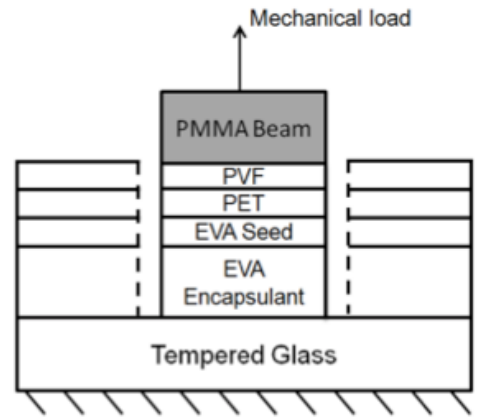
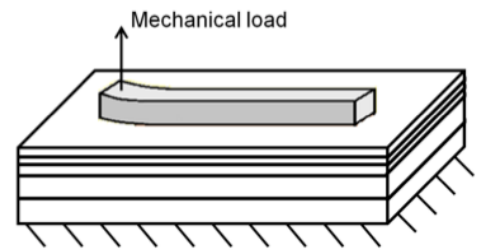
single cantilever beam, backsheet

Debond Energy decreased with aging duration







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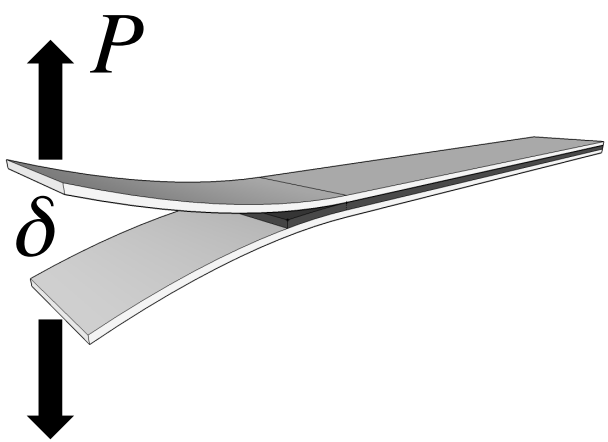
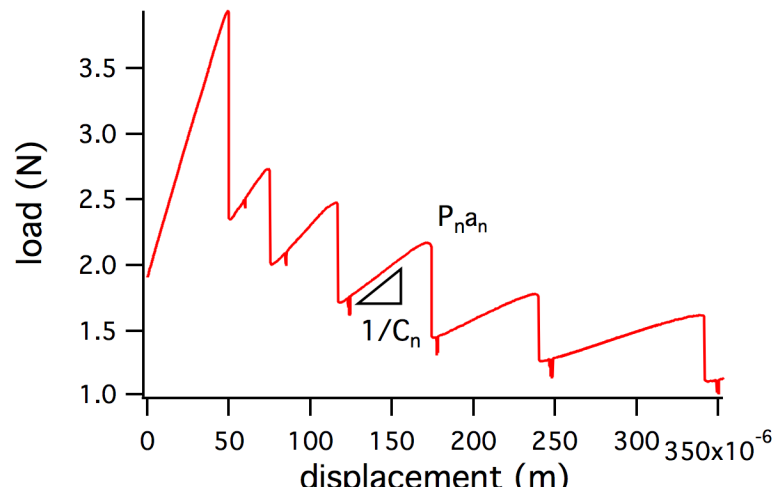
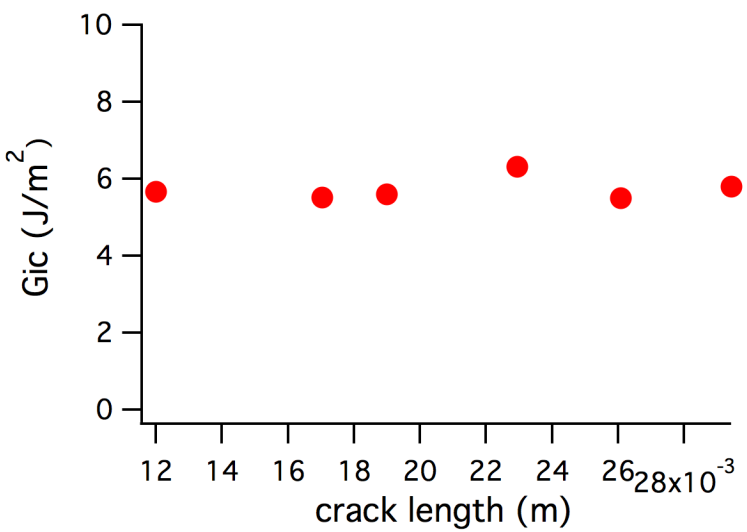
double cantilever beam (DCB)

