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Sherlock Theory Reference



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Chapter 1: Introduction to the Sherlock Theory Guide

Welcome to the theory guide for the Ansys Sherlock™ electronics reliability prediction software. This guide explains the theory and methods behind the Sherlock application's failure analysis predictions. Each section is dedicated to a single design/failure issue and provides the following information: An introduction to the design issue or failure mechanism, a clear explanation of the technique the Sherlock application uses to analyze failure risk, data which demonstrates that the software's techniques are in line with industry best practices and accurately predicts real-world performance, mathematical equations used in the analyses, and a bibliography which will point you to the relevant research and theory behind the Sherlock application's techniques.

Note:

It's important to read the [Sherlock User's Guide](#) before accessing the theory guide content. The user's guide will help you become familiar with Sherlock's capabilities and workflow. A firm understanding of the Sherlock application is essential before delving into the substantial content of the *Sherlock Theory Reference*.

Chapter 2: Solder Fatigue Caused by Thermal Cycling-Theory

Note:

It's important to read the [Sherlock User's Guide](#) before accessing the theory guide content. The user's guide will help you become familiar with Sherlock's capabilities and workflow. A firm understanding of the Sherlock application is essential before delving into the substantial content of the *Sherlock Theory Reference*.

Topics covered in this chapter:

- 2.1. Overview of Thermo-Mechanical Solder Joint Fatigue
- 2.2. BGA Model
- 2.3. Quad Flat No-Lead (QFN) Package
- 2.4. Leadless Ceramic Chip Carrier (LCCC)
- 2.5. Leadless Model
- 2.6. Ceramic Column Grid Array

2.1. Overview of Thermo-Mechanical Solder Joint Fatigue

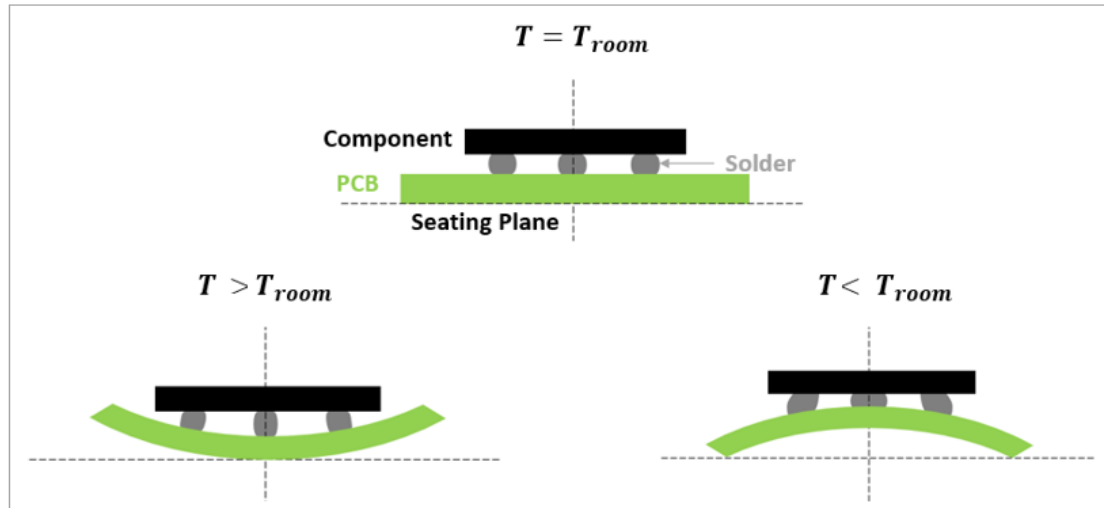
Topics covered in this section:

- 2.1.1. What is Thermo-Mechanical Solder Joint Fatigue?
- 2.1.2. What are the drivers for Thermo-Mechanical Solder Joint Fatigue?
- 2.1.3. Temperature Profiles
- 2.1.4. Thermal Shock

2.1.1. What is Thermo-Mechanical Solder Joint Fatigue?

Solder joints, also known as interconnects, provide the electrical, thermal, and mechanical connections between electronic components (passive, discrete, and integrated) and the substrate or board to which it is attached. A solder joints can be a first level connection (die to substrate) or a second level connection (component package to printed board). This module assesses the thermo-mechanical fatigue behavior of second-level solder joints.

The fatigue performance of solder joints is significantly influenced by the board properties, thermal stresses, and package dimensions. During changes in temperature, as shown in [Figure 2.1: Effect of Thermal Cycling \(p. 4\)](#), the component and printed board will expand or contract by dissimilar amounts due to differences in their respective coefficient of thermal expansion (CTE).

Figure 2.1: Effect of Thermal Cycling**Note:**

When originally published in the 22.1 version of the documentation, [Figure 2.1: Effect of Thermal Cycling \(p. 4\)](#) contained an error: The bottom formulas ($T > T_{room}$ and $T < T_{room}$) were transposed. The image above has been corrected.

This difference in expansion or contraction will place the second-level solder joint under a repetitive shear load. Typically, the shear load, or stress, is sufficient to cause inelastic strain of the solder joint. Repeated temperature cycling (from diurnal cycles and power-on/power-off events, for example) leads to an accumulation of strain which can damage the solder joint. With each additional temperature cycle, this damage increases, resulting in crack propagation and eventual failure of the solder joint.

The failure of solder joints due to thermo-mechanical fatigue is one of the dominant wear-out mechanisms in electronic products. Failure is primarily due to inappropriate design, inappropriate material selection, and challenging use environments which result in relatively short times to failure.

2.1.2. What are the drivers for Thermo-Mechanical Solder Joint Fatigue?

Thermo-mechanical solder joint fatigue is driven by the following factors :

- **Temperature Profile:** Maximum and minimum temperatures, dwell times at maximum and minimum temperature
- **Component Design:** Such as size, number of I/O's, and other factors
- **Component Material:** Such as CTE, elastic modulus, and other properties
- **Solder:** Geometry (size and shape), material (such as SnPb, SAC)
- **Printed Circuit Board:** Thickness, and in-plane material properties (CTE, elastic modulus)

2.1.3. Temperature Profiles

When running a Solder Fatigue analysis in Sherlock, Ansys does not recommend using complex Thermal Profiles that have multiple temperatures. When a Thermal Profile specifies multiple dwells, Sherlock uses only the dwell times and the maximum and minimum temperatures. If a Thermal Profile has multiple ramp rates defined, Sherlock uses the computed average of the ramp rates to determine the thermal shock factor.

Sherlock is capable of running a Solder Fatigue analysis with *multiple* thermal profiles. In such cases, Sherlock uses Miner's Rule to account for all the profiles you have defined. Miner's Rule is a well-known cumulative damage model for fatigue. It assumes that the damage done by a Thermal Profile is proportional to the number of cycles it is applied to the model.

Miner's Rule:

$$\sum_{i=1}^k \frac{n_i}{N_i} = C \quad (2.1)$$

where:

n_i is the number of cycles accumulated at stress S_i .

N_i is the average number of cycles to failure at stress S_i .

C is the fraction of life consumed by exposure to the cycles at the different stress levels. Failure is set to occur when $C = 1$.

2.1.4. Thermal Shock

Sherlock uses the ramp rate to determine whether a thermal shock or thermal cycle is being applied. Ramp rate is calculated as follows:

$$\text{Ramp Rate} = \frac{\Delta T}{\text{Ramp Time}} \quad (2.2)$$

where:

$$\Delta T = (\text{Max Temp}) - (\text{Min Temp})$$

Ramp Time, Max Temp, and Min Temp are as defined in the Thermal Profile.

A Thermal Shock Factor (TSF) is introduced and factored into the calculations, as shown in [Equation 2.3 \(p. 6\)](#), after the cycles to failure calculation is completed. TSF is assigned based on the ramp rate:

- Any ramp rate **below 15°C/minute** will have a TSF of one.
- For any ramp rate **between 15°C/minute** and **30°C/minute**, the TSF is linearly interpolated between 1 and 1.25.
- For any ramp rate **between 30°C/minute** and **60°C/minute**, the TSF is linearly interpolated between 1.25 and 1.5.
- Any ramp rate **above 60°C/minute** will have a TSF of 1.5.

$$\text{Adjusted Cycles to Failure} = \frac{\text{Original Cycles to Failure}}{\text{Thermal Shock Factor}} \quad (2.3)$$

2.2. BGA Model

This section provides an overview of the BGA model where the following topics are covered:

- 2.2.1. BGA Overview
- 2.2.2. How Does the Software Assess BGA Solder Fatigue?
- 2.2.3. Input Parameters
- 2.2.4. Effective Mechanical Properties
- 2.2.5. Cycles to Failure for a Solder Ball Under the Die Shadow
- 2.2.6. Cycles to Failure for a Solder Ball Under a Package Corner
- 2.2.7. Validation Data
- 2.2.8. Life Prediction Plot
- 2.2.9. Solder Fatigue Scoring
- 2.2.10. References (BGA Model)

2.2.1. BGA Overview

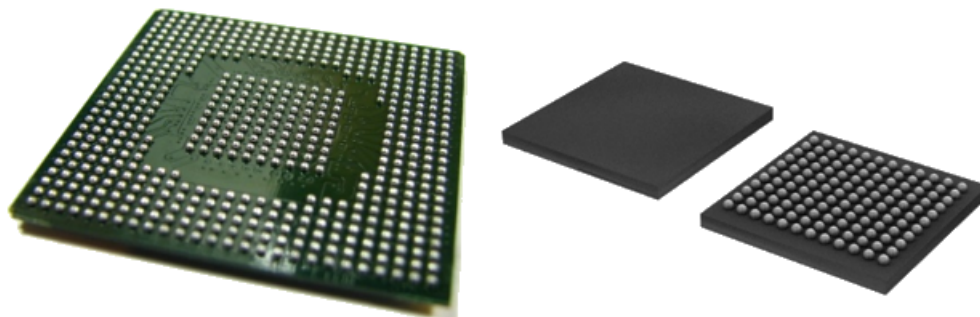
Ball Grid Arrays (BGAs) are surface mount packages used mainly for integrated circuits (ICs). These high-density packages are particularly advantageous due to their high number of interconnection pins. The thermal mechanical failure of a BGA is the result of shear strain during repeated temperature fluctuations. Shear strain is a function of two factors: the distance to neutral point and the mismatch between coefficients of thermal expansion (CTE). The CTE mismatch causes fractures to develop and solder joints to crack over time.

There are many types of BGAs. This section of the theory guide covers overmolded organic based BGA devices. The BGA solder model is valid for wire bonded BGAs as well as the flip chip BGAs.

Note:

Ceramic ball grid arrays (CBGA) are not included in this section. BGA's with a ceramic substrate will be covered in the section on the CBGA Model (soon to be released).

Sherlock's BGA Model is based on a Morrow strain energy damage model, where strain energy is converted to cycles to failure. The coefficients used in Sherlock are stored in Sherlock's solder library, and they are similar to those used by Syed (p. 25). For the purposes of this theory guide, only low-cycle fatigue (<10,000 cycles) are considered.

Figure 2.2: BGA (Ball Grid Array) Packages

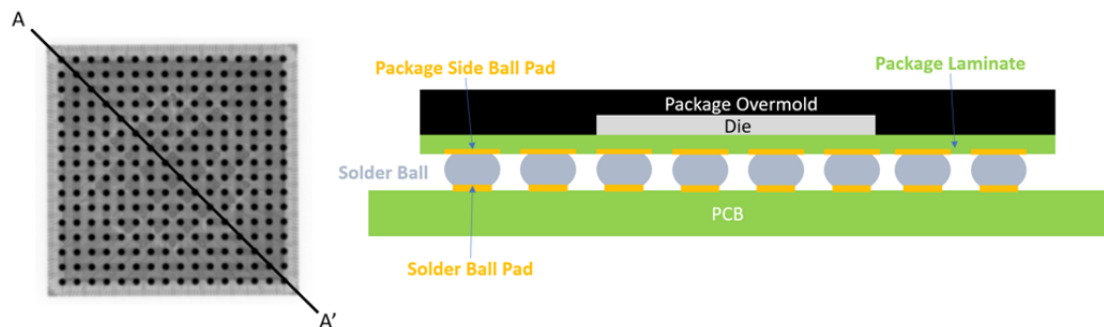
2.2.2. How Does the Software Assess BGA Solder Fatigue?

Note:

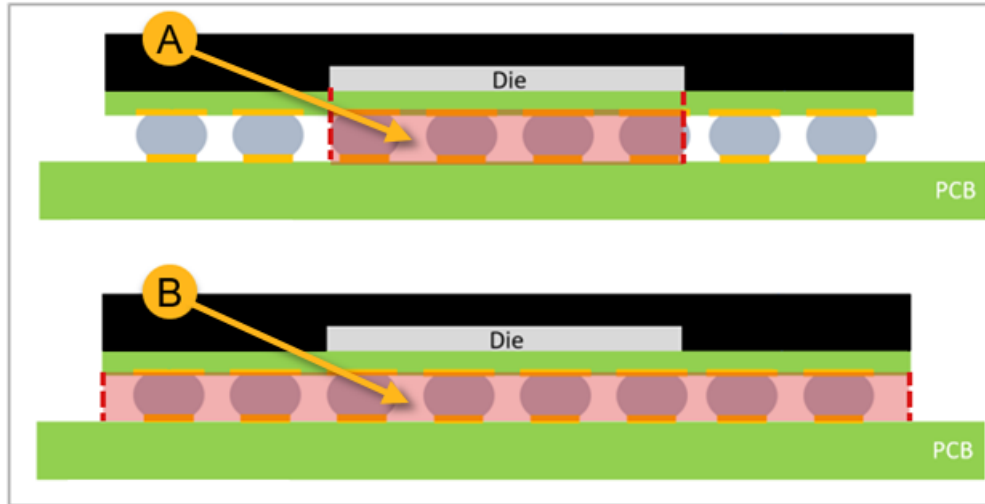
As of the current release:

- Sherlock assumes—regardless of the selected ball pattern—the existence of a ball at each corner of the package and checks for a solder ball at each corner of the die. Sherlock then computes time to failure at each location.
- Sherlock does not account for ball pitch.
- The Sherlock BGA model is calibrated for standard thermal profiles. Profiles with small changes in temperature should be used with caution.

The Solder Fatigue analysis in Sherlock uses a proprietary analytical model for different packages. As an analytical tool, system level effects are not considered in the model. This means a component at the center of the board will give the same result as a component near a mount point. For BGA packages, solder failures are generally observed at the corner solder balls, under the die, and under the package shadows. For this reason, the calculations are always considered along the package diagonal, as shown in [Figure 2.3: Sample BGA Structure \(p. 7\)](#).

Figure 2.3: Sample BGA Structure

The analytical model in Sherlock computes two sets of **Cycles To Failure (CTF)** calculations: One under the die shadow (A, in the figure below) and another under the package shadow (B). The highest damage between the two modes will be attributed to the lowest of the two failure cycles.

Figure 2.4: Die Shadow (A), Package Shadow (B)

The purpose behind the analytical model is to compute the effective shear modulus of the package. It takes into account all solder types and the effective material properties of the laminate, die, and the overmold. Sherlock incorporates the effect of the package side ball pad and the solder ball pad by applying correction factors to the diameter of the solder balls. These factors $d_{\text{correction factor, pad diameter}}$, $d_{\text{correction factor, pad size}}$ are covered later under [Diameter Corrections](#) (p. 16).

Sherlock finds the effective shear modulus for two regions:

- The region under the die shadow (component's interior)
- The overall region under the package (component's exterior- the summation of component's interior and the region of the package outside the die shadow)

To determine the effective shear modulus, other material properties such as Young's modulus, Poisson's ratio, and CTE for the component's interior and exterior must be computed. The analytical model uses the rule of mixtures for the component's interior (package overmold, die, and laminate), the component's exterior (package overmold and laminate) and the component's corner, that is, the effective properties at the corners of the package caused by the interaction between the component's interior and exterior regions.

Once the effective shear modulus is determined for the region under the die shadow and for the overall package, inelastic strain energy (ΔW) on the solder is determined based on each of the above components. The strain energy is later used in a model similar to Syed's model to predict cycles.

$$\Delta W = \sigma_{\text{Shear}} \cdot \varepsilon \quad (2.4)$$

$$N_f = (\text{Strain Energy Coefficient} \cdot \Delta W)^{-1} \quad (2.5)$$

2.2.3. Input Parameters

The analytical model for BGA fatigue prediction from thermal cycling uses the following inputs:

2.2.3.1. Thermal Parameters

2.2.3.2. Die Parameters

2.2.3.3. Laminate Parameters

2.2.3.4. Overmold Parameters

2.2.3.5. Solder Ball Parameters

2.2.3.6. PCB Parameters

A brief explanation of each parameter is provided in this section. For more details, refer to [Solder Fatigue Analysis in the *Sherlock User's Guide*](#).

2.2.3.1. Thermal Parameters

In Sherlock, you can create a Thermal Profile using the **Thermal Profile Editor** found in the **Life Cycle Editor** under **Thermal Event** (see [Project Life Cycles in the *Sherlock User's Guide*](#)). Below (Figure 2.5: Thermal Profile Example (p. 9)) is an example of a Thermal Profile which represents thermal cycling between 10 and 65. From the thermal cycle, Sherlock calculates the average temperature and change in temperature for the analysis as shown in equations below.

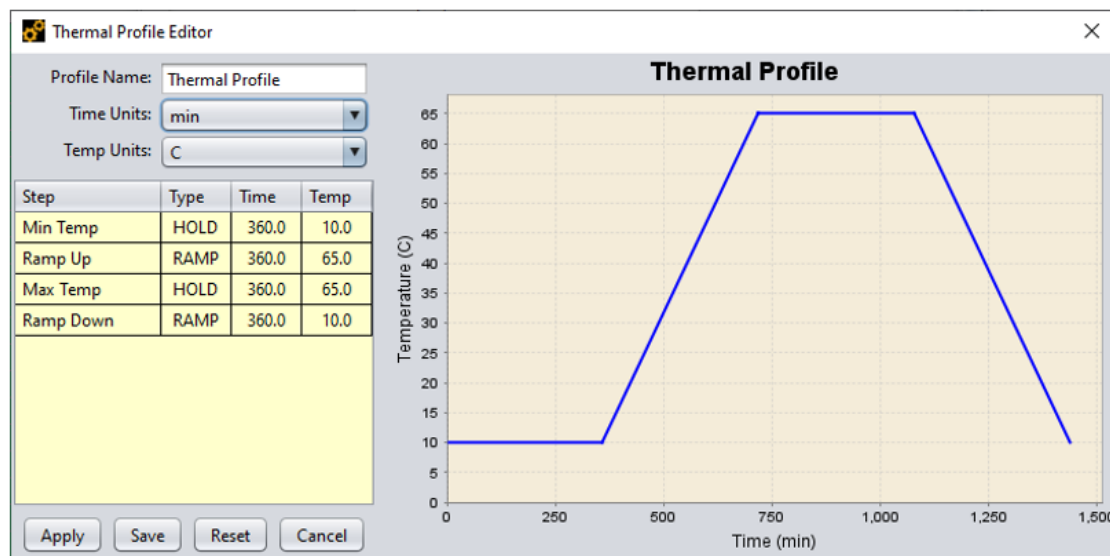
$$T_{\text{mean}} = \frac{(T_{\text{max}} + T_{\text{min}})}{2}$$

Mean temperature

$$\Delta T = T_{\text{max}} - T_{\text{min}}$$

Change in temperature

Figure 2.5: Thermal Profile Example



2.2.3.2. Die Parameters

In Sherlock the die parameters are specified under the **Die** tab in the **Part Properties** window as shown below (Figure 2.6: Die Parameters, Example (p. 10)). Sherlock uses the die length, die width, and die thickness in conjunction with other part properties to calculate the half-diagonal length of the die, the coefficient of thermal expansion, the elastic modulus, and Poisson's ratio of the die. The terms are listed below:

L_{die}

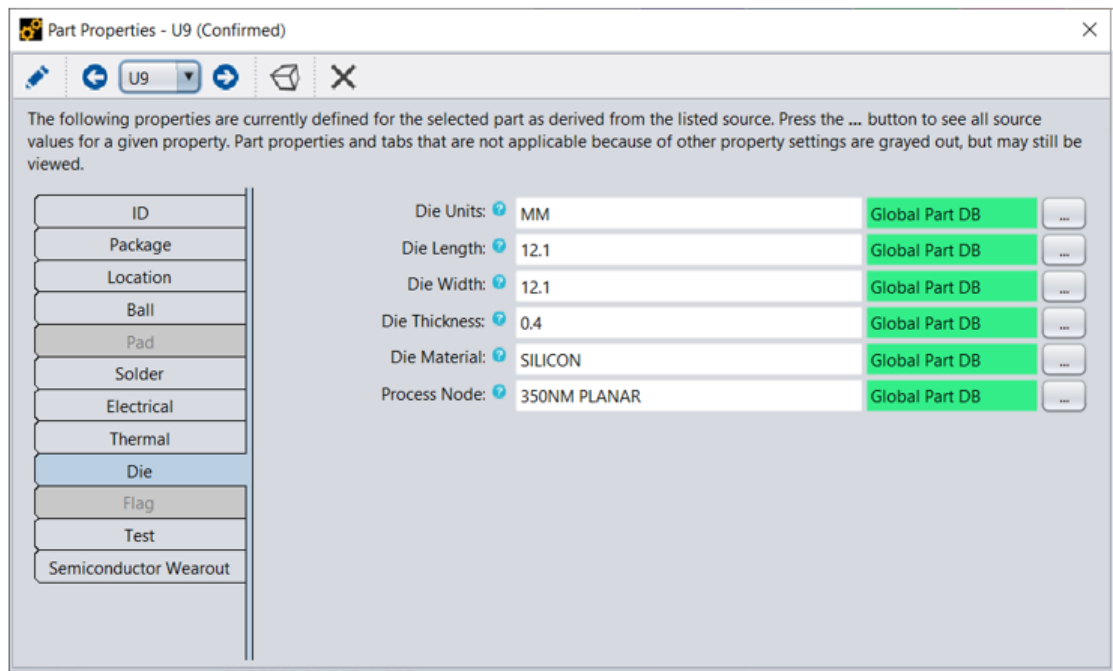
Length of die

W_{die}

Width of die

t_{die}	Thickness of die
$L_2^{\text{die}}=0.5\times\sqrt{L_{\text{die}}\times L_{\text{die}}+W_{\text{die}}\times W_{\text{die}}}$	Half the diagonal length of the die
CTE_{die}	Coefficient of thermal expansion of the die
E_{die}	Elastic modulus of the die
ν_{die}	Poisson's ratio for the die

Figure 2.6: Die Parameters, Example



2.2.3.3. Laminate Parameters

The laminate parameters are specified under the **Package** tab of the **Part Properties** (see [Figure 2.7: Laminate Properties, Example \(p. 11\)](#)). The length and width of the laminate is assumed to be the same as the length and width of the component, respectively. Sherlock uses the length and width of the component and the thickness of the laminate in conjunction with other part properties to calculate the area of the laminate, its half-diagonal length, its coefficient, its elastic modulus, as well as Poisson's ratio.

L_{lam}	Length of laminate
W_{lam}	Width of laminate
t_{lam}	Thickness of laminate
$A_{\text{lam}}=L_{\text{lam}}\times W_{\text{lam}}$	Area of laminate
$L_2^{\text{lam}}=0.5\times\sqrt{L_{\text{lam}}\times L_{\text{lam}}+W_{\text{lam}}\times W_{\text{lam}}}$	Half the diagonal length of laminate
CTE_{lam}	Coefficient of thermal expansion of the laminate
E_{lam}	Elastic modulus of the laminate

ν_{lam}

Poisson's ratio for the laminate

Figure 2.7: Laminate Properties, Example

The following properties are currently defined for the selected part as derived from the listed source. Press the ... button to see all source values for a given property. Part properties and tabs that are not applicable because of other property settings are grayed out, but may still be viewed.

Property	Value	Source
Package Name:	BGA676	Global Part DB
Package Type:	BGA	Global Part DB
Package Mount:	SMT	Global Part DB
Package Units:	MM	Global Part DB
Package Length:	2.70E+1	Global Part DB
Package Width:	27.0002	Global Part DB
Package Thickness:	1.4	Global Part DB
Overmold Thickness:	0.65	Global Part DB
Laminate Thickness:	0.75	Global Part DB
Model Part:	ENABLED	Guess
Corner Shape:	SQUARE	Global Part DB
Corner Radius:	0	Global Part DB
Corner Face:	TOP_BOTTOM	Global Part DB
Material:	EPOXYENCAPSULANT	Global Part DB
Overmold Material:	OVERMOLD-BGA	User
Junction Res (C/W):	15.0	Global Part DB
Weight (gram):	2.624E+0	Global Part DB

2.2.3.4. Overmold Parameters

The overmold parameters are specified under the **Package** tab of the **Part Properties** window. Sherlock uses the thickness of the overmold in conjunction with other part properties to calculate the coefficient of thermal expansion of the overmold, its elastic modulus, as well as Poisson's ratio.

 t_{over}

Thickness of the overmold

 CTE_{over}

Coefficient of thermal expansion for overmold

 E_{over}

Elastic modulus for overmold

 ν_{over}

Poisson ratio for overmold

Figure 2.8: Overmold Properties, Example

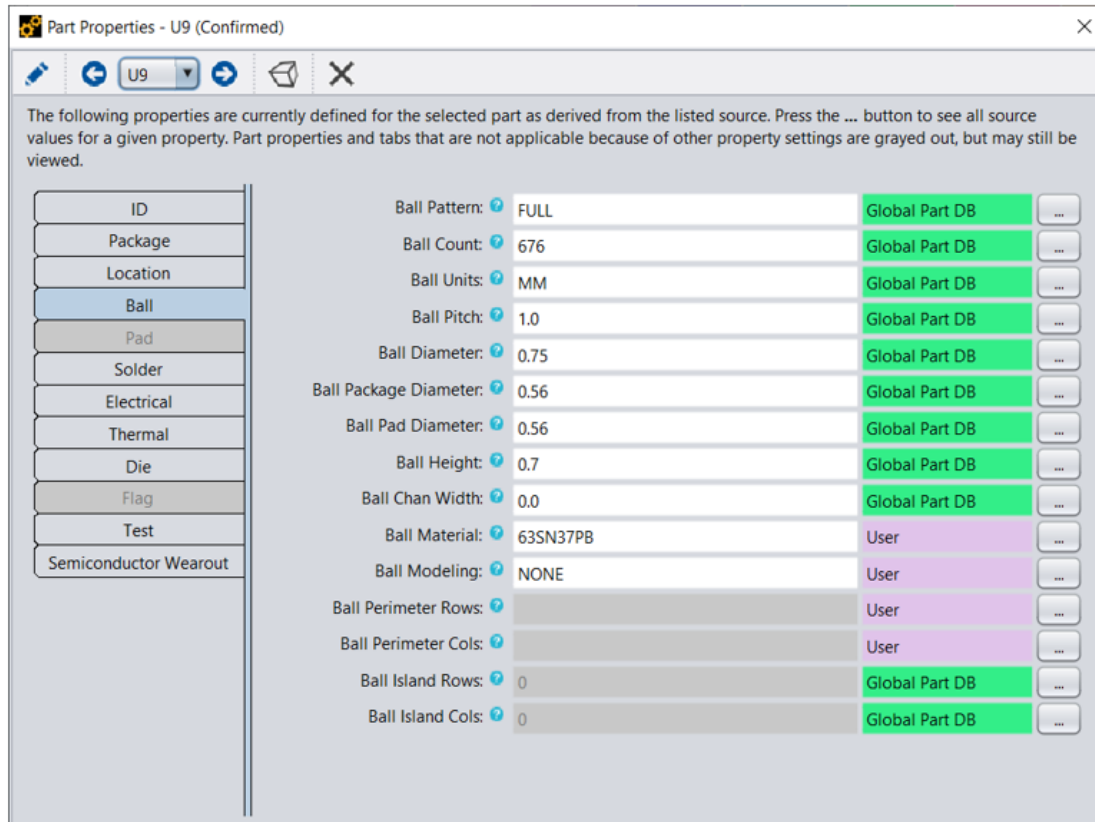
Part Properties - U9 (Confirmed)

The following properties are currently defined for the selected part as derived from the listed source. Press the ... button to see all source values for a given property. Part properties and tabs that are not applicable because of other property settings are grayed out, but may still be viewed.

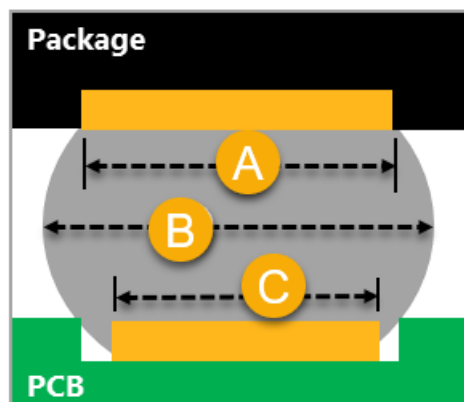
Property	Value	Source
ID		
Package		
Location		
Ball		
Pad		
Solder		
Electrical		
Thermal		
Die		
Flag		
Test		
Semiconductor Wearout		
Package Name:	BGA676	Global Part DB
Package Type:	BGA	Global Part DB
Package Mount:	SMT	Global Part DB
Package Units:	MM	Global Part DB
Package Length:	2.70E+1	Global Part DB
Package Width:	27.0002	Global Part DB
Package Thickness:	1.4	Global Part DB
Overmold Thickness:	0.65	Global Part DB
Laminate Thickness:	0.75	Global Part DB
Model Part:	ENABLED	Guess
Corner Shape:	SQUARE	Global Part DB
Corner Radius:	0	Global Part DB
Corner Face:	TOP_BOTTOM	Global Part DB
Material:	EPOXYENCAPSULANT	Global Part DB
Overmold Material:	OVERMOLD-BGA	User
Junction Res (C/W):	15.0	Global Part DB
Weight (gram):	2.624E+0	Global Part DB

2.2.3.5. Solder Ball Parameters

Figure 2.9: Ball Properties, Example (p. 13) shows the ball properties specified in Sherlock. Sherlock uses the ball diameter, ball height, ball count, ball pad diameter, and ball package diameter. The elastic modulus of the ball is assumed to be the same as the given solder for the BGA and is specified as such in the ball material field.

Figure 2.9: Ball Properties, Example

d_{ball}	Ball diameter (see B below (p. 13))
h_{ball}	Ball height
N_{ball}	Ball count
E_{ball}	Elastic modulus for a ball
$d_{\text{ball pad}}$	Ball pad diameter (C, below (p. 13))
$d_{\text{ball package}}$	Ball package diameter (A, below (p. 13))

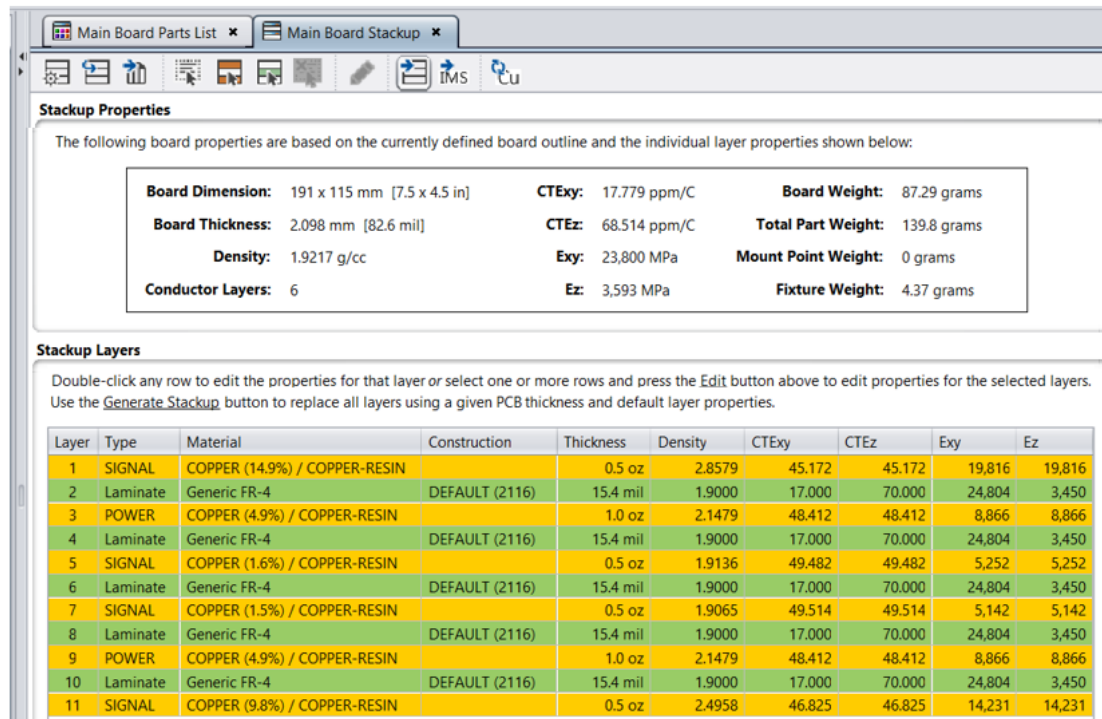
Figure 2.10: Solder Ball Nomenclature

2.2.3.6. PCB Parameters

The CTE, modulus, and Poisson's ratio for the stackup are used for the PCB in the analytical model. Sherlock computes the effective stackup properties based on the rule of mixtures. An example of a stackup in Sherlock is shown in [Figure 2.11: Sample PCB Properties \(p. 14\)](#).

CTE_{PCB}	Coefficient of thermal expansion for the PCB
E_{PCB}	Elastic modulus for the PCB
ν_{PCB}	Poisson Ratio for the PCB

Figure 2.11: Sample PCB Properties



2.2.4. Effective Mechanical Properties

There are two areas most prone to solder fatigue failure from low cycle fatigue: corner solder balls under a die shadow and package-corner balls. For this reason, the mechanical properties of the BGA's interior as well as its exterior must first be calculated. The interior properties are used to calculate the failure of a solder ball under the corner die shadow, and the exterior properties are used to calculate failure of a package-corner solder ball.

2.2.4.1. Interior

Elastic modulus for the component's interior:

$$E_{\text{inside}} = \frac{t_{\text{die}} \times E_{\text{die}} + t_{\text{lam}} \times E_{\text{lam}} + (t_{\text{over}} - t_{\text{die}}) \times E_{\text{over}}}{t_{\text{lam}} + t_{\text{over}}} \quad (2.6)$$

Total coefficient of thermal expansion for inside of the component:

$$CTE_{\text{inside}} = \frac{CTE_{\text{die}} \times E_{\text{die}} \times t_{\text{die}} + CTE_{\text{lam}} \times E_{\text{lam}} \times t_{\text{lam}} + CTE_{\text{over}} \times E_{\text{over}} \times (t_{\text{over}} - t_{\text{die}})}{E_{\text{inside sum}}} \quad (2.7)$$

where:

$$E_{\text{inside sum}} = t_{\text{die}} \times E_{\text{die}} + t_{\text{lam}} \times E_{\text{lam}} + (t_{\text{over}} - t_{\text{die}}) \times E_{\text{over}} \quad (2.8)$$

Effective Poisson's ratio for the component's interior:

$$\nu_{\text{inside}} = \frac{t_{\text{die}} \times \nu_{\text{die}} + t_{\text{lam}} \times \nu_{\text{lam}} + (t_{\text{over}} - t_{\text{die}}) \times \nu_{\text{over}}}{t_{\text{sum}}} \quad (2.9)$$

2.2.4.2. Exterior

Elastic modulus for the component's exterior:

$$E_{\text{outside}} = \frac{E_{\text{lam}} \times t_{\text{lam}} + E_{\text{over}} \times t_{\text{over}}}{t_{\text{sum}}} \quad (2.10)$$

Coefficient of thermal expansion for the component's exterior:

$$CTE_{\text{outside}} = \frac{CTE_{\text{lam}} \times E_{\text{lam}} \times t_{\text{lam}} + CTE_{\text{over}} \times E_{\text{over}} \times t_{\text{over}}}{E_{\text{outside sum}}} \quad (2.11)$$

where:

$$E_{\text{outside sum}} = E_{\text{lam}} \times t_{\text{lam}} + E_{\text{over}} \times t_{\text{over}} \quad (2.12)$$

Poisson ratio for the component's exterior:

$$\nu_{\text{outside}} = \frac{t_{\text{lam}} \times \nu_{\text{lam}} + t_{\text{over}} \times \nu_{\text{over}}}{t_{\text{sum}}} \quad (2.13)$$

Elastic modulus for the component's exterior:

$$E_{\text{outside}} = \frac{t_{\text{lam}} \times E_{\text{lam}} + t_{\text{over}} \times E_{\text{over}}}{t_{\text{sum}}} \quad (2.14)$$

2.2.4.2.1. Corner

Coefficient of thermal expansion for the corner of the component:

$$CTE_{\text{corner}} = \frac{CTE_{\text{inside}} \times L_2^{\text{die}}}{L_2^{\text{lam}}} + \frac{CTE_{\text{outside}} \times (L_2^{\text{lam}} - L_2^{\text{die}})}{L_2^{\text{lam}}} \quad (2.15)$$

Elastic modulus for the corner of the component:

$$E_{\text{corner}} = \frac{E_{\text{outside}} \times (L_2^{\text{lam}} - L_2^{\text{die}})}{L_2^{\text{lam}}} + \frac{E_{\text{inside}} \times L_2^{\text{die}}}{L_2^{\text{lam}}} \quad (2.16)$$

Poisson's ratio for the corner of the component

$$\nu_{\text{corner}} = 0.5 \times (\nu_{\text{outside}} + \nu_{\text{inside}}) \quad (2.17)$$

PCB Poisson's ratio

$$\nu_{\text{PCB}} = 0.15 \quad (2.18)$$

2.2.4.3. Solder Ball Properties

Area of one solder ball

$$A_{1\text{ ball}} = 0.25 \times \pi \times d_{\text{ball}} \times d_{\text{ball}} \quad (2.19)$$

Area comprising all solder balls

$$A_{\text{all ball}} = N_{\text{ball}} \times A_{1\text{ ball}} \quad (2.20)$$

Shear modulus for a solder ball

$$G_{\text{ball}} = \frac{E_{\text{ball}}}{2 \times (1 + 0.36)} \quad (2.21)$$

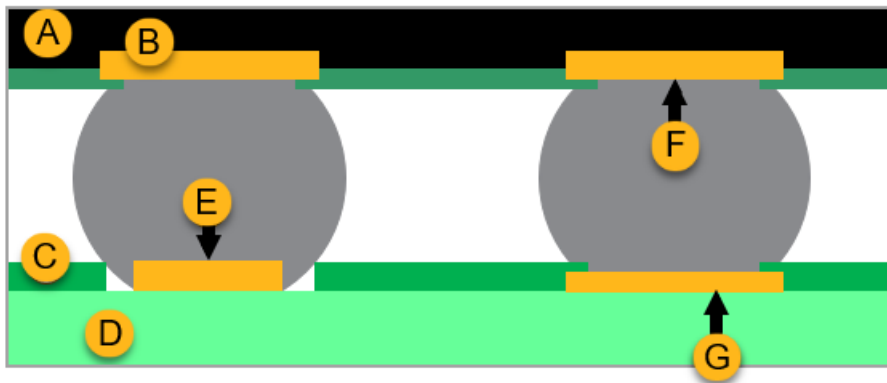
Effective shear modulus of ball

$$\text{Effective Shear Modulus}_{\text{ball}} = \frac{G_{\text{ball}} \times A_{\text{all ball}}}{A_{\text{lam}}} \quad (2.22)$$

Diameter Corrections

Solder joint reliability (SJR) depends on various parameters, one of the most important being solder pad size. The stress induced on the solder varies, depending on the surface area of the solder that is in contact with the PCB-side copper pad (E, below) and the package-side copper pad (F) which leads to variations in solder fatigue life. SJR also depends on variations between the PCB and the substrate-copper pad size (G). The smaller the contact surface, the higher the stress concentration will be and vice-versa. Sherlock's Solder Fatigue model was developed without differentiating between pad definition (SMD vs NSMD).

Figure 2.12: BGA Pad Surfaces



Key to [Figure 2.12 \(p. 16\)](#)

A- Package

C- Solder
mask

E- PCB-side copper bond pad

G- Substrate-copper pad size

B - Copper
pad

D- Mask

F- Package-side copper bond pad

In Sherlock's Solder Fatigue model, the variation in the pad size is captured by the pad size correction factor, $d_{\text{correction factor, pad size}}$, as shown in [Equation 2.23 \(p. 17\)](#). As a general rule, manufacturer data sheets recommend the pad diameter should be ~80% of the ball diameter for maximum reliability. Sherlock's Solder Fatigue model for BGA is calibrated to reflect this:

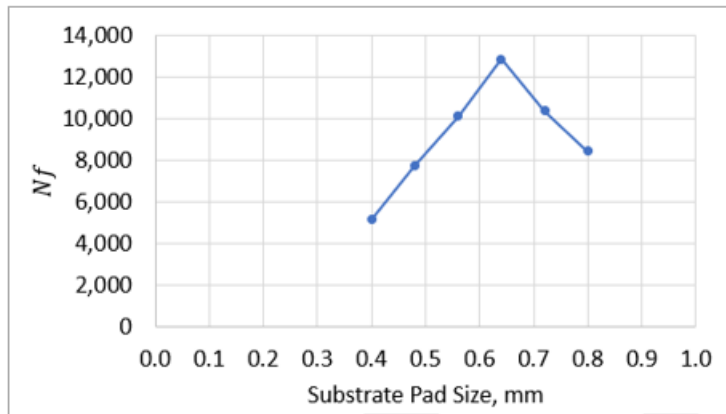
$$d_{\text{correction factor, pad size}} = 1 + \left(6 \times \left(\frac{d_{\text{ball pad}} + d_{\text{ball package}}}{2} - (0.8 \times d_{\text{ball}}) \right) \right)^4 \quad (2.23)$$

As mentioned previously, SJR also depends on variations between the PCB and the substrate-copper pad size (G, above). According to the literature, a ratio of 1:1 between the PCB and the substrate pad is ideal for maximum fatigue life. Otherwise, an imbalance in the shear stress develops if the ratio is anything other than 1:1. The higher the imbalance, the higher the probability of cracking on the side that has lower pad size. Sherlock captures the variation in the pad diameter through the pad diameter correction factor, $d_{\text{correction factor, pad diameter}}$, as shown in Equation 2.24 (p. 17).

$$d_{\text{correction factor, pad diameter}} = 1 + \frac{|d_{\text{ball package}} - d_{\text{ball pad}}|}{\left(1/d_{\text{ball package}} + 1/d_{\text{ball pad}} \right)^{-1}} \quad (2.24)$$

As you can see, if the top and bottom solder pad diameters are equal, the correction factor is 1, meaning no correction is needed. The graph below shows the effect of the correction factor on cycles-to-failure for a BGA package having a ball size of 0.8mm. The figure plots the life by fixing the PCB pad size while changing the substrate pad size. Notice, at 0.64 mm (80% of the ball diameter), the model predicts maximum life for the component.

Figure 2.13: Nf vs Substrate Pad Size Constant PCB Pad Size, 0.64 mm, Ball Diameter, 0.8 mm



2.2.5. Cycles to Failure for a Solder Ball Under the Die Shadow

As mentioned earlier, the two prevalent locations where a solder joint failure occurs is at the corner ball under the die shadow and the corner ball of the package. Typically, the area under the die shadow has the lowest CTE. However, the failure site is influenced by the laminate properties and die properties. For this reason, calculations at both the die shadow corner and package corner are necessary when determining the cycles to failure.

Note:

$B2_{\text{shadow}}$ is a placeholder parameter used to compute the stress under the die shadow ($\text{Stress}_{\text{shadow}}$). $S2_{\text{shadow}}$ is the uncorrected stress.

$$B2_{\text{shadow}} = \sqrt{\frac{\text{Effective Shear Modulus}_{\text{ball}}}{h_{\text{ball}}} \times \left(\frac{1 - \nu_{\text{inside}}}{E_{\text{inside}} \times t_{\text{sum}}} + \frac{1 - \nu_{\text{PCB}}}{E_{\text{PCB}} \times t_{\text{PCB}}} \right)} \quad (2.25)$$

$$S2_{\text{shadow}} = 2(CTE_{\text{inside}} - CTE_{\text{PCB}}) \times \frac{\text{Effective Shear Modulus ball}}{B2_{\text{shadow}} \times h_{\text{ball}}} \times \tanh\left(B2_{\text{shadow}} \times 0.4142 \times \left(\frac{L}{2}\right)_{\text{die}}\right) \times \Delta T \quad (2.26)$$

$$\text{Stress}_{\text{shadow}} = d_{\text{correction factor, pad size}} \times d_{\text{correction factor, pad diameter}} \times |S2_{\text{shadow}}| \quad (2.27)$$

$$\text{Strain Range Max}_{\text{shadow}} = \frac{|CTE_{\text{PCB}} - CTE_{\text{inside}}| \times \Delta T \times \left(\frac{L}{2}\right)_{\text{die}}}{h_{\text{ball}}} \quad (2.28)$$

$$\text{Adj Strain Range}_{\text{shadow}} = \text{Strain Range Max}_{\text{shadow}} \times \frac{t_{\text{Max Dwell}}}{\text{Critical Dwell Time}}^{0.136} \exp\left(\text{Activation Energy} \times \left(\frac{1}{\text{Critical Max Temperature}} - \frac{1}{T_{\text{Max K}}}\right)\right) \quad (2.29)$$

where critical dwell time, activation energy, and critical max temperature are all solder dependent.
 $T_{\text{Max K}}$ is the maximum temperature ($T_{\text{Max K}}$) in Kelvin.

$$\text{Strain Energy}_{\text{shadow}} = \text{Adj Strain Range}_{\text{shadow}} \times \text{Stress}_{\text{shadow}} \quad (2.30)$$

$$\text{Cycles to Failure}_{\text{shadow}} = \frac{1}{\text{Strain Energy Coefficient} \times \text{Strain Energy}_{\text{shadow}}} \quad (2.31)$$

2.2.6. Cycles to Failure for a Solder Ball Under a Package Corner

Note:

$B2_{\text{corner}}$ and $S2_{\text{corner}}$ are intermediate calculation variables used to compute the stress under a package corner ($\text{Stress}_{\text{corner}}$).

$$B2_{\text{corner}} = \sqrt{\frac{\text{Effective Shear Modulus ball}}{h_{\text{ball}}}} \times \left(\frac{1 - \nu_{\text{corner}}}{E_{\text{corner}} \times t_{\text{sum}}} + \frac{1 - \nu_{\text{PCB}}}{E_{\text{PCB}} \times t_{\text{PCB}}} \right) \quad (2.32)$$

$$S2_{\text{corner}} = 2(CTE_{\text{corner}} - CTE_{\text{PCB}}) \times \frac{\text{Effective Shear Modulus ball}}{B2_{\text{corner}} \times h_{\text{ball}}} \times \tanh\left(B2_{\text{corner}} \times 0.4142 \times \left(\frac{L}{2}\right)_{\text{lam}}\right) \times \Delta T \quad (2.33)$$

$$\text{Stress}_{\text{corner}} = d_{\text{correction factor, pad size}} \times d_{\text{correction factor, pad diameter}} \times |S2_{\text{corner}}| \quad (2.34)$$

$$\text{Strain Range Max}_{\text{corner}} = \frac{|CTE_{\text{PCB}} - CTE_{\text{corner}}| \times \Delta T \times \frac{L}{2}_{\text{lam}}}{h_{\text{ball}}} \quad (2.35)$$

$$\text{Adj Strain Range}_{\text{shadow}} = \text{Strain Range Max}_{\text{shadow}} \times \frac{t_{\text{Max Dwell}}}{\text{Critical Dwell Time}}^{0.136} \exp\left(\text{Activation Energy} \times \left(\frac{1}{\text{Critical Max Temperature}} - \frac{1}{T_{\text{Max K}}}\right)\right) \quad (2.36)$$

where Critical Dwell Time, Activation Energy, and Critical Max Temperature are all solder dependent.
 $T_{\text{Max K}}$ is the maximum temperature ($T_{\text{Max K}}$) in Kelvin.

$$\text{Strain Energy}_{\text{corner}} = \text{Adj Strain Range}_{\text{corner}} \times \text{Stress}_{\text{corner}} \quad (2.37)$$

$$\text{Cycles to Failure}_{\text{corner}} = \frac{1}{\text{Strain Energy Coefficient} \times \text{Strain Energy}_{\text{corner}}} \quad (2.38)$$

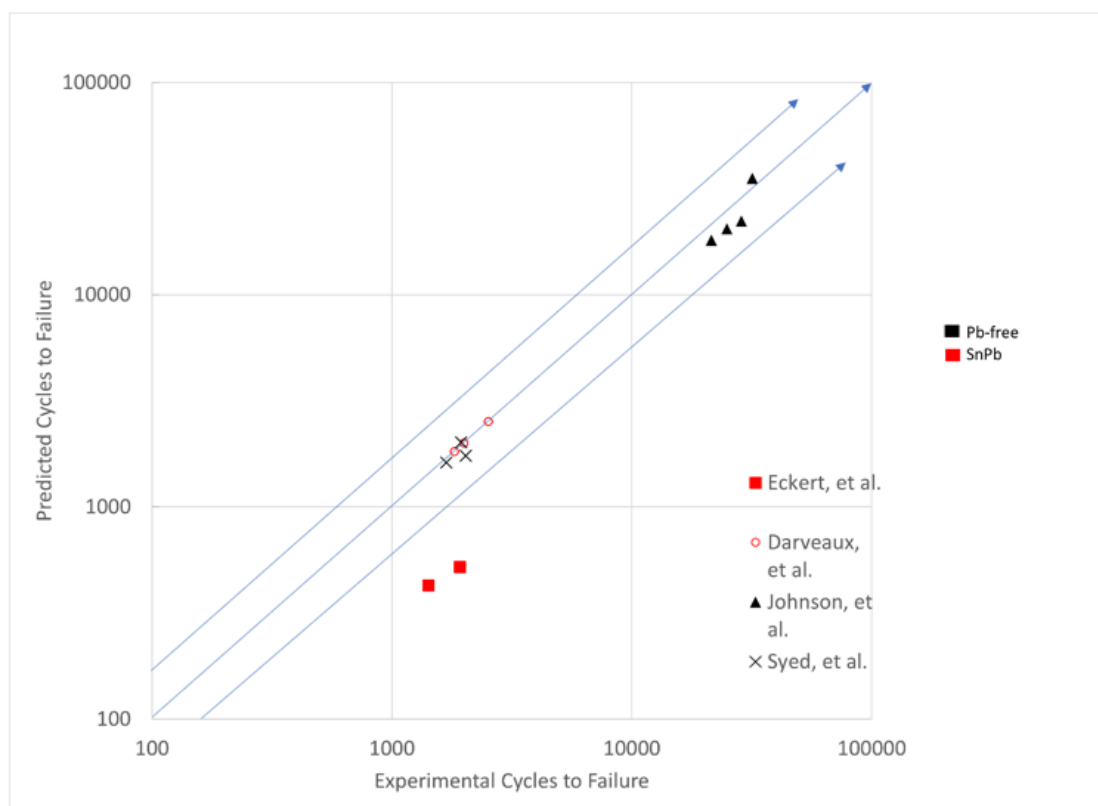
Sherlock will compare the cycles to failure values for solder balls under the die shadow as well as solder balls under a package corner and then choose the lowest value as the cycles to failure for the BGA component.

2.2.7. Validation Data

To validate the output of this module, Ansys gathered many examples of temperature cycling data for a variety of overmolded plastic ball grid array (BGA) and chip scale (CSP) packages. Packages were soldered to a printed board with either SnPb or SAC305.

Thermo-mechanical fatigue predictions for these configurations were then generated by the software and compared to experimental data. The results are displayed in the figure below. It is important to note that the validation was done by extracting experimental datapoints from published literature. Despite the inferences sometimes required to extract data from published literature, the software proved highly accurate, with the majority of predictions within the 2X boundaries defined within the figure.

Figure 2.14: BGA Model Validation



2.2.8. Life Prediction Plot

Life Prediction Plots in Sherlock are available for both individual components as well as the entire system. The plot represents the component's or system's probability of failure (POF, in %) against time to failure (TTF). The units for TTF, chosen by the user, will always be consistent with that of the service life. Sherlock uses a two-parameter Weibull distribution for life prediction as shown in [Equation 2.39 \(p. 20\)](#). The plot in Sherlock represents the unreliability component of the distribution, which

can also be recognized as the cumulative density function, represented by [Equation 2.40 \(p. 20\)](#), of the Weibull Distribution.

$$F(t) = \frac{\beta}{\eta} \left(\frac{t}{\eta} \right)^{\beta-1} e^{-\left(\frac{t}{\eta}\right)^\beta} \quad (2.39)$$

where:

β is the Weibull slope

η is the scale parameter

t is time

$$PoF(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^\beta} \quad (2.40)$$

The Weibull slope in [Equation 2.40 \(p. 20\)](#) describes the rate at which the components fail. [Figure 2.15: Weibull Slope Variation \(p. 20\)](#) shows the impact of the Weibull slope on the probability of failure for a service life of five years. The default Weibull slope is three, but you can adjust it as needed for different components by using the **Low-Cycle Fatigue** tab in the **Solder Editor**, as shown below ([Figure 2.16: Solder Editor \(p. 21\)](#)).

Figure 2.15: Weibull Slope Variation

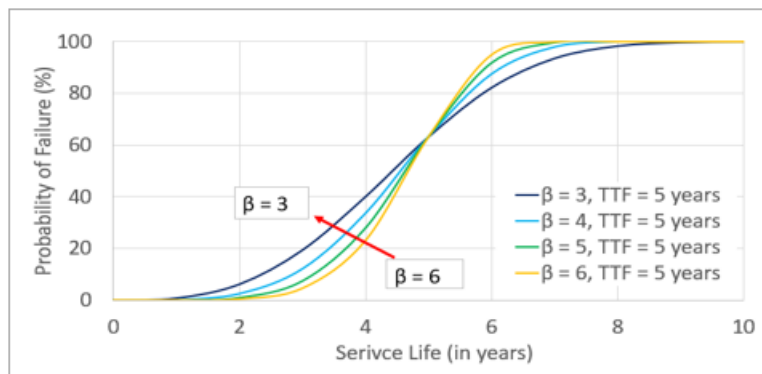


Figure 2.16: Solder Editor

Solder Editor - 63SN37PB

Modify the solder properties as needed and press the **Save** button to update the Solder Library.

Material Properties
Mechanical
Secant Modulus
High-Cycle Fatigue
Correction Factors
Low-Cycle Fatigue
User

Low-Cycle Fatigue

Critical Dwell Time: 20.0 min

Activation Energy (Ea): 1414.0

Critical Max Temp: 368.0

Strain Energy Coefficient: 6.061E-4

CC Calibration Factor: 1:0.0:1.0; 1:3.2:1.0; 2:0.0:1.0; 2:3.2:1.0; 3:0

Leaded Calibration Factor: 2.0

Thermal Shock Factor CC: 15,1.0 | 30,1.25 | 60,1.5

Thermal Shock Factor BGA: 15,1.0 | 30,1.25 | 60,1.5

Thermal Shock Factor LCCC: 15,1.0 | 30,1.25 | 60,1.5

Thermal Shock Factor Leaded: 15,1.0 | 30,1.25 | 60,1.5

Thermal Shock Factor QFN: 15,1.0 | 30,1.25 | 60,1.5

Thermal Shock Factor ThruHole: 15,1.0 | 30,1.25 | 60,1.5

Thermal Shock Factor Default: 15,1.0 | 30,1.25 | 60,1.5

Weibull Beta BGA: 3.0

Weibull Beta CBGA: 3.0

Weibull Beta CC: 3.0

Weibull Beta LCCC: 3.0

Weibull Beta Leaded: 3.0

Weibull Beta QFN: 3.0

Weibull Beta ThruHole: 3.0

In Sherlock, the PoF for a given *component* can be acquired from the **Results Table**: Right-click the component of interest from the **Results Table** to display the context menu, and select **View Life Prediction** as shown below. This will display the PoF plot for that *component*. For *system* level reliability, click the **Life Prediction** tab (B, below) to display the life prediction plot of all the components combined. (See Figure 2.18: System Level Life Prediction Plot (p. 22).)

Figure 2.17: Finding Individual Component Predictions (A) vs. System Level Predictions (B)

File

Score Card
Life Prediction
CAF Failure
Part Validation
Solder Fatigue

Filters

RefDes	Package	Part Type	Model	Side	Material	Solder	Max dT (C)	Damage	TTF (hrs)	Cycles To Fail	Fail Prob
R1	2512	RESISTOR	CC	TOP	ALUMINA	63SN37PB		7.0E-1	1,418.67	1,064	29.5
R2	2010	RESISTOR	CC	TOP	ALUMINA	63SN37PB		4.2E-1	2,369.33	1,777	7.2

Table (2)

RefDes Package Part Type Model Side Material Solder Max dT (C) Damage TTF (hrs) Cycles To Fail Fail Prob

R1 2512 RESISTOR CC TOP ALUMINA 63SN37PB 7.0E-1 1,418.67 1,064 29.5

R2 2010 RESISTOR CC TOP ALUMINA 63SN37PB 4.2E-1 2,369.33 1,777 7.2

View Part Properties
View Life Prediction
Export Table
Customize

Summary Life Prediction Time To Fail Table

When calculating system level reliability, Sherlock uses a slightly modified form of Lusser's law. In this approach, Sherlock calculates the system level reliability as the product of the reliabilities of all *unique* components which make up the system.

The reason Sherlock considers only unique components is because the Solder Fatigue module does not take into account system level effects. For example, a component at the center of the board will give the same result as the identical component located near a mount point. As a result, if Sherlock considers *all* components (rather than all *unique* components), then the product of identical reliabilities will artificially lower system level reliability predictions. Of course, in the real world, if two identical components on a PCB pass the requirement, it should improve rather than diminish the reliability prediction for the board. So, by considering only unique components in the system, Sherlock avoids this kind of strange outcome.

Figure 2.18: System Level Life Prediction Plot

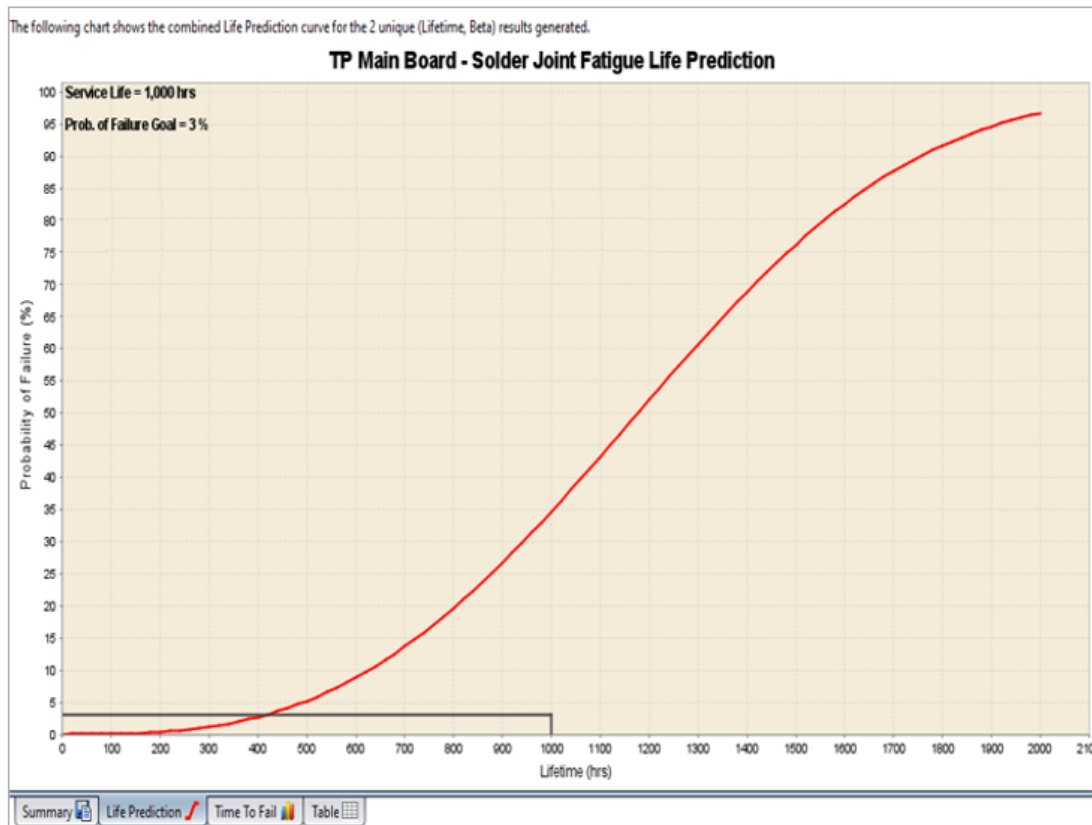
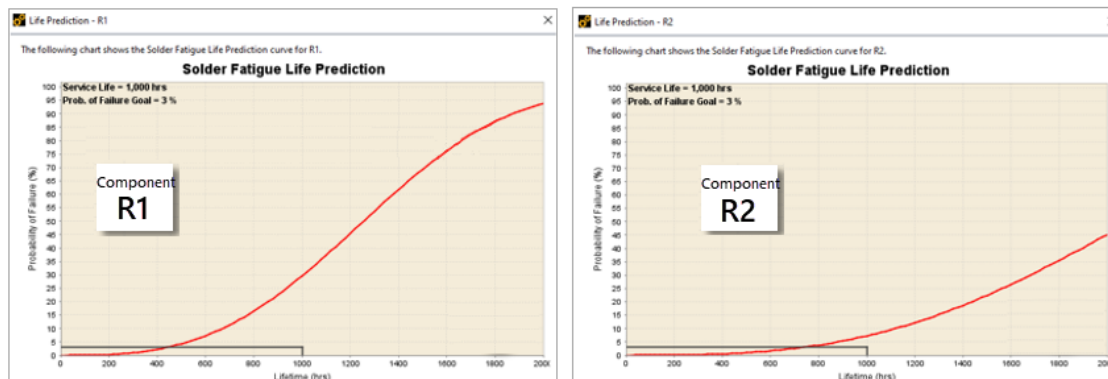


Figure 2.19: Component Life Prediction Plot

2.2.9. Solder Fatigue Scoring

Sherlock scoring for Solder Fatigue ranges between zero and ten. If the failure probability is the same as the failure probability goal (that is, if the ratio of failure goal to failure probability is one), the component is certain to fail and a score of zero is assigned. If the ratio is greater than ten, a score of ten is assigned. For any ratio between one and ten, Sherlock linearly interpolates in log scale between zero and ten. The score represents the safety factor between the failure goal and the actual failure computed from Sherlock. The scoring logic is shown below:

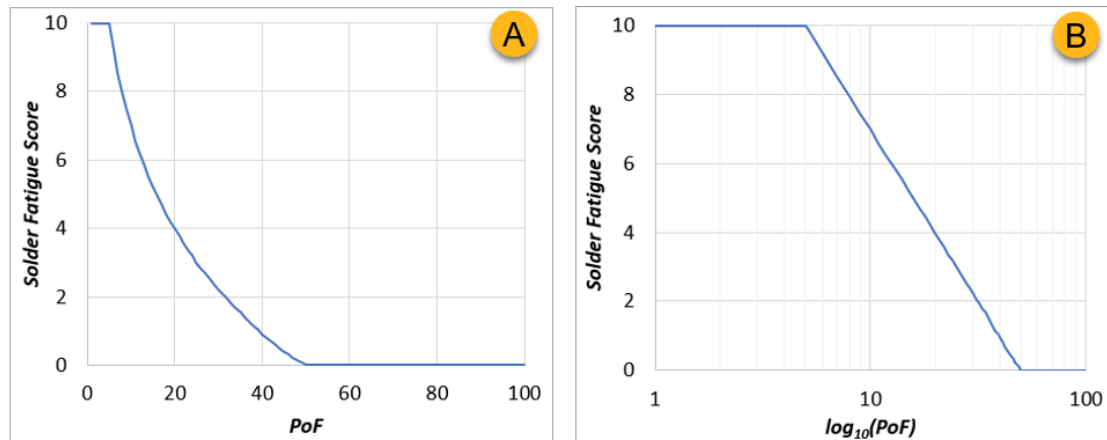
- If $(\text{Reliability Goal} / \text{Failure Probability}) < 1$, score = 0
- If $1 < (\text{Reliability Goal} / \text{Failure Probability}) < 1.4$,

$$\text{score} = 10 \log_{10} \left(1.4 * \left(\frac{(\text{Reliability Goal} / \text{Failure Probability}) - 1}{0.4} \right) \right)$$

- If $1.4 < (\text{Reliability Goal} / \text{Failure Probability}) < 10$,

$$\text{score} = 10 \log_{10} (\text{Reliability Goal} / \text{Failure Probability})$$
- If $(\text{Reliability Goal} / \text{Failure Probability}) > 10$, Score = 10

The figure below shows the score for different probabilities of failure for a failure goal of 50% as a percentage (A) and as a log percentage (B).

Figure 2.20: Probability of Failure vs Score

2.2.10. References (BGA Model)

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12. Webster, J., Pan, J., & Toleno, B. (2004). Investigation of the Lead-free Solder Joint Shear Performance. *Soldering and Surface Mount Technology*, 16(2), 77-87.
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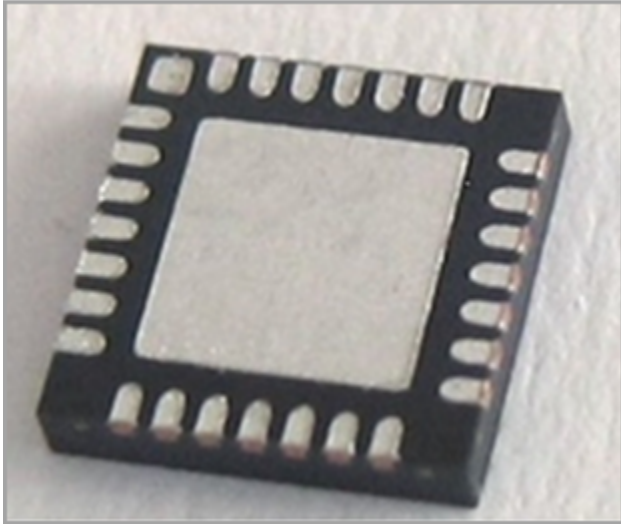
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2.3. Quad Flat No-Lead (QFN) Package

When designing consumer electronics and electronics for high reliability applications, engineers have increasingly turned to the Quad Flat No-Lead package to take advantage of its benefits: the reduced size of its footprint, its improved electrical properties owing to the absence of solder bumps and leads, and its low thermal resistance. Furthermore, the capability of multi-row QFN packages (compared to conventional QFN packages) match that of low density ball grid arrays (BGAs). (Tseng et al., 2010 (p. 35) and Frear et al., 2001 (p. 35)). Unlike similar CSP (chip scale packages), QFN packages with SnAgCu solder have shown to be more resistant to thermo-mechanical fatigue at more extreme thermal cycles (Vanderve et al., 2007 (p. 35)).

Figure 2.21: QFN Package



Section Summary:

- 2.3.1. How the Software Assesses Thermo-Mechanical Solder Fatigue
- 2.3.2. Validation Data
- 2.3.3. References (QFN Package)

2.3.1. How the Software Assesses Thermo-Mechanical Solder Fatigue

Section Summary:

- 2.3.1.1. Input Parameters
- 2.3.1.2. Material Properties
- 2.3.1.3. Effective Mechanical Properties - Partitioning QFNs into Three-Layer Structures
- 2.3.1.4. QFN Package Effective CTE and E Across Mold Compound Tg
- 2.3.1.5. Effect of Solder Fillet on Fatigue Life Predictions
- 2.3.1.6. Effective Mechanical Properties
- 2.3.1.7. Cycles to Failure

2.3.1.1. Input Parameters

The following terminology describes the physical and material properties of a QFN, the PCB, and their thermal profiles. These parameters are further subdivided into the different segments that comprise the inputs for the analytical model.

Temperature Profile

Maximum dwell temperature: $T_{\max}$

Minimum dwell temperature: $T_{\min}$

Low temperature dwell time: $T_{\text{dwell}, \min}$

High temperature dwell time: $T_{\text{dwell}, \max}$

Component

Thickness: t_{QFN}

Length: L_{QFN}

Width: W_{QFN}

Number of Leads: N_{QFN}

Die

Length of die: L_{die}

Half-diagonal distance of the die: L_2^{die}

Width of the die: W_{die}

Thickness of the die: t_{die}

CTE of the die: CTE_{die}

Elastic modulus of the die: E_{die}

Poisson's ratio of the die: ν_{die}

Copper Flag

CTE of the copper flag: CTE_{copper}

Poisson's ratio of the copper flag: ν_{copper}

Thickness of the copper flag: t_{copper}

Length of the copper flag: L_{copper}

Half-Diagonal Distance: L_2^{copper}

Width of the copper flag: W_{copper}

Modulus of the copper flag: E_{copper}

Overmold

CTE of overmold: $CTE_{overmold}$

Poisson's ratio of overmold: $\nu_{overmold}$

Thickness of overmold: $t_{overmold}$

Length of overmold: $L_{overmold}$

Half-diagonal distance of overmold: $L_2^{overmold}$

Width of overmold: $W_{overmold}$

Elastic modulus of overmold: $E_{overmold}$

Glass transition temperature of overmold: $T_{g, overmold}$

Solder Attach (component pad)

Length of solder: L_{solder}

Height of solder : h_{solder}

Width of solder : W_{solder}

Poisson's ratio of solder : ν_{solder}

PCB (board pad)

Thickness of PCB: t_{PCB}

CTE of PCB: CTE_{PCB}

Elastic modulus of PCB: E_{PCB}

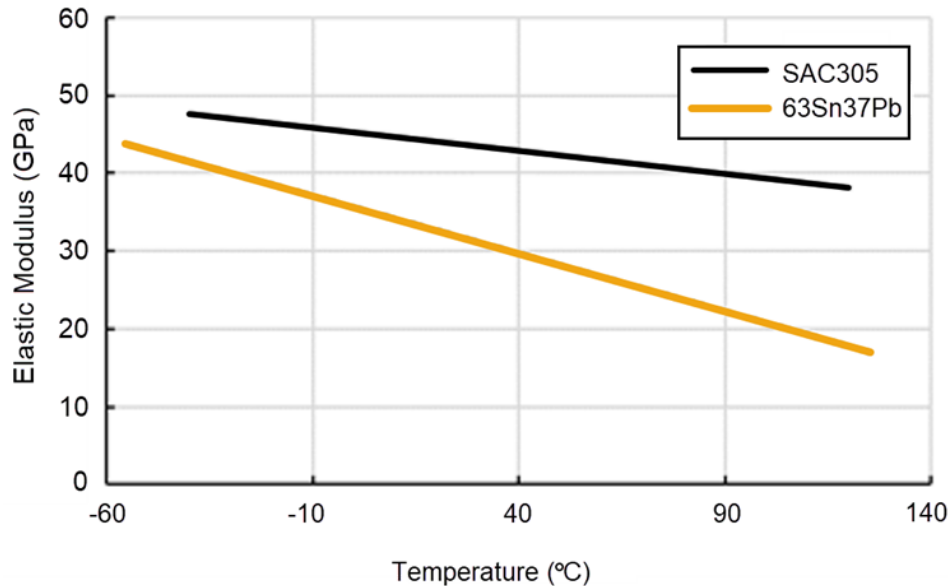
Shear modulus of PCB: G_{PCB}

2.3.1.2. Material Properties

Solder alloys exhibit viscoplastic behavior, and the elastic modulus of many conventional solder alloys exhibit a linear relationship with temperature. The maximum temperature of the thermal cycle is the point where peak strain energy density is considered. See, for example, the chart below which plots the temperature dependent elastic modulus for SAC305 and 63Sn37Pb solder alloys. Also, refer to [Equation 2.41 \(p. 28\)](#) which represents the temperature dependent modulus of SAC305 solder alloy.

$$E_{solder \text{ at } T_{Max}} = 59533 - 66.667(273 + T_{max}) \quad (2.41)$$

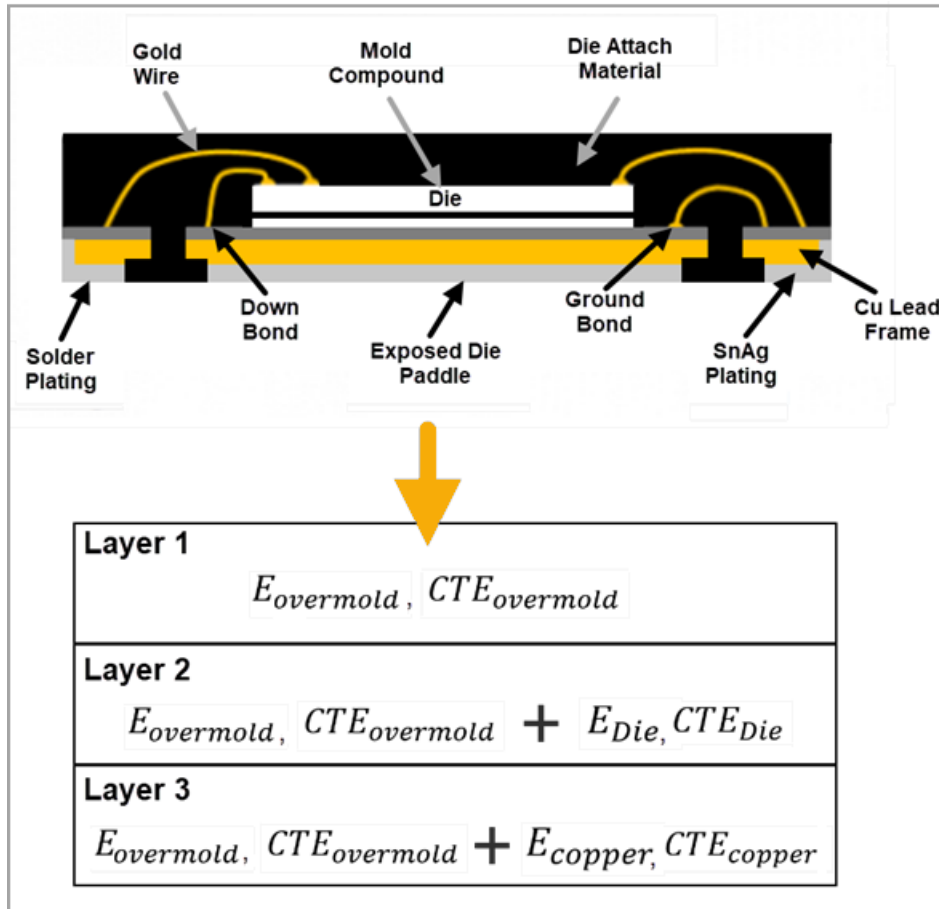
Figure 2.22: Elastic modulus as function of temperature for SAC305 and 63Sn37Pb solder alloys



2.3.1.3. Effective Mechanical Properties - Partitioning QFNs into Three-Layer Structures

QFNs are idealized into horizontal slices based on a continuous-attach, tri-layer architecture, as illustrated below (Chen et al., 1979 (p. 35)). This analysis permits the adjustment of overmold properties. Additionally, Sherlock limits the selections of coefficients of thermal expansion (CTE) and elastic modulus (E) so they do not exceed the applicational boundaries of the theory.

Figure 2.23: Layer schematic for the effective CTE calculation



$$CTE_{\text{Layer 1}} = CTE_{\text{Overmold}} \quad (2.42)$$

$$E_{\text{Layer 1}} = E_{\text{Overmold}} \quad (2.43)$$

$$CTE_{\text{Layer 2}} = \frac{CTE_{\text{die}} L_2^{\text{die}}}{L_2^{\text{Overmold}}} + \frac{CTE_{\text{Overmold}} (L_2^{\text{Overmold}} - L_2^{\text{die}})}{L_2^{\text{Overmold}}} \quad (2.44)$$

$$E_{\text{Layer 2}} = \frac{L_2^{\text{Overmold}}}{\left(\frac{L_2^{\text{die}}}{E_{\text{die}}} + \frac{L_2^{\text{Overmold}} - L_2^{\text{die}}}{E_{\text{Overmold}}} \right)} \quad (2.45)$$

$$CTE_{\text{Layer 3}} = \frac{CTE_{\text{copper}} L_2^{\text{copper}}}{L_2^{\text{Overmold}}} + \frac{CTE_{\text{copper}} L_{\text{solder}}}{L_2^{\text{Overmold}}} + \frac{CTE_{\text{Overmold}} (L_2^{\text{Overmold}} - L_{\text{solder}} - L_2^{\text{copper}})}{L_2^{\text{Overmold}}} \quad (2.46)$$

$$E_{Layer\ 3} = \frac{L_2^{overmold}}{\left(\frac{L_2^{copper} + L_{solder}}{E_{copper}} + \frac{L_2^{overmold} (L_2^{copper} + L_{solder})}{E_{overmold}} \right)} \quad (2.47)$$

$$CTE_{effective} = \frac{t_{overmold} CTE_{Layer\ 1} E_{Layer\ 1} + t_{die} CTE_{Layer\ 2} E_{Layer\ 2} + t_{copper} CTE_{Layer\ 3} E_{Layer\ 3}}{(t_{package} - t_{copper} - t_{die}) * E_{Layer\ 1} + t_{die} E_{Layer\ 2} + t_{copper} E_{Layer\ 3}} \quad (2.48)$$

$$E_{effective} = \frac{(t_{package} - t_{copper} - t_{die}) * E_{layer\ 1} + t_{die} E_{layer\ 2} + t_{copper} E_{layer\ 3}}{t_{package}} \quad (2.49)$$

where

$$L_2^{overmold} = \frac{\sqrt{(L_{overmold})^2 + (W_{overmold})^2}}{2} \quad (2.50)$$

$$L_2^{die} = \frac{\sqrt{(L_{die})^2 + (W_{die})^2}}{2} \quad (2.51)$$

$$L_2^{copper} = \frac{\sqrt{(L_{copper})^2 + (W_{copper})^2}}{2} \quad (2.52)$$

2.3.1.4. QFN Package Effective CTE and E Across Mold Compound T_g

Lower CTE overmolds decrease the board level reliability of QFN packages. The following hyperbolic model accounts for the overmold's temperature dependent CTE and modulus across its T_g. [Equation 2.53 \(p. 30\)](#) and [Equation 2.54 \(p. 30\)](#) represent the temperature dependent CTE and the modulus of the overmold, respectively.

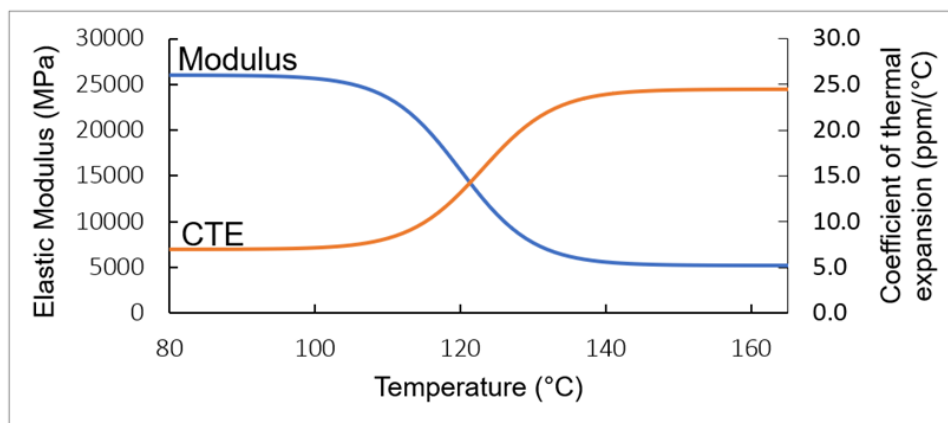
$$CTE_1(T) = \frac{2.5CTE_{overmold}}{2} \left(1.8 + \tanh \left(\frac{T_{avg} - T_g^{overmold}}{S} \right) \right) \quad (2.53)$$

$$E_1(T) = \frac{0.8E_{overmold}}{2} \left(1.5 + \tanh \left(-1 \times \frac{T_{max} - T_g^{overmold}}{S} \right) \right) \quad (2.54)$$

In cases where the maximum profile temperature (T_{max}) exceeds the overmold material's T_g, the effective stiffness of the overmold decreases due to a reduction in the material's elastic modulus and an increase in the coefficient of thermal expansion (CTE). The decrease in the modulus is influenced by the temperature difference between the materials T_{max} and T_g. In order to compensate for this effect, the equivalent strain range decreases to a value similar to that of the strain difference for a package with slightly lower T_{max}.

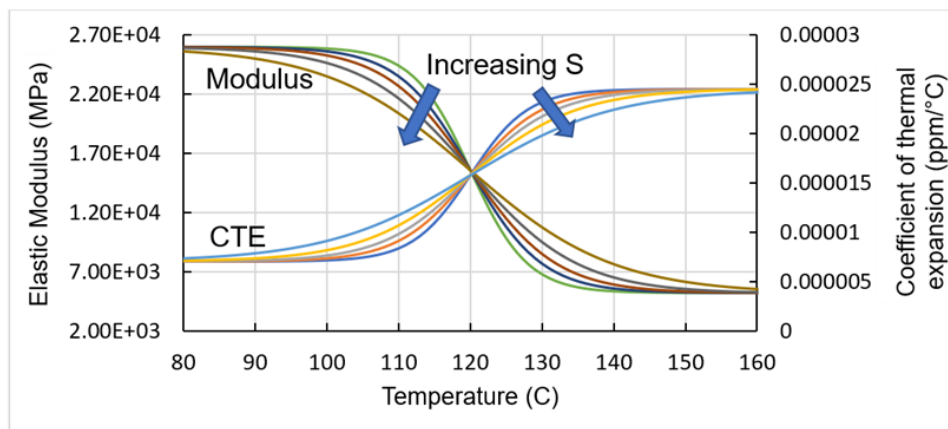
The model accounts for the increase in CTE by defaulting to an increase of approximately 3.5x. Similarly, the decrease in modulus is modeled by a 5x decrease. To reiterate, these changes occur as temperature cycles increase beyond the overmold's T_g. CTE and E are derived from analyzing material behavior of several epoxy molding compounds. To illustrate, the following figure displays the evolution of the CTE and E for a material with (1) CTE: 7 ppm/°C, (2) E: 26,000 MPa, and (3) T_g: 120 °C

Figure 2.24: This figure illustrates the changes in mold compound CTE and E as the temperature increases across the material's T_g .



In the above plot, the distinct contours are influenced by shape parameters which are scalar quantities incorporated into the model to account for material behavior as it transitions across the T_g . The figure below conveys the models' sensitivity to shape parameters: The increased transition regions correspond to a decrease in the shape factor values.

Figure 2.25: As the shape factors increase from 8 to 20, the material experiences slower transitions.



