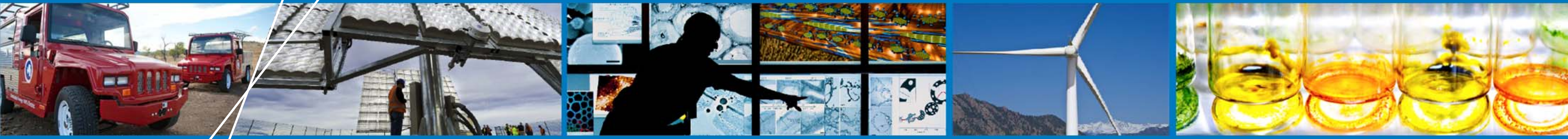
Modeling Metal Fatigue As a Key Step in PV Module Life Time Prediction



NREL PVMRW

Nick Bosco

February 28 2012

NREL/PR-5200-54565

outline

- **Modeling metal fatigue**
  - Time independent (case studies):
    - Ribbon fatigue: wind loading
    - Ribbon fatigue: thermal loading
  - Time dependent, solder fatigue

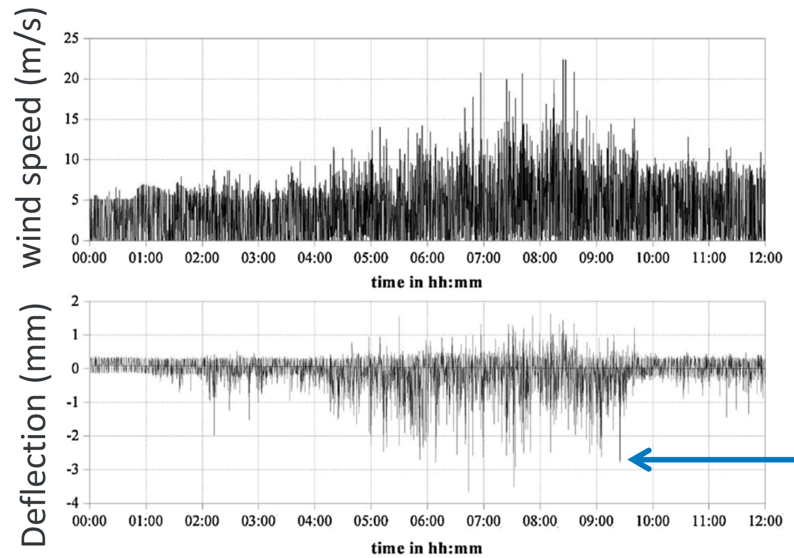
ribbon fatigue: wind loading

Mode	Mechanism	Driving Force
solder bond cracking	mechanical fatigue	wind
		transportation
	thermal fatigue	weather
ribbon cracking		