thin metal film on glass







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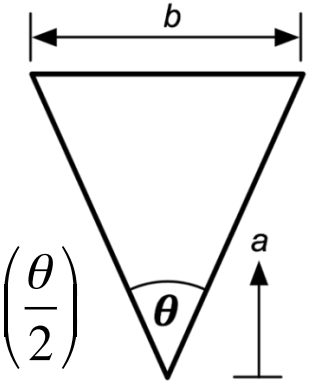
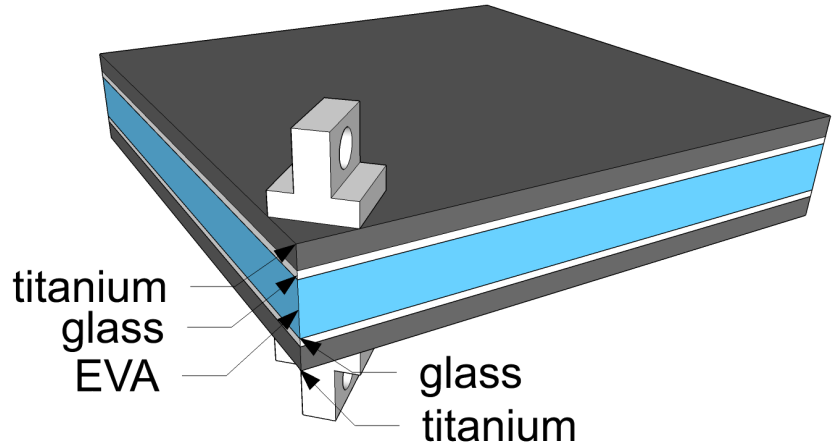
corner adhesion test

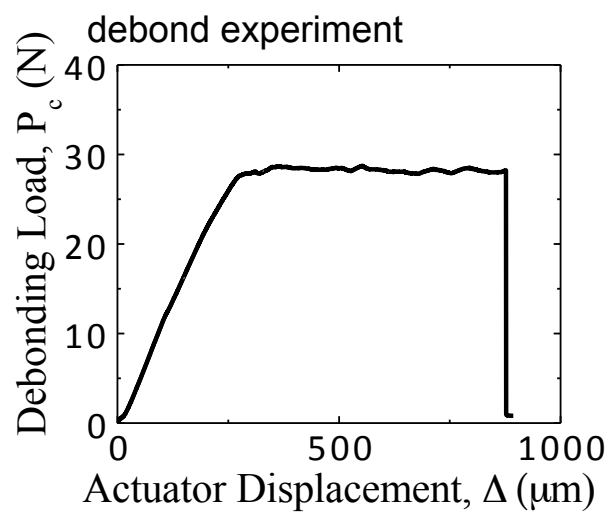
$$G = \frac{P^2}{2b}\frac{dC}{da}$$



$$b = 2a\tan\left(\frac{\theta}{2}\right)$$



$$G = \frac{12P_P^2}{E\left(2\tan\left(\frac{\theta}{2}\right)\right)^2 h^3}$$



- Compliance becomes independent of crack length
- Crack will extend at a constant, critical load

