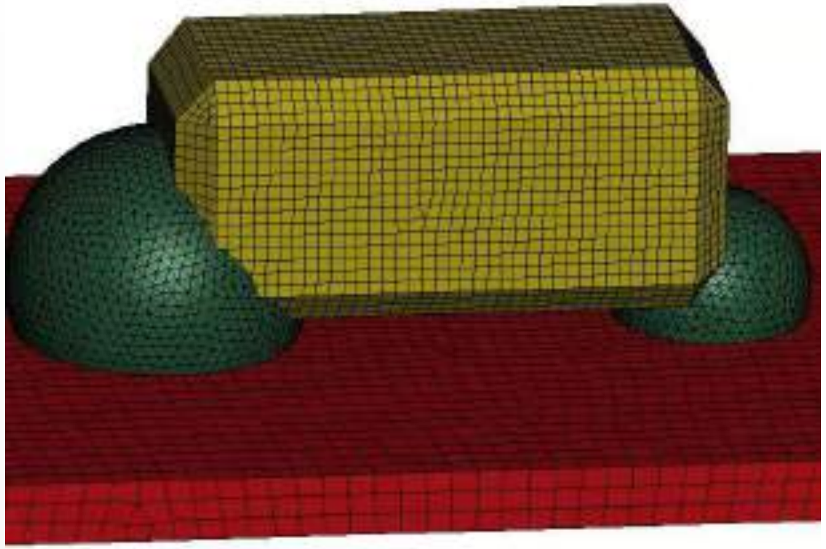


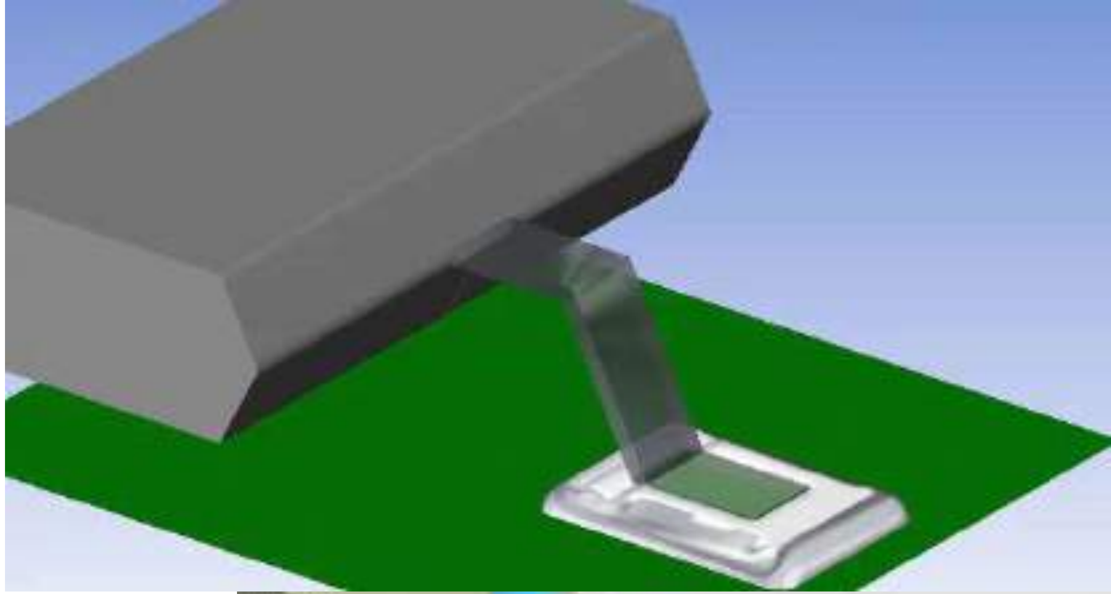
Solder Joint Reliability mechanical simulation methods overview

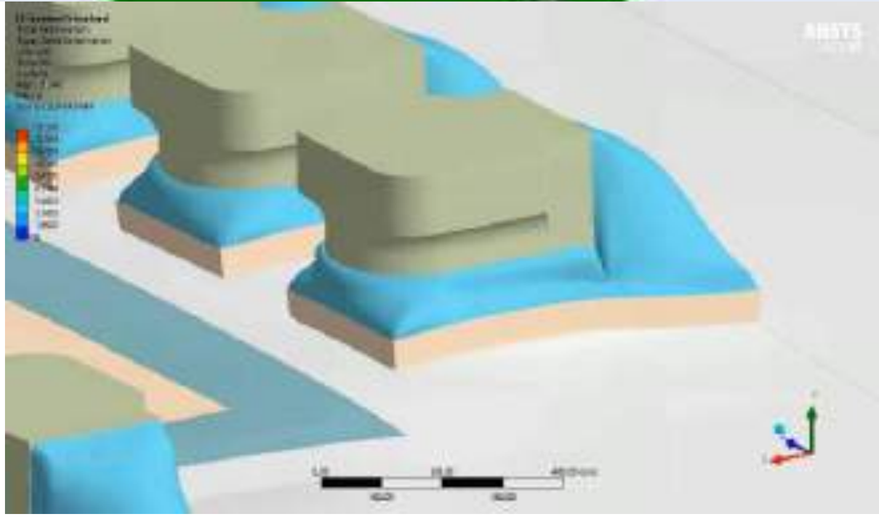
Tom David 2025

Tom.David@ansys.com

Agenda

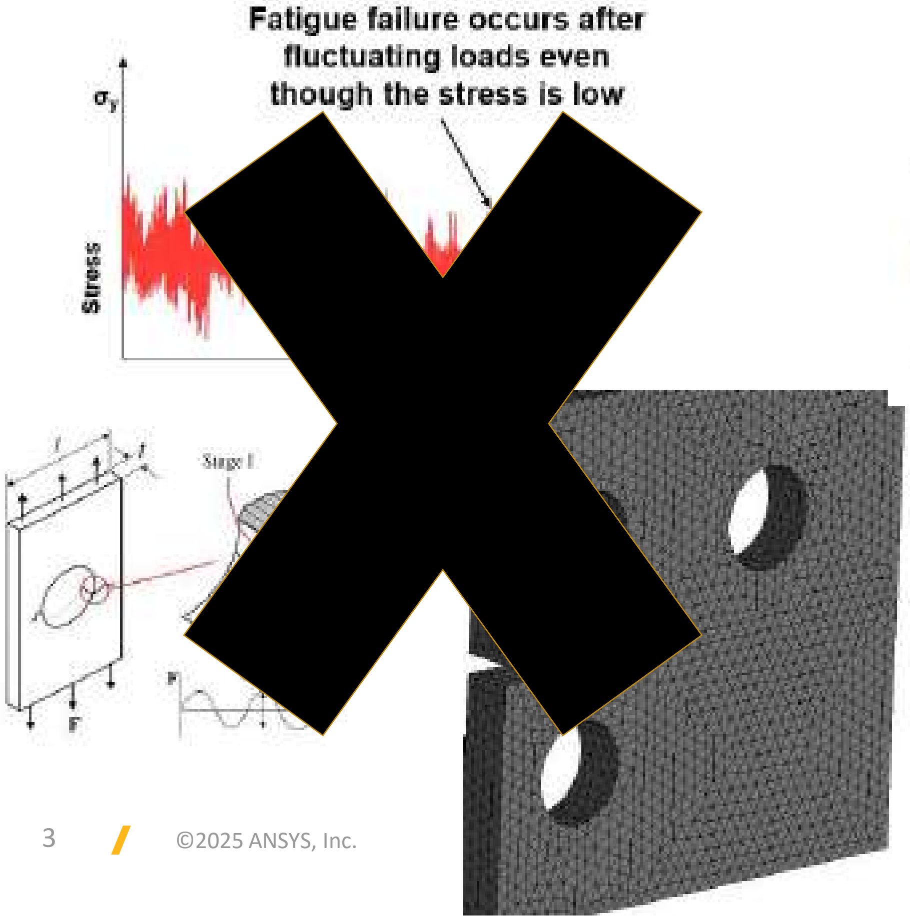
- Brief overview
  - Fatigue
  - Reliability and Physics of Failure – Solder Joints
  - Solder fatigue
- 1D approach
  - Thermal cycles
- 3D approaches
  - “2.5D” linear model
  - Detailed non-linear model
- Solder reflow simulation



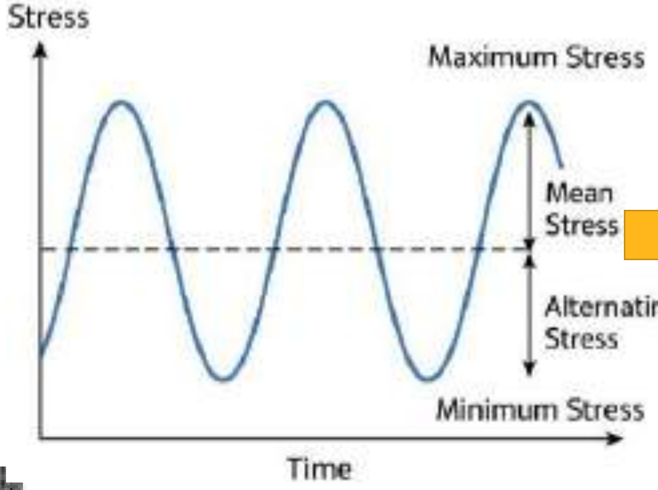


Fatigue

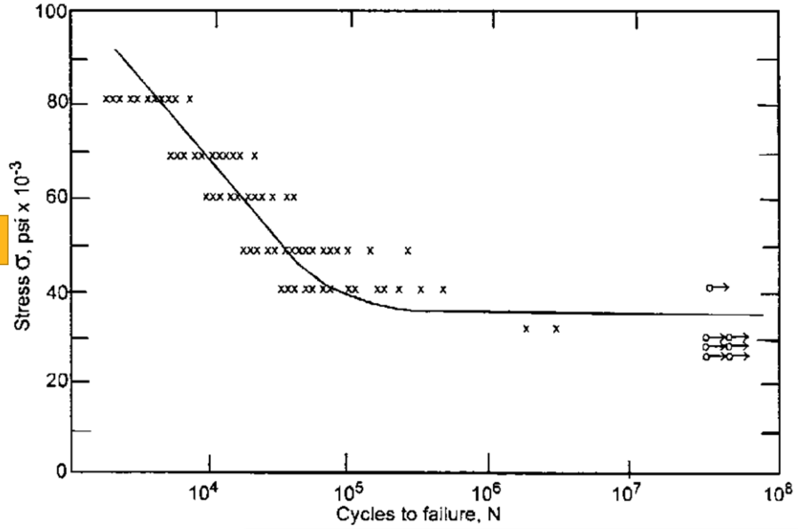
- Transient loading
- Failure at stress lower the yield stress