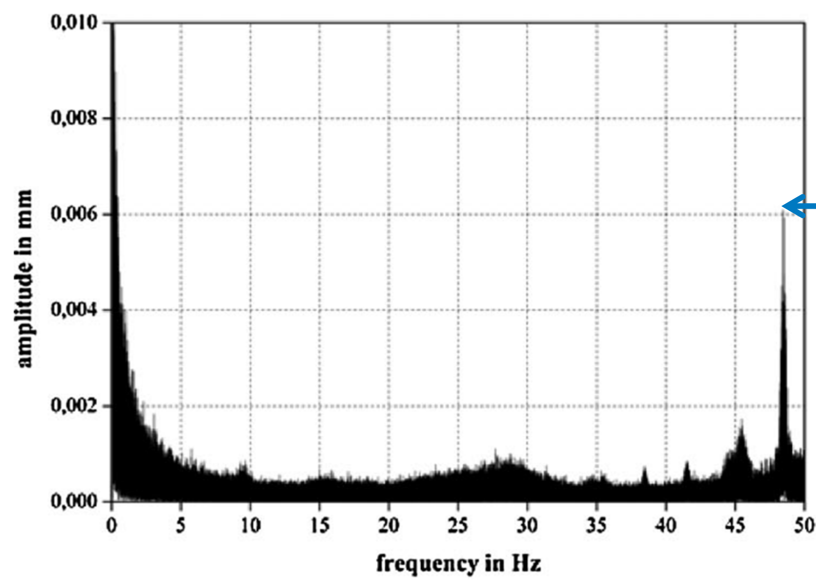
prediction

ribbon fatigue: wind loading

driving force



low freq:
3mm
200/day

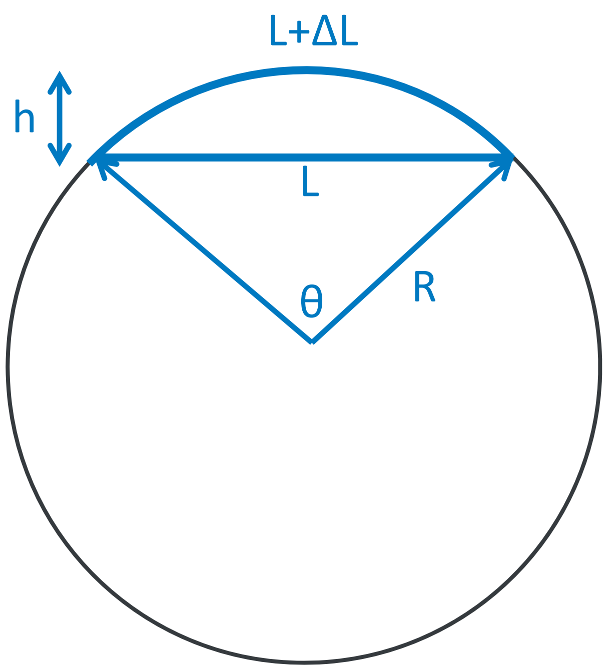


high freq:
6 µm
50 Hz

Assmus, M., S. Jack, et al. (2011). "Measurement and simulation of vibrations of PV-modules induced by dynamic mechanical loads." Progress in Photovoltaics: Research and Applications **19**(6): 688-694.

ribbon fatigue: wind loading

driving force



$$R = \frac{h}{2} + \frac{L^2}{8h} = \frac{L}{2\sin\left(\frac{\theta}{2}\right)}$$

$$L + \Delta L = R\theta$$

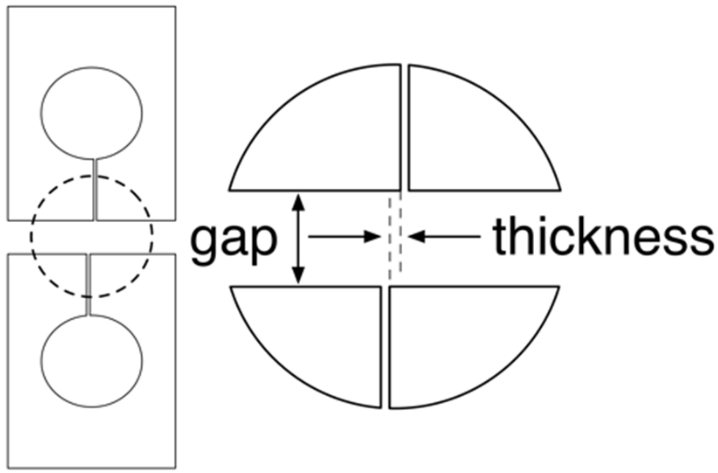
$$\varepsilon = \frac{\Delta L}{L}$$

Assumptions:

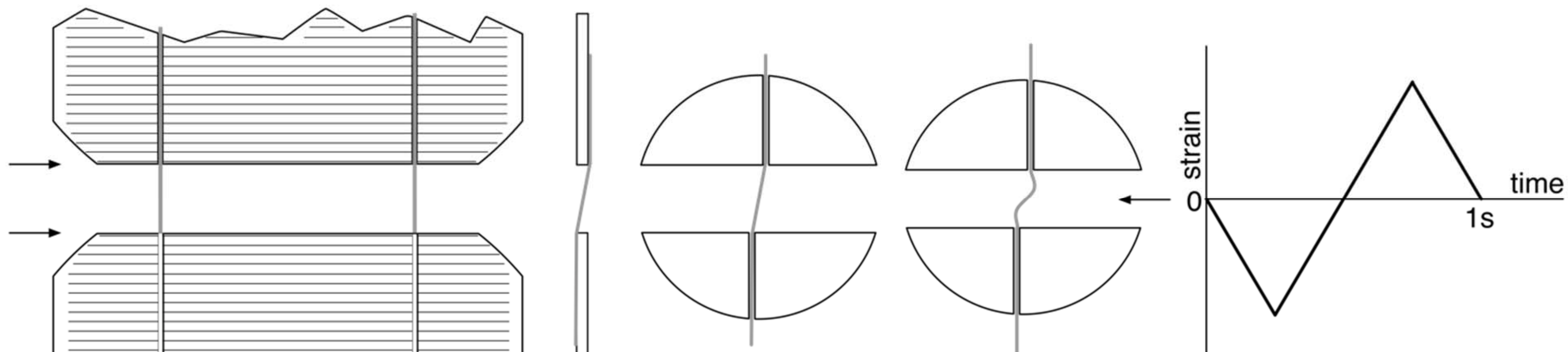
- Pinned connections
- Semicircular bending
- Glass-Glass module
- No shear lag
- *1620*x810 mm