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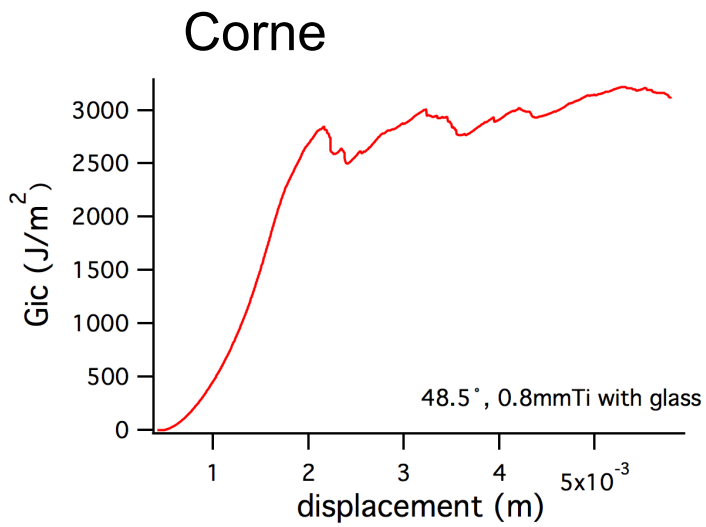
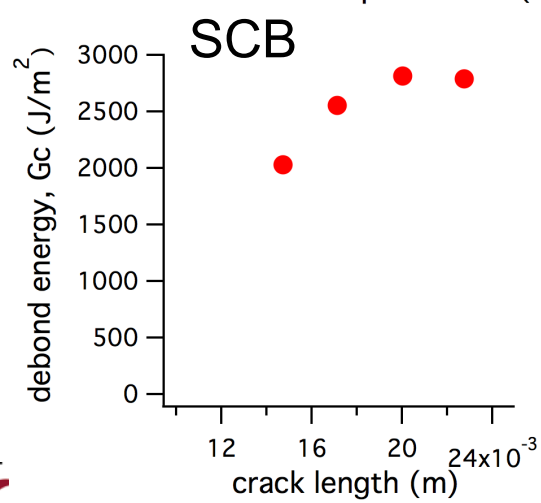
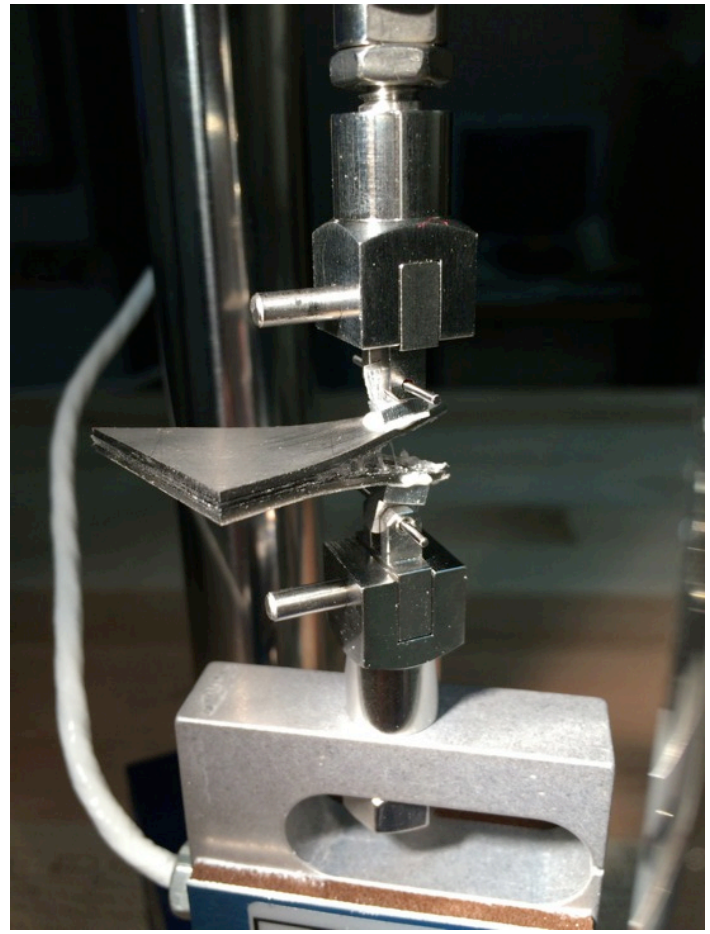
corner adhesion test, coupon level







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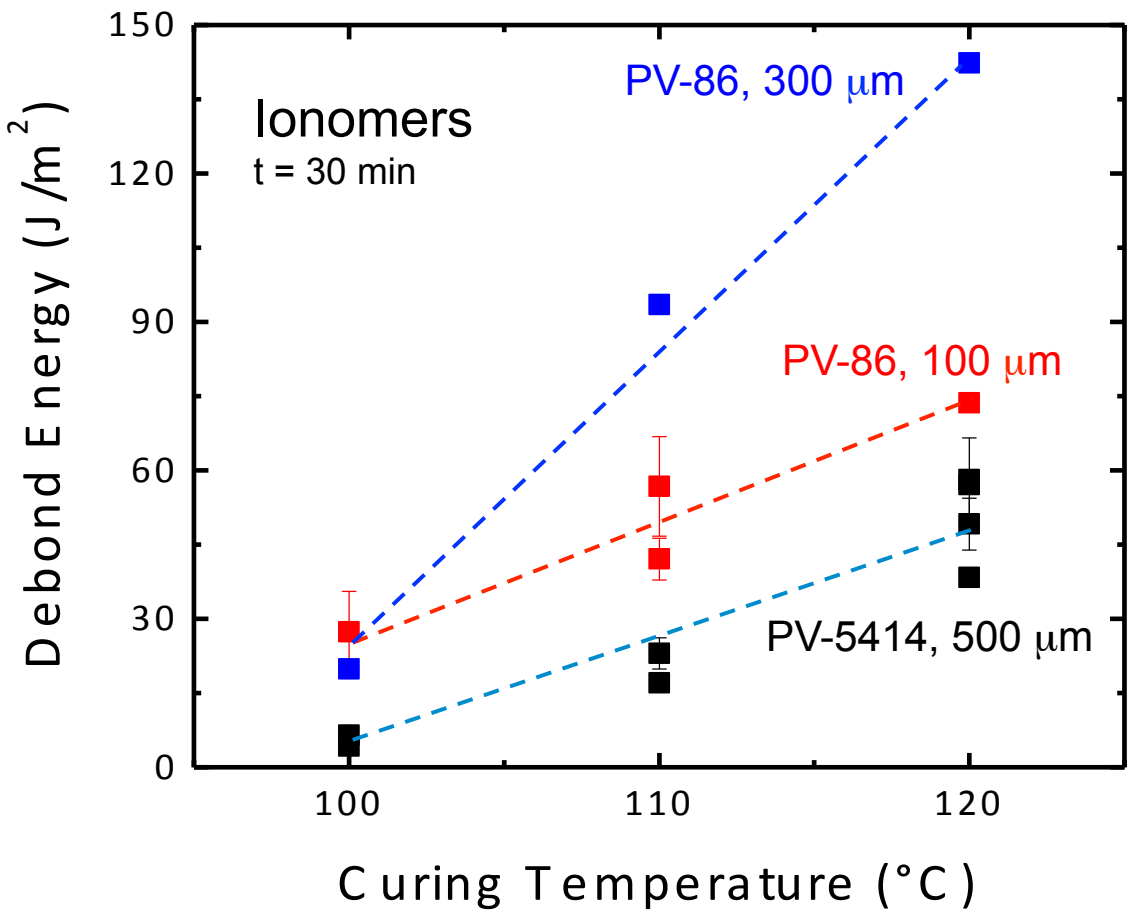
corner adhesion test, coupon level