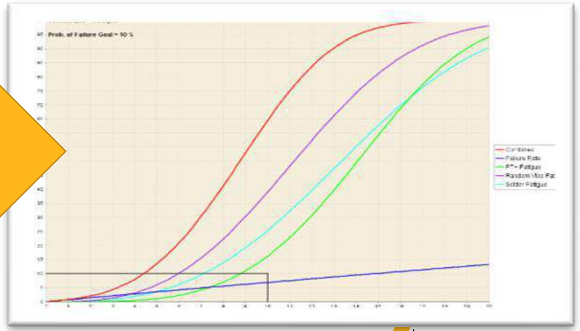
- static/periodic load
- Load mapping



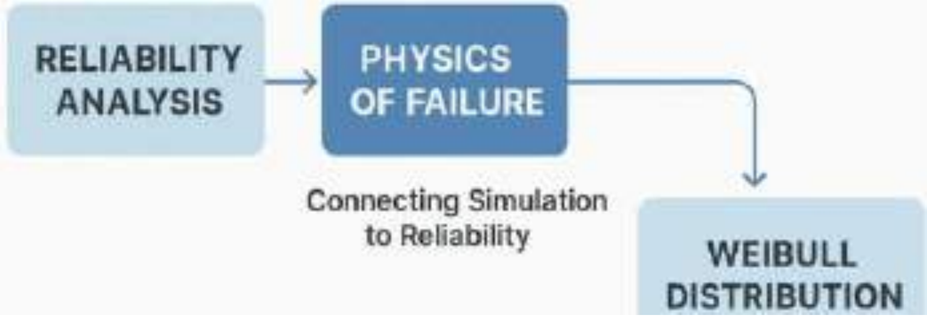
- Material fatigue model
  - Example SN curve



Cycles to failure, N



Reliability and Physics of Failure in Solder Joints



RELIABILITY ANALYSIS

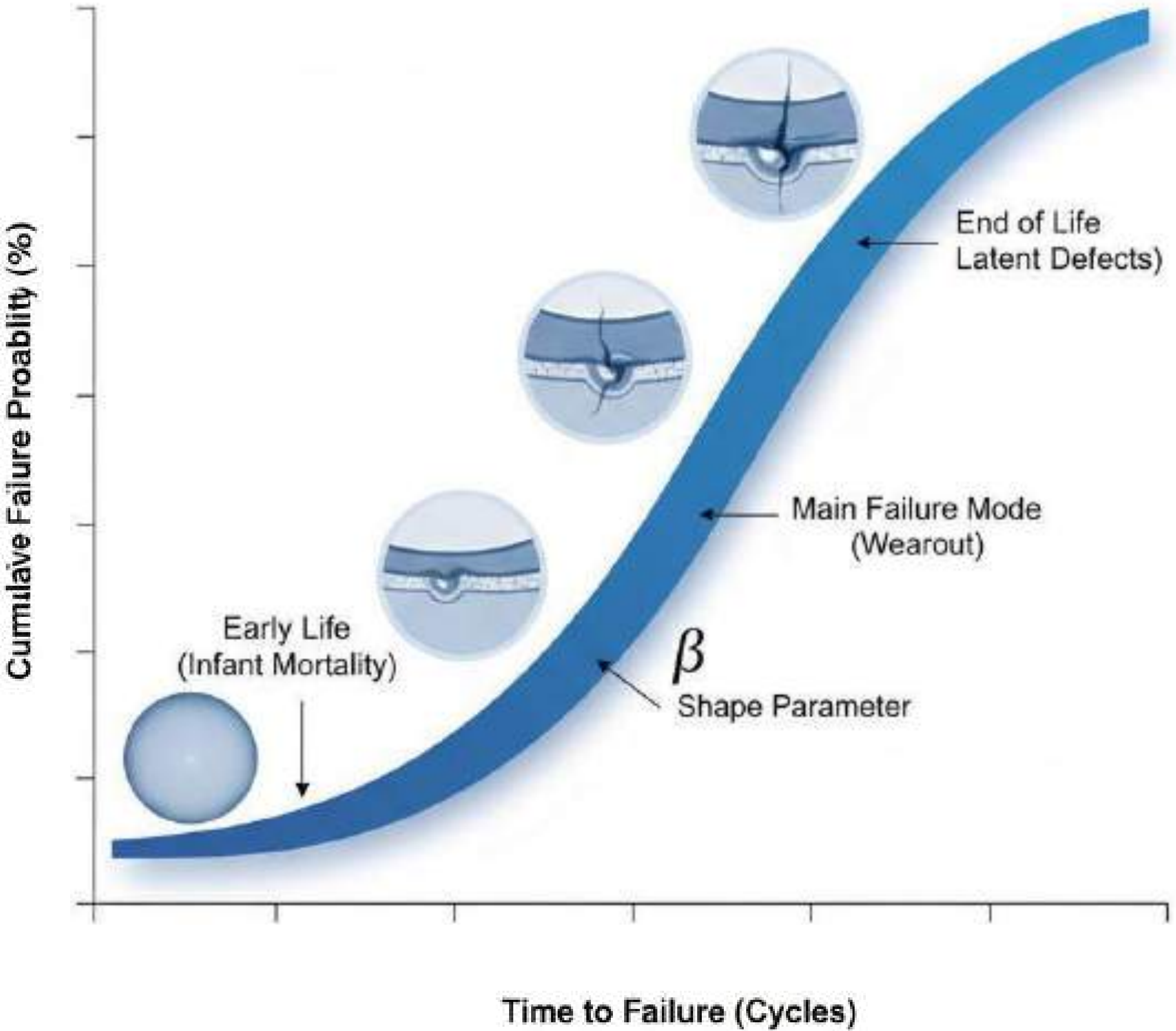
PHYSICS OF FAILURE

Connecting Simulation to Reliability

WEIBULL DISTRIBUTION

- Reliability Analysis:
  - Assesses how long solder joints last under thermal, mechanical, or vibration loads, **translating simulation or test data into lifetime predictions**.
- Physics of Failure:
  - Explains **why joints fail** — linking stress, strain, and temperature to damage mechanisms like fatigue cracking, creep, and intermetallic growth.
- Weibull Distribution:
  - A statistical model used to describe time-to-failure variability. Its shape parameter (β) indicates how failure rate changes over time
  - Solder joint failures show **natural statistical scatter** due to microstructural differences and process variations; Weibull fitting helps **quantify reliability** and compare designs

Weibull Distribution for Solder Fatigue

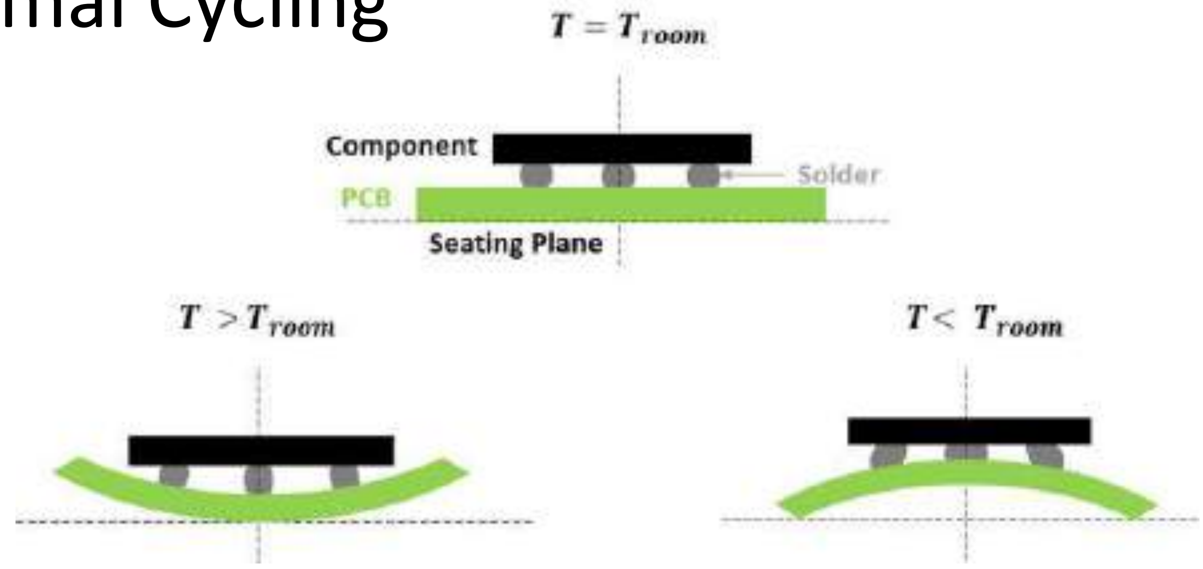


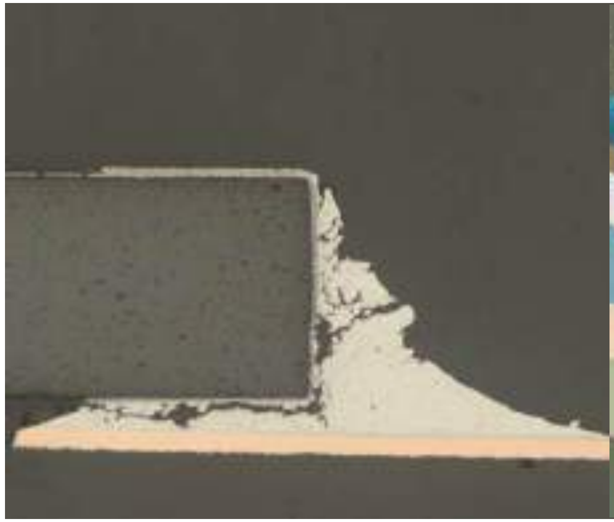
Solder Fatigue Analysis Due to Thermal Cycling

- Solder joints connect the components to the board

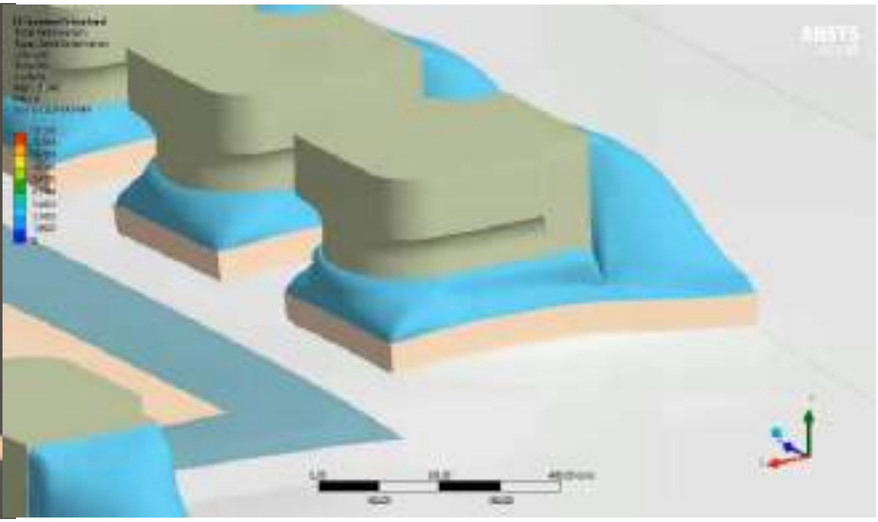
- Under thermal cycling, the PCB and the components will **expand or contract** by dissimilar amounts due to differences in their respective **coefficient of thermal expansion (CTE)**

- Cycle after cycle, the solder will **get damaged until it breaks**.