2.3.1.5. Effect of Solder Fillet on Fatigue Life Predictions

Researchers have shown that when a solder fillet is formed, it prolongs the solder joint fatigue life. One example of this effect can be seen in 164 I/O, 12x12 mm body size, dual row QFNs (Frear et al., 2001 (p. 35)). Additionally, 8x8 mm body size QFN packages with solder fillets have shown to have an increased fatigue life of 240 cycles to failure (Chen, 1979 (p. 35)). This amounts to a 27% increase in fatigue life. The improvement in lifetime greatly depended on the die to package ratio, solder joint height, and solder fillet geometry. Currently, Sherlock does not account for the toe fillet formation of the solder joint because a majority of QFN devices do not have solderability plating on the cut end of their solder pad, so the formation of a toe fillet is not guaranteed. The current assumption is that the crack occurs along the component solder pad length and that dimension is used for the calculations.

With the above-mentioned considerations in mind, the detailed methodology, based on Chen's model (Chen, 1979 (p. 35)), is presented by the equations below. These equations are package-specific and account for the geometry, interconnect structure, and material properties of the component and the PCB. Starting with the elastic modulus, a shear modulus is developed.

Keeping in mind the considerations mentioned above, the detailed methodology based on Chen's model (Chen, 1979 (p. 35)) is presented in the equations below. These equations are package-specific and account for the geometry, interconnect structure, as well as the material properties of the component and the PCB. Starting with the elastic modulus, a shear modulus is developed.

$$G_{max} = \frac{E_{solder}^{max}}{2(1+\nu_{solder})} \quad (2.55)$$

$$G_{min} = \frac{E_{solder}^{min}}{2(1+\nu_{solder})} \quad (2.56)$$

$$A_{fraction} = \frac{N_{bond\ pads} * L_{solder} * W_{solder} + L_{copper} * W_{copper}}{L_{QFN} * W_{QFN}} \quad (2.57)$$

2.3.1.6. Effective Mechanical Properties

With the area fraction given in Equation 2.57 (p. 32), the area-weighted shear modulus is calculated below. Equation 2.58 (p. 32) to Equation 2.70 (p. 33) incorporate PCB properties using Sherlock's stackup editor.

$$\bar{G}_{max} = G_{max} * A_{fraction} \quad (2.58)$$

$$\bar{G}_{min} = G_{min} * A_{fraction} \quad (2.59)$$

Equations Equation 2.60 (p. 32) and Equation 2.61 (p. 32) are intermediary equations used to calculate the stress (as shown below)

$$\beta_{min} = \sqrt{\frac{\bar{G}_{min}}{h_{solder}} \left(\frac{1}{E_{effective} t_{componentQFN}} \right) + \left(\frac{1}{E_{PCB} t_{PCB}} \right)} \quad (2.60)$$

$$\beta_{max} = \sqrt{\frac{\bar{G}_{max}}{h_{solder}} \left(\frac{1}{E_{effective} t_{componentQFN}} \right) + \left(\frac{1}{E_{PCB} t_{PCB}} \right)} \quad (2.61)$$

$$\gamma_{at\ min T} = \frac{|CTE_{PCB} - CTE_{effective}| \bar{G}_{min} * \tanh(\beta_{min} * L_{overmold})}{\beta_{min}} \quad (2.62)$$

$$\gamma_{at\ max T} = \frac{|CTE_{PCB} - CTE_{effective}| \bar{G}_{max} * \tanh(\beta_{max} * L_{overmold})}{\beta_{max}} \quad (2.63)$$

From Hooke's Law, the following elastic moduli are calculated:

$$\bar{\tau}_{min\ Shear} = \left| \frac{\gamma_{at\ min\ T}}{\bar{G}_{min}} \right| \quad (2.64)$$

$$\bar{\tau}_{max\ Shear} = \left| \frac{\gamma_{at\ max\ T}}{\bar{G}_{max}} \right| \quad (2.65)$$

$$\gamma_{min\ Stress} = \bar{\tau}_{min\ Shear} * G_{min} \quad (2.66)$$

$$\gamma_{max\ Stress} = \bar{\tau}_{max\ Shear} * G_{max} \quad (2.67)$$

$$\gamma_{total\ Stress} = \gamma_{min\ Stress} + \gamma_{max\ Stress} \quad (2.68)$$

$$\Delta\gamma_{\min} = \frac{|CTE_{PCB} - CTE_{effective}| (T_{mean} - T_{\min}) L_2^{overmold}}{h_{solder}} \quad (2.69)$$

$$\Delta\gamma_{\max} = \frac{|CTE_{PCB} - CTE_{effective}| (T_{\max} - T_{mean}) L_2^{overmold}}{h_{solder}} \quad (2.70)$$

$$\bar{\gamma}_{\min} = \Delta\gamma_{\min} \left(\frac{t_{dwell\ min}}{t_{critical}} \right)^{0.136} e^{Activation\ Energy \left(\frac{1}{critical\ Max\ T} - \frac{1}{T_{minK}} \right)} \quad (2.71)$$

$$\bar{\gamma}_{\max} = \Delta\gamma_{\max} \left(\frac{t_{dwell\ max}}{t_{critical}} \right)^{0.136} e^{Activation\ Energy \left(\frac{1}{critical\ Max\ T} - \frac{1}{T_{maxK}} \right)} \quad (2.72)$$

Strain energy calculations were completed for upper and lower temperature regimes, while accounting for damage accumulation during cold dwell periods and T_g behavior. In the previous model, calculations were only completed at higher temperature. This current model is valid at both hot and cold temperature regimes. This technique calculates the strain energy density of the solder joint at its interface by idealizing a hysteresis loop from the lower and upper limits of the strain-stress estimations.

$$\Delta W_{\min} = \frac{|\bar{\gamma}_{\min} * \gamma_{\min\ Stress}|}{2} \quad (2.73)$$

$$\Delta W_{\max} = \frac{|\bar{\gamma}_{\max} * \gamma_{\max\ Stress}|}{2} \quad (2.74)$$

$$Strain\ Energy = \Delta W_{\min} + \Delta W_{\max} \quad (2.75)$$

2.3.1.7. Cycles to Failure

$$Cycles\ to\ Failure = \frac{1}{Strain\ Energy\ Coefficient * Strain\ Energy} \quad (2.76)$$

Note that the Strain Energy Coefficient is solder dependent.

2.3.2. Validation Data

To validate the output of this module, Ansys gathered published data on thermal cycling of various QFN components (presented in the graph below). The model showed good correlation with experimental data obtained for variety of QFN packages, thermal profiles and solder alloys (SAC305 and SnPb). It is important to note that the validation was done by extracting experimental datapoints from published literature.

Thermo-mechanical fatigue predictions for the configurations shown below were performed using Sherlock ADA™ using the available published input parameters. The table below ([Table 2.1: Sample material properties illustrated in model example \(p. 34\)](#)) provides the linear-elastic material properties for materials used as input parameters. Sherlock's predictions and experimental values were completed and adjusted for a 63.2% probability of failure. The results are displayed in the figure below ([Figure 2.26: QFN model validation, data extracted from key sources \(p. 34\)](#)). Predictions results are found to be well within a factor of 2X within experimental values. Majority of predictions are placed within 50% of published values.

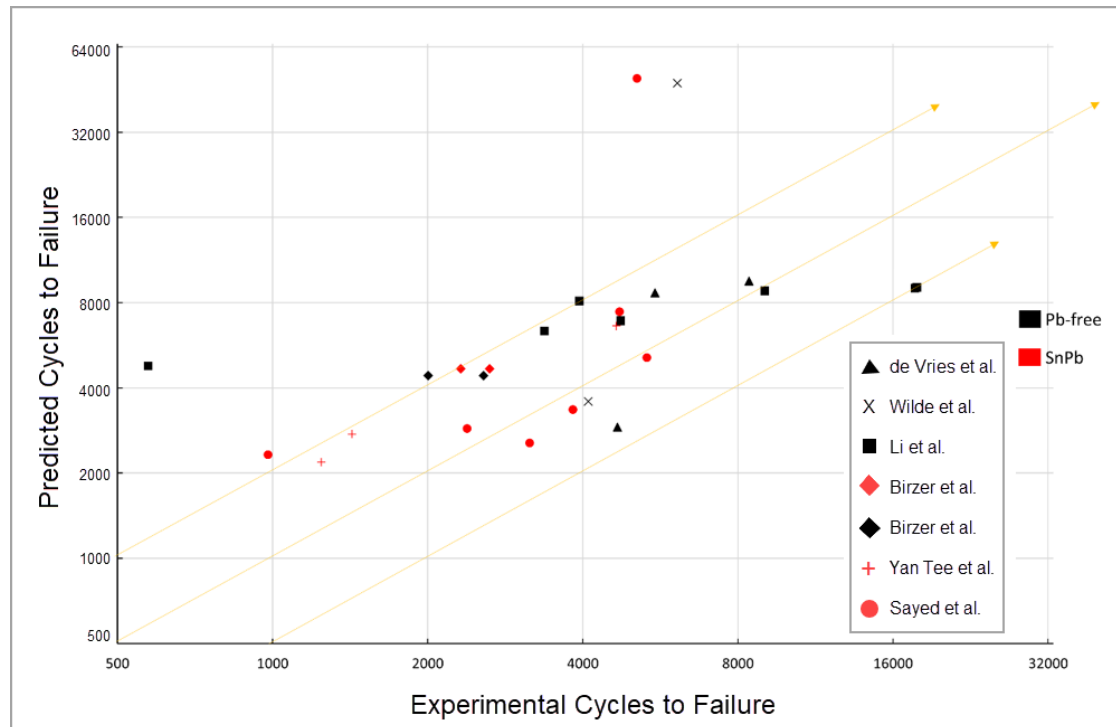
Solder fatigue life predictions are sensitive to the reflowed solder joint height. QFN components can have large variation in solder joint height due to thermal pad solder mask layout, stencil type &

thickness, pick and place operation and reflow profile settings. Ansys recommends using known solder joint height for input parameters based on cross-sectional information.

Table 2.1: Sample material properties illustrated in model example

	CTE (ppm)	Modulus (GPa)	Poisson's ratio
Ceramic	6.8	241	0.195
Die	2.6	120	0.22
PCB	17	27	0.18
SAC305	28.2	Figure 2.22: Elastic modulus as function of temperature for SAC305 and 63Sn37Pb solder alloys (p. 28)	0.3
63Sn37Pb	21.6		0.3

Figure 2.26: QFN model validation, data extracted from key sources



As indicated in the graph, there are a few outliers. These discrepancies are likely driven by thinner solder joints or voids and defects in the solder joint. The low CTE mismatch between the overmold and the PCB lends to a higher predicted fatigue life than what is shown in the experimental result. This logic is described in the Engelmaier theory and can be reviewed in *An Engelmaier Model for Leadless Ceramic Chip Devices with Pb-free Solder*.

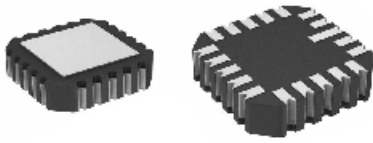
2.3.3. References (QFN Package)

1. Birzer, C., Stoeckl, S., Schuetz, G., & Fink, M. (2006). *Reliability Investigations of Leadless QFN Packages until End-of-Life with Application-Specific Board-Level Stress Tests*. 56th Electronics Components and Technology Conference, San Diego, CA, USA.
2. Chen, W. T. & Nelson, C.W. (1979) Thermal stress in bonded joints. *IBM Journal of Research and Development* 23(2), 179-188.
3. De Vries, J., Jansen, M., & van Driel, W. (2009). Solder-joint reliability of HVQFN-packages subjected to thermal cycling. *Microelectronics Reliability*, 49(3), 331-339.
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8. Tseng, A., Lin, M., Hu, B., & Chen, J.W. (December 2010). *Advanced QFN surface mount application notes development*. Electronics Packaging Technology Conference (EPTC), 12th.
9. Vandeveld, B., Gonzalez, M., Limaye, P., Ratchev, P., & Beyne, E. (2007). Thermal cycling reliability of SnAgCu and SnPb solder joints: a comparison for several IC-packages. *Microelectronics Reliability*, 47(2), 259-265.
10. Vianco, P. & Neilsen, M. K. (2015). *Thermal mechanical fatigue of a 56 I/O plastic quad-flat nolead (PQFN) package*. SMTA International Conference.
11. Wilde, J. & Zukowski, E. (2007, May). *Comparative Analysis for μ BGA and QFN Reliability*. 8th. International Conference on Thermal, Mechanical and Multiphysics Simulation and Experiments in Micro-Electronics and Micro-Systems.

2.4. Leadless Ceramic Chip Carrier (LCCC)

This section explains the theory behind Sherlock's calculations when performing a failure analysis of an LCCC device (Leadless Ceramic Chip Carrier). The LCCC is a surface mount ceramic package that has no leads but, instead, has flat metal contacts, or pads. Because these pads are susceptible to large temperature differences, their solder joints are prone to cracking.

The LCCC package has a recess in its ceramic substrate where the silicon die is placed and is then sealed using a ceramic lid. Generally, its constituent material makes the package stiff and is attached to the PCB using solder. During thermal cycling, the solder joints connecting the ceramic chip carrier (or substrate) to the PCB tend to undergo cyclic strain, leading to reliability issues.



Sherlock uses a closed-form reliability model based on the strain energy density of the solder. It is an extension of the Engelmaier [5] formulation of maximum strain range of the solder joint. The fatigue model considers a simplified structural system that accounts for different stiffnesses of the structure to determine the stresses during the thermal cycle. These strain and stress results are then used to determine the strain energy of the solder joint. This theory guide considers only low-cycle fatigue (< 10,000 cycles).

Topics covered in this section:

[2.4.1. How does the Software Assess LCCC Solder Fatigue?](#)

[2.4.2. Input Parameters](#)

[2.4.3. LCCC/CC Solder Fatigue Model](#)

[2.4.4. Validation Data](#)

[2.4.5. References \(LCCC\)](#)

2.4.1. How does the Software Assess LCCC Solder Fatigue?

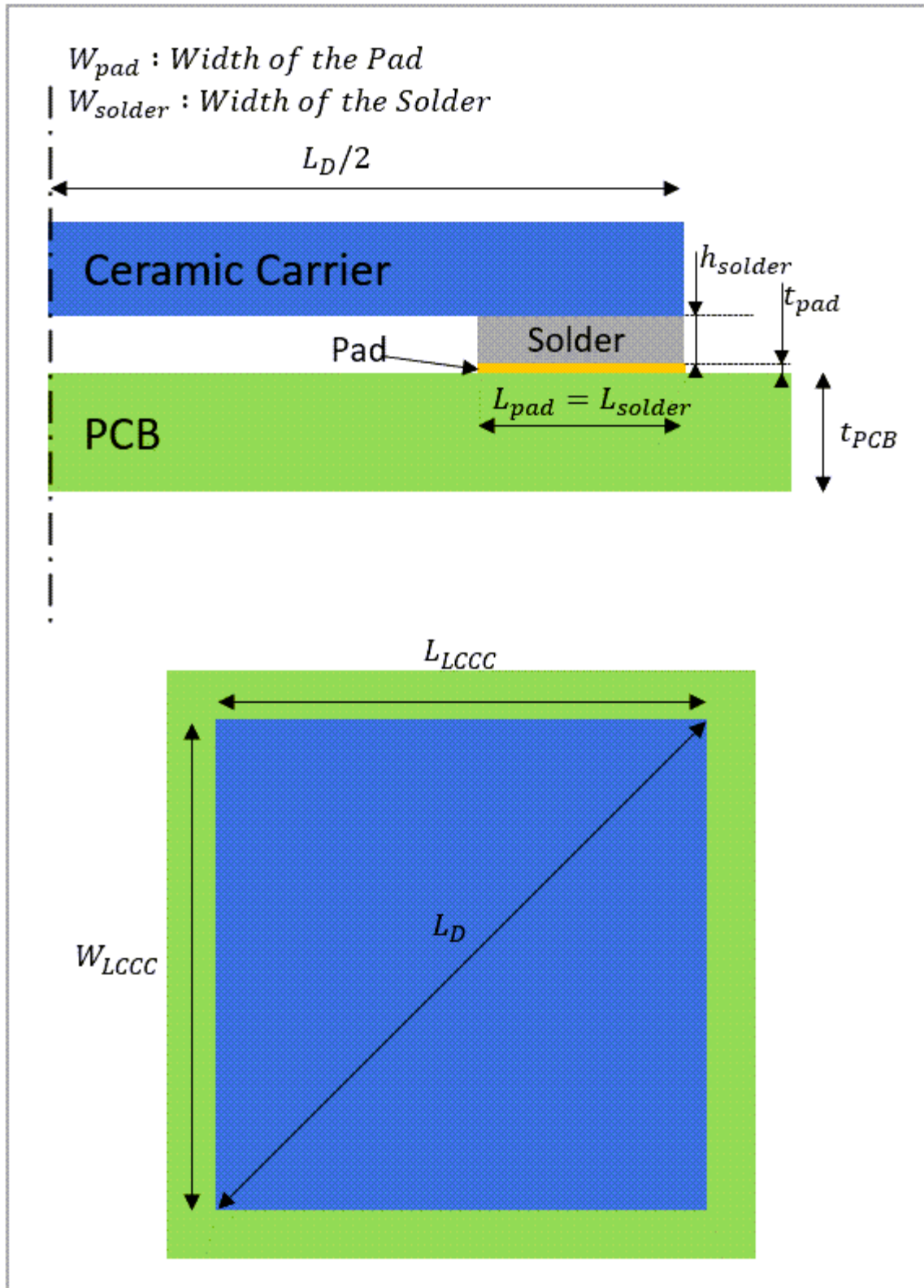
In general, an LCCC package attached to the board can be represented by a combination of axial and shear springs. Sherlock uses the following spring stiffness values to represent an LCCC package:

- PCB axial stiffness: K_{PCB}
- PCB-bond pad interface stiffness: $K_{\text{PCB-bond pad}} = K_{\text{foundation}}$
- Bond-pad shear stiffness: $K_{\text{copper pad}}$
- Solder shear stiffness: K_{solder}
- Component axial stiffness: $K_{\text{comp}} (K_{\text{CC}} \text{ or } K_{\text{LCCC}})$

Sherlock computes each of the above stiffness values based on the geometry and material used. It then determines the solder's stress and strain value based on displacement compatibility. This approach is based on the following principle: Under a given thermal profile, the axial displacement in a structure (in this case, determined by the CTE mismatch between the package and the PCB) is the same as it would be when determined through the effective stiffness of the structure.

Inelastic strain energy (ΔW) is then calculated to determine solder fatigue life (N_f). Due to the structures of the component and substrate (or PCB), axial and shear deformation will be dominant. For this reason, Sherlock can safely ignore the deformation and corresponding strain caused by bending. The figure below shows the simplified structure that explains all the stiffness elements in the actual package.

Figure 2.27: LCCC Structure Example



2.4.2. Input Parameters

The analytical model for BGA fatigue prediction during thermal cycling uses the following inputs:

- 2.4.2.1. Thermal Parameters
- 2.4.2.2. Package Parameters
- 2.4.2.3. Solder Pad Parameters
- 2.4.2.4. Solder Joint Parameters
- 2.4.2.5. PCB Parameters

A brief explanation of each parameter is provided in this section. For more details, refer to [Solder Fatigue Analysis in the Sherlock User's Guide](#).

2.4.2.1. Thermal Parameters

In Sherlock, you can create a Thermal Profile using the **Thermal Profile Editor** (see [Project Life Cycles in the Sherlock User's Guide](#) for details). An example of a Thermal Profile is shown in the image below, depicting a thermal cycle between a $T_{\min}$ of 10°C and $T_{\max}$ of 65°C. From the thermal cycle, Sherlock calculates the mean temperature and the changes in temperature according to the equations below.

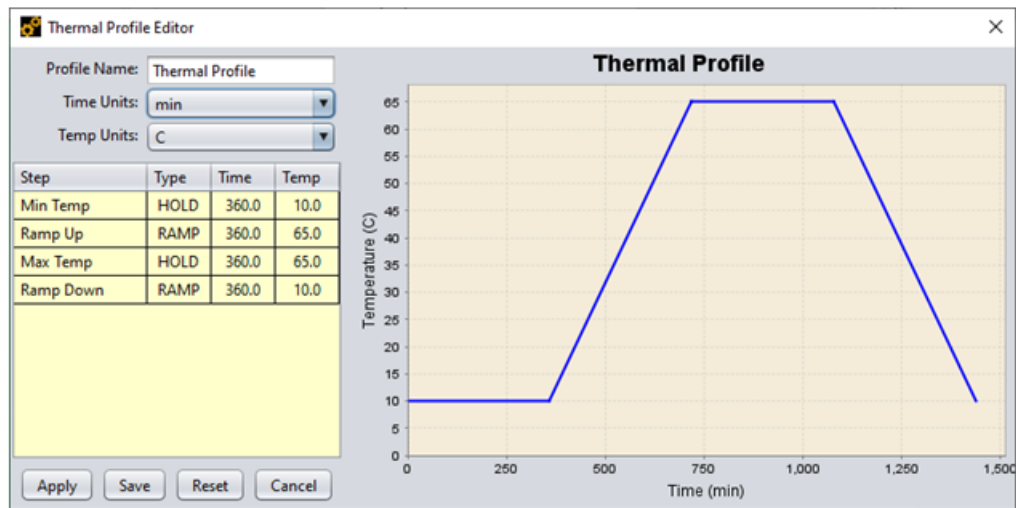
$$T_{\text{mean}} = \frac{(T_{\text{max}} + T_{\text{min}})}{2}$$
$$\Delta T_{\text{hot}} = T_{\text{max}} - T_{\text{mean}}$$
$$\Delta T_{\text{cold}} = T_{\text{mean}} - T_{\text{min}}$$

Mean temperature

Change in temperature

Change in temperature

Figure 2.28: Thermal Profile Example



2.4.2.2. Package Parameters

The package parameters are specified within the **Part Properties** dialog, under the **Package** tab as shown below. Sherlock uses the length, width, and thickness of the component, in conjunction

with other properties, to calculate the area of the laminate and the half-diagonal length of the package.

Figure 2.29: LCCC Package Properties

Package Name:	LCCC-44
Package Type:	LCCC
Package Mount:	SMT
Package Units:	MM
Package Length:	16.51
Package Width:	16.51
Package Thickness:	1.75
Overmold Thickness:	
Laminate Thickness:	
Model Part:	ENABLED
Corner Shape:	SQUARE
Corner Radius:	0
Corner Face:	
Material:	ALUMINA
Overmold Material:	
Junction Res (C/W):	
Weight (gram):	1.7411

L_{comp}	Length of the component
W_{comp}	Width of the component
E_{comp}	Elastic modulus of the component
CTE_{comp}	Coefficient of thermal expansion of the component
$\frac{L_D}{2}$	Half the diagonal length of the component
$\frac{L_D}{2} = 0.5 \times \sqrt{(L_{\text{comp}})^2 + (W_{\text{comp}})^2}$	

Sherlock uses the dimensions of the component to calculate component stiffness (K_{comp}). For the leadless chip carrier component, axial expansion is considered to happen along the diagonal length. In contrast, due to the nature of its construction, the *leaded* ceramic chip component will expand along its length rather than its diagonal length, contrary to what is shown in [Figure 2.27: LCCC Structure Example](#) (p. 37).

Note:

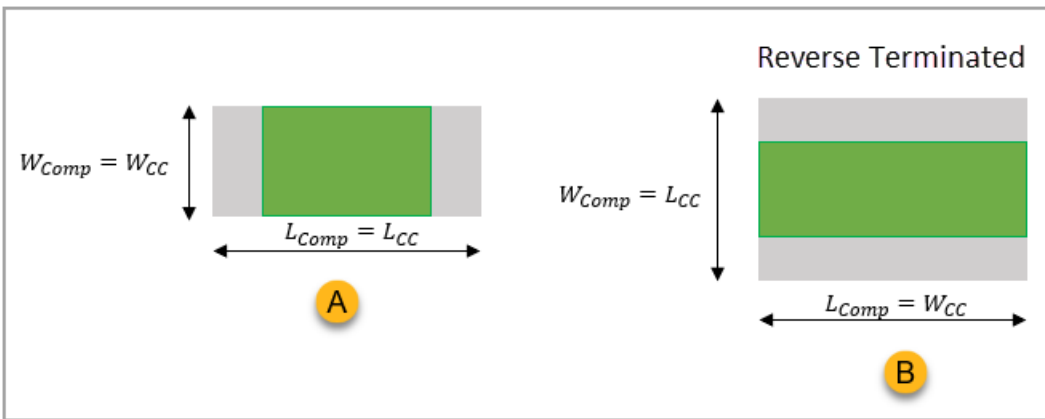
Versions of Sherlock prior to 2022 R1 use package length instead of half-diagonal length for the component stiffness calculation. The difference will not change life predictions

significantly (less than ten cycles' difference) as package length is less sensitive to component stiffness.

Note:

The Sherlock application does not support reverse terminated CC components. See B in [Figure 2.30 \(p. 40\)](#) below for an example of a reverse terminated component: The length and width of the component are reversed, so the termination is along the longer side of the component which increases axial stiffness. Fatigue life for reverse terminated components is usually higher (close to two times higher) than its regular counterpart. Decreasing the length of the chip component (L_{CC}) increases fatigue life. Support for reverse terminate components will be available in a future release of the Sherlock application.

Figure 2.30: CC Component Structures



2.4.2.3. Solder Pad Parameters

As shown in [Figure 2.27: LCCC Structure Example \(p. 37\)](#), solder pads are assumed to have the same length and width of the solder joint itself. The pad parameters are shown here:

L_{pad}	Length of the solder pad
W_{pad}	Width of the solder pad

2.4.2.4. Solder Joint Parameters

The solder joint parameters are specified under the **Solder** tab of the **Part Properties** dialog. Here you can also select the **Solder Model**. The figure below shows the dropdown option for the LCCC (A) and CC (B) models. Sherlock uses the same calculation for both. The only difference between the two solder fatigue models is the length used for computing the component axial stiffness K_{comp} . The solder area (A_{solder}) is calculated by adjusting the length and width of the solder pad using calibration factors C_1 and C_2 . The two calibration factors, along with calibration factor C_3 used for adjusting the strain energy, improve the correlation of predicted life results between Sherlock and the experimental results found in the literature.

Figure 2.31: Solder Part Properties, Example

The figure displays two examples of the Solder Part Properties dialog box. Both examples show a sidebar with tabs for ID, Package, Location, Lead, Pad, Solder, Electrical, Thermal, Die, Flag, Test, and Semiconductor Wearout. The main area contains fields for Solder Material (DEFAULT), Stencil Units (MM), Solder Thickness (0.0635), and Solder Model. In the top example (A), the Solder Model is set to LCCC MODEL. In the bottom example (B), the Solder Model is set to CC MODEL.

$$L_{\text{solder}} = C_1 \times L_{\text{pad}}$$

$$W_{\text{solder}} = C_2 \times W_{\text{pad}}$$

$$h_{\text{solder}} = t_{\text{solder}}$$

$$A_{\text{solder}} = L_{\text{solder}} \times W_{\text{solder}}$$

$$E_{\text{solder}}$$

$$G_{\text{solder}} = \frac{E_{\text{solder}}}{2 \times (1 + 0.36)}$$

Length of solder joint

Width of solder joint

Height of solder joint

Area of solder joint

Elastic modulus of solder

Shear modulus of solder

2.4.2.5. PCB Parameters

The PCB properties used in the solder fatigue analysis are extracted from the stackup properties. Sherlock computes the effective stackup properties based on the rule of mixtures. An example of a stackup in Sherlock is shown below.

Figure 2.32: Stackup Properties in Sherlock

The screenshot shows the Sherlock software interface. The top bar has tabs for 'Main Board Parts List' and 'Main Board Stackup'. Below the tabs is a toolbar with various icons. The main window is titled 'Stackup Properties' and contains a text box stating: 'The following board properties are based on the currently defined board outline and the individual layer properties shown below:'. Below this text box is a table of properties:

Board Dimension:	191 x 115 mm [7.5 x 4.5 in]	CTExy:	17.779 ppm/C	Board Weight:	87.29 grams
Board Thickness:	2.098 mm [82.6 mil]	CTEz:	68.514 ppm/C	Total Part Weight:	139.8 grams
Density:	1.9217 g/cc	Exy:	23,800 MPa	Mount Point Weight:	0 grams
Conductor Layers:	6	Ez:	3,593 MPa	Fixture Weight:	4.37 grams

Below the properties table is a section titled 'Stackup Layers'. It contains a text box with instructions: 'Double-click any row to edit the properties for that layer or select one or more rows and press the Edit button above to edit properties for the selected layers. Use the Generate Stackup button to replace all layers using a given PCB thickness and default layer properties.' Below the text box is a table of stackup layers:

Layer	Type	Material	Construction	Thickness	Density	CTExy	CTEz	Exy	Ez
1	SIGNAL	COPPER (14.9%) / COPPER-RESIN		0.5 oz	2.8579	45.172	45.172	19,816	19,816
2	Laminate	Generic FR-4	DEFAULT (2116)	15.4 mil	1.9000	17.000	70.000	24,804	3,450
3	POWER	COPPER (4.9%) / COPPER-RESIN		1.0 oz	2.1479	48.412	48.412	8,866	8,866
4	Laminate	Generic FR-4	DEFAULT (2116)	15.4 mil	1.9000	17.000	70.000	24,804	3,450
5	SIGNAL	COPPER (1.6%) / COPPER-RESIN		0.5 oz	1.9136	49.482	49.482	5,252	5,252
6	Laminate	Generic FR-4	DEFAULT (2116)	15.4 mil	1.9000	17.000	70.000	24,804	3,450
7	SIGNAL	COPPER (1.5%) / COPPER-RESIN		0.5 oz	1.9065	49.514	49.514	5,142	5,142
8	Laminate	Generic FR-4	DEFAULT (2116)	15.4 mil	1.9000	17.000	70.000	24,804	3,450
9	POWER	COPPER (4.9%) / COPPER-RESIN		1.0 oz	2.1479	48.412	48.412	8,866	8,866
10	Laminate	Generic FR-4	DEFAULT (2116)	15.4 mil	1.9000	17.000	70.000	24,804	3,450
11	SIGNAL	COPPER (9.8%) / COPPER-RESIN		0.5 oz	2.4958	46.825	46.825	14,231	14,231

 E_{PCB}

Modulus for the PCB

 ν_{PCB}

Poisson's ratio for the PCB

 t_{PCB}

Thickness for the PCB

Shear modulus for the PCB

$$G_{PCB} = \frac{E_{PCB}}{2 \times (1 + 0.18)}$$

 CTE_{PCB}

Coefficient of thermal expansion for the PCB

Note:

In Sherlock, in-plane CTE_{xy} and Young's modulus E_{xy} are used for CTE_{PCB} and E_{PCB} respectively. $\nu_{PCB} = 0.3$ is also used for all calculations.

2.4.3. LCCC/CC Solder Fatigue Model

For a given thermal profile, the strain energy (ΔW) applied to the solder is calculated for both ΔT_{hot} and ΔT_{cold} . Assuming the total axial displacement of the structure due to its temperature change (for ΔT_{hot}) is $U_{\Delta T_{hot}}^{total}$, the total axial displacement can be written as

$$U_{\Delta T_{max}}^{total} = \text{abs}(CTE_{comp} - CTE_{PCB}) \cdot \Delta T_{hot} \cdot \frac{L_D}{2} \quad (2.77)$$

Due to the difference in their CTE, the ceramic component does not expand as much as the PCB at higher temperatures, thereby straining the solder. Assuming that F is the differential force generated due to the difference in CTE, then the displacement due to the force should also be equal to $U_{\Delta T_{hot}}^{total}$.

$$U_{\Delta T_{\max}}^{\text{total}} = F / K_{\Delta T_{\text{hot}}}^{\text{combined}} \quad (2.78)$$

In the equation above, K_{combined} is the effective stiffness of the structure. With reference to [Figure 2.27: LCCC Structure Example \(p. 37\)](#), the effective stiffness can be calculated as a series combination as shown here:

$$K_{\Delta T_{\text{hot}}}^{\text{combined}} = \left(\frac{1}{K_{\text{PCB}}} + \frac{1}{K_{\text{foundation}}} + \frac{1}{K_{\text{copper pad}}} + \frac{1}{K_{\text{solder}}} + \frac{1}{K_{\text{comp}}} \right)^{-1} \quad (2.79)$$

$$K_{\Delta T_{\text{hot}}}^{\text{combined}} = \left(\frac{1}{\frac{2E_{\text{PCB}}A_{\text{PCB}}}{L_{\text{comp}}}} + \frac{1}{\frac{9G_{\text{PCB}}\frac{W_{\text{pad}}}{2}}{2 \cdot V_{\text{PCB}}}} + \frac{1}{\frac{G_{\text{pad}}A_{\text{pad}}}{t_{\text{pad}}}} + \frac{1}{\frac{G_{\text{solder}}^{\text{solder}}A_{\text{solder}}}{h_{\text{solder}}}} + \frac{1}{\frac{E_{\text{comp}}A_{\text{comp}}}{L_{\text{comp}}}} \right)^{-1} \quad (2.80)$$

In the equation above, $K_{\text{foundation}}$ represents the shear stiffness of a rigid pad on a half-space. Due to the size of the copper pad and the PCB, the pad is a relatively stiff material on an elastic foundation. Sherlock assumes that the PCB width is at least twice the width of the pad. The effect of the PCB surrounding the package is taken into consideration by adjusting the PCB stiffness. All the other stiffness parameters in the equation above are self-explanatory. From the combined stiffness, the elastic portion of the stress and strain are determined by the following two equations:

$$\sigma_{\Delta T_{\text{hot}}}^e = \frac{F}{A_{\text{solder}}} = \frac{K_{\Delta T_{\text{hot}}}^{\text{combined}} U_{\Delta T_{\text{hot}}}^{\text{total}}}{L_{\text{solder}} W_{\text{solder}}} \quad (2.81)$$

$$\varepsilon_{T_{\text{hot}}}^e = \frac{\sigma_{\Delta T_{\text{hot}}}^e}{G_{T_{\text{hot}}}^{\text{solder}}} \quad (2.82)$$

The total strain is given by [Equation 2.83 \(p. 43\)](#). Therefore, the plastic strain is given by [Equation 2.84 \(p. 43\)](#).

$$\varepsilon_{T_{\text{hot}}}^t = \frac{U_{\text{total}}}{h_{\text{solder}}} = \varepsilon_{T_{\text{hot}}}^e + \varepsilon_{T_{\text{hot}}}^p \quad (2.83)$$

$$\varepsilon_{T_{\text{hot}}}^p = \varepsilon_{T_{\text{hot}}}^t - \varepsilon_{T_{\text{hot}}}^e \quad (2.84)$$

Then, the inelastic (plastic) strain and Engelmaier equation are used to correct the maximum strain for viscoplastic creep effects. The corrected maximum strain range is shown below:

$$\varepsilon_{\Delta T_{\text{hot}}}^{\max} = \varepsilon_{T_{\text{hot}}}^p \cdot \left(\frac{t_{\text{dwell-max}}}{t_{\text{critical}}} \right)^{0.136} e^{E_a \left(\frac{1}{T_{\text{critical}}} - \frac{1}{T_{\max} + 273.15} \right)} \quad (2.85)$$

The procedure above applies to $\Delta T = \Delta T_{\text{hot}}$. The same procedure can be used to determine $\varepsilon_{\Delta T_{\text{cold}}}^{\max}$. Finally, Sherlock calculates the inelastic strain energy for the temperature range $(T_{\max}, T_{\min})$, as shown in the equation below:

$$\Delta W = \varepsilon_{\Delta T_{\text{hot}}}^{\max} \cdot \sigma_{\Delta T_{\text{hot}}}^e + \varepsilon_{\Delta T_{\text{cold}}}^{\max} \cdot \sigma_{\Delta T_{\text{cold}}}^e \quad (2.86)$$

Fatigue life (N_f) is computed from the strain energy and incorporates the calibration factor C_3 . Sherlock's model for SnPb solder is shown here:

$$N_f = (SE_{\text{coeff}} \cdot C_3 \cdot \Delta W)^{-1} \quad (2.87)$$

As explained earlier in [Solder Joint Parameters \(p. 40\)](#), Sherlock uses the calibration factor C_3 . This improves the correlation between Sherlock's results (predicted fatigue life and cycles to failure) and results obtained from experimental results and solder fatigue literature. In the above solder fatigue model, the critical dwell time t_{critical} , activation energy E_a , critical max temperature T_{critical} , and strain

energy coefficient SE_{coeff} are solder dependent. In Sherlock, you can adjust these properties in the **Low-Cycle Fatigue** tab found in the **Solder Editor** (see the image below). You can also edit the **Calibration Factor** from the same tab. The default CC Calibration is as shown below in Table 2.2: Calibration Factors Used since Sherlock 2023R2 (p. 44).

Figure 2.33: Solder Editor, Example

Solder Editor - SAC305

Modify the solder properties as needed and press the **Save** button to update the Solder Library.

Low-Cycle Fatigue

Critical Dwell Time: 360.0 min

Activation Energy (Ea): 2185.0

Critical Max Tem...: 378.0

Strain Energy Coefficient: 0.001

CC Calibration Fact...: 1:0.0:0.5; 1:3.2:0.5; 2:0.0:1.0; 2:3.2:1.0; 3:0

Leaded Calibration Factor: 2.0

Thermal Shock Factor C...: 15, 1.0 | 30, 1.25 | 60, 1.5

Thermal Shock Factor BG...: 15, 1.0 | 30, 1.25 | 60, 1.5

Thermal Shock Factor LC...: 15, 1.0 | 30, 1.25 | 60, 1.5

Thermal Shock Factor Leaded: 15, 1.0 | 30, 1.25 | 60, 1.5

Thermal Shock Factor QF...: 15, 1.0 | 30, 1.25 | 60, 1.5

Thermal Shock Factor ThruHo...: 15, 1.0 | 30, 1.25 | 60, 1.5

Thermal Shock Factor Default: 15, 1.0 | 30, 1.25 | 60, 1.5

Weibull Beta BGA: 3.0

Weibull Beta CBGA: 3.0

Weibull Beta CC: 3.0

Weibull Beta LCC...: 3.0

Weibull Beta Leaded: 3.0

Weibull Beta QFN: 3.0

Weibull Beta ThruHole: 3.0

Prev SAC305 Next

Save Reset Cancel

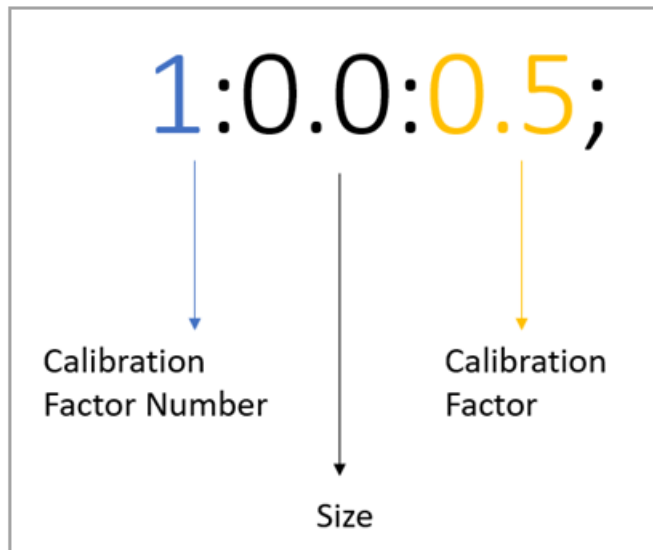
Table 2.2: Calibration Factors Used since Sherlock 2023R2

Material	Size (mm)	C1	C2	Size	C3
63Sn37Pb	0 to 3.2	0.5	1.0	0 to 3.2	1.0
	>3.2	0.5	1.0	3.2 to 5	Linear interpolation between 1.0 and 1.5
				>5	1.5
Pb90Sn10	0 to 3.2	0.5	1.0	0 to 3.2	1

	>3.2	0.5	1.0	3.2 to 5	Linear interpolation between 1.0 and 1.5
				>5	1.5
	0 to 3.2	0.5	1.0	0 to 3.2	1.0
SAC305	>3.2	0.5	1.0	3.2 to 5	Linear interpolation between 1.0 and 1.5
				>5	1.5
	0 to 3.2	0.5	1	0 to 3.2	1
SENJU M794	>3.2	0.5	1	3.2 to 5	Linear interpolation between 1.0 and 1.5
				>5	1.5
	0 to 3.2	0.5	1.0	0 to 3.2	1.0
SN100C	>3.2	0.5	1.0	3.2 to 5	Linear interpolation between 1.0 and 1.5
				>5	1.5

For example, the CC factors for SAC305 are displayed in Sherlock as:

1:0.0:0.5; 1:3.2:0.5; 2:0.0:1.0; 2:3.2:1.0; 3:0.0:1.0; 3:5.0:1.5; interpolate(3:3.2:1.0, 3:5.0:1.5, 0.1)



1: 0.0:0.5;

1: 3.2:0.5;

2: 0.0:1.0;

2: 3.2:1.0;

3: 0.0:1.0;

3: 5.0:1.5

3: interpolate(3:3.2:1.0, 3:5.0:1.5, 0.1)

For Size > 0, C1 = 0.5

For Size > 3.2, C1 = 0.5

For Size > 0, C2 = 1

For Size > 3.2, C2 = 1

For Size > 0, C3 = 1

For Size > 5, C3 = 1.5

For 5 > Size > 3.2, C3 = linearly interpolated. (The 0.1 is a placeholder. Starting with Sherlock 2024

R1, linear interpolation does not require any increments.)

2.4.4. Validation Data

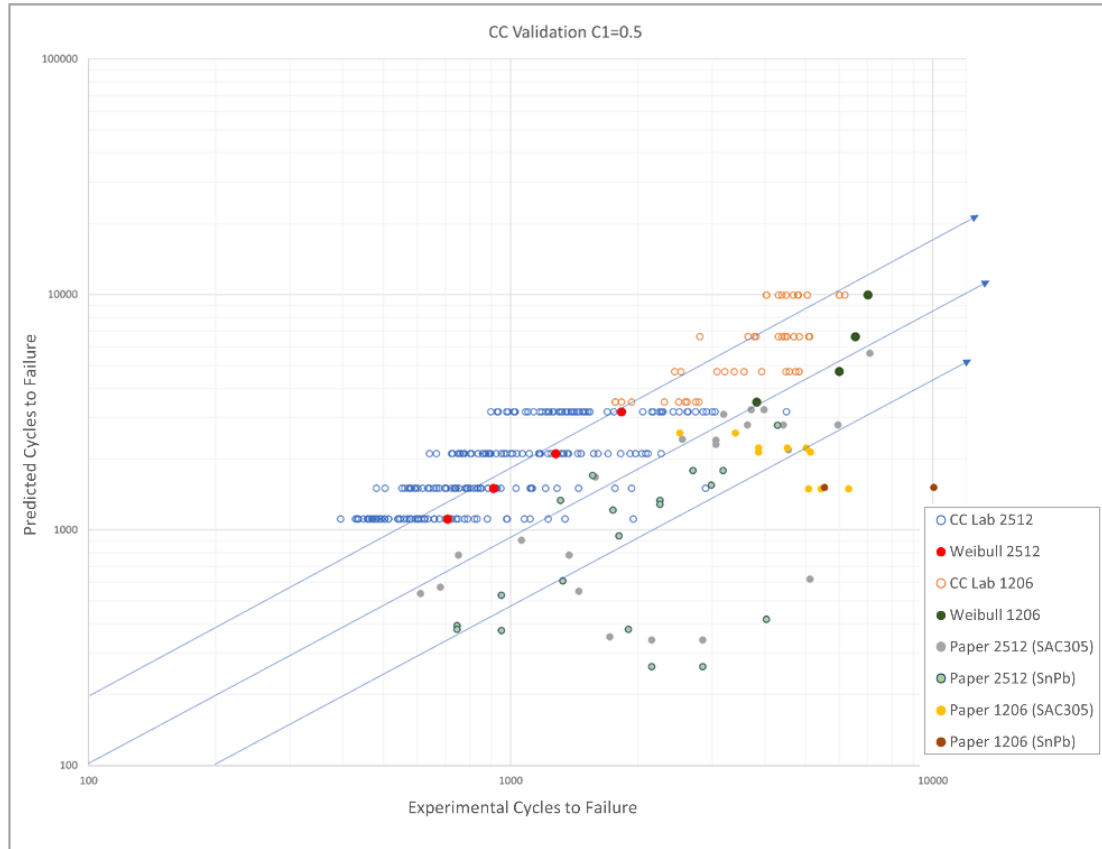
To validate the output of this module, Ansys conducted a literature review of temperature cycling data for a variety of ceramic chip packages (CC). It is important to note that the validation was done by extracting experimental datapoints from published literature. However, the literature contains a wide spread of data, and using it requires inferring some key package parameters. For those reasons, Ansys decided to conduct its own in-house thermal cycling on two common chip resistors: the 2512 and 1206. Packages were soldered to a printed board using SAC305 solder.

Thermo-mechanical fatigue predictions for these configurations were then generated by Sherlock and compared to experimental data. The results are displayed in the tables below. Despite some assumptions regarding test parameters of published literature results (such as board properties, for example), the software proved highly accurate, with the majority of predictions within the 2X boundaries defined in the figures below.

In Sherlock version 2023 R1, the CC factor C1 was changed to a default value of 0.5 based on the results of our controlled in-house thermal cycling. Ansys found that a C1 factor of 0.5 best represents the in-house and literature data. Previous versions had a default of $C1 = 1$. Validation was conducted with both C1 factors as shown below. While the software defaults to a recommended C1 factor of 0.5, any C1 factor between 0.5 and 1 can be used.

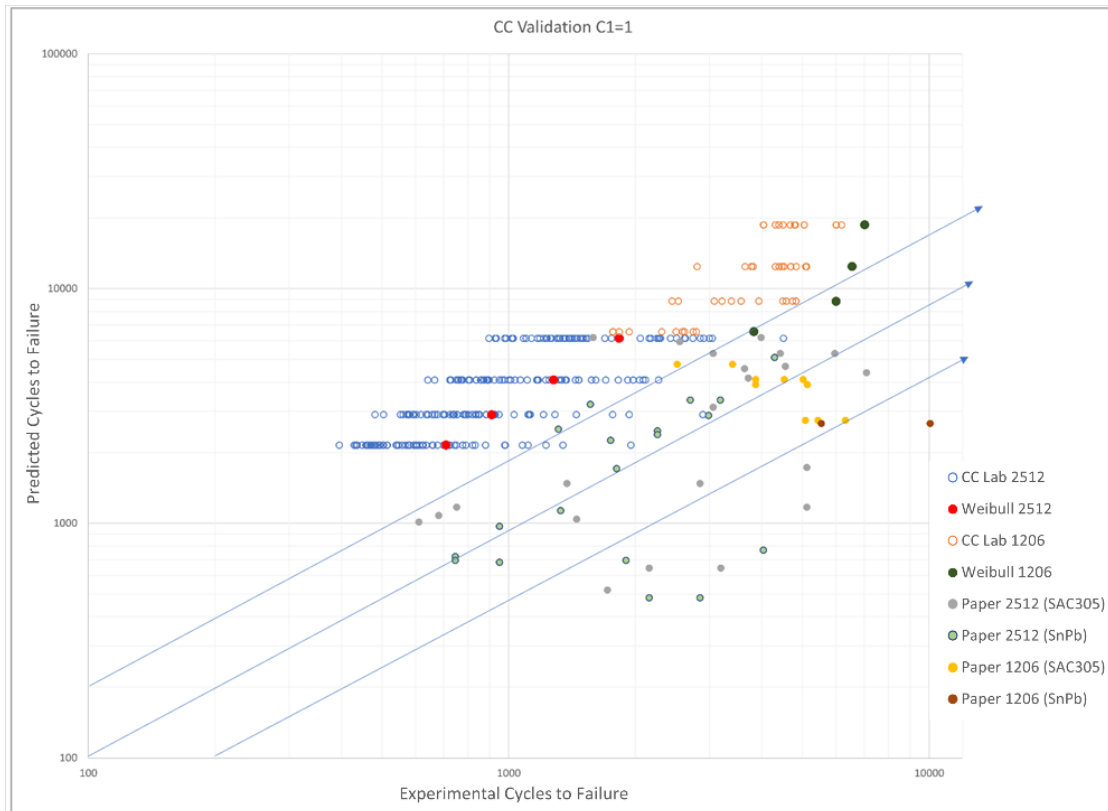
Below, the data sources shown in [Figure 2.34: CC Model Validation C1 = 0.5 \(p. 47\)](#) are defined:

- **CC Lab 2512:** In-house thermal cycling datapoints for 2512 chip resistors
- **Weibull 2512:** In-house thermal cycling characteristic life for 2512 chip resistors
- **CC Lab 1206:** In-house thermal cycling datapoints for 1206 chip resistors
- **Weibull 1206:** In-house thermal cycling characteristic life for 1206 chip resistors
- **Paper 2512 (SAC305):** Experimental datapoints from published literature for 2512 chip resistors with SAC305 solder
- **Paper 2512 (SnPb):** Experimental datapoints from published literature for 2512 chip resistors with SnPb solder
- **Paper 1206 (SAC305):** Experimental datapoints from published literature for 1206 chip resistors with SAC305 solder
- **Paper 1206 (SnPb):** Experimental datapoints from published literature for 1206 chip resistors with SnPb solder

Figure 2.34: CC Model Validation C1 = 0.5

Definition of data sources for [Figure 2.35: CC Model Validation C1 = 1 \(p. 48\)](#):

- **CC Lab 2512:** In-house thermal cycling datapoints for 2512 chip resistors
- **Weibull 2512:** In-house thermal cycling characteristic life for 2512 chip resistors
- **CC Lab 1206:** In-house thermal cycling datapoints for 1206 chip resistors
- **Weibull 1206:** In-house thermal cycling characteristic life for 1206 chip resistors
- **Paper 2512 (SAC305):** Experimental datapoints from published literature for 2512 chip resistors with SAC305 solder
- **Paper 2512 (SnPb):** Experimental datapoints from published literature for 2512 chip resistors with SnPb solder
- **Paper 1206 (SAC305):** Experimental datapoints from published literature for 1206 chip resistors with SAC305 solder
- **Paper 1206 (SnPb):** Experimental datapoints from published literature for 1206 chip resistors with SnPb solder

Figure 2.35: CC Model Validation C1 = 1

Anslys' In-House Thermal Cycling

Eight circuit boards were used for Ansys' series of in-house tests. Each board contained forty 2512s and forty 1206s. A total of 59 2512s, 59 1206s, and one thermocouple were monitored on a datalogger at four different temperature profiles with 15-minute dwell times. All chip resistors were soldered using SAC305. The thermal cycling concluded when >50% of each resistor-type failed. The failure criteria for a resistor was a >50% increase in resistance. For milder temperature profiles, time constraints made the >50% failure criteria impractical for the 1206 resistors, so testing was stopped at 6,348 cycles.

Thermal cycling temperature profiles:

- Condition 1: -40°C to 125°C
- Condition 2: -15°C to 125°C
- Condition 3: 10°C to 125°C
- Condition 4: 35°C to 125°C

Digital Image Correlation (DIC) and Dynamic Mechanical Analysis (DMA) were conducted to determine the CTE and the modulus of the boards. The results were 15.9 ppm and 23800 MPa respectively. The cycles-to-failure were collected, and the Weibull++ software application was used to determine characteristic life, which was then compared to Sherlock's generated results.

To visualize the data, the Weibull++ application was used to create an overlay plot. From left to right, condition 1, condition 2, condition 3, and condition 4 are displayed, as shown in figures [Figure 2.36 \(p. 49\)](#) and [Figure 2.37 \(p. 50\)](#). Because Sherlock uses a two-factor Weibull, Ansys analyzed the test data using a two-factor Weibull as well. As you can see, the data from each temperature condition behaves the same way. As the temperature difference decreases, the characteristic life increases.

Figure 2.36: Resistor 2512: Weibull++ for all temperature conditions

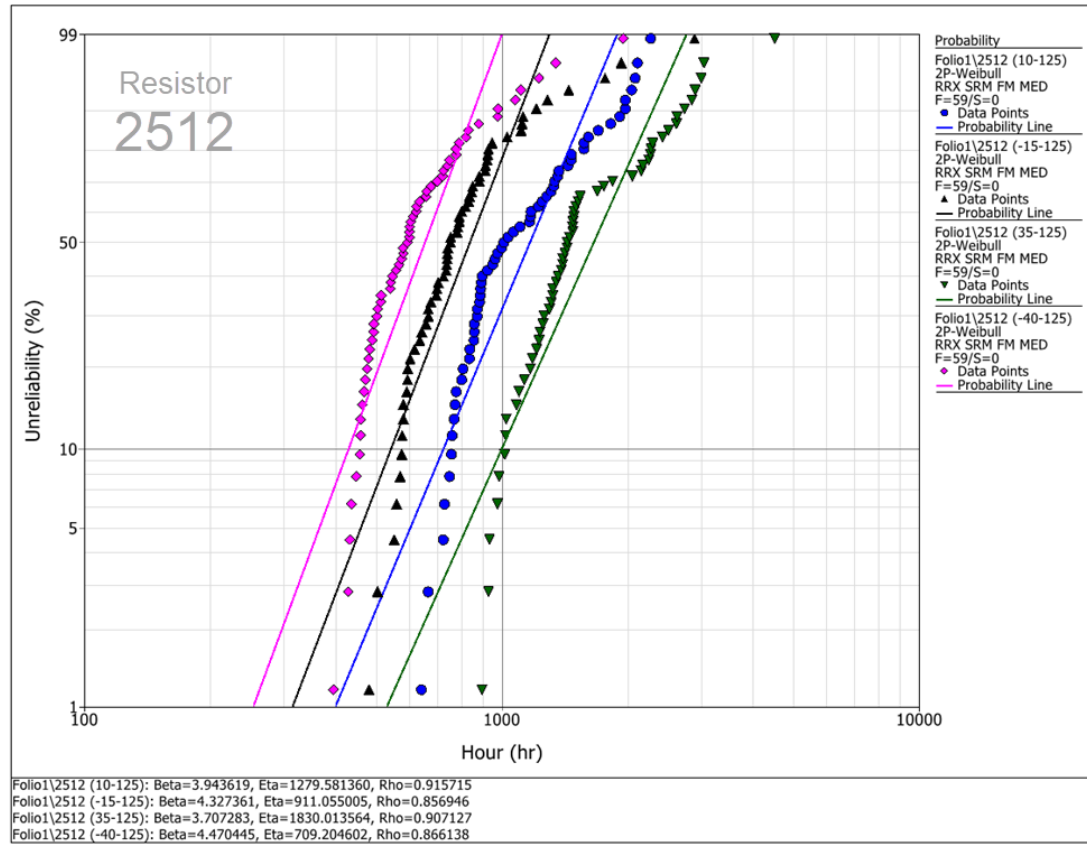
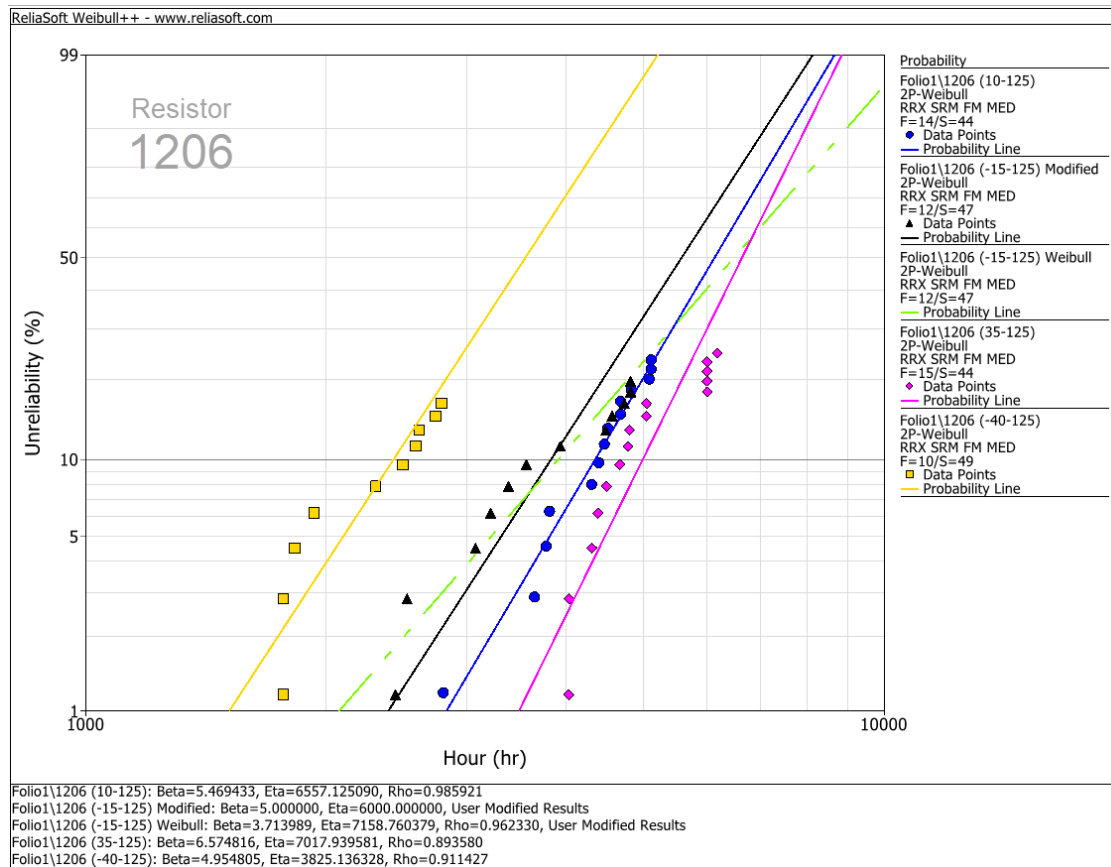


Figure 2.37: Resistor 1206 Weibull++ for all temperature conditions

Because the 1206s did not reach the expected failure criteria in the amount of time available, all obtained failure data was used. As such, the original result for Condition 2 (-15°C to 125°C) when generated in Weibull++ indicated that the characteristic life was 7,158 cycles. This is shown by the green dashed line. When analyzing the rest of the temperature conditions, it was evident that the result was likely skewed because of the low number of failures recorded. As such, a characteristic life of 6,000 cycles was deemed a better approximation and is represented by the solid black line.

Cross Sectional Images of Resistors

Figure 2.38: Cross section of 2512 resistor #26, left, 2.5x zoom

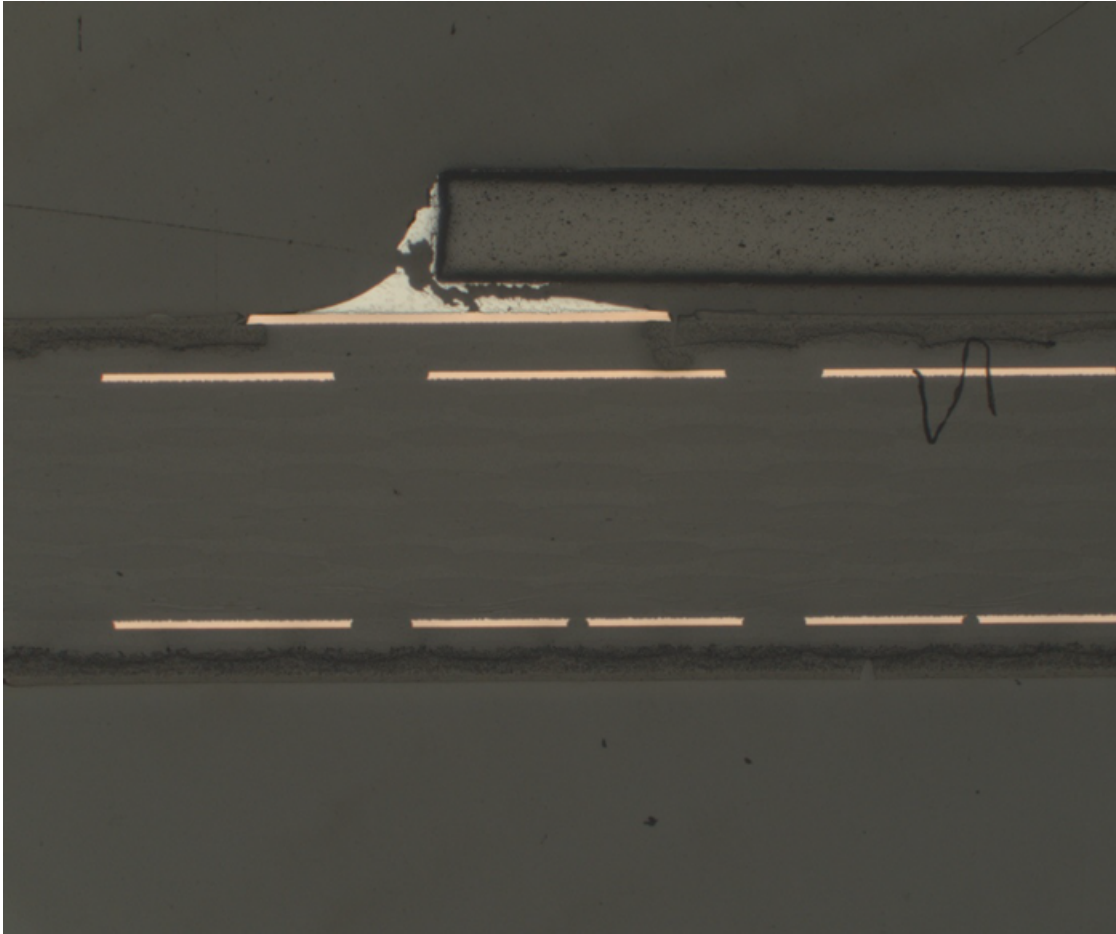


Figure 2.39: Cross section of 2512 resistor #26, right, 2.5x zoom

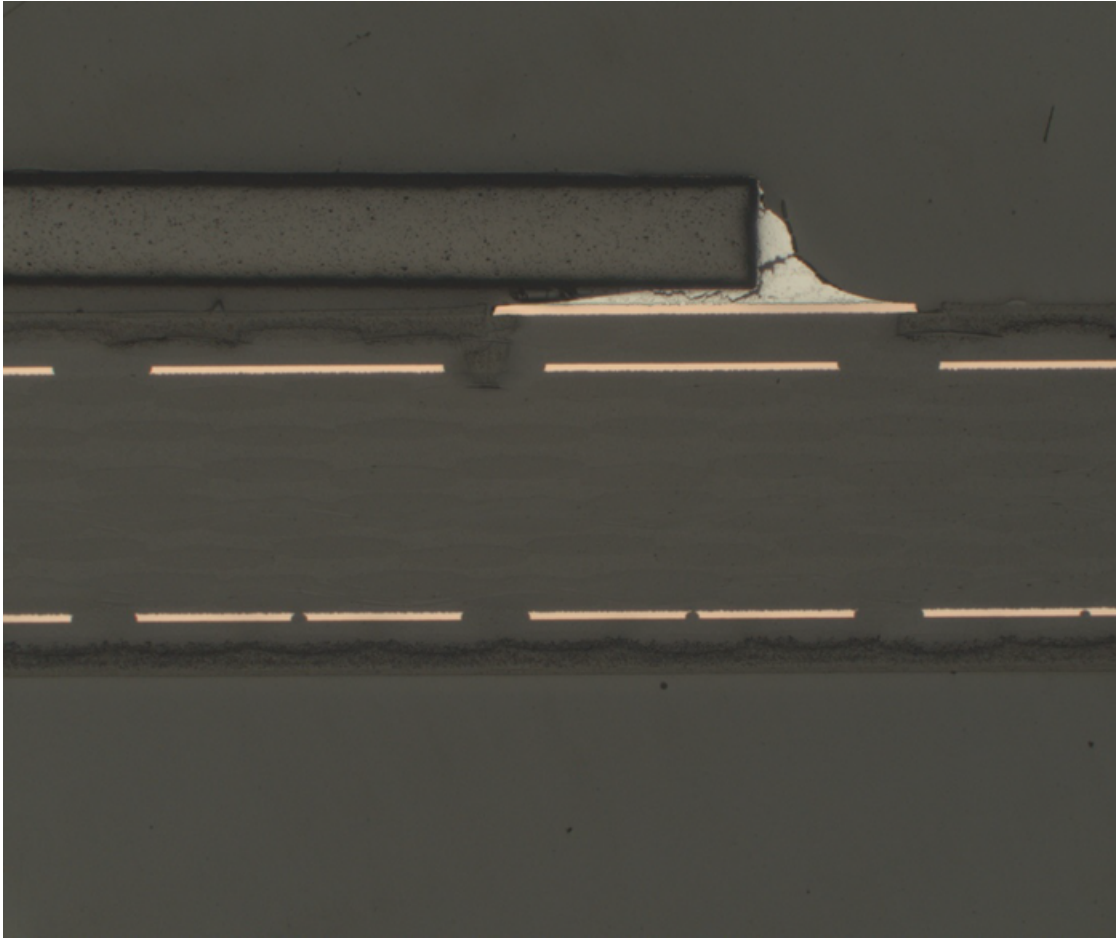


Figure 2.40: Cross section of 1206 resistor #54, left, 10x zoom

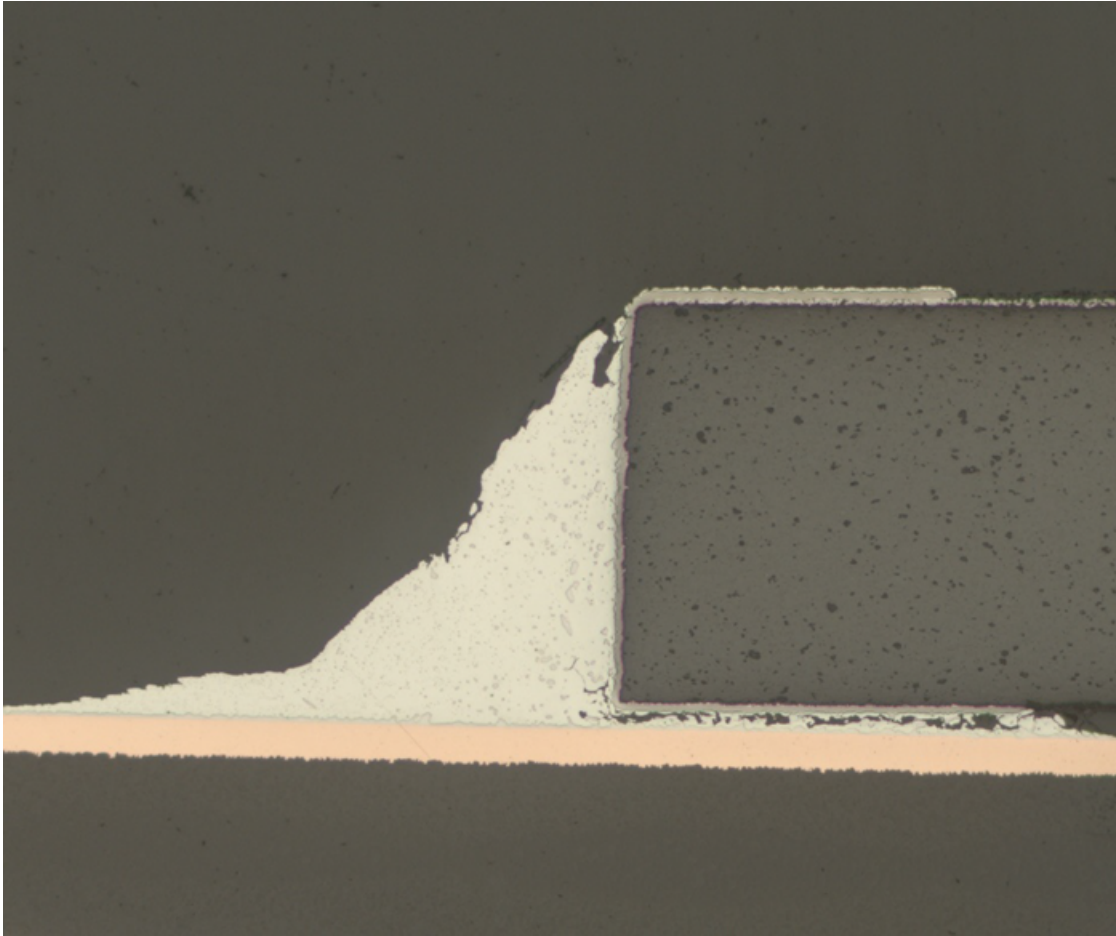
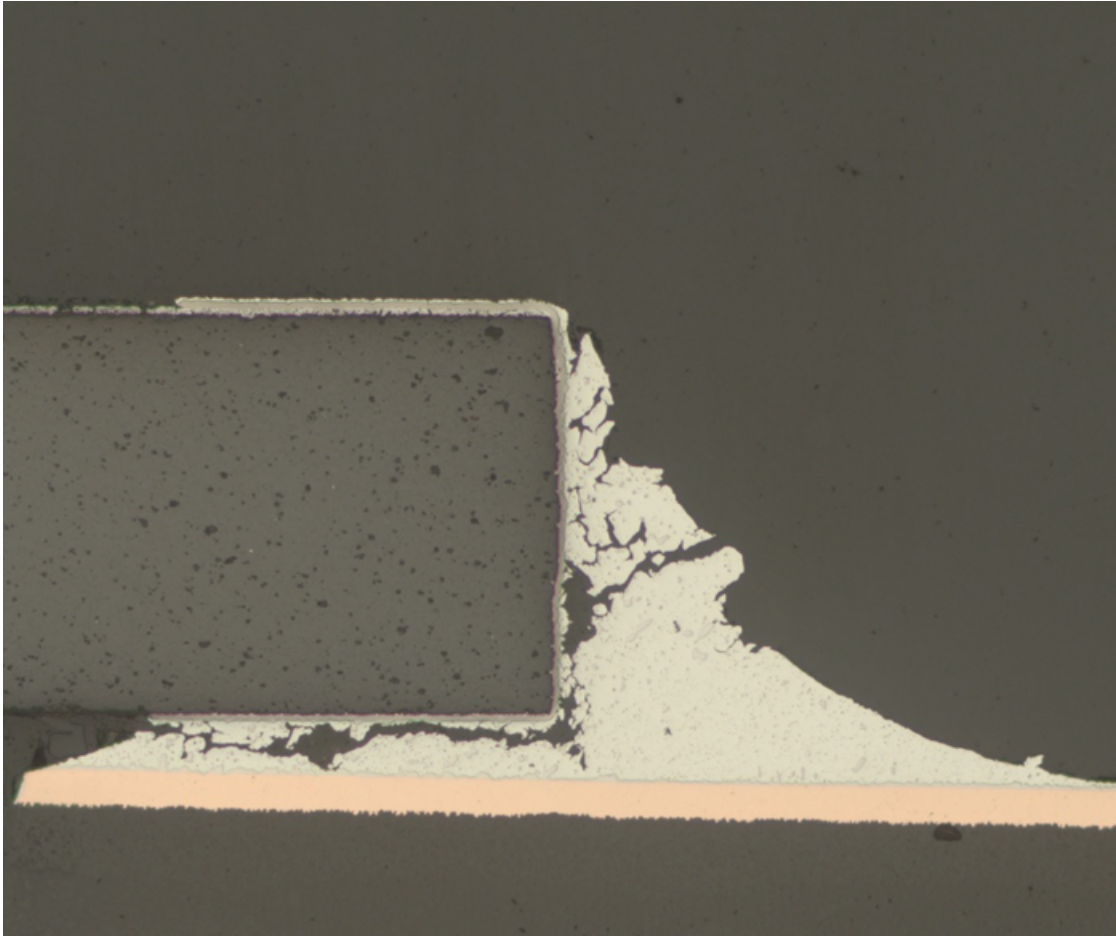


Figure 2.41: Cross section of 1206 resistor #54, right, 10x zoom



2.4.5. References (LCCC)

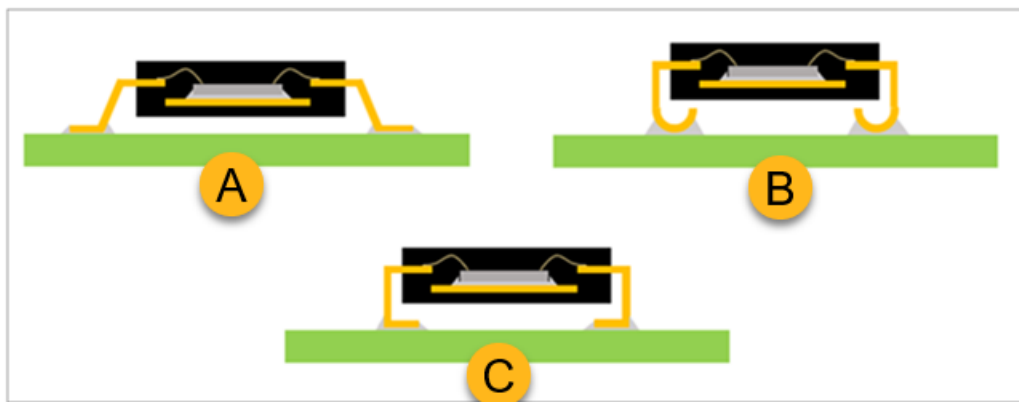
1. *Chip Resistors Plots* [Excel file].
2. Caswell, Greg & Serebreni, Maxim. *The impact of glass style and orientation on the reliability of SMT components* [PowerPoint slides]. DfR Solutions.
3. Collins, M. N., Punch, J., Coyle, R., Reid, M., Popowich, R., Read, P., & Fleming, D. (October 2011). Thermal fatigue and failure analysis of SnAgCu solder alloys with minor Pb additions. *IEEE Transactions on Components, Packaging, and Manufacturing Technology*, 1(10), 1594-1600.
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9. Suhling, J. C., Gale, H. S., Johnson, R. W., Islam, M. N., Shete, T., Lall, P., Bozack, M. J., & Evans, J. L. (2004). Thermal cycling reliability of lead free solders for automotive applications. *2004 Inter Society Conference on Thermal Phenomena*, 350-357.
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2.5. Leaded Model

Leaded devices are surface mount components that are attached to a printed circuit board through leads. Most packages have standard lead shapes, but they can be nearly any shape and size. A few examples are shown in the figure below. Sherlock assumes that all leaded devices consist of a lead frame onto which a silicon die is attached and that the die is covered with an epoxy casing.

Figure 2.42: Lead Shape Examples: (A) Gull Wing, (B) J-Lead, (C) C-Lead



When a leaded device undergoes thermal cycling, the difference between a component's coefficient of thermal expansion (CTE) and that of the PCB causes a mismatch in their thermal deformations. This mismatch bends the lead and subjects the solder material to shear strain. When these materials are repeatedly subject to strain, the cycle leads to crack initiation, followed by crack growth, and eventually to fatigue failure of the solder joint.

Topics covered in this section:

- [2.5.1. How does the Software Assess Thermo-Mechanical Solder Fatigue?](#)
- [2.5.2. Input Parameters](#)
- [2.5.3. Leaded Analytical Model](#)

2.5.4. Validation Data

2.5.1. How does the Software Assess Thermo-Mechanical Solder Fatigue?

In general, the Solder Fatigue Module in Sherlock uses industry standard methodology along with proprietary analytical inputs for predicting the failure of different packages. As an analytical tool, Sherlock does not consider system level effects but rather examines the effects the component and the board have on the solder joint. When considering leaded solder fatigue, Sherlock calculates the stress and strain on the solder joint to determine strain energy density (ΔW) as shown in [Equation 2.88 \(p. 56\)](#). Later, Sherlock uses the strain energy in a model similar to Syed's model to predict solder fatigue life. (N_f).

$$\Delta W = \frac{\sigma_{\text{solder}} \times \varepsilon_{\text{solder}}}{2} \quad (2.88)$$

$$N_f = (\text{strain energy coefficient} \times \Delta W)^{-1} \quad (2.89)$$

Solder stress (σ_{solder}) in [Equation 2.88 \(p. 56\)](#) depends on the stiffness combination of the PCB (K_{PCB}) and the lead (K_{lead}). Of the two, the element with the lower stiffness drives the failure. The combined stiffness is shown here in [Equation 2.90 \(p. 56\)](#).

$$\frac{1}{K_{\text{combined}}} = \frac{1}{K_{\text{PCB}}} + \frac{1}{K_{\text{lead}}} \quad (2.90)$$

The solder stress is then determined ([Equation 2.91 \(p. 56\)](#)). The overall thermal expansion (δ_{thermal}) of the package caused by the temperature change (ΔT) is calculated as shown in [Equation 2.93 \(p. 56\)](#).

$$\sigma_{\text{solder}} = \frac{F_{\text{solder}}}{A_{\text{solder}}} \quad (2.91)$$

$$F_{\text{solder}} = K_{\text{combined}} \times \delta_{\text{thermal}} \quad (2.92)$$

$$\delta_{\text{thermal}} = \alpha_{\text{package}}^{\text{effective}} \times \Delta T \times \frac{L_D}{2} \quad (2.93)$$

where L_D , is package diagonal length.

2.5.2. Input Parameters

Sherlock's analytical model for leaded fatigue prediction during thermal cycling uses the following inputs:

2.5.2.1. Thermal Parameters

2.5.2.2. Package and Overmold Parameters

2.5.2.3. Lead Parameters

2.5.2.4. Die Properties

2.5.2.5. Solder Parameters

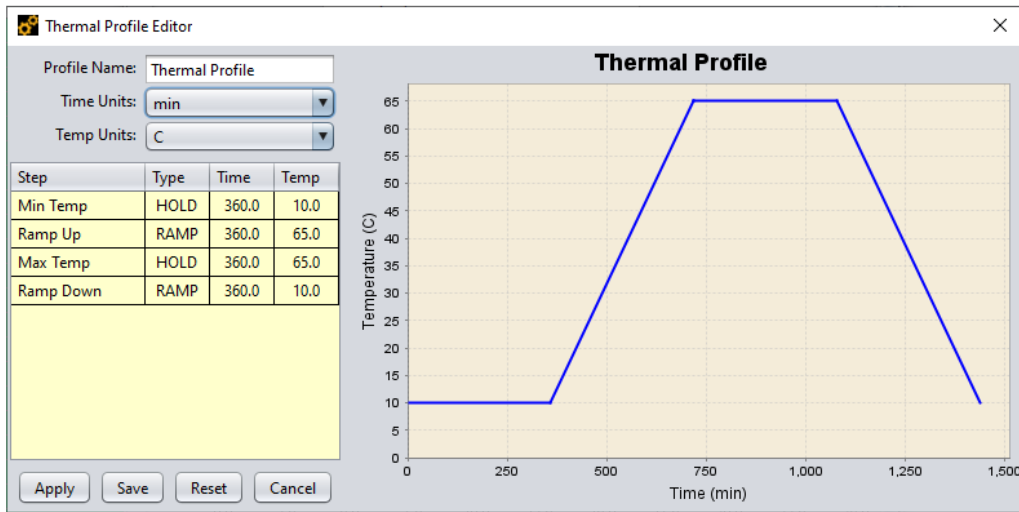
2.5.2.6. PCB Parameters

A brief explanation of each parameter is provided below, along with links to the relevant sections in the Sherlock User's Guide.

2.5.2.1. Thermal Parameters

In Sherlock, you can create a Thermal Profile using the **Thermal Profile Editor** (found in the **Life Cycle Editor** under **Thermal Event**). Below is an example of a profile for thermal cycling between 10°C and 65°C. From the thermal cycle, Sherlock calculates the change in temperature for the analysis as shown below.

Figure 2.43: Thermal Profile in Sherlock, Example



- $T_{\max}$ Maximum temperature from the Thermal Profile
- $T_{\min}$ Minimum temperature from the Thermal Profile
- $\Delta T = T_{\max} - T_{\min}$ Change in temperature

For more information on Life Cycles and Thermal Profiles, see the following sections in the Sherlock User's Guide: [Project Life Cycles](#) and [Thermal Event](#).

2.5.2.2. Package and Overmold Parameters

The Package and Overmold parameters are specified under the **Package** tab of the **Part Properties** window, as shown in the image below. Sherlock uses the same material and dimensions (except for thickness) for the Package and Overmold. The thickness for the Overmold is the difference between the Package and the Lead Thickness.

Part Properties are explained in detail in the Sherlock User's Guide. See the section [Sherlock Part Properties](#). See also [The Part Properties Viewer](#).

Figure 2.44: Package Parameters, Example

ID	Package Name:	LSOP-16 (MO-272DA)	User
Package	Package Type:	LSOP	User
Location	Package Mount:	SMT	User
Lead	Package Units:	MM	User
Pad	Package Length:	4.9	User
Solder	Package Width:	3.9	User
Electrical	Package Thickness:	1.375	User
Thermal	Overmold Thickness:	0.43	Guess
Die	Laminate Thickness:	1.2	Guess
Flag	Model Part:	ENABLED	User
Test	Corner Shape:	SQUARE	User
Semiconductor Wearout	Corner Radius:	0	User
	Corner Face:	TOP_BOTTOM	Guess
	Material:	OVERMOLD-LEADED	User
	Overmold Material:		User
	Junction Res (C/W):	1.500e+1	Guess
	Weight (gram):	0.0499	User

L_{package}

Length of package

W_{package}

Width of package

t_{package}

Thickness of package

α_{package}

Coefficient of thermal expansion of the package

E_{package}

Elastic modulus of the package

$L_{\text{overmold}}=L_{\text{package}}$

Length of overmold

$W_{\text{overmold}}=W_{\text{package}}$

Width of overmold

$t_{\text{overmold}}=t_{\text{package}}-t_{\text{lead}}$

Thickness of overmold

$\alpha_{\text{overmold}}=\alpha_{\text{package}}$

Coefficient of thermal expansion of the overmold

$E_{\text{overmold}}=E_{\text{package}}$

Modulus of the overmold

$L_D^{\text{package}}=\sqrt{L_{\text{overmold}}^2+W_{\text{overmold}}^2}$

Diagonal length of package

2.5.2.3. Lead Parameters

The lead parameters are specified under the **Lead** tab of **Part Properties** as shown below.

Figure 2.45: Lead Properties, Example

ID	Lead Count:	16	User	...
Package	Lead Geometry:	GULLWING	User	...
Location	Lead Material:	COPPER	User	...
Lead	Lead Stiffness:	161.41	Guess	...
Pad	Lead Units:	MM	User	...
Solder	Lead Height:	0.74	User	...
Electrical	Lead Width:	0.25	User	...
Thermal	Lead Thickness:	0.21	User	...
Die	Lead Foot Length:	0.62	User	...
Flag	Lead Hole Diameter:	0.5264965543462902	User	...
Test	Lead Modeling:	ENABLED	User	...
Semiconductor Wearout	Lead Layout:	DUAL_LONG	User	...
	Lead Pitch:	0.5	User	...
	Lead Bend (degrees):	90.0	User	...
	Lead Shoulder:	0.38	User	...
	Lead Standoff:	0.05	User	...
	Lead Long Count:	0	User	...
	Lead Short Count:	0	User	...
	Sink Length:	1	User	...
	Sink Width:	4.9	User	...
	Sink Thickness:	0.21	User	...