Effect of Curing on Ionomer Bonding Strength



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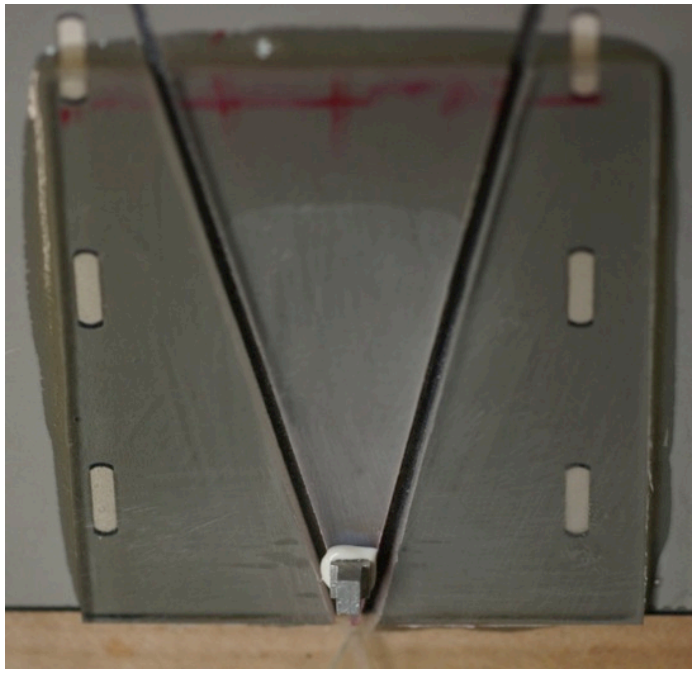
corner adhesion test, module level



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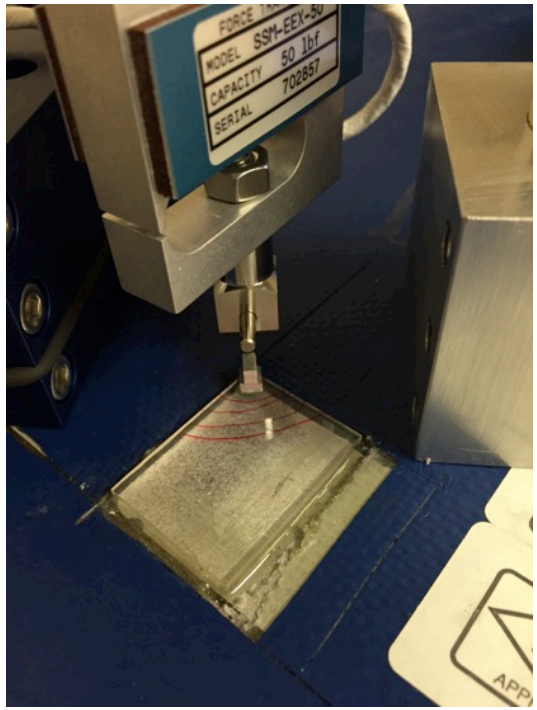
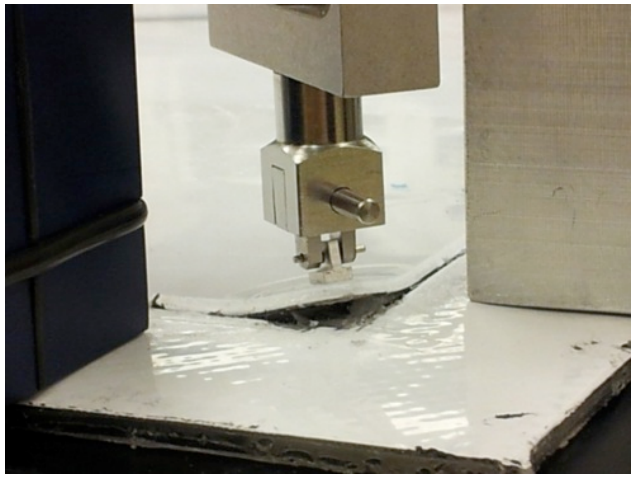
corner adhesion test, module level