low freq: 3 mm = 0.00107 %
high freq: 6 µm = 4.27e-9 %

mechanism: fatigue experiment

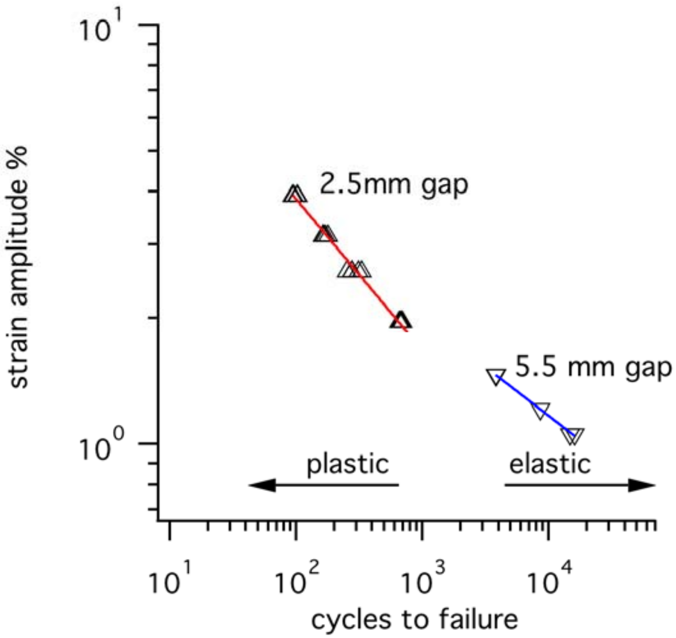


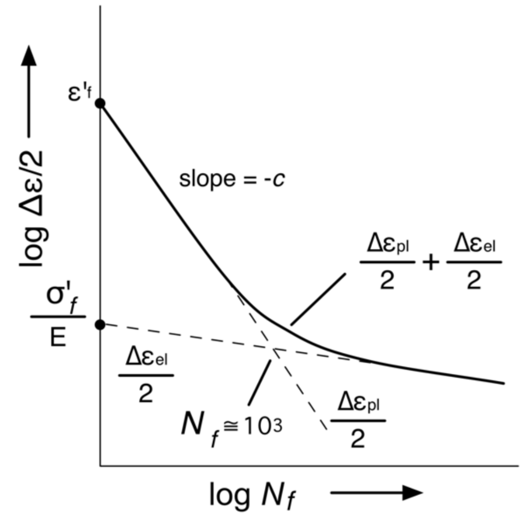
Grips fabricated to simulate ribbon attachment



load "cool" cycle

ribbon fatigue: wind loading mode



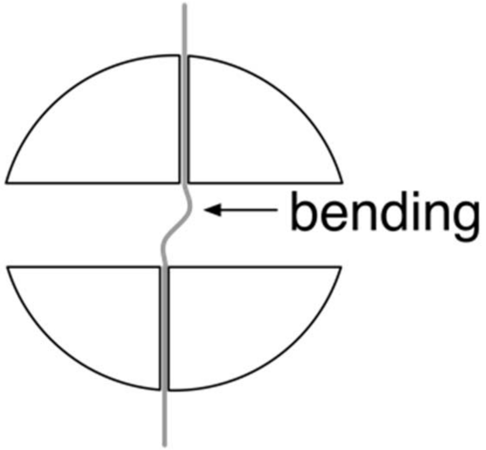


$$\frac{\Delta\varepsilon_{pl}}{2} = \varepsilon'_f \left(2N_f\right)^{-c}$$

$$\frac{\Delta\varepsilon_{el}}{2} = \frac{\sigma'_f}{E}\left(2N_f\right)^{-b}$$

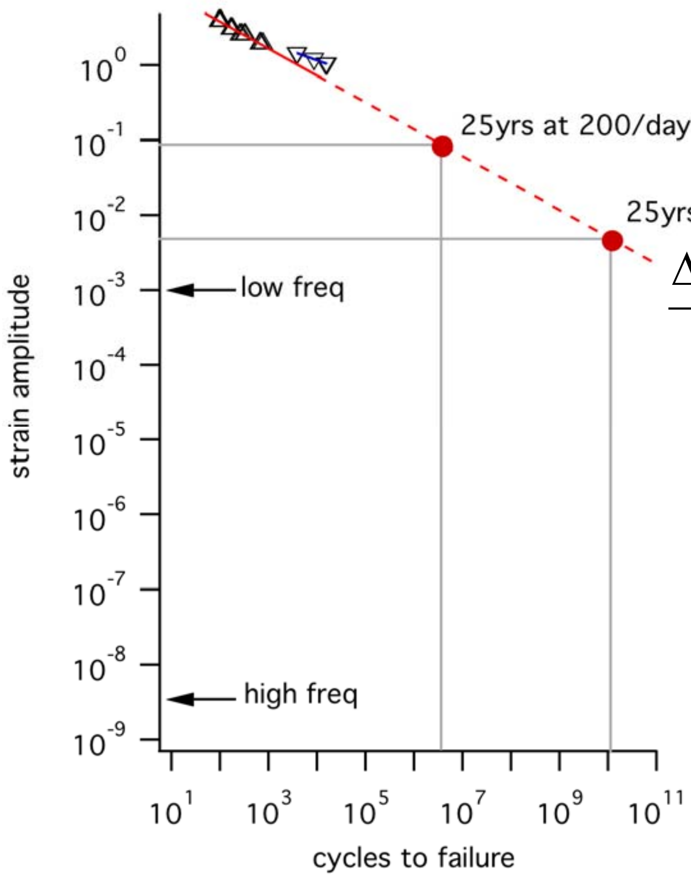
a longitudinal strain is imposed, but the ribbon is straining in bending

