Via Reliability:
Stresses and Strains Explained

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ACB Technology seminar

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EDM
Electronic Design & Manufacturing

Electronic Design & Manufacturing program MISSION

To support industry *in the development of high quality, reliable and cost-effective electronic modules (PBA) by means of* ***knowledge*** *creation and sharing,* ***scientifically sound methodologies*** *and* ***collaboration*** *throughout the electronic supply chain.*

Collective

- Awareness creation
- Design Guidelines
- PBA development tools
- Seminars - training

Bilateral

- Consultancy
- Knowledge transfer
- Implementation
- Training

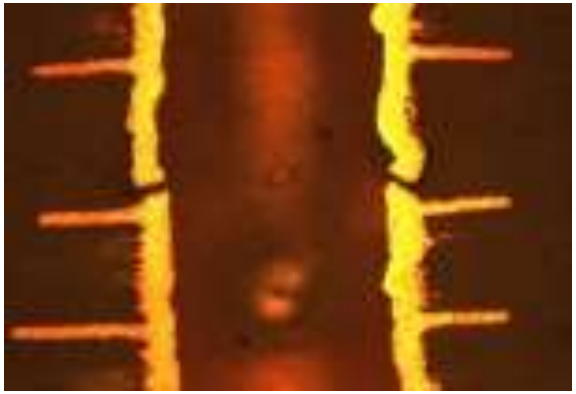
Better electronics at reduced cost through science based design & production methodologies.

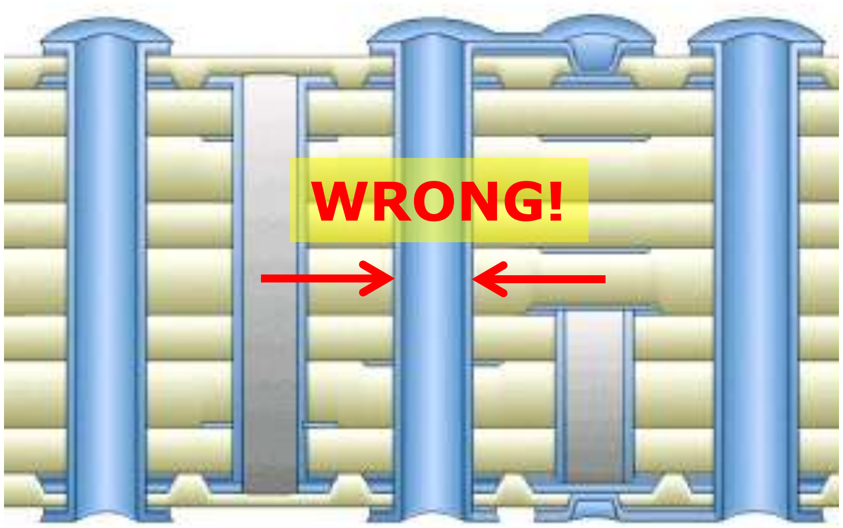
Outline

1. Via fatigue failure: basics
2. Via elastic strain during operation
   Fundamental understanding and new analytical model
3. Via plastic strain
4. Conclusions

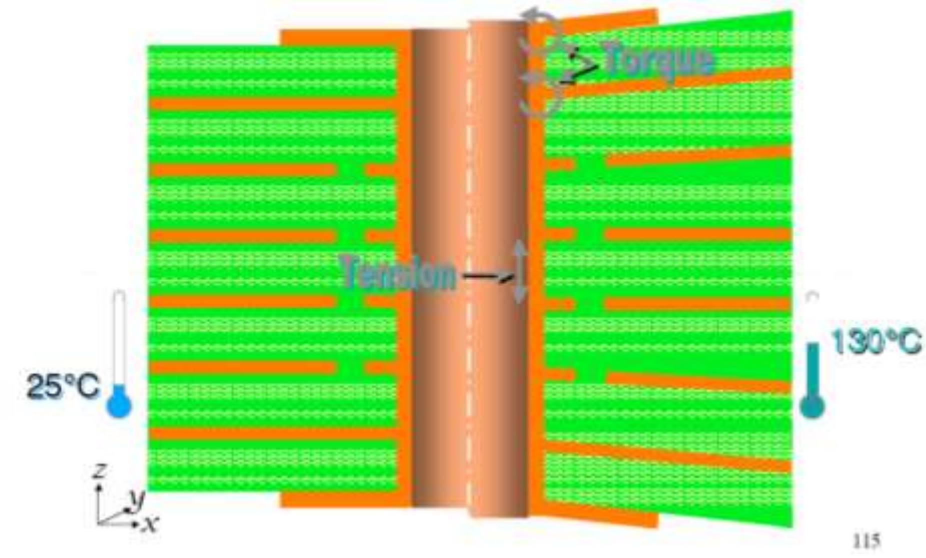
1. Via fatigue failure: basics

- Driving force: Difference in CTE between laminate and Cu-plating of via
- Via cracking observed for PTVs
  - Worse with decreasing via diameter
  - Worse with increasing PCB thickness



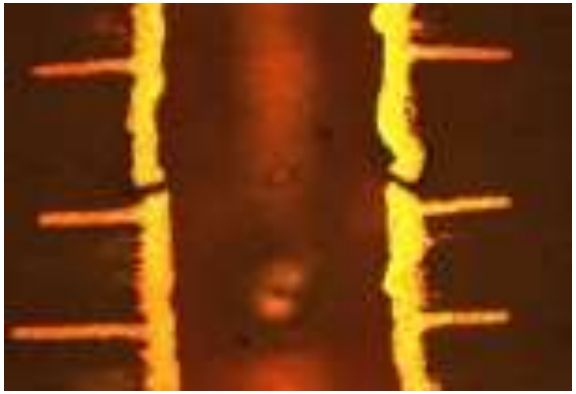


Paul Reid, PWB Interconnect solutions



1. Via fatigue failure: basics

- High cycle fatigue (elastic)
  – During product use due to thermal cycling
- Low cycle fatigue (plastic)
  – During soldering due to high temperature excursions
- "medium" cycle fatigue (elastic/plastic)
  – During accelerated testing (-40°C/125°C)

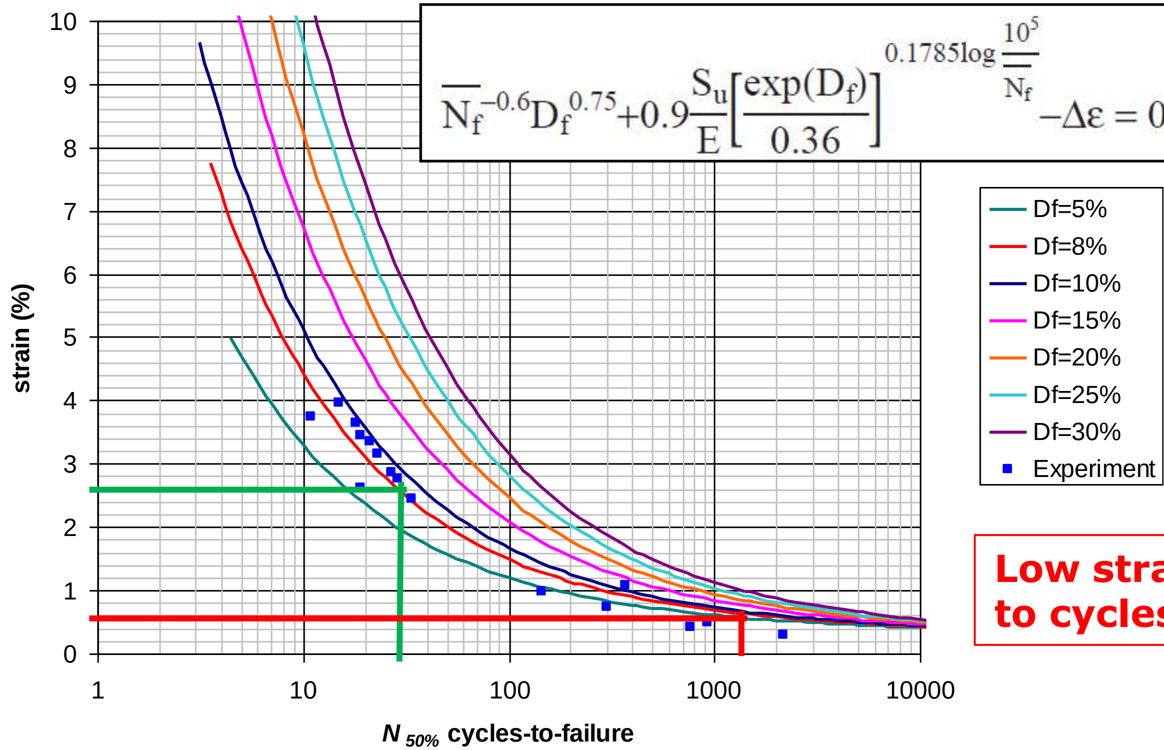


- Reliability prediction required
  – Analytical closed form preferred instead of time consuming and expensive Finite Element Analysis
  – Model (Engelmaier): IPC-D-279 *(Design Guidelines for Reliable SMT PBA)*
- **EDM target:**
  – **Improve physical understanding of influencing parameters**
  – **Improve analytical model using FEA as virtual test**