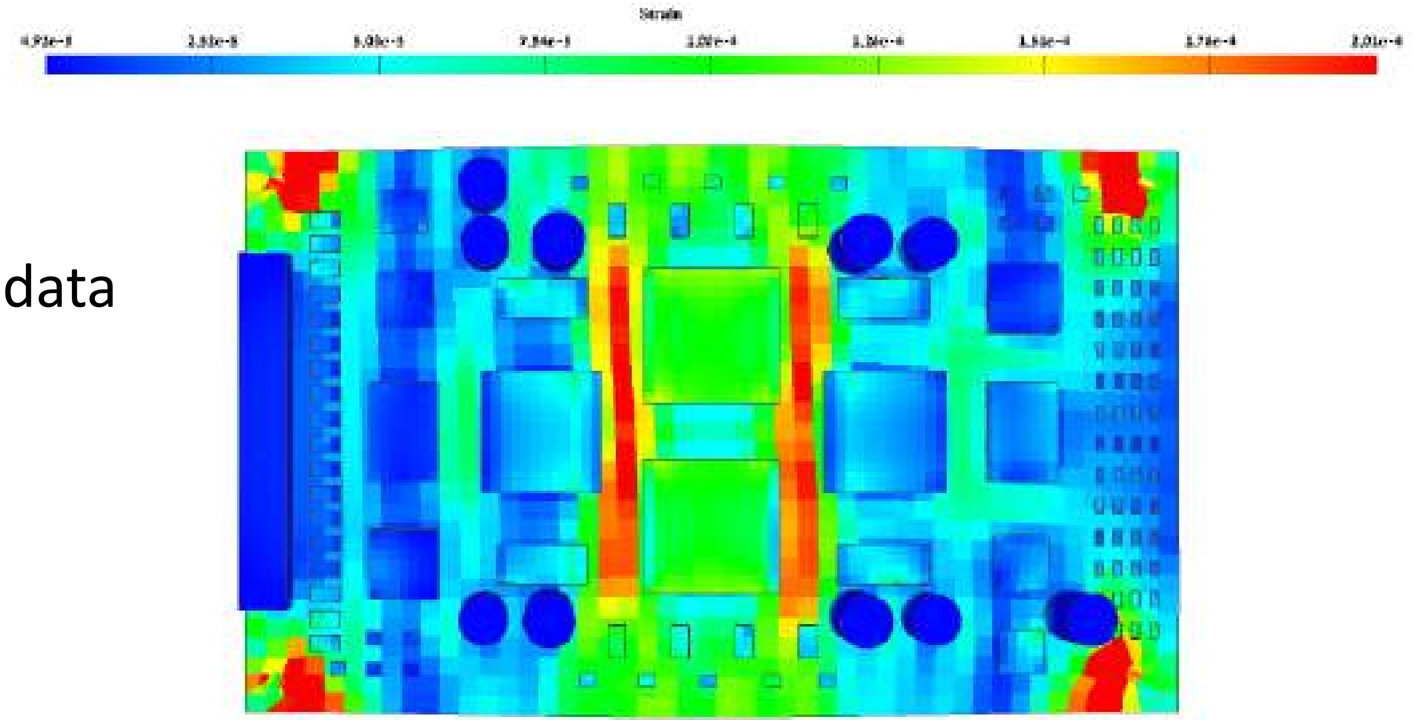
Failure due to thermal cycling 1206 Resistor #54, Right, 10x zoom

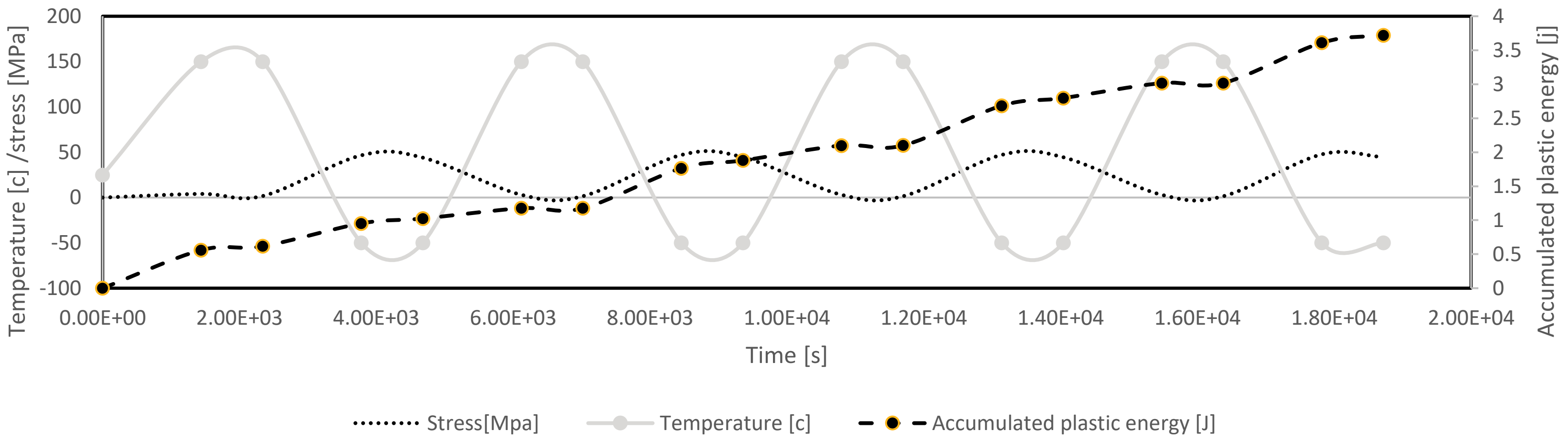


Simulation of a solder deformation on a QFN component under 2 thermal cycles (scaled)

Fatigue indicator

- Connect between test or simulation data to product life prediction
- Solder fatigue example: stress vs accumulated plastic energy





→

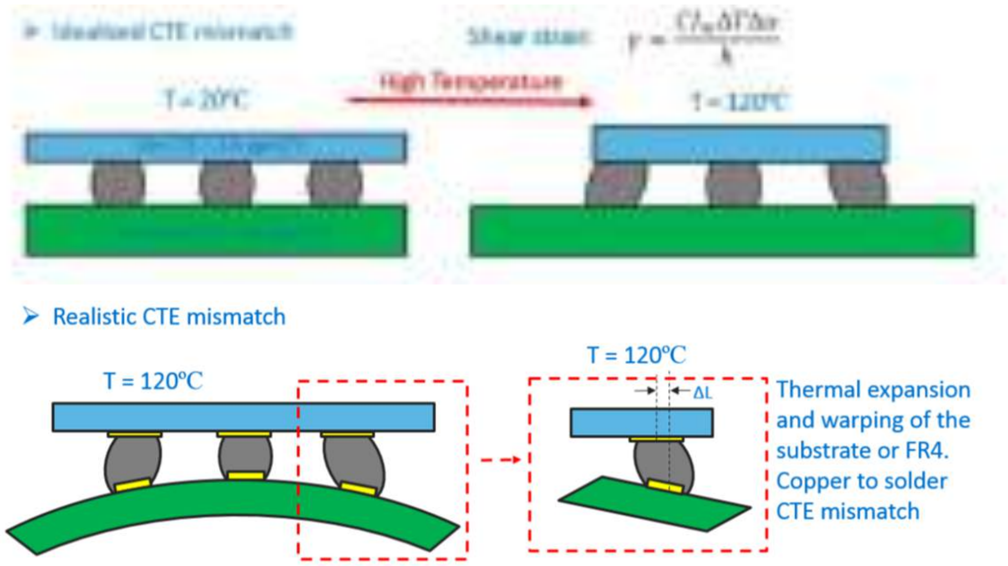
1D
approach

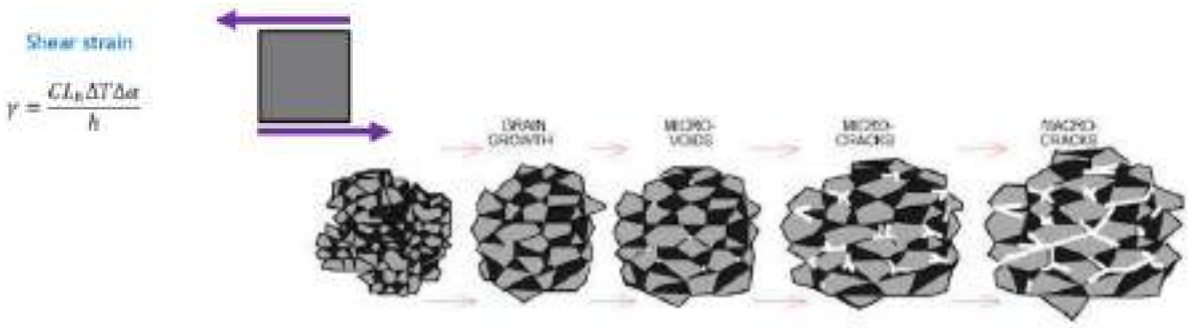
Solder fatigue calculations

Scope of Solder Fatigue Analysis(1D approach)

1D approach

- The fatigue performance of solder joints is significantly influenced by the board properties, thermal profile, and package properties
- Solder Fatigue analysis is **an analytical analysis**. Results are based on models and semi-empirical laws
- Solder Fatigue analysis does consider the CTE mismatch **but not** System Level Effects, warpage and 3D effects





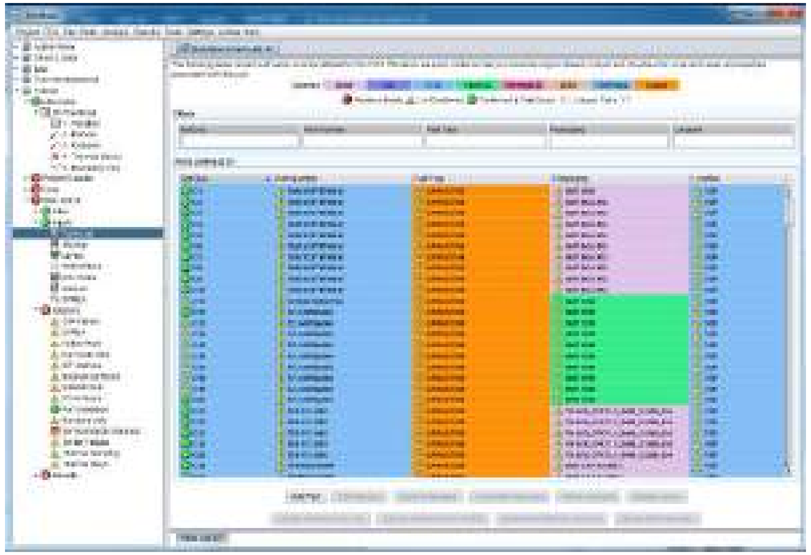
Source: Werner Engelmaier, Engelmaier Associates, L.C.