strain amplitudes evaluated likely have a large plastic component



ribbon fatigue: wind loading mode

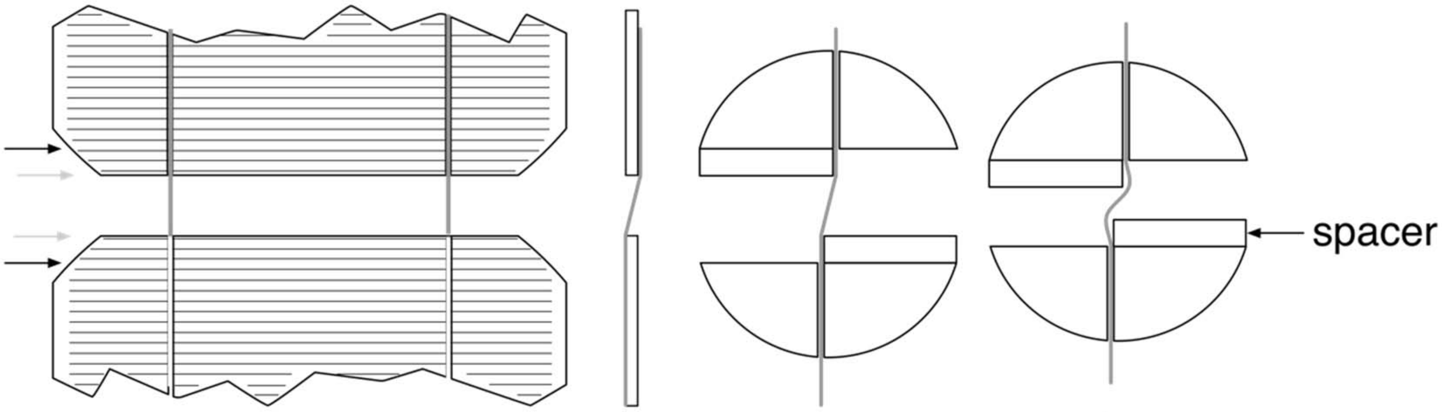
vibration due to wind loading will not result in ribbon fatigue within a module's lifetime.



$$\frac{\Delta \varepsilon_{pl}}{2} = \varepsilon'_f \left(2N_f\right)^{-c}$$

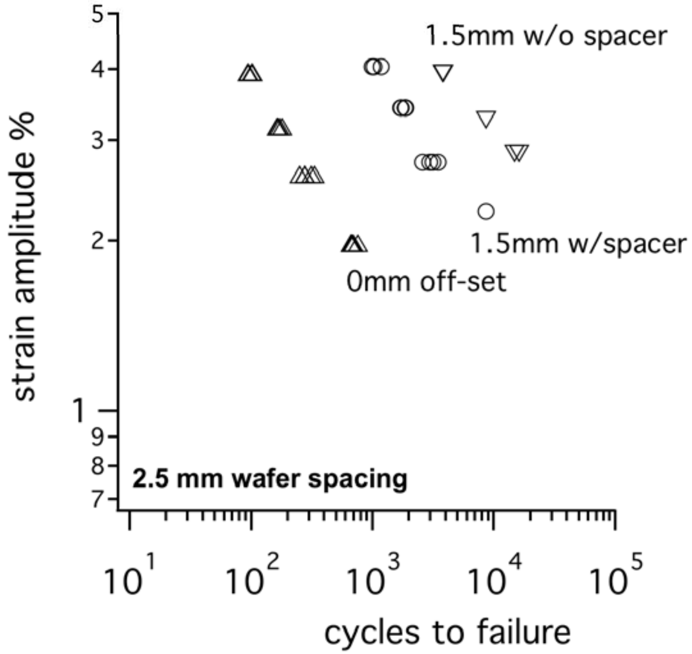
ribbon fatigue

fatigue experiment: off-set



incorporating an un-soldered length provides strain relief and longer lifetimes

ribbon constraint is a significant factor for these measurements



ribbon fatigue: thermal loading

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← prediction

ribbon fatigue: thermal loading

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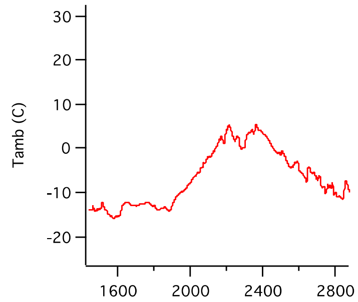
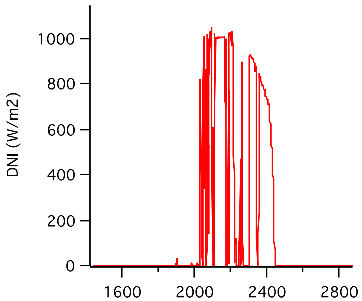
ribbon cracking		