1. Via fatigue failure: basics

- Wöhler curve describes fatigue behavior of metals (IPC-D-279)

$$\overline{N_f}^{-0.6} D_f^{0.75} + 0.9\frac{S_u}{E}\left[\frac{\exp(D_f)}{0.36}\right]^{0.1785\log\frac{10^5}{\overline{N_f}}} - \Delta\varepsilon = 0$$



FE analysis of experimental points by Melina Lofrano, imec

Ref.: EDM's DfM Guideline: PCB Specification

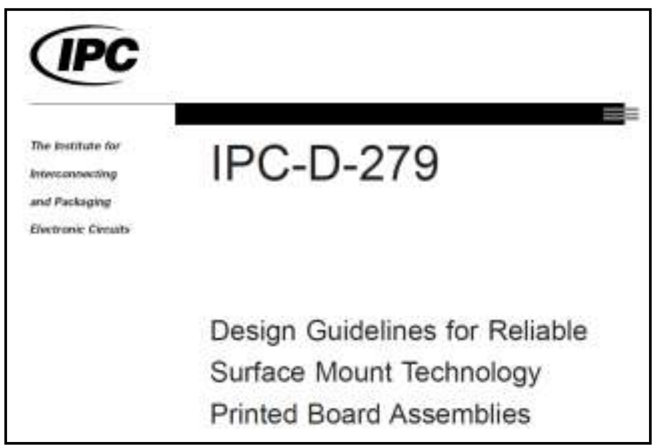
Low strain: higher sensitivity to cycles-to-failure

- Cycles-to-failure determined by amount of cyclic strain
- **Strain range** needs to be analyzed by FEM

1. Via fatigue failure: basics
Strain model

- **Elastic** Engelmaier's "2-beam" model (IPC-D-279/Eq. B6)
  Displacement and force equilibrium

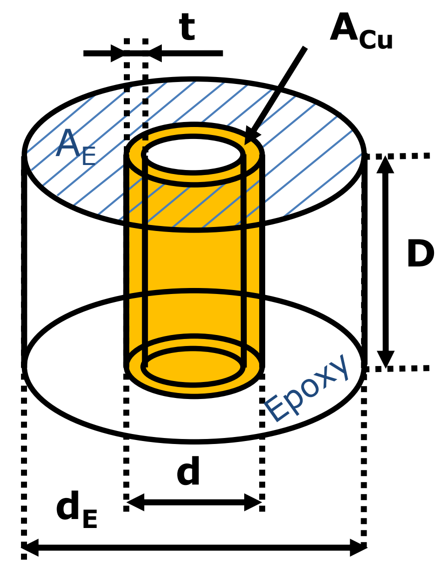
$$\Delta\varepsilon_{Cu,z} = \frac{\sigma_{Cu,z}}{E_{Cu}} = \frac{FE_E(\Delta T) - FE_{Cu}(\Delta T)}{1 + \frac{A_{Cu}}{A_E}\frac{E_{Cu}}{E_E}}$$


IPC
The Institute for Interconnecting and Packaging Electronic Circuits
IPC-D-279
Design Guidelines for Reliable Surface Mount Technology Printed Board Assemblies

Empirical relationship:

$$A_E = \frac{\pi}{4}[d_E^2 - d^2] \quad d_E = \frac{D}{2} + 2d$$

$$A_E = \frac{\pi}{4}\left[\frac{D^2}{4} + 4Dd + 3d^2\right]$$



- **Validity of expression for epoxy loading area A_E?**
- **Use FEM to check model and validity of A_E**

2. Via elastic strain
FEM simulations

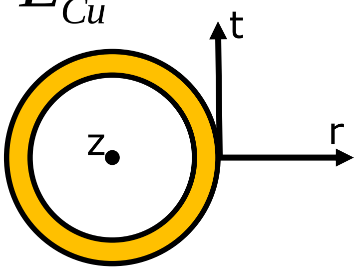
- 2-D axisymmetric FEM simulations show

$$\varepsilon_{Cu,z} \neq \frac{\sigma_{Cu,z}}{E_{Cu}}$$

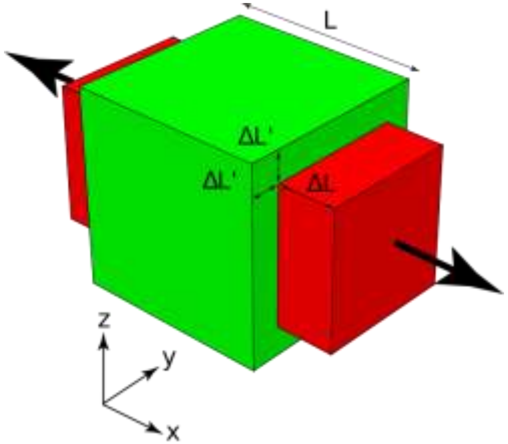
- Engelmaier → up to 30% error in Cu-strain

Poisson effect in copper needs to be included

$$\varepsilon_{Cu,z} = \frac{1}{E_{Cu}}(\sigma_{Cu,z} - \nu_{Cu}\sigma_{Cu,r} - \nu_{Cu}\sigma_{Cu,t})$$

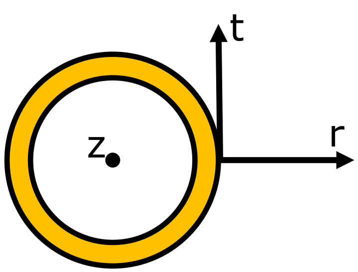


r=radial
t=circumferential
z=axial



2. Via elastic strain
Physical effect

- In plane stress in epoxy 'pulls' on barrel in r-direction, thereby causing circumferential tensile stress in barrel: the barrel is pulled 'open': this **reduces** the axial strain.



r=radial
t=circumferential
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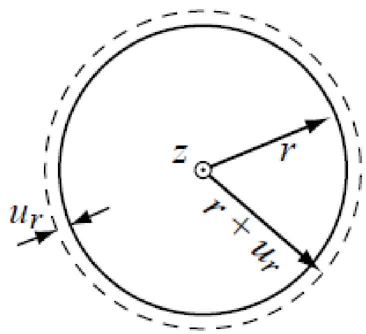
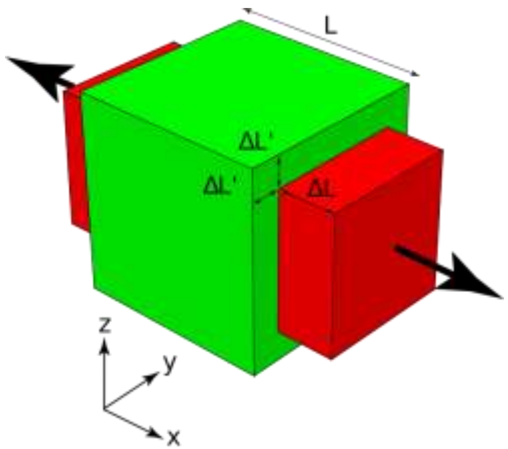




- Epoxy is anisotropic
  - E_z (2.8GPa) important for tensile axial stress in barrel
  - E_{xy} (17GPa-stiffer due to glass fibers) important for reducing tensile axial stress in barrel
- Poisson effect in epoxy can be neglected
  - FEM: 1% impact on strain in Cu

2. Via elastic strain
Interpretation analytical solution

- Approximate solution for $\upsilon_E = 0, \alpha_{E,xy} = \alpha_{Cu}$

$$\Delta\varepsilon_{Cu,z} = \frac{FE_{E,z}(\Delta T) - FE_{Cu,z}(\Delta T)}{1 + \frac{A_{Cu,z}}{\boxed{A_{E,z}}} \frac{E_{Cu}}{E_z} \boxed{\frac{E_{Cu} + (1-\nu_{Cu}^2)E_{xy}}{(1-\nu_{Cu}^2)E_{Cu} + (1+\nu_{Cu})^2(1+2\nu_{Cu})E_{xy}}}}$$