Ref : System Level Effects on Solder Joint Reliability / Maxim Serebreni

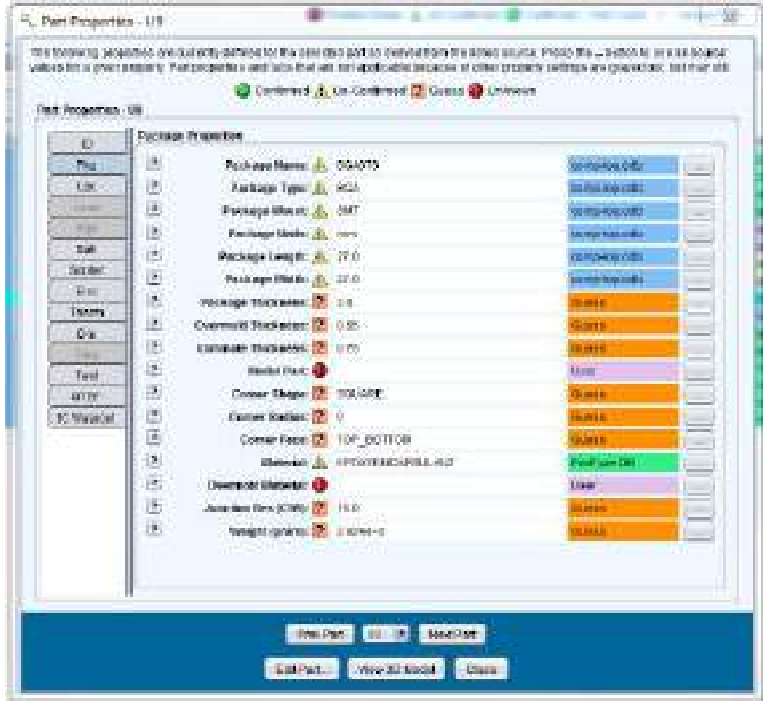
Components + packages libraries

1D approach

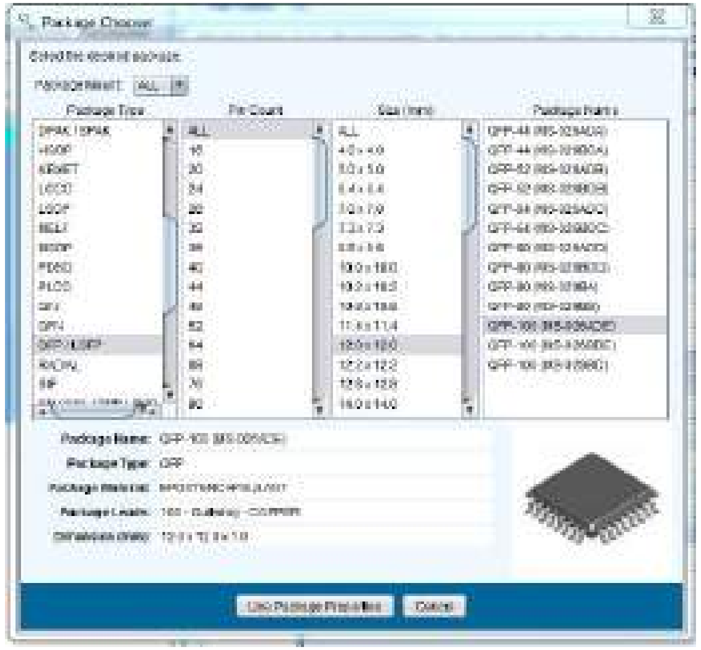
Locating geometric and material properties for the large number of components on PCBs from libraries.



Automatically defines components properties



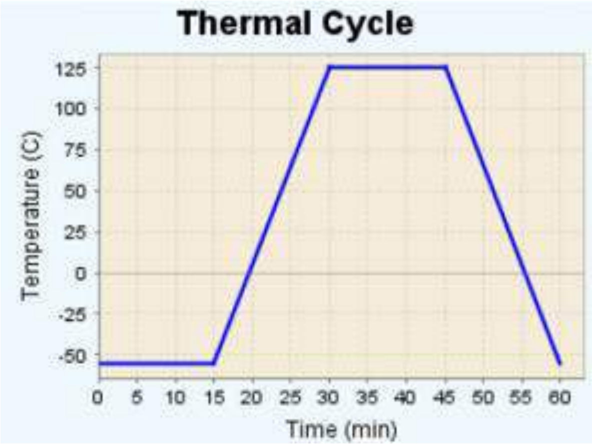
Package library

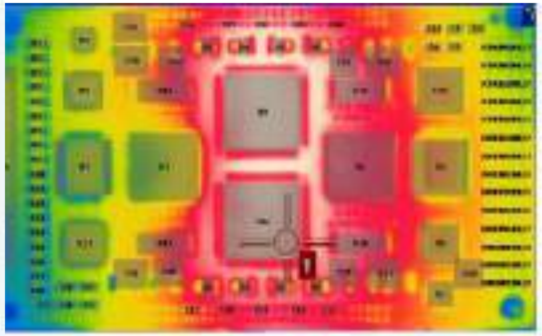


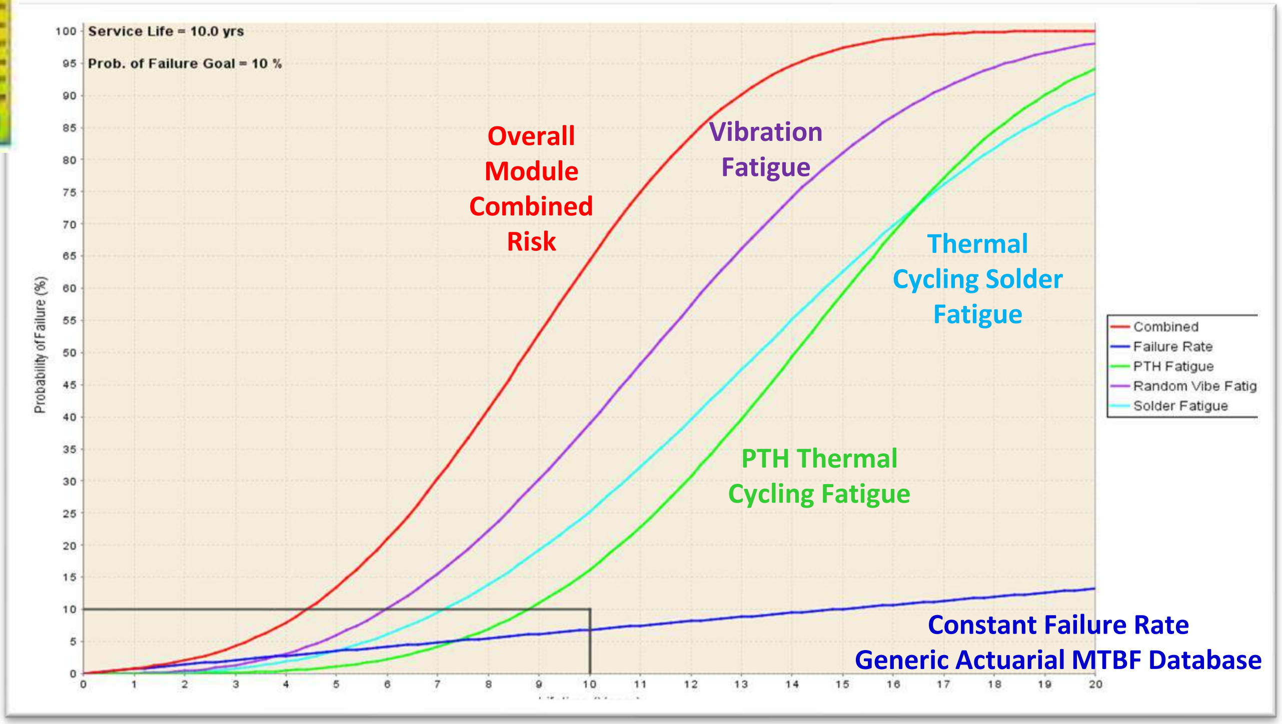
Actionable Post-Processing – Time-To-Failure Life Predictions

→ 1D approach

Reliability Physics Analysis provides Time-to-Failure Predictions for every component based on Physics of Failure techniques. Multiple failure modes can be considered.







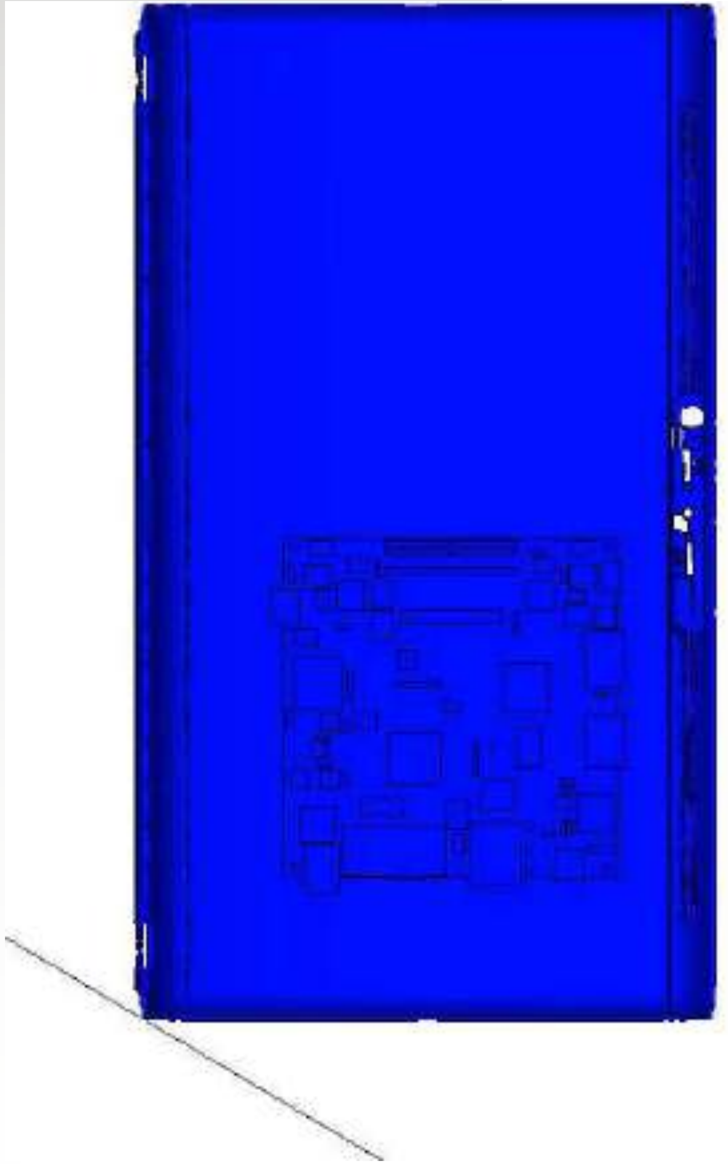
Overall Module Combined Risk

Vibration Fatigue

Thermal Cycling Solder Fatigue

PTH Thermal Cycling Fatigue

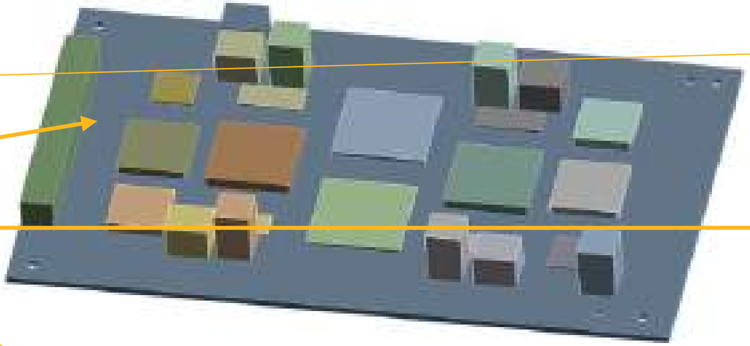
Constant Failure Rate
Generic Actuarial MTBF Database