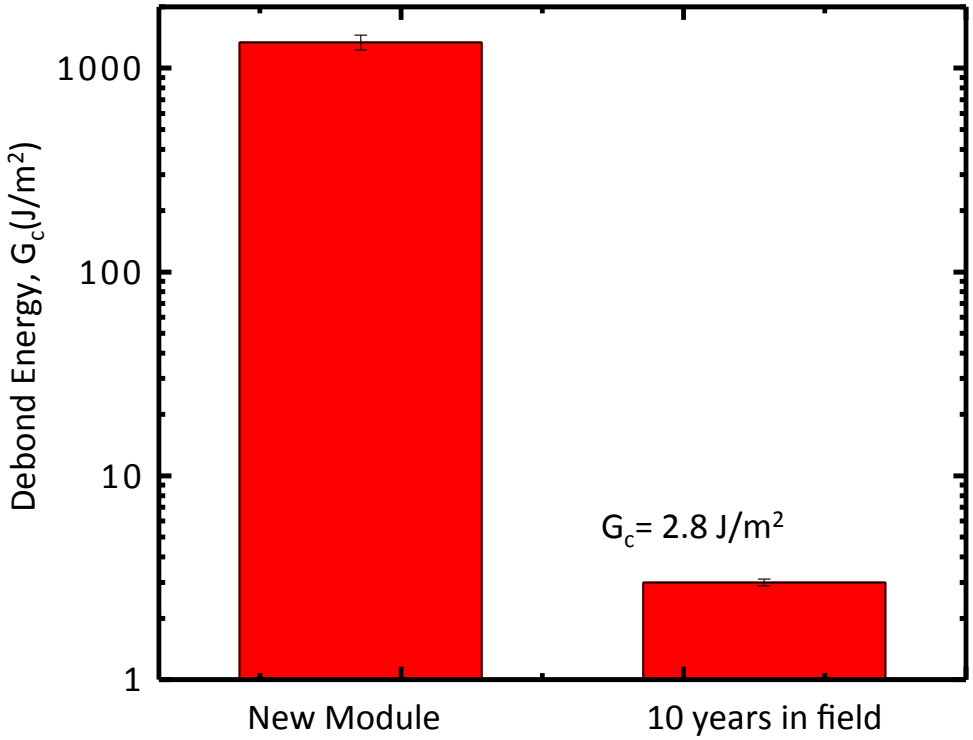
applied to module cell

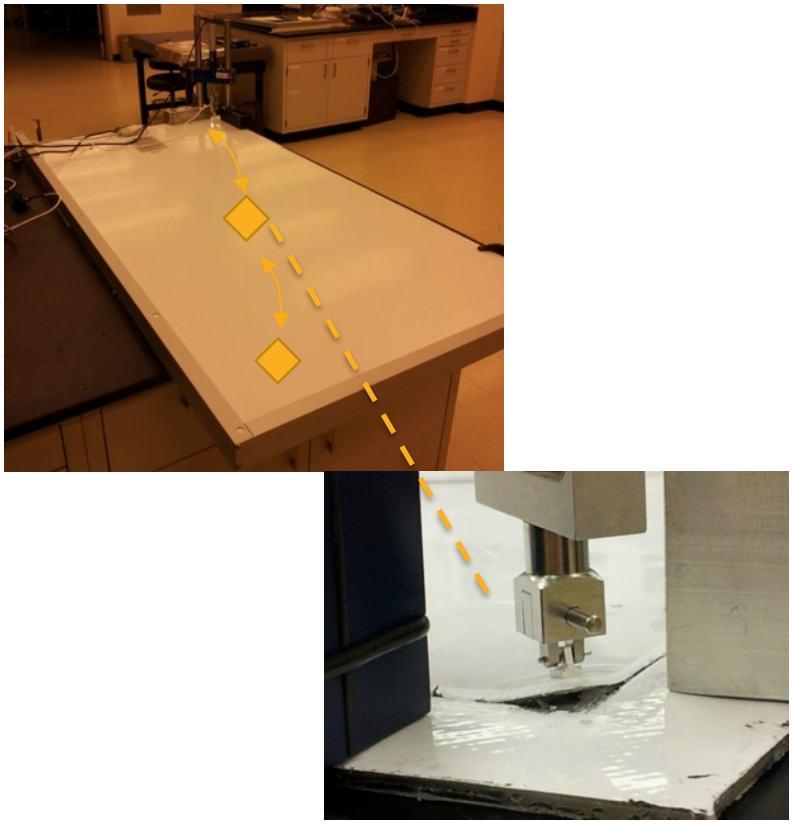


applied to module backsheet

corner adhesion test, module level

debond energy decreased 500-fold after 10 years in Florida