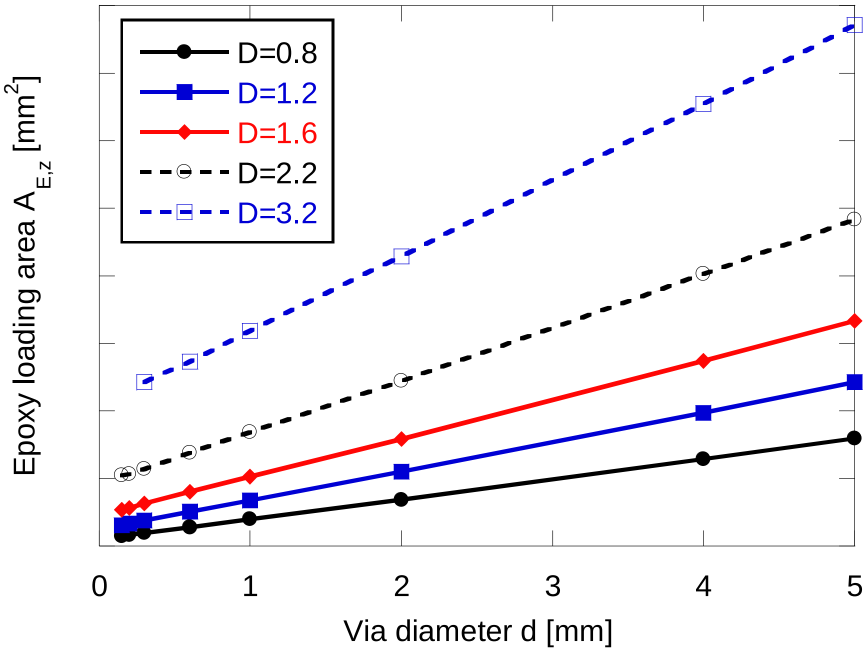
In-plane young’s modulus epoxy E_{xy} impacts

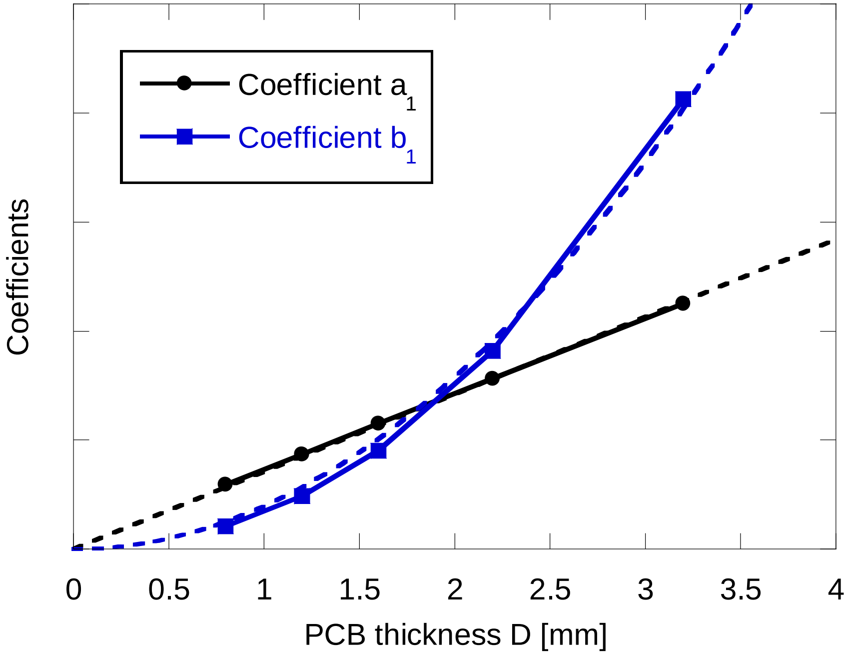
- Poisson correction factor to Engelmaier model (range 1.1-1.13)
- Epoxy loading area $A_{E,z}$

2. Via elastic strain
$A_{E,z}$ extraction based on FEM

Extracting $A_{E,z}$ by fitting analytical model to FEM strain data

- Linear function of via diameter d: $A_{E,z}=b_1+a_1*d$





- Dependency coefficient a_1 on D: Linear
- Dependency coefficient b_1 on D: Parabolic

2. Via elastic strain $A_{E,z}$ extraction based on FEM

- New model: $$A_{E,z} = b_1 + a_1 d = b_2(E_{xy})D^2 + a_2(E_{xy})Dd$$

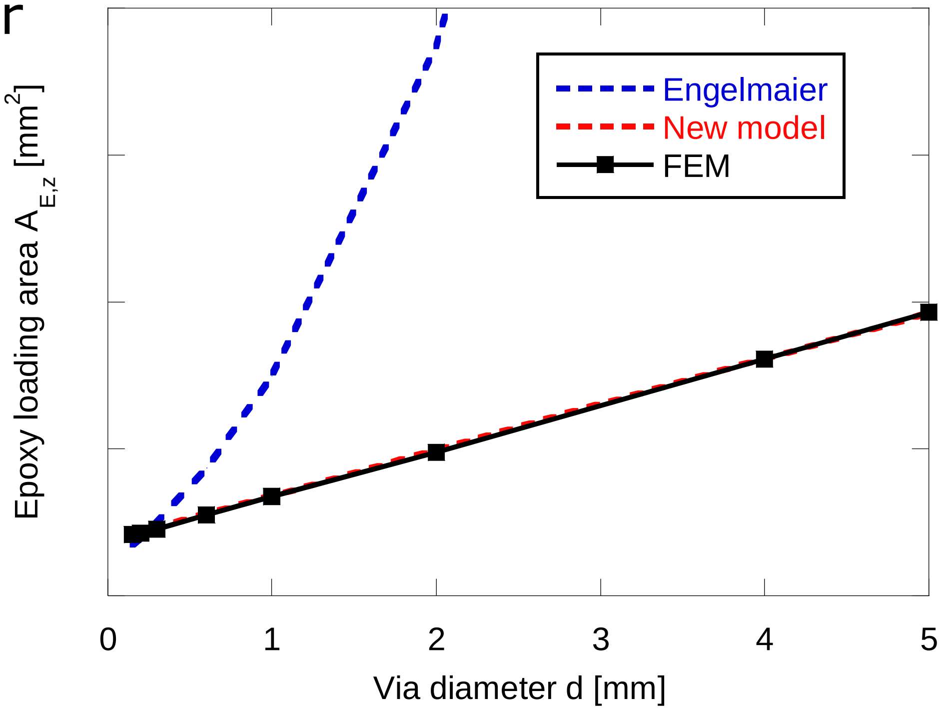
- Engelmaier: dependency d^2 is wrong

→ strain overestimated for large via diameters

$$A_E = \frac{\pi}{4}[d_E^2 - d^2]$$

$$d_E = \frac{D}{2} + 2d$$

$$A_E = \frac{\pi}{4}\left[\frac{D^2}{4} + 4Dd + 3d^2\right]$$

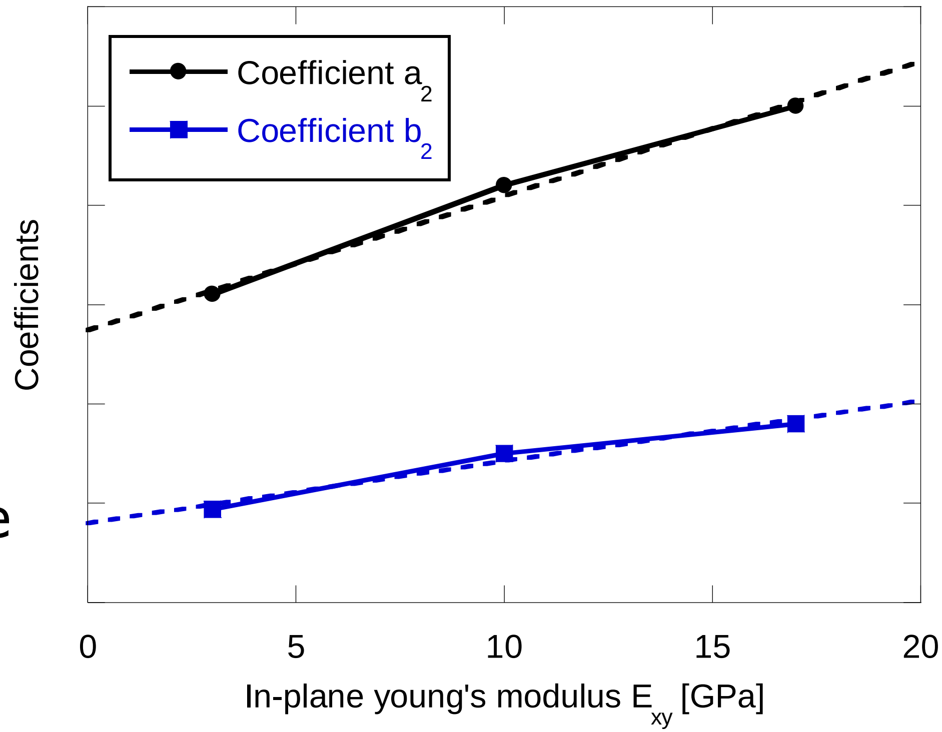


2. Via elastic strain
$A_{E,z}$ dependency on Epoxy XY-stiffness

Laminate property (E_{xy}) dependency of $A_{E,z}$

- Coefficients a_2 and b_2 can be approximated by a linear function of E_{xy}

$$\begin{aligned} A_{E,z} &= b_1 + a_1 d \\ &= b_2(E_{xy})D^2 + a_2(E_{xy})Dd \end{aligned}$$