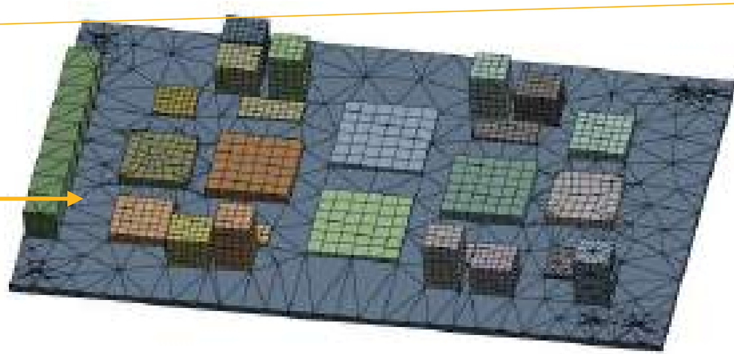


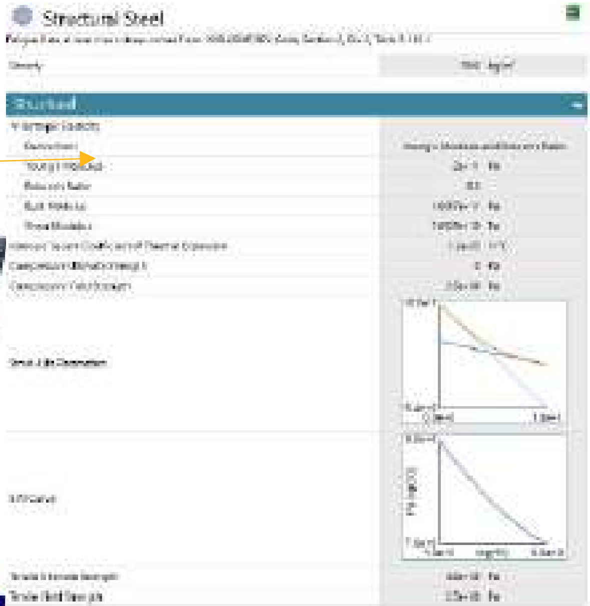
Finite Element Analysis methods

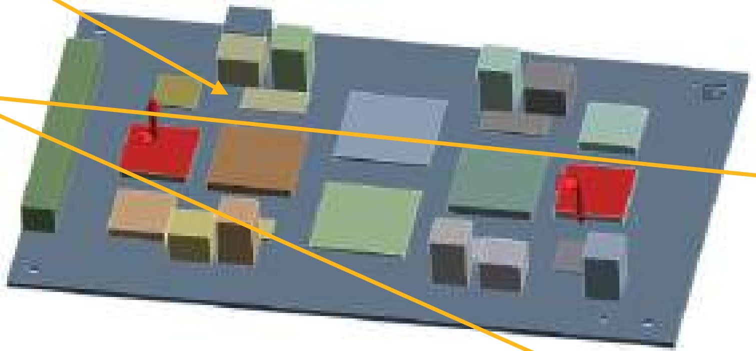
Mechanical simulation process overview

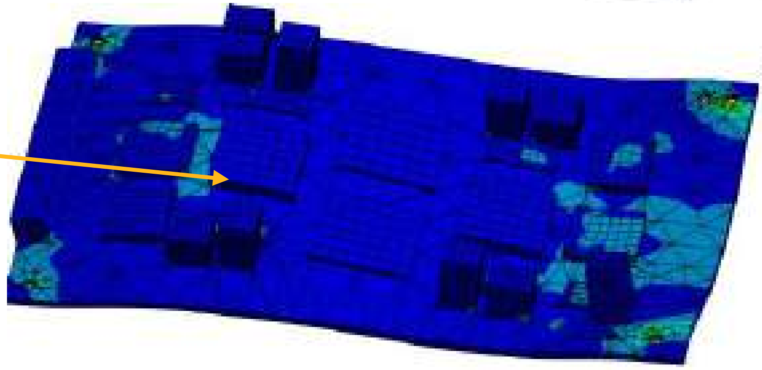
- Engineering Data
- Geometry
- Model
- Setup
- Solution
- Results

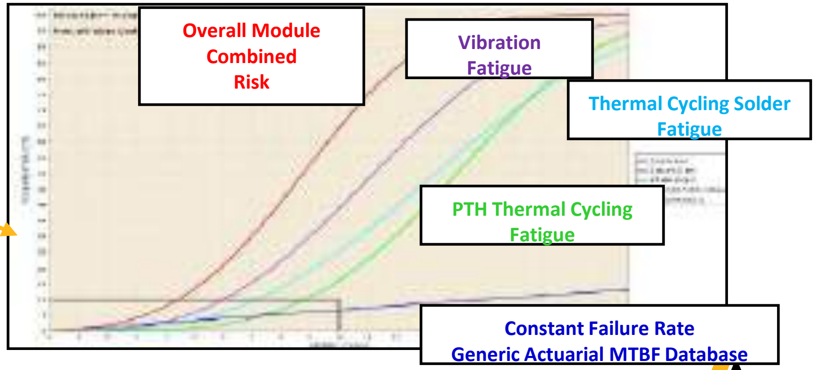








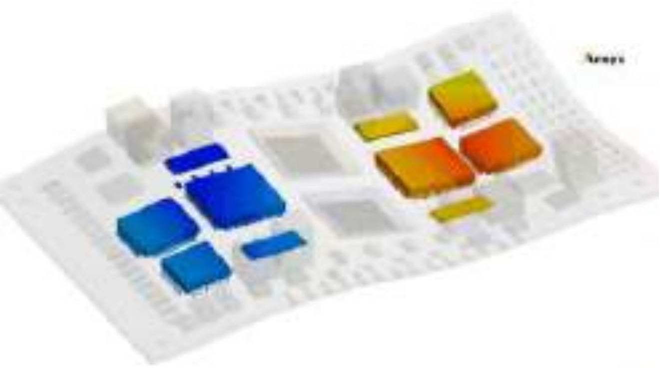




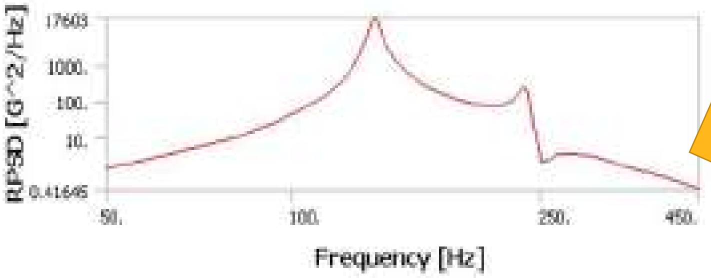
Solder joint failure due to shock & vibration

2.5D approach

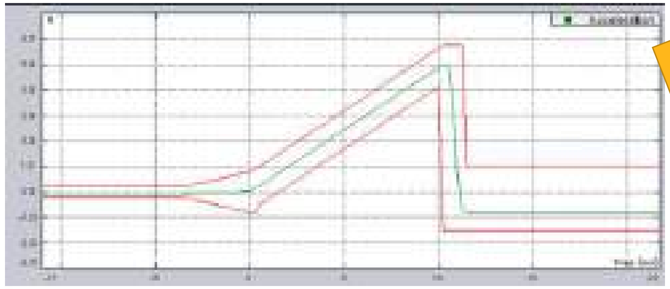
- Board level reliability



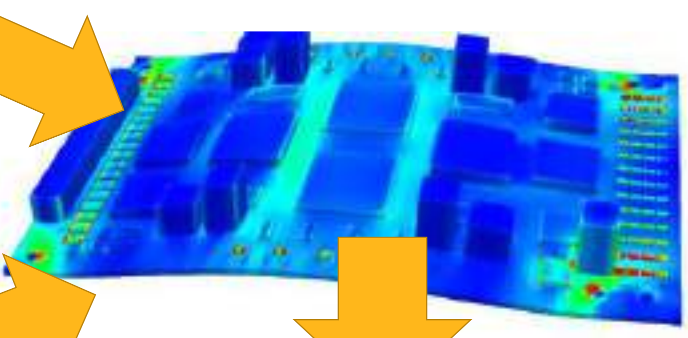
PSD profile



Shock profile

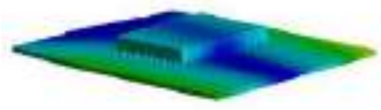


Stain result

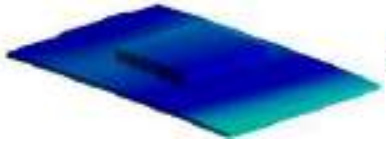


Weibull

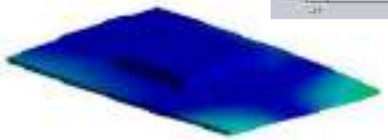
Natural frequencies



Mode 1



Mode 2



Mode 3

3D
approach

Detailed Solder Joint Fatigue Modeling
3D Nonlinear FEA Approach

Common Material models

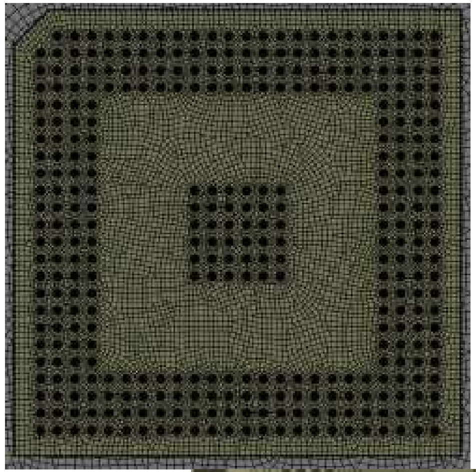
3D approach

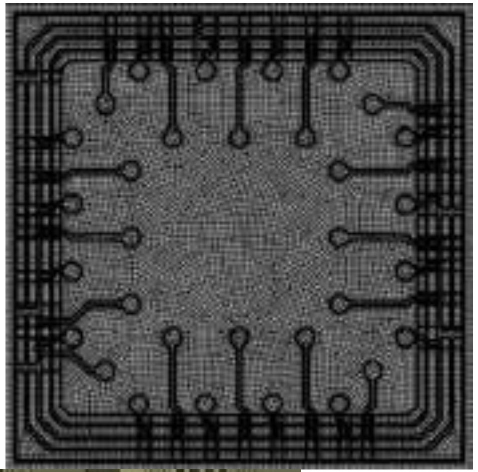
- **Linear Elastic:** Simplest approach; assumes purely elastic behavior, suitable for quick comparative studies or low-strain cases
- **Anand Model:** Captures viscoplastic behavior under cyclic thermal loading; widely used for solders
- **Garofalo Model:** Describes steady-state creep response at high temperatures using a hyperbolic sine relation
- **Elastic–Plastic**: Adds plastic deformation beyond yield, useful for capturing limited inelasticity without full creep modeling
- **Creep Power Law:** Empirical model for long-term deformation under constant stress and temperature

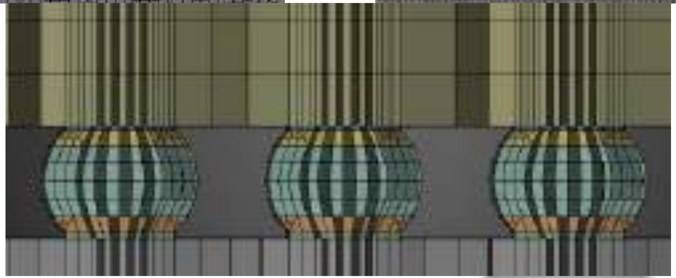
Geometry 3D model

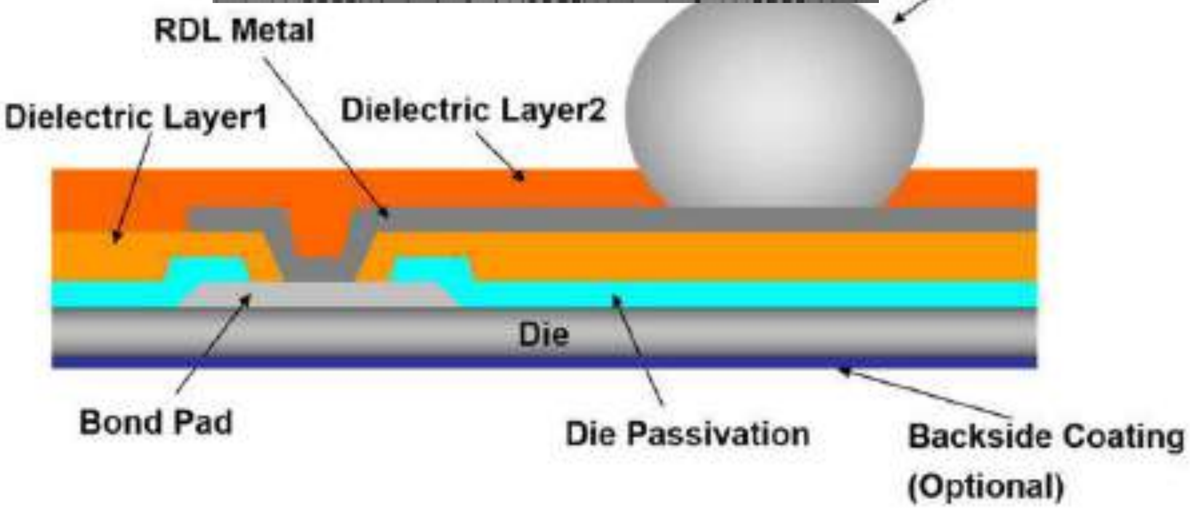
- More geometries are taken into account (pads, layers, smd/nsdm, etc…)
- Location and details of the modeling of each solder balls are more precise
- Use symmetry if possible
- Approaches:
  - Detailed modeling all solder balls
  - Detailed modeling of corner balls only
  - Simple Large model to a submodel