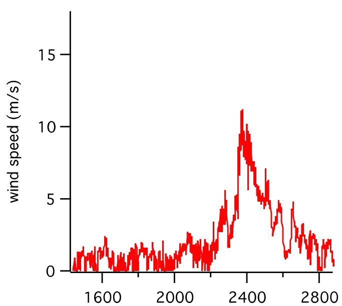
prediction

ribbon fatigue: thermal loading

driving force



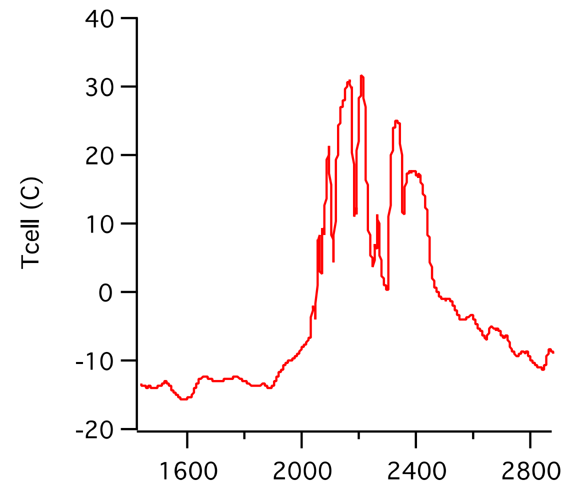




cell temperature is evaluated in one-minute intervals

$$T_{cell} = T_{amb} + E\exp\left(a + b \cdot WS\right) + E\frac{\Delta T}{1000}$$

$$T_{cell}\left(t+1\right) = T_{cell}\left(t\right)\alpha + T_{cell}\left(t+1\right)\left(1-\alpha\right)$$

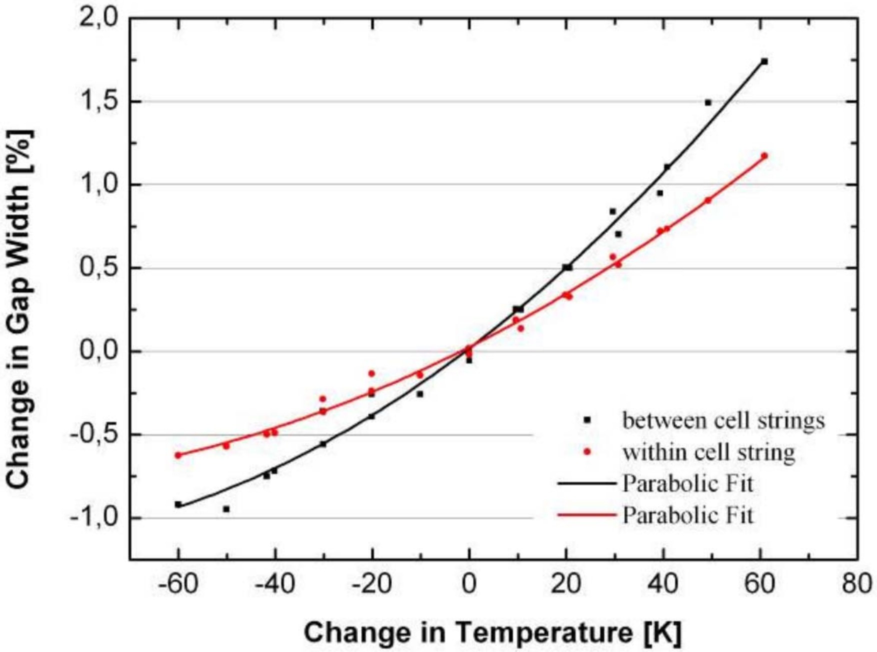


ribbon fatigue: thermal cycling

driving force

empirical relationship between temperature change and ribbon strain

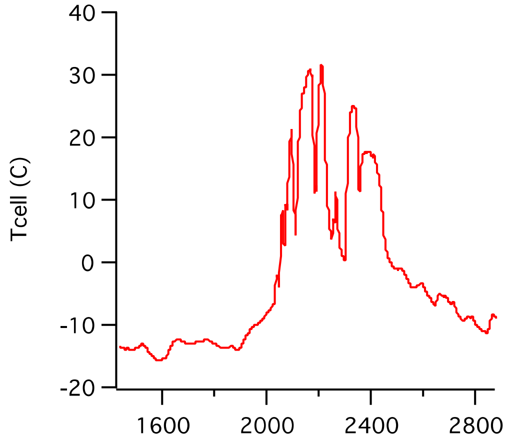
$$\Delta\varepsilon = A_1 + B_1\Delta T + B_2\Delta T^2$$



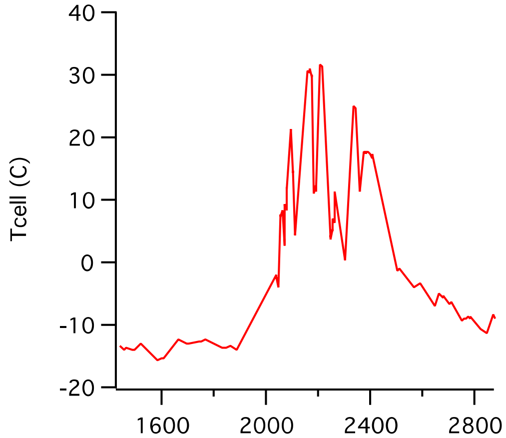
Meier, R., F. Kraemer, et al. (2010). Reliability of copper-ribbons in photovoltaic modules under thermo-mechanical loading. Photovoltaic Specialists Conference (PVSC), 2010 35th IEEE.