H_{lead}	Height of lead
W_{lead}	Width of lead
t_{lead}	Thickness of lead
α_{lead}	Coefficient of thermal expansion of the lead
E_{lead}	Modulus of the lead
$W_{\text{lead}}^{\text{foot}}$	Foot length of the lead

2.5.2.4. Die Properties

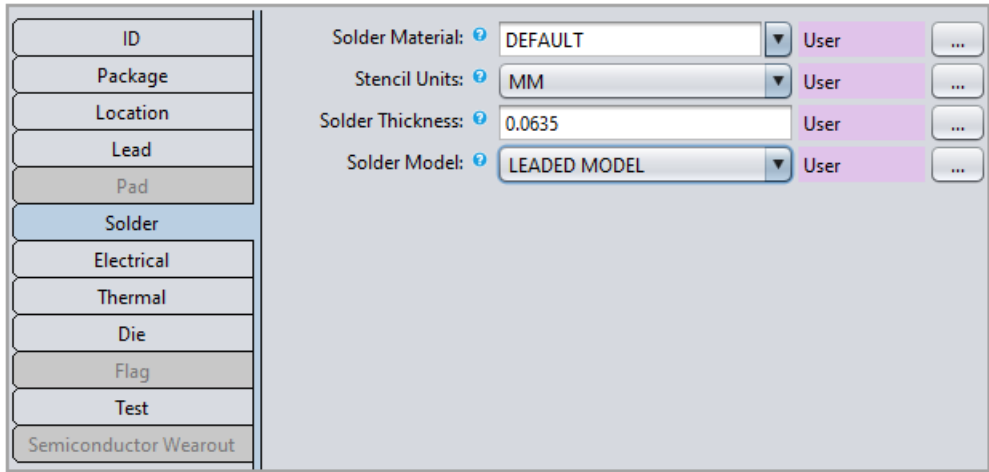
Die parameters of the package are specified under the **Die** tab of **Part Properties**.

L_{die}	Length of die
W_{die}	Width of die
t_{die}	Thickness of die
α_{die}	Coefficient of thermal expansion of the die
E_{die}	Modulus of the die
$L_D^{\text{die}} = \sqrt{L_{\text{die}}^2 + W_{\text{die}}^2}$	Diagonal length of the die

2.5.2.5. Solder Parameters

In Sherlock, the solder length and width are the same as the lead foot length and width. Solder thickness, however, can be defined under the **Solder** tab in the **Part Properties Editor**.

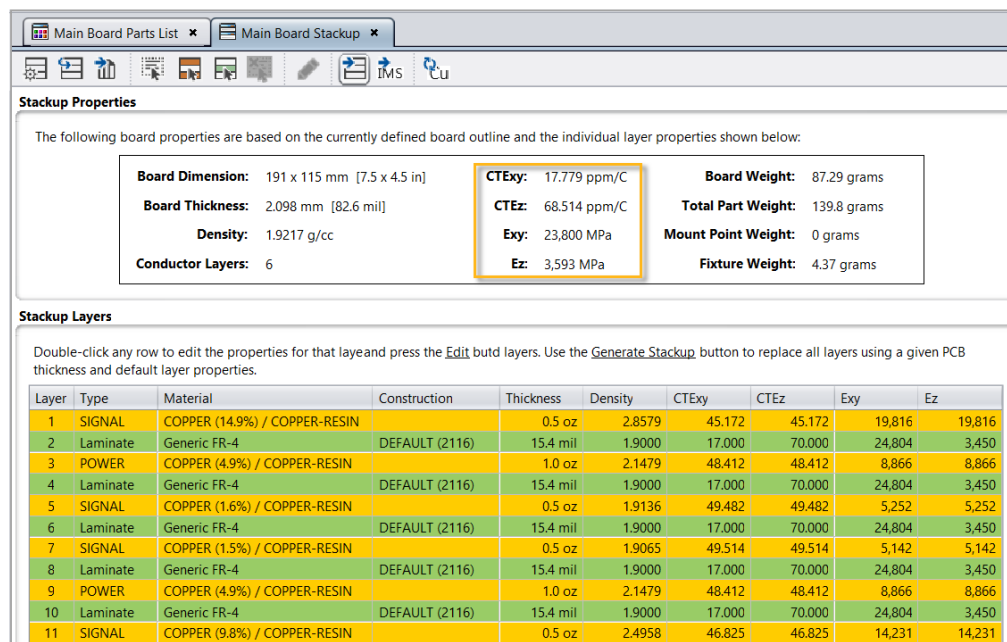
Figure 2.46: Solder Parameters, Example



- L_{solder} Length of solder
- W_{solder} Width of solder
- t_{solder} Thickness of solder
- A_{solder} Coefficient of thermal expansion of the solder

2.5.2.6. PCB Parameters

The CTE, modulus, and Poisson's ratio of the stackup are used for the PCB in the calculation of the analytical model. Sherlock computes the effective stackup properties based on the rule of mixtures. An example of a stackup is shown below.

Figure 2.47: PCB Properties, Example


α_{PCB}	Coefficient of thermal expansion of the PCB
E_{PCB}	Elastic modulus of the PCB
ν_{PCB}	Poisson's ratio for the PCB
t_{PCB}	Thickness of PCB

2.5.3. Leaded Analytical Model

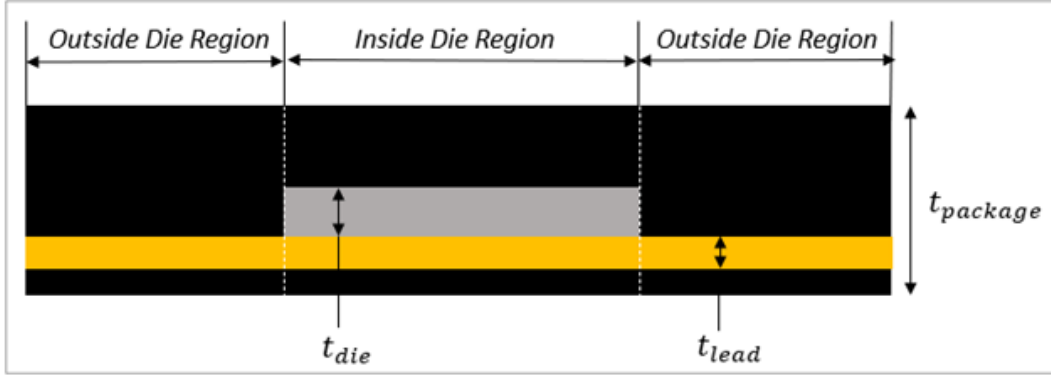
The mechanics behind the Leaded Model were discussed in the [introduction \(p. 55\)](#). This section explains how Sherlock formulates the combined stiffness of the component (K_{combined}) as well as the overall package CTE ($\alpha_{\text{package}}^{\text{overall}}$). It also covers how Sherlock arrives at the Life Prediction of the Leaded Model using its determined CTE and stiffness value.

This section covers the following topics:

- 2.5.3.1. Effective Package Material Calculation
- 2.5.3.2. Combined Stiffness Calculation
- 2.5.3.3. Strain Energy Density Calculation
- 2.5.3.4. Life Prediction Calculation

2.5.3.1. Effective Package Material Calculation

In its analyses, Sherlock considers the volume of a leaded device to be comprised of the leads, the die, the lead-frame, and the overmold. Portions of the volume can be classified as occupying the inside-die-region or the outside-die-region (see image below). For simplicity, Sherlock assumes the model's lead and lead-frame occupy a constant thickness in the package volume. The die thickness (t_{die}), package thickness (t_{package}), and lead thickness (t_{lead}) are illustrated here:

Figure 2.48: Leaded Package Simplification

Based on the figure above, the overmold thickness of the inside die region is given by:

$$t_{\text{package}}^{\text{inside package}} = t_{\text{package}} - t_{\text{lead}} - t_{\text{die}} \quad (2.94)$$

The effective modulus and the CTE of the inside die region are calculated through the rule of mixtures, as shown in Equation 2.95 (p. 62) and Equation 2.96 (p. 62), respectively.

$$E_{\text{package}}^{\text{Inside Die}} = \frac{E_{\text{lead}} \times t_{\text{lead}} + E_{\text{package}} \times t_{\text{package}}^{\text{Inside Die}} + t_{\text{die}} \times E_{\text{die}}}{t_{\text{package}}} \quad (2.95)$$

$$\alpha_{\text{package}}^{\text{Inside Die}} = \frac{E_{\text{lead}} t_{\text{lead}} \alpha_{\text{lead}} + E_{\text{package}}^{\text{package}} \alpha_{\text{package}} + E_{\text{die}} t_{\text{die}} \alpha_{\text{die}}}{E_{\text{package}}^{\text{Inside Die}} \times t_{\text{package}}} \quad (2.96)$$

Similarly, the effective modulus and CTE of the outside die region are calculated using equations Equation 2.97 (p. 62) and Equation 2.97 (p. 62), respectively.

$$t_{\text{package}}^{\text{Outside Die}} = t_{\text{package}} - t_{\text{lead}} \quad (2.97)$$

$$E_{\text{package}}^{\text{Outside Die}} = \frac{E_{\text{lead}} \times t_{\text{lead}} + t_{\text{package}}^{\text{Outside Die}} \times E_{\text{package}}}{t_{\text{package}}} \quad (2.98)$$

$$\alpha_{\text{package}}^{\text{Outside Die}} = \frac{E_{\text{lead}} t_{\text{lead}} \alpha_{\text{lead}} + E_{\text{package}}^{\text{Outside Die}} t_{\text{package}}^{\text{Outside Die}} \alpha_{\text{package}}}{E_{\text{package}}^{\text{Outside Die}} \times t_{\text{package}}} \quad (2.99)$$

Then the effective package CTE can be determined as shown in the equation below:

$$\alpha_{\text{package}}^{\text{effective}} = \frac{\alpha_{\text{package}}^{\text{Outside Die}} \times \left(\frac{L_D^{\text{package}}}{2} - \frac{L_D^{\text{die}}}{2} \right)}{\frac{L_D^{\text{package}}}{2}} + \frac{\alpha_{\text{package}}^{\text{Inside Die}} \times \frac{L_D^{\text{die}}}{2}}{\frac{L_D^{\text{package}}}{2}} \quad (2.100)$$

2.5.3.2. Combined Stiffness Calculation

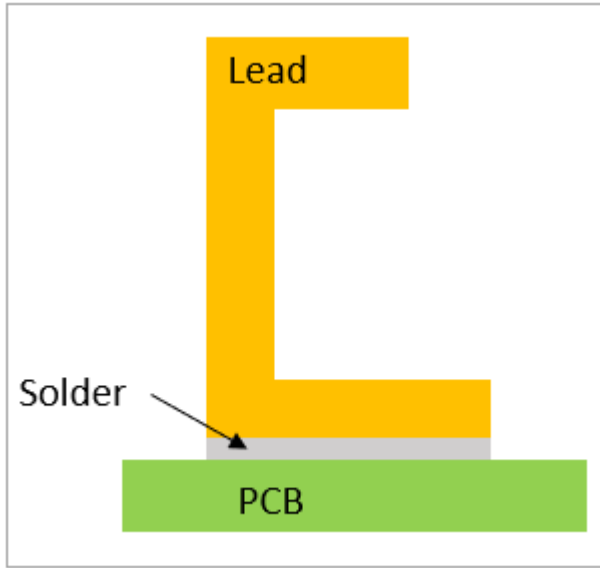
As seen in equations Equation 2.91 (p. 56) and Equation 2.92 (p. 56), it is imperative to calculate the lead and PCB stiffnesses to determine the stresses on the solder joint. As shown below, Figure 2.49: Lead, Solder Joint, and PCB (p. 63), the lead can be simplified as a cantilever beam soldered to the PCB at its foot-end. During thermal cycling, the difference in the CTE between the PCB and package will bend the lead, straining the solder. The more stiff the lead and PCB are, the higher the strain will be on the solder, and vice versa. Given that each element is a spring, with stiffnesses K_{PCB} and K_{lead} , the combined stiffness of the assembly can be captured using springs in parallel

as shown in Equation 2.101 (p. 63). By simplifying the lead as a cantilever beam, the stiffness of the lead can be determined using Equation 2.102 (p. 63).

$$\frac{1}{K_{\text{combined}}} = \frac{1}{K_{\text{PCB}}} + \frac{1}{K_{\text{lead}}} \quad (2.101)$$

$$K_{\text{lead}} = \frac{3E_{\text{lead}}I_{\text{lead}}}{H_{\text{lead}}^3} = \frac{3E_{\text{lead}}\left(\frac{W_{\text{lead}}t_{\text{lead}}^3}{12}\right)}{H_{\text{lead}}^3} \quad (2.102)$$

Figure 2.49: Lead, Solder Joint, and PCB



The PCB stiffness along the package diagonal length can be calculated using the axial stiffness formulation as shown in Equation 2.103 (p. 63).

$$K_{\text{PCB}} = \frac{EA}{L} = \frac{E_{\text{PCB}}A_{\text{PCB}}}{L_{\text{PCB}}} = \frac{2E_{\text{PCB}}t_{\text{PCB}}W_{\text{PCB}}}{\frac{L_D^{\text{die}}}{2}} \quad (2.103)$$

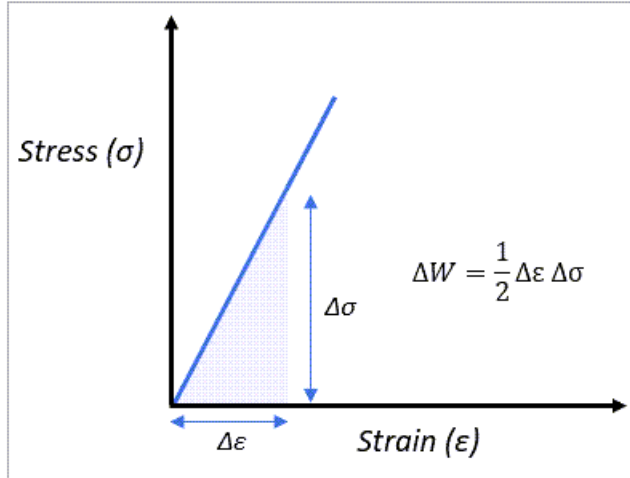
Note:

When calculating solder joint fatigue predictions for stub leads, Sherlock uses a leaded model formula based on the Euler-Bernoulli beam bending theory. Due to the geometric simplifications in the software, Sherlock models the stub leads as short beams which do not meet the assumptions in the Euler-Bernoulli beam theory. When running a Solder Fatigue, you may enter the lead stiffness manually for stub leads. This will override the computed stiffness.

2.5.3.3. Strain Energy Density Calculation

Strain energy density (ΔW) is defined as energy for deforming any material per unit volume. From the stress-strain curve, the energy density can be determined as the area under the curve as shown in Figure 2.50: Area Under Stress-Strain Curve (p. 64).

$$\Delta W = \frac{1}{2} \text{ base height} = \frac{1}{2} \Delta \epsilon \Delta \sigma \quad (2.104)$$

Figure 2.50: Area Under Stress-Strain Curve

The model in Sherlock finds the strain energy density on the solder during thermal cycling. The stress and strain during thermal cycling (ΔT) can be determined from the solid mechanics formulation as shown below:

$$\sigma_{\text{solder}} = \frac{F_{\text{solder}}}{A_{\text{solder}}} \quad (2.105)$$

$$\sigma_{\text{solder}} = \frac{K_{\text{combined}} \delta_{\text{thermal}}}{A_{\text{solder}}} \quad (2.106)$$

$$\sigma_{\text{solder}} = \frac{K_{\text{combined}} \times |\alpha_{\text{PCB}} - \alpha_{\text{package}}^{\text{effective}}| \times \Delta T \times \frac{L_{\text{package}}}{2}}{A_{\text{solder}}} \quad (2.107)$$

$$\epsilon_{\text{solder}} = \frac{|\alpha_{\text{PCB}} - \alpha_{\text{package}}^{\text{effective}}| \times \Delta T \times \frac{L_{\text{package}}}{2}}{t_{\text{solder}}} \quad (2.108)$$

2.5.3.4. Life Prediction Calculation

The strain energy is adjusted to account for field condition by incorporating the accelerated life testing factor, using the Norris-Landsberg model as shown in equation [Equation 2.109 \(p. 64\)](#).

Sherlock also uses a leaded calibration factor, $C_{\text{CF}}^{\text{leaded}}$, to improve the correlation between the predicted and experimental solder life.

$$\Delta W_{\text{calibrated}} = \frac{\Delta W}{C_{\text{CF}}^{\text{leaded}}} \quad (2.109)$$

Figure 2.51: Leaded Calibration Factor

$$Adj.\Delta W = \Delta W_{\text{Calibrated}} \left(\frac{t_{\text{dwell-max}}}{t_{\text{critical}}} \right)^{0.136} e^{E_a \left(\frac{1}{T_{\text{critical}}} - \frac{1}{T_{\text{max}} + 273.15} \right)} \quad (2.110)$$

$$N_f = (SE_{\text{Coeff}} Adj.\Delta W)^{-1} \quad (2.111)$$

where,

$t_{\text{dwell-max}}$, is the maximum dwell time in the given thermal profile

t_{critical} , is the critical dwell time for the selected solder material

E_a , is the activation energy for the selected solder material

T_{critical} , is the critical temperature for the selected solder material

T_{max} , is the maximum temperature in the given thermal profile

SE_{Coeff} , is the strain energy coefficient for the selected solder material

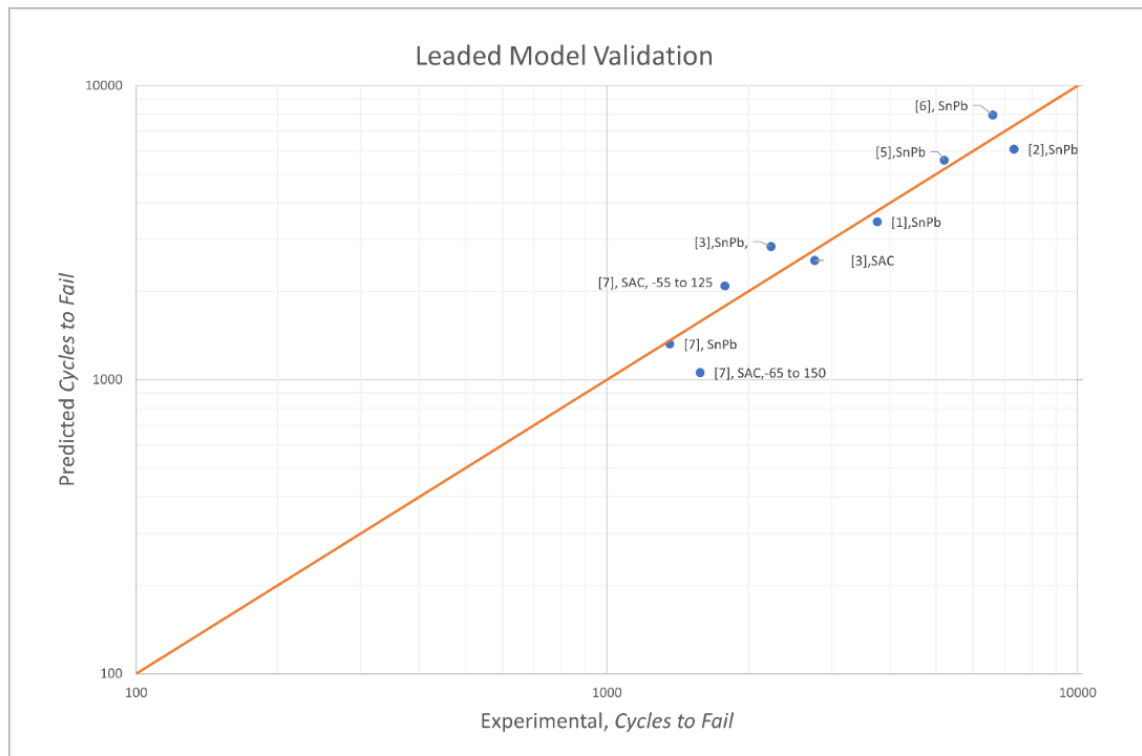
N_f , is the predicted solder life

All the solder constants can be defined and adjusted under the **Low Cycle Fatigue** tab in the **Solder Editor** window, as shown in [Figure 2.51: Leaded Calibration Factor \(p. 65\)](#).

2.5.4. Validation Data

To validate the output of this module, Ansys gathered many examples of temperature cycling data for a variety of leaded packages including TSOP, PQFP, and FQFP. The packages were soldered to a printed board with either SnPb or SAC305. Then, the thermo-mechanical fatigue predictions for these configurations were generated by the software and compared to experimental data. The results are displayed in the figure below. It is important to note that the validation was done by extracting experimental datapoints from published literature. Given the inferences sometimes required to extract data from published literature, the software is highly accurate, with the majority of predictions falling within 2X.

Figure 2.52: Leaded Model Validation Plot



2.5.4.1. Worked Example

Thermal cycle

$$T_{\max}=125$$

$$T_{\min}=-55$$

$$t_{\text{dwell}}=10$$

$$t_{\text{max dwell}}=10$$

$$\Delta T=125-(-55)=180$$

Package properties

$$L_{\text{package}}=28$$

$$W_{\text{package}} = 28$$

$$t_{\text{package}} = 3.4$$

$$\text{CTE}_{\text{package}} = 2.2 \times 10^{-5}$$

$$E_{\text{package}} = 13790$$

Lead properties

$$H_{\text{lead}} = 1.875$$

$$W_{\text{lead}} = 0.23$$

$$t_{\text{lead}} = 0.15$$

$$E_{\text{lead}} = 120700$$

$$\text{CTE}_{\text{lead}} = 1.7 \times 10^{-5}$$

Overmold properties

$$L_{\text{overmold}} = 28$$

$$W_{\text{overmold}} = 28$$

$$\text{CTE}_{\text{overmold}} = 2.2 \times 10^{-5}$$

$$t_{\text{overmold}} = 3.4$$

$$t_{\text{Lead-frame}} = 3.4 - 0.15 = 3.25$$

$$E_{\text{overmold}} = 13790$$

$$\frac{L}{2}_{\text{overmold}} = 0.5 \times \sqrt{28^2 + 28^2} = 19.8$$

Die properties

$$L_{\text{die}} = 0.01$$

$$W_{\text{die}} = 0.01$$

$$t_{\text{die}} = 0.01$$

$$E_{\text{die}} = 131000$$

$$\frac{L}{2}_{\text{die}} = 0.5 \times \sqrt{0.01^2 + 0.01^2} = 0.00707$$

Solder attach

$$L_{\text{solder}} = 0.45$$

$$h_{\text{solder}} = 0.015$$

$$W_{\text{solder}} = 0.23$$

$$A_{\text{solder}} = 0.45 \times 0.23 = 0.1035$$

PCB properties

$$E_{\text{PCB}} = 11100$$

$$\text{CTE}_{\text{PCB}} = 1.5 \times 10^{-5}$$

$$t_{\text{PCB}} = 1.6$$

2.5.4.2. Effective Mechanical Properties

Effective properties, inside die region:

$$E_{\text{inside die}} = \frac{120700 \times 0.15}{3.4} + \frac{13790 \times (3.25 - 0.01)}{3.4} + \frac{0.01 \times 131000}{3.4} = 18851.35 \quad (2.112)$$

$$\begin{aligned} \text{CTE}_{\text{inside die}} &= (3.25 - 0.01) \times 1.5 \times 10^{-5} \times \frac{13790}{18851.35 \times 3.4} + 0.15 \times 1.7 \times 10^{-5} \\ &\times \frac{120700}{(18851.35 \times 3.4)} + 0.01 \times 2.9 \times 10^{-6} \times \frac{131000}{(18851.35 \times 3.4)} = 2.02 \times 10^{-5} \end{aligned} \quad (2.113)$$

Effective properties, outside die region:

$$E_{\text{outside package}} = \frac{120700 \times 0.15}{3.4} + \frac{13790 \times 3.25}{3.4} = 18506.6 \quad (2.114)$$

$$\begin{aligned} \text{CTE}_{\text{outside package}} &= 3.25 \times 2.2 \times 10^{-5} \times \frac{13790}{18506.6 \times 3.4} + 0.15 \times 1.7 \times 10^{-5} \\ &\times \frac{120700}{18506.6 \times 3.4} = 2.06 \times 10^{-5} \end{aligned} \quad (2.115)$$

$$\begin{aligned} \text{CTE}_{\text{outside die}} &= 2.2 \times 10^{-5} \times \frac{(19.8 - 0.00707)}{19.8} + \frac{2.02 \times 10^{-5} \times 0.00707}{19.8} \\ &= 2.056 \times 10^{-5} \end{aligned} \quad (2.116)$$

2.5.4.3. Stress and Strain Calculations

$$\text{Stiffness}_{\text{PCB}} = 11100 \times 1.6 \times 2 \times \frac{0.23}{19.8} = 412.63 \quad (2.117)$$

$$\Delta\alpha = |1.15 \times 10^{-5} - 2.025 \times 10^{-5}| = 5.561 \times 10^{-6} \quad (2.118)$$

$$\Gamma = 5.561 \times 10^{-6} \times 180 \times \frac{19.8}{0.015} = 1.32 \quad (2.119)$$

$$\text{Stiffness}_{\text{lead}} = \frac{3 \times 120700 \times \frac{(0.23 \times 0.15^3)}{12}}{1.875^3} = 3.55 \quad (2.120)$$

$$\text{Stiffness}_{\text{total}} = \left(\frac{1}{412.63} + \frac{1}{3.55} \right)^{-1} = 3.52 \quad (2.121)$$

$$\text{Displacement} = 5.561 \times 10^{-6} \times 180 \times 19.8 = 0.0198 \quad (2.122)$$

$$\text{Force} = 0.0198 \times 3.52 = 0.0698 \quad (2.123)$$

$$\text{Stress} = \frac{0.0698}{0.1035} = 0.675 \quad (2.124)$$

$$\text{Strain Energy} = 0.675 \times \frac{1.32}{2} = 0.446 \quad (2.125)$$

2.5.4.4. Cycles to Failure

$$\text{Calibrated Strain Energy} = \frac{0.446}{2} = 0.223 \quad (2.126)$$

The Calibration Factor is solder dependent.

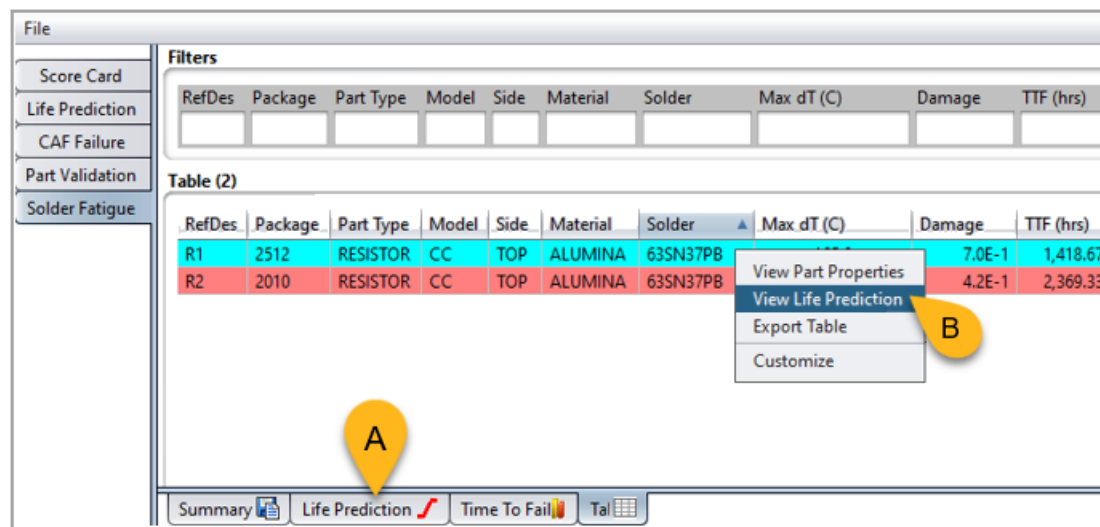
$$\text{Adj Strain Energy} = 0.223 \times \frac{10^{0.136}}{20} \exp\left(1414 \times \left(\frac{1}{368} - \frac{1}{125}\right)\right) = 0.271 \quad (2.127)$$

$$\text{Cycles to Failure} = \frac{1}{6.06 \times 10^{-4} \times 0.271} = 6082 \quad (2.128)$$

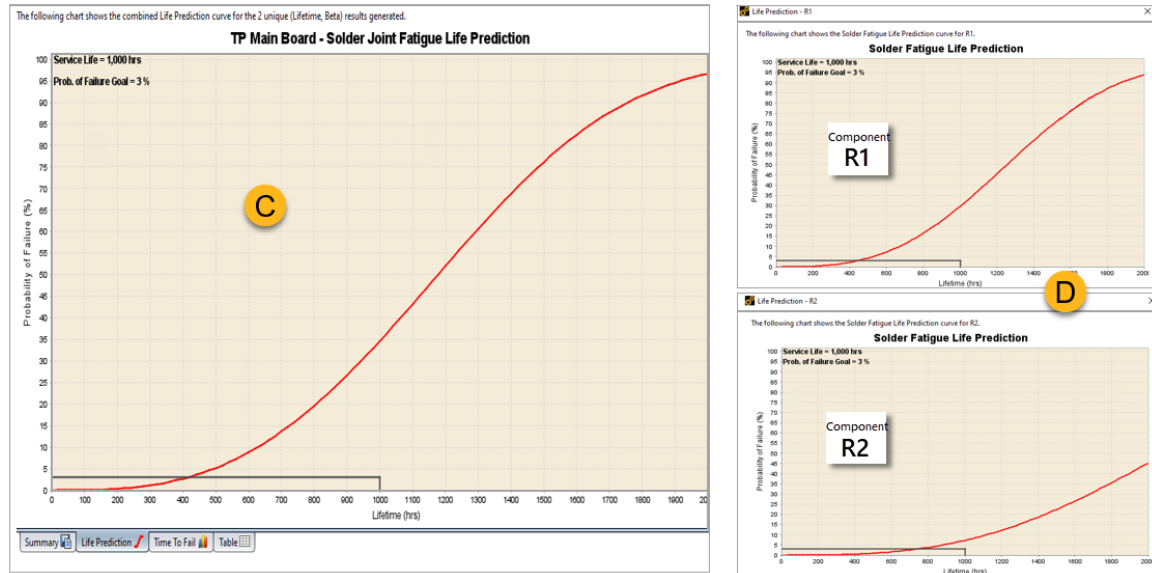
2.5.4.5. Life Prediction Plot

The Life Prediction Plot in Sherlock is available for both individual components as well as for the entire system. From the **Results Table**, click the **Life Prediction** tab (A, below) to see the plot for the whole system. To see the plot for a single component, right-click the corresponding table row and select **View Life Prediction** from the context menu (B).

Figure 2.53: Viewing Life Prediction Plots



The Life Prediction Plot (see examples below) represents the Probability of Failure (PoF), as a percentage, of the component (or system) against the Time To Failure (TTF). The units for the TTF are based on the Service Life you specified.

Figure 2.54: Life Prediction Plots: C- System Level. D- Component Level (R1 and R2)

Sherlock uses two-parameter Weibull distribution for life prediction as shown in [Equation 2.129](#) (p. 70). The plot in Sherlock represents the unreliable component of the distribution, which can also be recognized as the cumulative density function of the Weibull distribution as shown in [Equation 2.130](#) (p. 70).

$$F(t) = \frac{\beta}{\eta} \left(\frac{t}{\eta} \right)^{\beta-1} e^{-\left(\frac{t}{\eta}\right)^{\beta}} \quad (2.129)$$

where:

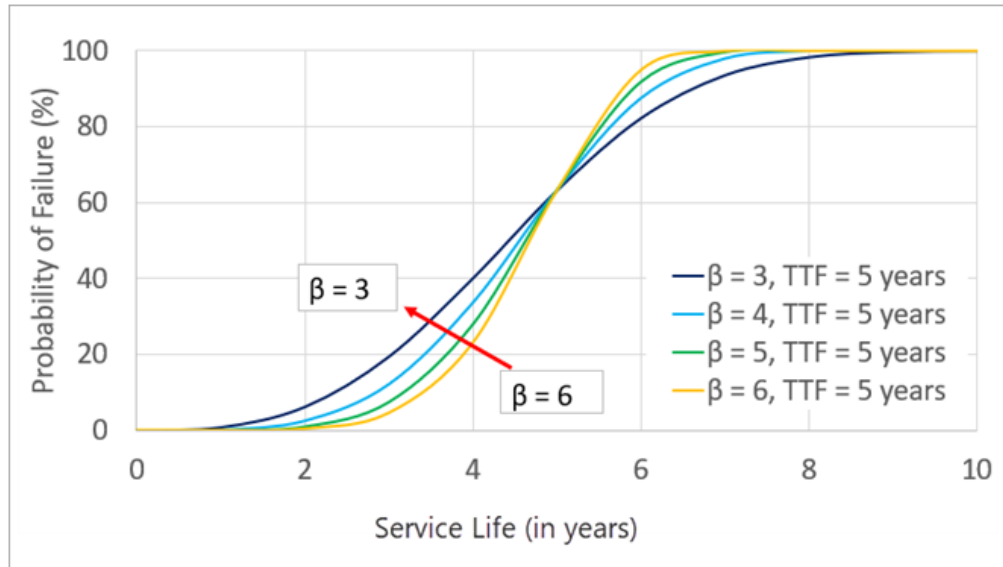
β , is the Weibull slope

η , is the scale parameter

t , is the time

$$PoF(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} \quad (2.130)$$

The Weibull slope in [Equation 2.89](#) (p. 56) describes the rate at which the components fail. The figure below shows the impact of the Weibull slope for the POF for a Service Life of five years. The Weibull slope for the Solder Fatigue of different components can be adjusted as needed from Sherlock's default value of 3 under the **Low-Cycle Fatigue** tab in the **Solder Editor** as shown in [Figure 2.56: Solder Editor](#) (p. 71).

Figure 2.55: Weibull Slope Variation**Figure 2.56: Solder Editor**

Solder Editor - 63SN37PB

Modify the solder properties as needed and press the **Save** button to update the Solder Library.

Material Properties
Mechanical
Secant Modulus
High-Cycle Fatigue
Correction Factors
Low-Cycle Fatigue
User

Low-Cycle Fatigue

Critical Dwell Time: 20.0 min

Activation Energy (Ea): 1414.0

Critical Max Temp: 368.0

Strain Energy Coefficient: 6.061E-4

CC Calibration Factor: 1:0.0:1.0; 1:3.2:1.0; 2:0.0:1.0; 2:3.2:1.0; 3:0

Leaded Calibration Factor: 2.0

Thermal Shock Factor CC: 15,1.0 | 30,1.25 | 60,1.5

Thermal Shock Factor BGA: 15,1.0 | 30,1.25 | 60,1.5

Thermal Shock Factor LCCC: 15,1.0 | 30,1.25 | 60,1.5

Thermal Shock Factor Leaded: 15,1.0 | 30,1.25 | 60,1.5

Thermal Shock Factor QFN: 15,1.0 | 30,1.25 | 60,1.5

Thermal Shock Factor ThruHole: 15,1.0 | 30,1.25 | 60,1.5

Thermal Shock Factor Default: 15,1.0 | 30,1.25 | 60,1.5

Weibull Beta BGA: 3.0

Weibull Beta CBGA: 3.0

Weibull Beta CC: 3.0

Weibull Beta LCCC: 3.0

Weibull Beta Leaded: 3.0

Weibull Beta QFN: 3.0

Weibull Beta ThruHole: 3.0

When creating the system level Life Prediction Plot (all components combined), Sherlock uses a slight modification of Lusser's law. In this approach, Sherlock calculates the system level reliability

as a product of reliabilities composed of *unique* components that make up the system—that is, identical components are reduced to a single component for the purpose of calculation.

One of the main reasons only unique components are considered is because the Solder Fatigue Module does not account for *system* level effects—meaning a component at the center of the board will give the same result as a component near a mount point. If Sherlock considered all components, then the product of identical reliabilities would artificially lower the overall system level reliability. This means that identical components could individually pass the reliability requirement, but the combined reliability could fail. In reality, if there is a PCB with two components that pass the requirement, there is no reason why the overall reliability of the board should fail. To avoid such scenarios, Sherlock considers only unique components of the system.

2.5.4.6. Solder Fatigue Scoring

Sherlock's scoring for Solder Fatigue ranges between 0 and 10. If the failure probability is the same as the failure probability goal, then the component is sure to fail and is assigned a Solder Fatigue score of 0. This happens when the ratio of the failure probability goal to failure probability equals 1. If the ratio is greater than 10, then a Solder Fatigue score of 10 is assigned. For any ratio in between 1 and 10, Sherlock linearly interpolates it into a log scale between 0 and 10. The Solder Fatigue score indicates the safety factor between the failure probability goal and the actual failure computed from Sherlock. The scoring logic is as shown below:

- If (Reliability Goal / Failure Probability) < 1, score = 0

- If $1 < (\text{Reliability Goal} / \text{Failure Probability}) < 1.4$,

$$\text{score} = 10 \log_{10} \left(1.4 \right)^* \left(\frac{(\text{Reliability Goal} / \text{Failure Probability}) - 1}{0.4} \right)$$

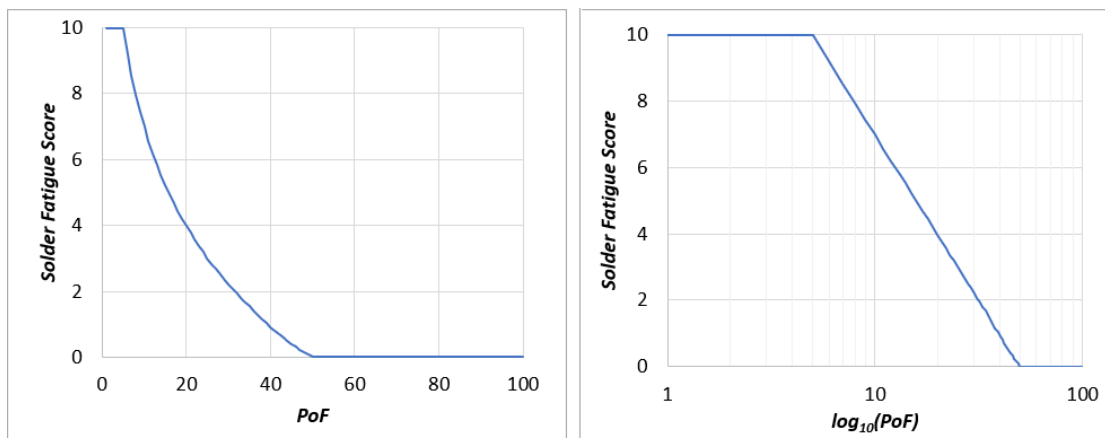
- If $1.4 < (\text{Reliability Goal} / \text{Failure Probability}) < 10$,

$$\text{score} = 10 \log_{10} (\text{Reliability Goal} / \text{Failure Probability})$$

- If (Reliability Goal / Failure Probability) > 10, Score = 10

The figure below shows the score for different probabilities of failure, for a failure goal of 50% in both percentage and log percentage.

Figure 2.57: Probability of Failure vs Score



2.5.4.7. References (Leaded Model)

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2. Chai, F., Osterman, M., & Pecht, M. (2012). Reliability of gull-wing and leadless packages subjected to temperature cycling after rework. *IEEE Transactions on Device and Materials Reliability*, 12(2), 510-519.
3. Darveaux, R. (1997, February). Solder joint fatigue model. *Proceedings of TMS Annual Meeting*, Orlando, FL, 213-218.
4. Kim, Chang H. (2013). Directional stiffness of electronic component lead. *International Journal of Engineering Research & Technology*, 2(11), 1846-1850.
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8. Lau, J., Dody, G., Chen, W., McShane, M., Rice, D., Erasmus, S., & Adamjee, W. (1992). Analytical and experimental studies of 208-pin fine pitch (0.5 mm) quad flat pack solder-joint reliability. *Circuit World*, 18(2), 13-19.
9. Lau, J. & Erasmus, S. (1993). Reliability of fine pitch plastic quad flat pack leads and solder joints under bending, twisting, and thermal conditions. *Transactions of the ASME - Journal of Electronic Packaging*, 115, 322-328.
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11. Wong, T. E., Kachatorian, L. A., & Cohen, H. M. (1999). J-lead solder joint thermal fatigue life model. *Transactions of the ASME - Journal of Electronic Packaging*, 121(3), 186-190.
12. Yeo, C. K., Mhaisalkar, S., & Pang H. L. J. (1996). Solder joint reliability study of 256 pin, 0.4 mm pitch, PQFP. *IEEE Electronic Components and Technology Conference*, 1222-1231.
13. Yoon, S. W., Hong, J. K., Kim, H. J., & Byun, K. Y. (2005). Board-level reliability of pb-free solder joints of TSOP and various CSPs. *IEEE Transactions on Electronics Packaging Manufacturing*, 28(2), 168-175.

2.6. Ceramic Column Grid Array

Topics covered in this section:

2.6.1. Failure Mode

2.6.2. The CCGA Analysis Model in Sherlock

2.6.3. Validation

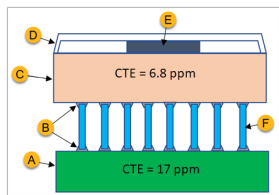
2.6.4. References

Ceramic area array packages are characterized by a low CTE (coefficient of thermal expansion) substrate along with a high I/O count. Their unique design permits them to be used on conventional FR4 and polyimide printed circuit boards (PCBs) that have a much higher CTE. You will often find ceramic substrate features in flip-chip ball grid array packages (FCBGA) and column grid array packages (CGA).

Ceramic ball grid array (CBGA) packages display the same solder-interconnect failures seen in conventional plastic ball grid arrays (BGAs). When subjected to repeated temperature fluctuations, shear strain and the distances-to-neutral-point (DNP) are dominant contributors to failure because of the CTE mismatch. Compared to CBGA packages, however, the increased height between the ceramic substrate and the PCB make Ceramic Column Grid Array (CCGA) components more reliable versus thermo-mechanical fatigue (TMF). The increased height reduces the effective strain at the region of concentrated stress among the solder interconnects. In addition to offering greater reliability, CCGAs have the advantage of a higher I/O count. The CCGA does come with some physical disadvantages, however: Compared to BGAs, CCGAs require a larger space and are less reliable under vibration loads.

Figure 2.58 (p. 74) shows the cross-section of a CCGA component in which the solder columns (F) are interposed between the thick, multi-layer, ceramic substrate and the printed circuit board. While CCGA packages use various column types and materials, the most common is a high-lead 90Pb10Sn solder column which ranges from 1.27 to 2.21 mm in height, although it could also be made of the high-lead 80Pb10Sn solder alloy. Additional column types are micro-coil spring NiAu and the 90Pb10Sn copper wrapped column. These permit a smaller column diameter and a reduced height compared to the high lead options. They also reduce pitch and increase I/O count. Most high density, copper-wrapped columns do not facilitate solder fillet formation, so the failure location tends to happen at the interface between the fillet and the column. See the literature for examples of failures in copper coil wrapped columns. (See References (p. 82) below.)

Figure 2.58: Cross- section of CCGA package (not to scale)



A - PCB • B - 63Sn37Pb Solder joint fillet • C - Multi-layer ceramic substrate • D - Lid • E - Flip-chip
• F - 90Pb10Sn column

During thermal loading, columns experience high bending loads near the top of the solder fillet. Repeated heating and cooling causes plastic strain to accumulate at the high stress region of the high lead column. This can cause the nucleation and propagation of fatigue cracks. Due to the CTE mismatch between the ceramic substrate and the PCB, horizontal displacement of the outermost column in the CCGA is primarily influenced by the column height and the coefficient of thermal expansion of both the ceramic substrate and the PCB. The substrate dimension, because it affects the distance to the neutral point (DNP), is another critical factor in determining the effective shear strain magnitude.

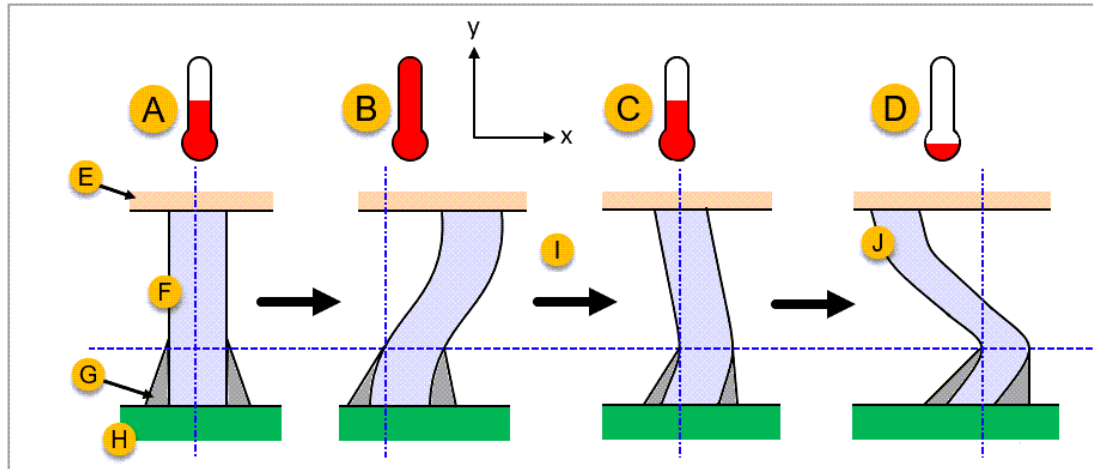
Sherlock offers an analytical approach to predict the life of CCGA component when subjected to thermal cycling. The analytical model is based on the CTE mismatch between the substrate and the PCB which

drives bending in high lead columns. It's important to understand that Sherlock's life predictions assume column failure, not solder fillet failure.

2.6.1. Failure Mode

Thermal expansion of the CCGA package subjects the outermost column to larger shear and bending loads. Figure 2.59 (p. 75) (Han, 1997 (p. 82)) illustrates the thermal deformation of the outermost column in a CCGA package during a single thermal cycle.

Figure 2.59: Schematic illustration of column deformation in CCGA package during thermal cycling



A - Reference temperature • B - Elevated Temperature • C - Reference Temperature • D - Cryogenic Temperature • E - Ceramic • F - High Melting Solder • G - Eutectic Solder • H - PCB • I - Permanent deformation of eutectic solder • J - Region of large tensile strain

During the first heating ramp to an elevated temperature, the PCB expands more than the ceramic substrate due to the larger CTE of the PCB. During the elevated temperature, the high-lead solder columns undergo large plastic deformation, along with creep strain accumulation during the dwell period. During the high temperature dwell, the 63Sn37Pb solder fillet also undergoes creep deformation which leads to column rotation toward the neutral axis of the bending direction. During subsequent cooling to the low temperature dwell, the relative displacement is not completely recovered. This is due to the local mismatch between the 63Sn37Pb fillet and 90Sn10Pb column. As the package contracts, the solder fillet constrains the bottom section of the column, so it is unable to creep as much as the top section.

As the component continues to cool toward the coolest temperature, the substrate-side fillet continues to contract, resulting in an S-shape column between both solder fillets. This repeated deformation results in a high stress concentration region in the interface between the high-lead column and the fillet edge. In an accelerated thermal cycling environment, repeated deformation mimics the behavior of a paper clip that is repeatedly bent, with failure happening at the interface between the high-lead column and the fillet edge. The elevated temperature contributes more damage than the cold dwell period. However, due to the large amount of bending at both temperature extremes, it is necessary to calculate damage at the cold dwell period in order to accurately estimate damage that happens over the entire thermal cycle.

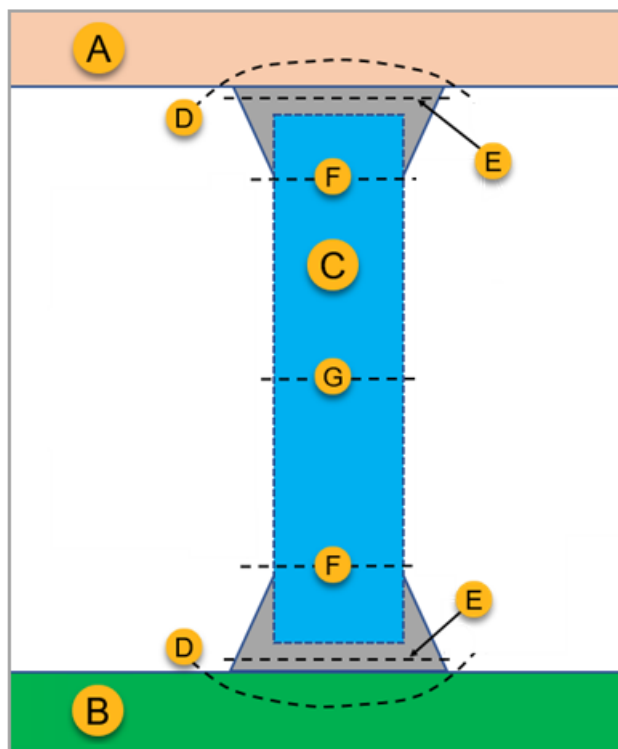
Two major factors contribute to column failure at the 63Sn37Pb solder fillet: the solder fillet size and column stiffness. Solder fillet size depends on the assembly quality between the column and the PCB

copper pad. Some factors that lead to poor solder fillet formation are stencil offset from the copper pad and a thin solder stencil. These lead to an insufficient volume of printed solder, causing inadequate fillet formation during reflow. In some high IO CCGA packages, the final solder fillet size depends on the pad-to-column diameter.

When a package has a high IO count with pad diameters nearly identical to column diameters, this prevents a sufficient amount of solder from wetting along the sides of the solder column, resulting in a very thin solder interconnect which is intended to serve as an extension of the high-lead solder column. A region of high stress concentration develops at the solder fillet-column interface because of the differences in mechanical behavior between the two lead solders. This stress region becomes a local source for fatigue crack nucleation and propagation, resulting in lower fatigue life compared to components in which crack propagation occurs through the high-lead solder column.

Failure location primarily depends on three factors: column material (Cu or high lead solder), solder fillet geometry, and the solder alloy (SnPb versus Pb-free). Most high-lead column CGAs utilize 63Sn37Pb solder. CuCGA have been demonstrated to possess a superior fatigue life to that of SnPb CCGA with the same physical dimensions under equivalent thermal cycles (Park et al., 2008 (p. 83)). Figure 2.60 (p. 76) illustrates potential failure locations in CCGA columns.

Figure 2.60: Schematic illustration of column deformation in CCGA packages under various loading modes.



A - Ceramic • B - PCB • C - Solder • D- Pad Cratering • E - Cracking in solder joint 63Sn37Pb • F - Cracking of high lead column at fillet • G - Cracking of high lead column at center

When excessive package warpage and bending occur, pad cratering becomes a concern, although it is unlikely to happen on the ceramic substrate because of its hardness and low CTE. Where pad cratering failure becomes a greater concern is with the small, copper-coil wrapped columns with small copper pads like those found in high I/O CCGA packages (Ghaffarian, 2016 (p. 82)). Preconditions of pad and column configuration result in smaller solder joints between the PCB and the column and, once again, shift the location of crack propagation from the high-lead solder column to the smaller

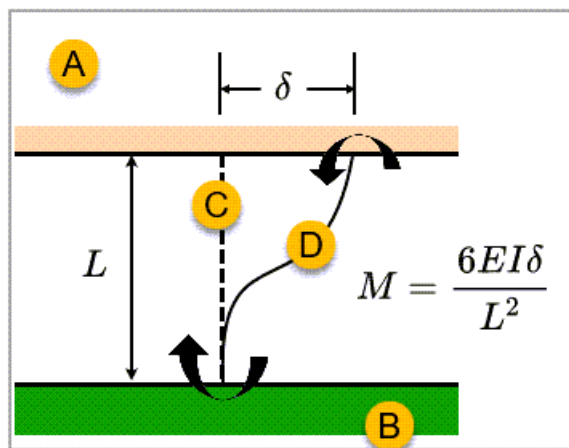
solder and stiffer solder fillet. Due to local mismatch between the PCB and the high-lead solder fillet, large bending stresses localize at the periphery of copper pads resulting in pad cratering.

2.6.2. The CCGA Analysis Model in Sherlock

The dominant failure mechanism addressed in Sherlock's CCGA analysis model is fatigue failure in the high-lead solder column. This mechanism is directly proportional to the bending loads applied to the solder columns by the thermal expansion mismatch between the board and the ceramic substrate. Sherlock uses a closed form analytical formulation for this calculation. It is a parametric approach to fatigue life prediction. In addition, you can use this analytical model as a tradeoff tool for optimizing reliability performance on the board level where CCGA components are needed.

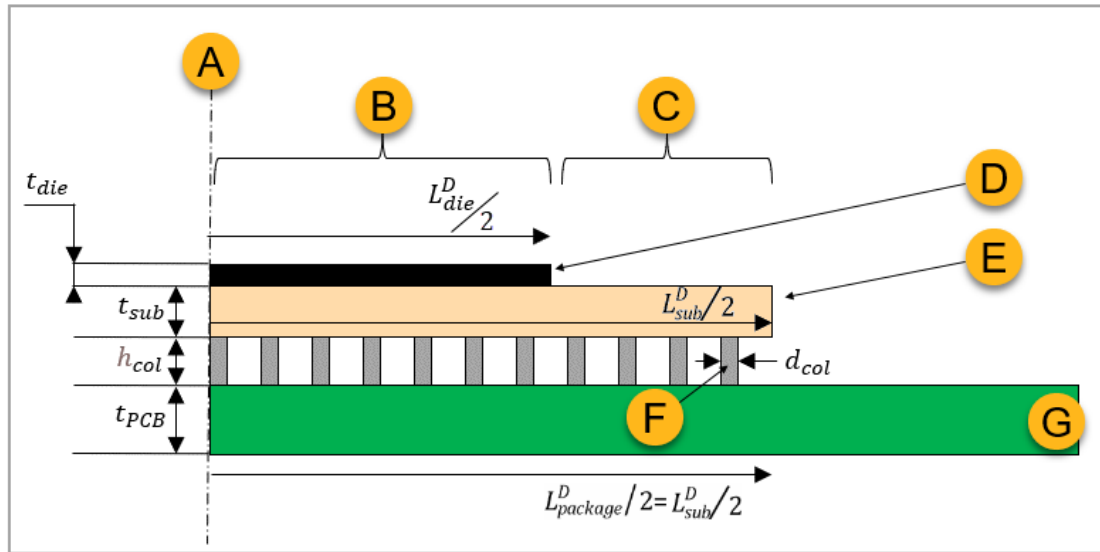
Sherlock's analytical model for CCGA calculates the total inelastic strain energy density (ΔW_{SED}) the column material experiences at its distance from the neutral point during thermal fluctuation. The energy term considers the effects of both the hot and the cold dwell time during thermal cycling. For the energy calculation, Sherlock computes the stress at the column tip of the package side, assuming beam-bending due to the fixed end moments. Strain, however, is computed based on the CTE differences between the PCB and the effective package material. To account for the dwelling effect from the thermal profile, Sherlock scales strain using the Norris-Landsberg equation. [Figure 2.61 \(p. 77\)](#) shows a simple illustration of column bending due to fixed end moment.

Figure 2.61: Column deformation in CCGA package under various loading modes



A - Package • B - PCB • C - Undeformed Column • D - Deformed Column

[Figure 2.62 \(p. 78\)](#) below shows the model parameters and the physical and material properties of a CCGA package.

Figure 2.62: Diagonal Cross-Section of CCGA

A - Centerline • B - Die Region • C - Corner Region • D - Die • E - Substrate • F - Column • G - PCB

Temperature Profile:

$T_{\max}$	Thermal Profile Maximum Temperature
$T_{\min}$	Thermal Profile Minimum Temperature
T_{mean}	Mean Temperature
T_{cold}	Cold Temperature Difference
T_{hot}	Hot Temperature Difference
$T_{\text{dwell}}^{\text{cold}}$	Dwell Time at $T_{\min}$
$T_{\text{dwell}}^{\text{hot}}$	Dwell Time at $T_{\max}$

Package Parameters– Substrate:

L_{sub}	Length of Substrate
W_{sub}	Width of Substrate
t_{sub}	Thickness of Substrate
E_{sub}	Elastic Modules of Substrate
ν_{sub}	Poisson's ratio of substrate
a_{sub}	CTE of substrate
L_{sub}^D	Diagonal length of substrate

Package Parameters– Die

L_{die}	Length of Die
W_{die}	Width of Die
t_{die}	Thickness of Die
E_{die}	Elastic Modulus of Die
ν_{die}	Poisson's ratio of die
a_{die}	CTE of die
L_{die}^D	Diagonal length of die

Package Parameters– Columns

d_{col}	Column Diameter
h_{col}	Column Height
P_{col}	Column Pitch
N_{col}	Number of Columns

PCB Parameters

t_{PCB}	Thickness of PCB
E_{PCB}	Elastic modulus of PCB

α_{PCB}

CTE of PCB

2.6.2.1. Shear Stress & Strain Calculation in Column

The shear stress calculation approach in Sherlock's analytical model is derived from Chen and Nelson's methodology for two elastic layers joined by one bonded joint (Chen et al., 1979 (p. 82)). According to Chen's model, Equation 2.131 (p. 79) gives the maximum shear stress at $T_{\max}$ along the length of the bonded joint.

$$\tau_{\text{col}}^{\Delta T_{\text{hot}}} = \frac{(\alpha_{\text{PCB}} - \alpha_{\text{package}}^{\text{eff}}) \Delta T_{\text{hot}} G_{\text{col}}^{\text{eff-hot}} \tanh\left(\frac{\beta_{\Delta T_{\text{hot}}} l_{\text{sub}}^D}{2}\right)}{\beta_{\Delta T_{\text{hot}}} h_{\text{col}}} \quad (2.131)$$

where,

$\alpha_{\text{package}}^{\text{eff}}$ is the effective package CTE.

ΔT_{hot} is the difference between T_{mean} and $T_{\max}$.

$G_{\text{col}}^{\text{eff-hot}}$ is the effective column shear modulus at $T_{\max}$.

$\beta_{\Delta T_{\text{hot}}}$ is given by equation Equation 2.132 (p. 79).

$\tau_{\text{col}}^{\Delta T_{\text{hot}}}$ is the column shear stress at $T_{\max}$.

$$\beta_{\Delta T_{\text{hot}}} = \sqrt{\frac{G_{\text{col}}^{\text{eff-hot}}}{h_{\text{col}}} \left[\frac{1}{E_{\text{package}}^{\text{eff}} t_{\text{sub}}} + \frac{1}{E_{\text{PCB}} t_{\text{PCB}}} \right]} \quad (2.132)$$

Likewise, Chen's model calculates stress at ΔT_{cold} by considering properties at $T_{\min}$. In CCGA packages, the column material is used for the bonding material. Shear stress is then calculated for the hot and cold dwell separately by considering the temperature dependent column modulus. To take into account the effects of the I/O pins, the column modulus is adjusted based on its area ratio with respect to the package area. This is illustrated in Equation 2.133 (p. 79). The shear modulus for the column uses Equation 2.134 (p. 79) and the shear strain (Equation 2.135 (p. 79)) is determined from the stress and modulus for energy calculation. As of Sherlock 2023 R2, Poisson's ratio in Equation 2.134 (p. 79) defaults to 0.36.

$$E_{\text{col}}^{\text{eff-hot}} = \frac{A_{\text{col}}}{A_{\text{package}}} E_{\text{col}}^{\text{hot}} = \frac{N_{\text{col}} \frac{\pi}{4} (d_{\text{col}})^2}{L_{\text{sub}} W_{\text{sub}}} E_{\text{col}}^{\text{hot}} \quad (2.133)$$

$$G_{\text{col}}(\text{eff-hot}) = \frac{E_{\text{col}}(\text{eff-hot})}{2(1+0.36)} ; G_{\text{col}}(\text{eff-cold}) = \frac{E_{\text{col}}(\text{eff-cold})}{2(1+0.36)} \quad (2.134)$$

$$\gamma_{\text{col}}^{\Delta T_{\text{hot}}} = \frac{\tau_{\text{col}}^{\Delta T_{\text{hot}}}}{G_{\text{col}}^{\text{eff-hot}}} ; \gamma_{\text{col}}^{\Delta T_{\text{cold}}} = \frac{\tau_{\text{col}}^{\Delta T_{\text{cold}}}}{G_{\text{col}}^{\text{eff-cold}}} \quad (2.135)$$

2.6.2.2. Package Material Properties Calculation

For a CCGA package, the effective material properties in the stress calculation shown above are determined by combining the effective material properties of the die region and the corner region of the package by the rule of mixture (see Figure 2.62 (p. 78)). This accounts for the die size on the substrate. The equations below give the effective modulus $E_{\text{die}}^{\text{eff}}$ (Equation 2.136 (p. 80)) and the CTE, $\alpha_{\text{die}}^{\text{eff}}$ (Equation 2.137 (p. 80)).

$$E_{die}^{eff} = \frac{t_{die}E_{die} + t_{sub}E_{sub}}{t_{die} + t_{sub}} \quad (2.136)$$

$$\alpha_{die}^{eff} = \frac{t_{die}E_{die}\alpha_{die} + t_{sub}E_{sub}\alpha_{sub}}{t_{die}E_{die} + t_{sub}E_{sub}} \quad (2.137)$$

Then, Equation 2.138 (p. 80) and Equation 2.138 (p. 80) determine the effective modulus and CTE for the package.

$$E_{package}^{eff} = \left(\frac{1}{E_{die}^{eff}} \frac{L_{die}^D}{L_{sub}^D} \frac{t_{sub}}{t_{die} + t_{sub}} + \frac{1}{E_{sub}} \frac{(L_{sub}^D - L_{die}^D)}{L_{sub}^D} \right)^{-1} \quad (2.138)$$

$$\alpha_{package}^{eff} = \frac{L_{die}^D \alpha_{die}^{eff} + (L_{sub}^D - L_{die}^D) \alpha_{sub}}{L_{sub}^D} \quad (2.139)$$

2.6.2.3. Column Bending Stress Calculation

By treating the columns as beams fixed at two ends, as shown in Figure 2.61 (p. 77), you can calculate the bending stress (or normal stress) on the column due to moment. Equation 2.140 (p. 80) provides the bending moment of beams under such loading conditions. Equation 2.141 (p. 80) gives the stresses caused by the bending moment. Usually, the bending stress is orders of magnitude larger than the shear stress and, generally speaking, is the predominant factor in the overall strain energy density.

$$M_{col}^{\Delta T_{hot}} = \frac{6E_{col}^{\Delta T_{hot}} I_{col} \delta_{col}^{\Delta T_{hot}}}{h_{col}^2} \quad ; \quad M_{col}^{\Delta T_{cold}} = \frac{6E_{col}^{\Delta T_{cold}} I_{col} \delta_{col}^{\Delta T_{cold}}}{h_{col}^2} \quad (2.140)$$

$$\sigma_{col}^{\Delta T_{hot}} = \frac{M_{col}^{\Delta T_{hot}} \frac{d_{col}}{2}}{I_{col}} \quad ; \quad \sigma_{col}^{\Delta T_{cold}} = \frac{M_{col}^{\Delta T_{cold}} \frac{d_{col}}{2}}{I_{col}} \quad (2.141)$$

Equation 2.142 (p. 80) calculates the moment of inertia for a column with diameter d_{col} . The tip displacement δ_{col} of the column can be derived from the strain determined in Equation 2.135 (p. 79) and the column height h_{col} as shown in Equation 2.143 (p. 80).

$$\sigma_{col}^{\Delta T_{hot}} = \frac{M_{col}^{\Delta T_{hot}} \frac{d_{col}}{2}}{I_{col}} \quad ; \quad \sigma_{col}^{\Delta T_{cold}} = \frac{M_{col}^{\Delta T_{cold}} \frac{d_{col}}{2}}{I_{col}} \quad (2.142)$$

$$\delta_{col}^{\Delta T_{hot}} = \gamma_{col}^{\Delta T_{hot}} h_{col} \quad ; \quad \delta_{col}^{\Delta T_{cold}} = \gamma_{col}^{\Delta T_{cold}} h_{col} \quad (2.143)$$

2.6.2.4. Column Strain Calculation

Equation 2.144 (p. 80) provides the maximum strain on the column, caused by the CTE differences between the substrate and the PCB, during heating and cooling. Strain is scaled using the Norris-Landzberg equation (Equation 2.145 (p. 80)), an empirical correction to account for the dwelling effect. The equation correlates the increase in strain accumulation with the increase in dwell time and vice versa. The Coffin-Manson fatigue equation predicts cycles-to-failure by correlating calculated strain energy density using damage parameters for the high-lead solder alloy of the columns.

$$\epsilon_{col}^{\Delta T_{hot}} = \frac{(\alpha_{PCB} - \alpha_{package}^{eff}) \Delta T_{hot} \frac{L_{sub}^D}{2}}{h_{col}} \quad ; \quad \epsilon_{col}^{\Delta T_{cold}} = \frac{(\alpha_{PCB} - \alpha_{package}^{eff}) \Delta T_{cold} \frac{L_{sub}^D}{2}}{h_{col}} \quad (2.144)$$

$$adj. \quad \epsilon_{col}^{\Delta T_{hot}} = \epsilon_{col}^{\Delta T_{hot}} \left(\frac{t_{dwell}^{hot}}{t_{critical}^{hot}} \right)^{0.136} e^{\left(\frac{E_a}{k} \left(\frac{1}{T_{critical}} - \frac{1}{T_{max}} \right) \right)} \quad (2.145)$$

$$adj. \quad \epsilon_{col}^{\Delta T_{cold}} = \epsilon_{col}^{\Delta T_{cold}} \left(\frac{t_{dwell}^{cold}}{t_{critical}^{cold}} \right)^{0.136} e^{\left(\frac{E_a}{k} \left(\frac{1}{T_{critical}} - \frac{1}{T_{min}} \right) \right)} \quad (2.146)$$

where

$\text{adj.}\varepsilon_{\text{col}}^{\Delta T_{\text{hot}}}$ is the adjusted strain between mean and max temperature.

$\text{adj.}\varepsilon_{\text{col}}^{\Delta T_{\text{cold}}}$ is the adjusted strain between mean and min temperature.

$t_{\text{dwell}}^{\text{hot}}$ is the dwell time in mins at maximum temperature (from the Thermal Profile).

$t_{\text{dwell}}^{\text{cold}}$ is the dwell time in mins at minimum temperature (from the Thermal Profile).

t_{critical} is the **Critical Dwell Time** in mins for high lead solder (from [Figure 2.63 \(p. 81\)](#)).

T_{critical} is the **Critical Max Temp**, in K (from [Figure 2.63 \(p. 81\)](#)).

T_{max} is the maximum temperature in K (from the Thermal Profile).

T_{min} is the minimum temperature in K (from the Thermal Profile).

E_a is Activation Energy specific to solder in eV.

k is Boltzmann Constant in eV/K.

2.6.2.5. Cycle to Failure Calculation

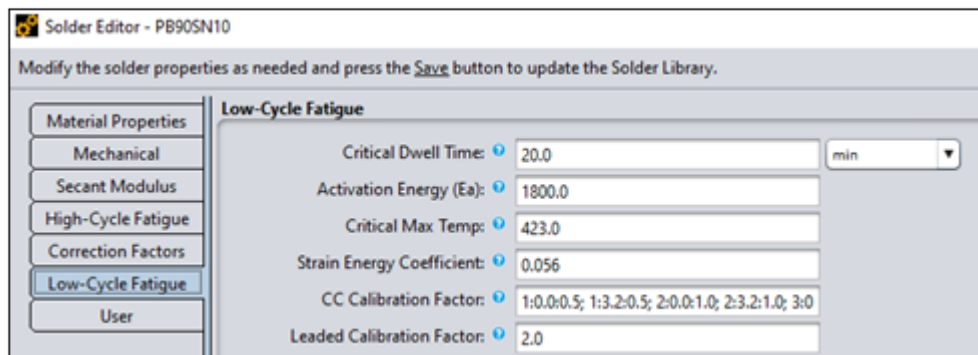
[Equation 2.147 \(p. 81\)](#) calculates the total strain energy density for the thermal cycle's temperature range, and [Equation 2.148 \(p. 81\)](#) predicts cycles-to-failure.

$$\Delta W_{\text{SED}} = \left| \text{adj.} \varepsilon_{\text{col}}^{\Delta T_{\text{hot}}} \cdot \sigma_{\text{col}}^{\Delta T_{\text{hot}}} \right| + \left| \text{adj.} \varepsilon_{\text{col}}^{\Delta T_{\text{cold}}} \cdot \sigma_{\text{col}}^{\Delta T_{\text{cold}}} \right| \quad (2.147)$$

$$N_f = (C_1 \cdot \Delta W_{\text{SED}})^n \quad (2.148)$$

Solder-specific parameters in [Equation 2.146 \(p. 80\)](#) and [Equation 2.148 \(p. 81\)](#) are user-definable, such as critical dwell time (t_{critical}), critical max temperature (T_{critical}), the strain energy coefficient (C_1), and activation energy over the Boltzmann constant (E_a/k). You can adjust all these parameters using the Solder Editor as shown below in [Figure 2.63 \(p. 81\)](#). The Sherlock model uses a solder exponent, n , of -1.453. This is specific to high lead (90Pb10Sn) solder. The quantity E_a/k in [Equation 2.146 \(p. 80\)](#) is defined as the Activation Energy (E_a) in [Figure 2.63 \(p. 81\)](#).

Figure 2.63: Solder Editor



2.6.3. Validation

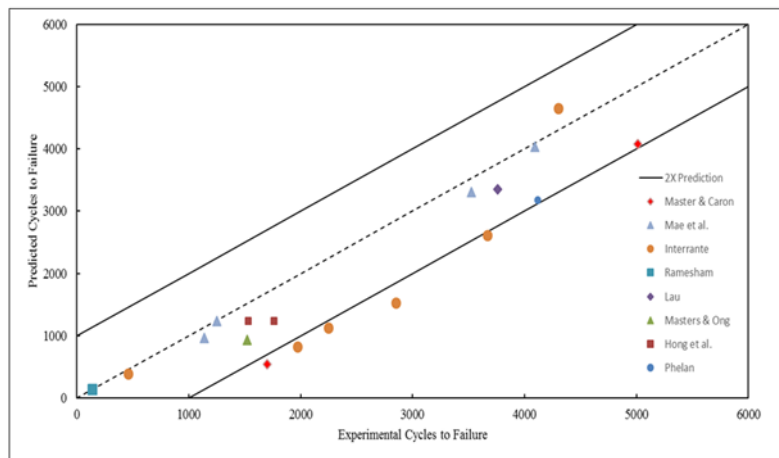
Sherlock's analytical model was validated by accelerated thermal cycling experiments. The experimental results came from a combination of industry and academic research efforts aimed at characterizing the fatigue performance of CCGA packages. The analysis set forth in this document does not include

local variations in the data set which is caused by non-standardized assembly practices among CCGA components. Currently, no single standard exists which defines the solder paste volume requirements or the pad-size-to-column diameter for the CCGA reflow process. For this reason, the final solder quality between researchers was not included as a factor. It is assumed to be constant.

Sherlock then generated thermo-mechanical fatigue predictions for these configurations, and they were compared to the experimental data. The results are displayed in [Figure 2.64 \(p. 82\)](#) below. The graph shows the experimental datapoints from published literature. Some experimental data points may deviate from the predicted values because material properties, package characteristics, or solder alloy information was unavailable at the time of analysis. Column diameters and ceramic substrate thicknesses are estimated based on standard component definitions.

Although Sherlock's predictions deviate from some data points, the analytical model is designed to provide conservative predictions. Without over-predicting the chance of failure, the model includes a safety factor which accounts for the potential tolerances inherent in the non-standard assembly process of CCGA components.

Figure 2.64: Predicted and experimental cycles to failure



2.6.4. References

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Chapter 3: Thermal Mech Theory

Note:

It's important to read the [Sherlock User's Guide](#) before accessing the theory guide content. The user's guide will help you become familiar with Sherlock's capabilities and workflow. A firm understanding of the Sherlock application is essential before delving into the substantial content of the *Sherlock Theory Reference*.

The Thermal Mech feature in Sherlock is a tool for analyzing an electronic assembly to assess potential failures caused by temperature cycling. These failures are driven by differences in the coefficients of thermal expansion (CTE) among the various materials which comprise the assembly. The different expansion rates of the parts and ensuing deformations account for stress in the assembly.

In Sherlock, the Thermal Mech analysis uses a finite element model to simulate the deformations in the electronic assembly, taking into account the temperature-dependent properties of each material. By creating specific Thermal Events, you can simulate thermal cycles and reflow cycles to identify the strain behind each component failure.

Beginning with version 2021 R2, Sherlock uses the Ansys Mechanical solver to perform its thermo-mechanical analysis. CalculiX will no longer be used. Prior to version 2023 R1, heat transfer analysis was not supported. Now, a complete suite of thermo-mechanical analysis tools is available. This includes the ability to incorporate Part Temperature Rise and to process Thermal Maps (using CSV or images files).

Similar to previous releases, Thermal Mech in 2023 R1 locates the maximum δ strain (delta strain in micro strain, $\mu\epsilon$) for the components in the assembly. Currently, reliability prediction and scoring are not available. However, you can use the strain values outside the Thermal Mech tool to carry out reliability studies.

Section Summary:

- [3.1. Thermal Mech Analysis](#)
- [3.2. Thermal Mech Strain](#)
- [3.3. Thermal Mech Analysis Results](#)
- [3.4. Thermal Mech Results Table](#)
- [3.5. Graphical FEA Results](#)

3.1. Thermal Mech Analysis

Thermal Mech analysis in Sherlock consists of three parts:

1. Preparing the electronic board for the analysis

2. Solving the model
3. Post-Processing the results for δ strain (p. 107)

Once the necessary input data for the analysis is configured, Sherlock runs the analysis and automatically computes the strain that leads to component failure. The Thermal Mech module in Sherlock uses the following input data for its analysis.

- [Thermal Events](#) and Custom Uniform Temperatures
- Part Temperature Rise, Thermal Map (CSV), Thermal Map (Image)
- [Parts List](#)
- Size and location of all parts, plated through-holes, and cutouts
- Circuit card mechanical properties (stackup data)
- Mesh Properties
- [Mount Points](#)

Thermal Events in Sherlock are temperature profiles applied to the electronic assembly during a thermo-mechanical analysis. When you create a Thermal Event, you specify a temperature profile and the number of cycles it will be applied to the assembly. As shown below, Sherlock provides a complete interface for defining all facets of the Thermal Event, including the **Thermal Profile** (A, in [Figure 3.1: Thermal Event Editor \(p. 87\)](#)) and the number cycles (B) it will be applied to the assembly.

Because the Thermal Mech module in 2023 R1 does not make reliability predictions, some parameters in the **Thermal Event Editor** are not used in the calculations. Specifically, when Sherlock runs a Thermal Mech analysis, the following Thermal Event parameters are *not* used:

- **# of Cycles** (B)
- **Life Cycle State** (C)

Figure 3.1: Thermal Event Editor

Thermal Event Editor

Modify any of the following properties and press the **Save** button to update the current Thermal Event.

Identification

Name:

Description:

Thermal Event Settings

of Cycles: B

Life Cycle State: C

Thermal Profile A

Thermal Cycle

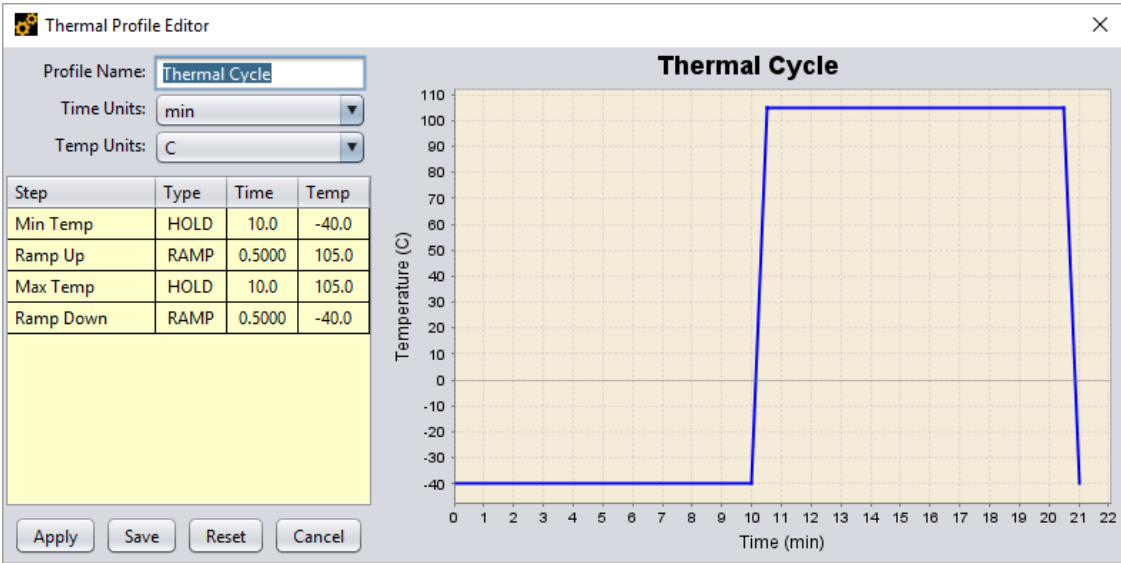
Temperature (C)

Time (min)

Buttons: Load Profile ... Edit Profile ... Save Profile ... Save Reset Cancel

Figure 3.2: Thermal Profile Editor (p. 88) shows the **Thermal Profile** used above to define the **Thermal Event**. Sherlock currently supports only HOLD-RAMP-HOLD-RAMP Thermal Profiles. Note that the **Time Units** setting in the **Thermal Profile Editor** is *not* used in the Thermal Mech analysis due to the nature of the steady-state/static analysis which does not use the parameter of time.

Figure 3.2: Thermal Profile Editor



With a defined Thermal Event, Sherlock can run a quick thermo-mechanical analysis where the electronic assembly is subjected to a simple isothermal rise condition. It represents a what-if scenario where the entire assembly is at a uniform temperature. Based on the Thermal Event definition, Sherlock carries out a two-step static structural analysis using the Ansys solver. In the first step, the assembly is subjected to the minimum temperature from the Thermal Event. In the second step, it is subjected to the maximum temperature. The strain from the structural analysis will be used for the δ strain calculation

In addition to creating Thermal Events in Sherlock, you can also run an isothermal thermo-mechanical analysis using custom temperature points (see **Custom Uniform Temps**, A in [Figure 3.3: Thermal Mech Properties](#) (p. 89)). This is an easy way to run a quick ramp-up or ramp-down analysis without having to define a Thermal Event. This feature is exclusively used for running an isothermal analysis and does not support any type of heat transfer analysis. Sherlock uses the custom temperature points to apply the uniform temperature in the Ansys solver.

Tip:

The **Custom Uniform Temps** field can take multiple temperature values, separated by a comma. The default unit is Celsius. However, each temperature you enter can have its own unit. For example:0°C,32°F, 273.15 K all specify the same temperature using different units.

Figure 3.3: Thermal Mech Properties

Thermal Mech Properties

Specify the desired analysis properties. The **Settings >> General Settings >> FEA Analysis** main menu option can also be used to specify FEA analysis properties across all projects and CCAs.

Data Source: **Generated**

Thermal Properties | Thermal Events

Reference Temp: **20.0** **C**

Custom Uniform Temps:

Analysis Properties

TM Result Count: **1**

Part Validation: **ENABLED**

PCB Modeling | Trace Modeling | Mount Points | Drill Holes | Part Modeling | Lead Modeling | Wire Bonds | Heat Sinks | Potting Regions | Mechanical Parts

Mesh Type: **Bonded**

Modeling Regions: **DISABLED**

PCB Model: **Uniform**

of PCB Materials: **100**

Element Order: **First Order**

Max Mesh Size: **2** mm

Vertical Mesh Size: **0.5** mm

Quads Preferred: **YES**

Save & Run | Save | Reset | Cancel | Help

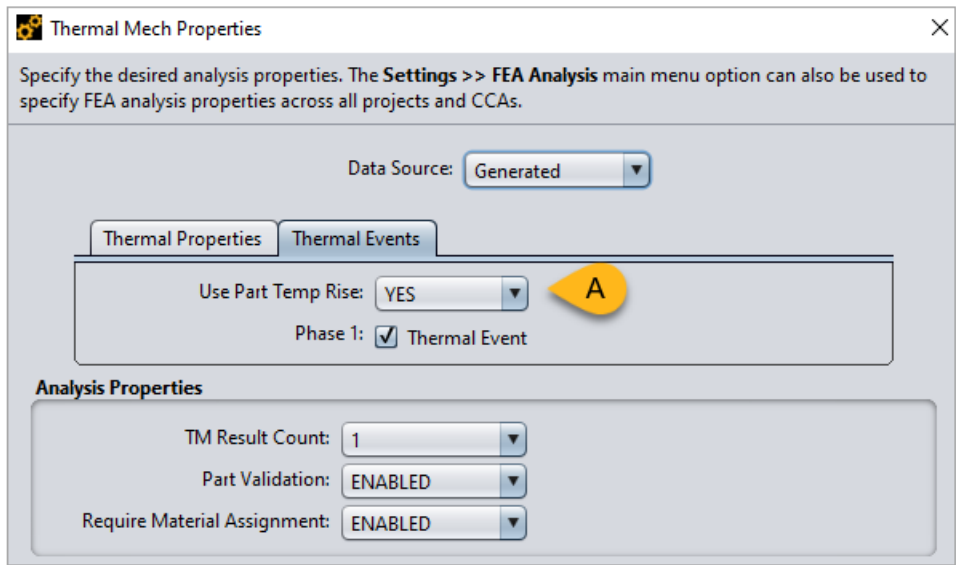
Starting with version 2023 R1, Sherlock supports thermal conduction analyses. Conduction can be represented using the components' Part Temperature Rise property or a by incorporating a Thermal Map (image or CSV file). The Part Temperature Rise property for a component defines its rise in temperature that occurs during operating conditions.

To run a Thermal Mech analysis with Part Temperature Rise, set **Use Part Temp Rise** to **YES** when setting up the analysis (see A in [Figure 3.4: Thermal Mech Properties, Part Temp Rise \(p. 90\)](#)). Sherlock will run a thermal analysis to identify the temperature distribution on the circuit card and follow it with a static structural analysis for strain distribution. You can set the **Temperature Rise** for each part in the circuit

card using the **Part Editor** (see B in [Figure 3.5: Part Editor \(p. 90\)](#)). It should be noted that Sherlock ignores the **Part Temp Rise** value for all components *unless* you set **Use Part Temp Rise** to **YES** (A, below) in the **Thermal Mech Properties** dialog.