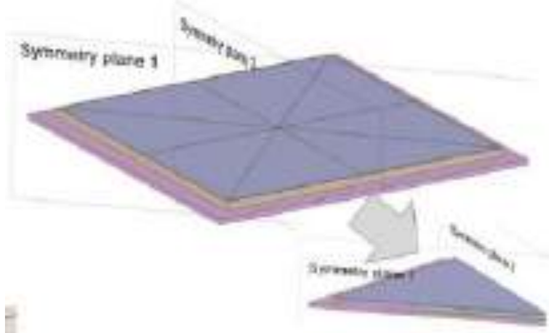
3D approach











Images taken from NXP AN3846 application brief
https://www.nxp.com/docs/en/application-note/AN3846.pdf

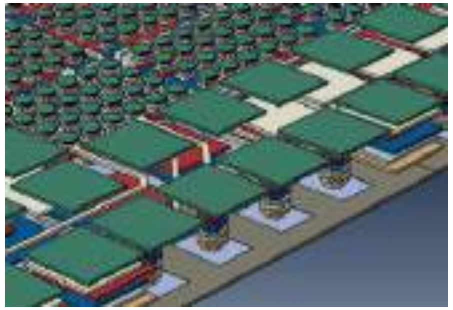
Detailed Component Modeling-automated tools

Challenge:

- Accurate Electronics Reliability simulations often relies on detailed modeling of leads, solder, and other features.

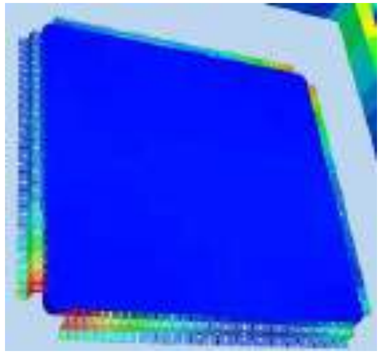
Solution:

- Ansys tools, such as Ansys Sherlock and Ansys SpaceClaim, provide techniques for rapidly generating detailed geometries of electronics components, or simplifying or defeaturing them for faster simulation runtimes.

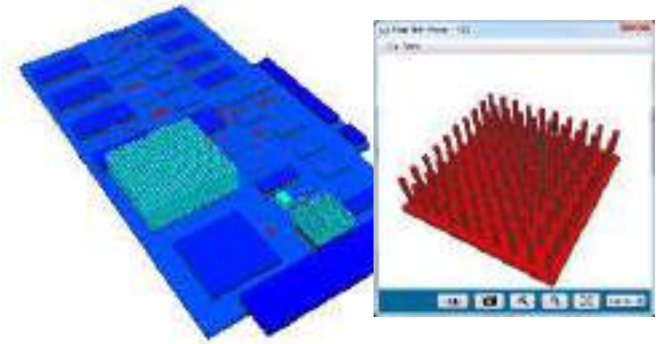


Traces and Vias

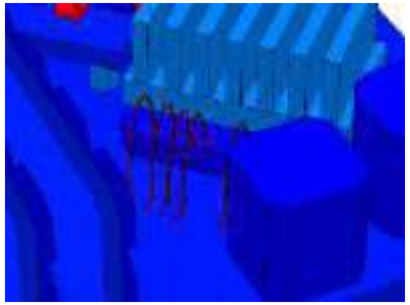
3D approach



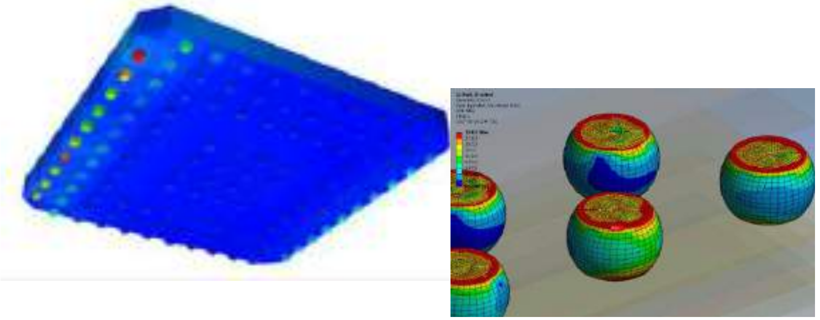
Leads



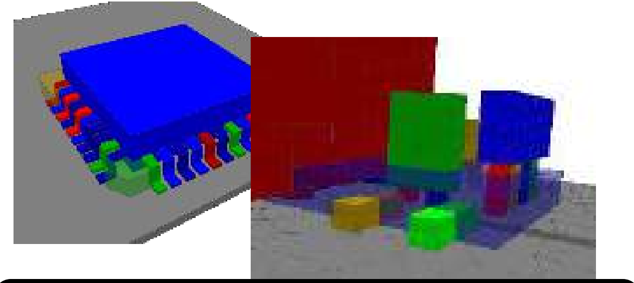
Heat Sinks



Wirebonds and Bare Die



Solder

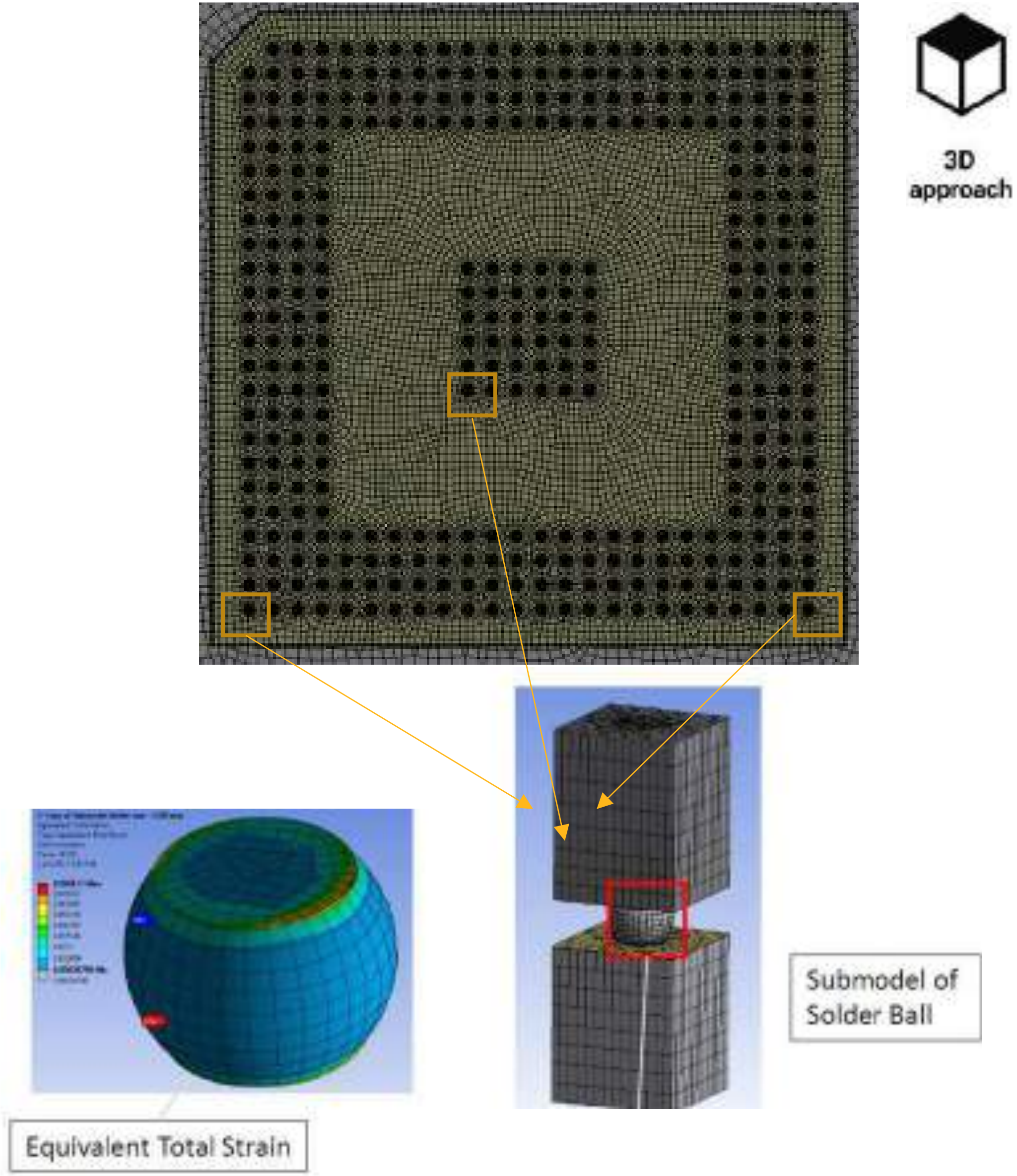


Coatings, Potting, Underfill

Submodel approach

3D approach

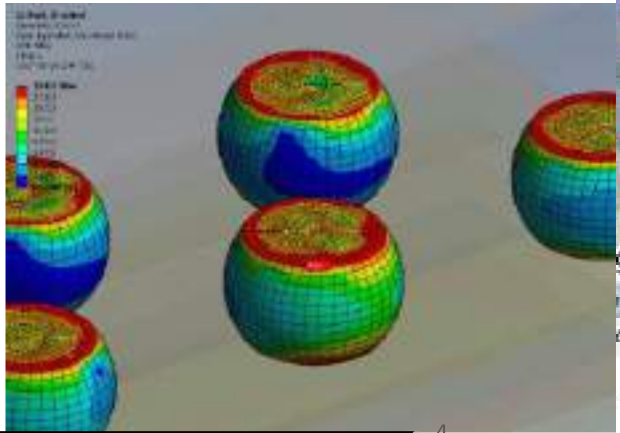
- Large simple model with less details and bigger mesh
- Result are sent as boundary condition to a submodel
- Submodel is more detailed and with more elements
- Same large model and submodel can be used to run different ball locations.
  - Moving between ball locations is just a matter of coordinate