ribbon fatigue: thermal loading mechanism

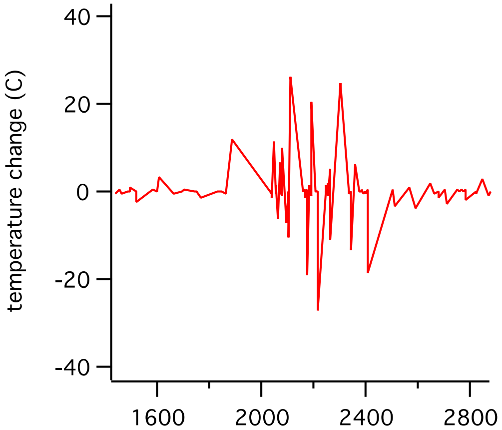
temperature history



identify peaks



extract ΔT



calculate strain

$$\Delta\varepsilon = A_1 + B_1\Delta T + B_2\Delta T^2$$

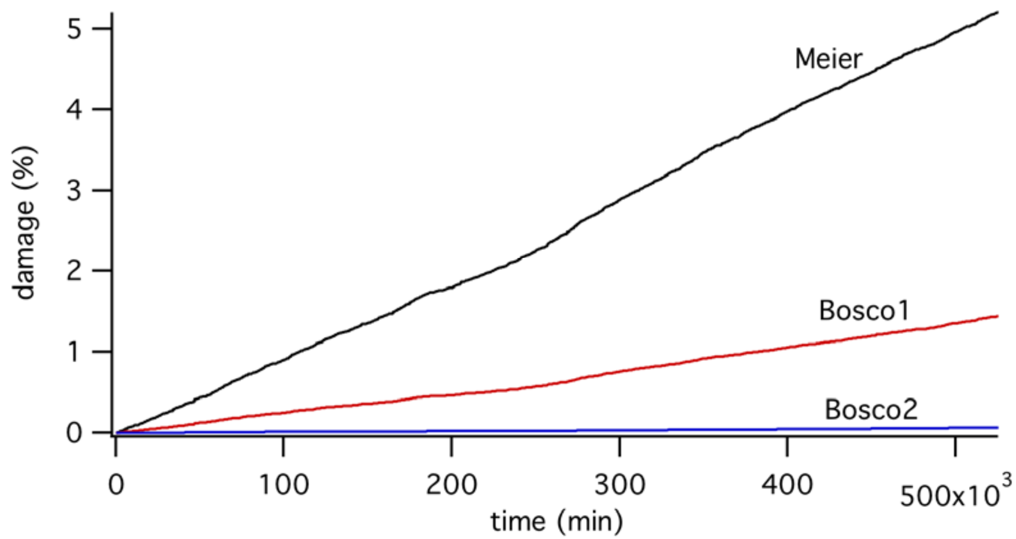
calculate cycles to failure

$$N_f = \left(\frac{\Delta\varepsilon}{a}\right)^{-1/c}$$

convert to damage

$$D = \sum_i^n \frac{1}{N_{f,i}}$$

ribbon fatigue: thermal loading mode



ribbon fatigue due to thermal loading may cause failure within a module's lifetime.

leaving an unsoldered length will extend the ribbon's lifetime.

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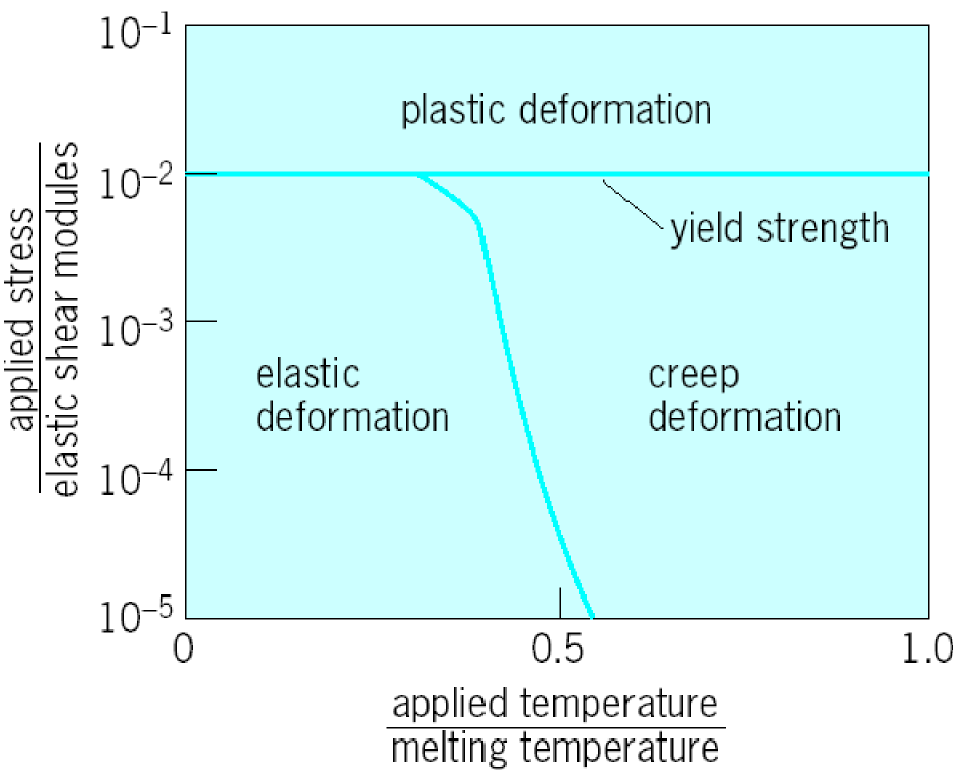
creep-fatigue