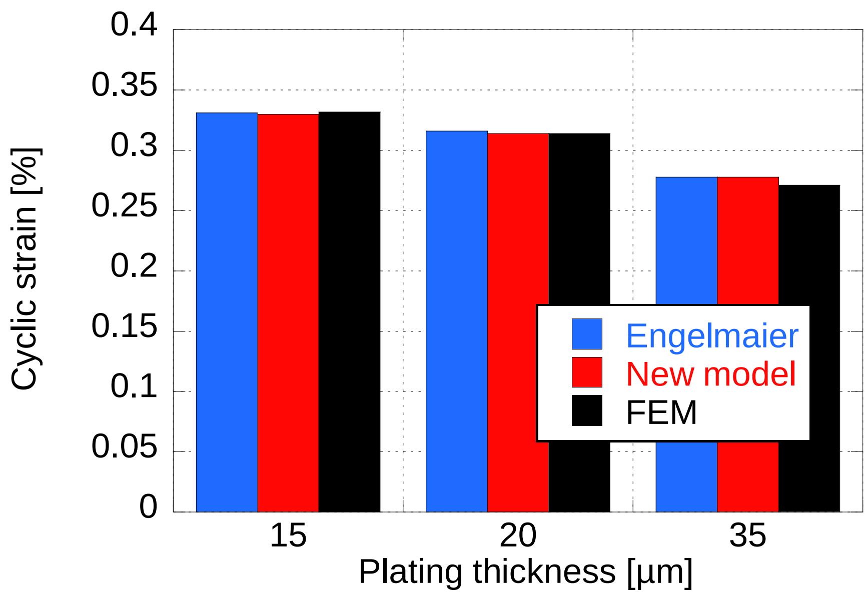
- Meaning:
  With increasing in-plane stiffness the zone of influence enlarges.

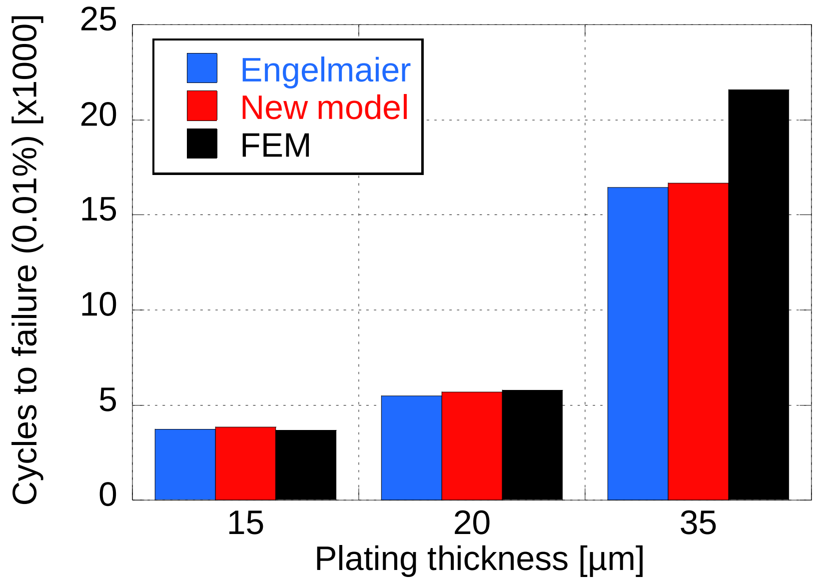
2. Via elastic strain
Model validation

- Comparison old (Engelmaier) and new model with FEM results
- Based on two PCB density classes
  - PCB thickness 2.2 mm and minimum **via diameter 0.6**
    - Aspect ratio 3.7
    - Relaxed end of standard PCB density class
  - PCB thickness 2.2 mm and minimum **via diameter 0.3**
    - Aspect ratio 7.3
    - Advanced end of standard PCB density class

2. Via elastic strain
Model validation – plating thickness

- D=2.2mm, **d=0.3mm**, CTE_z=50ppm/°C, ΔT=100°C

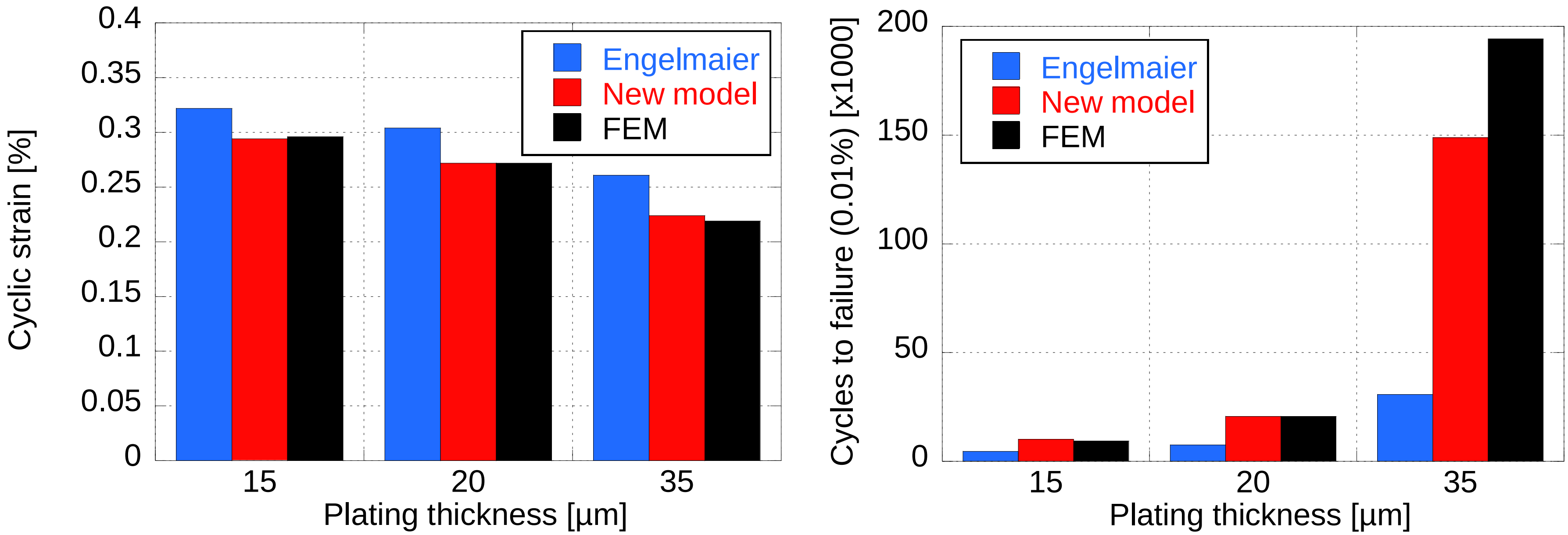




- Increasing plating thickness reduces strain
- Reduced strain leads to increased via lifetime

2. Via elastic strain
Model validation – plating thickness

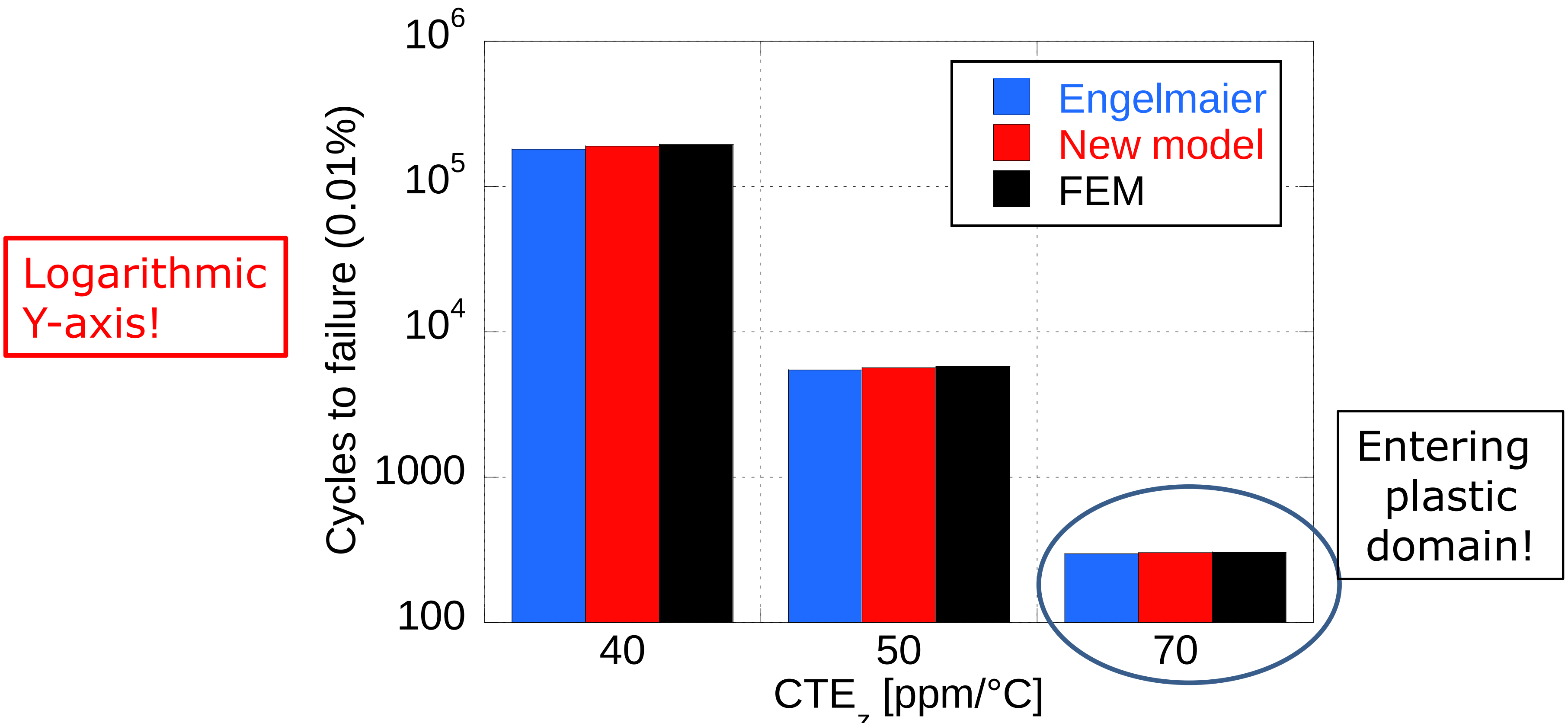
- D=2.2mm, **d=0.6mm**, CTE_z=50ppm/°C, ΔT=100°C