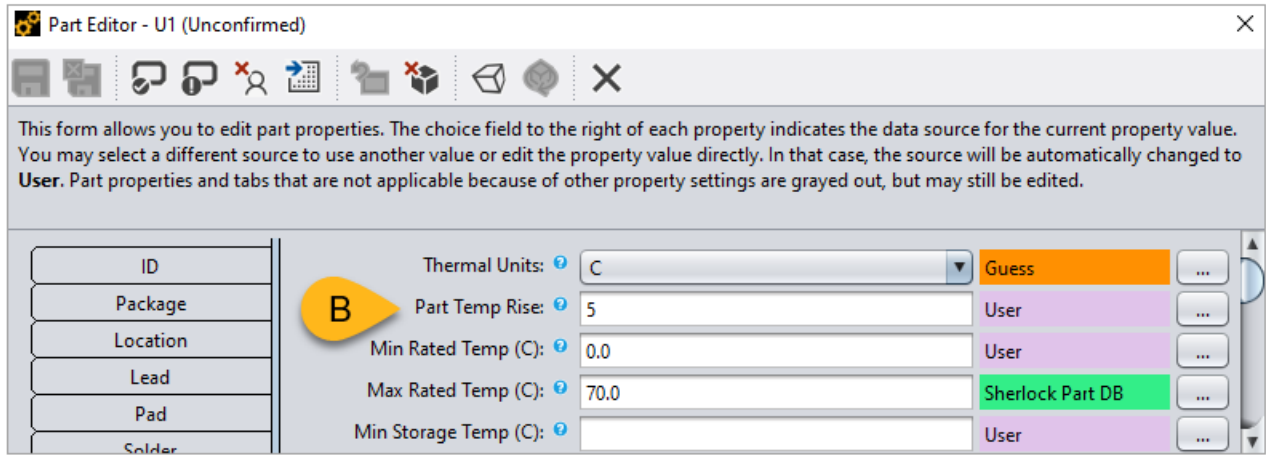
If you set **Use Part Temp Rise** to **NO**, Sherlock will skip the thermal analysis (unless the Thermal Event is associated with a Thermal Map) and run an isothermal, static structural analysis by applying a uniform temperature across the circuit card based on the Thermal Profile.

Figure 3.4: Thermal Mech Properties, Part Temp Rise



In the **Part Editor** shown below, you can set the **Part Temp Rise** property to a positive or a negative temperature value, or you can set it to **DEFAULT**. When set to **DEFAULT**, Sherlock does not apply any temperature boundary condition to the part. Rather, it solves for its respective nodal temperature based on other boundary conditions.

Figure 3.5: Part Editor



You can view the **Part Temp Rise** value for all parts on the circuit card using the **Parts List** (see below, [Figure 3.6: Parts List in Sherlock \(p. 91\)](#)). Be sure to [customize the table](#) so the **Part Temp Rise** column is displayed.

Figure 3.6: Parts List in Sherlock

ODB++ Tutorial Parts List

The following table contains all parts currently defined for this CCA. The items are color coded so that you know the origins of each component. Double-click on a row to view all properties associated with that part.

Sources: User AVL PCB PartsDB PackageDB BOM PickPlace Guess

Advanced Filter
Part Count: 221 Unique Parts: 17

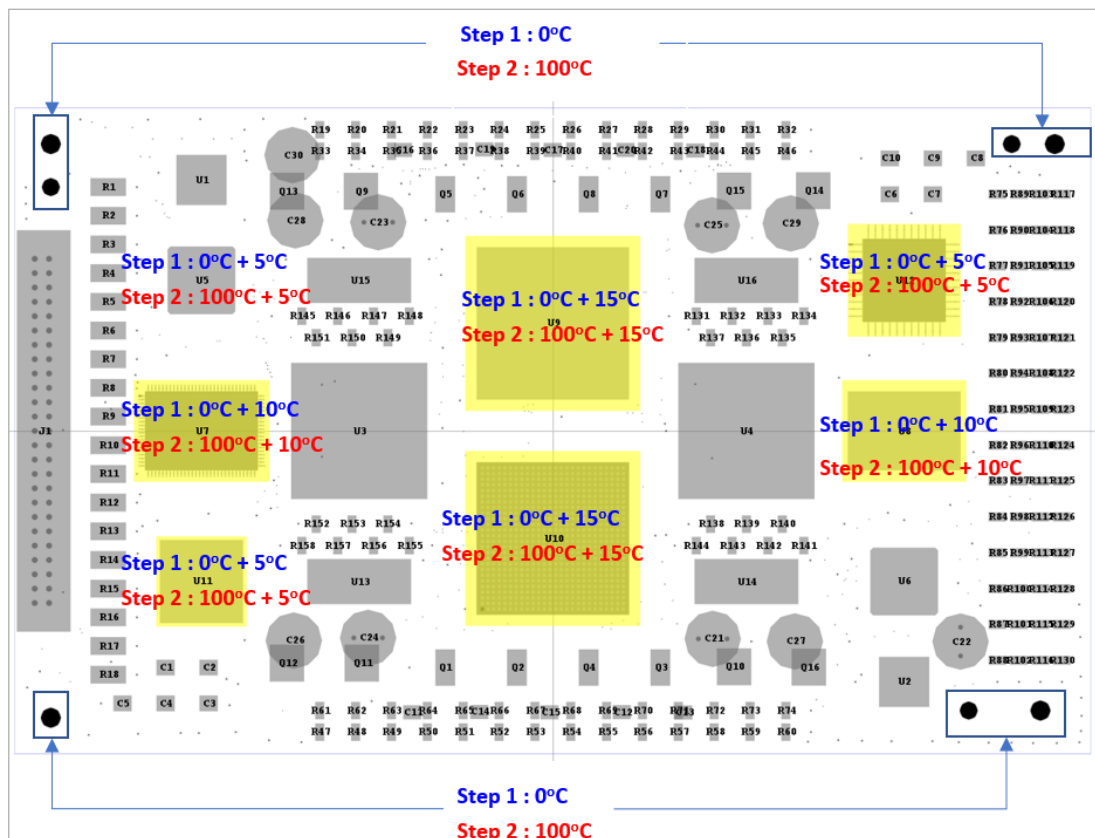
Reset Load Clear Apply Filter Save Properties

Parts Listing (221)

Ref Des	Part Number	Part Temp Rise	Part Type	Package Type	Manufacturer	Package	Location	Material
U1	UC3688Q	5	C	LCCC	TEXAS INSTRUMENTS	SMT LCCC-20	TOP	EPOXYENCAPSULANT
U5	DSPIC33F64G5608-E/PT	5	C	QFP	MICROCHIP TECHNOLOGY	SMT QFP-80	TOP	EPOXYENCAPSULANT
U11	HI-8435PQTF	5	C	QFP	HOLT INTEGRATED CIRCUITS	SMT QFP-44 (MO-084AB)	TOP	EPOXYENCAPSULANT
U12	HI-8435PQTF	5	C	QFP	HOLT INTEGRATED CIRCUITS	SMT QFP-44 (MO-084AB)	TOP	EPOXYENCAPSULANT
U7	IS61LPS12836A-200TQLI	10	C	QFP	ISSI INTEGRATED SILICON	SMT QFP-100 (MO-112CC-1)	TOP	EPOXYENCAPSULANT
U8	IS61LPS12836A-200TQLI	10	C	QFP	ISSI INTEGRATED SILICON	SMT QFP-100 (MO-112CC-1)	TOP	EPOXYENCAPSULANT
U9	XCV405E-6FG676I	15	C	BGA	XILINX	SMT BGA-676 (MS-034-AAL-1)	TOP	LAMINATE-BGA
U10	XCV405E-6FG676I	15	C	BGA	XILINX	SMT BGA-676 (MS-034-AAL-1)	TOP	LAMINATE-BGA
C1	TMC1CBTTE106M	DEFAULT	CAPACITOR	CBEND	AVX KYOCERA	SMT C-BEND-3528-12	TOP	TANTALUM
C2	TMC1CBTTE106M	DEFAULT	CAPACITOR	CBEND	AVX KYOCERA	SMT C-BEND-3528-12	TOP	TANTALUM
C3	TMC1CBTTE106M	DEFAULT	CAPACITOR	CBEND	AVX KYOCERA	SMT C-BEND-3528-12	TOP	TANTALUM
C4	TMC1CBTTE106M	DEFAULT	CAPACITOR	CBEND	AVX KYOCERA	SMT C-BEND-3528-12	TOP	TANTALUM

Thermal boundary conditions for the card shown in the above **Parts List** is illustrated in the following figure.

Figure 3.7: Part Temp Rise: Temperature Boundary Condition



In addition to Part Temperature Rise, Sherlock versions 2023 R1 and later give you the ability to assign temperature values to parts based on data contained in a CSV file. A sample CSV file in spreadsheet

form is shown below: One column contains the parts' **RefDes** while the other column contains temperature data. In Sherlock, this feature is called Thermal Map (CSV).

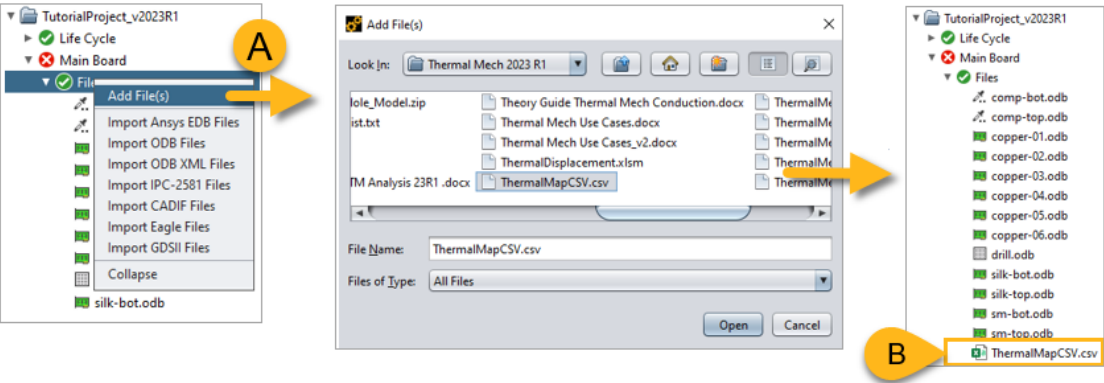
It is important to understand: While the Part Temp Rise values are added to the temperature from the Thermal Profile during an analysis, the Thermal Map (CSV) is handled differently. Temperature data from a CSV file is applied directly to the parts as is and is *not* added to the values from the Thermal Profile.

Figure 3.8: CSV File Containing Part Temperature Data

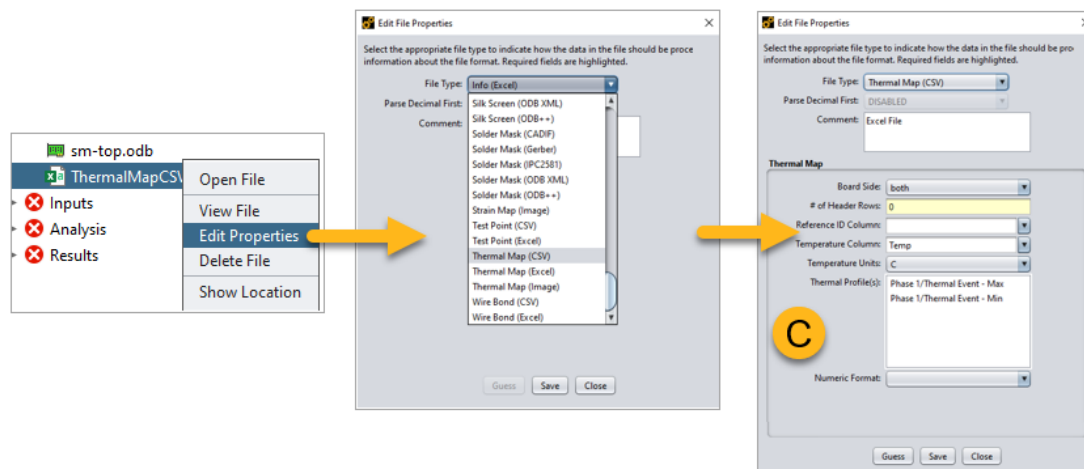
	A	B
1	RefDes	Temp (C)
2	U5	105
3	U7	110
4	U11	105
5	U9	115
6	U10	115
7	U12	105
8	U8	110

Figure 3.9: Adding CSV File to Sherlock (p. 92) illustrates how you can add a CSV file to a project in Sherlock. Right-click the **Files** object in the **Project Tree** and select **Add File(s)**. Use the **Add File(s)** dialog to navigate to and select the CSV file. When finished, the file will appear in the **File Tree** (B).

Figure 3.9: Adding CSV File to Sherlock



Once the CSV file has been added to the project, you must edit the file so Sherlock can process it correctly. As shown below (see [Figure 3.10: Configuring the CSV File \(p. 93\)](#)): Right-click the ThermalMapCSV.csv file and select **Edit Properties** in the context menu. In the **Edit File Properties** window, change the **File Type** to **Thermal Map (CSV)**. This opens the **Thermal Map** panel.

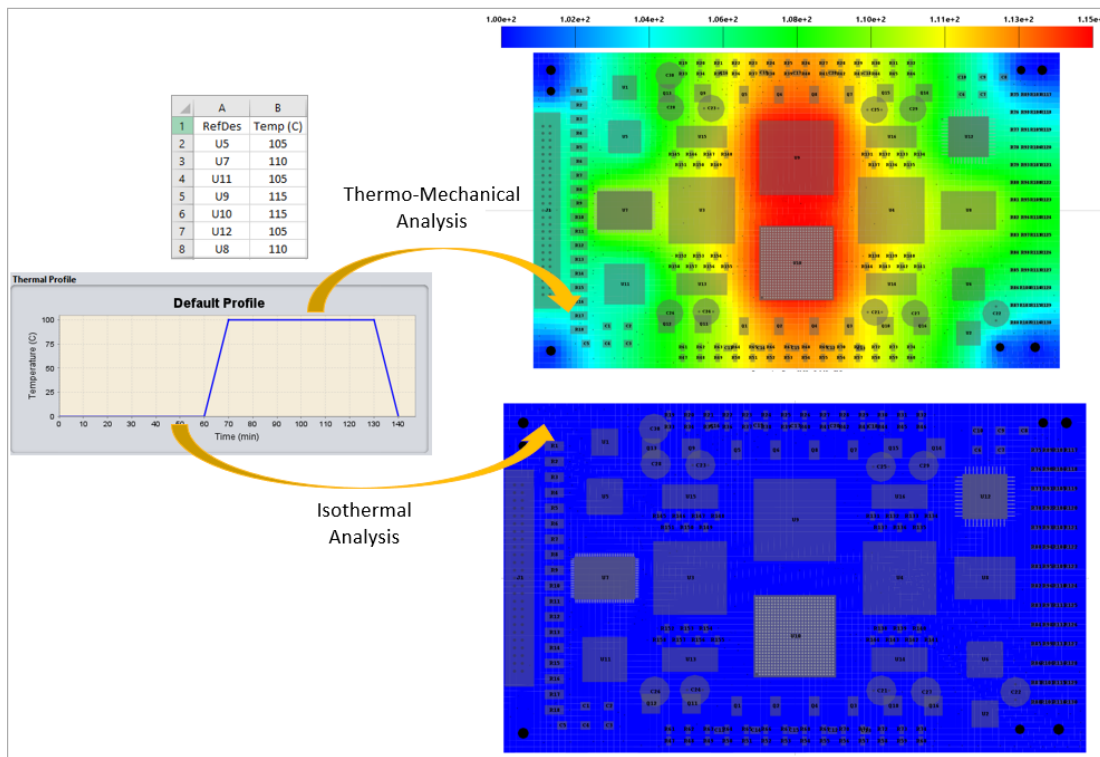
Figure 3.10: Configuring the CSV File

The **Board Side** option in the **Thermal Map** panel (C, above) is not used for a Thermal Map (CSV), so your selection is immaterial. The **# of Header Rows** dictates the number of header lines in the CSV file. Based on our format, [Figure 3.8: CSV File Containing Part Temperature Data \(p. 92\)](#), the first line is represented by the index 0.

For **Reference ID Column**, use the drop-down menu to select the column containing the **RefDes** data. Likewise, use the **Temperature Column** option to select the column containing the temperature data. Then set the **Temperature Units**. The **Thermal Profile(s)** selection is especially important: The field lists the minimum and maximum step of all the Thermal Events defined under the project Life Cycle. When using a CSV file, you must associate the file to one or more Thermal Events.

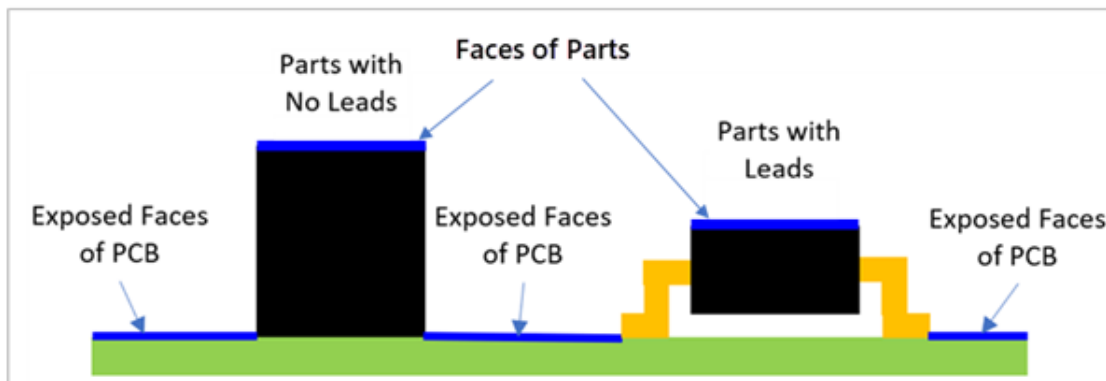
The figure below illustrates the effects of the CSV file (from [Figure 3.10: Configuring the CSV File \(p. 93\)](#)) being associated to the **Phase 1/Thermal Event - Max**. When Sherlock runs a thermo-mechanical analysis for a Thermal Profile, it runs a two-step thermal analysis. Then it runs a two-step structural analysis using the imported temperatures in the results (RTH) file from the previous thermal analysis. The two steps in both analyses correspond to the minimum temperature and the maximum temperature obtained from the Thermal Profile of the selected Thermal Event. When the CSV is associated with the **Phase 1/Thermal Event - Max**, it is automatically associated to the maximum step of the analysis. Therefore, the parts in the CSV file are assigned the temperature from the CSV file only for the maximum step of the analysis. If no file is associated with the minimum step of the Thermal Event (**Phase 1/Thermal Event - Min**), Sherlock does not run a thermal analysis but rather applies the minimum temperature from the event as a uniform temperature across the circuit card. The temperature distribution used for a static structural analysis is shown in the figure below.

Figure 3.11: Temperature Distribution with CSV file associated to Max Temperature of Thermal Profile

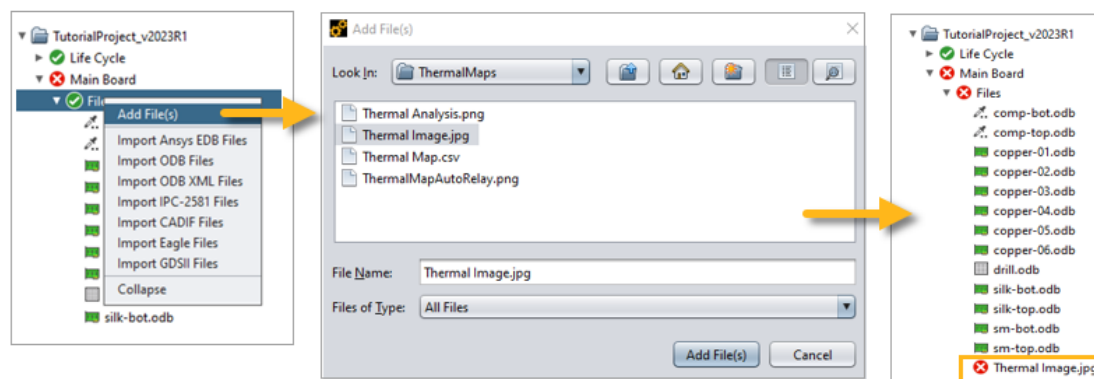


Similar to a Thermal Map (CSV), Sherlock versions 2023 R1 and later can also run a Thermal-Mech analysis using temperature data from images. When you provide the temperature distribution in image format, Sherlock runs the thermal analysis using temperature distribution obtained from the image and carries out a structural analysis from the thermal solve for displacements and strains. In contrast to an analysis which uses a Thermal Map (CSV) (where temperature is applied only to parts as boundary conditions), when Sherlock uses a Thermal Map (Image), boundary conditions are applied to all the exposed faces of the circuit card. This includes parts as well as the PCB, as shown in the figure below.

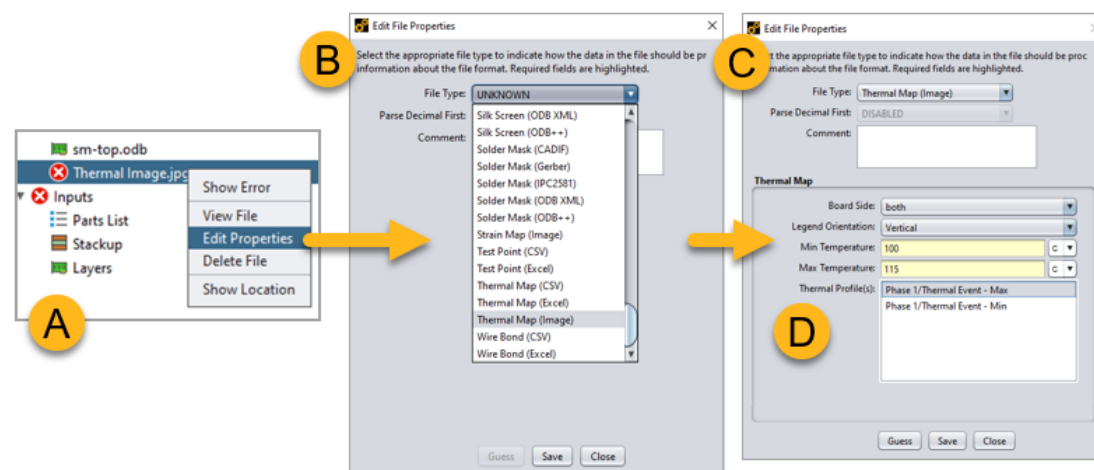
Figure 3.12: Temperature Distribution with Image file Associated to Max Temperature of Thermal Profile



Adding an image file to Sherlock for a Thermal Mech analysis is similar to adding the CSV file as shown below.

Figure 3.13: Adding Image file to Sherlock

Once the file has been added to the **Files Tree**, you must configure it so Sherlock can process it as a Thermal Map (Image): Right-click the **Thermal Image.jpg** file (A, below) to open **Edit File Properties** window (B). Set the **File Type** to Thermal Map (Image) (C). This opens the **Thermal Map** (D) options.

Figure 3.14: Adding Image file to Sherlock

Refer to [Figure 3.15: Configuring the Thermal Map \(Image\) File \(p. 96\)](#) below. Unlike a Thermal Map (CSV) analysis, Sherlock uses the **Board Side** selection (E) when using a Thermal Map (Image). You must let Sherlock know whether the image is of the top (**TOP**), bottom (**BOT**), or of **both** sides of the board. Use the **Legend Orientation** drop-down menu (F) to indicate whether the temperature legend is horizontal or vertical. Sherlock requires this information to interpret the temperature scale correctly. (As an example, in [Figure 3.17: Aligning Board Outline and Legend \(p. 97\)](#), the legend is vertical.) Finally, specify the **Min Temperature** and **Max Temperature** (G) represented in the thermal image.

Figure 3.15: Configuring the Thermal Map (Image) File

Edit File Properties

Select the appropriate file type to indicate how the data in the file should be processed and then enter the specific information about the file format. Required fields are highlighted.

File Type: Thermal Map (Image) ▼

Parse Decimal First: DISABLED ▼

Comment: Text Information File

Thermal Map

Board Side: both ▼ **E**

Legend Orientation: Vertical ▼ **F**

Min Temperature: 100 C ▼ **G**

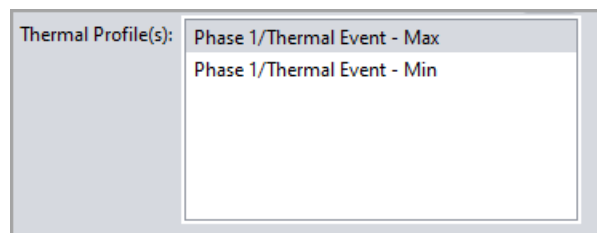
Max Temperature: 115 C ▼ **G**

Thermal Profile(s): Phase 1/Thermal Event - Max
Phase 1/Thermal Event - Min **H**

Buttons: Guess Save Close

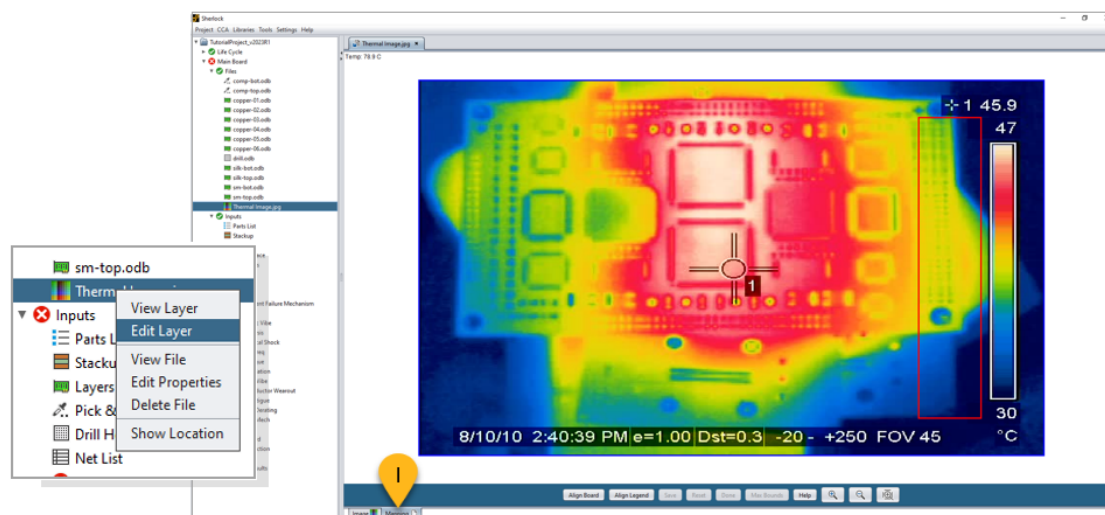
As with a Thermal Map (CSV) file, the **Thermal Profile(s)** selection field (H, above) lists the minimum and maximum steps of all the Thermal Events defined under the project Life Cycle. For any analysis using a thermal image file you must, associated it with one or more Thermal Events.

In this example, the image file will be associated with the Thermal Profile **Phase 1/Thermal Event – Max** as shown below in [Figure 3.16: Selecting the Thermal Event \(p. 97\)](#). This associates the image to the maximum step of the Thermal Event. Click **Save** in the **Edit File Properties** window to save the association.

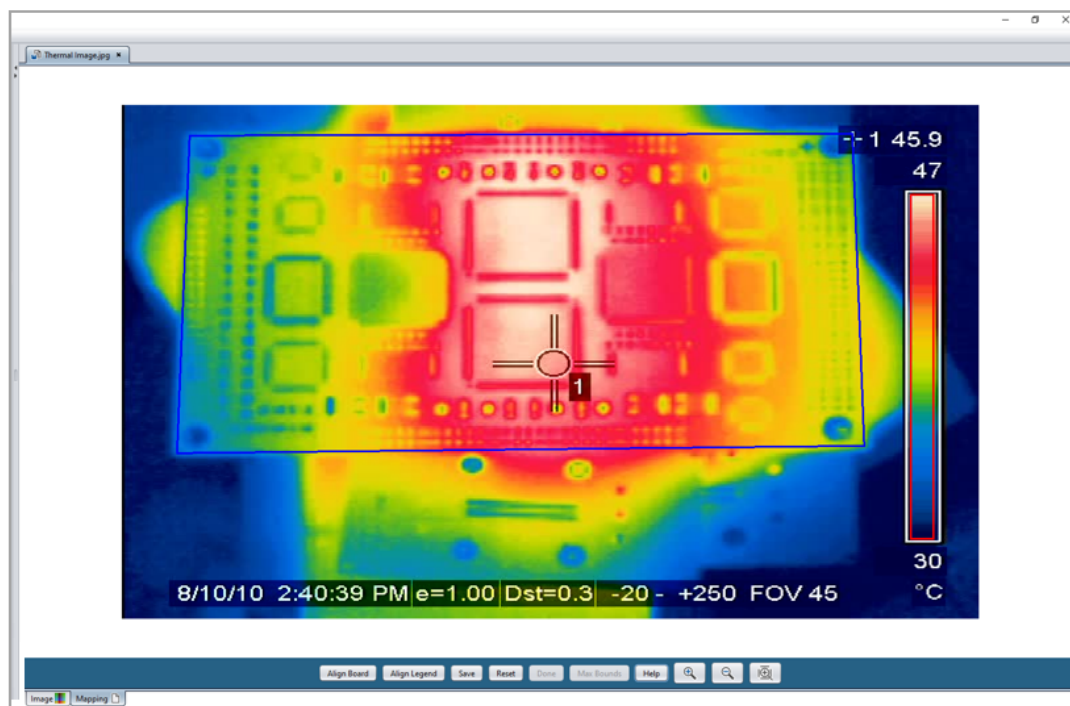
Figure 3.16: Selecting the Thermal Event**Tip:**

How Sherlock Handles Mount Points: It's important to understand how Sherlock applies temperature to mount points in the various kinds of analyses. Mount points are typically attached to the casing. During operation, represented by the thermal cycle in Sherlock, the mount points tend to rise to the thermal cycle temperature. By contrast, when a part generates heat on the PCB, there is only a slight temperature increase at the footprint of the component. When using a Thermal Map (CSV), Sherlock maintains the mount points at the temperature dictated by the *thermal cycle*. However, when using Thermal Map (Image), Sherlock respects your choice of Minimum and Maximum Temperature near the mount points and does not force the thermal cycle temperature at mount points as it will change the contour of the image you provide. In short, an accurate Thermal Map (Image) is especially important when it comes to mount points.

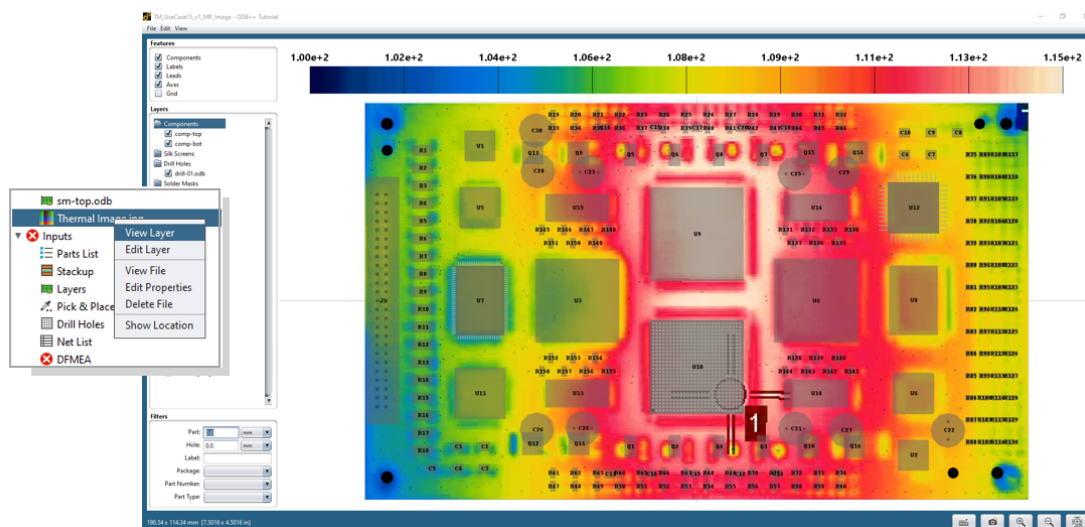
The next step in preparing the thermal image for the analysis is to help Sherlock identify the board outline and the legend in the image. To begin, right-click the image file in the **Project Tree** and select **Edit Layer**, as shown below. This opens the board image in Sherlock's viewer.

Figure 3.17: Aligning Board Outline and Legend

Click the **Mapping** tab (I, above). Then click the **Align Board** button and manually adjust the blue box so it corresponds with the board outline. When finished, **Save** the changes. Then click the **Align Legend** button and manually adjust the red box so it marks the boundaries of the legend. Again, **Save** the changes when finished. The figure below ([Figure 3.18: Board and Legend Alignment in Sherlock \(p. 98\)](#)) shows what the image looks like when the alignments are completed.

Figure 3.18: Board and Legend Alignment in Sherlock

When the alignments are saved, Sherlock gives you the option to overlay the thermal image onto the board within the **Layer Viewer** as shown below. The image shows that, at maximum temperature of the cycle, the Mount Points are at 100°C as expected. The maximum temperature is 115°C as represented by the reddish white in the image.

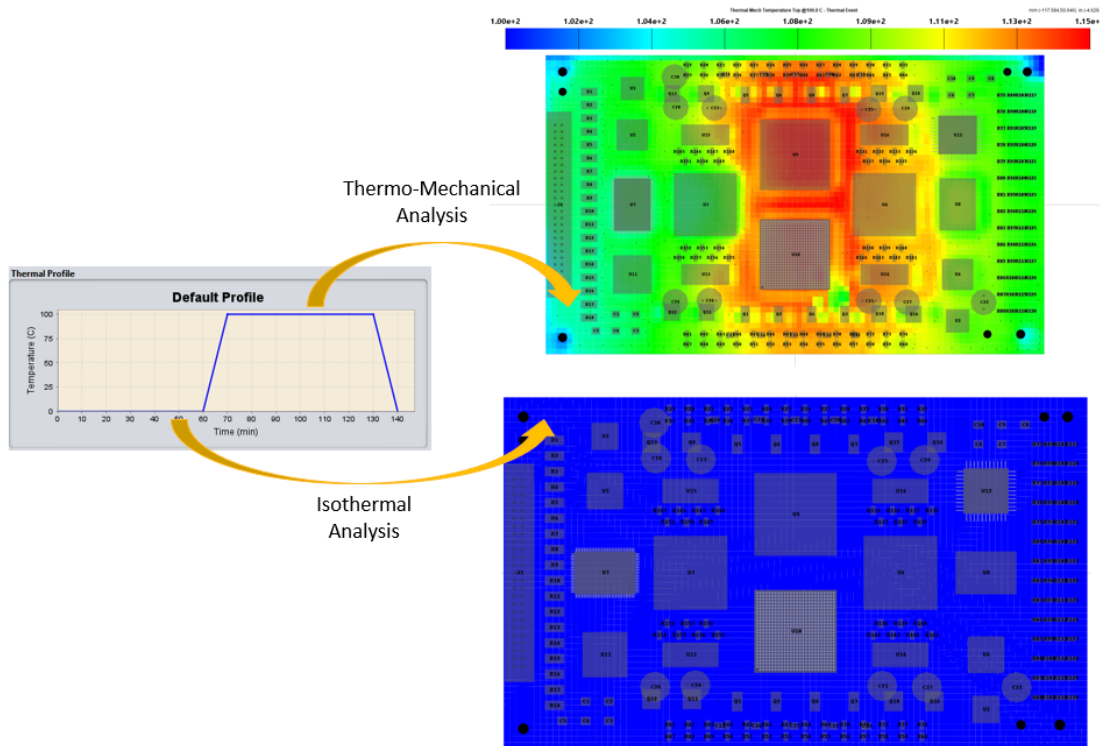
Figure 3.19: : Thermal Image in Layer Viewer

When Sherlock runs the thermo-mechanical analysis with the thermal distribution at the maximum temperature step, the temperature loading is applied to the exposed faces of the PCB (as shown in [Figure 3.12: Temperature Distribution with Image file Associated to Max Temperature of Thermal Profile \(p. 94\)](#)) including the faces of the parts and any potting regions. All the other nodes are solved for during the thermal analysis phase. Sherlock follows the thermal analysis with a static structural to de-

termine strain. The thermal loads used for structural analysis are as shown in [Figure 3.20: Thermal Loads from Thermal Map \(Image\)](#) (p. 99).

Remember, the Thermal Map (Image) was associated only with the *maximum* step of the Thermal Event (Phase 1 / Thermal Event). The *minimum* step was never associated with any image nor with a CSV file, so Sherlock treats this step as an isothermal loading condition.

Figure 3.20: Thermal Loads from Thermal Map (Image)



If you wish, you can add one image to the minimum step of a Thermal Event and another image to the maximum step. An example is shown below: The first thermal image file (A) is associated with the minimum step. The second image (B) is associated with the maximum step. The temperature distribution of the two maps is shown in [Figure 3.22: Two Thermal Maps: Temperature Distribution](#) (p. 100).

Figure 3.21: Two Thermal Map Image Files

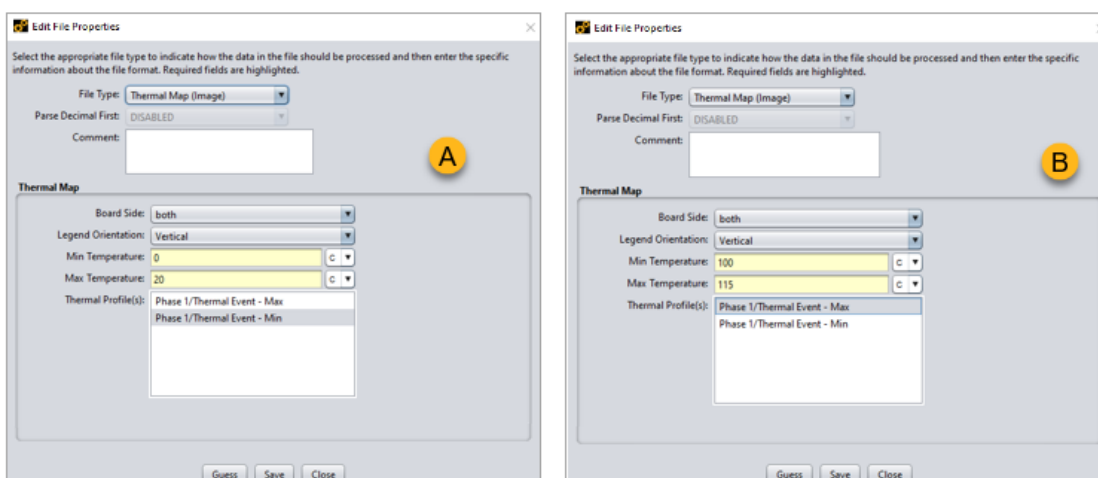
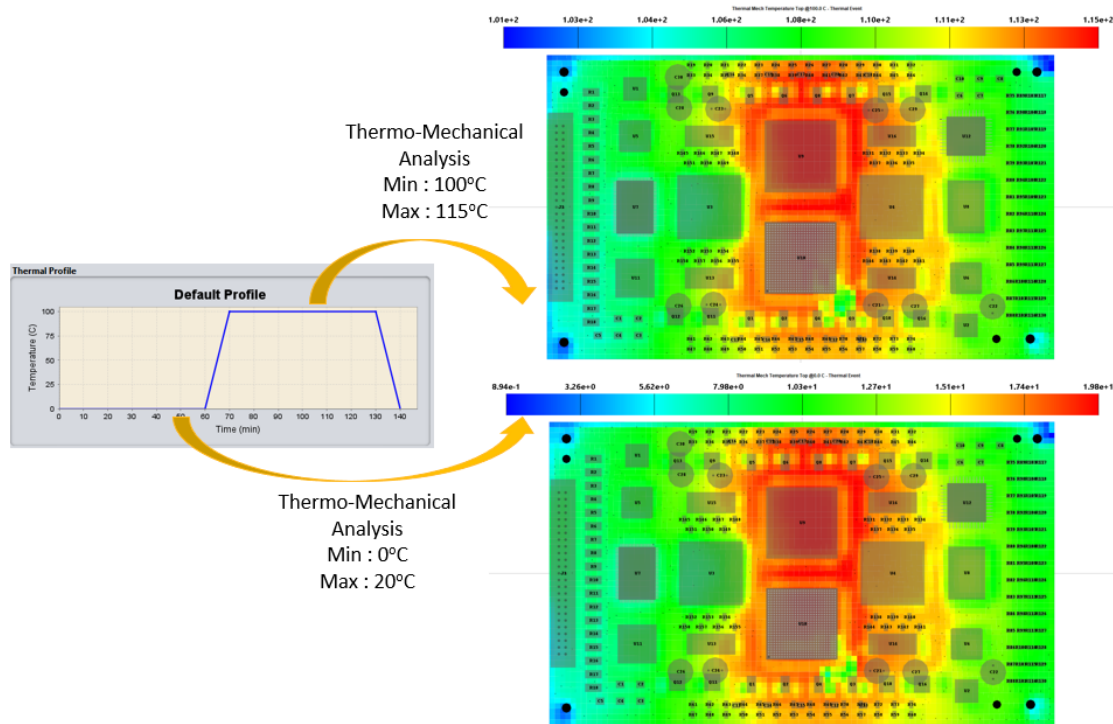


Figure 3.22: Two Thermal Maps: Temperature Distribution

Frequently Asked Questions: Part Temp Rise and Thermal Maps

1. Can two Images/CSV files be associated to a single Thermal Event ?

A step (minimum or maximum temperature) of a given Thermal Event cannot be associated with more than one thermal image. If, for example, you associate image-A with the Thermal Event-Max step and then associate image-B with the same step, image-B will override image-A. Sherlock will use image-B when running the analysis.

2. When does Part Temp Rise takes precedence?

When running a Thermal Mech analysis, Sherlock uses the Part Temp Rise property only when **Use Part Temp Rise** is set to **YES** when configuring the analysis (see [Figure 3.4: Thermal Mech Properties, Part Temp Rise \(p. 90\)](#)). If you want Sherlock to ignore Part Temp Rise, set **Use Part Temp Rise** to **NO**.

3. Can one step of the Thermal Event be associated with a Thermal Map (Image) and the other step be associated with a Thermal Map (CSV)?

Yes.

4. Does potting get temperature loads during Part Temp Rise or Thermal Map (CSV) ?

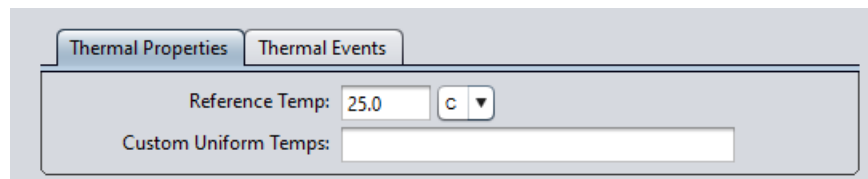
No, temperature load boundary conditions are *not* applied to potting geometries as for Part Temp Rise nor for Thermal Map (CSV). Temperature boundary conditions are applied only to *parts*. However, when running a Thermal-Mech analysis using Thermal Map (Images), Sherlock *does* apply temperature loading conditions to the potting Geometry.

For any given Thermal Event, Sherlock runs a static structural analysis using the Ansys solver for all analyses that do not entail conduction. In those cases, Sherlock assumes isothermal temperature rise. For an analysis that factors in conduction, Sherlock runs a thermal analysis followed by a static structural run from the previous thermal analysis. When one of the steps (minimum or maximum temperature) of a Thermal Event is associated with a Thermal Map (CSV/Images) while the other is not, Sherlock carries out static structural analysis (isothermal rise) for the step without the Thermal Map and carries out a thermo-mechanical analysis for the step that has the Thermal Map. The table below illustrates the possible combinations.

	Thermal Event	Thermal Condition	Analysis
Case 1	Both Steps	No Part Temp Rise	Static Structural
		No Thermal Map	
Case 2	Both Steps	Part Temp Rise	Thermal + Structural
Case 3	Step 1 – Min	No Thermal Map	Static Structural
	Step 2 – Max	Thermal Map	Thermal + Structural
Case 4	Step 1 – Min	Thermal Map	Thermal + Structural
	Step 2 – Max	Thermal Map	Thermal + Structural

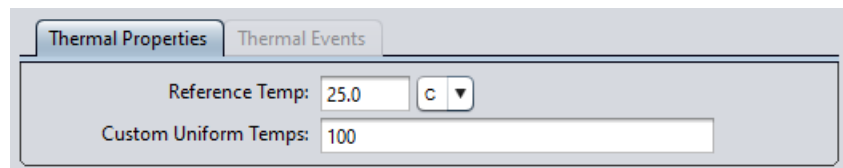
All analyses are carried out based on the reference temperature you set for the analysis (see below, [Figure 3.23: Reference Temperature for Thermal Analysis \(p. 101\)](#)). It is important to understand that, even though **Reference Temp** is under **Thermal Properties** tab, Sherlock also uses that value when running an analysis based on Thermal Events.

Figure 3.23: Reference Temperature for Thermal Analysis

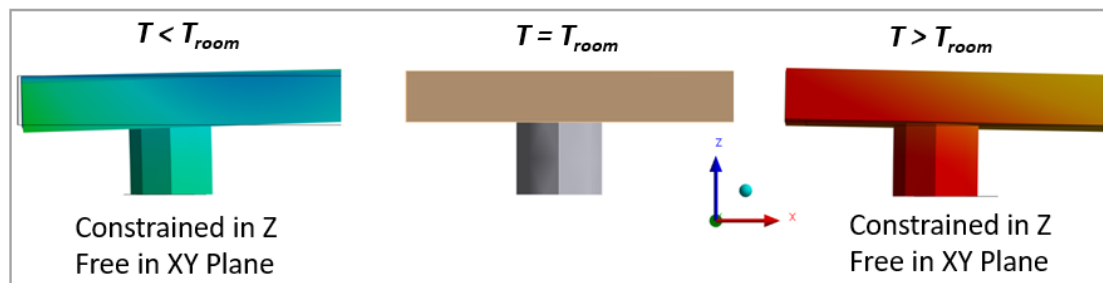


Notice in the figure below, when you run an analysis using **Custom Uniform Temperature**, the **Thermal Events** tab is grayed out automatically and cannot be used.

Figure 3.24: Custom Uniform Temperature Set Up

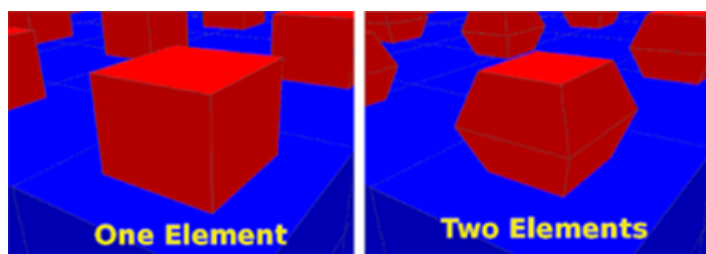


For all the Thermal Mech analyses in, Sherlock calculates thermal displacements at the mount points based on the chassis material. Mount points are not fixed in Sherlock but are assigned a displacement boundary condition during the structural analysis based on the temperature and the CTE of the chassis material. This ensures accurate in-plane expansion of the chassis material on the board. A graphical representation of thermal displacements is shown in the figure below. At room temperature (the reference temperature), the mount point remains undeformed. At various temperatures, the nodes of the mount points are displaced with respect to the center of the mount points based on the CTE of chassis.

Figure 3.25: Thermal Displacements of the Mount Pads in Sherlock

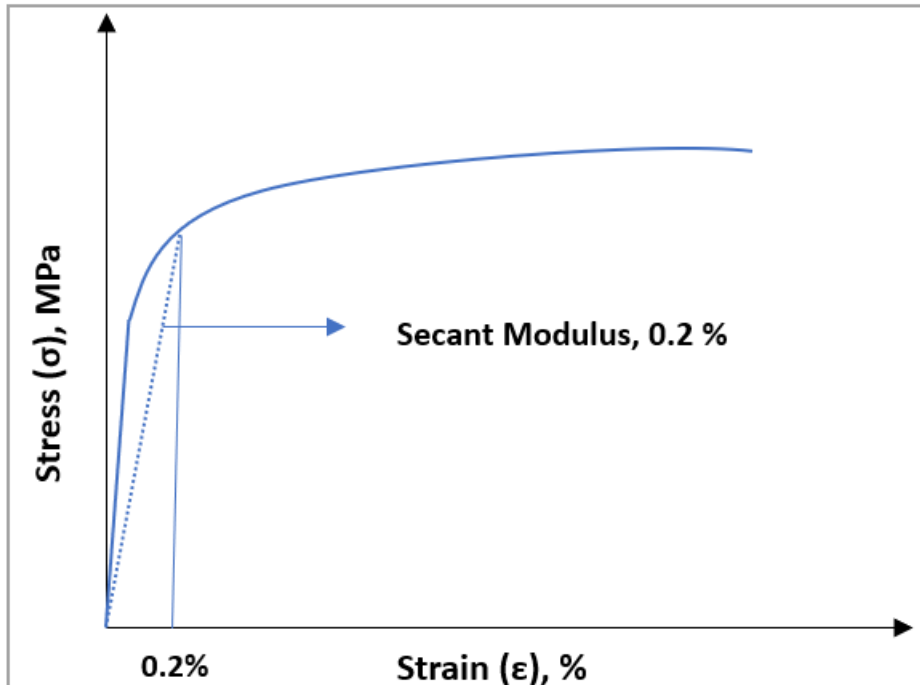
To accurately predict the thermal response of an electronic assembly, the following factors are crucial to the analysis: the size and location of the components and mount points, the mechanical properties of the PCB, solder properties, and lead properties. For this reason, Sherlock provides the necessary toolkit to create a new stack-up, to edit an existing stack-up, and to accurately define the parts and properties of a PCB. More information on how to define a circuit card along with its components can be found in the [Sherlock User's Guide](#).

Sherlock also provides the framework for running a thermal mech analysis. You have the tools to set up a finite element (FE) model and solve it in Ansys Mechanical. The FE model's accuracy depends on its geometry, its material properties, and the quality of the mesh. Sherlock provides mesh controls for modeling the PCB, parts, leads, mount points, and underfills (potting) to accurately represent the CAD model as a finite element model. More information on how to define the FE model for an electronic assembly can be found in the [FEA Modelling](#) section of the Sherlock User's Guide. To mesh the board and parts, Sherlock uses the Ansys meshing engine. For meshing leads, the Sherlock mesher is used. Also, the contacts in Sherlock are easily established using Constraint Equations (CE).

Figure 3.26: Solder Modelling

Currently, you can model [solder balls](#) in Sherlock as a single element or as a two-element model. Leads are modelled with one element through the thickness. For meshing the leads/solder with higher mesh density, it is currently recommended you mesh it outside of Sherlock, preferably in Ansys Mechanical. The electronic system can be quickly set up and exported into Ansys Mechanical for solving as well. More information on how to export an FE model in Sherlock is available in [Exporting a CCA from Sherlock to Workbench in the Sherlock User's Guide](#) in the Sherlock User's Guide.

In Thermal Mech, Sherlock supports temperature dependent secant modulus for solders. Secant modulus is defined as the modulus of a material at a specified strain or stress. Sherlock considers the secant modulus of solder at 0.2% strain. Such a modulus lets Sherlock simulate solder response near an elastic-plastic region, making the analysis more realistic than running the analysis in the elastic domain.

Figure 3.27: Secant Modulus

3.1.1. Overview of Thermal Mech Analysis in Sherlock 2023 R1

As discussed earlier, the thermal mech analysis module creates a finite element model by creating a mesh that includes all selected parts, holes, and cutouts. Sherlock performs a static linear structural analysis with uniform temperature *without* conduction/heat transfer. Based on whether the analysis includes heat transfer, Sherlock either runs a simple isothermal static structural analysis or thermos-mechanical analysis.

Temperature dependent material properties can be included, and for solder materials, secant modulus is used instead of elastic modulus. In general, secant modulus is defined as the modulus at any point in the inelastic region. A reasonable location is at 0.2 % strain.

When an electronic board is thermally cycled, the most important driver of fatigue-induced failure is the *difference* in the maximum strain at the two temperature extremes. This *difference* (delta) is a more significant driver than the maximum strains at each temperature extreme.

Sherlock typically uses equivalent strain. However, for the delta strain calculation, it's important to know whether the element is in tension or compression. To track the true signage of the stress value, Sherlock uses hydrostatic stress from the stress tensor as shown in [Equation 3.1 \(p. 103\)](#).

$$\sigma_{\text{hyd}} = \frac{SX + SY + SZ}{3} \quad (3.1)$$

where

σ_{hyd} is the hydrostatic stress

SX, SY, and SZ are the normal stress components in the X, Y, and Z directions.

If the hydrostatic stress is positive, the element is in tension. If the stress is negative, it confirms that the element is in compression. Sherlock then calculates the delta strain based on [Equation 3.3 \(p. 104\)](#).

$$\epsilon_{\text{Max Eq}}^{\text{Step1}} = \begin{cases} \epsilon_{\text{Max Eq}}^{\text{Step1}} \Leftrightarrow \sigma_{\text{Hyd}}^{\text{Step1}} > 0 \\ -\epsilon_{\text{Max Eq}}^{\text{Step1}} \Leftrightarrow \sigma_{\text{Hyd}}^{\text{Step1}} < 0 \end{cases} \quad (3.2)$$

$$\epsilon_{\text{Max Eq}}^{\text{Step2}} = \begin{cases} \epsilon_{\text{Max Eq}}^{\text{Step2}} \Leftrightarrow \sigma_{\text{Hyd}}^{\text{Step2}} > 0 \\ -\epsilon_{\text{Max Eq}}^{\text{Step2}} \Leftrightarrow \sigma_{\text{Hyd}}^{\text{Step2}} < 0 \end{cases} \quad (3.3)$$

$$\delta\text{Strain} = \left| \epsilon_{\text{Max Eq}}^{\text{Step1}} - \epsilon_{\text{Max Eq}}^{\text{Step2}} \right| \quad (3.4)$$

where

$\epsilon_{\text{Max Eq}}^{\text{Step1}}$ is the Maximum Equivalent Elemental/Surface Strain at step 1

$\epsilon_{\text{Max Eq}}^{\text{Step2}}$ is the Maximum Equivalent Elemental/Surface Strain at step 2

$\sigma_{\text{Hyd}}^{\text{Step1}}$ is the Hydrostatic Stress of the element at step 1

$\sigma_{\text{Hyd}}^{\text{Step2}}$ is the Hydrostatic Stress of the element at step 2

δStrain is the Delta Strain between step 1 and step 2

You can also import into Sherlock results from a thermo-mechanical analysis run in another application. The imported results will be used to calculate the maximum [δstrain \(p. 107\)](#) that drives component failure. You will find additional information on how strain is used in the analysis and how [δstrain \(p. 107\)](#) is calculated in the [Thermal Mech Strain \(p. 104\)](#) section below. To see a graphical representation of analysis results, you can use Sherlock's [2D Layer Viewer](#) and the [Results Viewer](#). For more information on results, see [Thermal Mech Analysis Results \(p. 107\)](#) below. All the modules in Sherlock use SI units in millimeters as the base unit. For details on how to setup a board for thermal mech analysis and how to import the results file into Sherlock, see the section [Finite Element Analysis Overview](#) in the Sherlock User's Guide.

3.2. Thermal Mech Strain

The information in this section applies to Sherlock versions 2021 R2 and later. When running a Thermal Mech analysis, Sherlock reports three strains for a given component. They are:

- Lead Strain (if the leads for the component are modelled)
- Part Strain
- PCB Strain

Lead strains are reported at three locations and are shown under the **Lead Tab** in the [Results Table \(p. 108\)](#).

- Max Lead Strain: Max Strain over the lead body
- Max Part Strain: Max Strain at the lead and part interface
- Max PCB Strain: Max Strain at the lead and PCB interface

3.2.1. Known Issue in the Previous Sherlock Versions

In the previous versions, Sherlock reported nodal strains which sometimes caused elevated strains to appear in the results, especially at the lead-component interfaces. This was due to the modulus difference between the lead and the component body. Sherlock now uses an improved approach for evaluating lead strain, PCB strain, and part strain. These changes are explained in the section below.

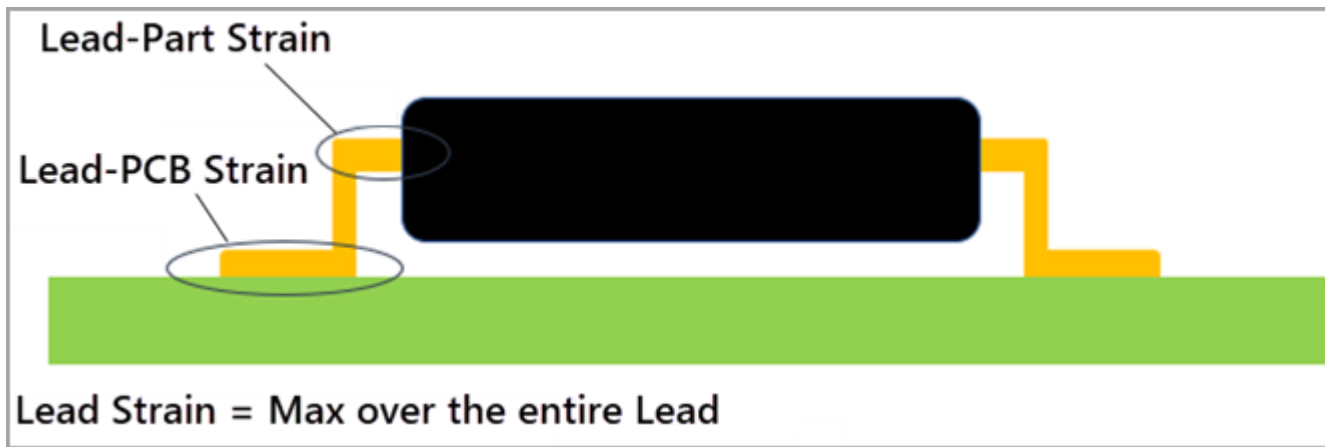
3.2.2. Lead Strain

For components with leads, strains are reported at three locations as mentioned earlier. A pictorial representation of these locations is shown below (Figure 3.28: Lead Strain (p. 105)). Max Lead Strain is the maximum strain over the entire body of the lead. Lead strains are computed as elemental von Mises stress over the elemental modulus, to avoid the issue discussed earlier (see [Known Issue in the Previous Sherlock Versions](#) (p. 105)). For a given lead, Sherlock identifies the elemental strain for all the elements in the lead body and reports the maximum as the Max Lead Strain. For the element showing the maximum strain value, elemental hydrostatic stress is computed using the expression below.

$$\text{HydroStatic Stress} = \frac{SX + SY + SZ}{3} \quad (3.5)$$

Hydrostatic stress is used to determine if the element is in compression or tension. Sherlock uses this data when calculating δstrain (p. 107). Lead-PCB Interface strain (displayed as **PCB Strain** under the **Leads Tab** in the **Results Table** (p. 108)), represents the maximum lead strain from the set of lead elements connected to the PCB. Likewise, the Lead-Part Interface Strain (displayed as **Part Strain** under the **Leads Tab** in the **Results Table**), is the maximum lead strain from the set of lead elements attached to that part.

Figure 3.28: Lead Strain



3.2.3. Part Strain

Part strains are computed only when the components are physically modelled in the FE model. When the part model is filtered out, part strain is not calculated. Parts may crack when the component is in tension. The failure can be captured by the elemental Von Mises strain

$$\varepsilon_n = \frac{\sigma_{vm-n}}{E} \quad (3.6)$$

where **n** is the element number.

The Part Strain for a component is equal to the maximum strain among all the elements of that component.

3.2.4. PCB Strain

Sherlock computes PCB Strains at the footprint of every component on the board. PCB bending causes component failure, and board bending can be captured by surface equivalent strain:

$$\sigma_n = \sqrt{\sigma_{\text{Avg Face } x}^2 + \sigma_{\text{Avg Face } y}^2 - \sigma_{\text{Avg Face } x} \sigma_{\text{Avg Face } y} + 3\sigma_{\text{Avg Face } xy}^2} \quad (3.7)$$

$$\sigma_{\text{Avg Face } x} = \frac{\sum_{n=1}^{n=k} \sigma_{(x)\text{element}_n}^{\text{(Unaveraged Nodal)}}}{k} \quad (3.8)$$

where $\mathbf{k} = 3$ (for wedge element) or $\mathbf{k} = 4$ (for hex elements) and where $\mathbf{n}$ is the element number.

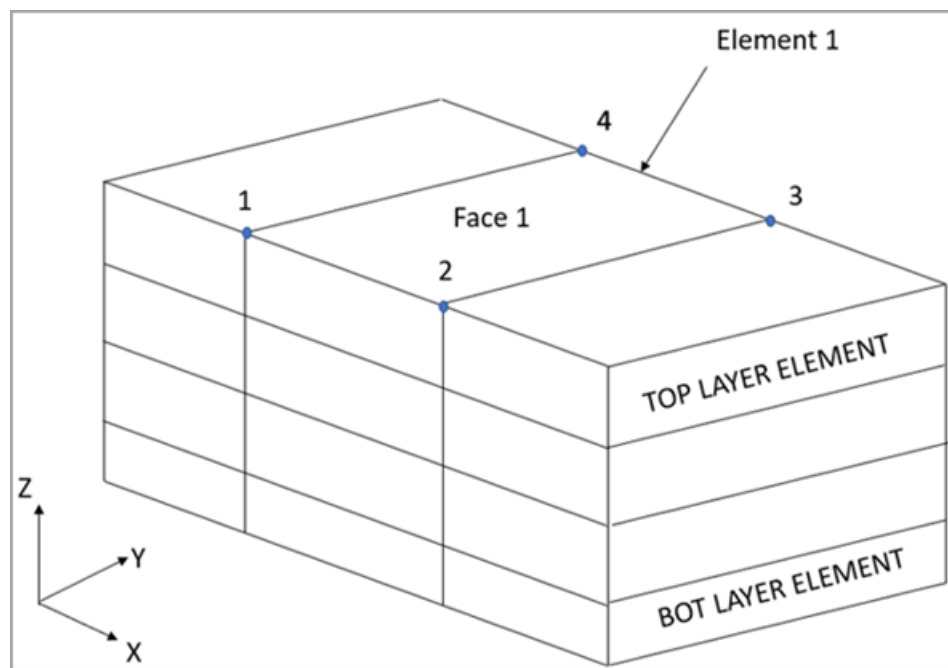
$$\sigma_{\text{Avg Face } y} = \frac{\sum_{n=1}^{n=k} \sigma_{(y)\text{element}_n}^{(\text{Unaveraged Nodal})}}{k} \quad (3.9)$$

where $\mathbf{k} = 3$ (for wedge element) or $\mathbf{k} = 4$ (for hex elements) and where $\mathbf{n}$ is the element number.

$$\sigma_{\text{Avg Face } xy} = \frac{\sum_{n=1}^{n=k} \sigma_{(xy)\text{element_n}}^{(\text{Unaveraged Nodal})}}{k} \quad (3.10)$$

where $\mathbf{k} = 3$ (for wedge element) or $\mathbf{k} = 4$ (for hex elements) and where $\mathbf{n}$ is the element number.

Figure 3.29: Surface Equivalent Stress



For parts *without* leads, the elements under the part's footprint are used. (These elements are shown as dark green in the figure below, A.) For parts that have leads, the elements under the footprint and under the leads are used (B in the figure below).

Figure 3.30: PCB Strain



3.2.5. Calculating δ strain

For a MIN-RAMP-MAX-RAMP profile, Sherlock essentially runs a two-step static structural analysis. For the first step, the analysis is run at the defined MIN temperature, and the second step is run at the defined MAX temperature. The δ strain for lead or PCB strain is computed as follows :

- Identify the Max Strain ($LS1$) at Step 1
- Identify the Hydrostatic Stress ($HS1$) for the element of max strain
- If $HS1 < 0$, $LS1 = -LS1$
- Identify the Max Lead Strain ($LS2$) at Step 2.
- Identify the Hydrostatic Stress ($HS2$) for the max lead strain element
- If $HS2 < 0$, $LS2 = -LS2$
- δ strain = $ABS (LS1 - LS2)$

3.3. Thermal Mech Analysis Results

The Thermal Mech analysis module generates the following types of results :

- Overall Summary of the analysis
- A Main **Results Table** (p. 108) displaying the maximum displacement, strain and δ strain (p. 107)
- Result Tables for Parts, Leads, and Mount Points displaying respective strains

- Graphical layers showing maximum displacement, stress, and strain

The overall summary of the analysis (see [Figure 3.31: Summary Tab \(p. 108\)](#) below) essentially consists of information about the thermal mech analysis results such as overall maximum displacement of the board and the maximum absolute δ strain ([p. 107](#)) on the board. The Summary Tab also shows information related to the board properties, the analysis process, and the mesh properties. (In Sherlock 2021 R2, scoring based on risk to failure is not provided.)

More information on the items listed above can be found in the [Thermal Mech Analysis Results](#) section of the Sherlock User's Guide. A general overview of the **Results Table** and Graphical FEA Results are detailed in the following sections.

Figure 3.31: Summary Tab

TM Bending	
Reference Temp:	25° C
Max Strain Phase:	On The Road
Max Strain Event:	4 - Thermal Shock
Max Abs Displacement:	3.1e-1 mm
Max Abs Strain:	5,680.19 $\mu\epsilon$
Max Temperature:	125.0° C
Min Temperature:	-40.0° C
Board Properties	
# of Nodes:	5,622
# of Elements:	5,475
# of Parts:	221
# of Mounts:	4
# of Holes:	0

3.4. Thermal Mech Results Table

Thermal Mech Result table can be accessed by selecting the **Thermal Mech** tab to examine the results generated for each part analyzed, as shown here:

Figure 3.32: Thermal Mech Result Table

RefDes	Package	Part Type	Side	Solder	Max Disp	Delta Strain
U13	TSOP-32 (MO-142...	IC	TOP	63SN37PB	2.3E-1	7,588.31
U15	TSOP-32 (MO-142...	IC	TOP	63SN37PB	2.3E-1	7,466.34
U16	TSOP-32 (MO-142...	IC	TOP	63SN37PB	2.4E-1	7,448.86
U14	TSOP-32 (MO-142...	IC	TOP	63SN37PB	2.3E-1	7,383.59
R4	2512	RESISTOR	TOP	63SN37PB	2.0E-1	4,611.32
R5	2512	RESISTOR	TOP	63SN37PB	1.9E-1	4,611.32
R6	2512	RESISTOR	TOP	63SN37PB	1.9E-1	4,540.47
R2	2512	RESISTOR	TOP	63SN37PB	2.0E-1	4,491.52
R3	2512	RESISTOR	TOP	63SN37PB	2.0E-1	4,491.52
R7	2512	RESISTOR	TOP	63SN37PB	1.9E-1	4,486.09
R8	2512	RESISTOR	TOP	63SN37PB	1.9E-1	4,391.04
R10	2512	RESISTOR	TOP	63SN37PB	1.9E-1	4,296.46
R12	2512	RESISTOR	TOP	63SN37PB	1.9E-1	4,250.75
R16	2512	RESISTOR	TOP	63SN37PB	2.0E-1	4,085.29

The **TM** tab is the main results table that contains the δstrain (p. 107) for each component for selected boundary condition. Regarding boundary conditions, the following scenarios are possible:

- Temperature cycle defined through a single Thermal Event
- Temperature cycle defined through multiple Thermal Events
- Temperature cycle defined through custom Temperature Data Points

When temperature cycle is defined through a single Thermal Event, Sherlock runs a static structural analysis from reference temperature to

1. Max Temp
2. Min Temp

For each component, δstrain is calculated as explained in [Thermal Mech Strain \(p. 104\)](#). The strain value in the table is displayed as micro strain ($\mu\epsilon$), as seen in [Figure 3.32: Thermal Mech Result Table \(p. 109\)](#). As Sherlock does not perform life predictions under Thermal Mech, the table rows are not color-coded.

When a temperature cycle is defined through multiple Thermal Events, Sherlock runs a static structural analysis for each Thermal Event. Sherlock then identifies the maximum δstrain (p. 107) across all the thermal events and displays it in the results table. When the temperature is defined through custom Uniform Temperature, Sherlock runs a static structural analysis from reference temperature to the defined temperature data point and identifies the maximum strain experienced by the component. If the leads

are explicitly modelled, the **Lead** tab will be available, showing lead strain information for the parts. If the leads are not modelled, the tab is not displayed.

The results table will display strain as discussed in [Thermal Mech Strain \(p. 104\)](#). If leads are modelled, Lead Strain, PCB Strain and Part Strain will be displayed for every single lead on the board. Starting with Sherlock 2021 R2, the **Parts** tab will be available. The tab provides PCB Strain, Part Strain, and the maximum of the three Lead Strains for all the components on the board. The **Lead** and **Parts** tab contain information from all the steps in the analysis, as shown below (see [Figure 3.33: Parts Tab \(p. 110\)](#) and [Figure 3.34: Leads Tab \(p. 111\)](#) below).

As mentioned earlier, the Lead Strain and Part Strain are based on Von Mises elemental stress. The **Mount Points** tab displays the maximum elemental strain value of the modelled mount points in the board. As with all other Sherlock tabular results, you can double-click any row to view the properties associated with a given part or select one or more rows to be exported to a CSV file.

Figure 3.33: Parts Tab

RefDes	Temperature	PCB Strain	Part Strain	Lead Strain
U16	-40.0	354.49	114.07	2,995.33
U16	125.0	475.32	170.41	4,460.78
U15	-40.0	384.51	113.72	3,002.14
U15	125.0	513.43	169.63	4,467.36
U14	-40.0	358.07	113.53	2,979.23
U14	125.0	476.75	169.63	4,418.67
U13	-40.0	396.66	114.41	3,045.70
U13	125.0	539.08	170.79	4,542.61
U12	-40.0	324.98	18.45	185.88
U12	125.0	515.50	21.58	245.32
U11	-40.0	355.48	15.73	181.00
U11	125.0	548.05	23.70	267.27
U10	-40.0	544.66	234.29	
U10	125.0	800.04	350.43	

Figure 3.34: Leads Tab

RefDes	Lead ID	Temperature	Max PCB Strain	Max Part Strain	Max Lead Strain
U16	1	-40.0	2,611.75	344.35	2,611.75
U16	1	125.0	3,898.86	519.88	3,898.86
U16	2	-40.0	2,580.81	318.50	2,580.81
U16	2	125.0	3,850.46	480.83	3,850.46
U16	3	-40.0	2,549.90	300.14	2,549.90
U16	3	125.0	3,802.08	451.45	3,802.08
U16	4	-40.0	2,535.33	293.84	2,535.33
U16	4	125.0	3,777.87	438.96	3,777.87
U16	5	-40.0	2,549.92	286.18	2,549.92
U16	5	125.0	3,797.85	424.85	3,797.85
U16	6	-40.0	2,566.72	286.78	2,566.72
U16	6	125.0	3,821.35	423.43	3,821.35
U16	7	-40.0	2,583.54	291.81	2,583.54
U16	7	125.0	3,844.87	428.82	3,844.87

3.5. Graphical FEA Results

The Thermal Mech analysis module generates 2D results layers showing the displacement, PCB strains, and PCB stresses experienced during the defined Thermal Event. The strains are displayed in micro strain. The strains and stresses are presented for both MIN and MAX temperatures of the profile and are available for both the TOP and BOTTOM surfaces of the PCB. The strain per element face is determined as explained in [PCB Strain \(p. 106\)](#). The results provided in the **2D Layer Viewer** are only for the PCB and not for the parts on the board. Use the Sherlock **3D Viewer** for viewing parts. An example of surface equivalent stress and strain of an element (board center) is shown below ([Figure 3.35: PCB Surface Strain \(p. 112\)](#)). For comparison, unaveraged nodal stresses for the same element in mechanical is also provided in [Table 3.1: Unaveraged Nodal Value in Ansys Mechanical at -40°C \(p. 112\)](#).

Figure 3.35: PCB Surface Strain

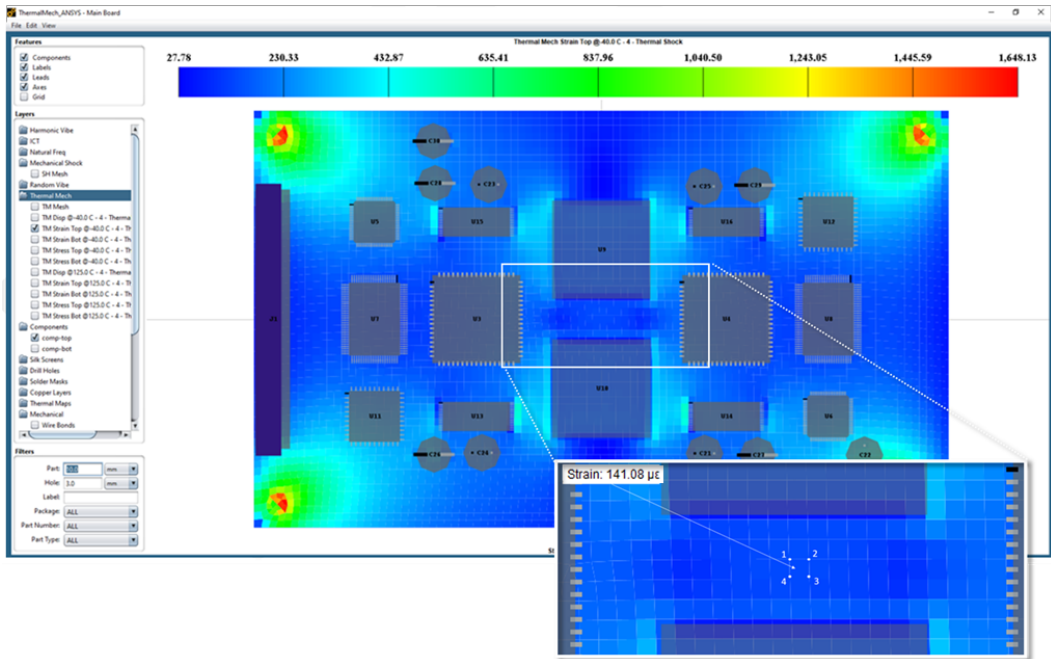
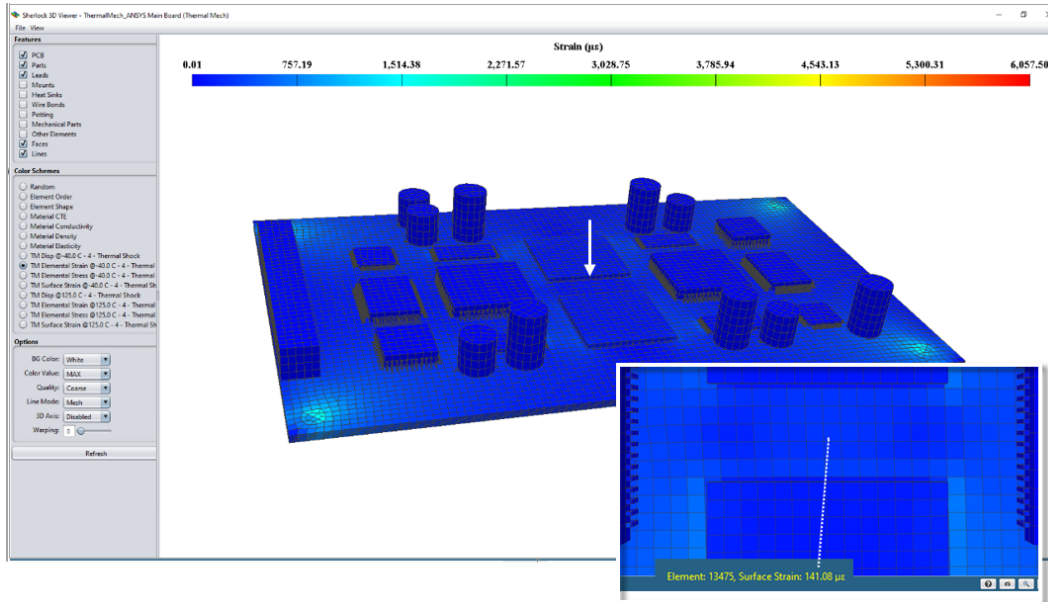


Table 3.1: Unaveraged Nodal Value in Ansys Mechanical at -40°C

Node	Stress Label	Stress (MPa)	Average Stress	Surface Stress	Modulus (Mpa)	Strain (μϵ)			
1	X	0.525849462	0.525694057	4.092791954	23799.517	171.9695384			
2	X	0.525860131							
3	X	0.525507629							
4	X	0.525559008							
1	Y	-3.802535057	-3.804499924						
2	Y	-3.806404352							
3	Y	-3.802615166							
4	Y	-3.806445122							
1	XY	1.11E-02	0.011091428						
2	XY	1.12E-02							
3	XY	1.10E-02							
4	XY	1.11E-02							

Elemental mean stress and strain can be viewed using Sherlock's **3D Viewer**, as shown below (Figure 3.36: Sherlock 3D Result Viewer (p. 113)). The inset illustrates how the **3D Viewer** enables you to view surface strain as well.

Figure 3.36: Sherlock 3D Result Viewer

Chapter 4: In-Circuit Testing (ICT) Theory

Note:

It's important to read the [Sherlock User's Guide](#) before accessing the theory guide content. The user's guide will help you become familiar with Sherlock's capabilities and workflow. A firm understanding of the Sherlock application is essential before delving into the substantial content of the *Sherlock Theory Reference*.

In-Circuit Testing (ICT)

During the manufacturing process, In-Circuit Testing (ICT) uses a collection of test probes and test fixtures on one or both sides of a circuit card to test electrical connections. Each test probe exerts a mechanical force (or displacement) at a specific circuit card location, called the test point. The combined effect of all these test point forces displaces the circuit card during the test, causing mechanical stresses to be experienced by each solder joint. If the stress values are high enough, one or more solder joints could fail.

There are several post-soldering processes during manufacturing that can lead to a sudden and excessive bending of the PCB. Flexure or bending of a printed circuit board is influenced by the load being applied, the rate at which the load is applied, the area and location of the load, the area and location of support, the printed circuit board material, and the printed board thickness. Depending on the location, magnitude, and speed at which the flexure occurs, components and solder joints on the board can be damaged. The damage can be determined by assessing board level strain. In Sherlock, board level strain is treated as a surface Equivalent strain.

Sherlock uses component specific critical strain to evaluate whether the board strain under the components can cause fatigue failure. The component critical strain is based on [IPC-9704 \(p. 135\)](#) guidelines which evaluate the maximum allowable stress a board can be subjected to before it breaks. Sherlock also assesses component failure due to overstress. Specifically, it addresses component overstress due to board bending and not the overstress that leads to component fracture. This document gives an overview of the ICT Analysis and the steps involved in the reliability calculation in Sherlock.

Chapter Topics:

- [4.1. ICT Analysis Settings](#)
- [4.2. ICT Analysis](#)
- [4.3. ICT Strain](#)
- [4.4. Post Processing: Life Prediction Calculation](#)
- [4.5. ICT Analysis Results](#)
- [4.6. ICT Result Table](#)
- [4.7. Life Prediction Curve](#)
- [4.8. Graphical FEA Results](#)

[4.9. Validation](#)[4.10. References](#)

4.1. ICT Analysis Settings

Sherlock's ICT analysis consists of three parts: 1) preparing the electronic board for analysis, 2) solving the model, and 3) post-processing the results for the reliability calculation. Once you have entered the input data and have defined post-processing, Sherlock runs the analysis and scores the components on the board, based on their risk of failure. The ICT analysis module requires the following input data:

- Life Cycle Reliability Goals
- ICT Fixtures and Test Points
- Application Time and Number of Events
- [Parts List](#)
- Size and location of all parts, plated through-holes, and cutouts
- Size and location of all test points and test fixtures
- [Circuit card mechanical properties](#)
- Mesh Properties
- Solder Properties

Life cycle reliability goals are reliability requirements an electronic system must fulfill in its lifetime. In Sherlock, the **Reliability Goals** section in the **Life Cycle Editor** allows you to enter the expected **Service Life** and **Reliability Metric**.

Figure 4.1: Life Cycle Editor

Life Cycle Editor

Modify any of the following properties and press the **Save** button to update the life cycle. You may also use the **Load Life Cycle** menu option to load a different life cycle from the file system or the **Save Life Cycle** menu option to save the current life cycle in a named file. Life cycle files can be used in across multiple projects and/or shared with other Sherlock users.

Identification

Name: Life Cycle

Description: Example for the Life Cycle Editor

Reliability Goals

Reliability Metric: 20 Prob. of Failure (%) ▼

Service Life: 5 year ▼

Save Reset Cancel

These values are utilized in post-processing to calculate Time to Failure (TTF) and to score a component's risk of failure by comparing the probability of failure with the reliability goal. Reliability, in general, is defined as the probability that an electronic device will perform its required function when subjected to a condition for a specified amount of time. In electronics, the reliability distribution can be modeled using a Weibull distribution, a probability density function that is expressed as follows :

$$F(t) = \frac{\beta}{\eta} \left(\frac{t-\gamma}{\eta} \right)^{\beta-1} e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} \quad (4.1)$$

where

β is the Weibull slope

η is the scale parameter

γ is the location parameter, set to 0 as Sherlock uses a two-parameter Weibull.

In Sherlock, the reliability calculations are based on the probability of failure distribution expressed using the reliability function $P(t)$:

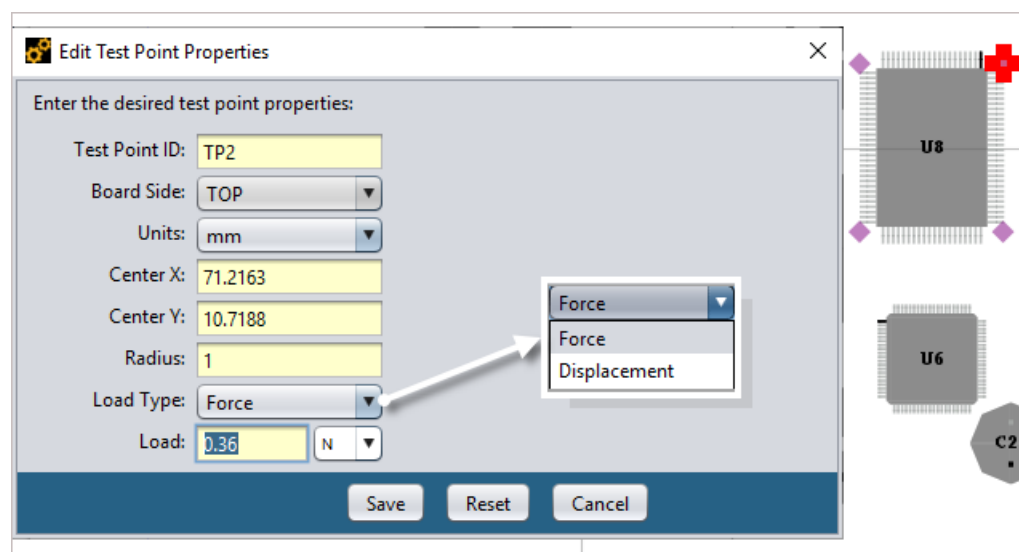
$$PoF(t) = 1 - P(t) = 1 - e^{-(\text{damage})^{\beta}} \quad (4.2)$$

The above equation can also be recognized as the cumulative distribution function (CDF) of probability density function for a 2-parameter Weibull distribution.