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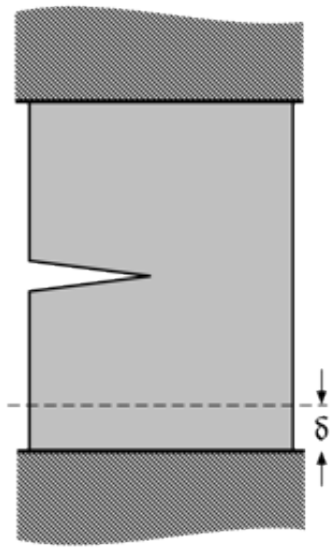
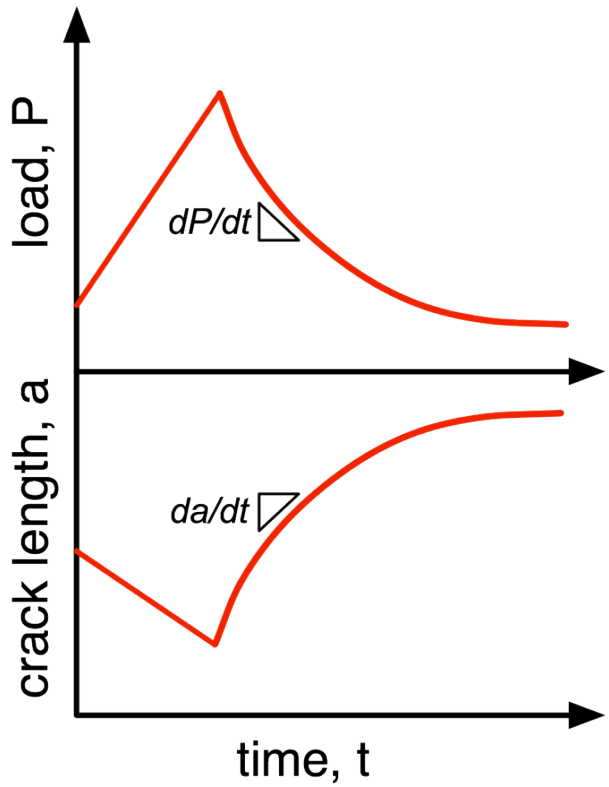
subcritical crack growth





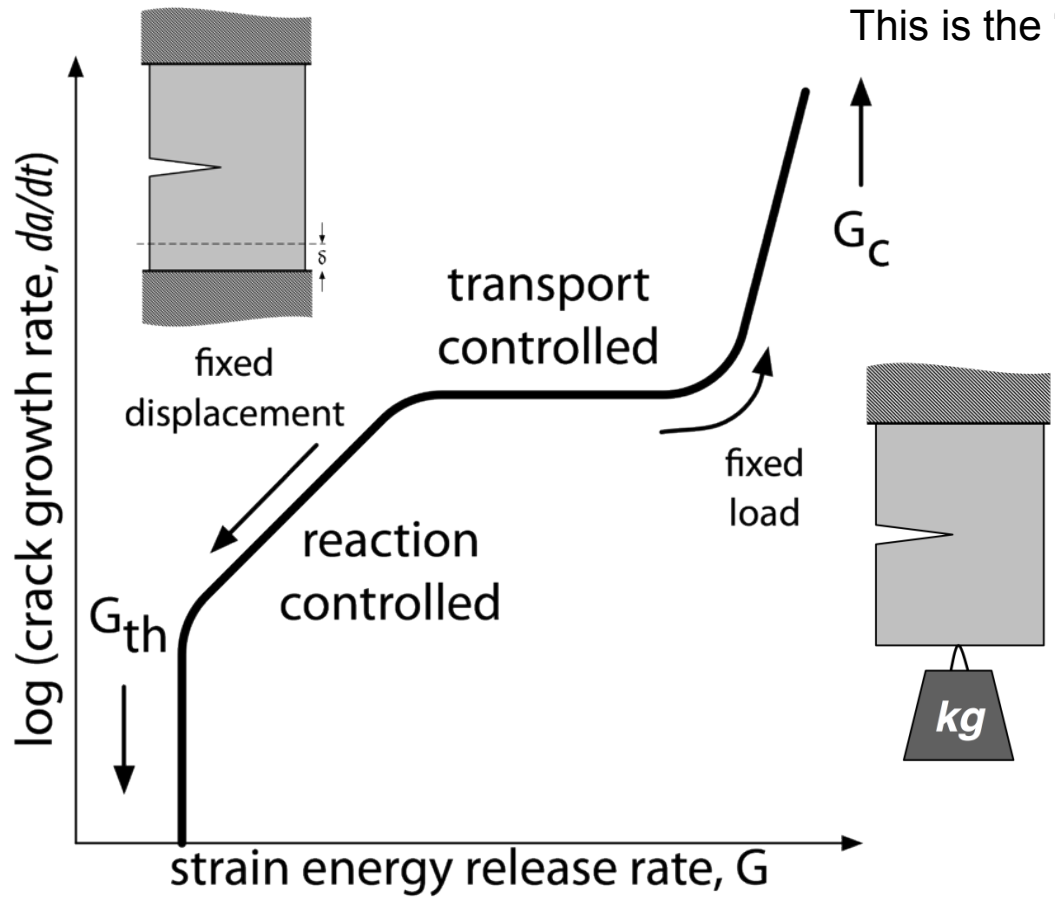
$$\frac{da}{dt} = -\left(\frac{dP}{dt}\right)\frac{ma^3 + b}{3Pma^2}$$