- Engelmaier overestimates strain for increased via diameter
- Via lifetime underestimated using Engelmaier

2. Via elastic strain
Model validation – thermal Z-expansion

- D=2.2mm, **d=0.3mm**, t=20µm, ΔT=100°C

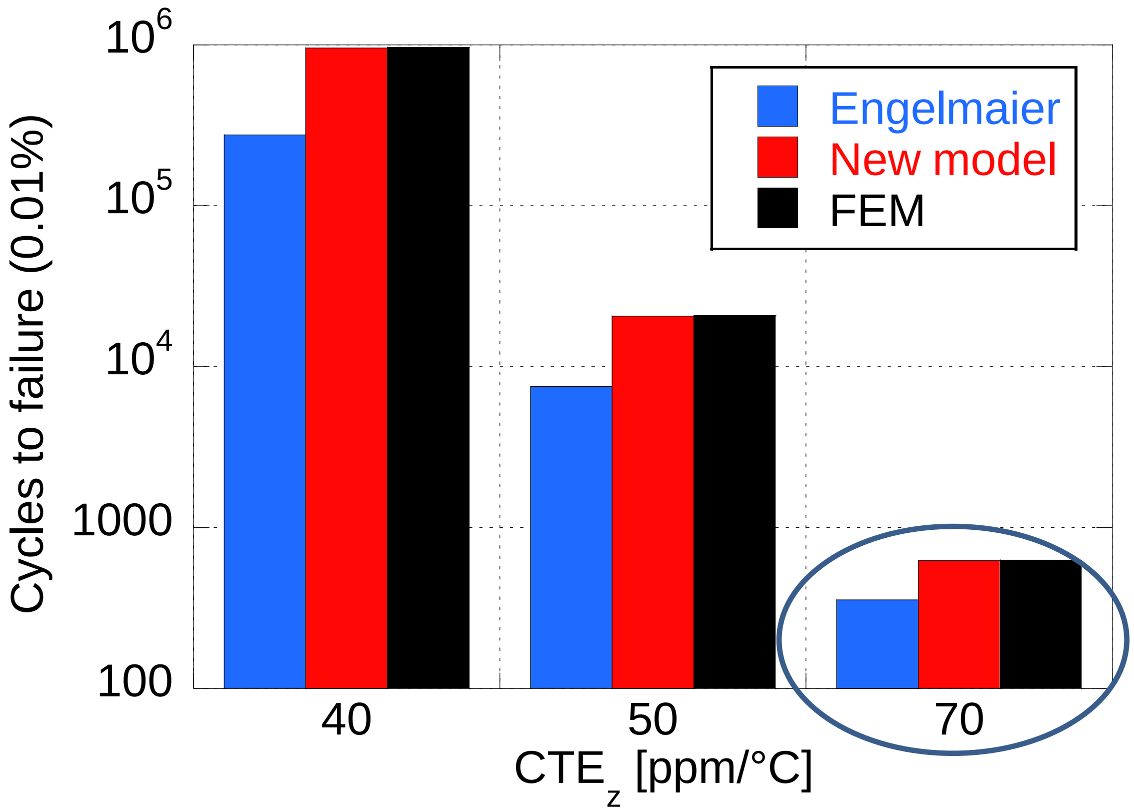


- Increased z-expansion of the epoxy **drastically** reduces via lifetime: laminate selection is critical!

2. Via elastic strain
Model validation - thermal Z-expansion

- D=2.2mm, **d=0.6mm**, t=20µm, ΔT=100°C

Logarithmic Y-axis!

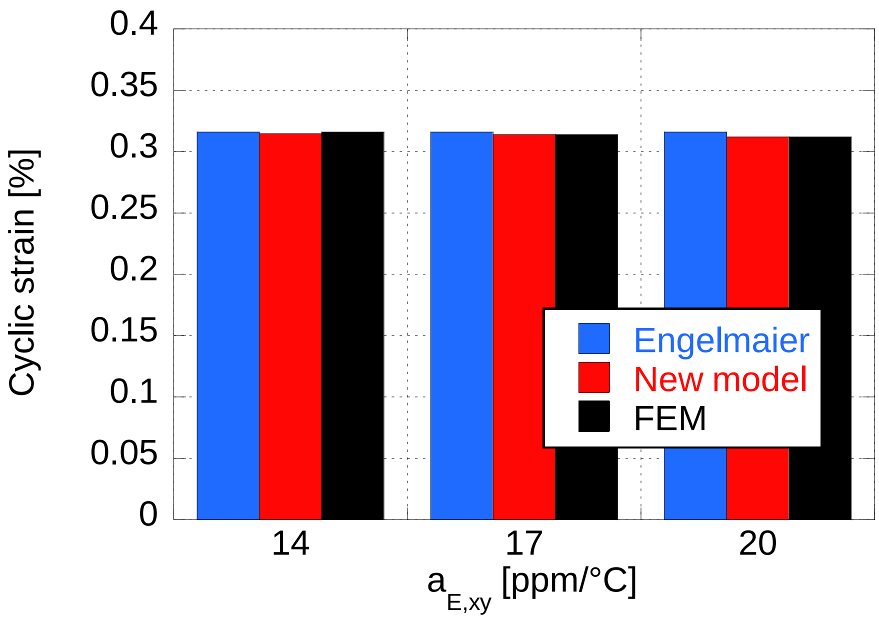


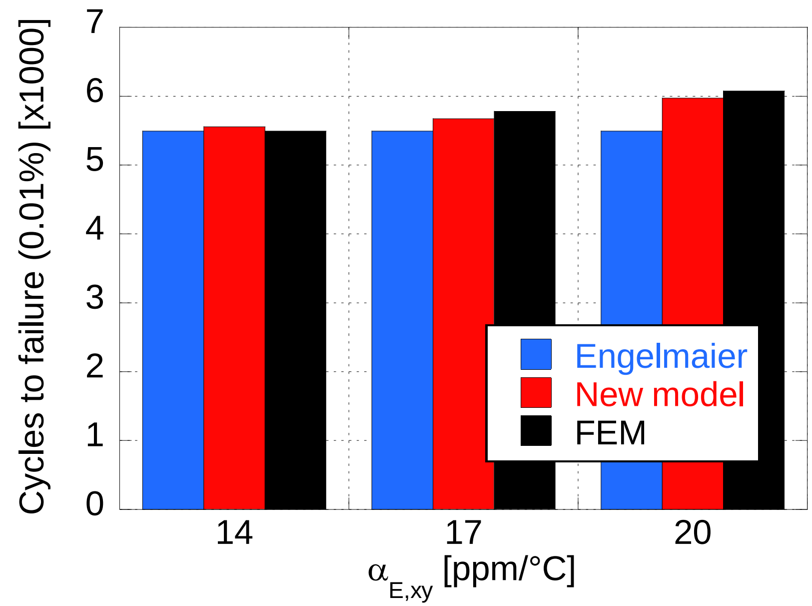
Entering plastic domain!