More information about damage calculation from the finite element (FE) strain result can be found in the section below, [Post Processing: Life Prediction Calculation \(p. 123\)](#).

An ICT analysis involves subjecting a PCB to bending loads. In Sherlock, the loads are defined using [Test Points](#). Supports for the board are defined using [ICT Fixtures](#). You can add or edit Test Points and fixtures within the **2D Layer Viewer**. You can apply loads either as a point force or a displacement as shown below ([Figure 4.2: Test Points \(p. 117\)](#)). The **Radius** property affects only how test points are displayed and has no bearing on Sherlock's calculations.

Figure 4.2: Test Points



Unlike other modules in Sherlock where you can add Loading Events under Life Cycle events, there are no separate Loading Events to define for an ICT analysis. To define the loads and fixtures, use **Edit Test Points** and **Edit Fixtures** in the **Layer Viewer**, and set the **Application Time** and **Number of Events** under the **ICT Analysis Properties** panel (see [Figure 4.3: ICT Analysis Properties](#) (p. 118)). **Application Time** determines the rate at which the load is applied, and the **Number of Events** defines the number of times the event occurs during the defined **Lifetime**.

Sherlock provides the necessary toolkit to create and edit stack-up details of PCBs and to accurately define the parts. Sherlock also provides tools for effectively managing all the parts in the system through the [Parts List](#). In the [Sherlock User's Guide](#), you will find additional information on how to define a circuit card and its components for any mechanical analysis.

Figure 4.3: ICT Analysis Properties

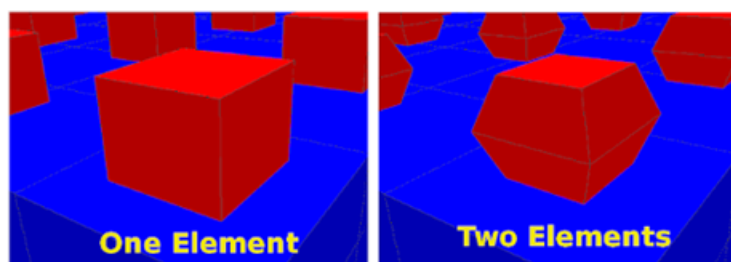
As is the case with any of its mechanical analyses, Sherlock gives you the complete framework for setting up your FE (Finite Element) model, and then Sherlock will solve the model using Ansys Mechanical APDL.

You will find mesh controls in Sherlock for the PCB, Parts, Leads, Mount Points, and Underfills (Potting) so you can accurately represent the CAD model as a finite element model. Sherlock uses the Ansys mesh engine for meshing all bodies in the assembly, except for leads which are meshed with Sherlock's native algorithms. Also, the contacts in Sherlock are created automatically using Constraint Equations (CE). (See **Bond Tolerance** under [Mesh Settings](#) in the [FEA Engine](#) section of the *Sherlock User's Guide*.)

Currently, solder balls in Sherlock can be modelled as a single-element or two-element model (see below), and leads are modelled with one element through the thickness. To mesh the leads/solder with higher

mesh density, you can set up the electronic system for export into Ansys Mechanical for meshing and solving. For complete information on how to create an FE model in Sherlock, refer to the [FEA Modeling](#) section in the [Sherlock User's Guide](#).

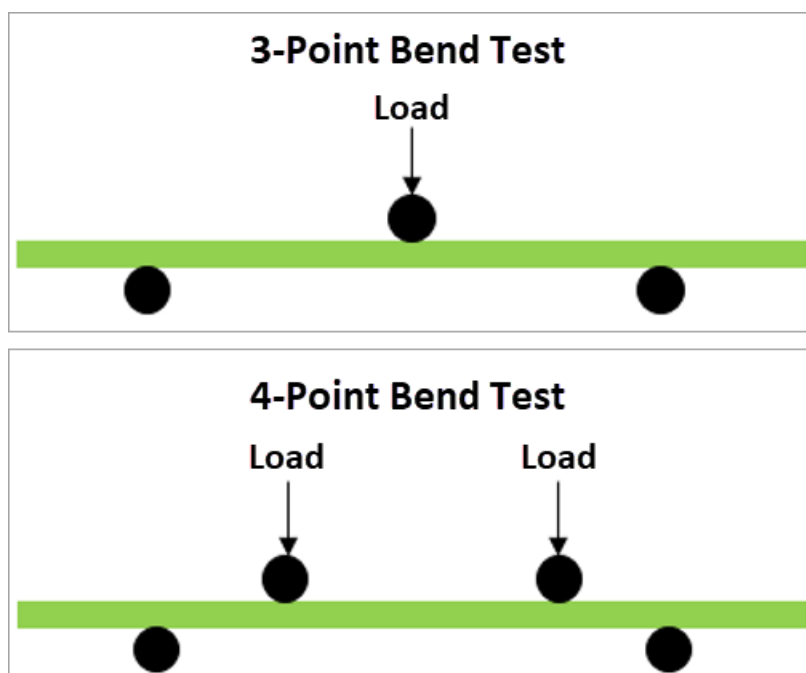
Figure 4.4: Solder Modelling



4.2. ICT Analysis

The In-Circuit Testing analysis in Sherlock is effectively the static structural analysis carried out in Ansys Mechanical. The [loads](#) for the analysis are applied either as displacements or point forces. For an ICT analysis run outside of Sherlock, you can import the results into Sherlock for generating reliability predictions. The results are also displayed in the 2D and 3D Viewers for a graphic representation. You will find detailed information on Sherlock's results in the [ICT Analysis Results](#) section of the user's guide. All the modules in Sherlock use SI units of millimeters as the base unit. Information on how to setup a board for an ICT analysis and how to import the results file when solved outside Sherlock is available in the [Workbench Integration](#) section of the *Sherlock User's Guide*.

Figure 4.5: Loading Conditions : 3 point and 4 point Bend Test



4.3. ICT Strain

Sherlock's ICT analysis results (in versions 2021 R2 and later) report three strains for a given component. They are:

- Lead Strain (if the leads for the component are modelled)
- Part Strain
- PCB Strain

Lead strains are reported at three locations.

- Max Lead Strain: Maximum strain over the lead body
- Max Part Strain: Maximum strain at the Lead and Component interconnect
- Max PCB Strain: Maximum strain at the Lead and PCB interconnect

These strains will be available under **Leads** tab in the results viewer (see the [Results Table \(p. 129\)](#) section).

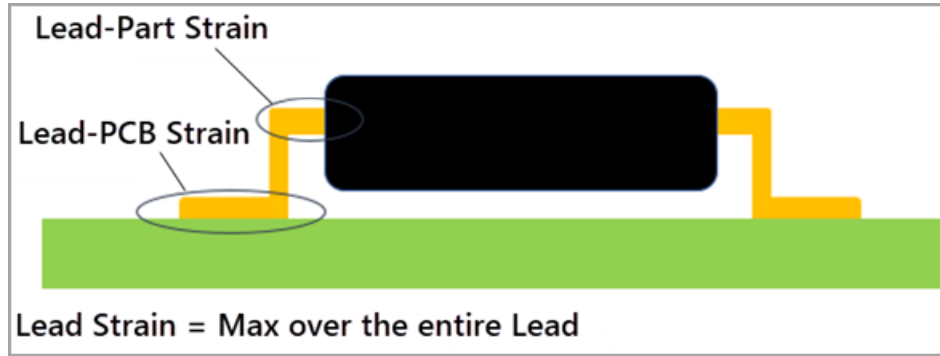
4.3.1. Known Issue in the Previous Sherlock Versions

In the previous version of Sherlock, nodal strains were reported. This sometimes resulted in elevated strains being reported, especially at the lead-to-component interface. This was due to the modulus difference between the lead and the component body. A different approach for evaluating lead strain, PCB strain, and part strain has been implemented. You may notice slight differences in the results due to these strain updates. More about the changes are explained in the following section.

4.3.2. Lead Strain

As mentioned earlier, strains for leaded components are reported at three location as illustrated in [Figure 4.6: Lead Strain \(p. 121\)](#). Max Lead Strain reports the maximum strain over the entire lead body. Lead strains are computed as elemental von Mises stress over the elemental modulus, to avoid the issue discussed earlier. For a given lead, Sherlock identifies the elemental strain for all the elements in the lead body and reports the maximum as the Max Lead Strain.

Lead-to-PCB interface strain (displayed as **Max PCB Strain** under the **Leads** tab in the [Results Table \(p. 129\)](#)), describes the maximum lead strain among the set of lead elements connected to the PCB. Likewise, the Lead-to-Part Interface strain (displayed as **Max Part Strain** under the **Leads Tab** in the [Results Table \(p. 129\)](#)), describes the maximum lead strain among the set of lead elements attached to the part.

Figure 4.6: Lead Strain

4.3.3. Part Strain

Part strains are computed when the components are physically modelled in the FE model. Parts may crack when the component is in tension. The failure can be captured by elemental von Mises strain determined by Equation 4.3 (p. 121). Part Strain for a component is the maximum strain among all the component's elements.

$$\varepsilon_n = \frac{\sigma_{VM-n}}{E_n} \quad (4.3)$$

where n is the element number.

4.3.4. PCB Strain

PCB Strains are computed at the footprint of every component on the board. PCB bending causes component failure, and the bending of the board can be captured by surface Equivalent strain as shown below.

$$\varepsilon_{\text{element}_n} = \frac{\sigma_{VM \text{ Avg Face}}}{E_{\text{element}_n}} \quad (4.4)$$

where n is the element number.

$$\sigma_{VM \text{ Avg Face}} = \sqrt{\sigma_{\text{Avg Face } x}^2 + \sigma_{\text{Avg Face } y}^2 - \sigma_{\text{Avg Face } x} \sigma_{\text{Avg Face } y} + 3\sigma_{\text{Avg Face } xy}^2} \quad (4.5)$$

$$\sigma_{\text{Avg Face } x} = \frac{\sum_{n=1}^{m=k} \sigma_{(x)\text{element}_n}^{(\text{Unaveraged Nodal})}}{k} \quad (4.6)$$

where $k = 3$ (for wedge element) or $k = 4$ (for hex elements) and where n is the element number.

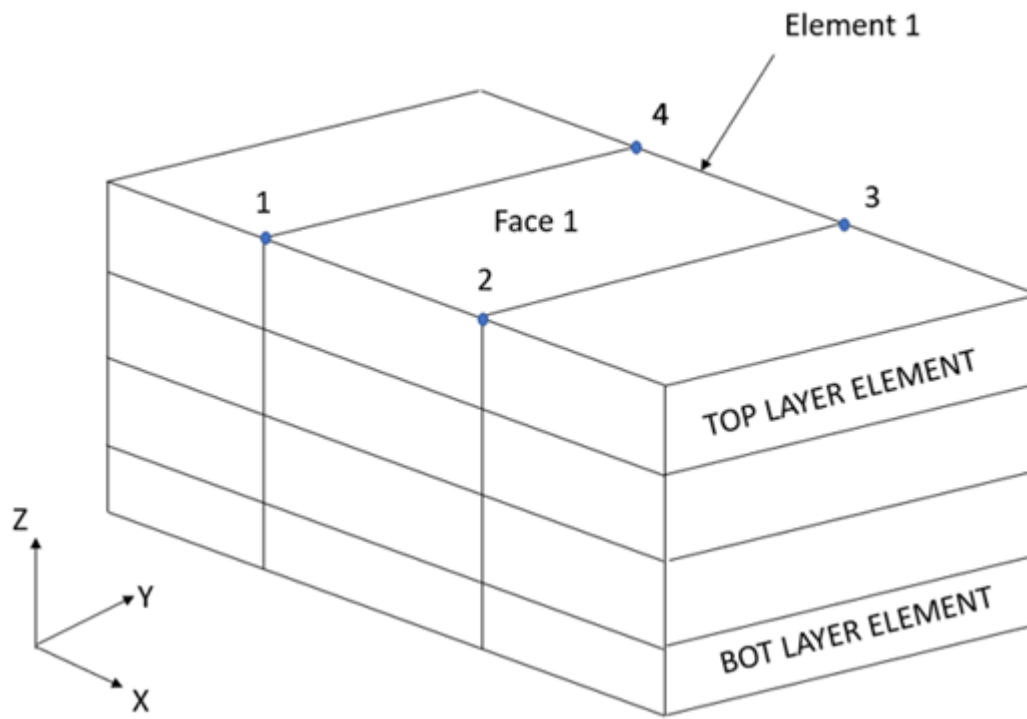
$$\sigma_{\text{Avg Face } y} = \frac{\sum_{n=1}^{m=k} \sigma_{(y)\text{element}_n}^{(\text{Unaveraged Nodal})}}{k} \quad (4.7)$$

where $k = 3$ (for wedge element) or $k = 4$ (for hex elements) and where n is the element number.

$$\sigma_{\text{Avg Face } xy} = \frac{\sum_{n=1}^{m=k} \sigma_{(xy)\text{element}_n}^{(\text{Unaveraged Nodal})}}{k} \quad (4.8)$$

where $k = 3$ (for wedge element) or $k = 4$ (for hex elements) and where n is the element number.

Figure 4.7: : Surface Equivalent Strain for brick elements



If the parts are not leaded, the elements under the footprint of the part are used in the calculation (see A in the figure below). For leaded parts, the elements under the footprint of the part and those under the leads are used (B, below). In the images below, the elements used in the calculation are DARK GREEN.

Figure 4.8: PCB Strain



4.4. Post Processing: Life Prediction Calculation

Sherlock's ICT analysis module is a simulation based on finite element analysis. Using board-level strain (PCB Strain) and component parameters, Sherlock determines how susceptible an electronic package is to interconnect failures during a board bending event. Calculating how much board-level critical strain a component can endure entails a combination of physics-based calculations and empirical parameters developed by [Steinberg \(2000\) \(p. 135\)](#). The main issue with this approach is that it is limited to simple board geometries (since the maximum deflection is always assumed to be at the center of the PCB) and does not account for board curvature. By utilizing FEA, the software can eliminate some of Steinberg's variables, and the equation can be simplified:

$$\varepsilon_c = \frac{\zeta}{c\sqrt{L}} \quad (4.9)$$

where:

ε_c is the component critical strain

ζ is the baseline board-level strain from IPC9704 for board flexure

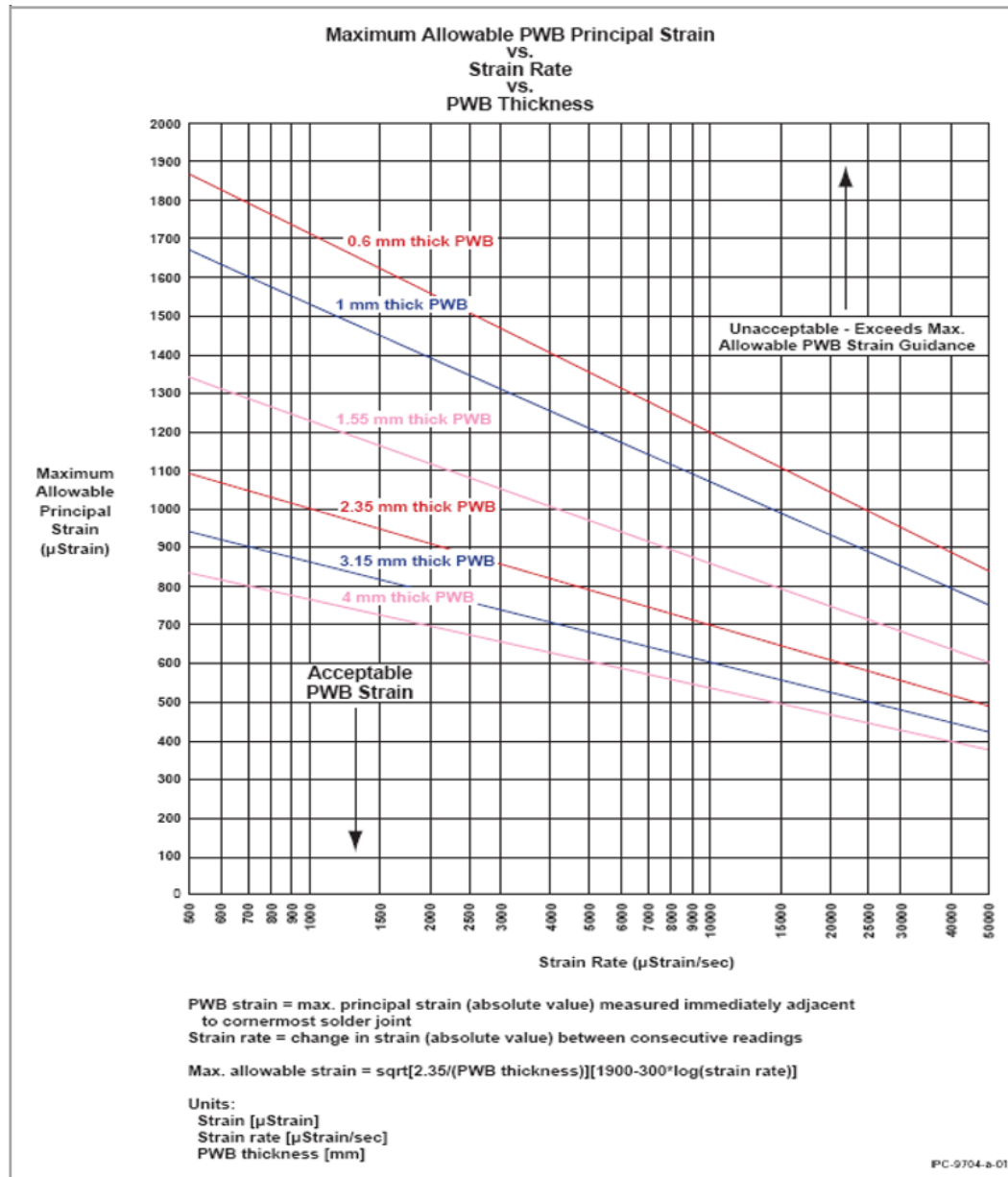
L is the diagonal length of the component

c is a component packaging constant (typically between 0.75 and 2.2)

The finite element simulation determines board level strains with the applied boundary conditions and point loads (which represent probe forces/displacement). Sherlock then post-processes the FE strain results and extracts the maximum FE strain under the component footprint.

This resulting strain is used to compute maximum allowable strain as published in [IPC-9704 \(2012\) \(p. 135\)](#). (See [Post Processing: Life Prediction Calculation \(p. 123\)](#).) The standard relates strain rate to the maximum allowable strain a bare board can sustain before it breaks. The critical strain is then derived from the maximum allowable strain. To ensure component sensitivity with critical strain, Sherlock normalizes the component specific factor $c\sqrt{L}$, with $c_{BGA}\sqrt{40}$, where the standard size of the BGA is assumed to be 40 mm in length.

$$\text{Critical strain } (\varepsilon_c) = \text{Max allowable strain } (\zeta) * \frac{c_{BGA} * \sqrt{40}}{c * \sqrt{L}} \quad (4.10)$$

Figure 4.9: IPC 9704, Max Allowable Strain

Even though the nature of a Shock and an ICT analysis are very similar, the critical strain in ICT specifically depends on the strain rate of the applied load. In a Shock analysis, the critical strain is assumed to be constant and is available as a user-defined constant. As Shock is assumed to be a high strain rate event, Sherlock assumes the highest strain rate from the IPC guideline which is 50,000 $\mu\epsilon/s$. Based on this guideline, the default value of 600 $\mu\epsilon$ for a nominal PCB thickness of 1.55 mm is assumed for a Shock analysis.

The strain rate for a given load is determined from the **Application Time** (shown in the figure below) and the FEA strain. PCB Strain is assumed as FEA Strain for components.

$$\text{Strain rate } (\mu\epsilon / \text{sec}) = \frac{\text{FEA Strain } (\mu\epsilon)}{\text{Application Time (sec)}} \quad (4.11)$$

Figure 4.10: Analysis Properties

Analysis Properties

Application Time: 1 sec

Number of Events: 10

Part Validation: ENABLED

The maximum allowable strain is then computed as discussed in [IPC-9704 \(p. 135\)](#) using the expression below.

$$\text{Max allowable strain } (\mu\epsilon) = \zeta = \sqrt{\left(\frac{2.35}{\text{PCB thickness}} \right)} * (1900 - 300 * \log_{10}(\text{strain rate})) \quad (4.12)$$

Note:

Known Issue in Previous Version of Sherlock: In the previous version of Sherlock, the strain rate ([Equation 4.10 \(p. 123\)](#)) was considered as strain, not as μstrain . Also, the Application Time was converted to a time that was consistent with the unit of Service Life. This made Sherlock's calculation result in a high strain rate which made the prediction conservative.

In ICT, failure can occur due to high cycle fatigue, low cycle fatigue, or overstress. The standard equation for predicting cycles to failure due to high cycle fatigue is the Basquin equation which relates stress or elastic strain to cycles to failure. The standard Basquin equation is shown here:

$$\sigma_a = \sigma'_f (2N_f)^b \quad (4.13)$$

where

σ_a is the cyclic stress amplitude

σ'_f is the fatigue strength coefficient, defined in the solder profile

N_f is the cycles to failure (typically the characteristic life)

b is the fatigue strength exponent, defined in the solder profile

Additionally, the Basquin equation can be expressed in terms of the elastic strain:

$$\frac{\Delta\epsilon_e}{2} = \frac{\sigma'_f}{E} (2N_f)^b \quad (4.14)$$

where

$\Delta\epsilon_e$ is the elastic strain range

E is the elastic modulus

The Basquin equation (as used in Sherlock) is written as

$$N_{f-\text{HighCycles}} = 10,000,000 * \left(\frac{\epsilon_c}{2 * \epsilon_{FEA}} \right)^{\text{FEA Power}} \quad (4.15)$$

where

ϵ_{FEA} is the maximum strain experienced by the component, PCB strain is considered.

ε_c is the critical strain as explained earlier

FEA Power is the fatigue exponent for any given solder, available in Sherlock's **High-Cycle Fatigue** tab in Sherlock's [Solder Editor](#)

$$\frac{\Delta\varepsilon_e}{2} = \varepsilon'_f (2N_f)^c \quad (4.16)$$

where

$\Delta\varepsilon_e$ is the elastic strain range

ε'_f is the fatigue ductility coefficient, the failure strain for a single reversal

ε'_f is the cycles to failure (typically the characteristic life)

c is the fatigue ductility exponent = $\frac{1}{\text{FEA Power}}$, where FEA Power is defined in the solder profile editor.

The Coffin-Manson Law (as used in Sherlock) can also be written as:

$$N_{f-\text{LowCycles}} = 1000 * \left(\frac{\varepsilon_c}{\varepsilon_{FEA}} \right)^2 \quad (4.17)$$

Combining both equations produces the Basquin-Coffin-Manson relation which gives the cycles to failure for any given device.

$$\text{Cycles to Failure (CTF)} = N_{f-\text{HighCycles}} + N_{f-\text{LowCycles}} \quad (4.18)$$

Damage is calculated from the total cycles to failure. Based on the above combination, Coffin-Manson dominates the total cycles to failure at low cycle fatigue, and Basquin equation dominates at high cycle failure.

$$\text{Damage} = \frac{\text{Number of Events}}{\text{Cycles to Failure}} \quad (4.19)$$

Finally, the Total Time to Failure (TTF) and Probability of Failure (PoF) is computed as,

$$\text{TTF} = \text{Cycles To Failure} * \frac{\text{Service life}}{\text{Number of events}} \quad (4.20)$$

$$\text{PoF} = 1 - e^{-\text{Damage}^\beta} \quad (4.21)$$

The Weibull Slope β is a user-defined value in Sherlock (see [Figure 4.11: Weibull Slope \(p. 127\)](#)), with a default value of 3 for wear outs. Notably, any overstress relation involves comparing the critical strain to the strain experienced by the component. If the strain seen by the component is higher than the critical strain, the component is said to be overstressed.

Figure 4.11: Weibull Slope

Solder Editor - 63SN37PB

Modify the solder properties as needed and press the **Save** button to update the Solder Library.

Low-Cycle Fatigue

Critical Dwell Time: 20.0 min

Activation Energy (Ea): 1414.0

Critical Max Temp: 368.0

Strain Energy Coefficient: 6.061E-4

CC Calibration Factor: 1:0.0:1.0; 1:3.2:1.0; 2:0.0:1.0; 2:3.2:1.0; 3:0

Leaded Calibration Factor: 2.0

Thermal Shock Factor CC: 15,1.0 | 30,1.25 | 60,1.5

Thermal Shock Factor BGA: 15,1.0 | 30,1.25 | 60,1.5

Thermal Shock Factor LCCC: 15,1.0 | 30,1.25 | 60,1.5

Thermal Shock Factor Leaded: 15,1.0 | 30,1.25 | 60,1.5

Thermal Shock Factor QFN: 15,1.0 | 30,1.25 | 60,1.5

Thermal Shock Factor ThruHole: 15,1.0 | 30,1.25 | 60,1.5

Thermal Shock Factor Default: 15,1.0 | 30,1.25 | 60,1.5

Weibull Beta BGA: 3.0

Weibull Beta CBGA: 3.0

Weibull Beta CC: 3.0

Weibull Beta LCCC: 3.0

Weibull Beta Leaded: 3.0

Weibull Beta QFN: 3.0

Weibull Beta ThruHole: 3.0

Prev 63SN37PB Next

Save Reset Cancel

Fatigue Score

Scoring is determined using the ratio of Life Cycle Goal to Failure Probability (Probability Goal / Probability of Failure). Sherlock assigns a score of zero to any part if the ratio is below two. If the ratio is ten or above, a score of ten is assigned. For any ratio in between two and ten, the score is linearly interpolated between one and ten. The basic intent here is this: Sherlock will deem a part "highly likely to fail" if the Probability Goal is less than two times the Probability of Failure and will deem it as "least likely to fail" if the Probability Goal is greater than ten times the Probability of Failure.

$$1. \text{ If } \frac{\text{Probability Goal}}{\text{Probability of Failure}} < 2 : \text{Score} = 0$$

$$2. \text{ If } 10 > \frac{\text{Probability Goal}}{\text{Probability of Failure}} > 2$$

$$\text{Score} = 1.125 \frac{\text{Probability Goal}}{\text{Probability of Failure}} - 1.125; \text{ Scored between 10 and 1}$$

$$3. \text{ If } \frac{\text{Probability Goal}}{\text{Probability of Failure}} > 10 \text{ Score} = 10$$

Overstress Scoring

Overstress scoring is calculated this way: If the strain is greater than the critical strain set by the user, a score of zero is assigned to the part. If the strain is lower than 200 $\mu\epsilon$, a score of ten is assigned. Anything in between critical strain and 200 $\mu\epsilon$, will be linearly interpolated between one and ten.

1. If $\frac{\text{Critical Strain}}{\text{FEA Strain}} < 1$: *Score = 0*

2. If $\text{Critical Strain} > \text{FEA Strain} > 200\mu\epsilon$

$$\text{Score} = \left(10 - 9 \left(\frac{\text{FEA Strain} - 200}{\text{Critical Strain} - 200} \right) \right) : \text{Scored between 1 and 10}$$

3. If $\text{FEA Strain} < 200\mu\epsilon$: *Score = 10*

4.5. ICT Analysis Results

The ICT Analysis module generates the following types of results:

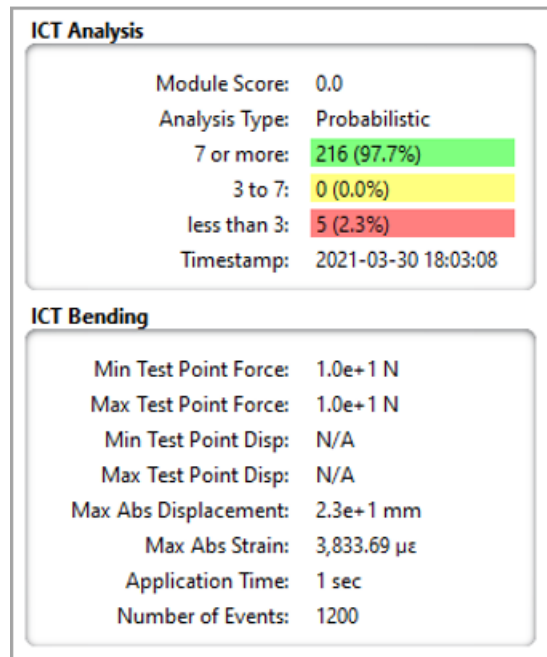
- Overall Summary of the analysis
- Main Result Table displaying the maximum displacement, strain and life predictions
- Result Tables for Parts, Leads, and Mount Points displaying respective strains
- Life Prediction Curve for the circuit card
- Graphical layers showing color-coded part scores (top and bottom sides)
- Graphical layers showing maximum displacement and strain during harmonic vibration events

The overall **Summary** of the analysis essentially consists of information about the ICT analysis results such as maximum displacement of the board and the maximum PCB strain on the board. It also shows the overall module score for the CCA and the score distribution for all the parts on the board by categorizing them into score bins of :

- 7 or more
- 3 to 7
- less than 3

Information related to board properties, the analysis process, and mesh properties are also provided to help you understand the FE information used in the calculation. You can find additional information on the items listed above in the [ICT Analysis Results](#) section of the *Sherlock User's Guide*. A general overview of the Results Table, Life Prediction Curve, and the Graphical FEA Results is provided in the following sections.

Figure 4.12: Summary Tab



4.6. ICT Result Table

You can access the ICT Results Table by selecting the **ICT Analysis** sub-tab to examine the detailed results generated for each part analyzed, as shown here:

Figure 4.13: ICT Table

Current Results - ICTPlotExample Main Board

File

Score Card

Life Prediction

ICT Analysis

Part Validation

Filters

RefDes	Package	Part Type	Side	Material	Weight	Max Disp	Max Strain	TTF (years)	Failure Prob	Score	Overstress Score	Failure Type
U16	TSOP-32 (MO-142...	IC	TOP	EPOXYENCAPSULANT	2.65E-1	1.4E1	648.00	>50	0.0	10.0	8.2	Overstress
U15	TSOP-32 (MO-142...	IC	TOP	EPOXYENCAPSULANT	2.65E-1	4.4E0	1,432.15	>50	0.0	10.0	4.6	Overstress
U14	TSOP-32 (MO-142...	IC	TOP	EPOXYENCAPSULANT	2.65E-1	1.4E1	682.71	>50	0.0	10.0	8.1	Overstress
U13	TSOP-32 (MO-142...	IC	TOP	EPOXYENCAPSULANT	2.65E-1	4.4E0	1,437.84	>50	0.0	10.0	4.5	Overstress
U12	QFP	IC	TOP	EPOXYENCAPSULANT	1.74E0	1.9E1	248.86	>50	0.0	10.0	9.8	Overstress
U11	QFP	IC	TOP	EPOXYENCAPSULANT	1.74E0	1.5E0	2,672.11	>50	0.0	10.0	0.0	Overstress
U10	BGA676	IC	TOP	EPOXYENCAPSULANT	2.62E0	9.6E0	1,839.88	11.0	8.9	1.3	0.0	Overstress
U9	BGA676	IC	TOP	EPOXYENCAPSULANT	2.62E0	9.6E0	1,692.37	19.5	1.7	10.0	0.0	Overstress
U8	QFP-100 (MO-112...	IC	TOP	EPOXYENCAPSULANT	1.41E0	1.9E1	279.84	>50	0.0	10.0	9.6	Overstress
U7	QFP-100 (MO-112...	IC	TOP	EPOXYENCAPSULANT	1.41E0	1.5E0	2,933.50	27.4	0.6	10.0	0.0	Overstress
U6	QFP	IC	TOP	EPOXYENCAPSULANT	7.06E-1	1.8E1	211.66	>50	0.0	10.0	9.9	Overstress
U5	QFP	IC	TOP	EPOXYENCAPSULANT	7.06E-1	1.4E0	2,524.75	>50	0.0	10.0	0.0	Overstress
U4	QFI-68 (MO-087AD)	IC	TOP	EPOXYENCAPSULANT	3.51E0	1.5E1	939.85	>50	0.0	10.0	5.9	Overstress
U3	QFI-68 (MO-087AD)	IC	TOP	EPOXYENCAPSULANT	3.51E0	4.7E0	2,166.25	>50	0.0	10.0	0.0	Overstress
U2	LCCC-20	IC	TOP	EPOXYENCAPSULANT	5.05E-1	1.8E1	159.32	>50	0.0	10.0	10.0	Fatigue
U1	LCCC-20	IC	TOP	EPOXYENCAPSULANT	5.05E-1	1.2E0	2,274.12	>50	0.0	10.0	4.1	Overstress
R158	1206	RESISTOR	BOT	ALUMINA	1.12E-2	2.4E0	2,024.03	>50	0.0	10.0	7.3	Overstress
R157	1206	RESISTOR	BOT	ALUMINA	1.12E-2	3.0E0	1,672.05	>50	0.0	10.0	7.9	Overstress
R156	1206	RESISTOR	BOT	ALUMINA	1.12E-2	3.7E0	1,616.11	>50	0.0	10.0	8.0	Overstress
R155	1206	RESISTOR	BOT	ALUMINA	1.12E-2	4.4E0	1,014.25	>50	0.0	10.0	8.9	Overstress
R154	1206	RESISTOR	BOT	ALUMINA	1.12E-2	4.0E0	1,180.69	>50	0.0	10.0	8.6	Overstress
R153	1206	RESISTOR	BOT	ALUMINA	1.12E-2	3.3E0	1,710.28	>50	0.0	10.0	7.8	Overstress
R152	1206	RESISTOR	BOT	ALUMINA	1.12E-2	2.6E0	2,095.98	>50	0.0	10.0	7.2	Overstress
R151	1206	RESISTOR	BOT	ALUMINA	1.12E-2	2.6E0	1,964.86	>50	0.0	10.0	7.4	Overstress
R150	1206	RESISTOR	BOT	ALUMINA	1.12E-2	3.3E0	1,621.70	>50	0.0	10.0	8.0	Overstress
R149	1206	RESISTOR	BOT	ALUMINA	1.12E-2	4.0E0	1,226.05	>50	0.0	10.0	8.6	Overstress
R148	1206	RESISTOR	BOT	ALUMINA	1.12E-2	4.4E0	1,751.11	>50	0.0	10.0	7.8	Overstress

Summary Life Prediction **ICT** Parts Leads Mount Points

The **ICT** tab displays the maximum displacement and the board strain experienced by all the parts on the board. The damage is calculated from the PCB strain value for a given component. In ICT, the reliability predictions are based only on PCB strain, unlike the results of Random Vibration and Harmonic Vibration where PCB strain or Lead strain might be used, depending on whether the component is leaded or not. As discussed in the [PCB Strain section \(p. 121\)](#) earlier, surface Equivalent strain is considered for PCB strain. Time to Failure (TTF) and Probability of Failure (PoF) are computed from the calculated "damage," and the Score is calculated from the Reliability Goal and PoF.

The ICT table rows are color-coded based on the Score assigned to each part, which is based primarily on the strain experienced by that part according to the ICT model. As with all other Sherlock tabular results, you can double-click any row to view the properties associated with a given part and/or select one or more rows to be exported to a CSV file. In Sherlock, RED means that the predicted score is less than three (less than three times the safety factor). YELLOW means the score is between three and seven. And GREEN means that the score is seven or more, indicating there is a very small probability the part will fail. You can double-click any row in the table to view all the properties associated with a selected part. When viewing Current Results, the properties will come from the current parts list.

Beginning with Sherlock 2021 R2, the **Parts** tab (shown below) is available. The **Parts** tab provide PCB Strain, Part Strain, and Lead Strain. Lead Strain is the maximum of the three Lead Strains for a given component.

Figure 4.14: Parts Tab

RefDes	Part Type	PCB Strain	Part Strain	Lead Strain
J1	JACK	3,644.54	27.20	737.08
U7	IC	2,933.50	180.24	5,025.48
Q12	TRANSISTOR	2,732.67	221.31	2,282.30
C1	CAPACITOR	2,722.27	341.22	
C4	CAPACITOR	2,701.98	324.17	
U11	IC	2,672.11	562.99	4,431.59
R14	RESISTOR	2,642.12	426.52	
R5	RESISTOR	2,623.80	416.20	
R7	RESISTOR	2,616.15	411.93	
R12	RESISTOR	2,615.82	426.39	
R13	RESISTOR	2,605.95	420.68	
Q13	TRANSISTOR	2,590.85	225.10	2,179.57
R6	RESISTOR	2,579.92	421.61	
R15	RESISTOR	2,557.11	425.17	
R10	RESISTOR	2,553.31	390.48	
R11	RESISTOR	2,550.75	413.15	

If the leads are explicitly modelled, the **Leads** tab appears. It displays lead strain information for each part as discussed in [Lead Strain \(p. 120\)](#). If the leads are not modelled, the tab will not be displayed.

Figure 4.15: Leads Tab

File

Score Card

Life Prediction

ICT Analysis

Part Validation

Filters

RefDes	Lead ID	Max PCB Strain	Max Part Strain	Max Lead Strain

Leads (840)

RefDes	Lead ID	Max PCB Strain	Max Part Strain	Max Lead Strain ▼
U7	21	5,025.48	2,622.26	5,025.48
U7	100	4,998.21	2,790.49	4,998.21
U7	50	4,895.37	2,519.57	4,895.37
U7	71	4,766.99	2,584.42	4,766.99
U7	22	4,762.22	2,322.06	4,762.22
U7	99	4,666.20	2,431.17	4,666.20
U7	49	4,623.12	2,231.60	4,623.12
U7	23	4,561.80	2,052.46	4,561.80
U13	16	4,486.02	772.01	4,486.02
U7	72	4,449.58	2,251.14	4,449.58
U7	48	4,447.63	1,979.61	4,447.63
U11	17	2,220.47	4,431.59	4,431.59
U7	98	4,422.90	2,113.91	4,422.90
U11	39	2,228.31	4,404.18	4,404.18
U13	15	4,391.90	732.92	4,391.90
U7	24	4,384.15	1,806.02	4,384.15

Summary

Life Prediction

ICT

Parts

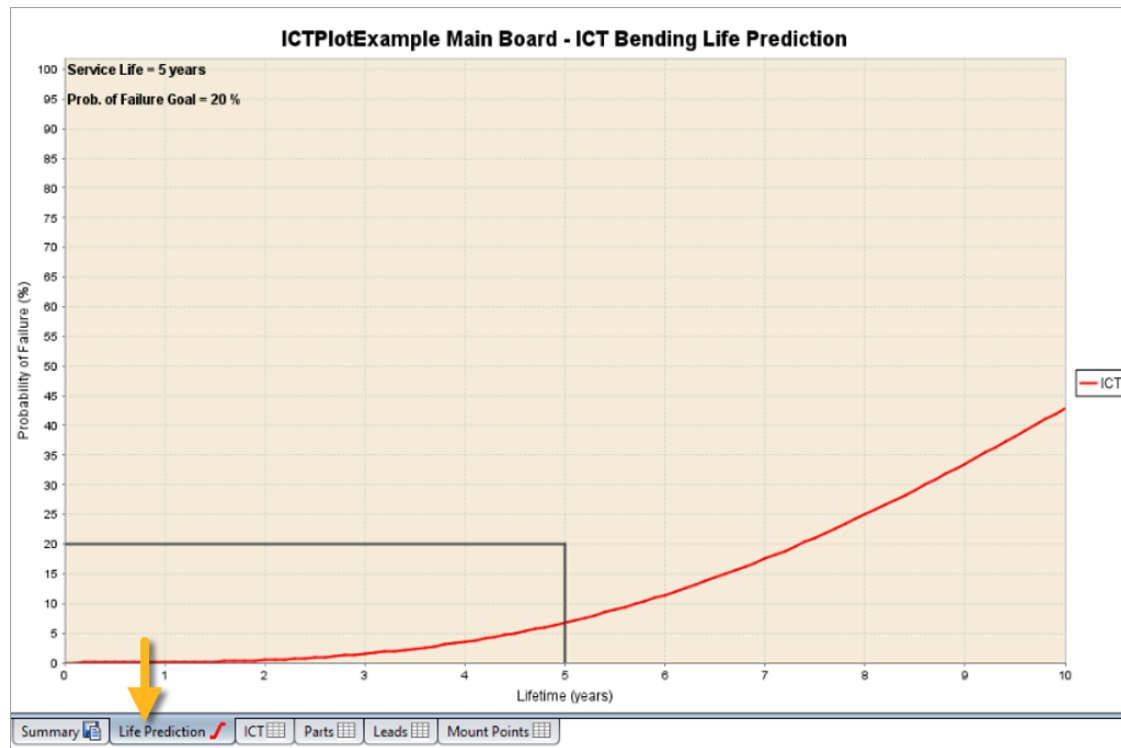
Leads

Mount Points

4.7. Life Prediction Curve

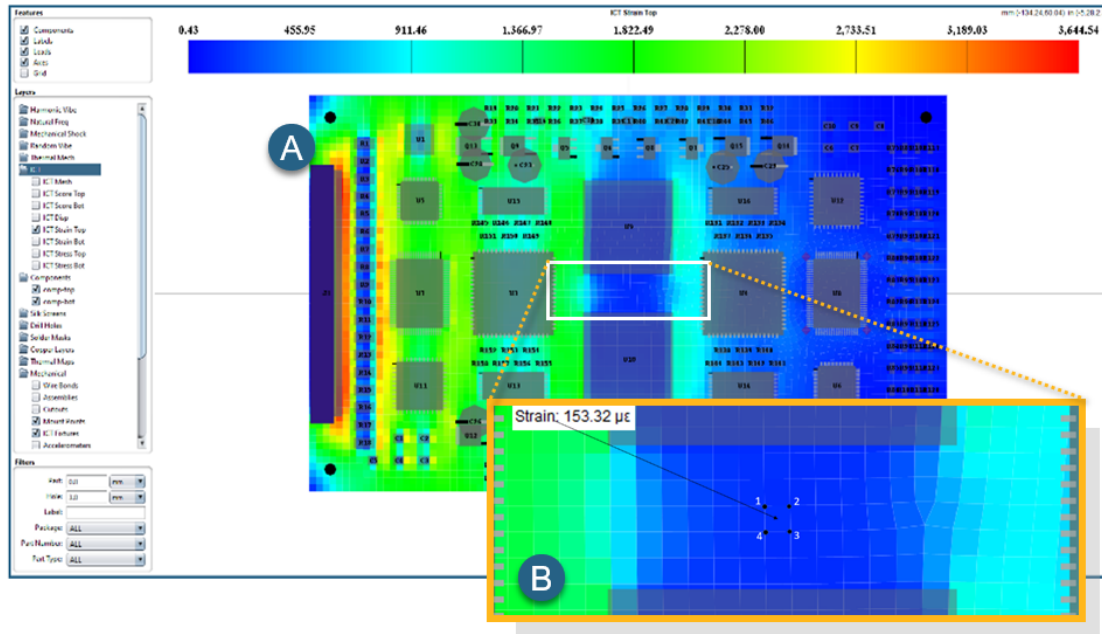
Sherlock provides a Life Prediction Curve for individual components as well as for the entire board. Clicking the **Life Prediction** tab displays the Life Prediction Curve (shown below) for the circuit card based on the Life Prediction Curves for each part analyzed.

The rectangular region in the lower left corner of the chart represents the desired Reliability Goal for the project. The top of the rectangle marks the Probability of Failure, and the right side marks the desired Service Life. If the curve stays below the top line up to the Service Life, the circuit card is predicted to meet its goals. The Life Prediction Curve of the circuit card is calculated by multiplying the reliabilities of the components on the board that have a unique Weibull Slope (β) and Time to Failure. The Probability of Failure for the Life Cycle Goals can be extracted from this plot.

Figure 4.16: Life Prediction Curve in Sherlock

4.8. Graphical FEA Results

The ICT Analysis module generates 2D Results Layers showing the displacement, PCB strains, and PCB stresses experienced during the analysis at both the top and bottom surface of the board (**top** and **bot** in the user interface). Strains are displayed in microstrain. The strain per element face is determined by surface equivalent stress as discussed in [PCB Strain \(p. 121\)](#). The results provided in the **Layer Viewer** are only for the PCB surface and not for the parts. (To view parts results, right-click **ICT Analysis** in the project tree and select **View 3D Model** or **View 3D Results**.) The earlier section, [ICT Strain \(p. 120\)](#), explained in detail how Sherlock calculates the PCB stress and strain. More about the 2D Layer Viewer can be found in the section [Graphical Result Layer \(p. 135\)](#) of *Sherlock's User's Guide*.

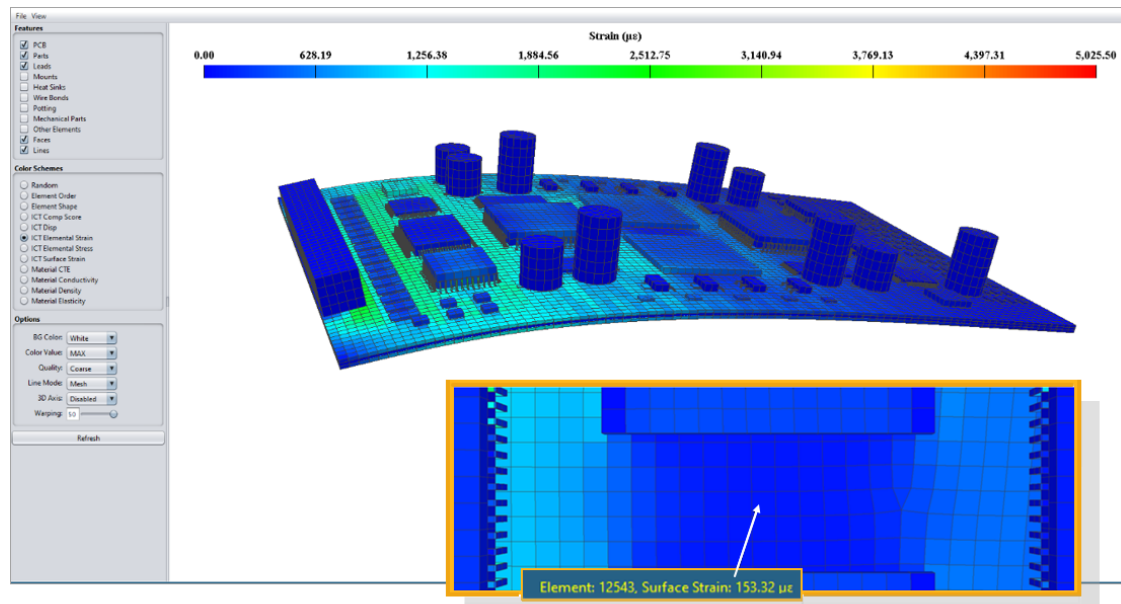
Figure 4.17: Layer Viewer showing TOP Strain (A) and Strain at Board Center (B)

For reference, the following table provides an example of surface equivalent stress and strain on a board element.

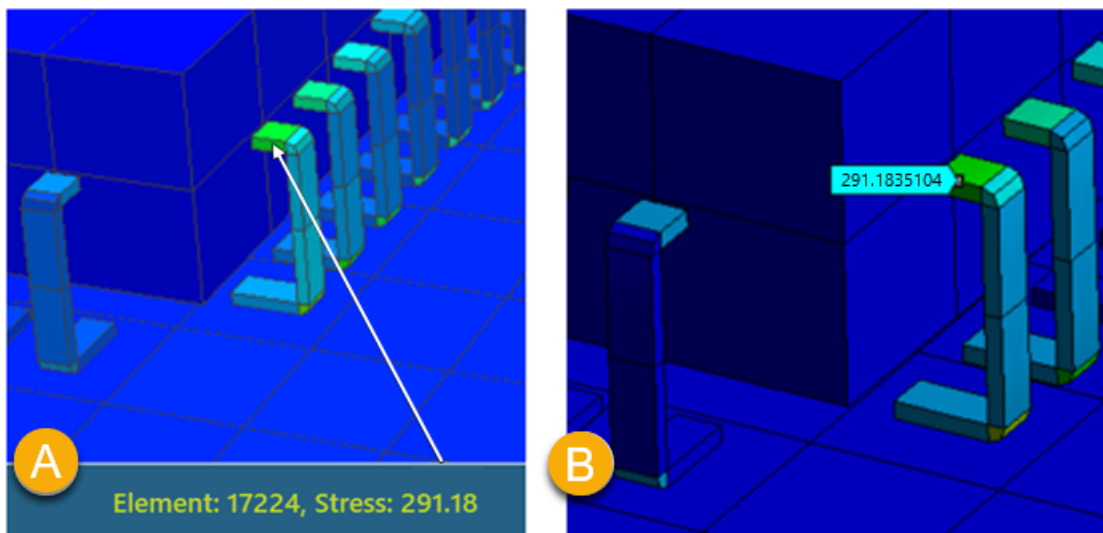
Table 4.1: Element Face Strain in Ansys Mechanical

Node	Stress Label	Stress (MPa)	Average Stress	Surface Stress	Modulus (MPa)	Strain (μStrain)			
1	X	4.103403568	3.995205879	3.649036053	23800	153.3208426			
2	X	3.892062426							
3	X	4.041901112							
4	X	3.943456411							
1	Y	3.281931639	3.155026615						
2	Y	3.023174047							
3	Y	3.277011156							
4	Y	3.037989616							
1	XY	-0.21642576	-0.039081277						
2	XY	-0.18599957							
3	XY	0.124395274							
4	XY	0.121704951							

You can view elemental mean stress and strain the using Sherlock's **3D Viewer** as shown in the figure below. The **3D Viewer** also has an option to view **Surface Strain**. The figure below shows the surface strain for the element at the center of the board. When compared to the 2D results above, you can see that the surface strains are consistent between the 3D and 2D Viewers.

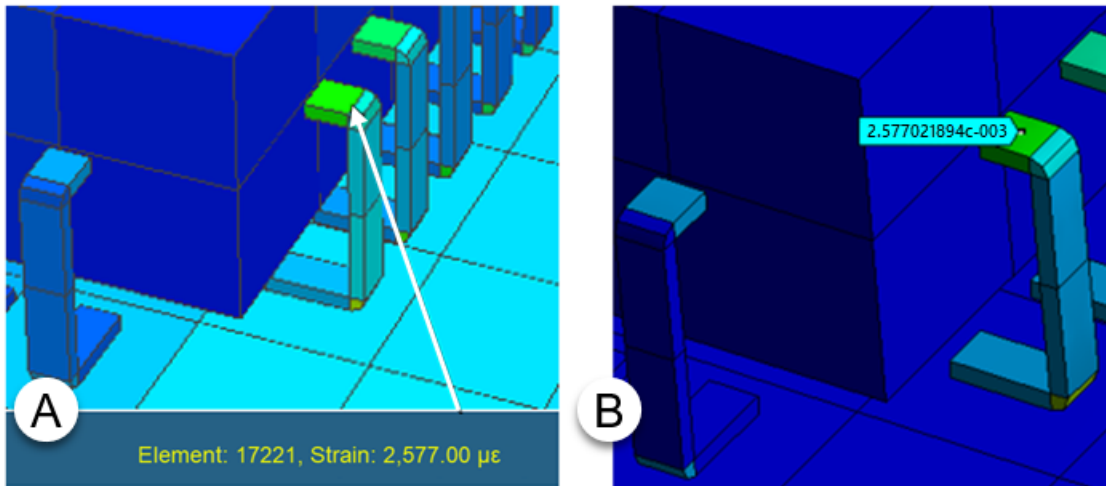
Figure 4.18: Sherlock 3D Viewer. Inset: Surface Strain at Center of Board

The following figures show a comparison of elemental mean stress for a lead element between Sherlock (A) and Ansys Mechanical (B) for the same results file.

Figure 4.19: A: Sherlock 3D Viewer: Elemental Mean Stress, B: Ansys Mechanical

The figure below shows the comparison between elemental mean strain for the same results file. Notably, the elemental modulus for the lead element is 113 MPa.

Figure 4.20: A: Sherlock 3D Viewer: Elemental Mean Strain [$\mu\epsilon$], B: Ansys Mechanical [ϵ]



4.9. Validation

Validation with robust experimental testing is currently being completed for this analysis. As soon as results have been consolidated, they will be published in this document.

4.10. References

1. IPC International. (2012). *IPC-9704: Printed circuit assembly strain gage test guideline*. <https://www.jedec.org/standards-documents>
2. Steinberg, D.S. (2000). *Vibration analysis for electronic equipment (3rd ed.)*. John Wiley & Sons, Inc.

Chapter 5: Random Vibration Theory

Note:

It's important to read the [Sherlock User's Guide](#) before accessing the theory guide content. The user's guide will help you become familiar with Sherlock's capabilities and workflow. A firm understanding of the Sherlock application is essential before delving into the substantial content of the *Sherlock Theory Reference*.

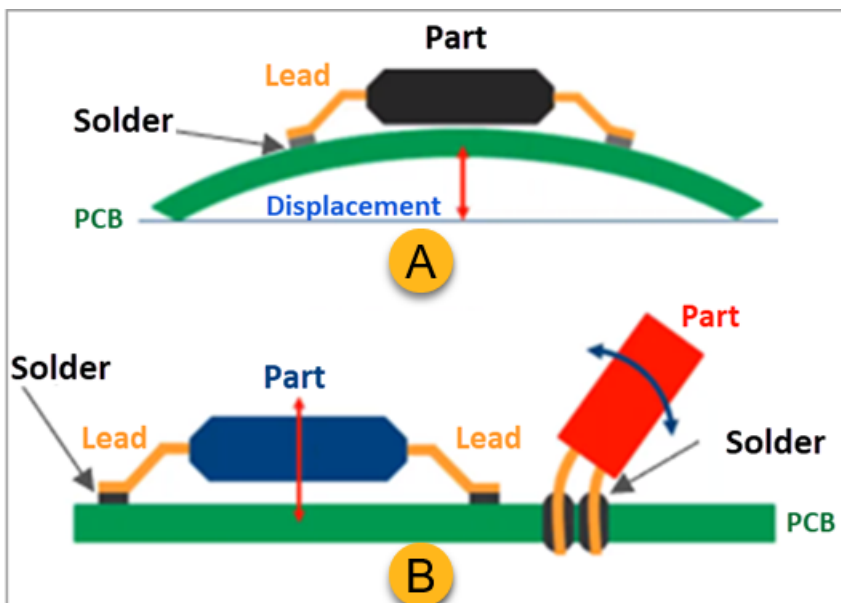
Introduction

Sherlock allows you to perform structural analyses on electronic assemblies and generate life predictions for the electronic components. This chapter explains the theory behind the reliability calculations performed by the Random Vibration Module. There are two failure mechanisms considered in Sherlock:

- Solder Failure
- Lead Failure

During a [Random Vibration Event](#), the circuit board is subjected to bending loads which strain the solder (see A, below) and leads to solder failure. Vibration loads can also bend component leads (B), inducing lead failure. From Sherlock 2021 R2, surface Equivalent Strain is used to determine solder failure, and elemental Equivalent Strain is used for predicting lead failure.

Figure 5.1: A: Solder Failure, B: Lead Failure



A complete electronic system typically includes an electronic box or chassis, a printed circuit board, and the board components. It is crucial to analyze the vibration response of the whole electronic system in order to determine the stresses that occur and the relevant failure mechanism for each component.

The degree to which a part experiences bending varies by component type and its attachment location on the board. When vibration is applied, the circuit card assembly typically responds at its natural frequencies. The resulting stresses will cause damage to the leads and solder joints, leading to crack propagation and eventual failure of the joint or lead.

Chapter Topics:

- 5.1. Random Vibration Analysis in Sherlock
- 5.2. Random Vibration Analysis
- 5.3. Random Vibration Strain
- 5.4. Post Processing – Life Prediction Calculation
- 5.5. Random Vibration Analysis Results
- 5.6. Life Prediction Curve
- 5.7. Graphical FEA Results
- 5.8. 3D Model/Results Viewing
- 5.9. References

5.1. Random Vibration Analysis in Sherlock

Performing a Random Vibration analysis in Sherlock consists of three stages:

1. Preparing the electronic board for the analysis
2. Solving the model
3. Post-Processing the results for reliability prediction

Once the necessary input data for the analysis and post-processing is defined, Sherlock runs the analysis automatically and scores the components on the board based on risk of failure.

The Random Vibration Analysis module in Sherlock uses the following input data in its calculations:

- [Life Cycle Reliability Goals](#) and [Random Vibration Events](#)
- Parts List
- Size and location of all the parts, plated through holes, mount points, and cutouts
- Circuit card mechanical properties (stackup data)
- Solder properties
- Circuit card outline
- Mesh properties
- Solder properties

Life Cycle reliability goals are reliability requirements (which you define) that your electronic system must fulfill over the course of its lifetime. To set your reliability requirements in Sherlock, use the **Reliability Goals** section of the **Life Cycle Editor** (shown below). Enter the expected **Service Life** and **Reliability Metric**. Sherlock uses these values during post-processing to calculate Time To Failure (TTF) and to score a component's failure risk.

Figure 5.2: Life Cycle Editor

Life Cycle Editor

Modify any of the following properties and press the **Save** button to update the life cycle. You may also use the **Load Life Cycle** menu option to load a different life cycle from the file system or the **Save Life Cycle** menu option to save the current life cycle in a named file. Life cycle files can be used in across multiple projects and/or shared with other Sherlock users.

Identification

Name:

Description:

Reliability Goals

Reliability Metric: Prob. of Failure (%) ▼

Service Life: year ▼

In general, reliability is defined as the probability that an electronic device will perform its required function when subjected to a specific condition for a particular period of time. In electronics, the reliability distribution can be modeled using the Weibull distribution. The Weibull distribution function is a probability density function expressed as follows:

$$F(t) = \frac{\beta}{\eta} \left(\frac{t-\gamma}{\eta} \right)^{\beta-1} e^{-\left(\frac{t-\gamma}{\eta}\right)^\beta} \quad (5.1)$$

where:

β is the Weibull slope

η is the scale parameter

γ is the location parameter, $\gamma = 0$, as Sherlock uses a two-parameter Weibull.

In Sherlock, the reliability calculations are based on the probability of failure distribution expressed using the reliability function $P(t)$ as,

$$PoF(t) = 1 - P(t) = 1 - e^{-(\text{damage})^\beta} \quad (5.2)$$

The above equation can also be recognized as the cumulative distribution function (CDF) of probability density function for a 2-parameter Weibull distribution.

More information about damage calculation from the finite element (FE) strain result can be found in the [Post Processing \(p. 152\)](#) section below.

Random Vibe Events are random vibration occurrences defined by the power spectral density [G^2/Hz] of the vibration signal. The load used during a Random Vibration analysis are based on one or more Random Vibe Events defined under the project Life Cycle. The relevant stresses are those that may accelerate one or more of the potential fatigue mechanisms. An example of a Random Vibration Profile used to test aircraft electronic panels is shown below. More information on how to define the Vibration Profile can be found under the [Random Event](#) section in the [Sherlock User's Guide](#).

Figure 5.3: Sample Random Vibe Profile

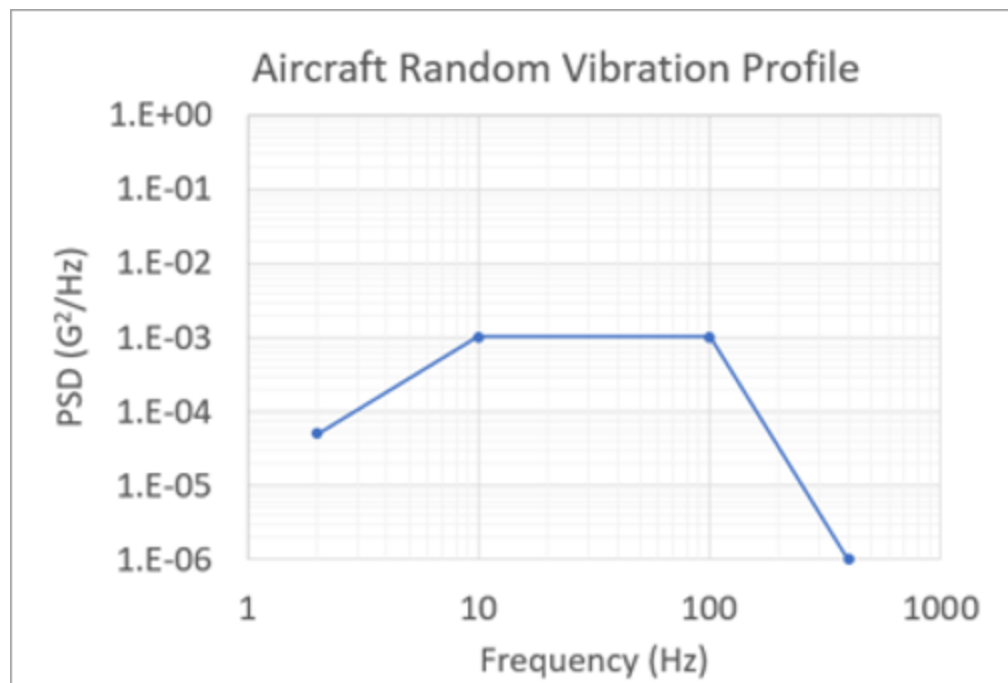


Figure 5.4: Random Vibe Profile Entered into Sherlock's Random Vibe Editor

Random Vibe Editor [X]

Modify any of the following properties and press the **Save** button to update the current Random Vibe.

Identification

Name:

Description:

Random Vibration Settings

Duration:

of Cycles:

Random Load Settings

PCB Orientation: XY Angle YZ Angle

Profile Type:

Random Profile

Load Direction: X Y Z

Aircraft Random Vibe Profile

Amplitude (G2/Hz)

Frequency (HZ)

Load Profile ... Edit Profile ... Save Profile ...

Save Reset Cancel

Currently, only unidirectional loads are supported in Sherlock. You can define the direction of vibration in relation to three principal directions: **X**, **Y**, and **Z**. If multiple Random Vibration Events are defined in the project Life Cycle as shown below, Sherlock performs a separate Random Vibration analysis for each Event and computes the accrued damage. Sherlock will base its life prediction calculation on the total damage.

Figure 5.5: Multi-Event

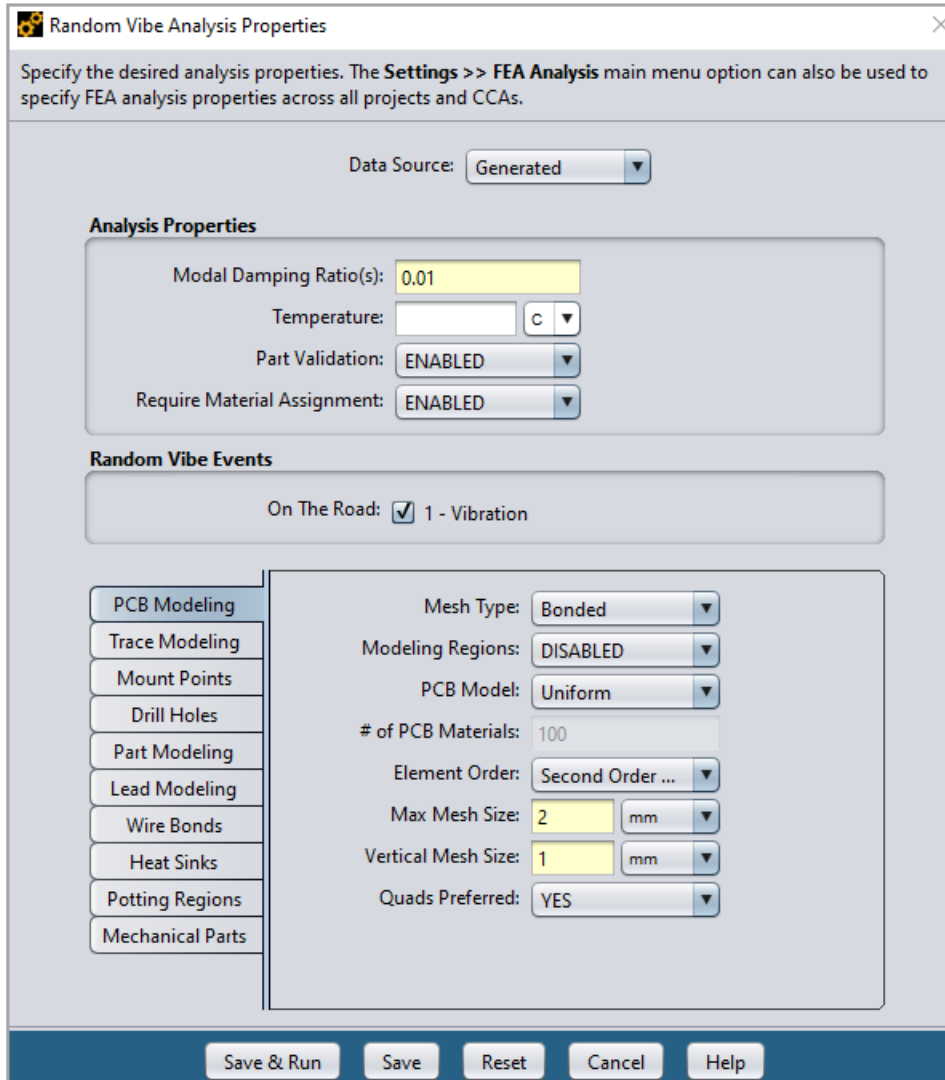
Sherlock has the capability of running the analysis directly as well as exporting the FE model for running the analysis outside the application. While Sherlock does not support the analysis of electronic systems with enclosure/housing directly, it can be used in combination with Ansys Mechanical to do so outside the application. You then can import the results back into Sherlock for failure prediction of the components.

As shown in [Figure 5.6: Analysis Properties \(p. 143\)](#), Sherlock provides the necessary framework for automatically setting up an FE model and solving it in Ansys Mechanical APDL. In addition to Ansys, Sherlock also supports ABAQUS and NX NASTRAN solvers.

For an accurate prediction of the dynamic response of the electronic assembly, the size and location of the components, mount points, mechanical properties of the PCB and solder/leads play a crucial role during random vibration. Boundary conditions in Sherlock can be defined using **Mount Point Properties** as shown in [Figure 5.7: Mount Point Properties \(p. 144\)](#). You can adjust the mount point type as needed along with its corresponding FE constraints under FEA Settings.

Along with setting up the boundary condition, Sherlock provides the necessary toolkit to create a new stack-up, edit an existing stack-up, and accurately define parts and details of the printed circuit board. Temperature dependent properties can be defined in Sherlock as well. When a random vibration analysis is run at an elevated temperature, as shown in [Figure 5.6: Analysis Properties \(p. 143\)](#), the material properties at the elevated temperature are used instead of those at the default temperature of 20°C.

Starting with Sherlock 2023 R1, the Modal Analysis frequency range will come directly from the Random Vibration Event. The minimum frequency of the range will be equal to the minimum frequency of the Random Vibration Event, and the maximum frequency of the range will be 1.5x the maximum frequency of the Vibration Event.

Figure 5.6: Analysis Properties

Random Vibe Analysis Properties

Specify the desired analysis properties. The **Settings >> FEA Analysis** main menu option can also be used to specify FEA analysis properties across all projects and CCAs.

Data Source: **Generated**

Analysis Properties

Modal Damping Ratio(s): **0.01**

Temperature: **C**

Part Validation: **ENABLED**

Require Material Assignment: **ENABLED**

Random Vibe Events

On The Road: ☒ 1 - Vibration

PCB Modeling

Trace Modeling

Mount Points

Drill Holes

Part Modeling

Lead Modeling

Wire Bonds

Heat Sinks

Potting Regions

Mechanical Parts

Mesh Type: **Bonded**

Modeling Regions: **DISABLED**

PCB Model: **Uniform**

of PCB Materials: **100**

Element Order: **Second Order ...**

Max Mesh Size: **2** mm

Vertical Mesh Size: **1** mm

Quads Preferred: **YES**

Save & Run **Save** **Reset** **Cancel** **Help**

Figure 5.7: Mount Point Properties

Edit mount point properties

Enter the desired properties for the mount point:

Mount Point Properties

Mount Point ID:

Mount Point Type:

Mount Point Units:

Mount Point Side:

Mount Point Height:

Mount Point Material:

Mount Point State:

Weight (gram):

Mount Point Shape

Shape Type:

Circle Diameter:

of Nodes:

Center X:

Center Y:

Rotation (degrees):

FEA Settings

Boundary Pt(s):

FEA Constraints: ☒ X-axis translation
☒ Y-axis translation
☒ Z-axis translation

Chassis Material:

Mount Pad

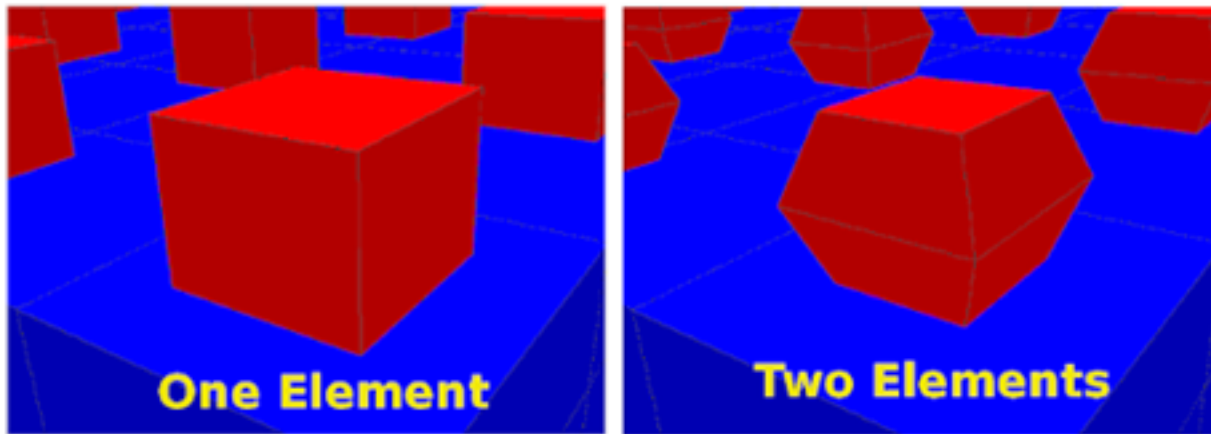
● = Constrained Nodes

Save Reset Cancel

While a housing or chassis cannot be represented as is, you can capture its interaction with the board by defining the mount pads and chassis material as needed. See [Mount Point Management](#) in the *Sherlock User's Guide*.

You will find mesh controls in Sherlock for the PCB, Parts, Leads, Mount Points, and Underfills (Potting) so you can accurately represent the CAD model as a finite element model. Sherlock uses the Ansys mesh engine for meshing all bodies in the assembly, except for leads which are meshed with Sherlock's native algorithms. Also, the contacts in Sherlock are created automatically using Constraint Equations (CE). (See **Bond Tolerance** under [Mesh Settings](#) in the [FEA Engine](#) section of the *Sherlock User's Guide*.)

Currently, solder balls in Sherlock can be modelled as a single-element or two-element model (see below), and leads are modelled with one element through the thickness. To mesh the leads/solder with higher mesh density, you can set up the electronic system for export into Ansys Mechanical for meshing and solving. For complete information on how to create an FE model in Sherlock, refer to the [FEA Modeling](#) section in the *Sherlock User's Guide*.

Figure 5.8: Solder Modeling

5.2. Random Vibration Analysis

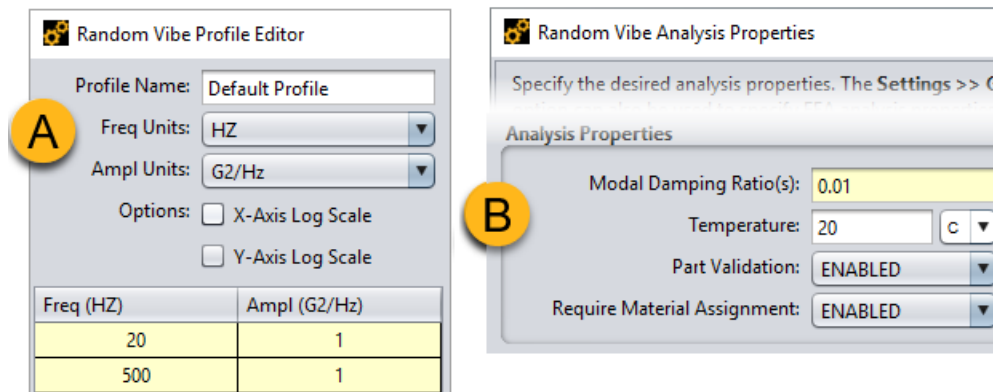
The Random Vibration analysis is a finite element analysis that is completed using two FEA simulations: a modal analysis in the frequency domain in Sherlock followed by a Random Vibration simulation in Ansys Mechanical. (More about the latter procedure is available in [Chapter 6.6 of Mechanical APDL 2020 R2 Structural Analysis Guide](#).) Similarly the procedure for ABAQUS on random vibs can be found in Abaqus Documentation. Nastran implementation of Random Vibration in Sherlock still uses 1G harmonic sweep. As discussed earlier, Sherlock then uses the analysis results for making reliability predictions.

Sherlock can also display the results in the **2D Layer Viewer** and the **Results Viewer** as described below in [Random Vibration Analysis Results](#). For an expanded explanation, see the [Vibration Analysis Results](#) section of the *Sherlock User's Guide*.

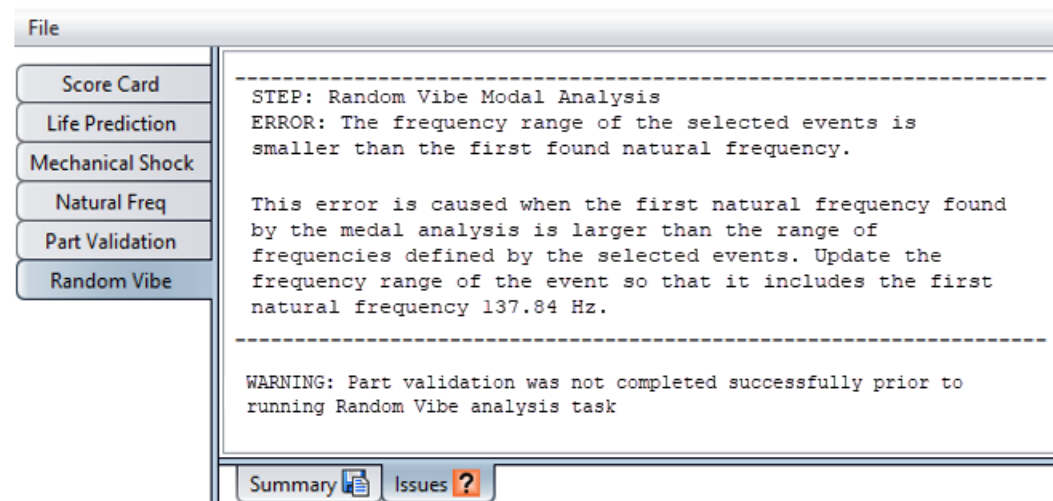
All the modules use millimeters for units of length. For information on how to setup a board for a Random Vibration analysis and how to import the result file when solved outside of Sherlock, see the [Finite Element Analysis Overview](#) in the *Sherlock User's Guide*.

Sherlock's vibration simulation uses modal-based damping which you can specify as **Modal Damping Ratio(s)** in the **Analysis Properties** form (shown below in [Figure 5.9: Frequency Range for PSD \(p. 146\)](#), B). When a single value is provided as an input, all modes will have the same value for the modal damping ratio. When multiple values are provided separated by commas (example: 0.025,0.020,0.015), then the respective values are used in order starting with the first mode (example: MDAMP,1,0.025 \$ MDAMP,2,0.02 \$ MDAMP,3,0.015). If there are five modes considered in the Random Vibration analysis but only three damping ratios are provided as input, user-provided values are used for the first three modes. For the remaining fourth and fifth modes, the last input value (that is, the value provided for the third mode) will be used (example: MDAMP,1,0.025 \$ MDAMP,2,0.02 \$ MDAMP,3,0.015, \$ MDAMP,4,0.015, \$ MDAMP,5,0.015).

The loads for [Random Vibration Analysis](#) are provided in terms of an input PSD as $\text{acceleration}^2/\text{Hz}$ across the range of frequencies to be tested. The input vibration is applied as a base vibration at the mount point locations. As mentioned earlier, the input PSD and the direction of vibration can be controlled through **Random Vibe Editor**. To complete a successful Random Vibration analysis, there must be at least one natural frequency mode within the defined frequency range. Because the modal analysis frequency range is based on what is specified for the Vibration Event, Sherlock will pick up all the modes of the frequency range defined for the Event.

Figure 5.9: Frequency Range for PSD

If the PSD frequency range is outside the modal analysis range, Sherlock will not run the Random Vibration analysis. It will give an error under the **Issues** tab as shown below. More information on other result tabs can be found in [Random Vibration Analysis Results \(p. 162\)](#).

Figure 5.10: PSD outside the Natural Frequency Range

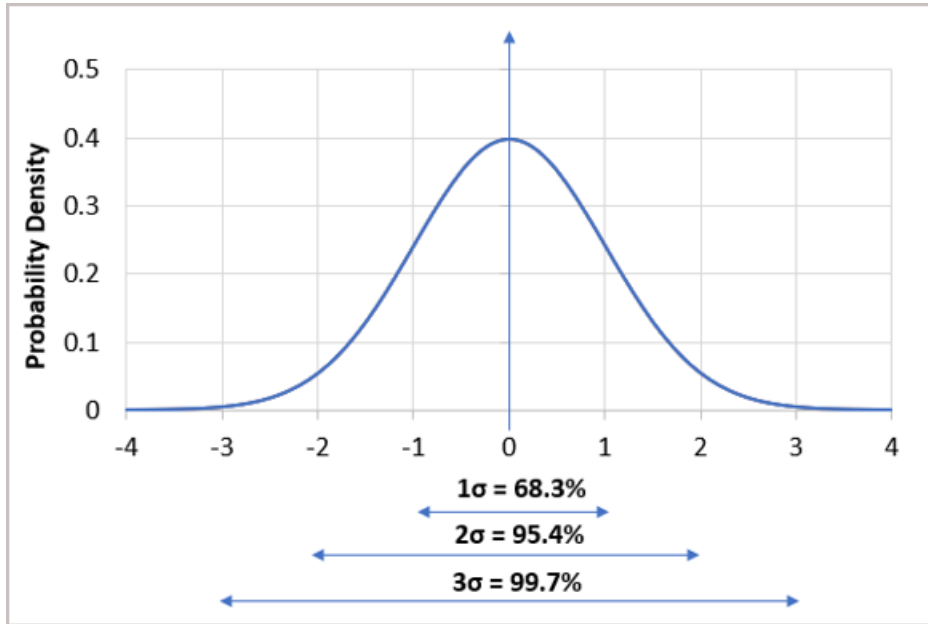
Because the Random Vibration analysis is probabilistic in nature, the results are expressed in terms of probability of occurrence. Most Random Events tend to follow a normal distribution as shown in [Figure 5.11: Normal Distribution Curve \(p. 147\)](#). The probability of occurrence is generally defined using standard deviation notation, σ (sigma). Sherlock uses the equivalent/von Mises strain derived from equivalent/von Mises stress as the failure indicator in the Random Vibration Module. More on the failure indicator is available below in [Strain Calculation \(p. 151\)](#).

In a Random Vibration analysis, if the von Mises stress results are observed at 1σ , it simply means that there is a 68.3 % chance that the given stress may occur. Likewise, if the stress is observed at 2σ and 3σ , there is a 95.4 % and 99.7 % chance respectively that the stress may occur at the given value.

In Ansys Mechanical APDL, the stresses and strains are expressed as tensors. Combined stresses are not available because combining tensors at a specific probability may not produce the same results. The only exception is for Equivalent Stress where Mechanical APDL uses special algorithms to provide the stress at a set probability level. For equivalent/von Mises stress, Ansys uses the [Segalman \(p. 168\)](#) approach

to obtain the results. More information on Random Vibration results can be found under [6.6.3 Review the Results](#) in the *Mechanical APDL Structural Analysis Guide*.

Figure 5.11: Normal Distribution Curve



Note:

In versions prior to 2022 R2, Sherlock uses calculated, modal-based damping based on [Equation 5.3 \(p. 147\)](#) for its vibration analysis, and it uses modal based damping that you can scale using the **Damping Modifier** (shown above in [Figure 5.9 \(p. 146\)](#), B), either increasing or decreasing the damping of the circuit card assembly. A ratio of 0.1 represents very little damping and is akin to rigid mounting. A ratio of 1.0 is more representative of chassis-mounted circuit card assemblies and will lower transmissibility. The idea behind the equation is to make the first mode (bending) dominant so that the displacement, caused by leaded-component sway modes at high frequencies, does not interfere with the actual physics of failure. The Damping Modifier relates to the Modal Damping Ratio by the following equation:

$$D_i = D_{\text{Sherlock}} * f^{\left(\frac{-1}{n_i+1}\right)} \quad (5.3)$$

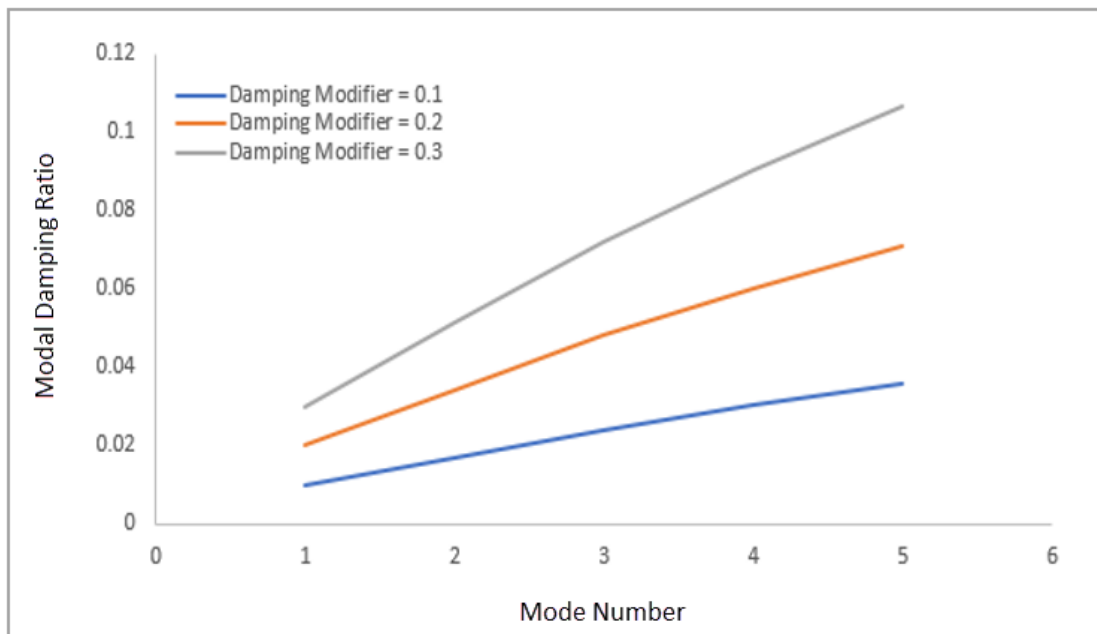
where

D_i is the Modal Damping Ratio for the i^{th} mode and is automatically calculated by Sherlock which is then used by the Mechanical APDL solver as MDAMP.