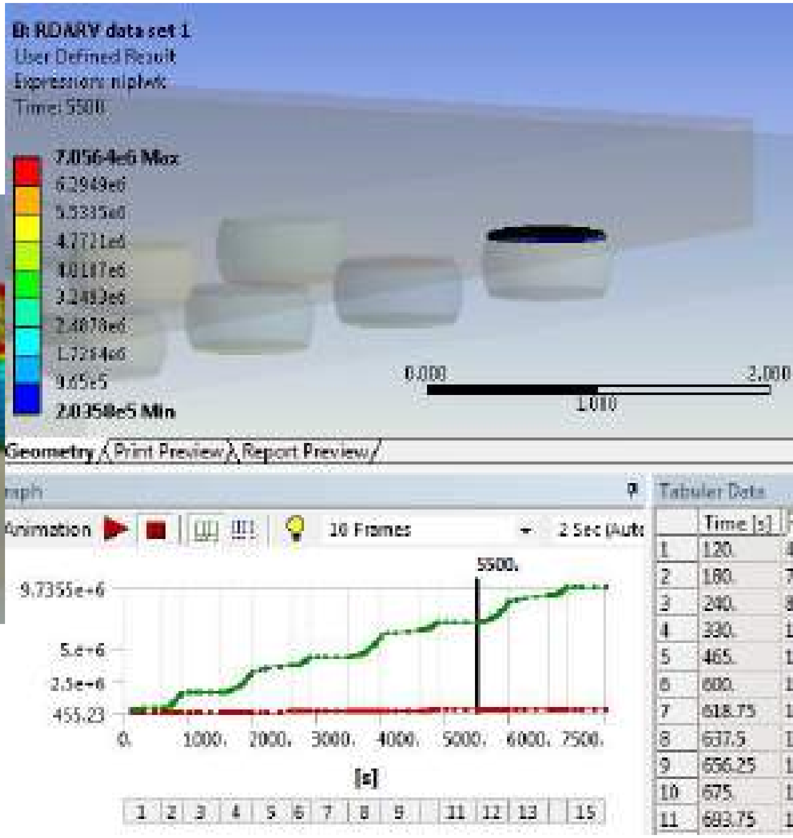


Results

3D approach

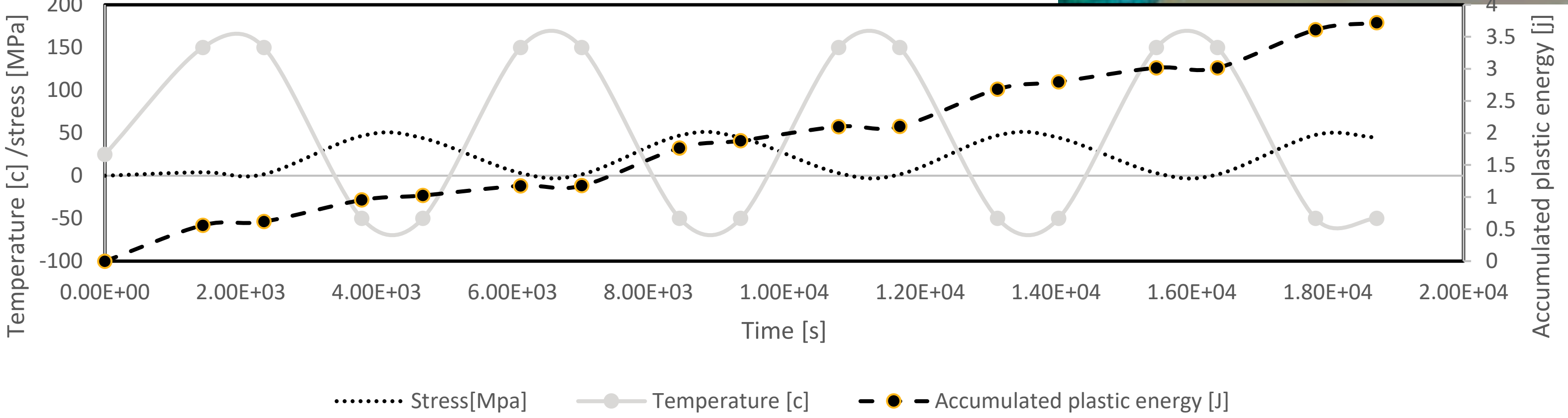
- Full 3D physical results such as strain,stresses etc and of course forces and displacements
- Fatigue indicator
- Accumulated damage cycle by cycle





B: ROARY data set 1
User Defined Result
Expression: nlplwk
Time: 5500

	Time [s]
1	120.
2	180.
3	240.
4	330.
5	465.
6	600.
7	618.75
8	637.5
9	656.25
10	675.
11	693.75

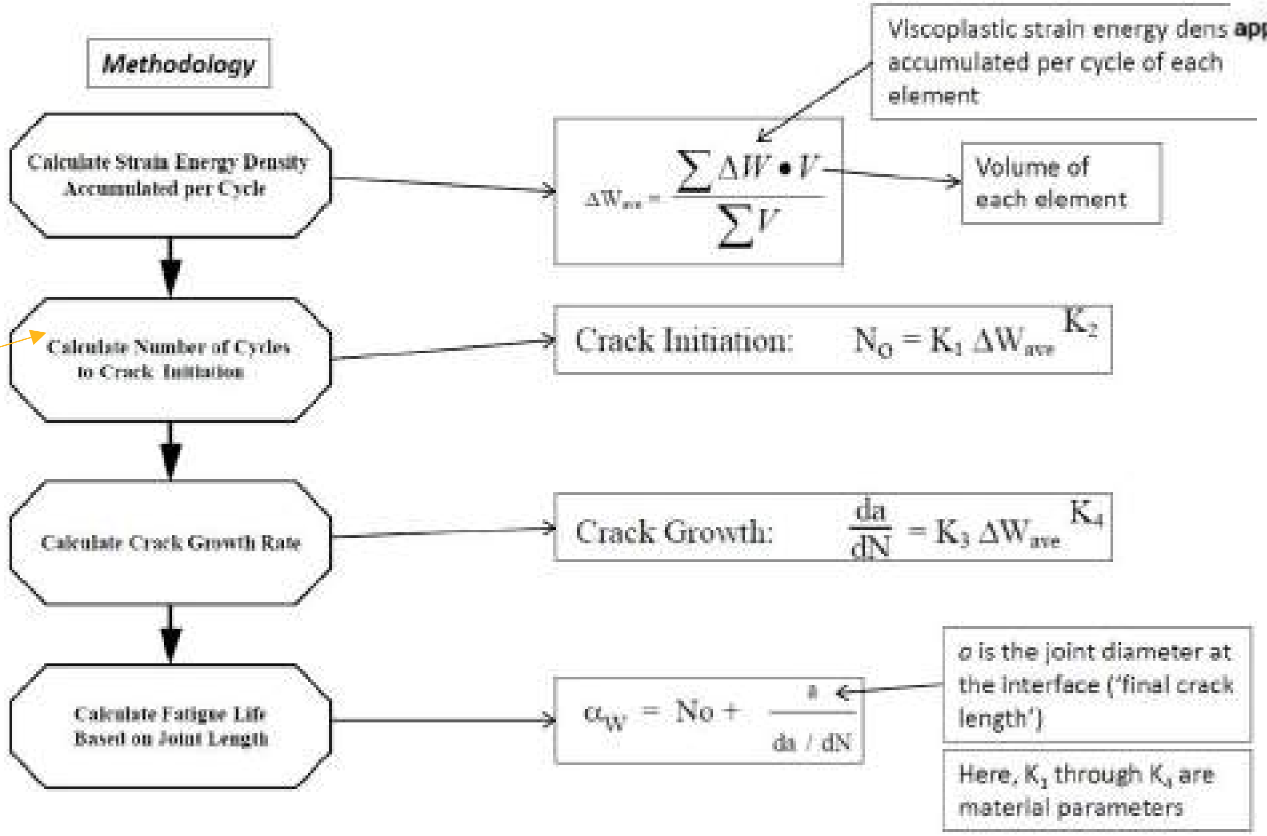


Solder fatigue reliability predictions

3D approach

Lifing Model

- Darveaux
- Energy-partitioning
- Syed Model
- Schubert Model
- Engelmaier Model
- …



Methodology

Calculate Strain Energy Density Accumulated per Cycle

$\Delta W_{ave} = \frac{\sum \Delta W \bullet V}{\sum V}$

Viscoplastic strain energy dens accumulated per cycle of each element

Volume of each element

Calculate Number of Cycles to Crack Initiation

Crack Initiation: $N_O = K_1 \, \Delta W_{ave}^{K_2}$

Calculate Crack Growth Rate

Crack Growth: $\frac{da}{dN} = K_3 \, \Delta W_{ave}^{K_4}$

Calculate Fatigue Life Based on Joint Length

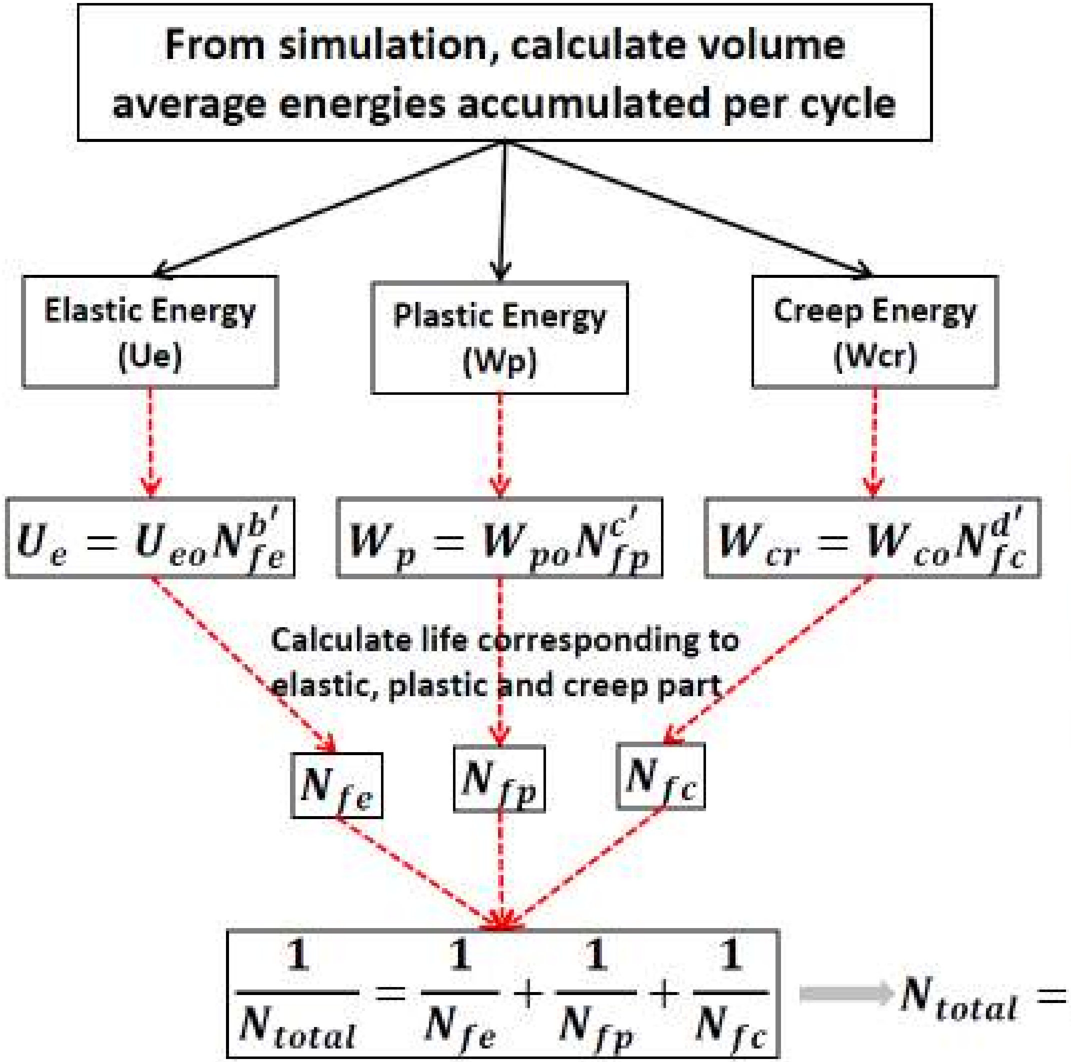
$\alpha_W = No + \frac{a}{da / dN}$

a is the joint diameter at the interface ('final crack length')