- Larger via diameter, larger Engelmaier model deviation

2. Via elastic strain
Model validation – thermal XY-expansion

- D=2.2mm, **d=0.3mm**, t=20µm, ΔT=100°C

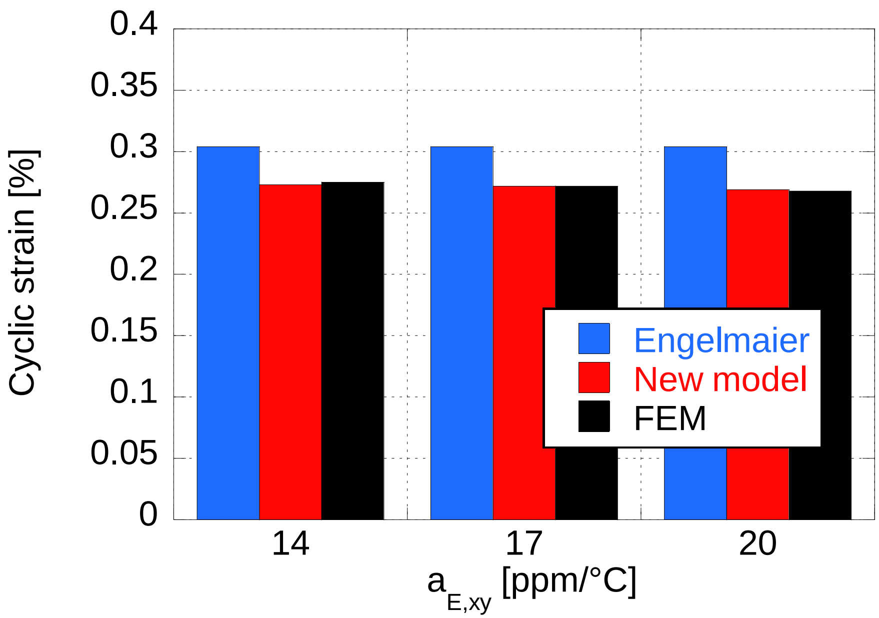


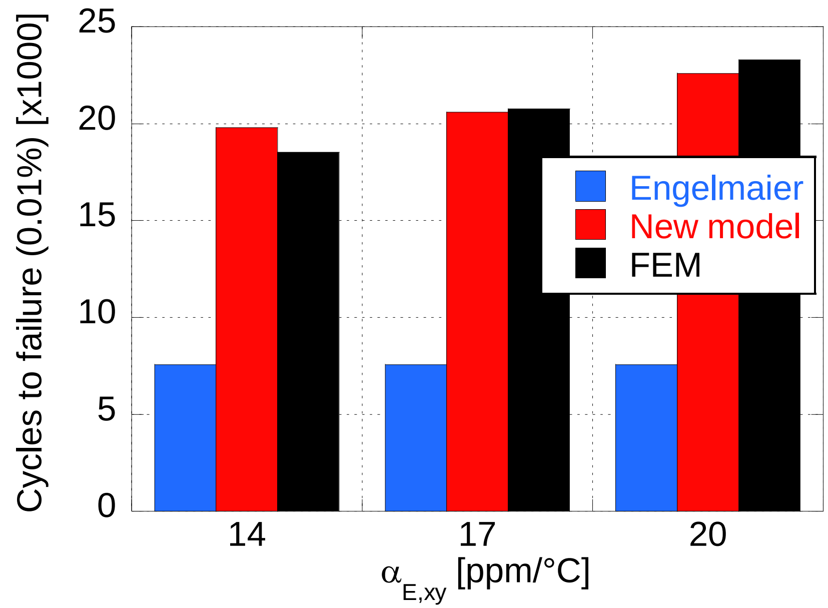


- Small impact $\alpha_{E,XY}$ for small hole diameters
- Not modeled by Engelmaier