Deformation mechanism map. (After M. F. Ashby and D. R. H. Jones, Engineering Materials I: An Introduction to Their Properties and Applications, 2d ed., Butterworth- Heimann, 1996)

Time independent

$$\frac{\Delta\varepsilon_{pl}}{2} = \varepsilon'_f \left(2N_f\right)^{-c}$$

Time dependent

$$\frac{d\varepsilon_p}{dt} = A\exp\left(-\frac{Q}{RT}\right)\left[\sinh\xi\frac{\sigma^*}{s^*}\right]^{1/m}$$

$$\sigma^* = \frac{s_h}{\xi}\left(\frac{d\varepsilon_p}{Adt}\exp\left(\frac{Q}{RT}\right)\right)^n \sinh^{-1}\left[\left(\frac{d\varepsilon_p}{Adt}\exp\left(\frac{Q}{RT}\right)\right)^m\right]$$

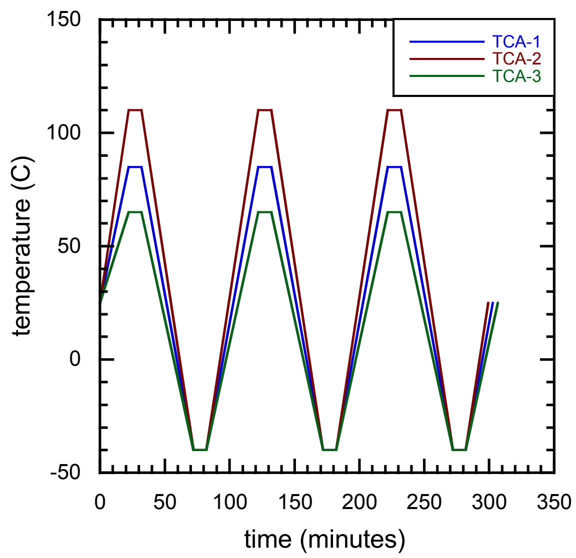
$$s^* = \hat{s}\left[\frac{\dot{\varepsilon}_{pl,eq}}{A}\exp\left(\frac{Q}{RT}\right)\right]^n$$

$$D \approx W_{pl} = \int |\sigma| d\varepsilon_{pl}$$

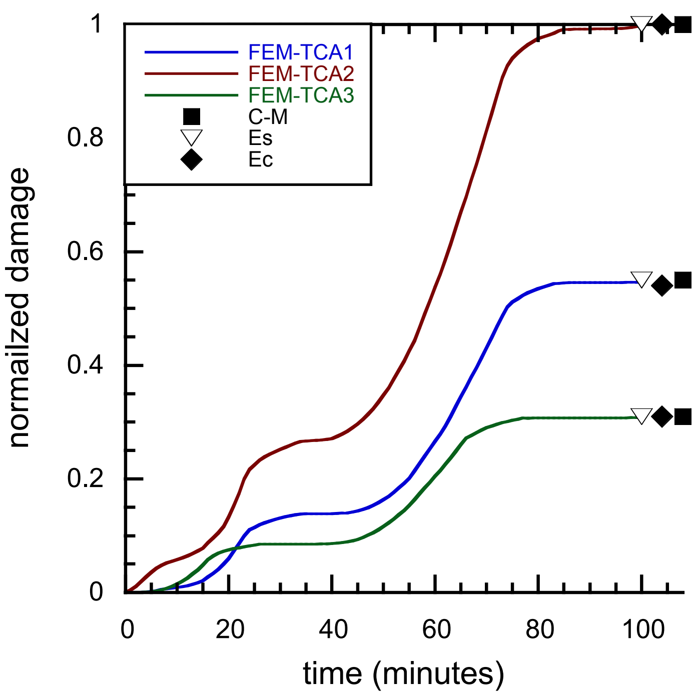
simulations and analysis

simulation

	TCA-1	TCA-2	TCA-3
T_{max} C	85	110	65
T_{min} C	-40	-40	-40
t_c (min)	100	100	100
t_d (min)	10	10	10