D_{Sherlock} is the Modal Damping Modifier input in Sherlock.

f is the natural frequency (in Hz) corresponding to mode number n_f .

[Figure 5.12 \(p. 148\)](#) shows how damping is adjusted for different damping modifiers for the first five modes, assuming the natural frequencies are 100 Hz, 200 Hz, 300 Hz, 400 Hz and 500 Hz. For more information on damping, refer to theories by [Dave S. Steinberg \(p. 168\)](#).

Figure 5.12: Modes vs Modal Damping Ratio

5.3. Random Vibration Strain

Since release 2021 R2, Sherlock reports three strains for a given component in Random Vibration. They are:

- Lead Strain (if the leads for the component are modelled)
- Part Strain
- PCB Strain

Lead strain is reported at three locations. These strains are displayed under the **Lead** tab in the Results Viewer (see [Results Table \(p. 165\)](#) below).

- Max Lead Strain: Maximum strain across the lead body
- Max Part Strain: Maximum Strain at the Lead and Component interconnect
- Max PCB Strain: Maximum strain at the Lead and PCB interconnect

5.3.1. Known Issue in the Previous Sherlock Versions

In the previous versions of Sherlock, nodal strains were reported, which sometimes led to elevated strain results, especially at the lead-to-component interface. This was caused by the modulus difference between lead and the component body. Sherlock now uses a different approach to evaluate lead strain as well as PCB and part strain. These updates may cause slight difference in the results due to the difference in the Segalman based strain and the nodal strain. These changes are explained further in the next section.

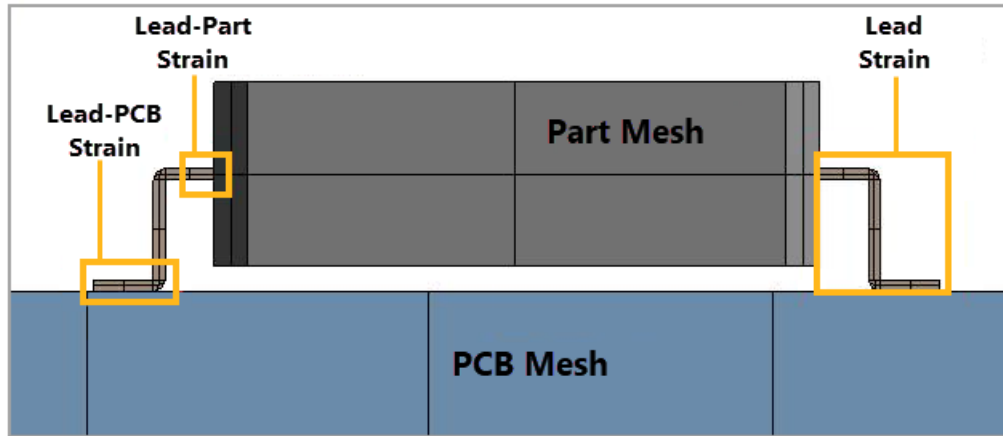
5.3.2. Lead Strain

For leaded components, strains are reported at three locations.

1. Lead Strain
2. Lead-Part Strain
3. Lead-PCB Strain

A pictorial representation of these sites is shown below, [Figure 5.13: Lead Strain \(p. 149\)](#).

Figure 5.13: Lead Strain



Max Lead Strain reports the maximum strain experienced by the lead body. Lead strains are computed as elemental Mean Equivalent stress over the elemental Young's modulus as given in the following equation:

$$\varepsilon_n = \frac{\sigma_{VM-n}}{E_n} \quad (5.4)$$

where n is the element number.

For a given lead, Element Strain is calculated for each element in the lead, and the maximum strain out of all elements is reported as the Lead Strain.

$$E_n = \frac{\sigma_{Eq-n}}{E_n} \quad (5.5)$$

where σ_{Eq-n} is Elemental Mean Equivalent Stress—that is, the average value of unaveraged nodal equivalent stress from all nodes attached to an element

E_n is Young's Modulus of Element n in the lead.

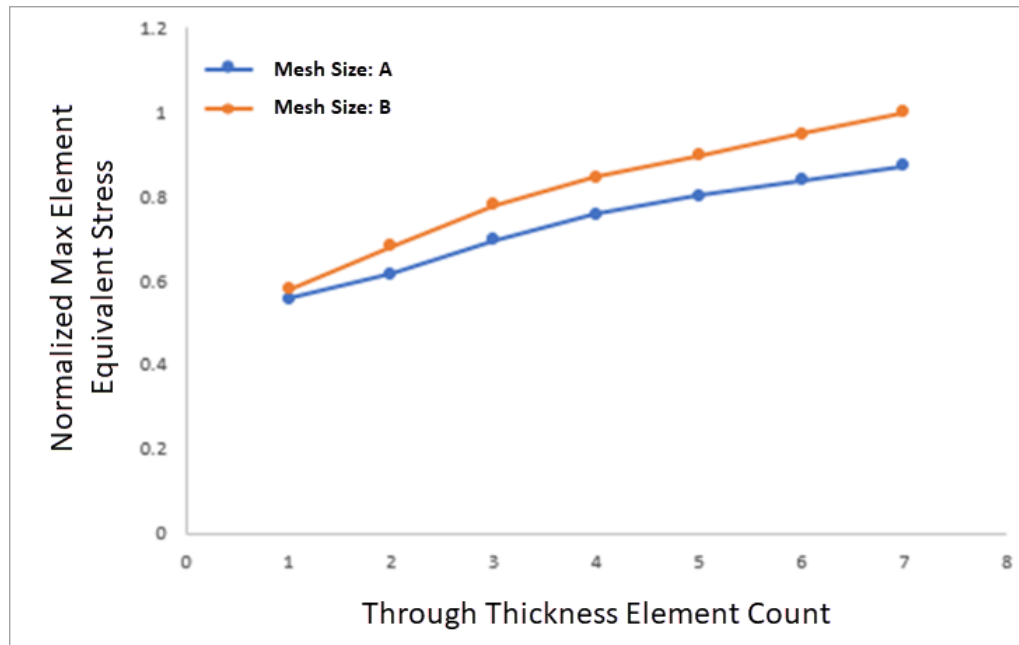
Lead-to-PCB interface strain (displayed as PCB Strain under the **Leads** tab in the **Results Table**) describes the maximum lead strain from the set of lead elements that are connected to the PCB.

Similarly, the Lead-Part interface strain (displayed as **Part Strain** under the **Leads** tab in the **Results Table**), describes the maximum lead strain among the lead elements attached to the part.

5.3.2.1. Sharp Corners in Leaded Device and Singularities

With electronic components, sharp corners in leads are unavoidable. Modelling relief angles makes meshing difficult. Meshing sharp corners in any FE tool introduces singularities and is a well-known FE issue. Performing a sensitivity study does not help in determining optimum mesh size. The graph below is from a sensitivity study of leads with two mesh sizes across different through-thickness element counts. Due to the presence of sharp corners, increasing the mesh density only amplifies any kind of singularity present. Since Sherlock 2021 R2, meshed leads are set to have only one element through the thickness. If you mesh the leads outside Sherlock, anything greater than three or four elements through the thickness increases the solve time exponentially.

Figure 5.14: Mesh Sensitivity



5.3.3. Part Strain

Part Strains are computed when the **Part Modeling** is enabled in the FE model. Parts may crack in tension. The failure can be captured by elemental Equivalent Strain ε_n as shown below. Equivalent Strain is calculated for each element representing the part, and the maximum strain out of all the elements (representing the part) is reported as the Part Strain.

$$\varepsilon_n = \frac{\sigma_{Eqv-n}}{E_n} \quad (5.6)$$

where σ_{Eqv-n} is the Elemental Equivalent Stress—that is, Equivalent Stress determined from the averaged value of the unaveraged nodal stresses of the element.

E_n is the Young's Modulus of element n in the part.

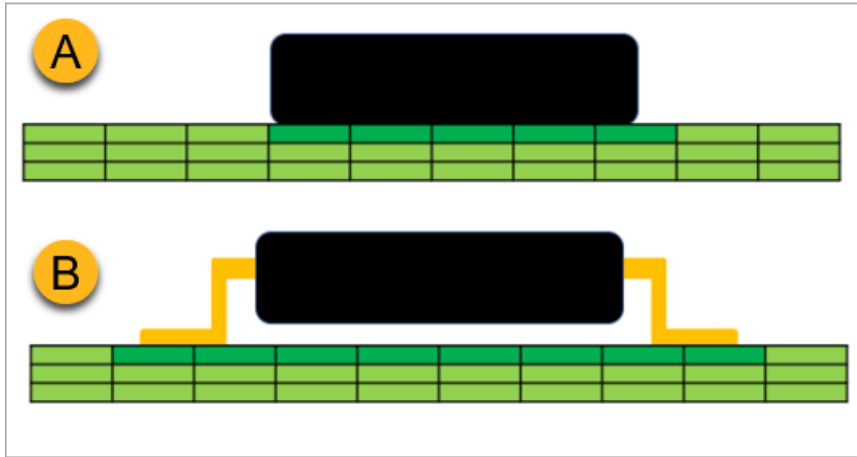
5.3.4. PCB Strain

PCB Strains are computed at the footprint of every component on the board. PCB bending causes component failure, and board-bending can be captured by Surface Equivalent Strain, as explained earlier in [Strain Calculation](#) (p. 151).

If a part does not have leads, the elements under the footprint of the part are used (see A in the figure below). If a part has leads, the elements under its footprint, which includes the leads, are used (B, below).

The components and the set of elements used for max PCB strain calculation are represented graphically in the image below. The elements under the footprint of the parts are dark green. All other PCB elements are light green. Surface Equivalent Strain is calculated for every element face of the component footprint on the PCB, and the maximum Surface Equivalent Strain calculated from those element faces is taken as the PCB strain under that part. Surface Equivalent Stress is computed as shown below in [Equation 5.7](#) (p. 151).

Figure 5.15: PCB Strain



$$\varepsilon_n = \frac{\sigma_{\text{Eqv Avg Face}}}{E_n} \quad (5.7)$$

$\sigma_{\text{Eqv Avg Face}}$ is the Surface Equivalent Stress—that is, the Equivalent Stress determined from the averaged value of the unaveraged corner nodal Segalman Stresses of the element face.

E_n is the Young's Modulus of element n in the part.

5.3.4.1. Strain Calculation

Surface Equivalent Strain is computed as

$$\varepsilon_n = \frac{\sigma_{VM-n}}{E_n} \quad (5.8)$$

where n is the element number.

There results from Random Vibration PSD analysis are probabilistic in nature, so it is not possible to combine the directional stresses or strains to compute the Equivalent stress and strain according to the regular formula given in [Combined Stresses and Strains in the Theory Reference](#). But it is

possible to calculate the equivalent stress as shown in the section [Equivalent Stress Mean Square Response](#). But there is no accepted direct mathematical procedure for calculating equivalent strain from a Random Vibration analysis. In a way, the equivalent strain determined by [Equation 5.8 \(p. 151\)](#) retains the probabilistic nature of the analysis. The Surface Equivalent strain is derived from the nodal unaveraged Equivalent stress on the PCB Element surface as explained here:

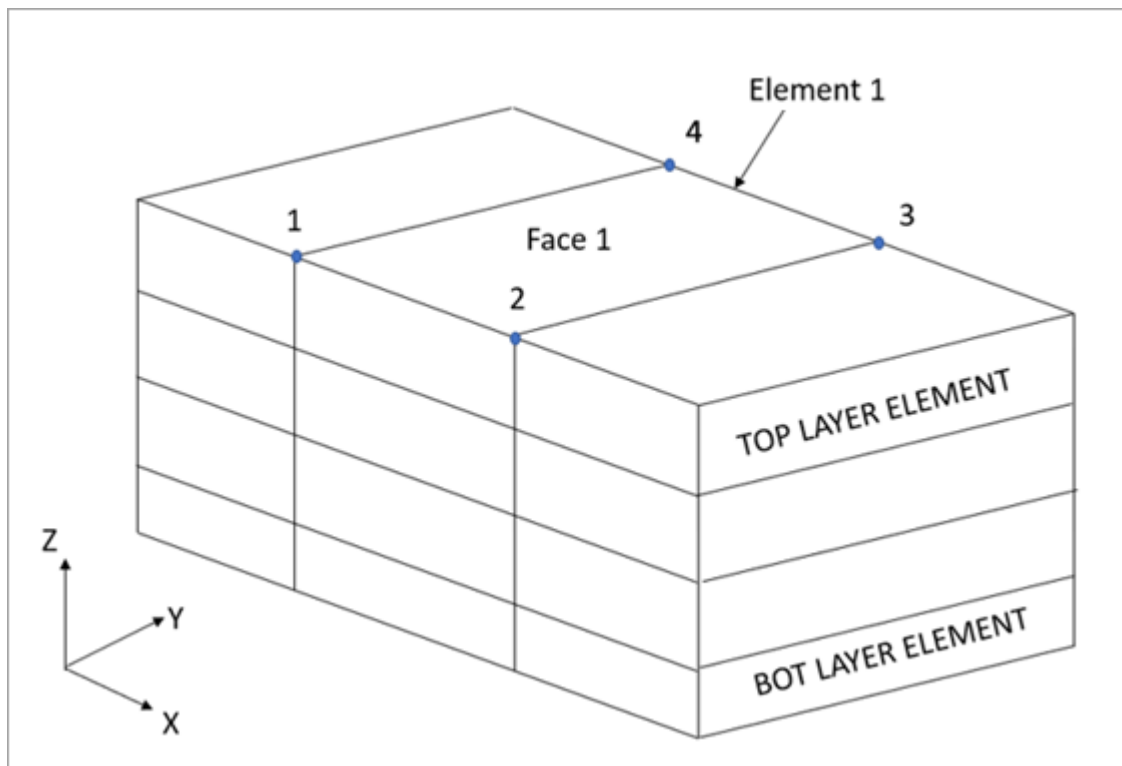
1. Extract the unaveraged nodal Equivalent stresses for all the nodes on each PCB element surface.
2. Average the unaveraged nodal Equivalent stresses on the surface for each element. (Each element will either have three or four nodes, depending on the element type.)
3. Surface Equivalent Strain = Averaged Face Equivalent Stress / Element Young's Modulus:

$$\sigma_{\text{Eq Avg Face}} = \frac{\sum_1^k \sigma_{\theta q-n}}{k} \quad (5.9)$$

where k is the number of nodes on the element face.

$\sigma_{\theta q-n}$ = Unaveraged Nodal Equivalent Stress

Figure 5.16: Surface Equivalent Strain



5.4. Post Processing – Life Prediction Calculation

Solder joint failure due to vibration is based on similar techniques developed by [Steinberg \(p. 168\)](#). The main modification is converting a displacement-based criterion to a board level strain criterion. The Steinberg critical PCB deflection is the maximum deflection at which a component will survive 20 million cycles during Random Vibration. The equation for the Steinberg critical PCB deflection is

$$Z_c = \frac{0.00022B}{chr\sqrt{L}} \quad (5.10)$$

where

B is the length of the PCB parallel to the component (in inches)

c is a component packaging constant (typically between 0.75 and 2.25) (Steinberg, 2000 (p. 168). p.217). Although Sherlock uses a similar methodology as Steinberg, it is not the same. Sherlock uses PCB strain where Steinberg uses deflection based on an unpopulated board. Since Sherlock uses FEA and the LCCC is ceramic, the software assumes a continuous attachment to the PCB which generates very high strains. For this reason, it is not necessary to decrease critical strain with the Correction Factor. If you wish, you can modify this value under the **Correction Factors** tab in the Solder Editor. If a Correction Factor is not listed for a specific package type, Sherlock uses the default value of 1.0.

h is the PCB thickness (in inches)

r is a relative position factor and is 1.0 when the component is located at the center of the PCB

L is the component length (in inches)

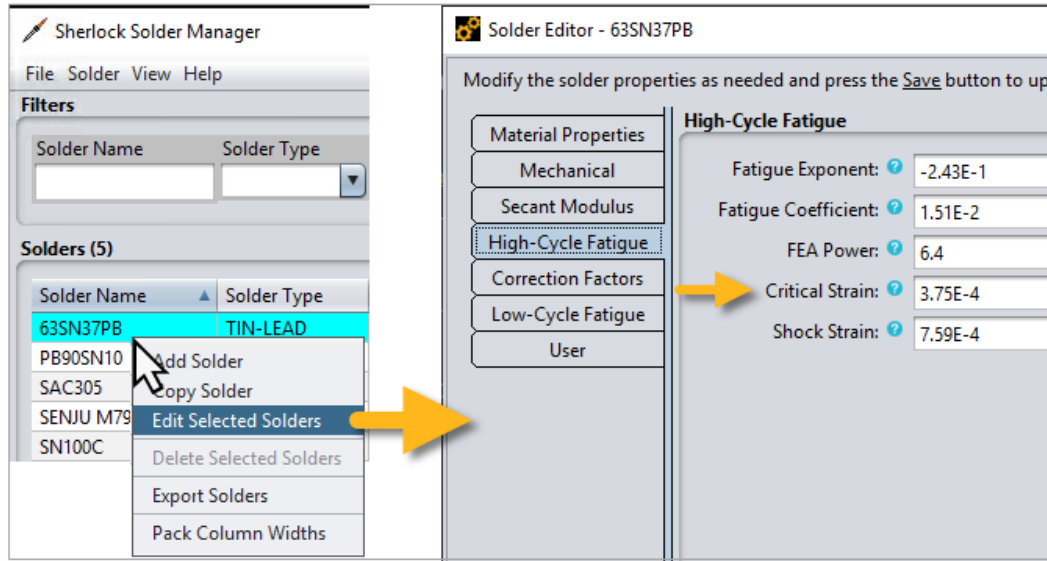
The main shortcoming of this approach is that it is limited to simple board geometries (since the maximum deflection is always assumed to be at the center of the PCB) and does not account for board curvature. By utilizing finite element modeling, the software can eliminate some of the variables in the Steinberg equation: board length **B**, position factor **r**, and board thickness **h**. This simplifies the equation:

$$\varepsilon_c = \frac{\zeta}{c\sqrt{L}} \quad (5.11)$$

The (zeta) represents a baseline board-level strain that is modified by the component size and type. It is analogous to 0.00022B (B is the edge length of the PCB) in Equation 5.10 (p. 153). It is displayed in Sherlock's **Solder Library** as **Critical Strain** in the **High-Cycle Fatigue** tab of the Solder Profile. (See the figure below.)

Note:

Steinberg's approach is limited to simple board geometries. Sherlock uses FEA and is not limited to simple board geometries.

Figure 5.17: High-Cycle Fatigue tab in Sherlock's Solder Editor

The baseline board-level strain represents the strain generated under a component of unit length at the center of the board with unit packaging constant. Sherlock uses a default value of $375 \mu\epsilon$ for this board-level strain during board bending. The value is derived from Steinberg's maximum displacement equation. According to Steinberg, the board bends sinusoidally (haversine) during vibration. Therefore, given a standard board length that is .06 inches thick, the maximum deflection is given by the expression below:

$$Z_c = \frac{0.00022B}{chr\sqrt{L}} = \frac{0.00022*5.8}{1*0.06*1*\sqrt{1}} = 0.021267'' \quad (5.12)$$

Curvature () for the haversine wave is given by the following expression:

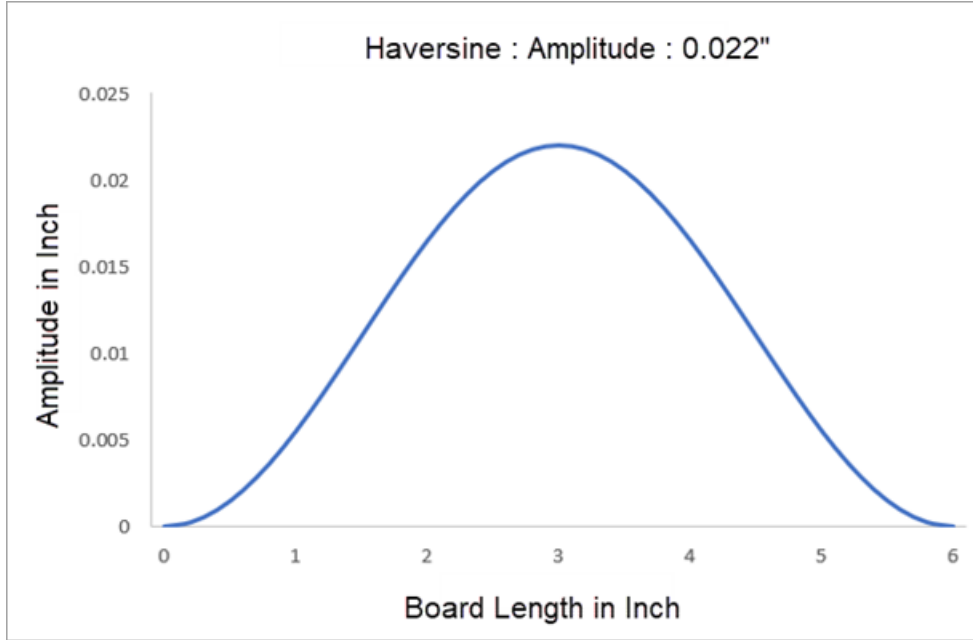
$$\kappa = \frac{2a\frac{\pi^2}{B^2}\cos\left(2\frac{\pi}{B}x\right)}{\left(1 + \left[2a\frac{\pi}{B}\cos\frac{\pi x}{B}\sin\frac{\pi x}{B}\right]^2\right)^{3/2}} \quad (5.13)$$

where:

is the deflection amplitude

B is the board length

is any point along the length of the board

Figure 5.18: Haversine Wave

An example of a deflection solution of a board with length six inches and deflection amplitude of 0.022 inches is provided in [Figure 5.18: Haversine Wave \(p. 155\)](#). The curvature for displacement calculated in [Equation 5.12 \(p. 154\)](#) is given below.

$$\kappa = \frac{2 \cdot 0.021267 \frac{\pi^2}{5.8^2} \cos\left(2 \frac{\pi}{5.8} \left(\frac{5.8}{2}\right)\right)}{\left(1 + \left[2 \cdot 0.021267 \frac{\pi}{5.8} \cos\frac{\pi(5.8)}{5.8} \sin\frac{\pi(5.8)}{5.8}\right]^2\right)^{3/2}} = \frac{2 \cdot 0.021267 \cdot \frac{\pi^2}{5.8^2}}{1} = 0.012479'' \quad (5.14)$$

The negative sign is ignored from the above result as direction of curvature is immaterial. Strain for the above curvature is given here:

$$\zeta = y \frac{1}{R} = y \cdot \kappa = \frac{0.06}{2} \cdot 0.012479 \cong 374 \mu\epsilon \quad (5.15)$$

is surface strain due to the curvature

y is distance from the neutral axis (half the thickness of the board)

$R = \frac{1}{\kappa}$ is the radius of curvature

When leads are disabled, Sherlock uses this critical strain value and the FEA computed strain values (surface elemental strain values) to make fatigue predictions using the Basquin equation:

$$N_{\text{FEA}} = N_C \left(\frac{\epsilon_c}{\epsilon_{\text{FEA}}} \right)^b \quad (5.16)$$

where:

N_{FEA} is the predicted number of cycles to failure

N_C is 20E6 ([Steinberg, 2000 \(p. 168\)](#), p.216)

ε_c is the component critical strain value from [Equation 5.12 \(p. 154\)](#). Sherlock uses the baseline board-level strain and scales the component critical strain based on the component type (**c**, packaging constant) and size (**L**, component diagonal length).

ε_{FEA} is the maximum surface elemental Equivalent Strain under the footprint of a given component. PCB Strain is considered here.

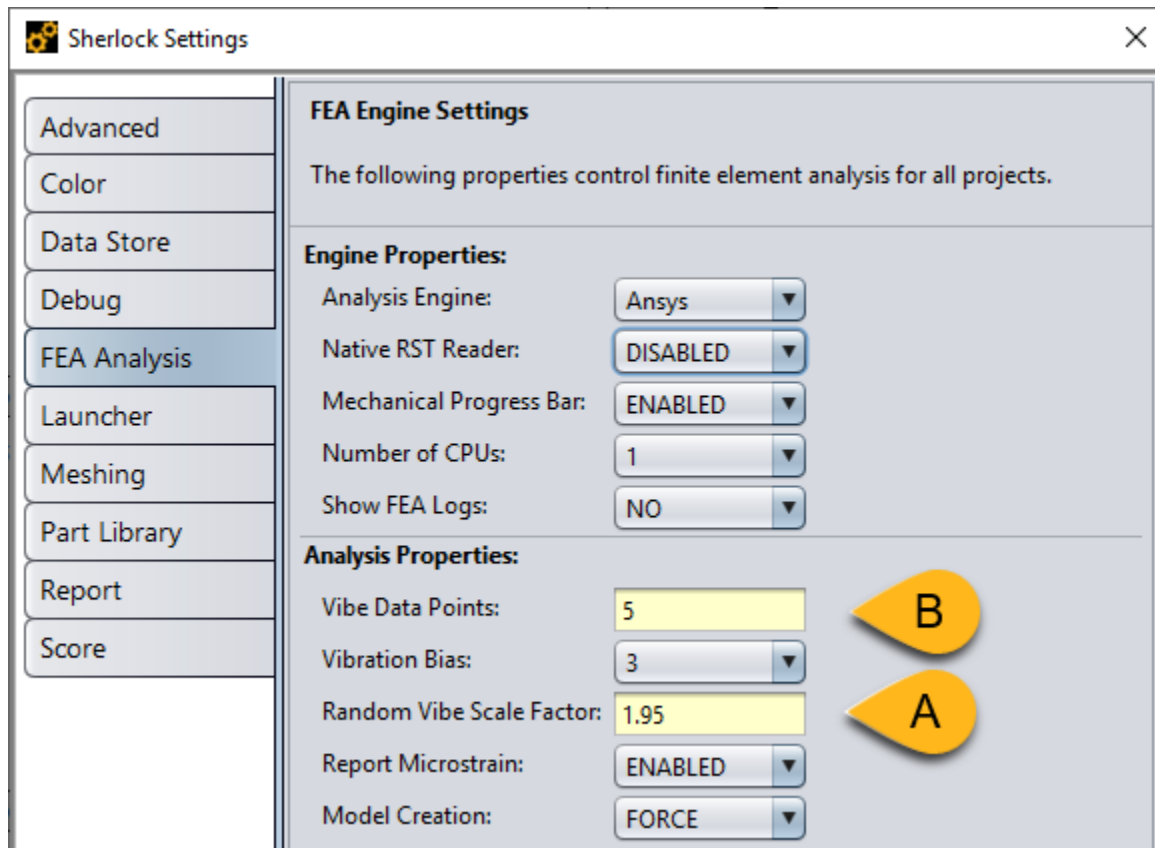
b is the fatigue exponent (displayed as **FEA Power** in the **High-Cycle Fatigue** tab in the **Solder Editor**, shown in [the figure above \(p. 154\)](#)) and is dependent on the solder alloy. This exponent is derived from correlation studies and physical testing data.

The scaling factor, which is industry specific, depends on the fatigue exponent and roughly varies between 1.7 to 2.05. For more information, refer to p. 213 of [Steinberg \(p. 168\) \(2000\)](#). For most solders, 1.95 can be used. This is the default value (**Random Vibe Scale Factor**) in Sherlock. The scaling factor can be adjusted in **Sherlock Settings** as shown in the figure below (A).

Results for a Random Vibration in Ansys Mechanical APDL are at 1σ RMS but can be scaled to any RMS value (2σ , 3σ , or any custom scaled σ value).

The **Vibe Data Points** (B, below) is specific to ABAQUS and is used to define points that make up the response curve. The RMS value in ABAQUS is calculated as area under the response curve.

Figure 5.19: Random Vibe Scale Factor



When leads (or solder balls in BGAs) are enabled, Sherlock uses the fatigue coefficient and the FEA-computed elemental Equivalent Strain values to make fatigue predictions using the Basquin equation:

$$N_{FEA} = \frac{1}{2} \left(\frac{\varepsilon_e}{\varepsilon_f} \right)^{\frac{1}{b}} \quad (5.17)$$

where

N_{FEA} is the predicted number of cycles to failure, also called CTF (Cycles to Failure).

ε_e is the maximum element Equivalent Strain value recorded in the lead (or solder ball). The strain values are derived from the elemental Equivalent Stress and the modulus of the element. Lead Strains are taken into account.

ε_f is the fatigue coefficient and is dependent on the lead (or solder ball) material. This value is derived from correlation studies and physical testing data.

b is the fatigue exponent (displayed as fatigue exponent in the **High-Cycle Fatigue** tab in Sherlock's **Solder Editor**) and is dependent on the lead (or solder ball) material. This exponent is derived from correlation studies and physical testing data.

Figure 5.20: High Cycle Fatigue Constant for SnPb

High-Cycle Fatigue	
Fatigue Exponent: ?	-2.43E-1
Fatigue Coefficient: ?	1.51E-2
FEA Power: ?	6.4
Critical Strain: ?	3.75E-4
Shock Strain: ?	7.59E-4

Total damage accumulated over a given Event duration is calculated from damage-per-cycle to failure and total number of applied cycles in a given service life. Cycles to failure (CTF) is the same as the predicted number of cycles to failure discussed earlier. The applied cycles is calculated from the zero-crossing frequency and total exposed time (in seconds). Zero crossings can be thought of as the average frequency the entire board is subjected to when a specific Random Vibration Event is applied.

The number of crossings with both positive and negative slopes are determined using the following equation (Steinberg (p. 168), 2000, p. 232, eq 9.70):

$$N_0^+ = \frac{1}{2\pi} \left(\frac{\sum \frac{P_i \Delta f_i Q_i^2}{\Omega_i^2}}{\sum \frac{P_i \Delta f_i Q_i^2}{\Omega_i^4}} \right)^{1/2} \quad (\text{Hz}) \quad (5.18)$$

where:

P_i = input PSD (G^2/Hz) value at natural frequency f_i taken from the Sherlock PSD Profile. Log-Log interpolation is used.

Ω_i is the natural frequency(s) in rad/sec ($2\pi f_i$)

Q_i = transmissibility at i^{th} resonant frequency (dimensionless) (Steinberg (p. 168), 2000, p. 34, eq 2.50)

$$Q_i = \frac{1}{2\xi_i}$$

ξ_i = Modal Damping Ratio(s), based on user-input under **Analysis Properties**.

$$\Delta f_i = \frac{f_i}{Q_i}$$

The damage reported in the Random Vibe Results Table gets capped at 1e-6 if the total damage is less than 1e-6.

$$\text{Total Damage} = \text{Applied Cycle} * \text{Damage Per Cycle} \quad (5.19)$$

$$\text{Applied Cycle} = \text{Zero Crossing Frequency (in Hz)} * \text{Total Exposure (in seconds)} \quad (5.20)$$

An example of calculation of Total Exposure from a given Service Life, Life Phase and Event is provided below for reference.

Table 5.1: Sample Calculation of Total Exposure

Service Life = 5 years		
Phase	Duration	3 hrs
	Cycles	1/day
Event	Duration	100 sec
	Cycles	0.5/min

Figure 5.21: Exposure, Event and Phase Settings in Sherlock

The figure consists of three screenshots of the Sherlock software interface, arranged vertically. Each window has a title bar with a small icon and a close button (X).

Top Window: Random Vibe Editor
 The window contains a text area for "Name" with the value "Random Event" and a larger text area for "Description". Below this is a section titled "Random Vibration Settings" with two rows of controls: "Duration: 100" with a unit dropdown set to "sec", and "# of Cycles: 0.5" with a unit dropdown set to "PER MIN". At the bottom, there is a "Service Life: 5" with a unit dropdown set to "year".

Middle Window: Life Phase Editor
 The window contains a text area for "Name" with the value "On The Road" and a larger text area for "Description" containing the text: "This is a sample collection of life cycle events that might be seen while a vehicle is moving down the road." Below this is a section titled "Phase Settings" with two rows of controls: "Duration: 3" with a unit dropdown set to "hr", and "# of Cycles: 1" with a unit dropdown set to "PER DAY".

Bottom Window: Random Vibe Editor
 This window is identical to the top one, showing the "Random Vibe Editor" settings with "Name: Random Event", "Duration: 100 sec", "# of Cycles: 0.5 PER MIN", and "Service Life: 5 year".

$$\text{Maximum Number of Phase Cycles in a Service Life} = \text{Maximum Cycles} \quad (5.21)$$

$$\text{Maximum Cycles} = \frac{5 \times 365.2422 \times 24}{3} = 14609.68 \quad (5.22)$$

If applied cycles exceed the maximum cycles possible, the phase cycle must be adjusted accordingly.

$$\text{Phase Cycles} = \text{Maximum Cycles, if Applied Cycles} > \text{Max Cycles} \quad (5.23)$$

Likewise, the maximum number of Event cycles in a phase represent the maximum number of Event cycles that can occur in that phase. If applied cycles exceed the maximum number of cycles, the number of applied cycles must be adjusted accordingly.

$$\text{Maximum Number of Events in a Phase} = \text{Maximum Cycles} = \frac{3 \times 3600}{100} = 108 \quad (5.24)$$

$$\text{Number of Required Event Cycles} = \text{Applied Cycles} = 3 \times 60 \times 0.5 = 90 \quad (5.25)$$

$$\text{Total Cycles in Service Life} = \text{Phase Cycle} \times \text{Event Cycles} = 1826.211 \times 90 = 164358.99 \quad (5.26)$$

For the given Event duration of 100 seconds, the total exposure time of the board to 164358.99 cycles can be computed as:

$$\text{Total Exposure} = 164358.99 \times 100 = 16435899.0 \text{ seconds} \quad (5.27)$$

Finally, the Total Time to Failure (TTF) and Probability of Failure (PoF) is computed as

$$\text{TTF} = \frac{\text{Service Life}}{\text{Total Damage}} \quad (5.28)$$

$$\text{PoF} = 1 - e^{-1 \times (\text{Total Damage})^\beta} \quad (5.29)$$

The Probability of Failure in Sherlock is based on Weibull distribution. The expression uses the Weibull slope (β) to describe the rate at which the components fail. The figure below shows the impact of the weibull slope, β , on probability of failure for TTF of 5 years. β , is a user-defined value with a default value of 3. Sherlock's **Solder Editor** (see [Figure 5.23: Weibull Slope Settings in Solder Editor \(p. 161\)](#)) can be used to change to the slope as needed.

Figure 5.22: Weibull Plot

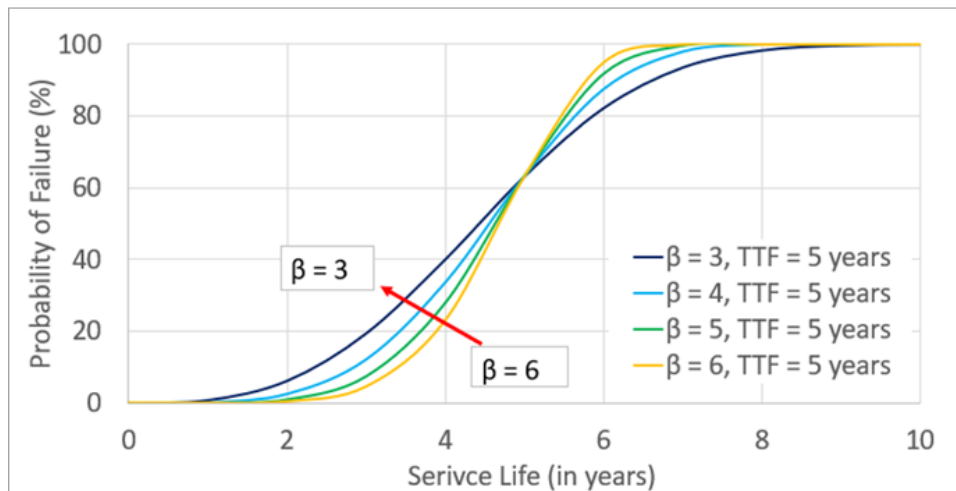


Figure 5.23: Weibull Slope Settings in Solder Editor

Solder Editor - 63SN37PB

Modify the solder properties as needed and press the **Save** button to update the Solder Library.

Low-Cycle Fatigue

Critical Dwell Time: 20.0 min

Activation Energy (Ea): 1414.0

Critical Max Temp: 368.0

Strain Energy Coefficient: 6.061E-4

CC Calibration Factor: 1:0.0:1.0; 1:3.2:1.0; 2:0.0:1.0; 2:3.2:1.0; 3:0

Leaded Calibration Factor: 2.0

Thermal Shock Factor CC: 15,1.0 | 30,1.25 | 60,1.5

Thermal Shock Factor BGA: 15,1.0 | 30,1.25 | 60,1.5

Thermal Shock Factor LCCC: 15,1.0 | 30,1.25 | 60,1.5

Thermal Shock Factor Leaded: 15,1.0 | 30,1.25 | 60,1.5

Thermal Shock Factor QFN: 15,1.0 | 30,1.25 | 60,1.5

Thermal Shock Factor ThruHole: 15,1.0 | 30,1.25 | 60,1.5

Thermal Shock Factor Default: 15,1.0 | 30,1.25 | 60,1.5

Weibull Beta BGA: 3.0

Weibull Beta CBGA: 3.0

Weibull Beta CC: 3.0

Weibull Beta LCCC: 3.0

Weibull Beta Leaded: 3.0

Weibull Beta QFN: 3.0

Weibull Beta ThruHole: 3.0

Prev 63SN37PB Next

Save Reset Cancel

Determining the score involves the ratio of the Life Cycle Goal and the Failure Probability (probability goal/probability of failure). A score of 0 is assigned to the part if the ratio is below 2. A score of 10 is assigned to the part if the ratio is above 10. For any ratio in between 2 and 10, the score is linearly interpolated between 1 and 10. The basic intent here is to categorize a part as “highly likely to fail” if the probability goal is less than 2x the probability of failure and to treat it as “least likely to fail” if the probability goal is greater than 10x the probability of failure

Score Calculation:

$$1. \text{ If } \frac{\text{Probability Goal}}{\text{Probability Of Failure}} < 2: \text{ Score} = 0$$

$$2. \text{ If } 10 > \frac{\text{Probability Goal}}{\text{Probability Of Failure}} > 2$$

$$\text{Score} = 1.125 \frac{\text{Probability Goal}}{\text{Probability Of Failure}} - 1.25; \text{ Scored between 10 and 1}$$

$$3. \text{ If } \frac{\text{Probability Goal}}{\text{Probability Of Failure}} > 10: \text{ Score} = 10$$

5.5. Random Vibration Analysis Results

The Random Vibration Analysis modules generate the following types of results:

- An overall **Summary** of the analysis (see [Figure 5.24: Result Summary \(p. 163\)](#))
- A **Random Vibe Results Table** displaying the maximum displacement, strain and life predictions (see [Figure 5.25: Random Vibe Table \(p. 164\)](#))
- Results tables for **Parts**, **Leads** and **Mount Points** displaying respective strains (in [Figure 5.26: Parts Table \(p. 164\)](#), the **Parts** table is shown as an example)
- **Life Prediction** curve for the circuit card
- Graphical layers showing color-coded part scores (top and bottom sides)
- Graphical layers showing maximum displacement, stress and strain during Random Vibration Events.

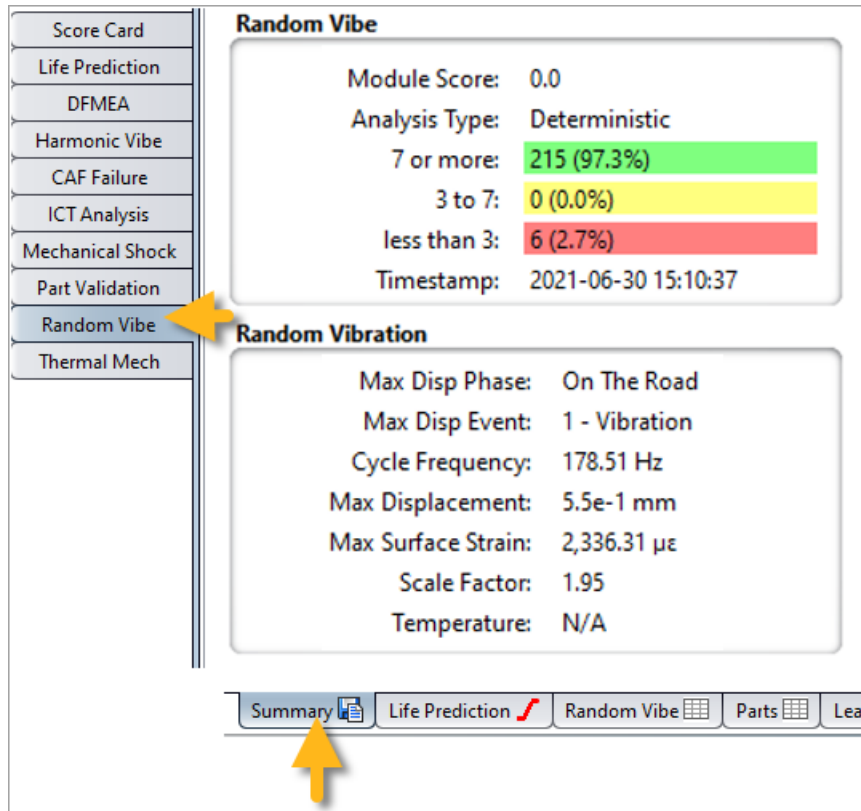
The **Summary** of the analysis essentially consists of information about Random Vibration results such as overall cycle frequency (zero-crossing frequency) of the system, maximum displacement of the board, and the maximum PCB Strain on the board. Sherlock computes the RMS frequency by determining the number of zero-crossings from [Equation 5.18 \(p. 157\)](#).

Sherlock also shows overall module score for the CCA and the score distribution for all the parts on the board by categorizing them into one of three categories:

- 7 or more
- 3 to 7
- Less than 3

The scoring is based on the [Score Calculation \(p. 148\)](#) discussed in the previous section. The **Summary** also contains information related to board properties and the analysis process. FE input information, such as mesh properties, is also provided. See the [Vibration Analysis Results](#) section in Sherlock User Guide for additional information on the items listed. A general overview of the Results Table, Life Prediction Curve, and Graphical FEA Results is available in the next sections.

Figure 5.24: Result Summary



The **Random Vibe Results Table** shown below consists of detailed results for each part analyzed. The color-coded tabular results provide a convenient way to focus on the specific parts that may fail prematurely because of Vibration Events. The table displays the maximum displacement and strain experienced by all the parts on the board. The damage is calculated from the strain value in the table. The column **Strain Source** provides the information on whether the strain is Surface Equivalent Strain or Elemental Equivalent Strain. In Sherlock, if any part is not modeled with the leads, the PCB strain is used for damage calculation. When leads are enabled, the maximum of the three lead strains is used for damage calculation. Time To Failure (TTF) and Probability of Failure (PoF) is computed from damage and the Score is calculated from the Reliability Goal and PoF. You will find detailed examples on how each of the parameters is computed in the [Post Processing Calculation \(p. 152\)](#) section above.

As with other color-coded displays in Sherlock, RED means that the predicted score is less than 3 (less than 3x safety factor), YELLOW means the score is between 3 and 7. And GREEN means that the score is 7 or more, indicating there is a very small probability that the part will fail.

Figure 5.25: Random Vibe Table

File	RefDes	Package	Part Type	Side	Solder	Max Disp	Strain	Damage	TTF (years)	Failure Prob	Score	Strain Source
Score Card	U10	BGA676	IC	TOP	63SN37PB	5.2E-1	415.79	9.6E1	0.1	100.0	0.0	PCB surface
Life Prediction	U9	BGA676	IC	TOP	63SN37PB	5.3E-1	345.22	2.9E1	0.2	100.0	0.0	PCB surface
Component Failure Mechanism	C5	C-BEND-3528-12	CAPACITOR	TOP	63SN37PB	7.3E-2	354.41	1.1E1	0.5	100.0	0.0	PCB surface
DFMEA	C8	C-BEND-3528-12	CAPACITOR	TOP	63SN37PB	8.4E-2	349.27	1.0E1	0.5	100.0	0.0	PCB surface
Harmonic Vibe	U3	QFJ-68 (MO-087AD)	IC	TOP	63SN37PB	5.0E-1	850.77	1.3E0	3.9	88.7	0.0	Lead 35
CAF Failure	U4	QFJ-68 (MO-087AD)	IC	TOP	63SN37PB	5.0E-1	793.37	5.8E-1	8.7	17.4	0.0	Lead 1
ICT Analysis	Q15	DPAK (TO-252AA)	TRANSISTOR	BOT	63SN37PB	4.6E-1	573.98	1.3E-2	>50	0.0	10.0	Lead 1
Mechanical Shock	Q9	DPAK (TO-252AA)	TRANSISTOR	BOT	63SN37PB	4.6E-1	561.86	1.0E-2	>50	0.0	10.0	Lead 1
Natural Freq	R23	1206	RESISTOR	BOT	63SN37PB	5.0E-1	456.37	1.1E-3	>50	0.0	10.0	PCB surface
PTH Fatigue	R22	1206	RESISTOR	BOT	63SN37PB	4.8E-1	456.37	1.1E-3	>50	0.0	10.0	PCB surface
Part Validation	R36	1206	RESISTOR	BOT	63SN37PB	4.8E-1	456.37	1.1E-3	>50	0.0	10.0	PCB surface
Random Vibe	R37	1206	RESISTOR	BOT	63SN37PB	5.0E-1	456.37	1.1E-3	>50	0.0	10.0	PCB surface
Semiconductor Wearout	R56	1206	RESISTOR	BOT	63SN37PB	4.6E-1	454.76	1.0E-3	>50	0.0	10.0	PCB surface
Solder Fatigue	R57	1206	RESISTOR	BOT	63SN37PB	4.4E-1	454.76	1.0E-3	>50	0.0	10.0	PCB surface
Thermal Derating	R70	1206	RESISTOR	BOT	63SN37PB	4.7E-1	454.76	1.0E-3	>50	0.0	10.0	PCB surface
Thermal Mech	R71	1206	RESISTOR	BOT	63SN37PB	4.4E-1	454.76	1.0E-3	>50	0.0	10.0	PCB surface
	Q11	DPAK (TO-252AA)	TRANSISTOR	BOT	63SN37PB	4.4E-1	439.48	6.0E-4	>50	0.0	10.0	Lead 1
	R52	1206	RESISTOR	BOT	63SN37PB	4.8E-1	406.42	5.0E-4	>50	0.0	10.0	PCB surface
	R51	1206	RESISTOR	BOT	63SN37PB	4.7E-1	406.42	5.0E-4	>50	0.0	10.0	PCB surface
	R65	1206	RESISTOR	BOT	63SN37PB	4.8E-1	406.42	5.0E-4	>50	0.0	10.0	PCB surface

Figure 5.26: Parts Table

Score Card	RefDes	Part Type	PCB Strain	Part Strain	Lead Strain
Life Prediction	R103	RESISTOR	619.12	341.69	
Component Failure Mechanism	R102	RESISTOR	583.53	321.58	
DFMEA	R117	RESISTOR	550.02	441.75	
Harmonic Vibe	R116	RESISTOR	533.10	377.88	
CAF Failure	J1	JACK	496.88	71.85	343.45
ICT Analysis	R23	RESISTOR	456.37	224.59	
Mechanical Shock	R22	RESISTOR	456.37	157.40	
Natural Freq	R36	RESISTOR	456.37	159.18	
PTH Fatigue	R37	RESISTOR	456.37	229.71	
Part Validation	R56	RESISTOR	454.76	205.97	
Random Vibe	R57	RESISTOR	454.76	158.62	
Semiconductor Wearout	R70	RESISTOR	454.76	191.89	
Solder Fatigue	R71	RESISTOR	454.76	178.18	
Thermal Derating	R130	RESISTOR	452.72	368.96	
Thermal Mech	C22	CAPACITO...	438.71	3.30	517.44
	U10	IC	415.79	236.32	
	R52	RESISTOR	406.42	145.46	
	R51	RESISTOR	406.42	224.45	
	R65	RESISTOR	406.42	216.85	
	R66	RESISTOR	406.42	156.28	

You can double-click any row in the table to view all the properties associated with a selected part. When viewing current results, the properties will be from the current parts list. If leads are explicitly modelled, the **Lead** tab will be available which contains lead strain information. The table will display strain as discussed earlier in [Random Vibration Strain \(p. 148\)](#). Starting with Sherlock 2021 R2, a **Parts** tab will be available. The tab will provide PCB Strain, Part Strain, and the maximum of the three Lead Strains (displayed as **Lead Strain**) for all components on the board. The table provides a quick way to compare the three strains for any component and check if the max of the three is consistent with the strain used for TTF calculation in the main Random Vibe Table.

Figure 5.27: Leads Table

File								
	RefDes	Lead ID	PCB Strain	Part Strain	Lead Strain	Damage	TTF (years) ▲	Failure Prob
Score Card	U3	35	637.62	850.77	850.77	1.3E0	3.9	88.7
Life Prediction	U3	51	592.47	820.38	820.38	8.5E-1	5.9	45.8
Component Failure Mechanism	U4	1	563.09	793.37	793.37	5.8E-1	8.7	17.4
DFMEA	U4	17	519.19	734.23	734.23	2.3E-1	21.4	1.3
Harmonic Vibe	Q5	1	701.90	273.17	701.90	1.4E-1	36.1	0.3
CAF Failure	Q3	1	681.19	255.36	681.19	9.8E-2	> 50	0.1
ICT Analysis	U3	1	501.28	676.29	676.29	9.0E-2	> 50	0.1
Mechanical Shock	U3	68	445.82	671.42	671.42	8.3E-2	> 50	0.1
Natural Freq	U4	34	424.56	658.49	658.49	6.6E-2	> 50	0.0
PTH Fatigue	U4	52	425.09	654.31	654.31	6.1E-2	> 50	0.0
PTH Fatigue	Q7	3	648.29	232.76	648.29	5.5E-2	> 50	0.0
Part Validation	U3	29	243.07	643.43	643.43	5.0E-2	> 50	0.0
Random Vibe	U3	18	409.86	641.09	641.09	4.8E-2	> 50	0.0
Semiconductor Wearout	Q5	2	627.72	281.67	627.72	3.8E-2	> 50	0.0
Solder Fatigue	U8	1	577.76	157.33	621.88	3.4E-2	> 50	0.0
Solder Fatigue	U4	35	461.11	621.83	621.83	3.4E-2	> 50	0.0
Thermal Derating	U4	51	458.11	620.33	620.33	3.3E-2	> 50	0.0
Thermal Mech	U3	58	215.02	613.90	613.90	2.9E-2	> 50	0.0
Thermal Mech	U3	28	212.54	613.44	613.44	2.9E-2	> 50	0.0
Thermal Mech	Q5	3	573.69	288.41	606.58	2.5E-2	> 50	0.0

Summary
Life Prediction
Random Vibe
Parts
Leads

5.6. Life Prediction Curve

Sherlock provides a life-prediction curve for individual components as well as for the entire board. The **Life Prediction** tab in the **Current Results** displays the life prediction curve for the circuit card based on the life prediction curve for each parts analyzed. The rectangular region in the lower left corner of the chart represents the **Reliability Goals** you selected for the project. The top boundary of the rectangle marks the **Probability of Failure** you selected, and the boundary on the right marks the desired **Service Life**. If the curve stays below the top line up to the **Service Life**, then the circuit card is predicted to meet its goals. Time to Failure is considered to be at the characteristic life which is a 63% probability of failure. Sherlock calculates the life prediction curve of the circuit card by multiplying the reliability of each component on the board having a unique Weibull Slope (β) and time to failure. The probability of failure for life cycle goals can be extracted from this plot. For example, at 17 years the associated resulting plot indicates that the probability of failure is 55% as shown below in [Figure 5.28: Life Prediction Plot in Sherlock](#) (p. 166).

Figure 5.28: Life Prediction Plot in Sherlock

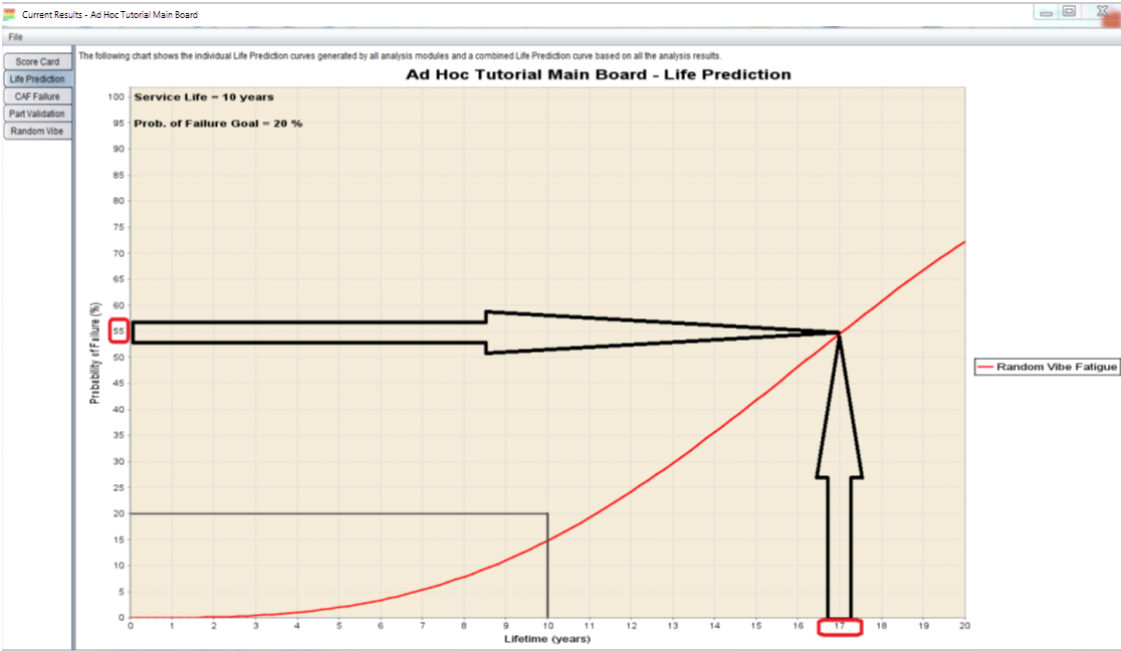
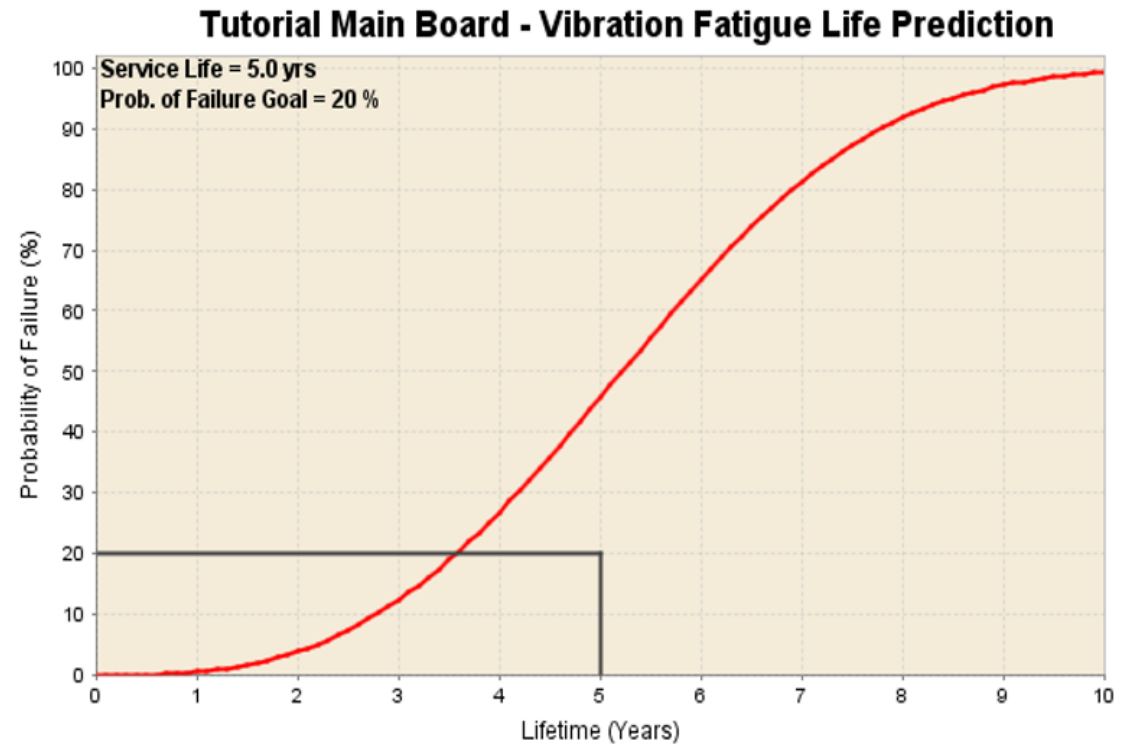


Figure 5.29: Example Plot for Life Prediction Curve

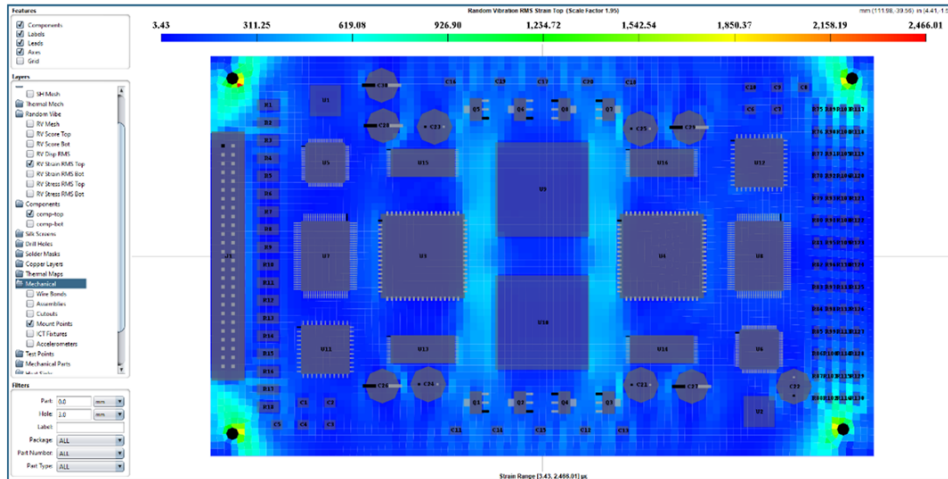


5.7. Graphical FEA Results

The Random Vibration Analysis module generates 2D results layers showing displacement, PCB strains, and PCB stresses experienced during the worst Vibration Event in the analysis. The worst Vibration Event is the one causing the maximum displacement response. The strains are displayed in microstrain. At

the top of the screen, the plot shows the RMS value at which the results were generated. The strain per element face is determined by averaging the von Mises stress at the nodes connected to the element's top face and determining the strain from the averaged stress and element modulus. The results provided in **Layer Viewer** are only for the PCB and not the parts. You can view the parts using the **3D Model/Results Viewer**. A detailed explanation of how Sherlock calculates the PCB stress, equation and strain, equation has already been covered earlier in the [Strain Calculation \(p. 151\)](#) section of this chapter. More about the **2D Layer Viewer** can be found in [Graphical Result Layer](#) section of *Sherlock Users Guide*.

Figure 5.30: Strain plot in Sherlock Layer Viewer



An example of surface Equivalent Stress and Strain of an element is provided below (Figure 5.31: Layer Viewer Strain Result at the center of the board in Sherlock (p. 167)). For comparison, unaveraged Equivalent Stress for the same element in Ansys Mechanical is also provided (See Table 5.2: Equivalent strain calculation from unaveraged (1.95 σ) stress for the same element (p. 167)).

Figure 5.31: Layer Viewer Strain Result at the center of the board in Sherlock

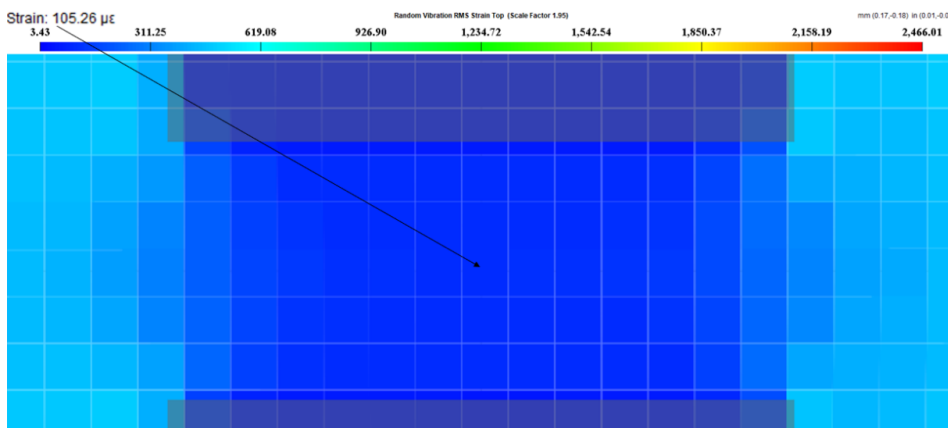


Table 5.2: Equivalent strain calculation from unaveraged (1.95 σ) stress for the same element

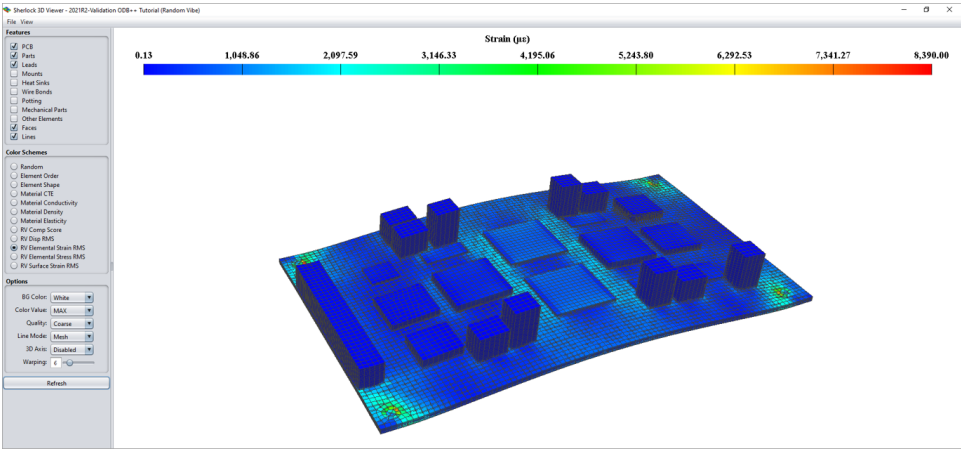
Unaveraged Equivalent Stress (MPa)	Averaged Equivalent Stress (MPa)	Modulus of the element (MPa)	Strain (mm/mm)	Strain in microstrain
2.502632	2.505243	23800	0.000105	105.2623

2.503988				
2.507226				
2.507124				

5.8. 3D Model/Results Viewing

You can view the relevant 3D FEA model and/or results by right-clicking the **Random Vibe** node in the **Project Tree** and selecting either **View 3D Model** or **View 3D Results**. This launches the Sherlock 3D viewer, allowing you to interactively view the 3D data. Selecting **3D Results** allows you to view elemental mean Equivalent Stress and Strain and the surface Equivalent Strain.

Figure 5.32: 3D Viewer



5.9. References

1. Ansys, Inc. [Performing a Random Vibration Analysis](#) in the *Structural Analysis Guide of the Mechanical APDL User's Guide* (2021 R1).
2. Segalman, D. J., Fulcher, C. W. G., Reese, G. M., & Field, R. V. (1998). *An efficient method for calculating RSM von Mises stress in a random vibration environment*. Proceedings of the 16th International Modal Analysis Conference (Vol. 1, Issue 3243, pp. 117-123). Santa Barbara, CA.
3. Steinberg, D.S. (2000) *Vibration Analysis for Electronic Equipment*, (3rd Edition). John Wiley & Sons.

Chapter 6: Mechanical Shock Theory

Note:

It's important to read the [Sherlock User's Guide](#) before accessing the theory guide content. The user's guide will help you become familiar with Sherlock's capabilities and workflow. A firm understanding of the Sherlock application is essential before delving into the substantial content of the *Sherlock Theory Reference*.

This document details the theory for the Mechanical Shock analysis module in Sherlock. Mechanical shock can be defined as the sudden application of a single or repetitive– but non-periodic– physical load due to acceleration that results in significant displacement or deformation. Common events that induce mechanical shock include drops, crashes, firing events, impacts, or explosions.

The performance of a solder joint when subjected to mechanical shock is primarily dictated by the ductility of the solder and the fragility of the interconnect structure (such as the intermetallic region, interface between the bond pad and the printed board, and so on). The strength of these regions and the amount of stress transmitted to them during the shock event will determine whether failure occurs or not.

In Sherlock, a Mechanical Shock analysis is run using transient structural analysis for a given shock load. The resulting surface strain is used in combination with the Basquin and Coffin-Mason equations to predict failure. Overstress failure can also occur during shock events. Once critical strain exceeds a certain value, the board may fail due to overstress. In Sherlock, that critical strain value is based on the board strain guidelines as per [IPC-9704 \(p. 201\)](#) during board flexing. The overstress addressed by Sherlock is the stress generated in the board and not the stress that drives failure of components due to fracture. This document discusses the surface strain used for the reliability calculation and provides a verification example that details the Time to Failure (TTF) calculation and compares the result with that from Sherlock.

This document does not address the chassis design which can be critical to mechanical shock robustness in electronic system. Improper chassis design can lead to the application of additional mechanical stresses to the circuit board outside the normal mechanical shock response of the circuit card assembly.

Chapter Topics:

- [6.1. Mechanical Shock Analysis Settings](#)
- [6.2. Mechanical Shock Analysis](#)
- [6.3. Strain Values](#)
- [6.4. Post Processing – Life Prediction Calculation](#)
- [6.5. Mechanical Shock Analysis Results](#)
- [6.6. Shock Results Table](#)
- [6.7. Life Prediction Curve](#)
- [6.8. Graphical FEA Results](#)

[6.9. Validation](#)[6.10. References](#)

6.1. Mechanical Shock Analysis Settings

Mechanical Shock analysis in Sherlock consists of three parts: 1) preparing the electronic board for the analysis, 2) solving the model, and 3) post-processing the results for reliability calculation. Once the input data for the analysis and the post-processing is entered, Sherlock runs the analysis automatically and scores the components on the board for risk of failure.

The Mechanical Shock analysis module in Sherlock makes use of the following input data:

- [Life Cycle Reliability Goals](#) and [Mechanical Shock Events](#)
- [Parts List](#)
- [Size and location of all parts, through-holes, mount points, and cutouts](#)
- [Circuit card mechanical properties \(stackup data\)](#)
- [Circuit card outline](#)
- [Mesh properties](#)
- [Solder Properties](#)

Life Cycle Reliability Goals are reliability requirements an electronic system must fulfill in its lifetime. In Sherlock, you will use the **Reliability Goals** section of the **Life Cycle Editor** to enter the expected **Service Life** and **Reliability Metric** for the assembly. These values are utilized during post-processing to calculate Time to Failure (TTF) and to score a component on its risk to failure by comparing the Probability of Failure with the Reliability Goal.

Reliability in general is defined as the probability that an electronic device will perform its required function when subjected to a specific condition for a specified period of time. In electronics, the reliability distribution can be modeled using the Weibull distribution. The Weibull distribution function is a probability density function (PDF) that is expressed as shown in [Equation 6.1 \(p. 171\)](#).

Figure 6.1: Life Cycle Editor

$$F(t) = \frac{\beta}{\eta} \left(\frac{t-\gamma}{\eta} \right)^{\beta-1} e^{-\left(\frac{t-\gamma}{\eta}\right)^\beta} \quad (6.1)$$

where

β is the Weibull slope

η is the scale parameter

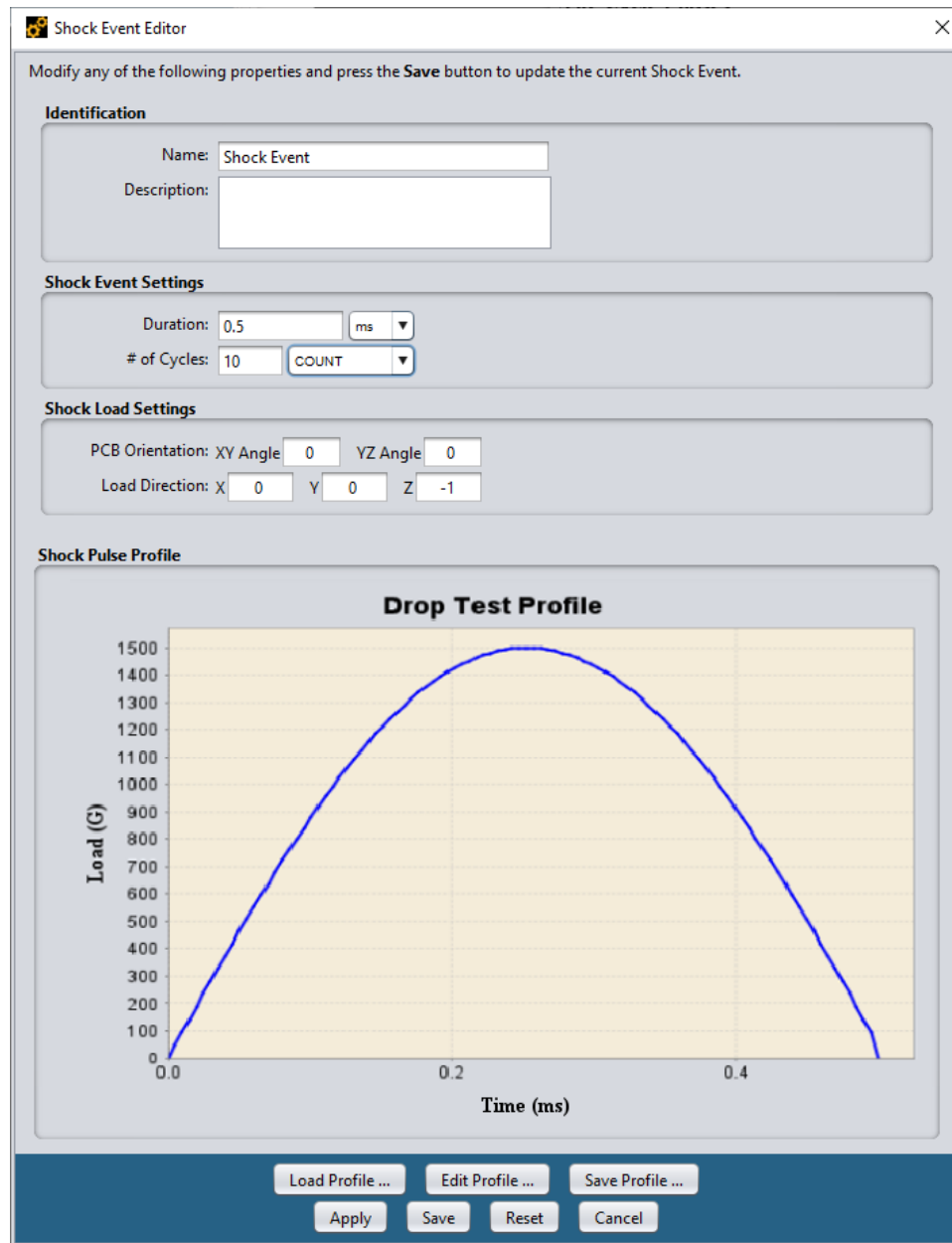
γ is the location parameter, set to 0 as Sherlock uses two-parameter Weibull

In Sherlock, the reliability calculations are based on the Probability of Failure distribution expressed using the reliability function $P(t)$ as shown in [Equation 6.2 \(p. 171\)](#). The equation can also be recognized as the cumulative distribution function (CDF) of a probability density function for a two-parameter Weibull distribution:

$$PoF(t) = 1 - P(t) = 1 - e^{-(\text{damage})^\beta} \quad (6.2)$$

More information about damage calculation from the finite element (FE) strain result can be found in the section below, [Post Processing – Life Prediction Calculation \(p. 183\)](#).

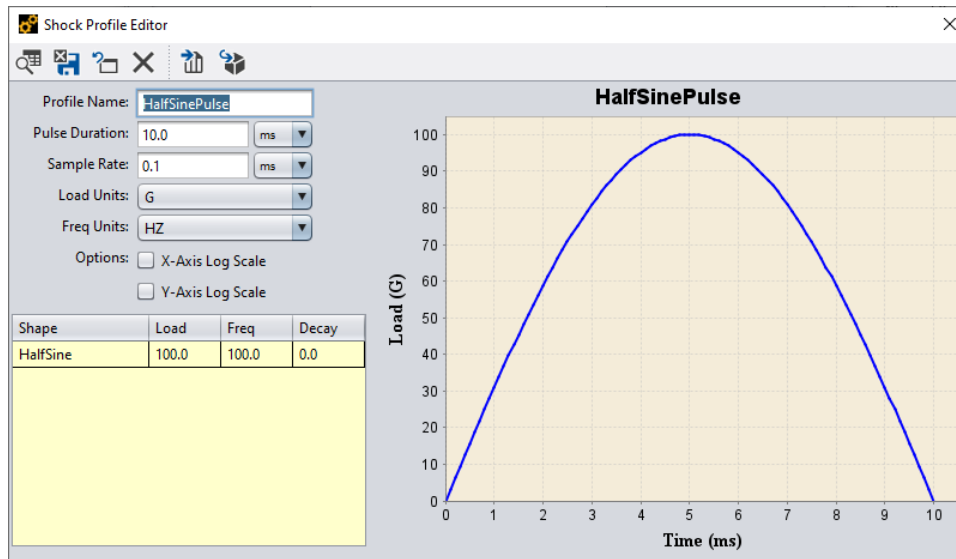
Mechanical Shock Events are acceleration-time history events that define the shape, time, and the amplitude of the shock pulse experienced by the electronic system/assembly. In Sherlock, these events are defined in terms of acceleration (G). The relevant stresses are those that may drive potential fatigue failure mechanisms during the analysis. For a drop test, [JEDEC-22b111A \(p. 201\)](#) recommends a half-sine curve acceleration pulse with a peak acceleration of 1500G in a time period of 0.5 ms (milliseconds). This profile is represented below as a Shock Event in Sherlock ([Figure 6.2: Drop Test Profile in the Shock Event Editor \(p. 172\)](#)).

Figure 6.2: Drop Test Profile in the Shock Event Editor

The shape of the profile can be changed using the **Shock Profile Editor** ([Figure 6.3: Shock Profile Editor](#) (p. 173)). The editor also provides predefined shapes which can be used to define the shock pulse for the event. These shapes are:

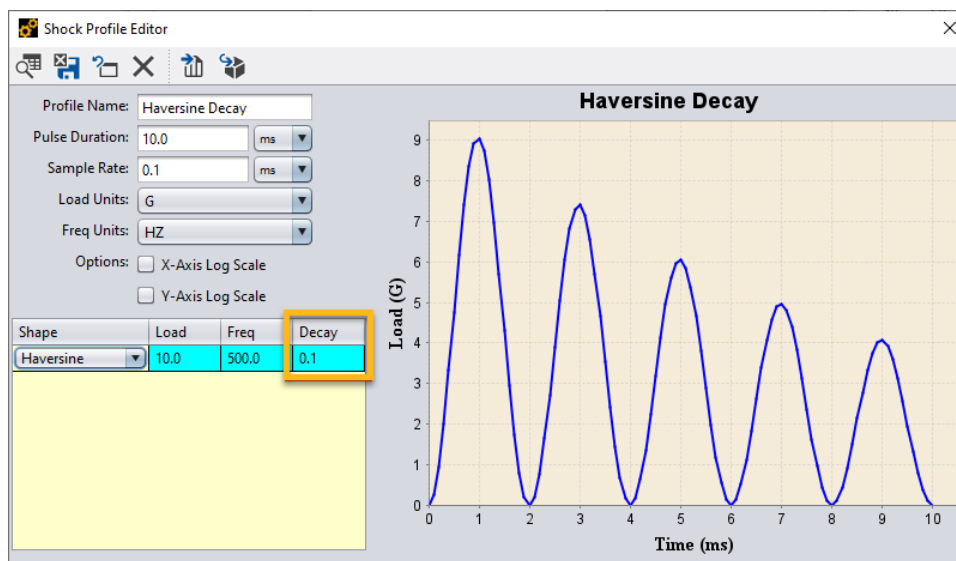
- Halfsine
- Fullsine
- Haversine
- Triangle
- Sawtooth

- Fullsquare
- Halfsquare

Figure 6.3: Shock Profile Editor

In the **Shock Profile Editor**, the **Sample Rate** parameter sets the rate at which the shock pulse is sampled. A minimum of ten data points is required for defining a shock pulse in Sherlock. You can adjust the number of data points by varying the **Pulse Duration** and **Sample Rate**.

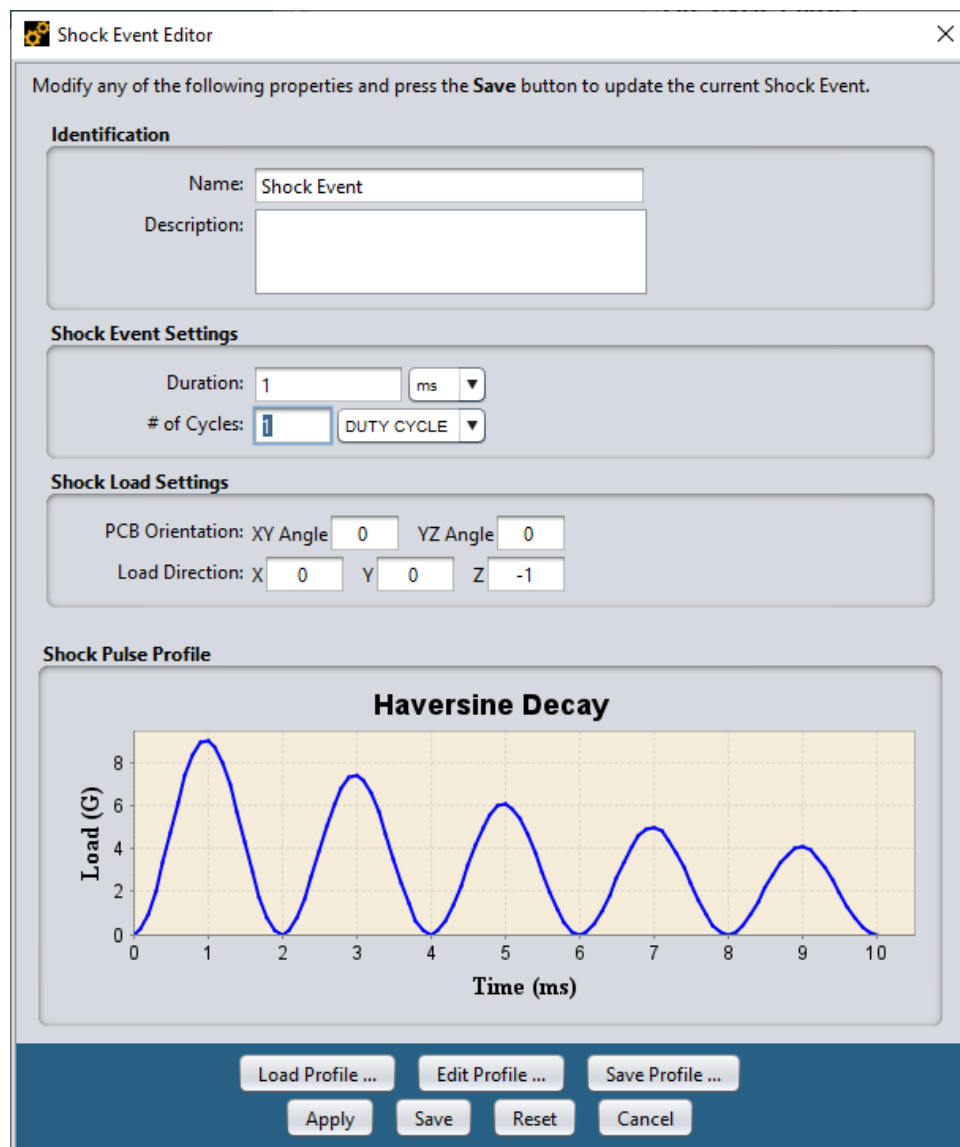
Use the parameter **Load Units** to specify the units of acceleration, and use **Freq Units** to specify units of frequency. Finally, the parameter **Decay** defines the amplitude reduction in the pulse as a function of time. An example profile with a **Decay** of 0.1 is shown in the figure below for reference. A decay of 0.1 represents a 10% drop in the amplitude per cycle.

Figure 6.4: Haversine Profile with 0.1 Decay

The **Shock Profile Editor** is designed so you can model effectively any shock pulse while the **Duration** parameter (under **Shock Event Settings**) allows you to scale the profile as needed. The haversine profile

for a pulse duration of 10 ms (see [Figure 6.4: Haversine Profile with 0.1 Decay \(p. 173\)](#)) is scaled to 1 ms under the **Shock Pulse Profile** as shown in [Figure 6.5: Haversine Decay Scaled to 1 ms \(p. 174\)](#). The profile is maintained as is, but the exposure duration is scaled by the parameter **Duration** under **Shock Event Settings** in the **Event Editor**.

Figure 6.5: Haversine Decay Scaled to 1 ms

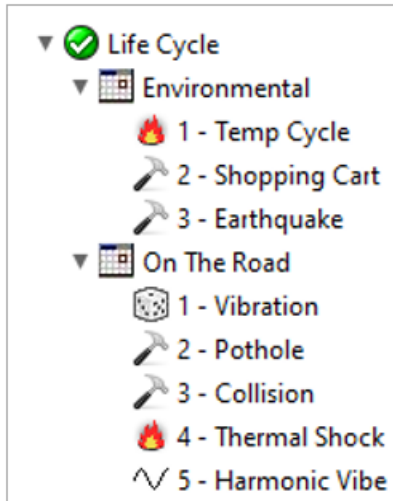


You can use Sherlock to test electronic systems that experience multiple shock loads as shown in [Figure 6.6: Multiple Events \(p. 175\)](#). Using the Life Cycle Reliability Goal you have defined (see [Figure 6.1: Life Cycle Editor \(p. 171\)](#)), Sherlock will calculate the damage for each event and combine the results to compute total damage. Sherlock uses total damage to calculate life predictions. More on damage calculation and life predictions are discussed in the section [Post Processing – Life Prediction Calculation \(p. 183\)](#).

You can also apply loads at an angle along any of the three-principal axes by orienting the PCB accordingly (see the **Shock Load Settings** in the [Figure 6.2: Drop Test Profile in the Shock Event Editor \(p. 172\)](#)). When PCB orientation is provided, the applied load gets resolved along the principal axes. You will find

more information about PCB Orientation the *Sherlock User's Guide*. See [Load Direction and PCB Orientation](#) in the chapter on Life Cycle Management.