$$G_n = \frac{P(t_n)^2}{2b} 3ma(t_n)^2$$

subcritical crack growth

V-G plots

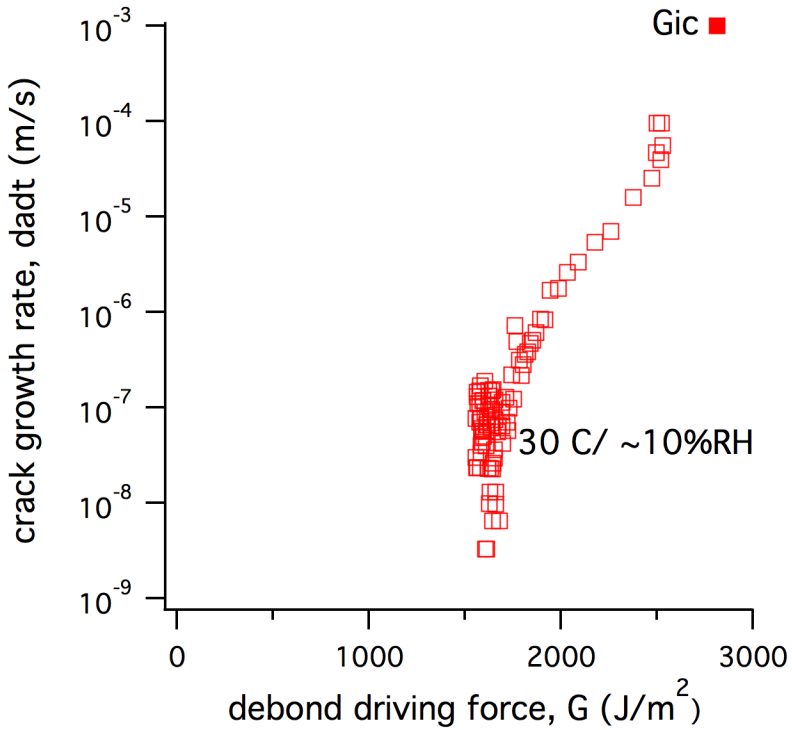
This is the “adhesive strength”



This is the “adhesive threshold”, or a stress at which cracks will not propagate. A reliable design will “live” here.

subcritical crack growth, SCB

Glass/ EVA



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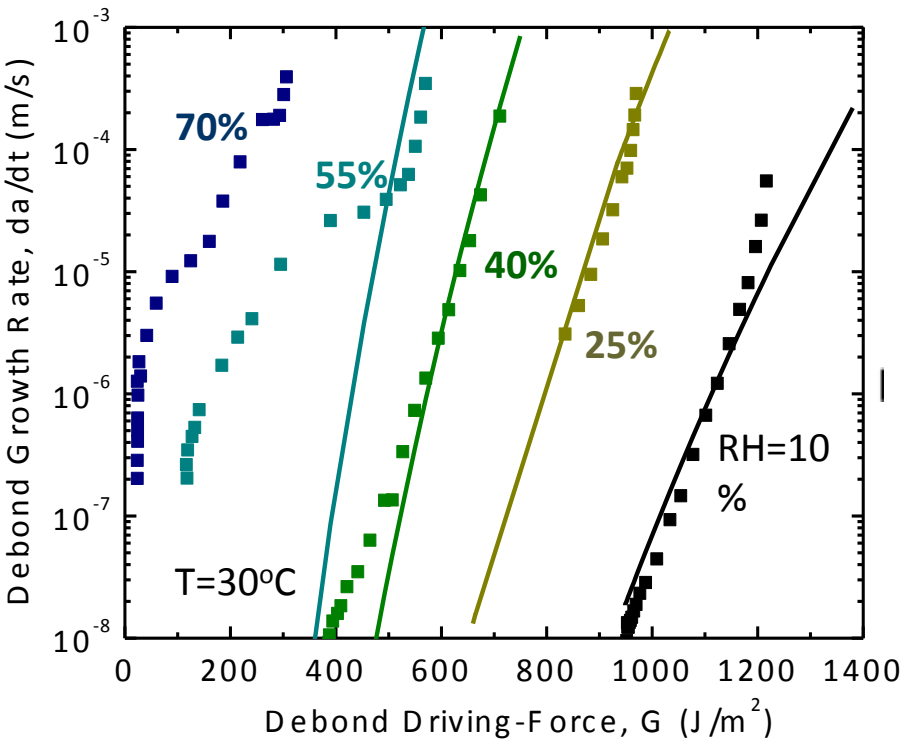
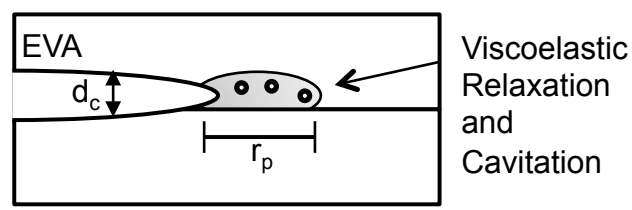
subcritical crack growth, SCB