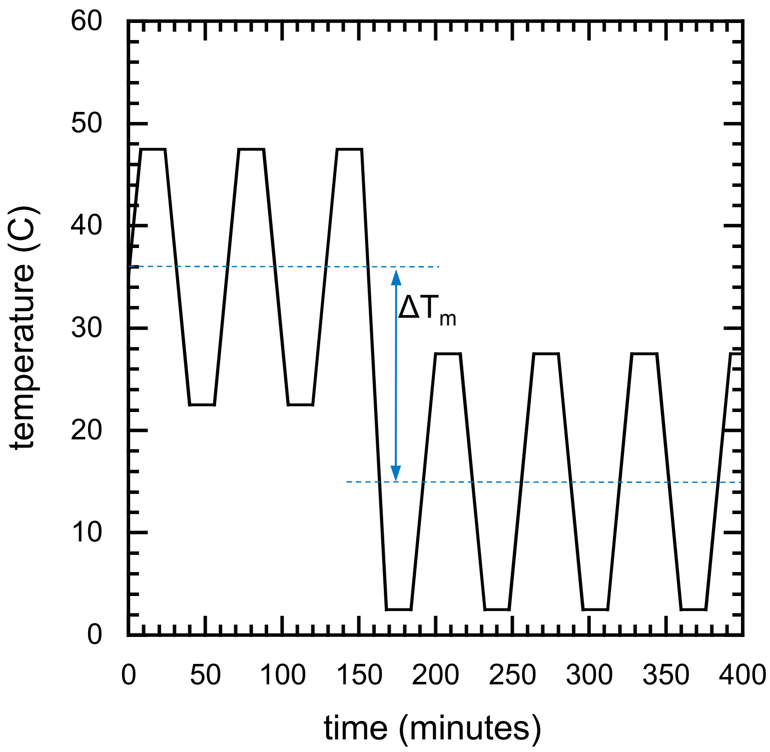
results FEM : empirical relationships



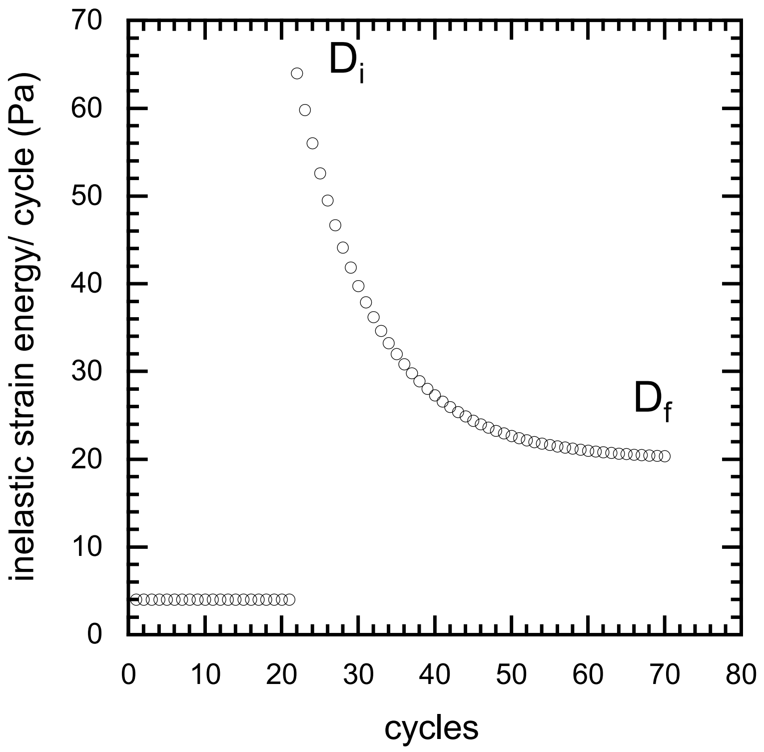
Empirical relationships may be effective for relating the damage done by various ALT

simulations and analysis

simulation



results



FEM is required to simulate temperature changes due to weather

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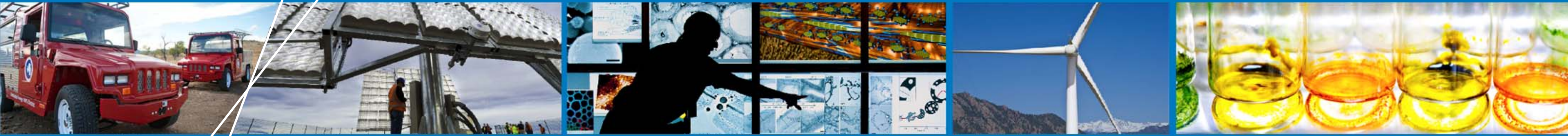
Comparison of accelerated testing with modeling to predict lifetime of CPV solder layers



2012 PV Module Reliability Workshop

***Timothy J Silverman*, Nick Bosco, Sarah Kurtz**

Mar. 1 Afternoon II – Modeling of CPV Reliability Issues

conclusions

- **Modeling metal fatigue**
  - Consider driving force and mechanism
  - Testing must represent service
- **Cu ribbon fatigue**
  - Wind loading is likely inconsequential
  - Thermal loading *is* significant
    - May be mitigated by proper ribbon routing
    - Ribbon shape and constraints are important
- **Solder fatigue**
  - Time dependency complicates modeling
  - Empirical models may relate ALT, but not service

Sample Text and Object Slide with Bar