Here, K_1 through K_4 are material parameters

Lifing: Energy Partitioning Approach

3D approach



From simulation, calculate volume average energies accumulated per cycle

Elastic Energy (Ue)

Plastic Energy (Wp)

Creep Energy (Wcr)

$$U_e = U_{eo} N_{fe}^{b'}$$

$$W_p = W_{po} N_{fp}^{c'}$$

$$W_{cr} = W_{co} N_{fc}^{d'}$$

Calculate life corresponding to elastic, plastic and creep part

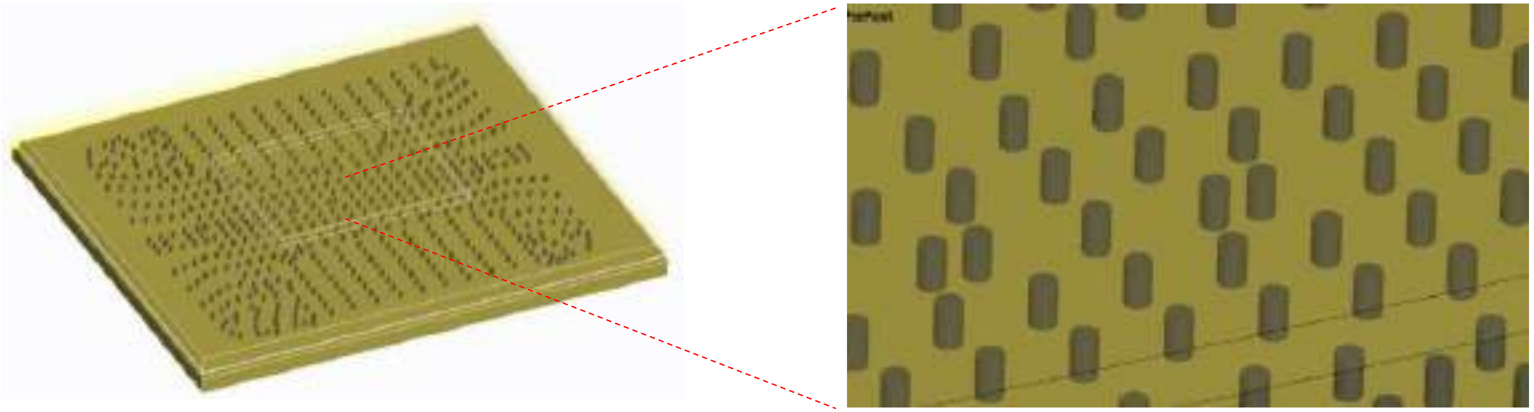
N_{fe} N_{fp} N_{fc}

$$\frac{1}{N_{total}} = \frac{1}{N_{fe}} + \frac{1}{N_{fp}} + \frac{1}{N_{fc}}$$

$\Rightarrow N_{total} = Fatigue\ Life\ Cycles$

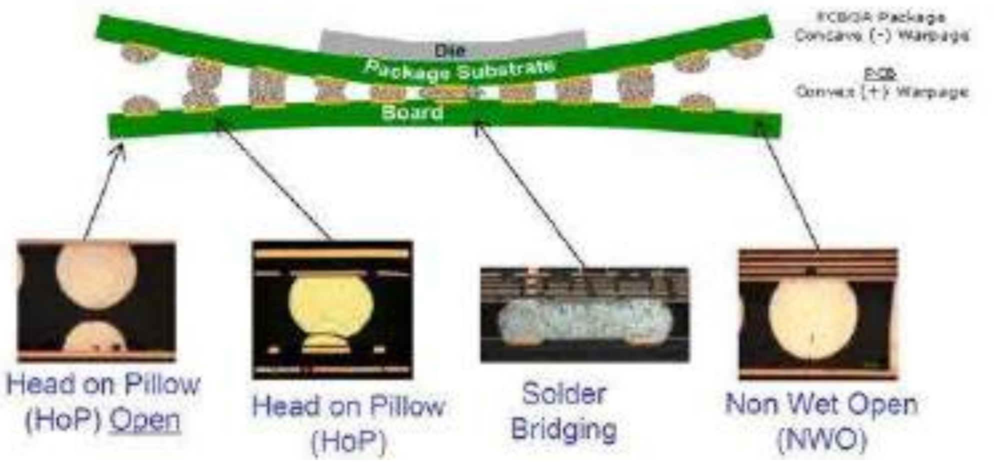
U_{eo}= Elastic coefficient
b' = Elastic exponent
W_{po}= Plastic coefficient
c' = Plastic exponent
W_{co}= Creep coefficient
d' = Creep exponent

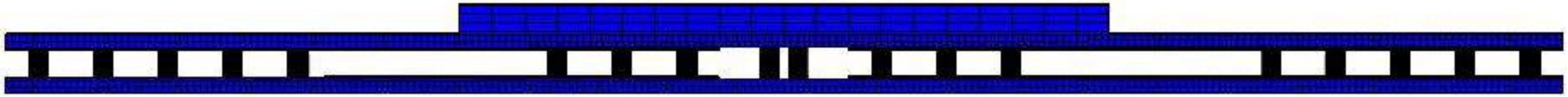
Solder Reflow and shape simulation



Common Solder Reflow Issues

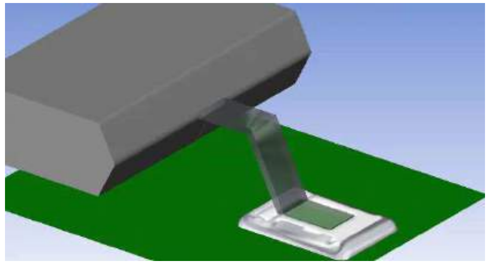
- **Head-On-Pillow (HOP):** Incomplete coalescence of solder balls, often due to oxidation or warping.
- **Non-Wet Open (NWO):** Component pads or leads fail to wet properly, causing open circuits.
- **Insufficient Solder:** Can lead to weak joints and poor mechanical reliability.
- **Solder Bridging:** Excess solder creates unintended connections between adjacent pads or pins.
- **Tombstoning**: Small components lift on one end during reflow due to uneven wetting.



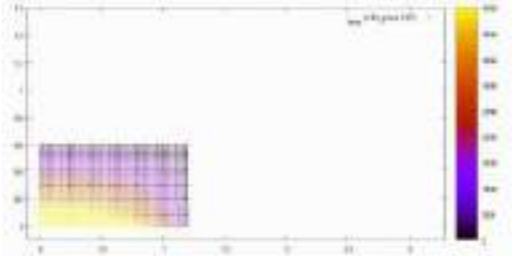


Simulation Methods

- **CFD**
- *(Computational Fluid Dynamics)*
- Treats molten solder as a **viscous fluid** with surface tension and wetting.
- Captures realistic **flow, coalescence, and joint formation**.
- **Highest accuracy**
- **High computational cost**

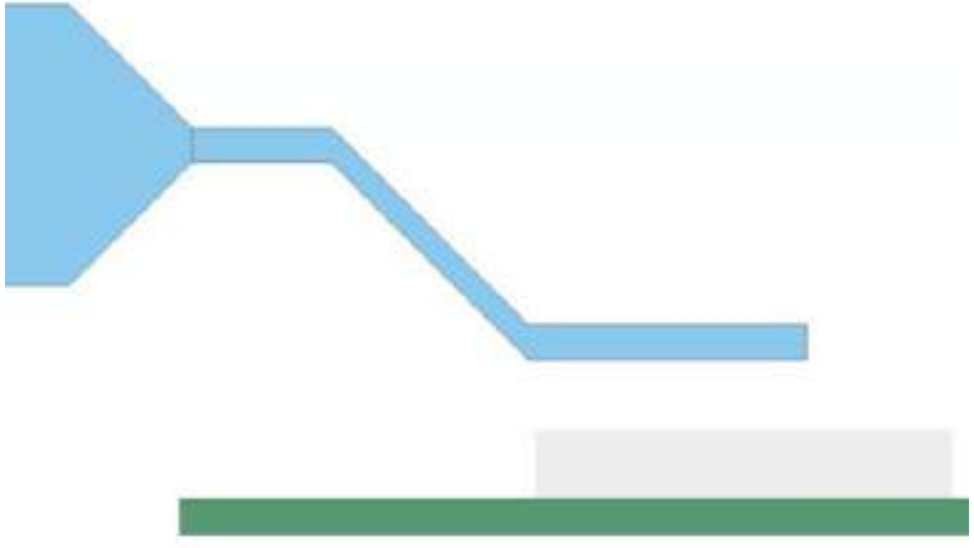


- **Particles- SPH / ISPG**
- *(Smoothed / Incompressible Smoothed Particle Galerkin)*
- Represents solder as **particles** interacting through fluid mechanics.
- **droplet merging and free surfaces** without meshing. No air bubbles
- **Highly flexible**
- **Moderate effort**



- **Hyperelastic Approach**
- Models molten solder as a **deformable solid** with hyperelastic laws.
- Simplifies **shape evolution** during melting and solidification
- **Fastest and most stable**
- **Lower accuracy**

Summary



- **1D Approach**:
  - Simplified thermal–mechanical representation.
  - Fast setup, low effort — good for early design comparisons.
  - Non system level effects captured
- **“2.5D” Linear Model:**
  - Includes board and package geometry with linear material behavior.
  - Moderate accuracy; efficient balance between speed and insight.
  - Best for system effects and non standard packages and ball patterns
- **3D Detailed Non-Linear Model:**
  - Full viscoplastic or creep material laws, full geometry.
  - High fidelity and fatigue prediction accuracy, but time-consuming and expertise-intensive.
- **Reflow Simulation:**
  - Models solder melting, wetting,bridging, and final joint formation.
  - Provides realistic starting conditions for fatigue and helps identify process-related defects (e.g., voids, bridging).

Fatigue Models

- Thermal Fatigue Models:
  - Analytical Models:
    - Strain range approach:
      - Acceleration factor (Norris Landzberg) $AF = \frac{N_1}{N_2} = \left(\frac{f_1}{f_2}\right)^{-m} \left(\frac{\Delta T_1}{\Delta T_2}\right)^{-n} e^{\frac{E_a}{K}\left(\frac{1}{T_{max1}} - \frac{1}{T_{max2}}\right)}$
      - Coffin-Manson $\frac{\varepsilon_P}{2} = \varepsilon'_f (2N)^c$
      - Engelmaier Equation $\Delta\gamma = F \frac{D \Delta\alpha \Delta T}{2h}$ $N_f = \frac{1}{2}\left(\frac{\Delta\gamma}{2\varepsilon'_f}\right)^{\frac{1}{c}}$ $c = -0.442 - 6x10^{-4}\bar{T} + 1.74x10^{-2}\ln(1 + f)$
    - Energy density approach
      - Blattau Model

$$(\alpha_2 - \alpha_1) \cdot \Delta T \cdot L_D = F \cdot \left(\frac{L_D}{E_1 A_1} + \frac{L_D}{E_2 A_2} + \frac{h_s}{A_s G_s} + \frac{h_c}{A_c G_c} + \left(\frac{2 - \nu}{9 \cdot G_b a} \right) \right) \quad \Delta W = 0.5 \cdot \Delta\gamma \cdot \frac{F}{A_s}$$

$$N_f = (0.001)^{-1}$$

  - Each model improves on the previous approach by incorporating additional physical parameters such as package and PCB geometry and material properties.