Figure 6.6: Multiple Events

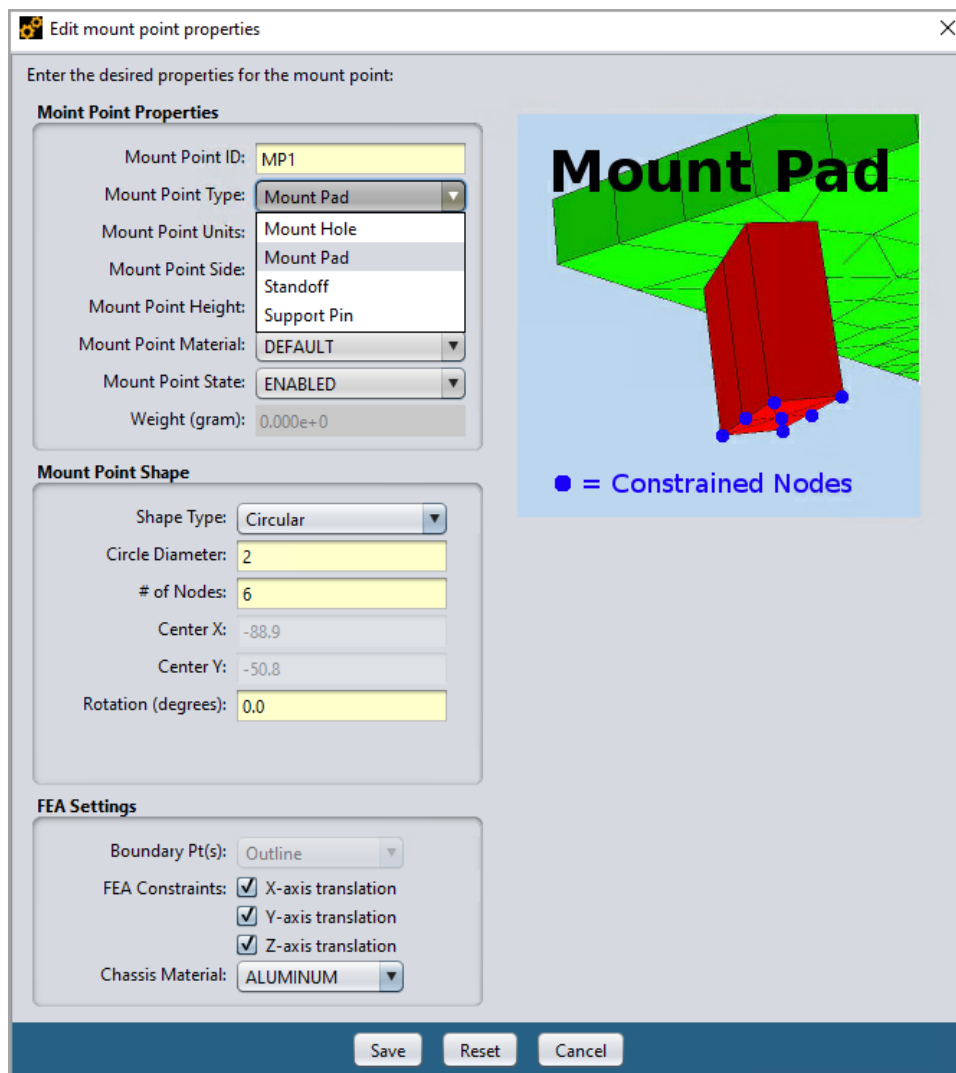


Sherlock has the capability of running the analysis directly as well as exporting the FE model for running the analysis outside the application. While Sherlock does not support the analysis of electronic systems with an enclosure or housing directly, it can be used in combination with Ansys Mechanical to do so outside the application. You then can import the results back into Sherlock for failure prediction of the components.

When Sherlock performs an analysis, certain information is crucial for generating an accurate prediction—such as the size and location of the components and mount points as well as the mechanical properties of the PCB, solder, and leads. Sherlock takes all these factors into account. Also, Sherlock allows you to define boundary conditions easily. You can edit mount points as needed using the dialog shown below ([Figure 6.7: Edit Mount Point Properties dialog \(p. 176\)](#)) and define the corresponding FE constraints using **FEA Settings**. Sherlock also provides the toolkit to create and edit stackup details of the PCB as well, along with the features you need to accurately define the parts. And Sherlock allows you to effectively manage all the parts in the system through the [Parts List](#).

More information on how to define a circuit card with components for any mechanical analysis is in the *Sherlock User's Guide*. In fact, the tutorial [Ad Hoc Project Creation](#) provides a concise overview.

Figure 6.7: Edit Mount Point Properties dialog

The dialog box is titled "Edit mount point properties" and contains three main sections: "Mount Point Properties", "Mount Point Shape", and "FEA Settings". The "Mount Point Properties" section includes fields for Mount Point ID (MP1), Mount Point Type (Mount Pad), Mount Point Units (Mount Hole), Mount Point Side (Mount Pad), Mount Point Height (Standoff), Mount Point Material (DEFAULT), Mount Point State (ENABLED), and Weight (gram) (0.000e+0). The "Mount Point Shape" section includes fields for Shape Type (Circular), Circle Diameter (2), # of Nodes (6), Center X (-88.9), Center Y (-50.8), and Rotation (degrees) (0.0). The "FEA Settings" section includes a Boundary Pt(s) dropdown (Outline), FEA Constraints checkboxes (X-axis translation, Y-axis translation, Z-axis translation), and Chassis Material (ALUMINUM). A 3D visualization of a red rectangular mount pad on a green surface is shown on the right, with blue dots at the base representing constrained nodes. A legend below the visualization states "● = Constrained Nodes".

Enter the desired properties for the mount point:

Mount Point Properties

Mount Point ID: MP1

Mount Point Type: Mount Pad

Mount Point Units: Mount Hole

Mount Point Side: Mount Pad

Mount Point Height: Standoff

Mount Point Material: DEFAULT

Mount Point State: ENABLED

Weight (gram): 0.000e+0

Mount Point Shape

Shape Type: Circular

Circle Diameter: 2

of Nodes: 6

Center X: -88.9

Center Y: -50.8

Rotation (degrees): 0.0

FEA Settings

Boundary Pt(s): Outline

FEA Constraints: ☒ X-axis translation
☒ Y-axis translation
☒ Z-axis translation

Chassis Material: ALUMINUM

● = Constrained Nodes

Save Reset Cancel

Figure 6.8: FEA Settings

Mechanical Shock Analysis Properties

Specify the desired analysis properties. The **Settings >> FEA Analysis** main menu option can also be used to specify FEA analysis properties across all projects and CCAs.

Data Source: **Generated**

Mechanical Shock Properties

Detect Transform: **DISABLED**

Analysis Properties

Min Frequency: **10** HZ Critical Shock Strain: **600** $\mu\epsilon$

Max Frequency: **2000** HZ Part Validation: **ENABLED**

Temperature: **C** Require Material Assignment: **ENABLED**

SH Result Count: **1**

Mechanical Shock Events

Environmental: ☒ 2 - Shopping Cart
☐ 3 - Earthquake

On The Road: ☐ 2 - Pothole
☐ 3 - Collision

Select All Clear All

PCB Modeling

Trace Modeling
Mount Points
Drill Holes
Part Modeling
Lead Modeling
Wire Bonds
Heat Sinks
Potting Regions
Mechanical Parts

Mesh Type: **Bonded**

Modeling Regions: **DISABLED**

PCB Model: **Uniform**

of PCB Materials: **100**

Element Order: **Second Order ...**

Max Mesh Size: **2** mm

Vertical Mesh Size: **1** mm

Min Mesh Angle: **15**

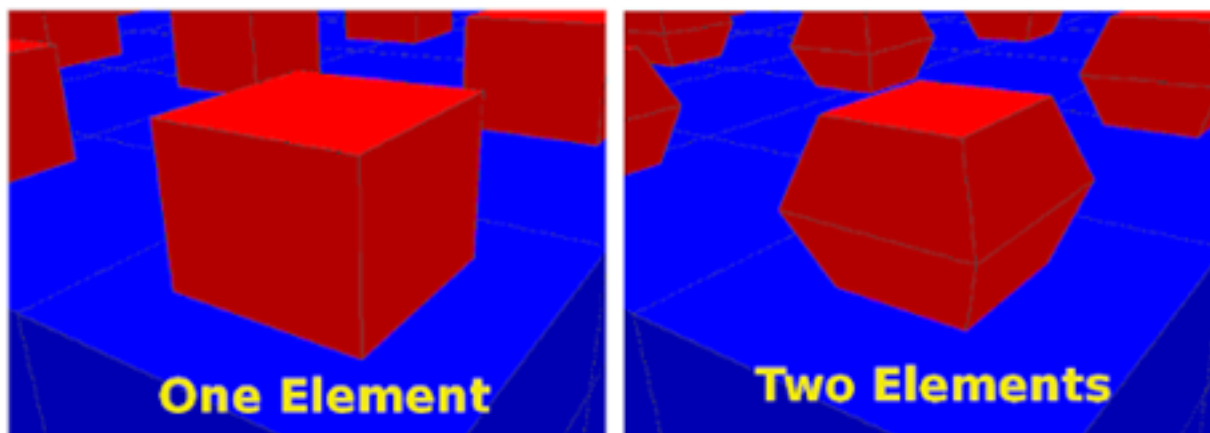
Min Quad Quality: **0.4**

Save & Run Save Reset Cancel Help

When running a Mechanical Shock analysis, as is the case for any mechanical analysis, Sherlock provides the framework for efficiently setting up an FE (Finite Element) model and solving it using Sherlock's default solver, Ansys Mechanical APDL. (Sherlock also supports ABAQUS and NX NASTRAN.) The accuracy of any FE model depends on the fidelity of its geometry, its material properties, and the mesh. Sherlock is able to efficiently read CAD geometries from an ECAD file and transform it into an MCAD file. Sherlock gives you the controls, as well, to adjust the mesh for the PCB, the Parts, Leads, Mount Points, and Underfills (Potting) so you can accurately represent the CAD model as an FE model. Sherlock uses the Ansys Meshing engine for meshing all bodies in the assembly, except for leads which are meshed with Sherlock's native meshing algorithm. Also, Sherlock automatically establishes contacts using Constraint Equations (CE). (See **Bond Tolerance** under [Mesh Settings](#) in the FEA Engine section of the Sherlock User's Guide.)

Currently, solder balls in Sherlock can be modelled as a single-element or two-element model (shown below), and leads are modelled with one element through the thickness. To mesh the leads/solder with higher mesh density, you can set up the electronic system for export into Ansys Mechanical for meshing and solving. For complete information on how to create an FE model in Sherlock, refer to the [FEA Modeling](#) section in the Sherlock User's Guide.

Figure 6.9: Solder Ball Modeling



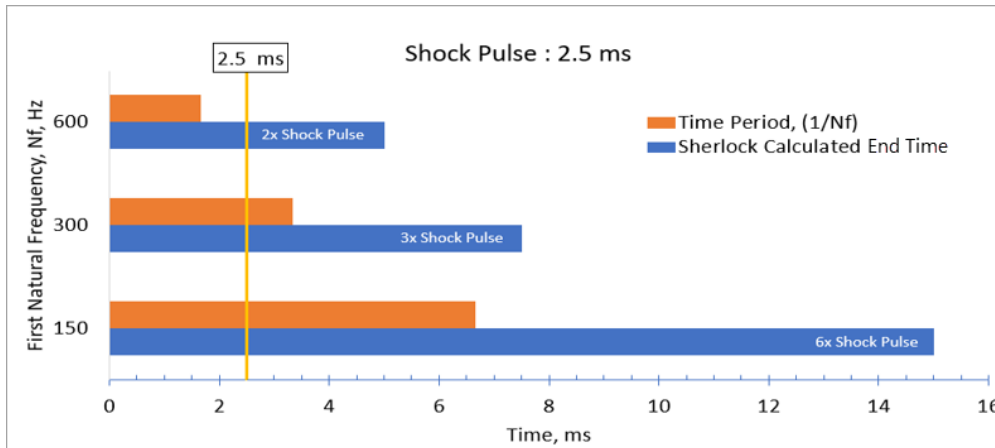
6.2. Mechanical Shock Analysis

Mechanical Shock analysis in Sherlock is essentially a finite element analysis that is transient in nature, that is, it deals with time-varying loads. The modifier is a default value and must *not* be changed.

After a shock pulse on any structure, it tends to vibrate or ring at its natural frequency. The maximum response during a shock analysis can occur during this ringing period. The Mechanical Shock analysis in Sherlock must provide enough time after the shock pulse to capture the responses during the ringing period. Sherlock does this by running a modal analysis prior to the Mechanical Shock analysis and determines the end time based on its first natural frequency.

For stiffer assemblies, the ringing period will be short due to its inherent high natural frequency. For more flexible assemblies, the ringing period is longer. Sherlock determines the end time of the Mechanical Shock analysis (transient analysis) so that the electronic assembly goes through at least a couple of peaks of its response cycle after the shock pulse input.

As shown in the graph ([Figure 6.10: Calculated End Time vs. Natural Frequency \(p. 179\)](#)), Sherlock dynamically calculates the end time based on the natural frequency of the system. For a system with 600 Hz as its first natural frequency, the end time is twice the shock pulse duration. For a system with 150 Hz, the end time is six times the shock pulse. For flexible materials, the end time might seem high, but in reality it is not. Consider a system with 150 Hz. After the shock pulse, the system needs at least 6.6 ms ($1/150$) to complete one full ringing cycle. In this case, Sherlock provides enough time for the system to complete nearly two full cycles. As a result, Sherlock does not miss any higher responses during ringing.

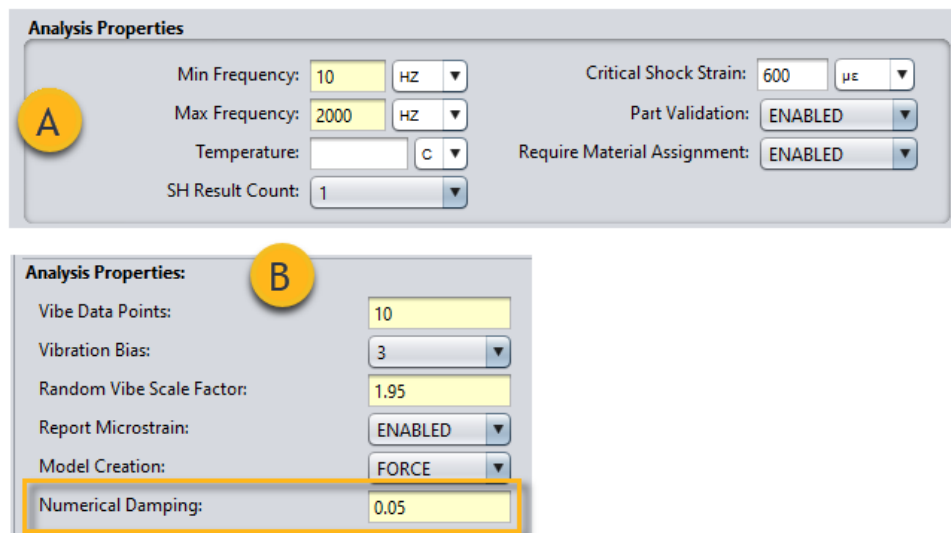
Figure 6.10: Calculated End Time vs. Natural Frequency

To ensure proper convergence, a numerical damping of 0.05 is used. In previous versions of Sherlock, the numerical damping value was specified under the label **Damping Modifier**. From 2022 R2, the label has been changed to **Numerical Damping**. Also, from 2022 R2, the damping value is no longer located under the **Mechanical Shock Analysis Properties** dialog but is now found under **Analysis Properties** in **Main Menu > Settings > FEA Analysis**.

For more information on numerical damping, refer to the *Mechanical APDL Theory Reference*: See the section [Generalized HHT- \$\alpha\$ Method](#), specifically [Equation 15.20 in the Theory Reference](#).

Note:

In older versions of Sherlock, **Numerical Damping** was called the **Damping Modifier**. Also, the value was set to -0.05 even though the input to Ansys Mechanical was always provided as +0.05. Beginning with Sherlock 2022 R2, positive numerical damping should be used for the Ansys Solver.

Figure 6.11: Analysis Properties: A- Mechanical Shock Analysis Properties dialog. B- Main Menu > Settings > FEA Analysis

You can use the **Temperature** field when your analysis involves temperature dependent properties. When Sherlock runs the shock analysis at the temperature you specify, the material properties for that temperature are used instead of those at the default value of 20°C. Use **Critical Shock Strain** to define the condition for overstress. This is a user-defined field with a default value of 600 $\mu\epsilon$. If the field is left blank, Sherlock calculates the critical shock strain from the **Shock Strain** specified in the properties of the solder and modifies it based on the part geometry. (Solder Properties and how to edit them are explained in the user's guide. See [Solder Management](#), specifically the section [Temperature-Dependent Material Properties](#).) Shock strain is discussed in the [Post Processing – Life Prediction Calculation](#) (p. 183) section of this document.

In addition to Sherlock's ability to run the analysis, it can also process the results of a shock analysis run by another application. You can import the results into Sherlock to generate reliability predictions. The theory behind the reliability prediction is explained in the section below, [Post Processing – Life Prediction Calculation](#) (p. 183). Sherlock provides a visual representation of the results in the **2D Layer Viewer** and the **3D Viewer**. You can find detailed information about the results in [Mechanical Shock Analysis Results](#) section of the *Sherlock User's Guide*. All the modules in Sherlock use SI units in millimeters as the base unit. Information on how to set up a board for a shock analysis and how to import the result file when solved outside of Sherlock can be found in the user's guide under [Mechanical Shock Analysis](#).

6.3. Strain Values

In its Mechanical Shock analysis, Sherlock reports three strains for a given component. They are:

- Lead Strain (if the leads for the component are modelled, Element Equivalent Strain)
- Part Strain (Element Equivalent Strain)
- PCB Strain (Surface Equivalent Strain)

Lead strains are reported at three locations and appear under the **Leads** tab in the [Results Table](#).

Note:

For Mechanical Shock and ICT, predictions are made using PCB strain, not Lead Strain, even though the leads are modelled.

- Max Lead Strain: Maximum strain over the lead body
- Max Part Strain: Maximum strain at the Lead and Component interconnect
- Max PCB Strain: Maximum strain at the Lead and PCB interconnect

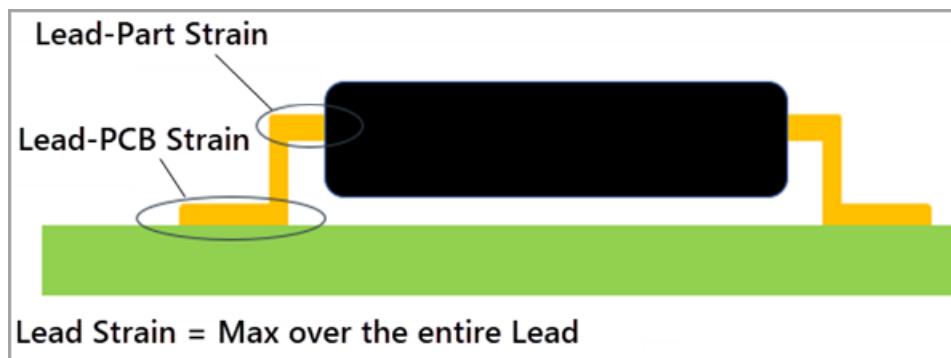
6.3.1. Known Issue in Previous Sherlock Versions

In the previous versions, Sherlock reported nodal strains which sometimes caused elevated strains to appear in the results, especially at the lead-component interfaces. This was due to the modulus difference between the lead and the component body. Sherlock now uses an improved approach for evaluating lead strain, PCB strain, and part strain. These changes are explained in the section which follows.

6.3.2. Lead Strain

For components with leads, strains are reported at three locations as mentioned earlier. These locations are shown in the figure below. Max Lead Strain reports the maximum strain experienced by the lead body. Lead strains are computed as elemental von Mises stress over the elemental modulus, to avoid the issue discussed in the [previous section \(p. 180\)](#). For a given lead, Sherlock identifies the elemental strain for all the elements in the lead body and reports the maximum as the Max Lead Strain.

Figure 6.12: Lead Strain



Maximum Lead-PCB Interface strain (displayed as **Max PCB Strain** under the **Leads** tab in the **Results Table**) describes the maximum lead strain among the set of lead elements that are connected to the PCB. Likewise, the maximum Lead-Part Interface strain (displayed as **Max Part Strain** under the **Leads** tab in the **Results Table**) describes the maximum lead strain among the set of lead elements attached to the part. (See [Sharp Corners in Leaded Device and Singularities \(p. 150\)](#) for information on mesh recommendation to deal with sharp corners in leads.) In Shock analysis, component reliability is based only on PCB Strain even though leads are modelled. The **Leads** tab only provides the lead strains at the above-mentioned locations. No prediction is made based on these strains.

6.3.3. Part Strain

Part strains are computed when the **Part Modeling** is **ENABLED** in the FE model. Parts may crack when the component is in tension. The failure can be captured by elemental von Mises strain using [Equation 6.3 \(p. 181\)](#).

$$\epsilon_n = \frac{\sigma_{VM-n}}{E} \quad (6.3)$$

where n is the element number.

The maximum strain of all the elements for a given component is taken as the Part Strain for that component.

6.3.4. PCB Strain

PCB strains are computed at the footprint of every component on the board because PCB bending can cause component failure. The bending of the board can be captured by surface Equivalent Strain as shown below.

$$\sigma_n = \sqrt{\sigma_{Avg\ Face\ x}^2 + \sigma_{Avg\ Face\ y}^2 - \sigma_{Avg\ Face\ x} \sigma_{Avg\ Face\ y} + 3\sigma_{Avg\ Face\ xy}^2} \quad (6.4)$$

$$\sigma_{\text{Avg Face } x} = \frac{\sum_{n=1}^{n=k} \sigma_{(x)_{\text{element}_m}}^{(\text{Unaveraged Nodal})_n}}{k} \quad (6.5)$$

where $k = 3$ (wedge) or 4 (hex), m is the element number.

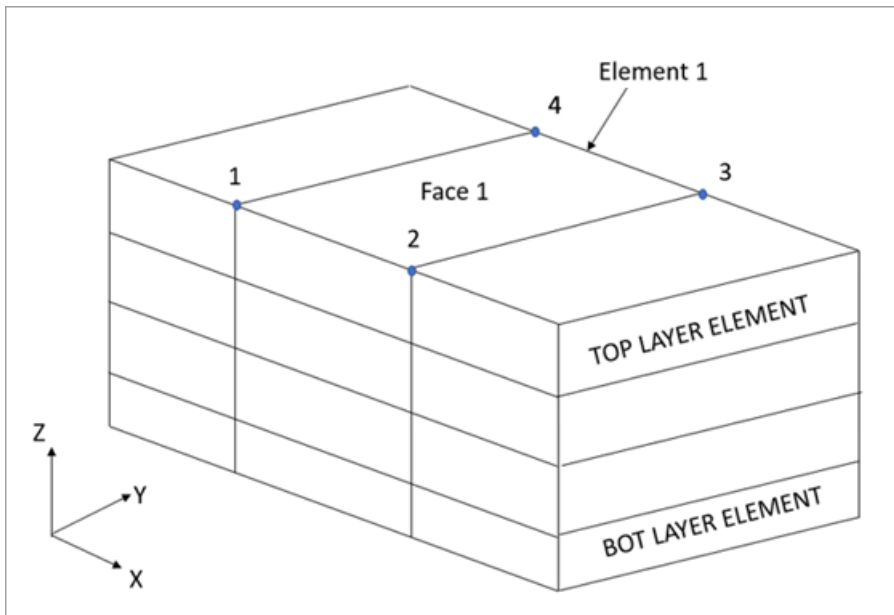
$$\sigma_{\text{Avg Face } y} = \frac{\sum_{n=1}^{n=k} \sigma_{(y)_{\text{element}_m}}^{(\text{Unaveraged Nodal})_n}}{k} \quad (6.6)$$

where $k = 3$ (wedge) or 4 (hex), m is the element number.

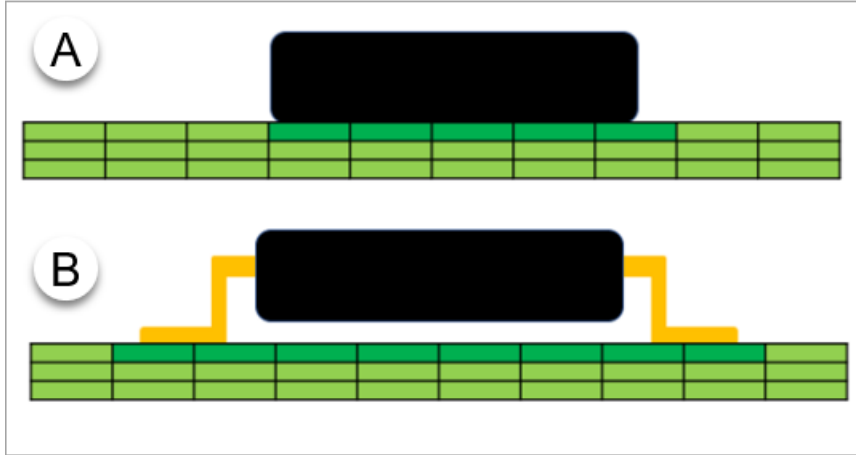
$$\sigma_{\text{Avg Face } xy} = \frac{\sum_{n=1}^{n=k} \sigma_{(xy)_{\text{element}_m}}^{(\text{Unaveraged Nodal})_n}}{k} \quad (6.7)$$

where $k = 3$ (wedge) or 4 (hex), m is the element number.

Figure 6.13: Surface Equivalent Strain



Note, if the parts do not have leads, the elements under the footprint of the part are used (A, in the image below). If the parts have leads, the elements under the footprint of the part and those under the leads are used (B). In the image below, the elements under the footprint of the part are dark green, and the all the other elements of the PCB are light green.

Figure 6.14: PCB Strain

6.4. Post Processing – Life Prediction Calculation

During mechanical shock exposure, high cycle fatigue, low cycle fatigue, and overstress mechanisms can occur. Due to the nature of the high cycle vibration, fully reversible elastic deformation is considered to have occurred (meaning the system can flex in concave as well as convex fashion). For low cycle vibration, deformation is considered to occur unidirectionally with no reversals (the system either flexes in a concave or a convex fashion). This difference is implemented in the Basquin equation and the Coffin-Manson equation ([Equation 6.10 \(p. 183\)](#) and [Equation 6.13 \(p. 184\)](#) respectively). The Basquin equation relates stress or elastic strain to the cycles to failure. The standard Basquin equation takes the form below :

$$\sigma_a = \sigma'_f (2N_f)^b \quad (6.8)$$

where

σ_a is the cyclic stress amplitude

σ'_f is the fatigue strength coefficient, defined in the solder profile

$2N_f$ is the cycles to failure (typically the characteristic life)

b is the fatigue strength exponent, defined in the solder profile

Additionally, the Basquin equation can be expressed in terms of the elastic strain:

$$\frac{\Delta \varepsilon_e}{2} = \frac{\sigma'_f}{E} (2N_f)^b \quad (6.9)$$

where

$\Delta \varepsilon_e$ is the elastic strain range

E is the elastic modulus

$$N_{f-\text{Highcycles}} = 10E6 * \left(\frac{\varepsilon_c}{2 * \varepsilon_{\text{FEA}}} \right)^{\text{FEA Power}} \quad (6.10)$$

where

ε_{FEA} is the maximum PCB strain at the footprint of a given component

$\text{FEA}_{\text{power}}$ is the fatigue exponent for any given solder, available in the **Solder Editor**

The following equation calculates component critical strain:

$$\varepsilon_c = \frac{\varepsilon_{\text{shock}}}{c * \sqrt{L}} \quad (6.11)$$

where

c is the component correction factor defined in the Solder Library on the **Correction Factors** tab for each package type. The default value for any package type *not* shown is 1.0.

L is the package diagonal length

$\varepsilon_{\text{shock}}$ is critical shock strain—the **Shock Strain** value defined in the **Solder Profile Editor**.

The shock strain is similar to the critical strain used in a vibration analysis, but for shock the strain is traditionally assumed to be two times higher than would result from vibration. Simply put, $\varepsilon_{\text{shock}} = 2\zeta$ where ζ is the baseline board-level strain for a component of unit length at the center of the board with unit packaging constant. The strain value is derived from Steinberg's maximum displacement equation. (For a detailed derivation, refer to [Cycles to Failure Calculation for Packages without Leads \(p. 220\)](#) in the *Harmonic Vibration Analysis* chapter.) Because lead-free solder is less compliant than leaded solder, a factor of ~1.5x is used for SAC. Due to the minimal data available for high-lead solder, the strain values from eutectic SnPb solder were carried over to high-lead solder. Also, because the mechanical properties of SAC are so similar to SENJU M794, the SAC properties were used for SENJU. Because Sn100C is a softer solder, it is assumed to have a critical strain similar to leaded solder.

Because of the reversible deformation that happens during shock events, the critical strain is assumed to be similar to that of a high cycle vibration. This is accomplished by knocking down the critical shock strain by a factor of two as depicted in [Equation 6.10 \(p. 183\)](#).

$$\frac{\Delta\varepsilon_e}{2} = \varepsilon'_f (2N_f)^c \quad (6.12)$$

where

$\Delta\varepsilon_e$ is the elastic strain range

ε'_f is the fatigue ductility coefficient, the failure strain for a single reversal

N_f is the cycles to failure (typically the characteristic life).

c is the fatigue ductility exponent = $\frac{1}{\text{FEA Power}}$ where FEA Power is defined in the solder profile editor.

The Coffin-Manson law (as used in Sherlock) can also be written as :

$$N_{f-\text{LowCycles}} = 1000 * \left(\frac{\varepsilon_c}{\varepsilon_{\text{FEA}}} \right)^2 \quad (6.13)$$

where

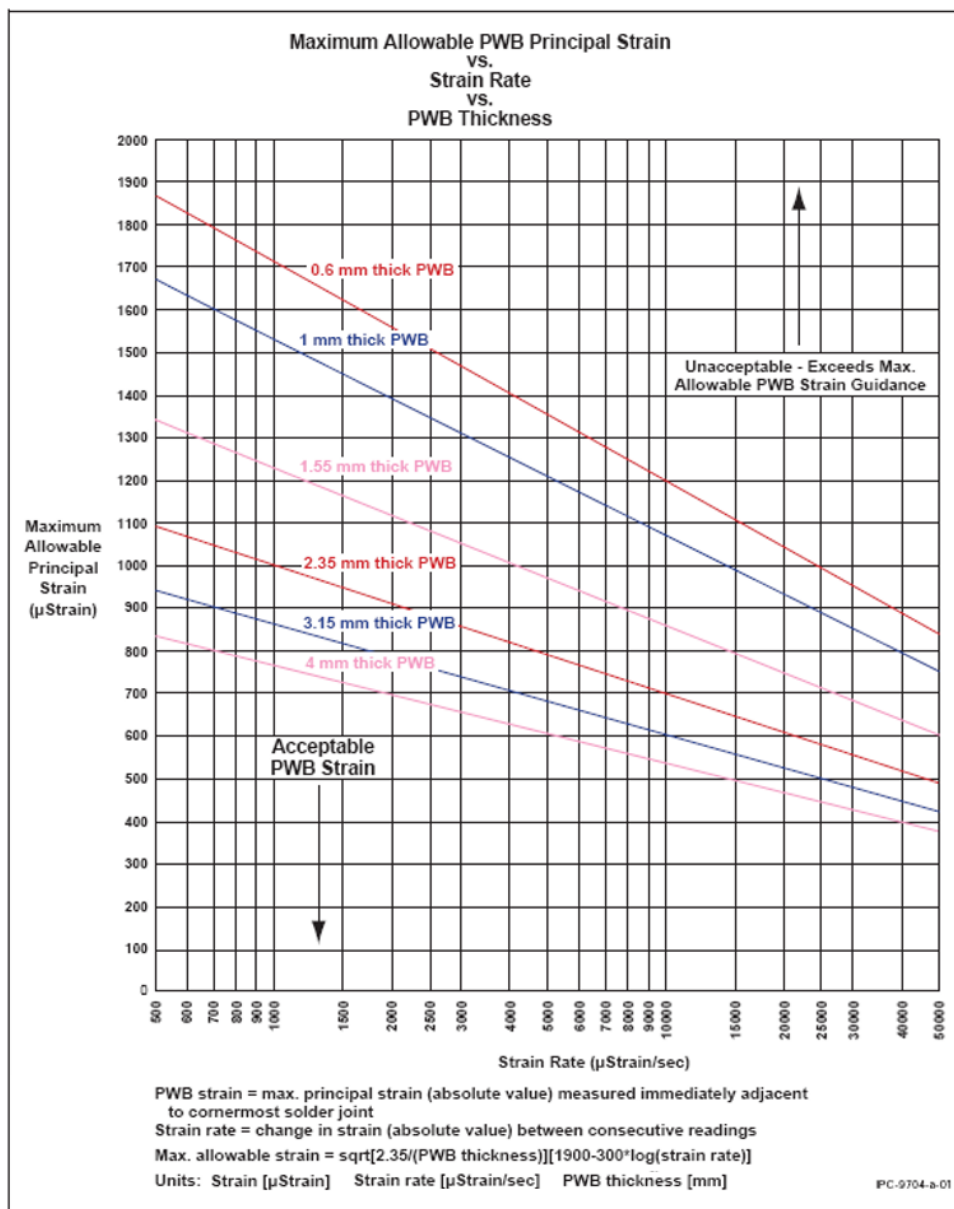
ε_c is the component critical strain

ε_{FEA} is the FEA strain at the footprint of a given component

Combining both equations produces the Basquin-Coffin-Manson relation which yields the cycles to failure for any device exposed to mechanical shock. Notably, any overstress relation involves comparing the critical strain to the strain experienced by the component. If the strain seen by the component is higher than the critical strain, the component is said to be overstressed—although it should be noted that Sherlock does not consider overstress unless computed cycles to failure is 1000 or less. In other words, a component cannot fail overstress if the cycles to failure is greater than 1000.

Because shock is assumed to be a high strain rate event, Sherlock assumes the highest strain rate from the IPC guideline (p. 201) (see [Figure 6.15: IPC-9704 - Strain Rate vs Maximum Allowable Strain \(p. 185\)](#)) which is 50,000 $\mu\epsilon/s$. Based on this guideline for shock, the default value of 600 $\mu\epsilon$ is assumed based on a nominal PCB thickness of 1.55 mm. The critical strain is a user-defined value and can be changed using the **Analysis Properties** dialog as shown in [Figure 6.11: Analysis Properties: A- Mechanical Shock Analysis Properties dialog. B- Main Menu > Settings > FEA Analysis \(p. 179\)](#).

Figure 6.15: IPC-9704 - Strain Rate vs Maximum Allowable Strain



After completing a Mechanical Shock analysis using FEA, the post-processing stage classifies the failure as either overstress or fatigue. If the strain is above the **Critical Shock Strain** entered under **Analysis Properties**, the failure is considered as overstress. If the strain is below the **Critical Shock Strain** value, the failure is considered to be a combination of low and high cycle fatigue.

$$\text{Cycles to Failure (CTF)} = N_{f-\text{Highcycles}} + N_{f-\text{Lowcycles}} \quad (6.14)$$

Damage is calculated from the cycles to failure. Based on the above combination, Coffin-Manson dominates at low cycle, and the Basquin equation dominates at high cycle failure.

$$\text{Total Damage} = \text{Applied Cycle} * \text{Damage Per Cycle} \quad (6.15)$$

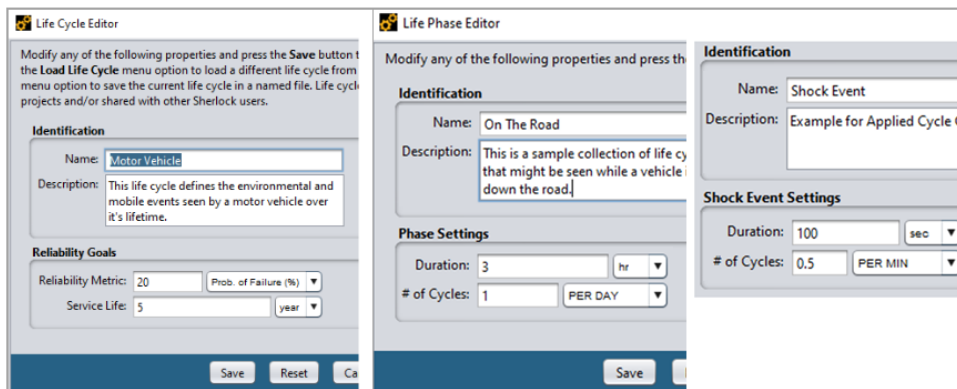
$$\text{Applied Cycle} = \text{Phase Cycles} * \text{Event Cycles} \quad (6.16)$$

For reference, below is an example of an applied cycles calculation for a given Service Life, Life Phase, and Event.

Table 6.1: Sample Service Life, Phase, and Event

Service Life	Phase		Event	
5 years	Duration	3 hrs.	Duration	100 sec
	Cycles	1 /day	Cycles	0.5 /min

Figure 6.16: Sample Service Life, Phase, Event Settings in Sherlock



The first step is to identify the maximum number of phase cycles in a given service life.

Maximum Number of Phase Cycles in Service Life = Maximum Phase Cycles

$$\text{Maximum Phase Cycles} = \frac{\text{Total Phase Duration in Service Life}}{\text{Phase Duration}}$$

$$\text{Maximum Phase Cycles} = \frac{5 [\text{years}] * 365.2422 [\text{days}] * 24 [\text{hrs}]}{3 [\text{hrs}]} = 14609.68 \text{ cycles}$$

Next, the number of applied Phase Cycles should be identified. From the example above, the **# of Cycles** (1), is applied per day over the **Service Life**. Therefore, the total number of cycles applied over the entire **Service Life** can be calculated as shown below :

$$\begin{aligned} \text{Number of Applied Phase Cycle} = \\ 5 [\text{years}] * 365.2422 [\text{days}] * 1 [\text{cycles/day}] = 1826.211 \end{aligned}$$

If applied Phase Cycles exceed the maximum Phase Cycles possible, the phase cycle will need to be adjusted appropriately.

Phase Cycles = Maximum Cycles, if Applied Phase Cycles > Maximum Cycles

Phase Cycles = Cycles, if Applied Phase Cycles < Maximum Cycles

Likewise, the maximum number of Event Cycles in a phase represents the maximum number of Event Cycles that can occur in that phase. If applied Event Cycles exceed the maximum number of Event Cycles, the number of applied Event Cycles must be adjusted as appropriate.

The maximum number of Event Cycles in a given Phase Duration is calculated as shown :

$$\text{Maximum Number of Event Cycles per Phase Duration} = \text{Maximum Event Cycles} \quad (6.17)$$

$$\text{Maximum Event Cycles} = \frac{\text{Total Event Duration per Phase Duration}}{\text{Event Duration}} \quad (6.18)$$

$$\text{Maximum Event Cycles} = \frac{3[\text{hrs.}] * 3600[\text{sec}]}{100[\text{sec}]} = 108 \text{ cycles} \quad (6.19)$$

$$\text{Number of Applied Event Cycles} = \text{Applied Event Cycles} = 3[\text{hrs.}] * 60[\text{min}] * 0.5 \text{ cycles /min} = 90 \text{ cycles} \quad (6.20)$$

$$\text{Total Applied Cycles in Service Life} = \text{Phase Cycle} * \text{Event Cycles} = 1826.211 * 90 = 164358.99 \text{ cycles} \quad (6.21)$$

Damage per cycle is calculated as one over cycles-to-failure (from Equation 6.14 (p. 186)), and the applied cycles is computed from the Phase Cycle and Event Cycles (from equation Equation 6.16 (p. 186)).

$$\text{Damage per cycle} = \frac{1}{\text{CTF}} \quad (6.22)$$

Finally, the Total Time to Failure (TTF), Probability of Failure (PoF), and Probability of Failure per cycle is computed as

$$\text{Time to Failure (TTF)} = \frac{\text{Service Life}}{\text{Total Damage}} \quad (6.23)$$

$$\text{Damage} = \frac{1}{\text{CTF}} * \text{Applied Cycles} \quad (6.24)$$

$$\text{POF} = 1 - e^{-\left(\frac{\text{Applied Cycles}}{\text{CTF}}\right)^\beta} \quad (6.25)$$

$$\text{PoF per cycle} = 1 - e^{-\left(\frac{1}{\text{CTF}}\right)^\beta} \quad (6.26)$$

If there are multiple shock events, the damage from each event is added together for computing total damage as per Miner's Rule, and the total damage is used to determine probability of failure (PoF), using Equation 6.25 (p. 187). The probability of failure per cycle, on the other hand, uses the lowest cycles to failure from multiple events.

For shock, it has been traditionally observed that the failure follows an exponential distribution. For this reason Sherlock uses a Weibull parameter β of 1 in both Equation 6.25 (p. 187) and Equation 6.26 (p. 187). Life Prediction for individual components is always made using the β value from Solder Editor, as shown in Figure 6.17: Weibull Beta (p. 188). You can set the Weibull value to 1 when running Shock in Sherlock to see consistent results between the Results Table and the Life Prediction Curve.

Any overstress relation involves comparing the critical strain (see Figure 6.11: Analysis Properties: A-Mechanical Shock Analysis Properties dialog. B- Main Menu > Settings > FEA Analysis (p. 179)) to the strain experienced by the component. If the strain experienced by the component is higher than the

critical strain, the component is said to be overstressed. The decision on whether failure is due to overstress or fatigue is based on the respective score.

Figure 6.17: Weibull Beta

Fatigue Scoring

Scoring is determined using the ratio of Life Cycle Goal to Failure Probability (Probability Goal / Probability of Failure). Sherlock assigns a score of zero to any part if the ratio is below two. If the ratio is ten or above, a score of ten is assigned. For any ratio in between two and ten, the score is linearly interpolated between one and ten. The basic intent here is this: Sherlock will deem a part "highly likely to fail" if the Probability Goal is less than two times the Probability of Failure and will deem it as "least likely to fail" if the Probability Goal is greater than ten times the Probability of Failure.

$$1. \text{ If } \frac{\text{Probability Goal}}{\text{Probability of Failure}} < 2 : \text{Score} = 0$$

$$2. \text{ If } 10 > \frac{\text{Probability Goal}}{\text{Probability of Failure}} > 2$$

$$\text{Score} = 1.125 \frac{\text{Probability Goal}}{\text{Probability of Failure}} - 1.125; \text{ Scored between 10 and 1}$$

3. If $\frac{\text{Probability Goal}}{\text{Probability of Failure}} > 10$ Score = 10

Overstress Scoring

For Overstress, if the FEA strain is greater than or equal to the critical strain set by the user, a score of zero is assigned to the part. If the FEA strain is lower than 50% of the critical strain, a score of ten is assigned. Anything in between critical strain and 50% of critical strain will be linearly interpolated between one and ten.

1. If $\frac{\text{Critical Strain}}{\text{FEA Strain}} < 1$: Score = 0
2. If Critical Strain > FEA Strain > 50% Critical Strain

$$\text{Score} = \left(\frac{9}{1} \left(\frac{\text{Critical Strain}}{\text{FEA Strain}} - 1 \right) \right) + 1$$
; Scored between 1 and 10
3. If $\frac{\text{Critical Strain}}{\text{FEA Strain}} > 2$: Score = 10

Prior to Sherlock 2023 R1, the Failure Type suggested in the Results Table was based on the worst of the above two scores. Starting with Sherlock 2023 R1, the cycle count for the FEA strain was also taken into consideration: If the component fails from overstress—that is, if the overstress score is lower than the fatigue score—Sherlock also checks whether the cycles to failure is below 1000. Only when the Overstress Score and the cycles to failure are both lower than 1000 is the Failure Type classified as Overstress.

6.5. Mechanical Shock Analysis Results

The Mechanical Shock analysis module generates the following types of results :

- An overall **Summary** of the analysis. See [Figure 6.18: Summary Panel \(p. 190\)](#) below.
- A **ResultsTable** displaying the Maximum Displacement, Strain, and Life Predictions. See [Figure 6.19: Shock Results Table \(p. 190\)](#).
- **Results Tables** for **Parts** (B), **Leads** (C), and **Mount Points** (not shown in this analysis), displaying their respective strains
- Graphical layers showing color-coded part scores (top and bottom sides)
- Graphical layers showing maximum displacement and strain during Shock Events.

The **Summary Panel** displays the overall summary of the analysis. Essentially, it displays basic information about the shock analysis results such as maximum displacement of the board and maximum PCB strain on the board. The **Summary Panel** also shows the overall module score for the CCA and the score distribution for all the parts on the board. Part scores are categorized into score bins of **7 or more**, **3 to 7**, and **less than 3**. FEA input details are also provided such as board properties, the analysis process, and mesh properties. The *Sherlock User's Guide* provides additional information on the results mentioned above in the section [Mechanical Shock Analysis Results](#). A general overview of the Results Table, the Life Prediction Curve and the Graphical FEA Results is provided in the following section.

Figure 6.18: Summary Panel

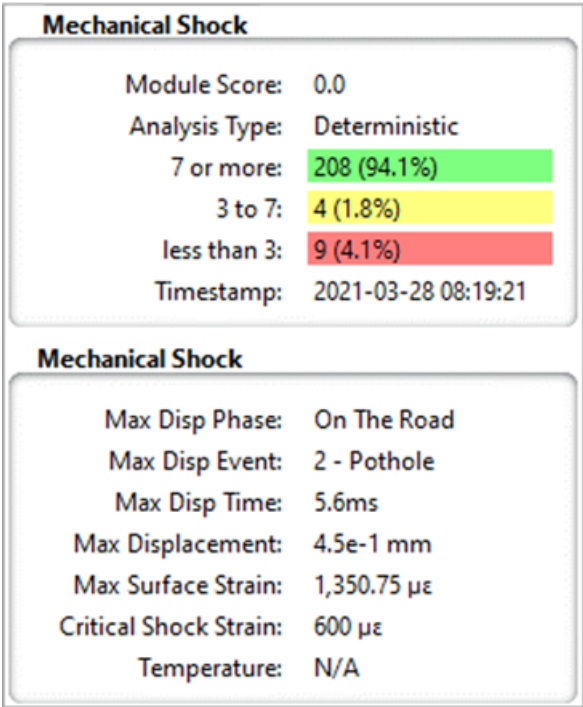
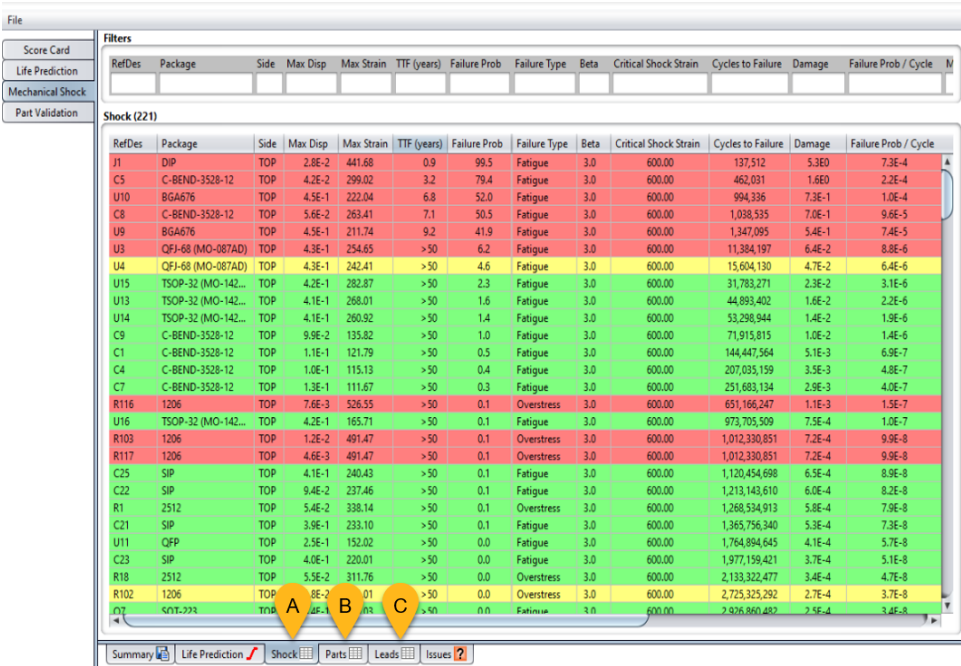


Figure 6.19: Shock Results Table



6.6. Shock Results Table

The Mechanical Shock **Results Table** displays detailed results for each part analyzed. The color-coded table makes it easy to identify the specific parts prone to fail prematurely. The table displays the maximum displacement and the board strain experienced by each part on the board. The damage is calcu-

lated from the PCB strain value for a given component. In Mechanical Shock, the reliability predictions are based only on PCB strain. This is in contrast to Random Vibration and Harmonic Vibration which use either PCB strain or lead strain depending on whether the component has leads or not. As discussed in [PCB Strain \(p. 181\)](#) earlier, surface Equivalent Strain is considered for PCB strain. Time to Failure (TTF) and Probability of Failure (PoF) are computed from Damage, and the Score is calculated from the Reliability Goal and PoF.

Note:

Currently, TTF calculations for leads are not available for Mechanical Shock analysis in Sherlock.

Figure 6.20: Leads Table

RefDes	Lead ID	Max PCB Strain Event	Max PCB Strain	Max Part Strain Event	Max Part Strain	Max Lead Strain Event	Max Lead Strain
U14	17	2 - Pothole	658.57	2 - Pothole	122.42	2 - Pothole	658.57
U16	32	2 - Pothole	655.87	2 - Pothole	123.47	2 - Pothole	655.87
U15	1	2 - Pothole	651.07	2 - Pothole	112.71	2 - Pothole	651.07
U14	1	2 - Pothole	650.09	2 - Pothole	122.46	2 - Pothole	650.09
U16	16	2 - Pothole	646.24	2 - Pothole	126.50	2 - Pothole	646.24
U14	18	2 - Pothole	637.27	2 - Pothole	106.60	2 - Pothole	637.27
U15	17	2 - Pothole	635.18	2 - Pothole	109.31	2 - Pothole	635.18
U16	31	2 - Pothole	634.24	2 - Pothole	109.97	2 - Pothole	634.24
U14	2	2 - Pothole	632.09	2 - Pothole	105.19	2 - Pothole	632.09
U15	2	2 - Pothole	631.76	2 - Pothole	98.97	2 - Pothole	631.76
U16	15	2 - Pothole	624.54	2 - Pothole	107.09	2 - Pothole	624.54
U15	18	2 - Pothole	618.29	2 - Pothole	96.90	2 - Pothole	618.29
U14	19	2 - Pothole	617.20	2 - Pothole	98.74	2 - Pothole	617.20
U13	32	2 - Pothole	616.50	2 - Pothole	99.70	2 - Pothole	616.50

Starting with Sherlock 2021 R2, a **Parts** tab is available as shown in the figure below. The **Parts** tab displays the following information for every part on the board: **PCB Strain**, **Part Strain**, and **Lead Strain** which is the maximum of the three lead strains. If the leads are explicitly modelled, a **Leads** tab is available which displays lead strain (as discussed earlier in [Lead Strain \(p. 181\)](#)) for every part. If the leads are not modelled, the tab will not be displayed.

Figure 6.21: Parts Table

Current Results - ShockPlot Main Board

File

Score Card

Life Prediction

Mechanical Shock

Part Validation

Filters

RefDes	Part Type	PCB Strain	Part Strain	Lead Strain

Parts (221)

RefDes	Part Type	PCB Strain	Part Strain	Lead Strain
U10	IC	222.04	160.15	
U9	IC	211.74	159.68	
U3	IC	254.65	58.43	447.43
U4	IC	242.41	51.75	416.86
J1	JACK	441.68	33.83	332.60
U11	IC	152.02	28.36	218.23
U12	IC	118.72	28.27	243.03
U14	IC	260.92	26.48	658.57
U16	IC	165.71	26.45	655.87
U15	IC	282.87	25.76	651.07
U13	IC	268.01	24.08	616.50
U8	IC	119.49	15.53	545.33
U5	IC	154.16	12.24	245.61
C21	CAPACITOR ELECTROLYTIC	233.10	11.02	319.96

Summary Life Prediction Shock Parts Leads Issues

If there is more than one Event in the analysis, the **Shock**, **Parts**, and **Leads** tables display the values for the Event that produced the maximum displacement. The **Mechanical Shock** panel under the **Summary** tab displays the Event that produced maximum displacement.

The **Failure Prob** column under the **Shock** tab is based on the total damage of all events. As with other color-coded displays in Sherlock, RED means the predicted score is less than 3 (less than 3x the safety factor), YELLOW means the score is between 3 and 7, and GREEN means that the score is 7 or more, indicating a very small probability the part will fail. You can double-click any row in the table to view all of the properties associated with a selected part.

When viewing **Current Results**, the properties are based on the current **Parts List**. When viewing archived results, the properties are based on a snapshot of the **Parts List** taken at the time the archive was made. You can also export one or more rows from the results table by right-clicking a row and selecting the **Export Table** option from the context menu. You may also view the **Life Prediction** chart for a specific part by right-clicking the applicable row and selecting **View Life Prediction** from the context menu.

Figure 6.22: Leads Table

RefDes	Lead ID	Max PCB Strain Event	Max PCB Strain	Max Part Strain Event	Max Part Strain	Max Lead Strain Event	Max Lead Strain
U14	17	2 - Pothole	658.57	2 - Pothole	122.42	2 - Pothole	658.57
U16	32	2 - Pothole	655.87	2 - Pothole	123.47	2 - Pothole	655.87
U15	1	2 - Pothole	651.07	2 - Pothole	112.71	2 - Pothole	651.07
U14	1	2 - Pothole	650.09	2 - Pothole	122.46	2 - Pothole	650.09
U16	16	2 - Pothole	646.24	2 - Pothole	126.50	2 - Pothole	646.24
U14	18	2 - Pothole	637.27	2 - Pothole	106.60	2 - Pothole	637.27
U15	17	2 - Pothole	635.18	2 - Pothole	109.31	2 - Pothole	635.18
U16	31	2 - Pothole	634.24	2 - Pothole	109.97	2 - Pothole	634.24
U14	2	2 - Pothole	632.09	2 - Pothole	105.19	2 - Pothole	632.09
U15	2	2 - Pothole	631.76	2 - Pothole	98.97	2 - Pothole	631.76
U16	15	2 - Pothole	624.54	2 - Pothole	107.09	2 - Pothole	624.54
U15	18	2 - Pothole	618.29	2 - Pothole	96.90	2 - Pothole	618.29
U14	19	2 - Pothole	617.20	2 - Pothole	98.74	2 - Pothole	617.20
U13	32	2 - Pothole	616.50	2 - Pothole	99.70	2 - Pothole	616.50

When setting up the FEA Analysis, it is possible to exclude parts from the FEA model based on part size. (See A in [Figure 6.23: Part Strain for Filtered Parts \(p. 194\)](#) where parts smaller than 10 mm have been filtered out.) If you wish to generate PCB strain results for parts you have excluded, set **Filtered Part Results** to **ENABLED** (B). In this configuration, Sherlock cannot determine Part Strain because the parts are not physically modeled, so Sherlock will display **Part Strain** as 0.00 $\mu\epsilon$ (C). This *does not* mean part strain is actually zero. To alert you to this condition, Sherlock generates a warning under the **Issues** tab as shown in [Figure 6.24: Issues Tab \(p. 194\)](#).

Note:

Remember, if you have filtered out parts in your analysis and you also set **Filtered Parts Results** to **ENABLED**, Sherlock cannot calculate Part Strain for the excluded parts. The 0.00 in the **Part Strain** column should be ignored for excluded parts. The **Issues** tab in the **Results Table** will alert you to this.

Figure 6.23: Part Strain for Filtered Parts

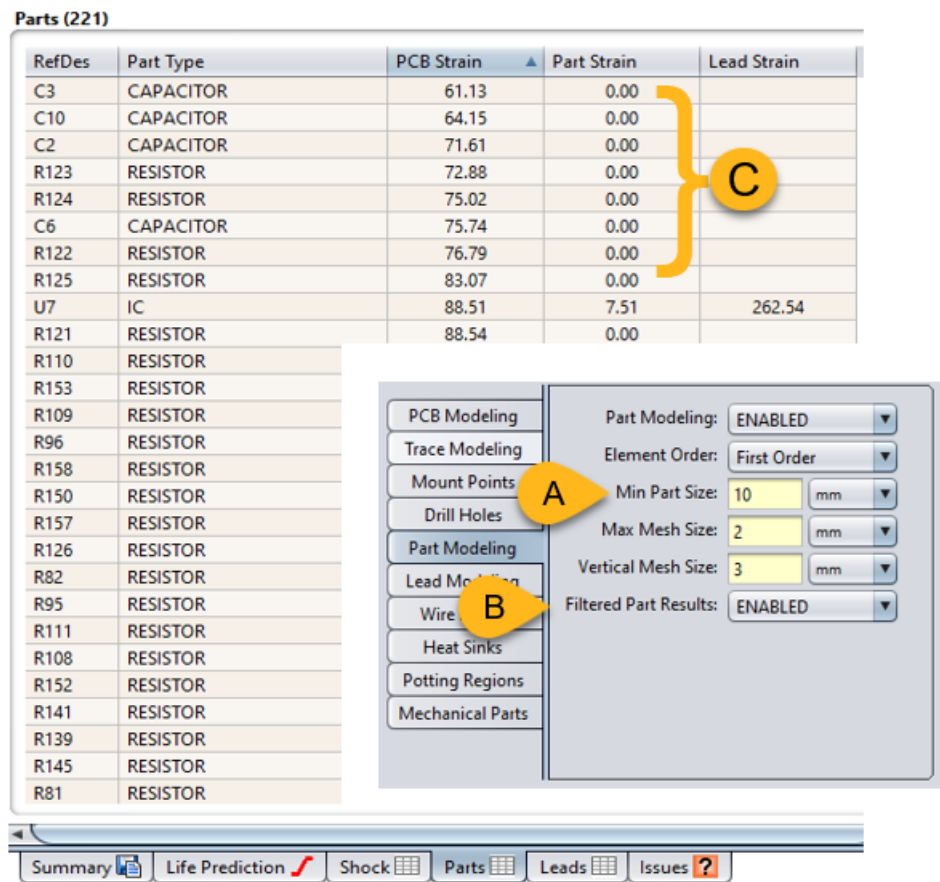
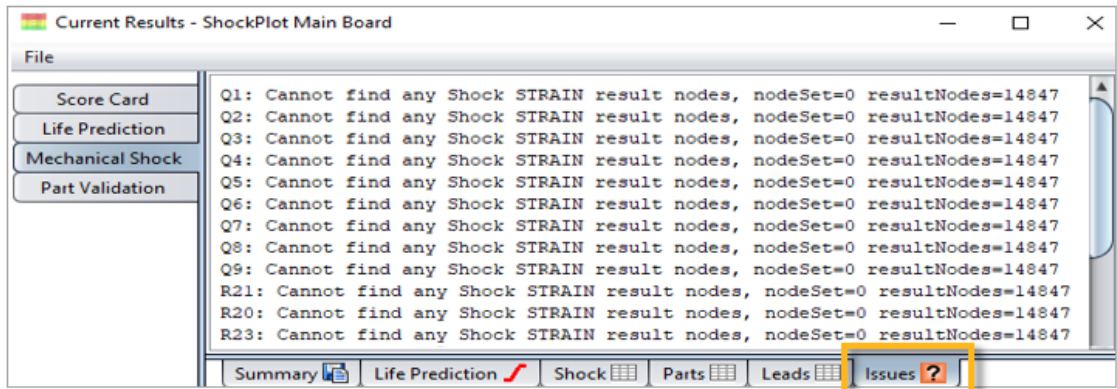


Figure 6.24: Issues Tab

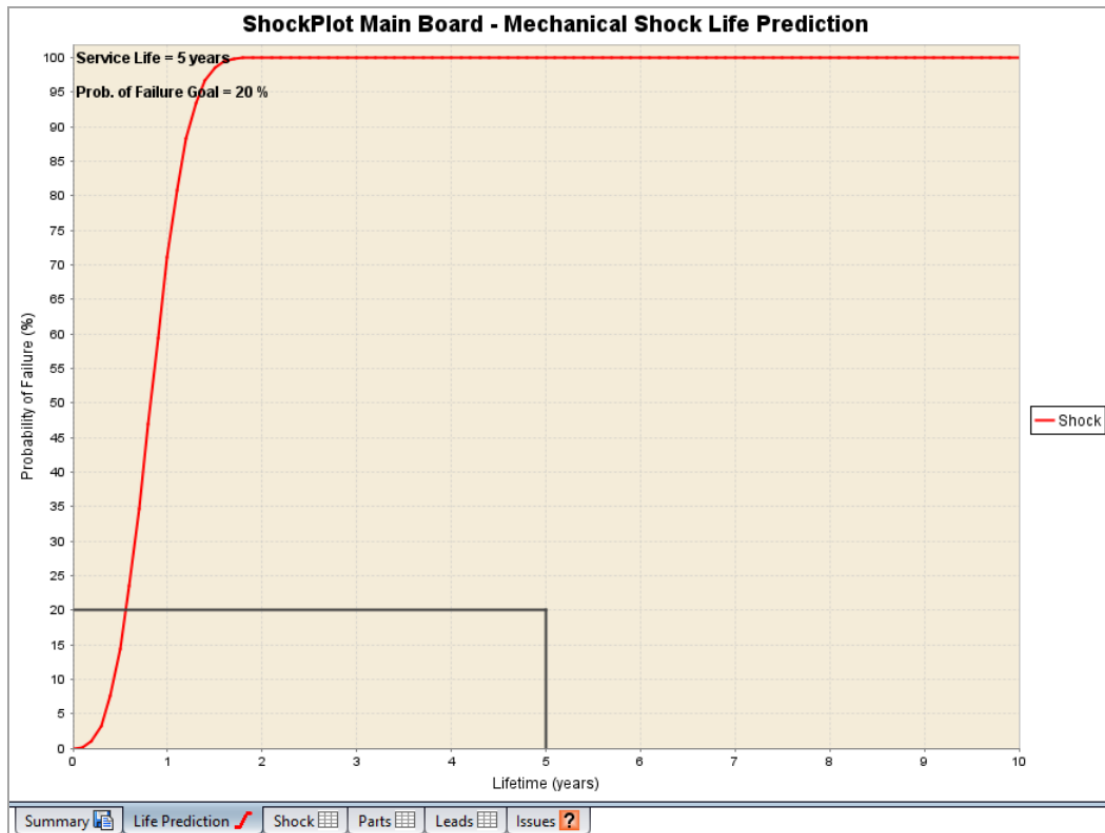


6.7. Life Prediction Curve

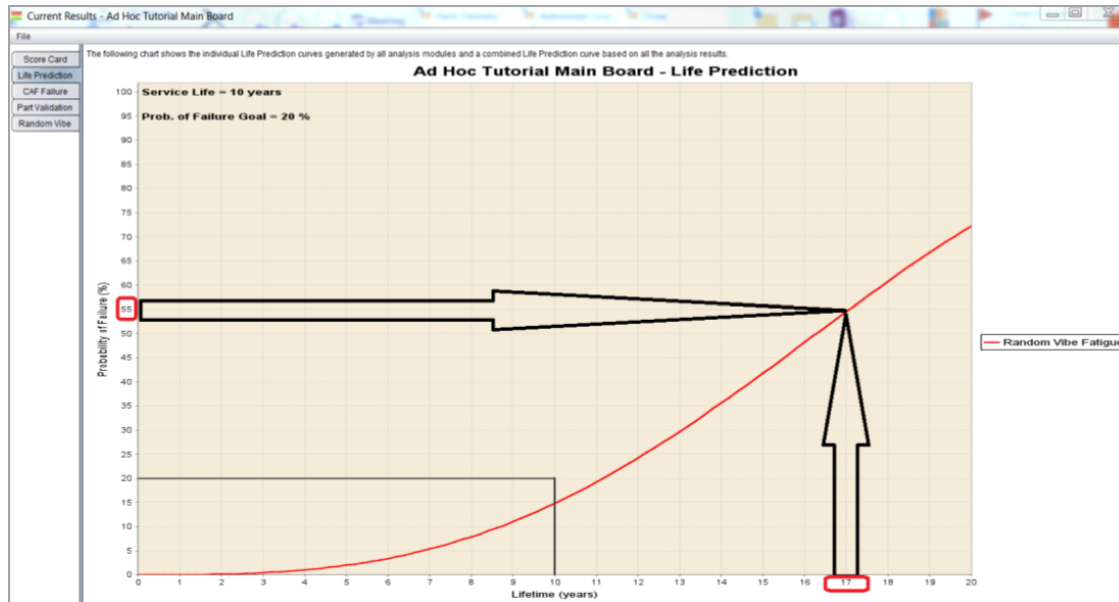
Sherlock generates a Life Prediction Curve for individual components as well as for the entire board. The Life Prediction Curve for the circuit card is based on the Life Prediction Curves for each part analyzed. Click the **Life Prediction** tab in the **Current Results** window to display the results for the whole board (see Figure 6.25: Life Prediction Curve (p. 195)). The rectangular region in the lower left of the chart represents the desired **Reliability Goals** for the project, bounded on top by the desired **Probability**

of Failure and bounded on the right by the desired **Service Life**. If the curve stays below the top line up to the **Service Life**, then the circuit card is predicted to meet its goals.

Figure 6.25: Life Prediction Curve



Sherlock calculates the Life Prediction Curve of the circuit card by multiplying the reliabilities of all the components on the board that have a unique Weibull Slope (β) and Time to Failure. The Probability of Failure for the Life Cycle Goals can be extracted from this plot. For example, see [Figure 6.26: Life Prediction Curve \(p. 196\)](#): The plot indicates that at 17 years the Probability of Failure is 55%.

Figure 6.26: Life Prediction Curve

6.7.1. Known Issue with Life Prediction Plots in Shock

When calculating the Probability of Failure for any component on the board (displayed as **Failure Prob** in the **Results** table), Sherlock assumes a Weibull slope (β) of 1, irrespective of the value in the column **Beta**. Refer to the earlier section [Post Processing – Life Prediction Calculation \(p. 183\)](#) for the reasons behind this assumption. The Life Prediction Curve for an individual component, however, is generated using the Weibull slope from column **Beta**.

6.8. Graphical FEA Results

The Mechanical Shock analysis module generates a **2D Results Layer** showing displacement, PCB strains, and PCB stresses experienced during the worst vibration event of the analysis. The worst vibration event is the one producing the maximum displacement response. The strains are displayed in microstrain. Strain per element face is determined by surface Equivalent Stress as discussed in [PCB Strain \(p. 181\)](#). The results provided in the **Layer Viewer** are for the PCB surface only, not for the parts. The results for the parts can be viewed using Sherlock's **3D Viewer**.

How Sherlock calculates the PCB stress and strain was covered earlier in [Strain Values \(p. 180\)](#). You can find more about the **2D Layer Viewer**, see the [Layer Viewer Tutorial](#) in the *Sherlock User's Guide*.

In the [Figure 6.27: 2D Layer Viewer \(p. 197\)](#), Sherlock's **2D Layer Viewer** displays the surface Equivalent Strain across the top surface of the entire board. The [Figure 6.28: PCB Strain in Layer Viewer at Board Center \(p. 197\)](#) zooms in to show the PCB strain for a single element at the center of the board. The subsequent table ([Table 6.2: PCB Strain from Unaveraged Results in Ansys Mechanical \(p. 198\)](#)) provides the unaveraged stresses of the same element generated by Ansys Mechanical. It also shows the calculation for PCB strain from the unaveraged stress values.

Figure 6.27: 2D Layer Viewer

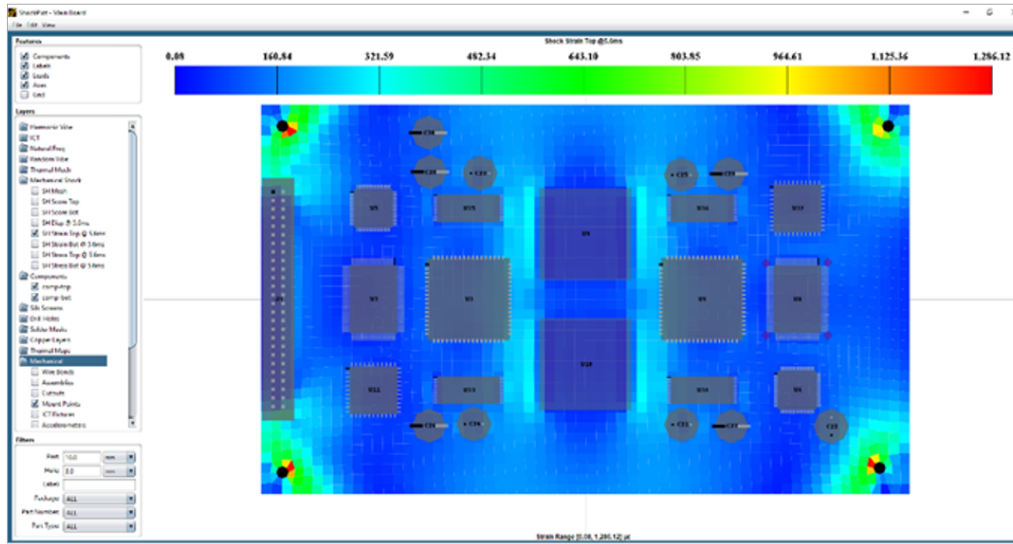


Figure 6.28: PCB Strain in Layer Viewer at Board Center

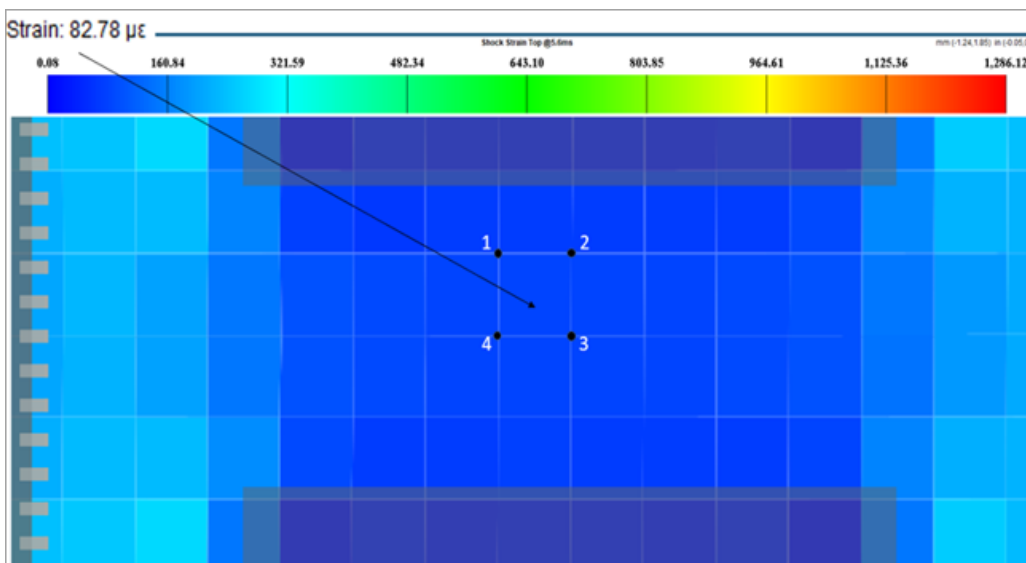


Figure 6.29: PCB Strain- Graphic Results from Ansys Mechanical

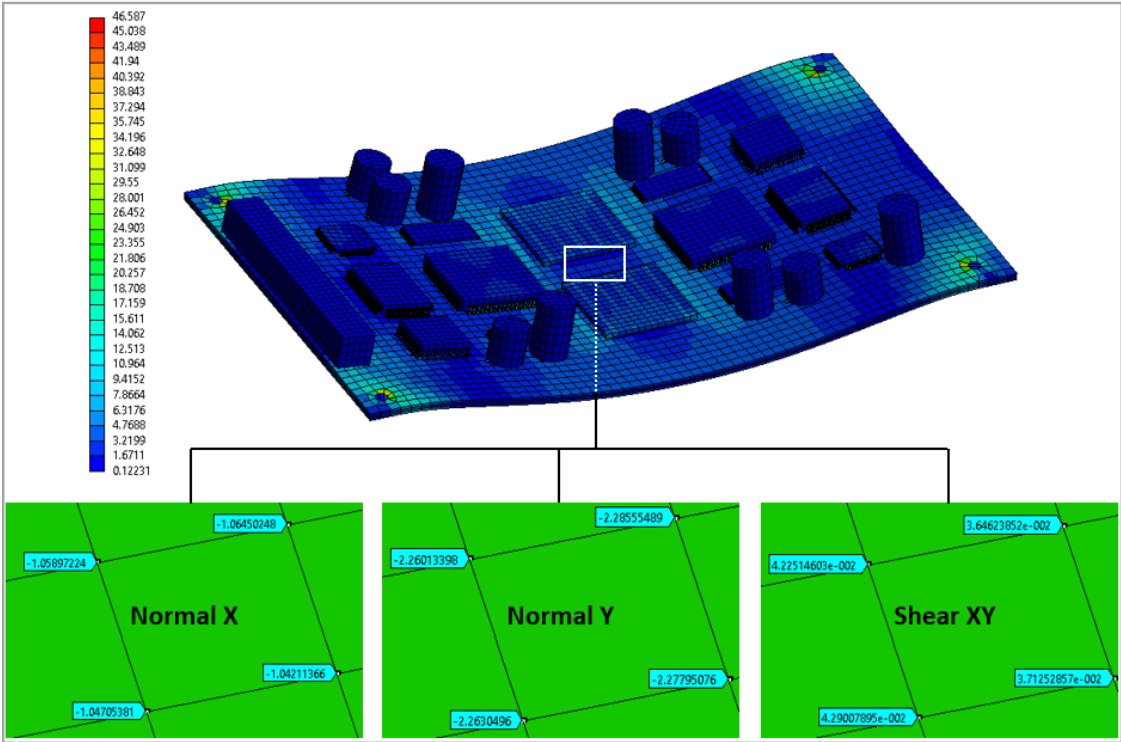
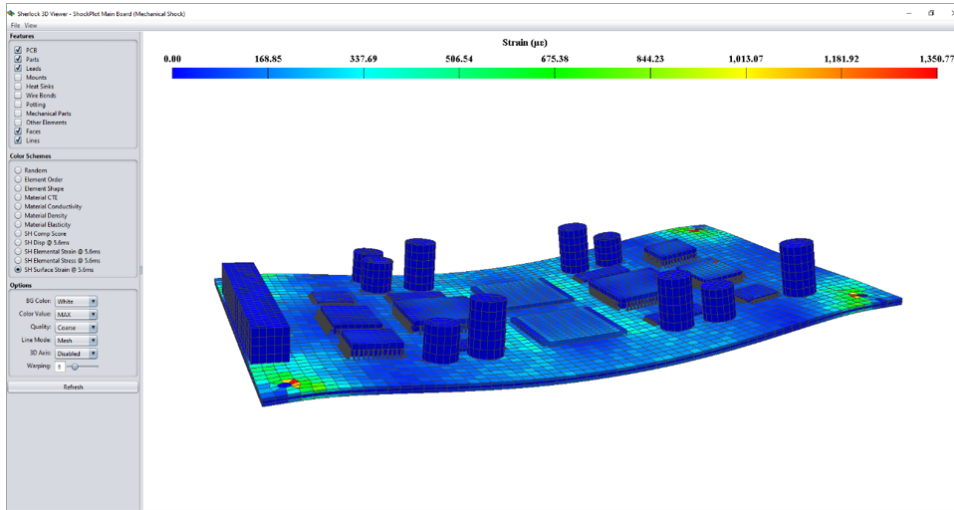
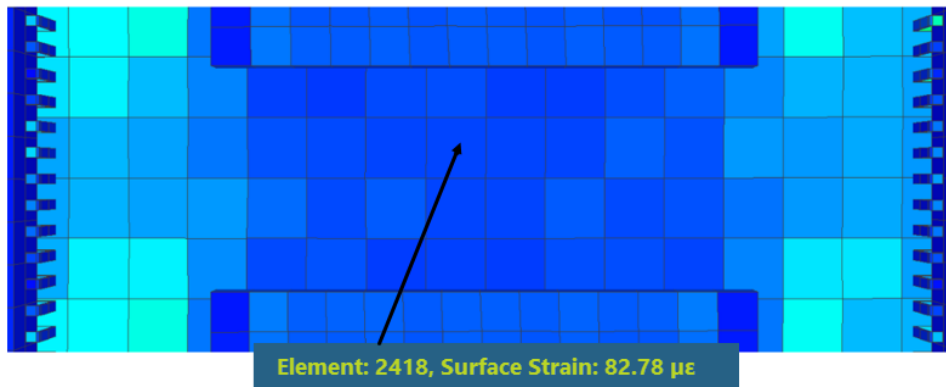


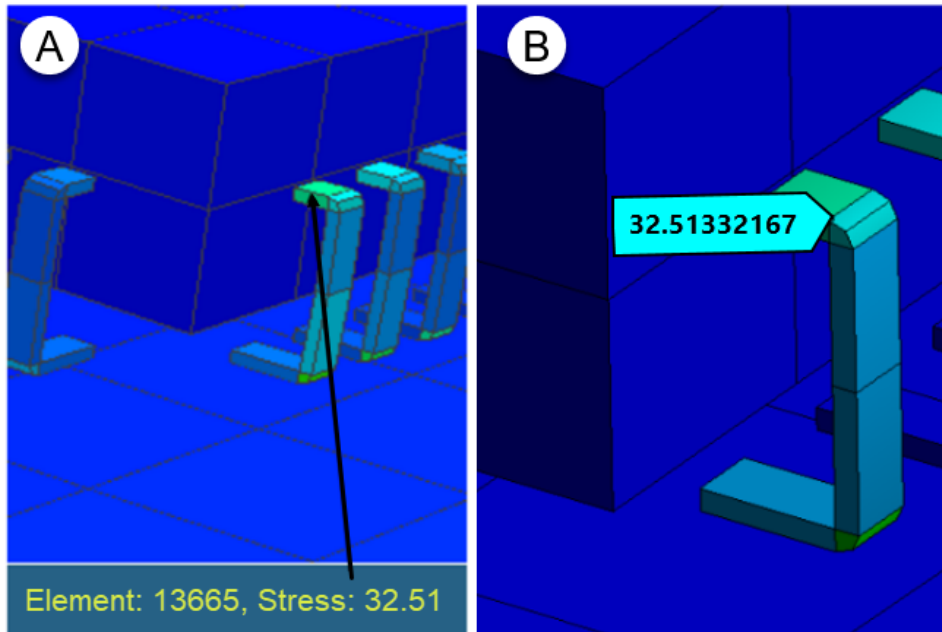
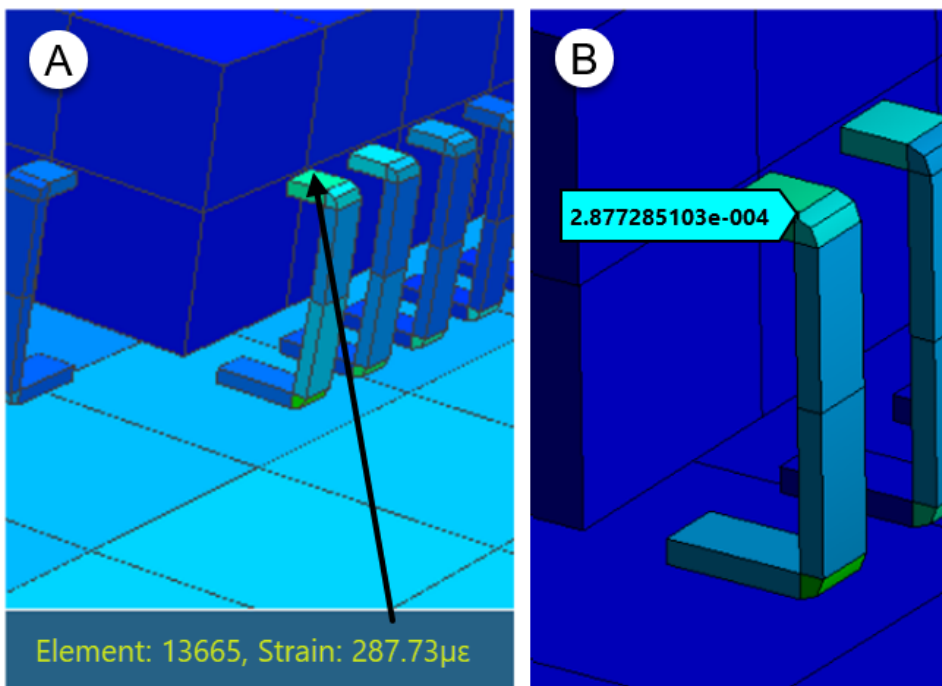
Table 6.2: PCB Strain from Unaveraged Results in Ansys Mechanical

Node	Stress Label	Stress (MPa)	Average Stress	Surface Stress	Modulus (MPa)	Strain (μɛ)			
1	X	-1.05897224	-1.053160548	1.970261723	23800	82.78410601			
2	X	-1.06450248							
3	X	-1.04705381							
4	X	-1.04211366							
1	Y	-2.26013398	-2.271672309						
2	Y	-2.28555489							
3	Y	-2.2630496							
4	Y	-2.27795076							
1	XY	4.23E-02	0.03968498						
2	XY	3.65E-02							
3	XY	4.29E-02							
4	XY	3.71E-02							

Sherlock's **3D Viewer** can display PCB strain as well as elemental Equivalent Stresses and Strains for all elements on the board. [Figure 6.30: Sherlock 3D Viewer \(p. 199\)](#) shows an overview of the board and the next figure zooms in to show the PCB strain at the center of the board. The surface strain for the board center is consistent with the result seen in the **2D Layer Viewer**.

Figure 6.30: Sherlock 3D Viewer**Figure 6.31: PCB Strain in Sherlock 3D Viewer**

The figures below show the elemental stress (top figure) and the elemental strain (bottom figure) for lead 35 of component U3. Both images show the lead-part interface strain. This feature allows you to quickly cross-verify the strain results from stress. In this case, the lead is made of copper, whose modulus is 113 GPa. For an elemental stress of 32.51 MPa, elemental strain will be $287.7\mu\epsilon$ as shown in the figures.

Figure 6.32: Elemental Stress at Lead 35, of U3 (A: Sherlock, B: Mechanical)**Figure 6.33: Elemental Strain at Lead 35, of U3 (A: Sherlock, B: Mechanical)**

6.9. Validation

Validation with robust experimental testing is currently being completed for this analysis. As soon as results have been consolidated, they will be published in this documentation.

6.10. References

1. IPC-9704 Guideline Document. (2012). <https://www.jedec.org/standards-documents>
2. JEDEC Standards. (2016). *Board Level Drop Test Method of Components for Handheld Electronic Products* (JESD22-B111A).

