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

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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

compliance

energy release rate
toughness
adhesion
debond energy

\[ G_c = \frac{dW_s}{dA} \]

\[ C = \frac{\delta}{P} \]

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

sample modification

peel test

cantilever beam
single cantilever beam
glass/EVA
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

\[
C \propto a^3
\]

\[
P_n \cdot a_n
\]

\[
\begin{align*}
C &= ma^3 + b \\
\frac{dC}{da} &= 3ma^2
\end{align*}
\]

\[
G = \frac{P^2}{2b} \frac{dC}{da} = \frac{P_n^2}{2b} 3ma_n^2
\]
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

\[ G_c (J/m^2) \]

\[ \text{crack length (m)} \]

\[ m=6.67 \]

\[ b=6.9 \times 10^{-6} \]

\[ \text{compliance (m/N)} \]

\[ a^3 \]
single cantilever beam, EVA
single cantilever beam, backsheet

Debond Energy decreased with aging temperature and RH.

Debond Energy, $G_c$ (J/m$^2$)

Ageing Temperature (°C)

Unaged

Ageing time = 1000 hrs
single cantilever beam, backsheet

Debond Energy decreased with aging duration

Debond Energy, $G_c$ (J/m$^2$)

Ageing Treatment Duration (hrs)

Unaged 200 400 600 800 1000

85°C, 85%RH

Debond Energy decreased with aging duration.

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double cantilever beam (DCB)

thin metal film on glass

\[ P \]

\[ \delta \]
corner adhesion test

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

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

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

![Diagram of corner adhesion test](image1)

![Graph of debonding load vs. actuator displacement](image2)
corner adhesion test, coupon level

![Graph showing GIC vs. displacement for Corne and SCB](image)

**Corne**

- Graph showing GIC (J/m²) against displacement (m)
- Data for 48.5°, 0.8mmTi with glass

**SCB**

- Graph showing debond energy, Gc (J/m²) against crack length (m)
- Data points indicate increasing Gc with crack length
corner adhesion test, coupon level

Effect of Curing on Ionomer Bonding Strength

Ionomers

t = 30 min

PV-86, 300 µm

PV-86, 100 µm

PV-5414, 500 µm

Debond Energy (J/m²)

Curing Temperature (°C)
corner adhesion test, module level
corner adhesion test, module level

applied to module cell

applied to module backsheets
corner adhesion test, module level

Debond energy decreased 500-fold after 10 years in Florida

Debond energy, \( G_c (\text{J/m}^2) \)

- New Module: \( G_c = 2.8 \text{ J/m}^2 \)
- 10 years in field:

![Image of corner adhesion test equipment]
subcritical crack growth

\[
\frac{da}{dt} = -\left(\frac{dP}{dt}\right) ma^3 + b \\
G_n = \frac{P(t_n)^2}{2b} 3ma(t_n)^2
\]
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

\[ G_{ic} \]

30 C/ ~10%RH

crack growth rate, \( \frac{da}{dt} \) (m/s)

debond driving force, \( G \) (J/m\(^2\))
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.

\[
\frac{da}{dt} = \frac{\pi \delta_c}{8 \varepsilon_y (\delta_c \varepsilon_y E_1)^{1/n}} G^{1/n} 10^{\frac{C_a (T+\gamma RH - T_{g-dry})}{C_b (T+\gamma RH - T_{g-dry})}}
\]
subcritical crack growth, SCB

Backsheet debond kinetics and lifetime prediction

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

\[
d a = k G^{1/n} \left( \frac{C_a(T+\gamma RH - T_{g-dry})}{C_b(T+\gamma RH - T_{g-dry})} \right) dt
\]
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

<table>
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<tr>
<th>Sample Properties</th>
<th>Material Properties</th>
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<tr>
<td>Stiffness</td>
<td>Elastic Modulus</td>
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<tr>
<td>Electrical Resistance</td>
<td>Electrical Resistivity</td>
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<tr>
<td>Strength</td>
<td>Toughness</td>
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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 straightforward using common mechanical test equipment

- Subcritical measurements allow modeling of adhesive degradation mechanisms and ultimately provide a lifetime prediction tool