2. Via elastic strain
Model validation – thermal XY-expansion

- D=2.2mm, **d=0.6mm**, t=20µm, ΔT=100°C

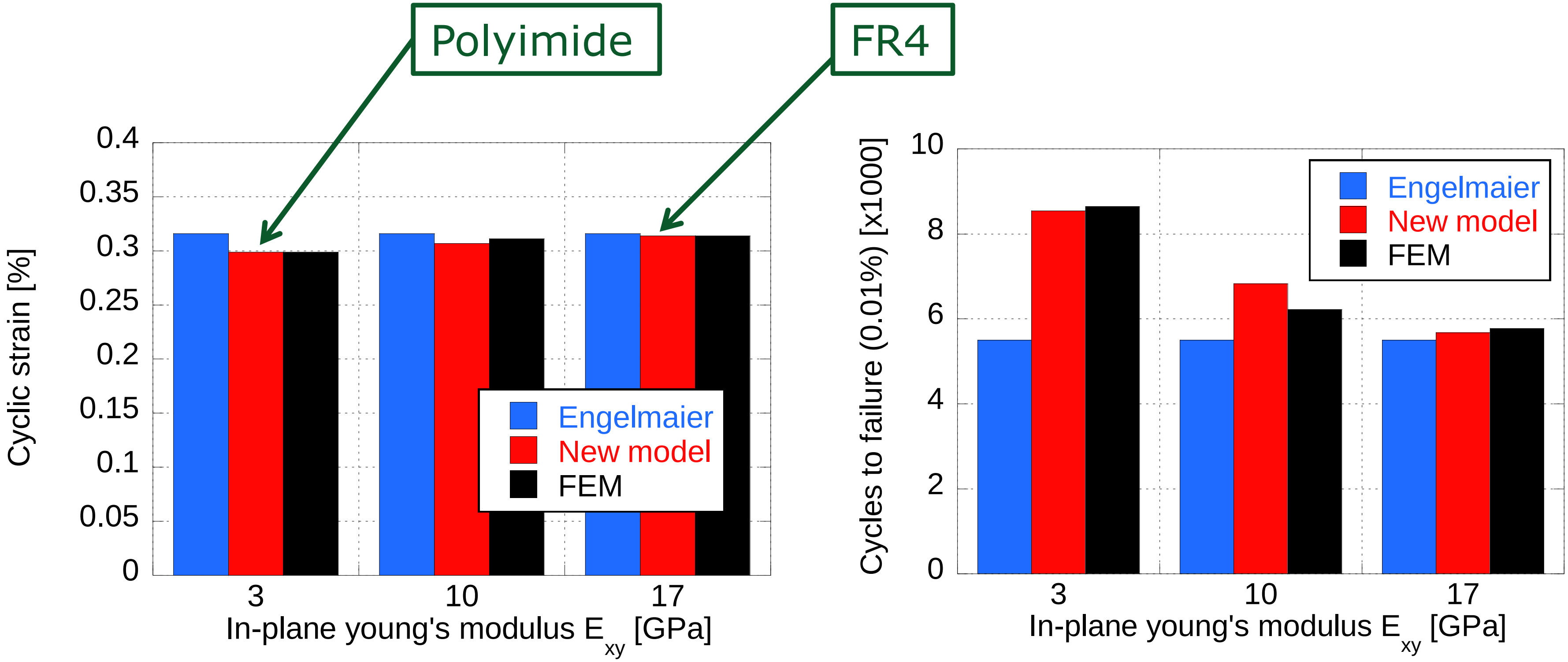




- Up to 25% impact of $\alpha_{E,XY}$ for large via diameter

2. Via elastic strain
Model validation – Epoxy XY-stiffness

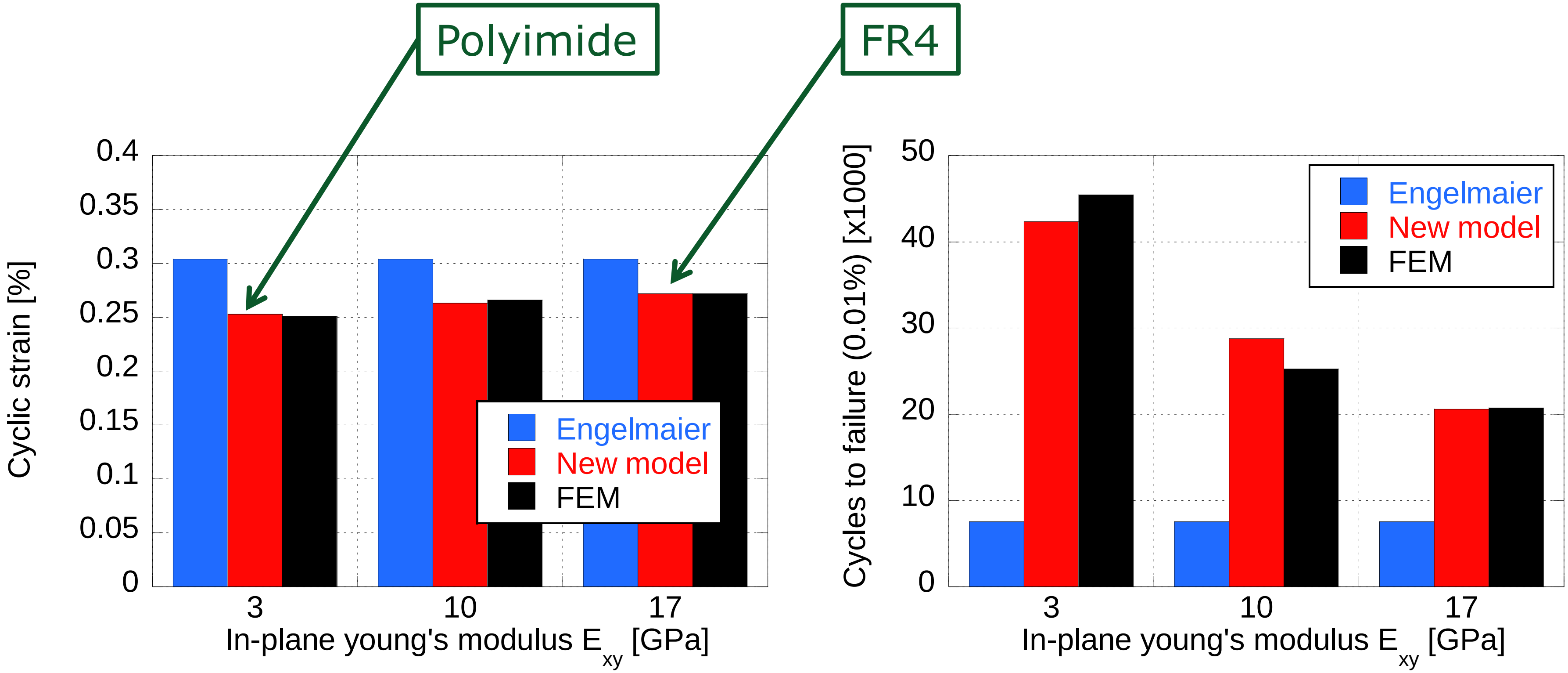
- D=2.2mm, **d=0.3mm**, t=20µm, ΔT=100°C



- Reduced E_{xy} increases via lifetime
- Not modeled by Engelmaier

2. Via elastic strain
Model validation – Epoxy XY-stiffness

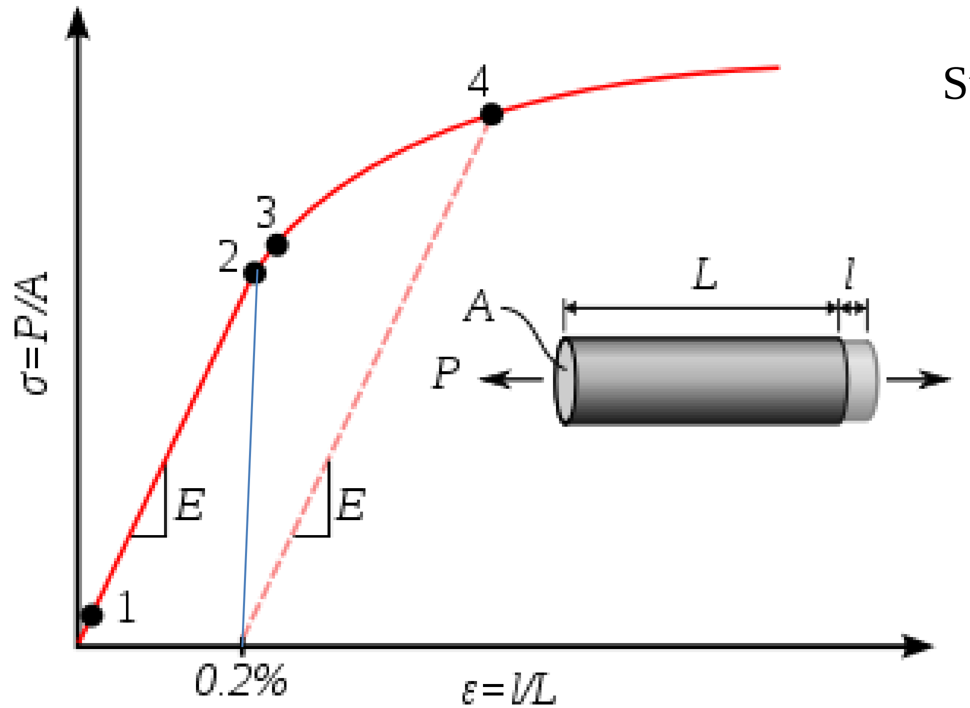
- D=2.2mm, **d=0.6mm**, t=20µm, ΔT=100°C

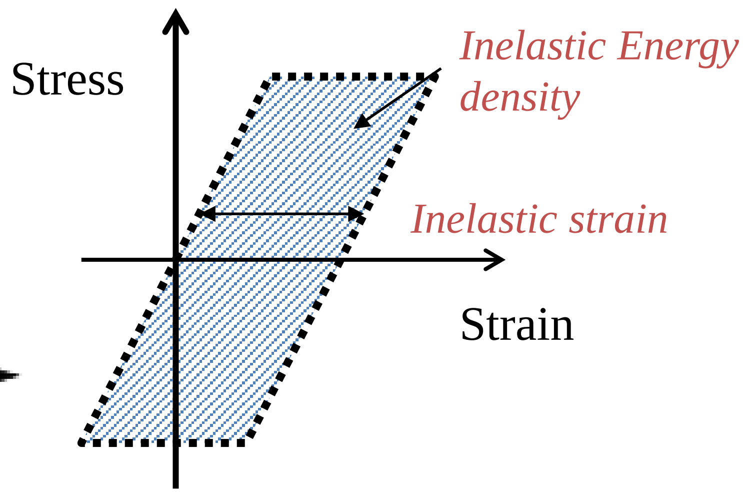


- Reduced E_{xy} increases via lifetime for large via diameter

3. Via plastic strain

- Large thermal mismatch drives Cu barrel into plastic deformation domain.