Glass/ EVA debond growth kinetics



debond growth of EVA encapsulant interfaces is controlled by the viscoelastic processes that are affected by water through the plasticization of the debond tip



$$\frac{da}{dt} = \frac{\pi}{8} \frac{\delta_c}{\varepsilon_y \left(\delta_c \varepsilon_y E_1\right)^{1/n}} G^{1/n} 10^{\frac{C_a\left(T+\gamma RH - T_{g-dry}\right)}{C_b + \left(T+\gamma RH - T_{g-dry}\right)}}$$

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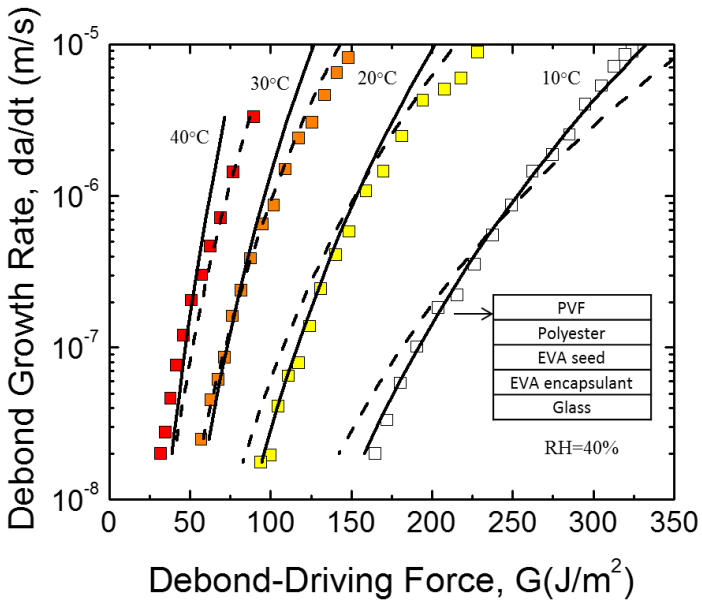
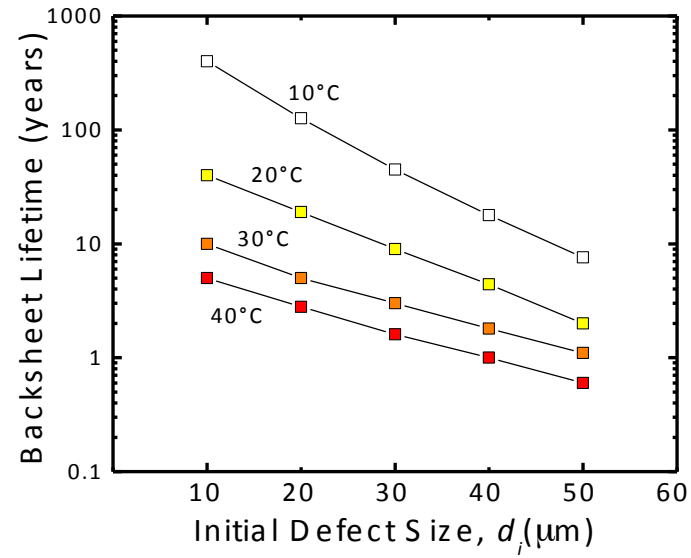
subcritical crack growth, SCB

Backsheet debond kinetics and lifetime prediction



$$\int_{a_i}^{a_f} da = \int_0^t \frac{da}{dt} dt$$



$$\frac{da}{dt} = kG^{1/n} 10^{\frac{C_a\left(T+\gamma RH-T_{g-dry}\right)}{C_b+\left(T+\gamma RH-T_{g-dry}\right)}}$$

direction

- Ongoing NREL scientific work is focused on applying the FM method to characterization for all PV adhesives
- We will develop protocols for applying this technique to all relevant material systems
- This work will provide the scientific basis for incorporating these techniques into future revisions of international standards

limitations of common adhesion tests

Sample Properties

- Stiffness
- Electrical Resistance
- *Strength*

Material Properties

- Elastic Modulus
- Electrical Resistivity
- *Toughness*

review

- FM based adhesion tests measure a quantitative material property
- Methods can be applied at both the coupon and module level and to all interfaces of the PV laminate
- Tests may be developed to be straight forward using common mechanical test equipment
- Subcritical measurements allow modeling of adhesive degradation mechanisms and ultimately provide a lifetime prediction tool