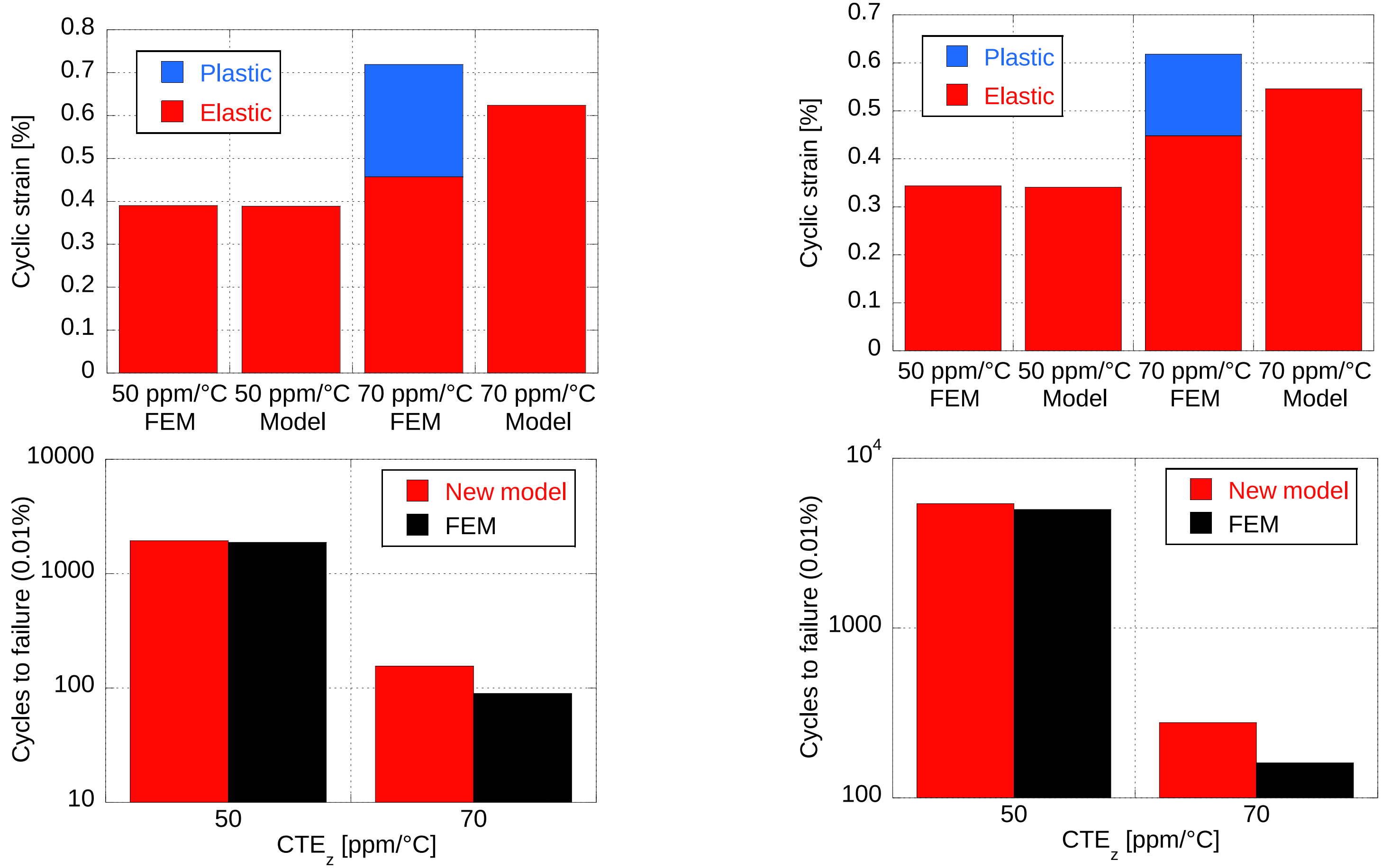


- Note:
  fatigue modeling elastic strain range limit = 2x 0.2% = 0.4%

3. Via plastic strain
Influence CTEz, ΔT=-40+125°C

- D=2.2mm, d=0.3mm

D=2.2mm, d=0.6mm

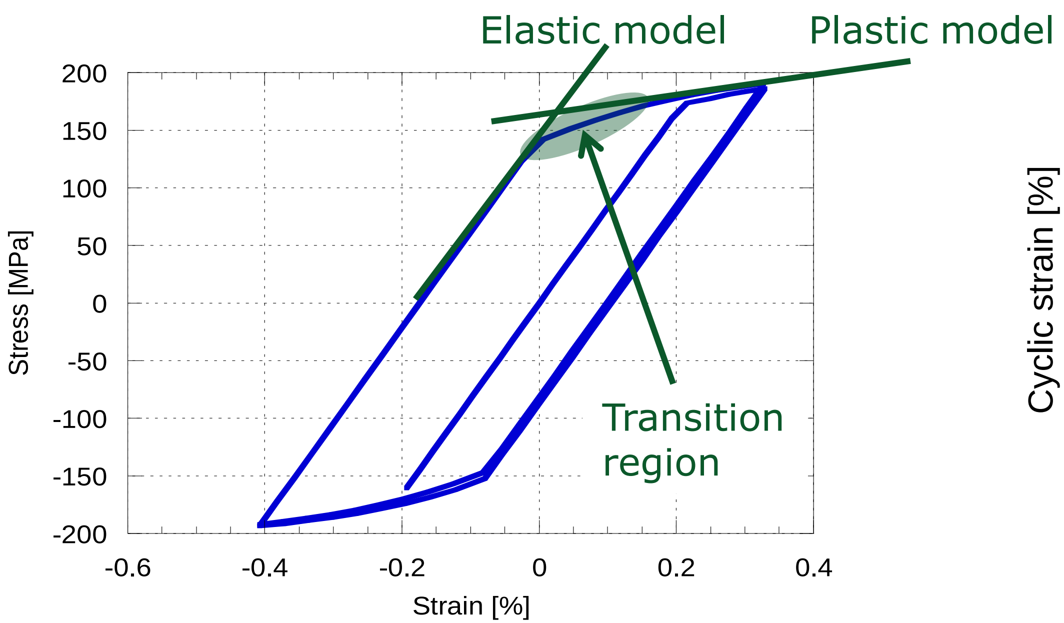


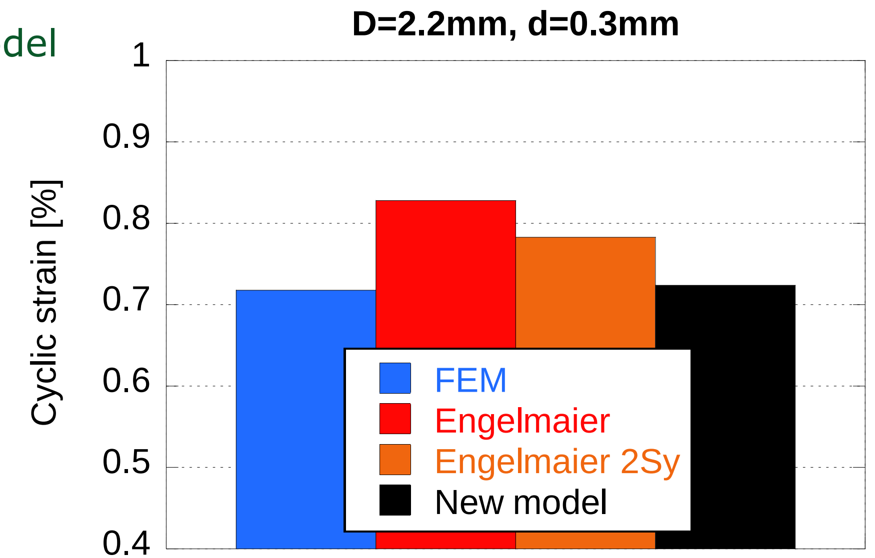
- CTEz=50ppm/°C: Cu elastic; CTEz=70ppm/°C: Cu plastic

Updated Plastic Engelmaier's 2-beam model (IPC-D-279/Eq. B7)

$$\Delta\varepsilon_{Cu,z} = \frac{FE_E(\Delta T) - FE_{Cu}(\Delta T) - 2S_y \dfrac{A_{Cu}}{A_E} \dfrac{E_{Cu} - E'_{Cu}}{E_{Cu} E_E}}{1 + \dfrac{A_{Cu}}{A_E} \dfrac{E'_{Cu}}{E_E}}$$

Same A_E as in elastic region!



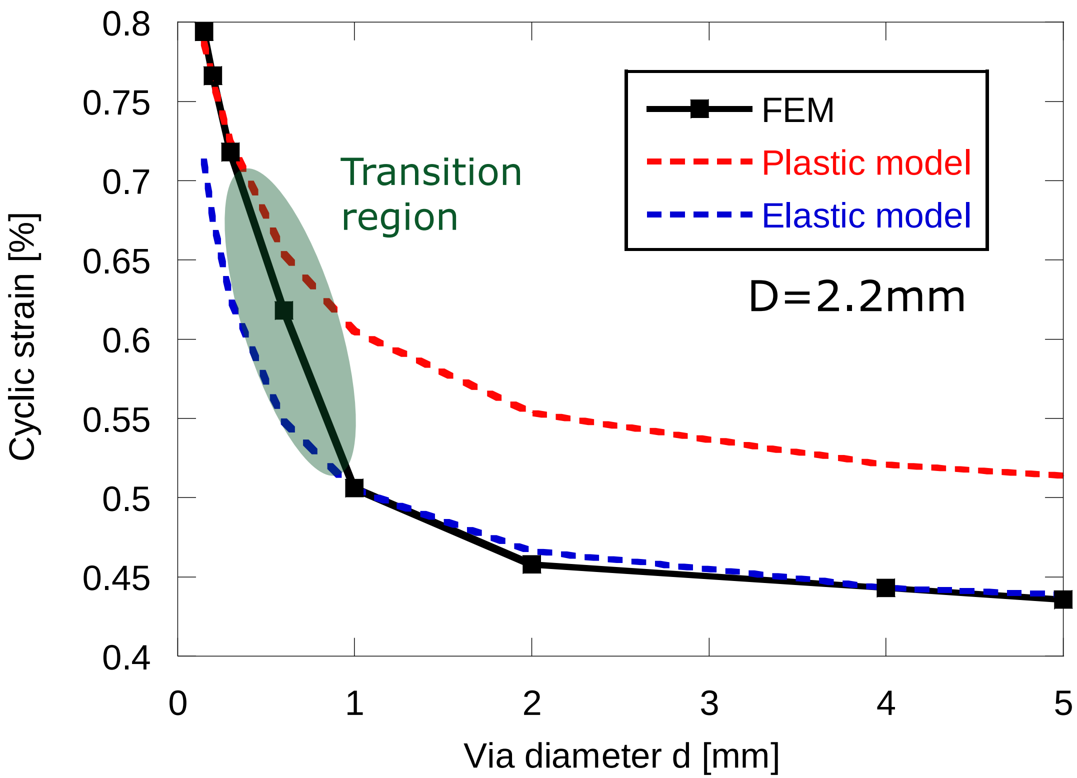


Engelmaier overestimates strain

Via plastic strain

- Δε < 0.5%: Elastic model
- 0.5% < Δε < 0.7%: Transition region
- Δε > 0.7%: Plastic model

Further modeling required for transition region



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4. Conclusions

- Via strain during operation and accelerated test
  - Poisson coefficient copper needs to be taken into account
  - Anisotropy of epoxy needs to be included
  - Correction factor to original Engelmaier model introduced
  - Improved model for epoxy loading area
    - Also dependent on Epoxy parameters
  - New model verified
    - For geometric dimensions
    - For material parameters
    - For temperature dependency
  - Epoxy loading area model validity confirmed in plastic region
  - Further modeling required for elastic-plastic transition region.

- New model will be included (mid 2012) in *DfM Guideline: PCB Specification V2*

Thank you!

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Met steun van het IWT