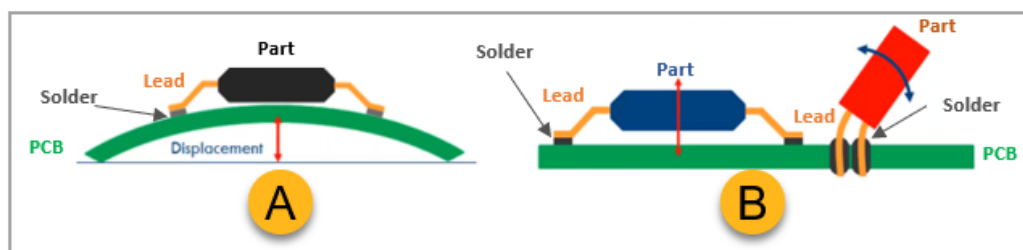
Chapter 7: Harmonic Vibration Analysis

Introduction

Sherlock is designed to run structural analyses on electronic assemblies and generate life predictions for the electronic components. This chapter explains the theory behind Sherlock's reliability calculations for an electronic assembly subjected to harmonic vibration.

When making reliability predictions, Sherlock considers two failure mechanisms: Solder Failure and Lead Failure. During a harmonic event, the electronic board can be subjected to bending loads, straining the solder which leads to solder failure (A in [Figure 7.1 \(p. 203\)](#)). Vibration loads can also bend leads, possibly causing them to fail (B in [Figure 7.1 \(p. 203\)](#)). Sherlock uses techniques like those developed by [Steinberg \(p. 227\)](#) to predict solder joint failure based on board surface strain during vibration. Lead failure predictions, on the other hand, employ equivalent element strain using the Basquin equation. The application of these theories in Sherlock's predictions will be explained in the sections that follow.

Figure 7.1: (A) Solder Failure, (B) Lead Failure



All electronic assemblies experience vibration throughout their lifecycles. The amplitude and frequency at which a printed circuit board (PCB) and electronic components vibrate depends on a number of factors such as the field of application, the mass of the electronic system, the properties of the materials used in the systems, and corresponding support systems, mounting type, and so on. In the aerospace industry, electronics are subjected to a frequency spectrum from 3 Hz to 5000 Hz with accelerations as high as 30 G for missiles ([Steinberg, 2000 \(p. 227\)](#)). Likewise, the automobile and transport industry see accelerations as high as 20 G ([Steinberg, 2000 \(p. 227\)](#)). With electronic systems prevalent in all industries and continually growing in number, it becomes crucial to analyze a system's response to both sinusoidal (harmonic vibration) and random vibration at a fast pace during the early design stage.

When designing electronic systems for high-reliability products, it's crucial to understand the effects of vibration on PCB bending, solder joint fatigue, and lead wire fatigue. The Harmonic Vibe module in

Ansys Sherlock gives you the tools to make fatigue-related failure predictions for both solder joints and leads under periodic loads.

Note:

This document does not address chassis design which can be critical to the mechanical robustness of an electronic system. A poorly designed chassis can subject the circuit board to additional mechanical stresses beyond the normal mechanical response.

Chapter topics:

- [7.1. Harmonic Vibe in Sherlock](#)
- [7.2. Damage Indicator- Harmonic Vibration](#)
- [7.3. Reliability Calculations in Sherlock](#)
- [7.4. References](#)

7.1. Harmonic Vibe in Sherlock

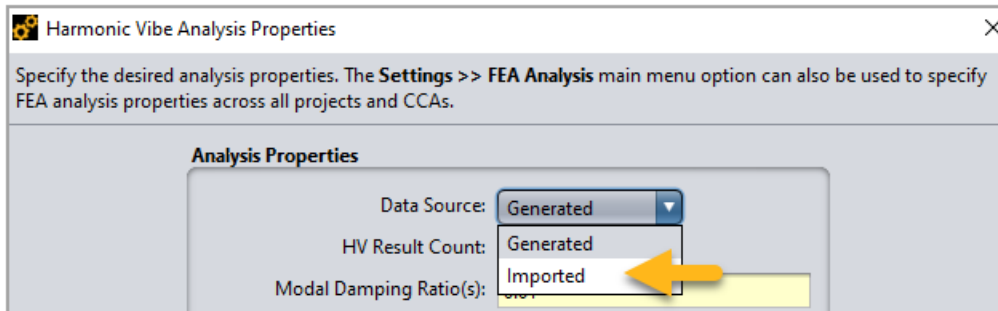
The Harmonic Vibration analysis in Sherlock consists of three parts:

1. **Pre-Processing**, which entails preparing the CCA (Circuit Card Assembly) for a Finite Element (FE) analysis.
2. **Solving**, where Sherlock uses the FE solver (Ansys by default) for solving the model by modal superposition technique.
3. **Post-Processing**, where Sherlock uses the FE results for the reliability calculations

A Sherlock project begins by importing an ECAD file. Currently, Sherlock supports:

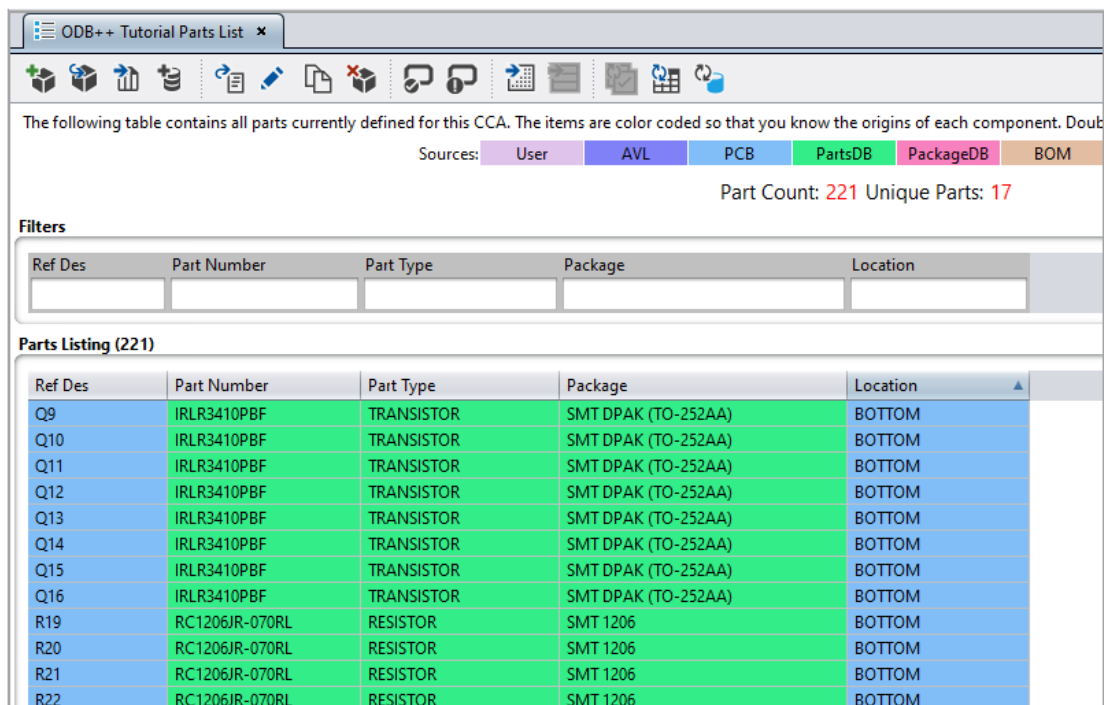
- Ansys EDB file
- ODB & ODB XML Archive
- IPC-2581 Archive
- CADIF Archive
- Eagle Archive
- GDSII files

The typical workflow looks like this: You import the ECAD file and enter the input data to configure the FE, and then Sherlock carries out the Harmonic Vibration analysis using the Ansys solver and then post-processes the results to score the board components based on their risk of failure (for other supported solvers, refer to [FEA Engine in the Sherlock User's Guide](#)). You can also export the CCA geometry from Sherlock to Ansys Mechanical where you can open the model for external meshing as well as solving. Once solved, you can import the Ansys result file (.rst) back into Sherlock by setting the **Data Source** to **Imported** (see [Figure 7.2 \(p. 205\)](#) below.) Once the results have been imported, you can task Sherlock to generate the reliability predictions.

Figure 7.2: Data Source Selection

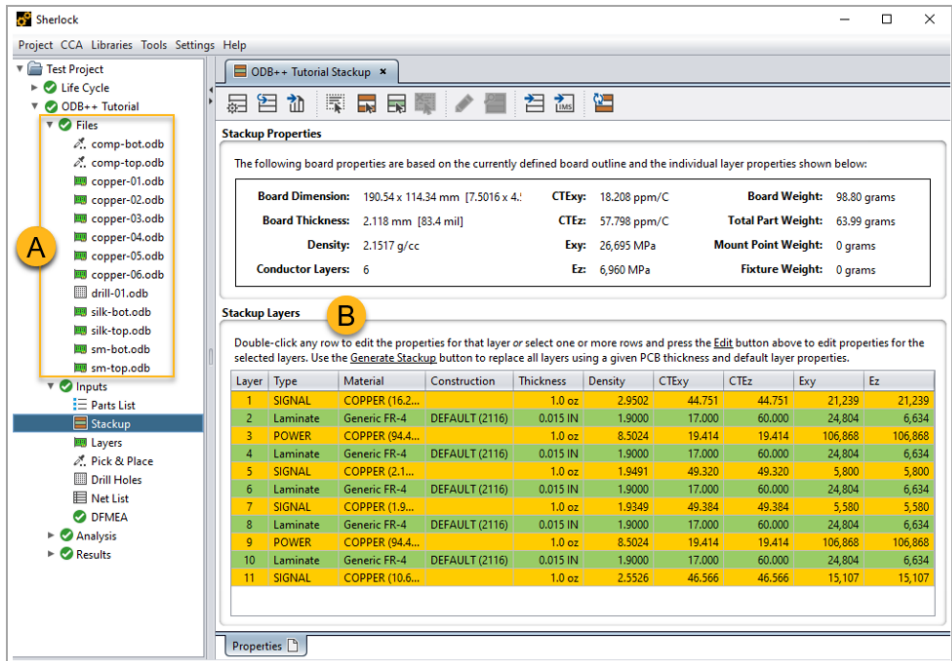
Sherlock automatically reads the ECAD file and extracts information on the parts and the printed circuit board (PCB). The user, on the other hand, defines the analysis inputs such as the [reliability requirements](#) (p. 206), the [loading conditions](#) (p. 208) (Harmonic Vibe Event definition), [mesh properties](#), and [material properties](#) (p. 210).

Sherlock employs a comprehensive Part Library which Ansys updates on a regular basis. (See [Part Library in the Sherlock User's Guide](#)). With the part information (specifically, the part number), Sherlock automatically pulls all the relevant Part information from the Library. This information can then be accessed through the Part Editor which you can launch from the Parts List. See [Update Parts List from Part Library in the Sherlock User's Guide](#) for instructions on how to update the parts from the Sherlock Parts Library.

Figure 7.3: Parts List in Sherlock

Sherlock's Layer Viewer allows you to examine many facets of the PCB such as traces, drill holes, card cutouts, the circuit card outline, the types of mount points, and their locations. Trace and drill definition files can be viewed from **Files** under the CCA as shown below (A in [Figure 7.4](#) (p. 206)). The PCB stackup, also extracted from the ECAD file, can be accessed from the Stackup table (B). Sherlock uses the Rule of Mixture for calculating PCB material properties.

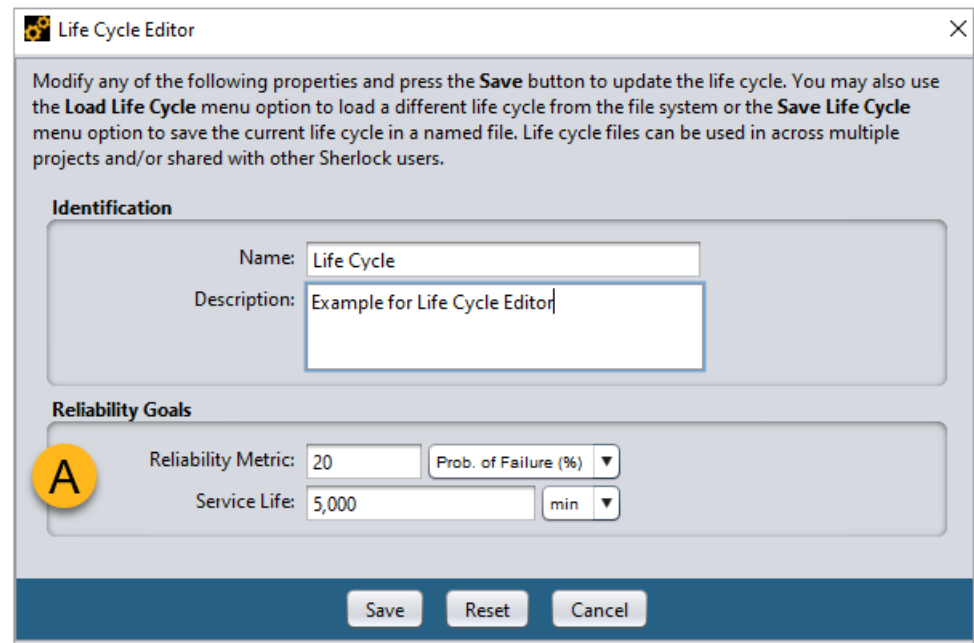
Figure 7.4: PCB Stackup



7.1.1. Life Cycle Reliability Goals

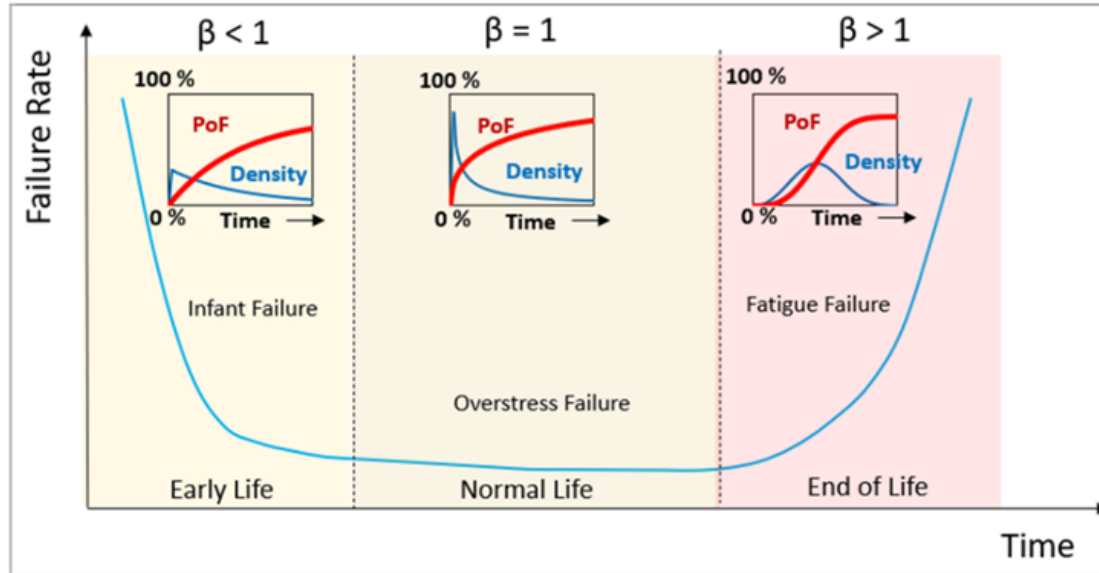
Life Cycle Reliability Goals are the user-defined reliability requirements an electronic system must meet in its lifetime. In Sherlock, the **Reliability Goals** section of the **Life Cycle Editor** (A, in [Figure 7.5 \(p. 206\)](#)) allows you to enter the expected **Service Life** and **Reliability Metric** of the system. Sherlock uses these values in *post-processing* (p. 225) to calculate damage. From this, Sherlock assigns a score to each component by comparing its probability of failure with the Reliability Goal.

Figure 7.5: Life Cycle Editor



Reliability, in general, is defined as the probability that an electronic device will perform its required function when subjected to a specific condition for a specified period of time. The failure rate of an electronic product is generally described by the bathtub curve, as shown in Figure 7.6 (p. 207). The curve describes the rate at which the product fails with respect to time.

Figure 7.6: Bathtub Curve



In the initial phase of the product, failures are mostly associated with material defects or issues in the manufacturing processes. Though failure in this early stage is usually high, over time the rate of failure decreases. This initial phase is called the infant mortality stage. The stage that follows is called normal life. The failure rate is almost constant during the normal life phase of the product. Typically, failures occurring in this phase are random in nature and are usually caused by overstress conditions. Towards the end of the product's life, the failure rate begins to creep upward. Failures during this phase are caused by fatigue-induced wear-out.

In the field of electronics, the failure distribution can be captured using the Weibull distribution (Equation 7.1 (p. 207)). Sherlock currently uses a two-parameter Weibull distribution. The two parameters in the distribution are the shape factor (β) and the scale factor (η).

$$F(t) = \frac{\beta}{\eta} \left(\frac{t-\gamma}{\eta} \right)^{\beta-1} e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} \quad (7.1)$$

where

β is the Weibull slope

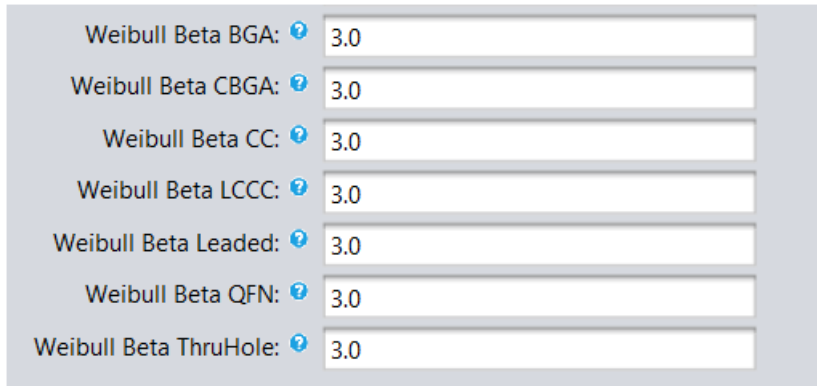
η is the scale parameter

γ is the location parameter ($\gamma=0$, as Sherlock uses the two-parameter Weibull)

Depending on the value of Weibull beta, the distribution can represent any of the three stages described by the bathtub curve in Figure 7.6 (p. 207). Because of the random nature of failure during the normal life phase, the failure distribution can be represented by a Weibull beta of 1. Anything lower than 1 represents the infant mortality stage, and anything greater than 1 represents wearout failure. Shock failure is representative of random failure, while vibration failure is associated with fatigue. For this reason, Sherlock uses a Weibull Beta of 1 for Shock and 3 (by default) for its vibration analysis

(Harmonic and Random). You can change this default beta value to any value you choose within the Solder Editor ([Figure 7.7 \(p. 208\)](#)). For any package type which is not listed in the Solder Editor, Sherlock uses a beta value of 3.0.

Figure 7.7: Weibull Beta in Solder Editor



Weibull Beta BGA:	3.0
Weibull Beta CBGA:	3.0
Weibull Beta CC:	3.0
Weibull Beta LCCC:	3.0
Weibull Beta Leaded:	3.0
Weibull Beta QFN:	3.0
Weibull Beta ThruHole:	3.0

The Weibull reliability function for a two-parameter Weibull distribution is given by [Equation 7.2 \(p. 208\)](#), and the probability of failure can be recognized as $1 - \text{Reliability}(t)$. Sherlock uses a component's time-to-failure from FEA strain as its characteristic life (life corresponding to 63.2% probability of failure). Based on that data point and the Weibull beta, Sherlock determines the probability of failure during the user-defined Service Life of the CCA.

See [Damage Calculation \(p. 223\)](#) to learn more about how Sherlock constructs the life plot for individual components. You will also learn how to interpret the plot.

$$\text{Reliability}(t) = e^{-\left(\frac{t}{t_0}\right)^\beta} = e^{-(\text{damage})^\beta} \quad (7.2)$$

For more information on [damage calculation \(p. 223\)](#) from the finite element (FE) strain result, see the [Reliability Calculation section \(p. 220\)](#) of this document.

7.1.2. Harmonic Vibe Events

In Sherlock, Harmonic Vibe Events define the loads applied to the electronic assembly. The load, in terms of acceleration and frequency, define the Harmonic Profile and can be edited in the **Harmonic Profile Editor** (click the **Edit Profile...** button to open the editor, A in [Figure 7.8 \(p. 209\)](#)). The relevant stresses are those that may accelerate one or more of the potential fatigue failures during the analysis. Other parameters you must define for Sherlock's reliability prediction are (refer to B in [Figure 7.8 \(p. 209\)](#)):

- The **Duration**: The time duration the electronic system is exposed to the load event.
- **# of Cycles**: The number of times the event load is applied to the board.
- **Sweep Rate**: The rate at which the load is applied.

Figure 7.8: Harmonic Event Editor

Harmonic Vibe Editor

Modify any of the following properties and press the **Save** button to update the current Harmonic Vibe.

Identification

Name: 5 - Harmonic Vibe

Description:

Harmonic Vibration Settings

Duration: 10 ms

of Cycles: 100 DUTY CYCLE

Sweep Rate: 1 octave/min

Harmonic Load Settings

PCB Orientation: XY Angle 0 YZ Angle 0

Profile Type: Uniaxial

Harmonic Profile

Load Direction: X 0 Y 0 Z -1

Default Profile

Load (G)

Frequency (Hz)

Load Profile ... Edit Profile ... Save Profile ...

Save Reset Cancel

For more information on how Sherlock uses **Duration**, **# of Cycles**, and the **Sweep Rate** when predicting failure, see [Reliability Calculation \(p. 227\)](#) and [Damage Calculation \(p. 223\)](#) sections of this document.

Loads in Sherlock can be applied as uniaxial, where the board is vibrated along one of the three principal axes, or as triaxial, where the board is vibrated along all three directions at the same time. For triaxial loading conditions, you must specify the load in the three principal directions as shown (C, [Figure 7.8 \(p. 209\)](#)). You can also apply loads at any angle to any of the three-principal axis by orienting the PCB accordingly. When PCB orientation is provided, the applied load gets resolved along the principal axes. More information about PCB Orientation in Sherlock can be found under [Load Direction and PCB Orientation in the Sherlock User's Guide](#). Sherlock also allows you to define multiple

Harmonic Vibration Events. With multiple Events defined, Sherlock's life predictions are based on the total damage which is the sum of damages from individual events.

7.1.3. Geometry, Mesh, and Material Information

A mechanical analysis of any electronic system should include its casing or housing. However, Sherlock does not model either of those when running an analysis—although, you can effectively set up and solve the model in Ansys Mechanical and then import the results into Sherlock to generate failure predictions. Aside from this limitation, Sherlock provides all the tools you need to convert an ECAD model into an MCAD. Sherlock's intuitive toolset (thoroughly explained in the [Sherlock User's Guide](#)) allows you to edit the geometry and the materials quickly. This allows you to run a board-level study early in the design process and optimize the design with confidence.

When running a Harmonic Vibration analysis, as in the case of any mechanical analysis, Sherlock provides the framework for you to set up the FE (finite element) model and then solves it in Ansys Mechanical APDL. Besides Ansys, Sherlock also supports ABAQUS and NX NASTRAN solvers.

Correctly factoring in the material properties, the mass of the system, and the boundary conditions is obviously essential to running an accurate analysis. In Sherlock, you can set the material properties for the printed circuit board and the parts can in the [Stackup](#) and the [Parts List](#) respectively. You can define boundary conditions in Sherlock using the **Edit mount point properties** dialog ([Figure 7.9 \(p. 211\)](#)). The mount point type can be adjusted as needed (A, [Figure 7.9 \(p. 211\)](#)) and its corresponding FE constraints (B) can be adjusted as well under **FEA Settings**.

Figure 7.9: Mount Point Properties

Edit mount point properties

Enter the desired properties for the mount point:

Mount Point Properties

Mount Point ID: MP3

Mount Point Type: Mount Pad

Mount Point Units: Mount Hole

Mount Point Side: Mount Pad

Mount Point Height: Standoff

Mount Point Material: DEFAULT

Mount Point State: ENABLED

Weight (gram): 0.000e+0

Mount Point Shape

Shape Type: Circular

Circle Diameter: 2

of Nodes: 6

Center X: -88.9

Center Y: 50.8

Rotation (degrees): 0.0

FEA Settings

Boundary Pt(s): Outline

FEA Constraints: ☒ X-axis translation
☒ Y-axis translation
☒ Z-axis translation

Chassis Material: ALUMINUM

Save Reset Cancel

Within Sherlock, it is possible to set up the necessary inputs for mesh generation and run the Harmonic analysis using the Ansys Mechanical APDL solver in background. Besides the Ansys solver, Sherlock also supports ABAQUS and NX NASTRAN solvers. Sherlock uses Ansys' meshing engine to mesh all bodies in the assembly, except for leads which are meshed with Sherlock's native algorithm.

Figure 7.10: Mesh Controls in Sherlock

PCB Modeling	Mesh Type: Bonded
Trace Modeling	Modeling Regions: DISABLED
Mount Points	PCB Model: Uniform
Drill Holes	# of PCB Materials: 100
Part Modeling	Element Order: First Order (Lin...)
Lead Modeling	Max Mesh Size: 4 mm
Wire Bonds	Vertical Mesh Size: 1 mm
Heat Sinks	Quads Preferred: YES
Potting Regions	
Mechanical Parts	

When solving within Sherlock, contacts between different parts and surfaces are established using constraint equations (CE). When setting up the analysis within Ansys Mechanical, you can define any type of contact which is applicable for a Harmonic analysis. For meshing the leads/solder balls with higher mesh density, the electronic system must be exported into Ansys Mechanical. For more information on how to export an FE model from Sherlock, see the [Ansys Workbench Integration](#) section of the *Sherlock User's Guide*.

7.1.4. Finite Element Analysis

Once you have entered the necessary inputs, Sherlock carries out the Harmonic Vibration analysis using a modal superposition technique. More about the procedure is available in the [Ansys Mechanical APDL Structural Analysis Guide](#) (p. 227). Likewise, the procedure used in ABAQUS and NX Nastran for harmonic vibration can be found in their respective documentation. As pointed out earlier (p. 205), Sherlock can import analysis results from other applications.

Once the analysis is complete, Sherlock uses the results to make reliability predictions. The results not only appear in table form, they are also displayed visually in the 2D Layer Viewer and the 3D Results Viewer. All the modules in Sherlock use SI units of millimeters as the base unit. For this reason, the FEA model must be solved in a consistent millimeter unit system. For more information on how to set up a board for harmonic analysis and how to import the result file, refer to [FEA- Harmonic Vibration in the Sherlock User's Guide](#).

Sherlock's vibration simulation uses modal-based damping which you can specify using the **Modal Damping Ratio(s)** field in the **Analysis Properties** panel (A in [Figure 7.11](#) (p. 213)). When a single value is provided as an input, all modes will have the same value for the modal damping ratio. When multiple values are provided separated by commas (example: 0.025,0.020,0.015), then the respective values are used in order, starting with the first mode (example: MDAMP,1,0.025 \$ MDAMP,2,0.02 \$ MDAMP,3,0.015). If there are five modes considered in the analysis but only three damping ratios are provided as input, user-provided values are used for the first three modes. For the remaining fourth and fifth modes, the last input value (that is, the value provided for the third mode) will be used (example: MDAMP,1,0.025 \$ MDAMP,2,0.02 \$ MDAMP,3,0.015, \$ MDAMP,4,0.015, \$ MDAMP,5,0.015).

Figure 7.11: Harmonic Vibe Analysis Properties

Harmonic Vibe Analysis Properties

Specify the desired analysis properties. The **Settings >> FEA Analysis** main menu option can also be used to specify FEA analysis properties across all projects and CCAs.

Analysis Properties

A

Data Source: Generated

HV Result Count: 1

Modal Damping Ratio(s): 0.025

Temperature: 25 C

Part Validation: ENABLED

Require Material Assignment: ENABLED

Filter By Event Frequency: DISABLED

Harmonic Vibe Events

On The Road: ☒ 5 - Harmonic Vibe

PCB Modeling

Trace Modeling

Mount Points

Drill Holes

Part Modeling

Lead Modeling

Wire Bonds

Heat Sinks

Potting Regions

Mechanical Parts

Mesh Type: Bonded

Modeling Regions: DISABLED

PCB Model: Uniform

of PCB Materials: 100

Element Order: First Order (Lin...)

Max Mesh Size: 4 mm

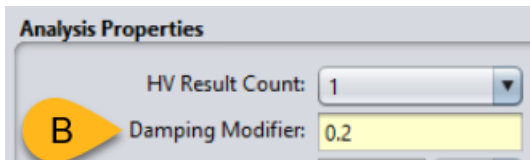
Vertical Mesh Size: 1 mm

Quads Preferred: YES

Save & Run Save Reset Cancel Help

Note:

Prior to Sherlock version 2022 R2, damping values were based on the Damping Modifier.



In versions prior to 2022 R2, Sherlock uses calculated, modal-based damping based on [Equation 7.3 \(p. 214\)](#) for its vibration analysis, and its scale can be edited using the **Damping Modifier** (B in image above). The **Damping Modifier** increases or decreases the damping of the circuit card assembly. Setting the **Damping Modifier** to 0.1, for example, represents very little damping and is akin to a rigid mounting. A damping modifier of 1.0 is more representative of a chassis-mounted circuit card assembly and will lower the transmissibility. The Damping Modifier relates to the Modal Damping Ratio by the following equation:

$$D_i = D_{\text{Sherlock}} * f^{\left(\frac{-1}{n_f+1}\right)} \quad (7.3)$$

where:

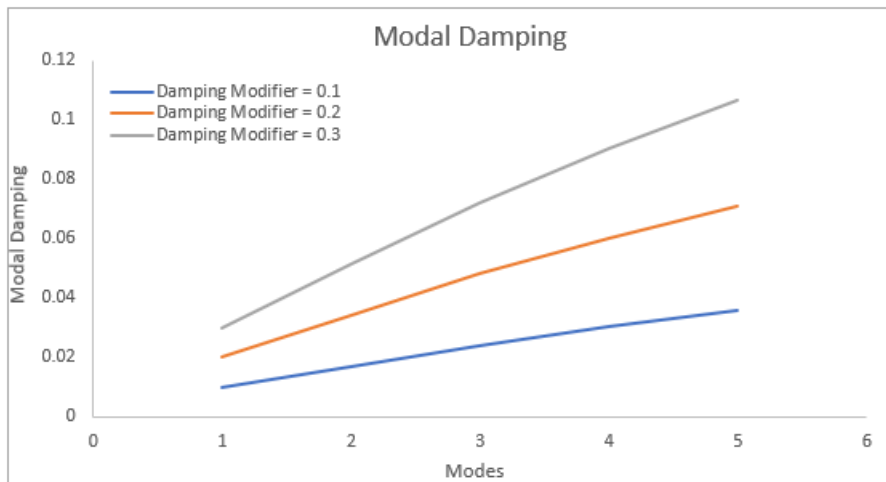
D_i is the Modal Damping Ratio for the i^{th} mode and is automatically calculated by Sherlock which is then used by the Mechanical APDL solver as **MDAMP**.

D_{Sherlock} is the Damping Modifier used in Sherlock.

f is the natural frequency corresponding to the mode number n_f .

[Figure 7.12: Modal Damping \(p. 214\)](#) shows how damping is affected by different damping modifiers. In this figure, the first five modes assume the natural frequencies of 100 Hz, 200 Hz, 300 Hz, 400 Hz and 500 Hz. For more information on damping, refer to [Steinberg \(2000\) \(p. 227\)](#).

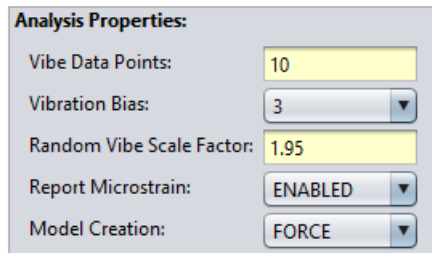
Figure 7.12: Modal Damping



For a harmonic response analysis, a cluster number is used to identify points around the natural frequency when running a vibration analysis. In most commercially available FE tools, the cluster number can be modified. In Sherlock, the number of steps for the analysis is controlled by **Vibe Data Points**

(see [Figure 7.13 \(p. 215\)](#)). **Vibration Bias** determines how scattered the points should be near the natural frequencies. To find the panel shown in [Figure 7.13 \(p. 215\)](#), click **Settings > FEA Analysis** in Sherlock's main menu.)

Figure 7.13: Vibe Data Point

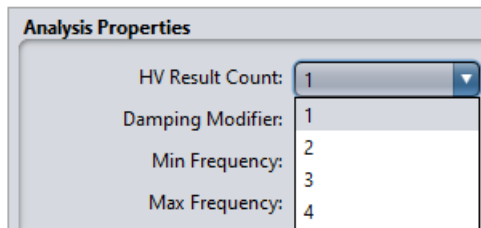


Analysis Properties:

Vibe Data Points:	10
Vibration Bias:	3
Random Vibe Scale Factor:	1.95
Report Microstrain:	ENABLED
Model Creation:	FORCE

Sherlock sweeps through the frequency range specified in harmonic event definition and computes the component damage at its modal peaks. The number of modal peaks Sherlock considers in the frequency sweep is controlled by **HV Result Count** under **Analysis Properties** as shown in [Figure 7.14 \(p. 215\)](#). (This setting is found in the **Harmonic Vibe Analysis Properties** dialog. See [\(p. 213\)](#).) Finally, total damage is computed for each component from the damage incurred at its individual modal peak. Reliability predictions for the components are then computed based on the total damage.

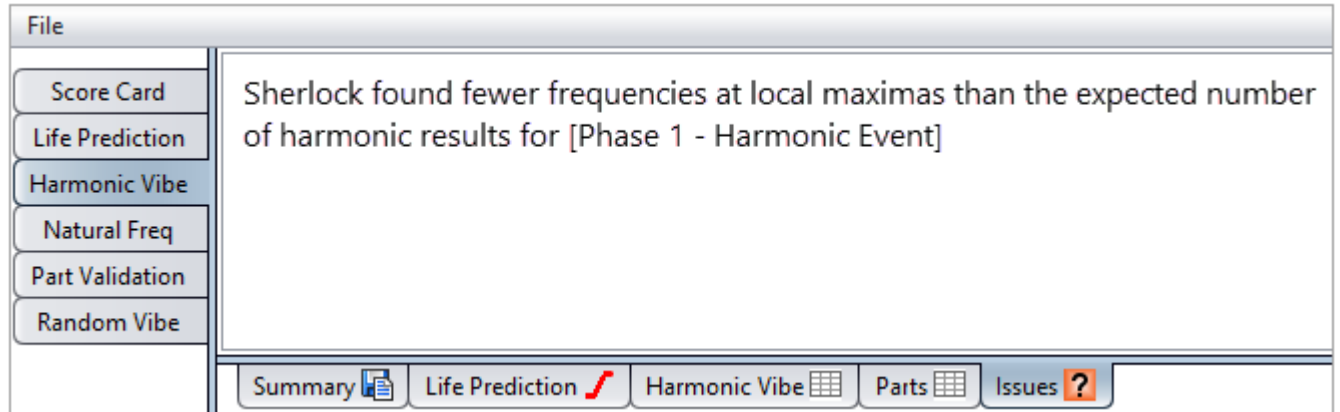
Figure 7.14: HV Result Count



Analysis Properties

HV Result Count:	1
Damping Modifier:	1
Min Frequency:	2
Max Frequency:	3
	4

If the number of modes in a given frequency range is lower than the number of modes requested in the **HV Result Count**, Sherlock will state it under the **Issues** tab in the Results Viewer ([Figure 7.15 \(p. 216\)](#)).

Figure 7.15: Issues Tab**Note:**

In versions prior to 2021 R2, damages from the first mode alone were considered, even though there might be components on the board experiencing higher damage at other modal frequencies.

7.2. Damage Indicator- Harmonic Vibration

Sherlock uses two damage indicators for its vibration analysis: PCB Surface Equivalent Strain (as shown in Figure 7.16 (p. 217)) for predicting reliability for packages without leads and Elemental Equivalent Strain for packages with leads, which includes solder balls.

Both the strain values are calculated as stress over the modulus of the underlying element. Failures during vibration are associated with high cycle fatigue, and the strains on the solder joints during high cycle vibration are generally within its elastic limit. For this reason, Sherlock considers linear elastic properties for all the materials during the analysis.

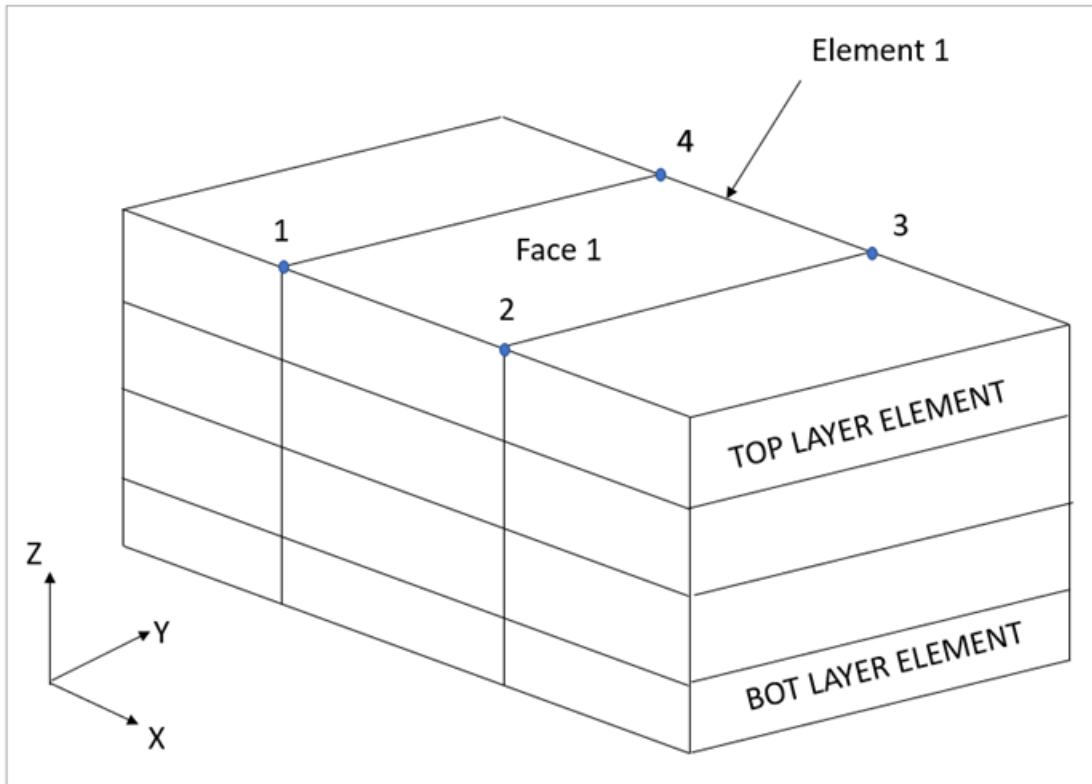
For packages without leads, Sherlock uses a technique similar to that of Steinberg's method. Steinberg relates the package failure to critical displacement, while Sherlock associates the failure with board bending strain driven by the critical displacement. PCB surface equivalent strain, a good indicator of bending strain on the board surface, was chosen as the damage indicator for packages without leads. For packages with leads, element equivalent strain is used in the standard Basquin equation for calculating cycles-to-failure (refer to the equations and Figure 7.16 (p. 217) below).

$$\sigma_n^{Face\ Avg.} = \sqrt{\sigma_X^2 + \sigma_Y^2 - \sigma_X \sigma_Y + 3\sigma_{XY}^2} \quad (7.4)$$

where n is the element number

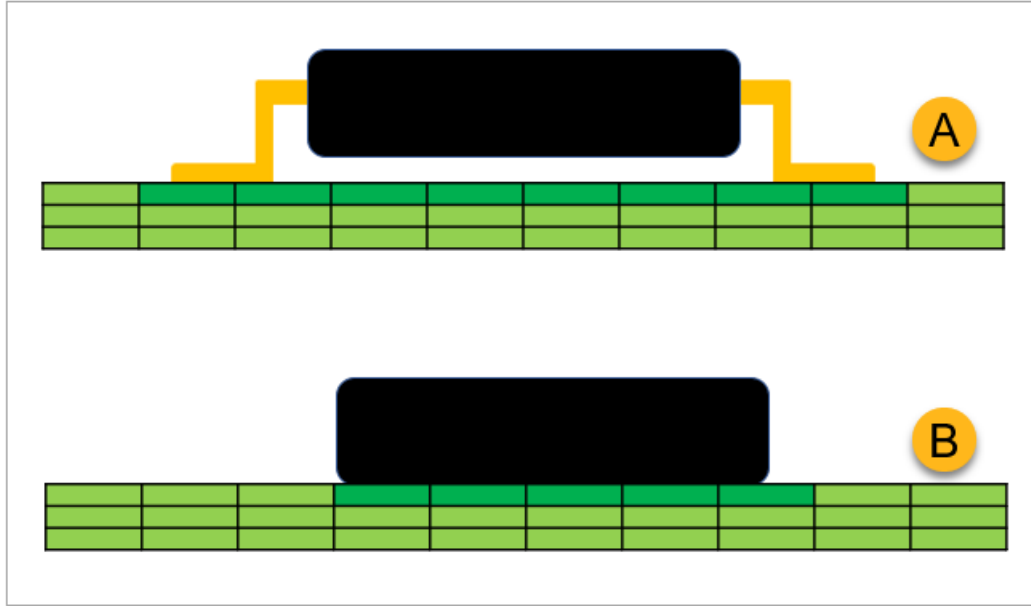
$$\sigma_{X,Y,XY} = Avg \left(\sigma_{X,Y,XY}^{UnAvg, Nodal} \right) \quad (7.5)$$

$$\sigma_{X,Y,XY}^{UnAvg, Nodal} = \sqrt{Re \left[\sigma_{X,Y,XY}^{UnAvg, Nodal} \right]^2 + Img \left[\sigma_{X,Y,XY}^{UnAvg, Nodal} \right]^2} \quad (7.6)$$

Figure 7.16: PCB Surface Equivalent Stress

7.2.1. PCB Surface Strain

PCB surface strains (PCB surface equivalent strain) are computed at the footprint of every component on the board. If a part has leads, the elements under its footprint as well as the leads are used (A in [Figure 7.17 \(p. 218\)](#)). If a part does not have leads, the elements under its footprint are used (B in [Figure 7.17 \(p. 218\)](#)). In [Figure 7.17 \(p. 218\)](#), elements under the footprint of the parts are *dark green*, and all other elements of the PCB are *light green*.

Figure 7.17: Elements considered for PCB Surface Equivalent Strain

7.2.2. Lead Strain

Elemental equivalent strain (Equation 7.7 (p. 218)) is used as a damage indicator for leads and parts. If a component has leads, the reliability prediction is always made using the elemental strain, not the PCB surface strain.

$$\epsilon_n^{\text{Ele.Mean}} = \frac{\sigma_n^{\text{Ele.Mean}}}{E_n} = \frac{\sqrt{\text{Re}(\sigma_n^{\text{Ele.Mean}})^2 + \text{Im}(\sigma_n^{\text{Ele.Mean}})^2}}{E_n} \quad (7.7)$$

where

n is the element number.

$\text{Re}(\sigma_n^{\text{Ele.Mean}})$ is the real part of the Elemental Mean Von Mises Stress for element n

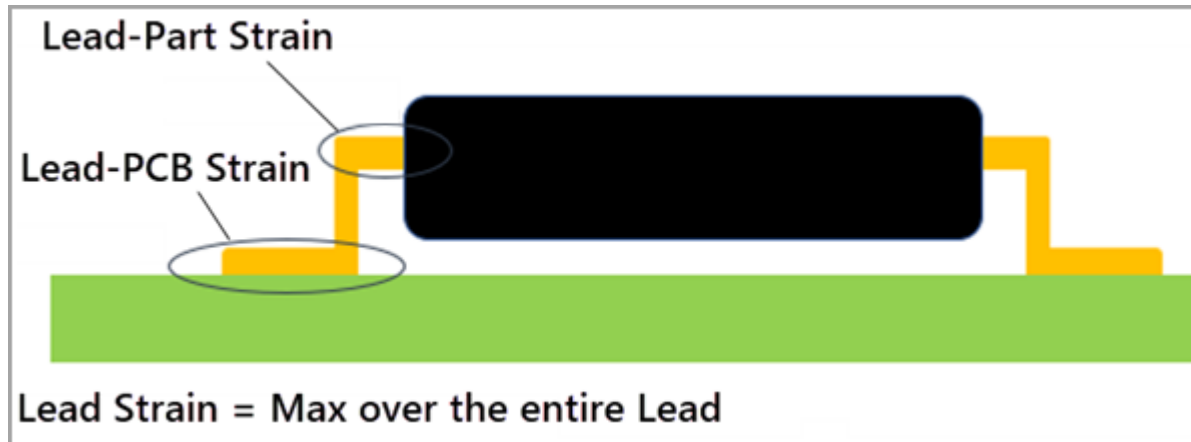
$\text{Im}(\sigma_n^{\text{Ele.Mean}})$ is the imaginary part of the Elemental Mean Von Mises Stress for element n

$\epsilon_n^{\text{Ele.Mean}}$ is the Elemental Mean Strain for element n

$\sigma_n^{\text{Ele.Mean}}$ is the Elemental Mean Von Mises Stress for element n

Lead strains are reported at three locations. These strains will be available under the **Lead** tab in the Results Viewer.

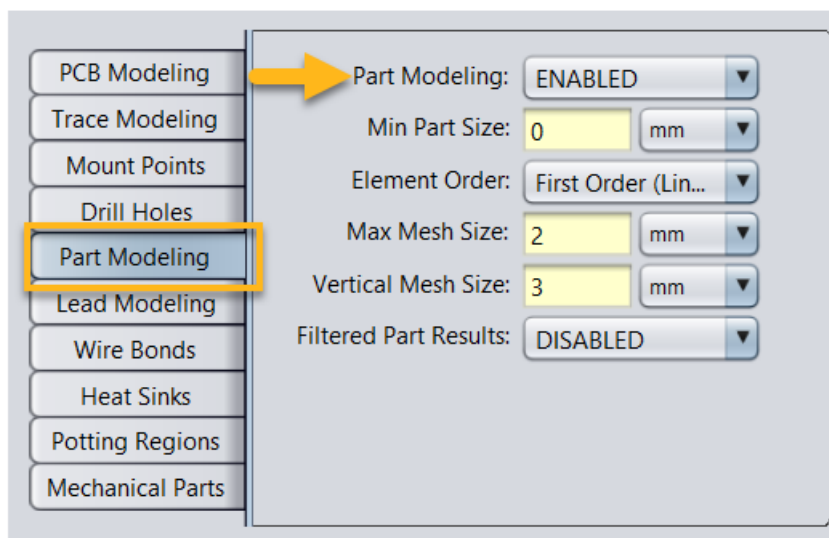
- Max Lead Strain: Maximum strain over the lead body
- Lead-PCB Strain: Maximum strain at the lead and PCB interconnect
- Lead-Part Strain: Maximum strain at the Lead and Component interconnect

Figure 7.18: Lead Strain

Sherlock identifies the elemental equivalent strain for all the elements in the lead body and reports the maximum as the **Max Lead Strain**. The maximum Lead-PCB interface strain (displayed as **PCB Strain** under the **Leads** tab in the [Results Table](#)) describes the maximum lead strain from the set of lead elements that are connected to the PCB. Likewise, maximum lead-part interface strain (displayed as **Part Strain** under the **Leads** tab in the [Results Table](#)), describes the maximum lead strain from the set of lead elements that are attached to the part. [Figure 7.18 \(p. 219\)](#) shows all the lead strain locations.

7.2.3. Part Strain

If you want Sherlock to calculate Part Strain, you must set **Part Modeling** to **ENABLED** in the **Harmonic Vibe Analysis Properties** dialog ([Figure 7.19 \(p. 219\)](#)). Parts may crack when under tension, and the failure can be captured by elemental equivalent strain. For each component, the maximum strain among all its elements is taken as the Part Strain for that component. Currently, Part Strain is displayed for user reference only. Sherlock does not use Part Strain for making predictions, such as component cracking.

Figure 7.19: Part Modeling Enabled in Harmonic Vibe Analysis Properties Dialog

7.3. Reliability Calculations in Sherlock

Sherlock makes reliability predictions, in terms of probability to failure, for all the components on a given board based on the damage indicator ([discussed in the previous section \(p. 216\)](#)), reliability metric, and life cycle details. The following discussion on reliability calculations is divided into three parts:

1. [Cycles to Failure \(p. 220\)](#) based on the damage indicators (PCB Surface Strain and Elemental Strain)
2. [Damage Calculation \(p. 223\)](#)
3. [Probability of Failure and Score \(p. 225\)](#)

7.3.1. Cycles to Failure Calculation for Packages without Leads

As indicated in the previous section, Sherlock uses board surface strain when calculating cycles-to-failure for packages without leads and uses elements equivalent strain for packages with leads. When determining vibration-induced solder failure for packages without leads, Sherlock's approach is based on techniques like those developed by [Steinberg \(2000\) \(p. 227\)](#). The main modification is where Sherlock converts a displacement-based criterion to a board-level strain criterion. Steinberg's critical PCB deflection at which a component will survive ten million cycles during a vibration event is given by the equation below:

$$Z_c = \frac{0.00022B}{chr\sqrt{L}} \quad (7.8)$$

where

B is the length of the PCB parallel to the component (in inches)

c is a component packaging constant (typically between 0.75 and 2.25, from [Steinberg \(2000\) \(p. 227\)](#))

h is the PCB thickness (in inches)

r is a relative position factor and is 1.0 when the component is located at the center of the PCB

L is the component length (in inches)

The main issue with this approach is that it is limited to simple board geometries (where the maximum deflection is always assumed to be at the center of the PCB). Although the above equation considers variables for different packaging and component positions, utilizing finite element modeling can eliminate some of the variables in the equation, such as board length (B), position factor (r), board thickness (h). [Equation 7.8 \(p. 220\)](#) can then be reduced to component-specific critical strain as shown in the equation below:

$$\epsilon_c = \frac{\zeta}{c\sqrt{L}} \quad (7.9)$$

where:

ϵ_c is a Component Critical Strain.

ζ is a Critical Strain for vibration, similar to Steinberg's critical deflection.

c is a component packaging constant (typically between 0.75 and 2.25)

L is the component diagonal length

is analogous to 0.00022B (B is the edge length of the PCB) but represents a baseline board-level strain (presented as Critical Strain in the solder profile under High-Cycle Fatigue) that is modified to accommodate component size and type. The baseline board-level strain represents the strain generated under a component of unit length at the center of the board with unit packaging constant. Sherlock uses a default value of 375 $\mu\epsilon$, assuming a worst-case scenario that puts maximum strain on the component during board bending. The value is derived from Steinberg's maximum displacement equation.

According to [Steinberg \(2000\) \(p. 227\)](#), the board bends sinusoidally (haversine) during vibration. Therefore, for a standard board length with 0.06 in thickness, the maximum deflection is given by the expression below:

$$Z_c = \frac{0.00022B}{chr\sqrt{L}} = \frac{0.00022*5.8}{1*0.06*1*\sqrt{1}} = 0.021267" \quad (7.10)$$

Curvature (κ) for the haversine wave is given by the following expression:

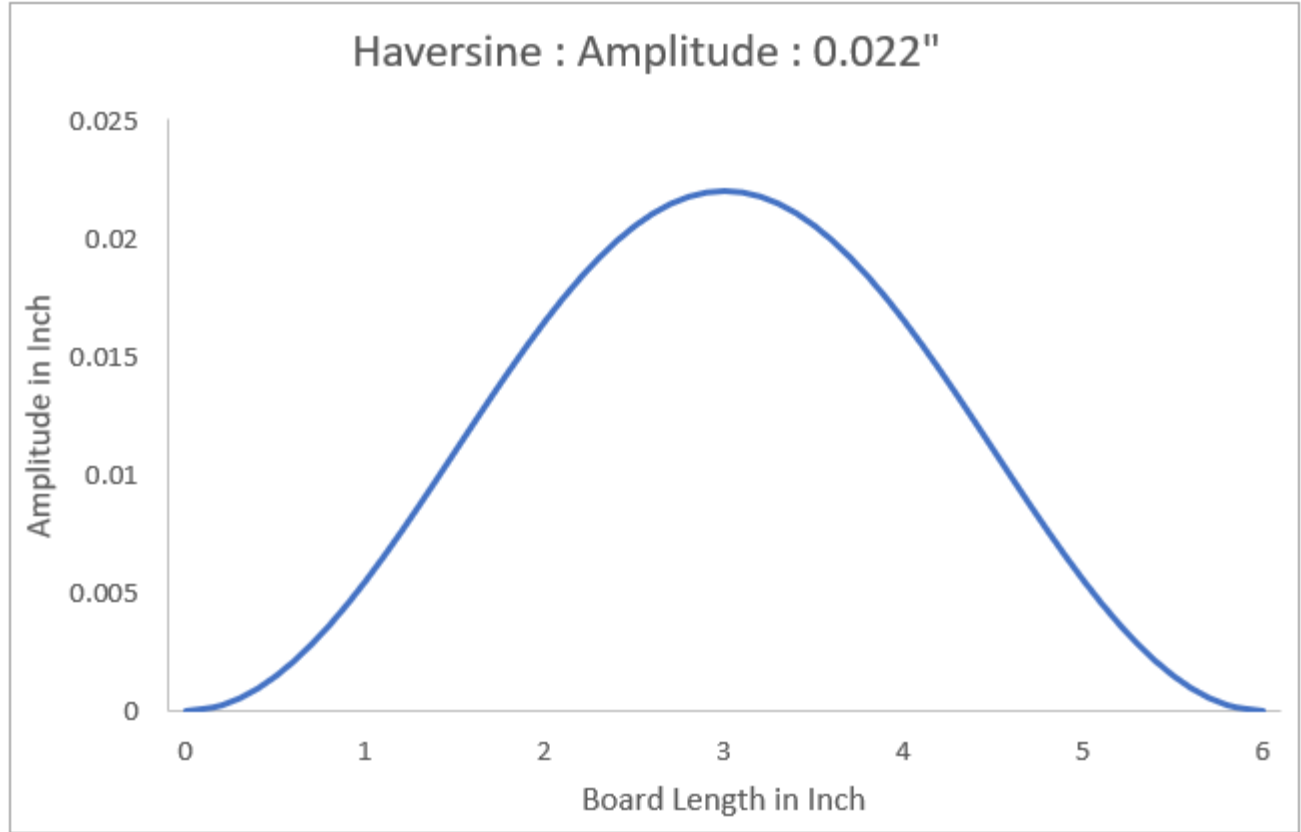
$$\kappa = \frac{2a\frac{\pi^2}{B^2}\cos\left(2\frac{\pi}{B}x\right)}{\left(1 + \left[2a\frac{\pi}{B}\cos\frac{\pi x}{B}\sin\frac{\pi x}{B}\right]^2\right)^{3/2}} \quad (7.11)$$

where:

a is the deflection amplitude

B is the board length

x is any point along the length of the board

Figure 7.20: Haversine Solution

An example of a deflection solution of a board with length of six inches and a deflection amplitude of 0.022 inches is provided in [Figure 7.20: Haversine Solution \(p. 222\)](#). The curvature for displacement calculated in [Equation 7.10 \(p. 221\)](#) is shown below.

$$\kappa = \frac{2 * 0.021267 \frac{\pi^2}{5.8^2} \cos\left(2 \frac{\pi}{5.8} \left(\frac{5.8}{2}\right)\right)}{\left(1 + \left[2 * 0.021267 \frac{\pi}{5.8} \cos\frac{\pi(5.8)}{5.8} \sin\frac{\pi(5.8)}{5.8}\right]^2\right)^{3/2}} = \frac{2 * 0.021267 * \frac{\pi^2}{5.8^2}}{1} = 0.012479'' \quad (7.12)$$

In the above result, the minus sign is ignored since the direction of curvature is immaterial. Strain for the above curvature is given by [Equation 7.13 \(p. 222\)](#). (See [DoITPoMS \(p. 227\)](#) for the theory.)

$$\zeta = y \frac{1}{R} = y * \kappa = \frac{0.06}{2} * 0.012479 \cong 374 \mu\epsilon \quad (7.13)$$

where:

ζ is the surface strain due to the curvature κ

y is the distance from the neutral axis, which is half the thickness of the board

$R = \frac{1}{\kappa}$ is the Radius of Curvature

With the component critical strain for ten million cycles ([Steinberg \(2000\) \(p. 227\)](#)), the cycles to failure for the FEA computed strain values (board surface strain values) can be determined using a typical S-N curve as shown here:

$$N_{FEA} = N_c \left(\frac{\varepsilon_c}{\varepsilon_{PCB\ Surface}^{FEA}} \right)^{FEA\ Power} \quad (7.14)$$

where:

N_{FEA} is the predicted number of cycles to failure (CTF) for ε_{FEA} .

N_c is 10E6, typical stress reversals seen in a harmonic vibration environment.

ε_c is the component critical strain value as explained in [Equation 7.9 \(p. 220\)](#).

$\varepsilon_{PCB\ Surface}^{FEA}$ is the maximum PCB strain at the footprint of a given component.

FEA Power is the SN curve fatigue exponent slope (the value can be adjusted under the **High Cycle Fatigue** tab in the Solder Profile Editor) and is dependent on the solder alloy. This exponent is derived from correlation studies and physical testing data.

7.3.2. Cycles to Failure Calculation for Packages with Leads

When leads (or solder balls in BGAs) are enabled in Sherlock, the software uses the fatigue coefficient and the FEA computed elemental equivalent strain values to make fatigue predictions using the Basquin equation:

$$N_{FEA} = \frac{1}{2} \left(\frac{\varepsilon_{Element}^{FEA}}{\varepsilon_f} \right)^{\frac{1}{b}} \quad (7.15)$$

where:

N_{FEA} is the predicted number of cycles to failure (CTF)

$\varepsilon_{Element}^{FEA}$ is the maximum element equivalent strain (one of the three lead strains) recorded from the lead (or solder ball)

ε_f is the fatigue coefficient and is dependent on the lead (or solder ball) material. This value is derived from correlation studies and physical testing data.

b is the fatigue exponent (displayed as **Fatigue Exponent** in the **High Cycle Fatigue** tab in the **Solder Profile Editor**, as shown in [Figure 7.21: Solder Fatigue Properties \(p. 223\)](#)) and is dependent on the lead (or solder ball) material. This exponent is derived from correlation studies and physical testing data.

Figure 7.21: Solder Fatigue Properties

Fatigue Exponent:	-2.43E-1
Fatigue Coefficient:	1.51E-2
FEA Power:	6.4
Critical Strain:	3.75E-4
Shock Strain:	7.59E-4

7.3.3. Damage Calculation

Damage accumulated over a component's service life is calculated as applied cycles over the number of cycles to fail. Cycles-to-failure is calculated as discussed in the previous section, and the applied

cycles during the service life are based on the event duration. Generally, when a board is subjected to a vibration sweep load, the sweep normally progresses from a minimum to maximum frequency and then back to the minimum value. It's important to understand that when a board is swept between two frequencies, damage to the components is maximum during resonance. For this reason, it is imperative to determine the total number of sweeps and the time spent at resonance during each sweep to accurately capture the total number of applied cycles the board will experience during its lifetime.

$$\text{Damage} = \frac{\text{Applied Cycles}}{\text{Cycles to Failure}} = \frac{N_{\text{Applied}}}{N_{\text{FEA}}} \quad (7.16)$$

$$\text{Applied Cycles} = t_{\text{resonance}} N_{\text{sweep}} f_{\text{modal}} \quad (7.17)$$

where

$t_{\text{resonance}}$ is the total time (in seconds) the board is at resonance.

N_{sweep} is the total number of sweeps the board is exposed to in its lifetime to sweep between the minimum and the maximum frequencies at a given sweep rate.

f_{modal} is the frequency at which most damage occurs (modal frequency)

The power of a modal response can be determined using the half-power bandwidth method. The duration at resonance through the half-power points (Steinberg, 2000 (p. 227)) per sweep can therefore be determined as shown in equation Equation 7.18 (p. 224). You can choose the number of modes you wish to include for resonance duration calculation (and therefore the damage), and Sherlock will automatically select the appropriate frequency bandwidth. This can be done from the **HV Result Count** drop-down option under **Analysis Properties** in Figure 7.14 (p. 215).

$$t_{\text{resonance}} = 60 \times 2 \frac{\log_e \left(\frac{1 + \frac{1}{2Q}}{1 - \frac{1}{2Q}} \right)}{R \log_e(2)} \quad (7.18)$$

where

$t_{\text{resonance}}$ is the total time (in seconds) the board is at resonance

Q is the transmissibility of the damaging frequency

R is the sweep rate in octaves/min

Note:

Prior to supporting direct modal damping in Sherlock, transmissibility was determined to be the square root of the damaging frequency, $Q = \sqrt{f}$. With direct modal damping, transmissibility can be determined as one over two times the modal damping, $Q = \frac{1}{2C}$, where C is modal damping.

On the other hand, if a board is subjected to harmonic sweep between any two frequencies (f_1, f_2) at a sweep rate of R octaves per minute, then time taken (in minutes) per sweep between the frequencies can be identified using equation Equation 7.19 (p. 224). The total number of sweeps in its service life can then be determined using equation Equation 7.20 (p. 225).

$$N_{\text{sweep}} = t_{\text{exposure}} \frac{365 \times 24 \times 60}{t_{\text{per sweep}}} \quad (7.19)$$

where

t_{exposure} is the vibration exposure time during the Service Life in years

$t_{\text{per sweep}}$ is the time (in minutes) per sweep between $f_{\min}$ and $f_{\max}$

$$t_{\text{per sweep}} = 2^{\frac{\log_2\left(\frac{f_{\max}}{f_{\min}}\right)}{R \log_2(2)}} \quad (7.20)$$

where

$t_{\text{per sweep}}$ is the time (in minutes) per sweep between $f_{\min}$ and $f_{\max}$

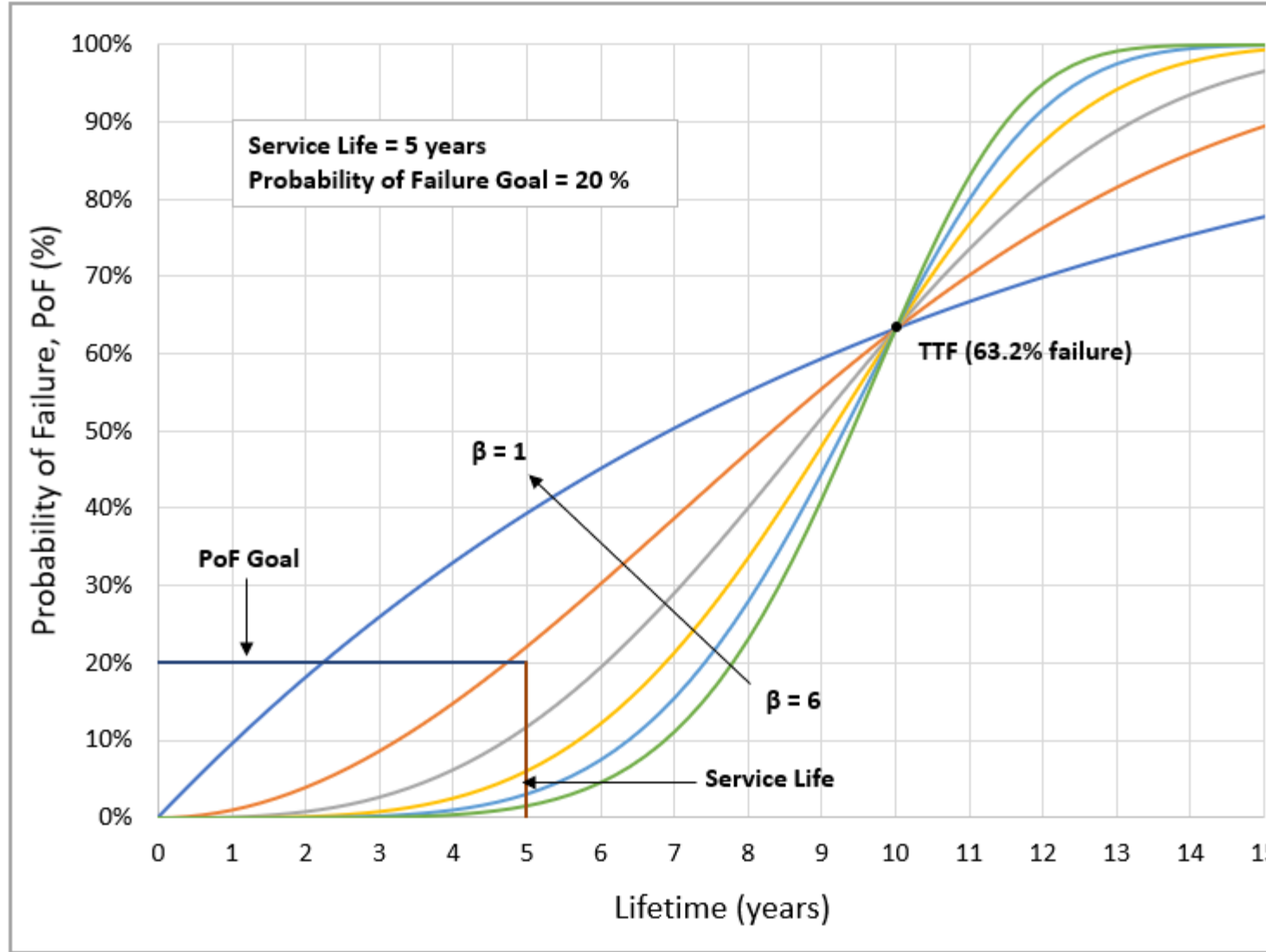
R is the sweep rate in octaves/minute

$f_{\max}$ is the upper range frequency in the harmonic sweep (the highest frequency in the harmonic profile, see [Figure 7.8 \(p. 209\)](#))

$f_{\min}$ is the lower range frequency in the harmonic sweep (the highest frequency in the harmonic profile, see [Figure 7.8 \(p. 209\)](#))

7.3.4. Probability of Failure & Scoring

A component's probability of failure (PoF) in Sherlock is the expected probability the component will fail at its Service Life. Given that the time to failure of the component marks 63.2% probability of failure (or characteristic life), the PoF of the component depends on the β (Weibull Beta/Weibull Shape Factor). As discussed in the previous section, overstress failure is generally associated with a β of 1, and fatigue due to wear-out is associated with a β greater than 1. [Figure 7.22 \(p. 226\)](#) shows the effect of Weibull beta using a probability of failure chart. The chart shows that if the failure is due to overstress, the chances of the component having failed in five years is closer to 40% than its goal of 20%. On the other hand, if the failure is caused by fatigue (assuming $\beta=3$), the chance of failure is much lower than 20% in five years.

Figure 7.22: Lifetime vs Probability of Failure

In Sherlock, the $TTF(t_{63.2\%})$ is based on the following simple ratio:

$$\frac{N_{\text{Applied}}}{N_{\text{FEA}}} = \frac{t_{\text{Service Life}}}{t_{63.2\%}} \Rightarrow \text{damage} = \frac{t_{\text{Service Life}}}{t_{63.2\%}} \quad (7.21)$$

The components PoF from the damage accumulated over its service life, represented by the point of intersection of the Service Life (vertical line) and the PoF curves in Figure 7.22 (p. 226), can be determined using the equation below.

$$\text{PoF} = 1 - \text{Reliability}(t) = 1 - e^{-(\text{damage})^\beta} \quad (7.22)$$

Based on the PoF and the PoF Goal, all components are assigned a score for easy comparison. A score of 0 is assigned to the part if the PoF Goal / PoF ratio is below 2. A score of 10 is assigned to the part if the ratio is above 10. For any ratio in between 2 and 10, the score is linearly interpolated between 1 and 10. The basic intent here is to deem a part as highly likely to fail if the probability goal is less than 2x the probability of failure and to treat it as least likely to fail if the probability goal is greater than 10x the probability of failure.

$$\text{SF} = \frac{\text{Probability of Failure Goal}}{\text{Probability of Failure}} \quad (7.23)$$

Safety Factor (SF)	Score
SF $\leq$ 2	0
2 < SF < 10	1 to 10 (linearly interpolated)
SF $\geq$ 10	10

7.4. References

1. [Ansys Documentation/Mechanical APDL/ Structural Analysis Guide/ Chapter 4: Harmonic Analysis](#) (2021)
2. Dissemination of IT for the Promotion of Materials Science (DoITPoMS): [TLP Library Bending and Torsion of Beams - Bending moments and beam curvatures](#)
3. Steinberg, D. S. (2000). *Vibration analysis for electronic equipment*. John Wiley & Sons.

Chapter 8: Natural Frequency Analysis

This section describes how Sherlock performs the Natural Frequency analysis, the basic theory behind it, and how Sherlock displays the results.

A natural frequency is a frequency at which a system resonates without any external forces. A complete electronic system typically includes a box/casing or chassis, printed circuit board(s) (PCB), and the various electronic components. Generally, a system has several natural frequencies, and if it is subjected to vibrational loads near those frequencies, it will experience high amplitude responses which can lead to system failure. For electronic systems, vibration events frequently happen during transportation and handling.

Sherlock's Natural Frequency analysis calculates the resonant frequencies of the circuit card assembly. These frequencies vary depending on geometry, stiffness, mass, and boundary conditions. Once the natural frequencies are discovered, you can then determine how the assembly will respond to different types of shock and vibration loads and the potential failure mechanisms that result.

Typical failure mechanisms include lead wire fatigue, connector contact corrosion, structural fatigue, solder joint fatigue, excessive deflection, and loose hardware. The degree of bending will differ based on the type of components and the area of the printed board. Vibration-induced fatigue is affected by the board's in-plane material properties, support-types, component design, material properties of the components, the location of components, solder joint geometry, and solder joint material.

In the end, the goal is to verify that the circuit card assembly itself is robust with regards to natural frequency and vibration. One way to achieve this is by verifying that vibrational loads do not occur at the board's natural frequencies.

8.1. Sherlock's Natural Frequency Analysis Module

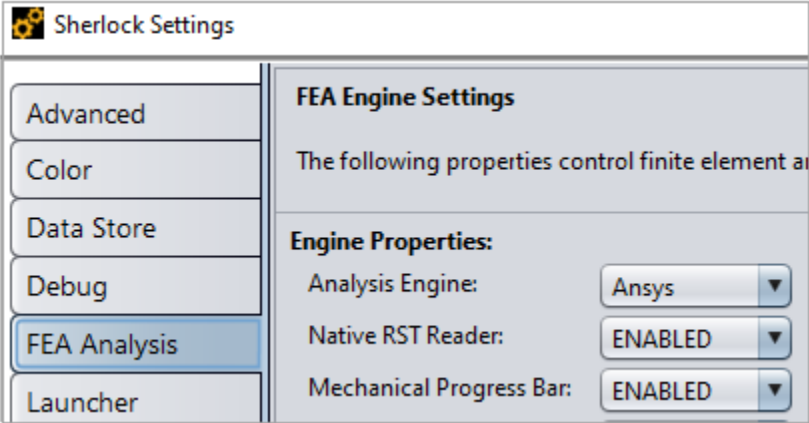
8.2. Natural Frequency Analysis Results

8.3.4. References

8.1. Sherlock's Natural Frequency Analysis Module

Sherlock's Natural Frequency module uses the Ansys modal solver. While Sherlock supports [ABAQUS \(p. 233\)](#) and [Nx NASTRAN \(p. 233\)](#) solvers, its default solver is Ansys. You can select the solver under the **FEA Engine Settings** options in the **Sherlock Settings** window as shown below. See [FEA Engine in the Sherlock User's Guide](#).

Figure 8.1: Solver Selection



Numerically, the Modal/Natural Frequency analysis is essentially an eigenvalue problem where the system is represented as a stiffness-mass matrix and solved for eigenvalues and eigenvectors. Eigenvalues represent the natural frequencies, and eigenvectors represent the mode shapes. Additional information on the theory behind the modal analysis can be found in [Modal Analysis](#) in Ansys' Mechanical APDL *Theory Reference*.

8.2. Natural Frequency Analysis Results

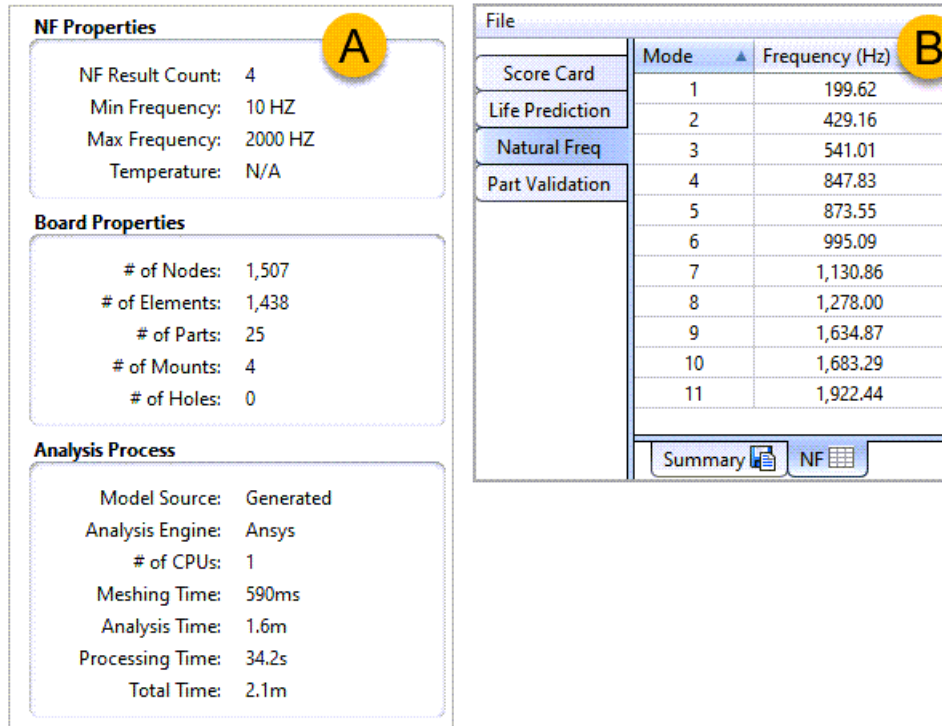
For any electronic assembly, you can quickly set up material properties and boundary conditions in Sherlock and launch a Natural Frequency analysis. Once the analysis is complete, Sherlock displays the modal frequencies and corresponding shapes in the **Results Viewer** and the **Results Table**. Sherlock's Natural Frequency analysis makes no predictions directly. Its purpose is to discover the modal frequencies and the mode shapes inherent to the electronic assembly.

The results generated by the analysis include a [Summary Panel](#) (A, below) that displays all the input settings used in the analysis, the total number of natural frequencies found within the specified frequency search range, and other properties such as the size and the complexity of the model.

Depending on the FEA engine that was used, the NF tab (B) lists all modes found in the analyzed frequency range. The results allow advanced users to validate the simulation against real-world measurements.

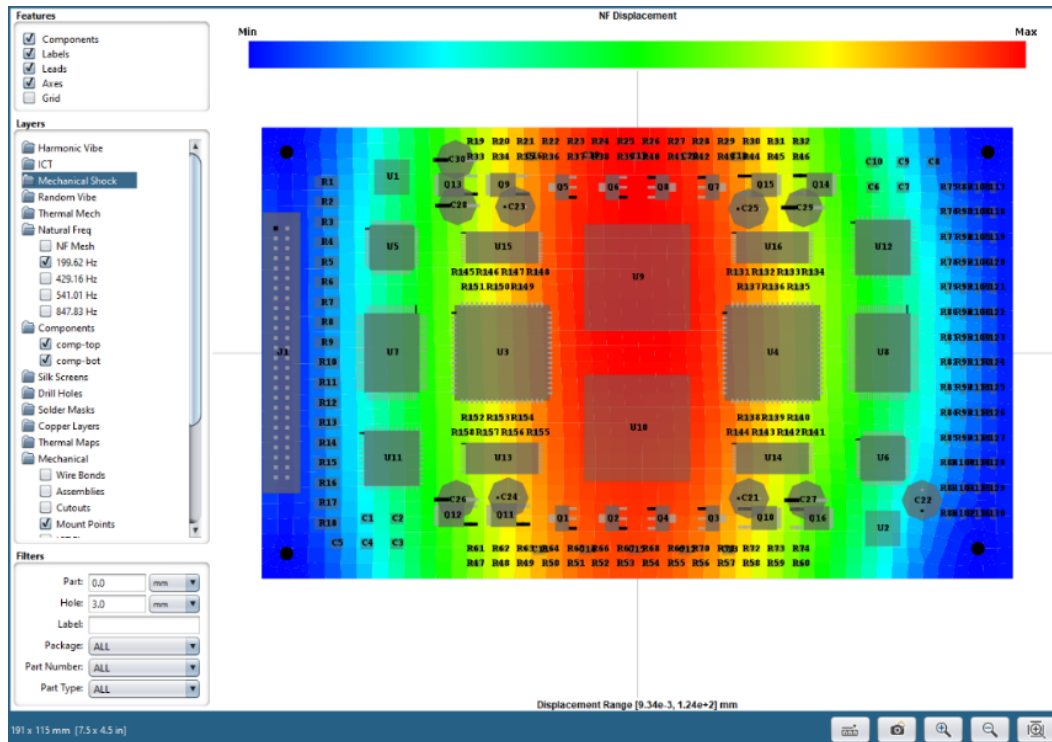
Note:

Prior to Sherlock 6.2.2, the NF panel was named as the **Eigenvalues Panel**.

Figure 8.2: (A) Summary Panel and (B) Natural Frequency Tab

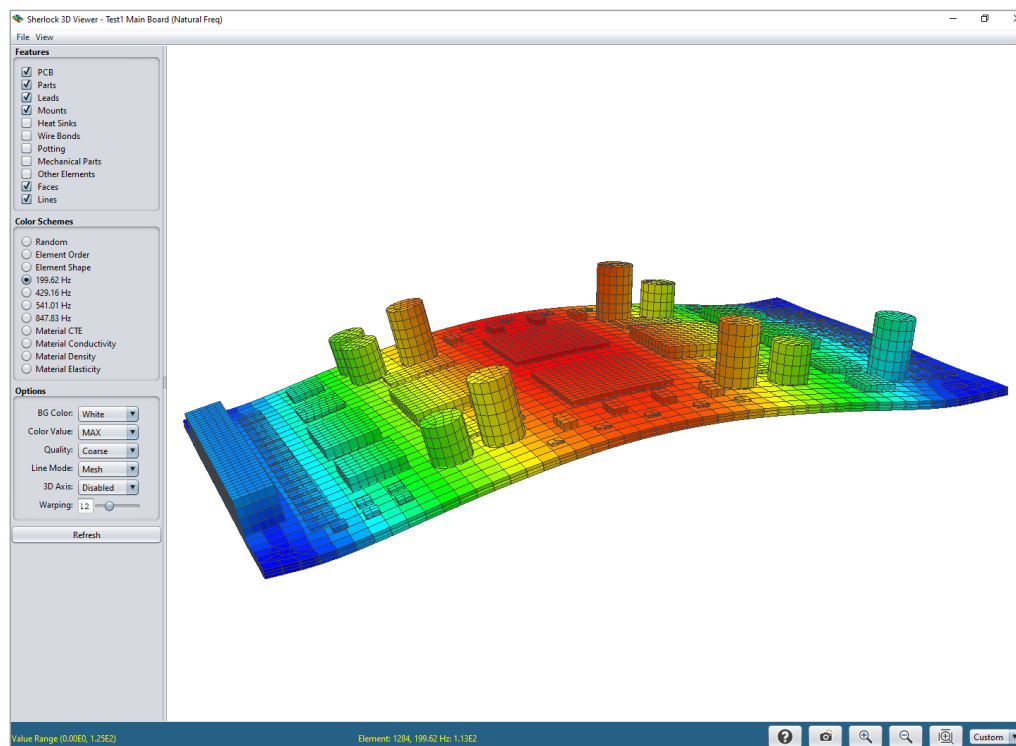
Graphical Results

The Natural Frequency analysis module also generates graphical results: one or more 2D result layers in the Layer Viewer (Figure 8.3 (p. 232)), depending on the value specified in the **NF Result Count** input property. (See [Natural Frequency Analysis Properties in the Sherlock User's Guide](#).) Each result shows the mode shape of the structure at a given natural frequency. For example, the following figure shows the mode shape at 158.66 Hz which is the first natural frequency for this electronic assembly.

Figure 8.3: 2D Layer Viewer

The displacement values are color-coded based on their magnitude, with the minimum displacement values shown as blue and the maximum values shown as red. Due to the nature of the modal analysis equations, the mode shape results are effectively qualitative. That is, exact values are not displayed on the color legend. Unlike other analyses, such as Random Vibration or Harmonic Vibration, no external excitations (such as forces or displacements) are applied to the system.

Sherlock also provides a 3D Viewer, shown below, displaying the results in even more detail. More information about the **Results Viewer** is available in [Sherlock 3D Viewer in the Sherlock User's Guide](#).

Figure 8.4: Sherlock Results Viewer

8.3.4. References

1. Modal Analysis in the *Structural Analysis Guide*
2. Abaqus Documentation, <https://abaqus-docs.mit.edu/>
3. Siemens Documentation, plm.automation.siemens.com/global/en/support/docs.html

Chapter 9: Stackup Theory Guide

Section Summary:

- 9.1. Laminate Layer Material Properties in Sherlock
- 9.2. Copper Layer Material Properties
- 9.3. PCB Stackup Calculation
- 9.4. References

Introduction: Overview of the Stackup

A typical printed circuit board (PCB) or printed wired board (PWB) has four basic components:

- **Prepreg:** A partially cured epoxy resin impregnated glass fabric which flows and cures under heat and pressure. This resin glues together the layers and fills in where the copper has been removed from the PCB core layers. Prepregs are generally placed between core layers. The dielectric constant of this layer varies, depending on the resin and the glass fabric properties—including the glass and construction style. These can also be viewed as bonding sheets that fuse the other PCB layers.
- **Core:** A fully cured epoxy resin (matrix) impregnated glass fabric (reinforcement) that typically has copper on both sides. The difference between the core layer and the prepreg layer is that the latter is not fully cured.
- **Copper foil:** A metal foil (etched to form a metal pattern, also called traces) that is used in circuit boards to conduct electricity and provide mechanical and electrical connections. It also provides electrical connection between components. Electrodeposited copper is plated on the conductor foils used in PCB's. Other types are the reverse-treated copper foil, wrought annealed copper foil, and double-treated and resistive foils, among others ([Coombs, 2001 \(p. 245\)](#)).
- **Solder mask:** A coating on the surface of the circuit board to insulate the copper traces and to define the regions where solder will be applied.

Another part of the PCB is the silkscreen which is used to label the electronic components on the board, show their part numbers, and so on. Among the constituent elements of the PCB, there are three materials that define the mechanical behavior of the circuit board:

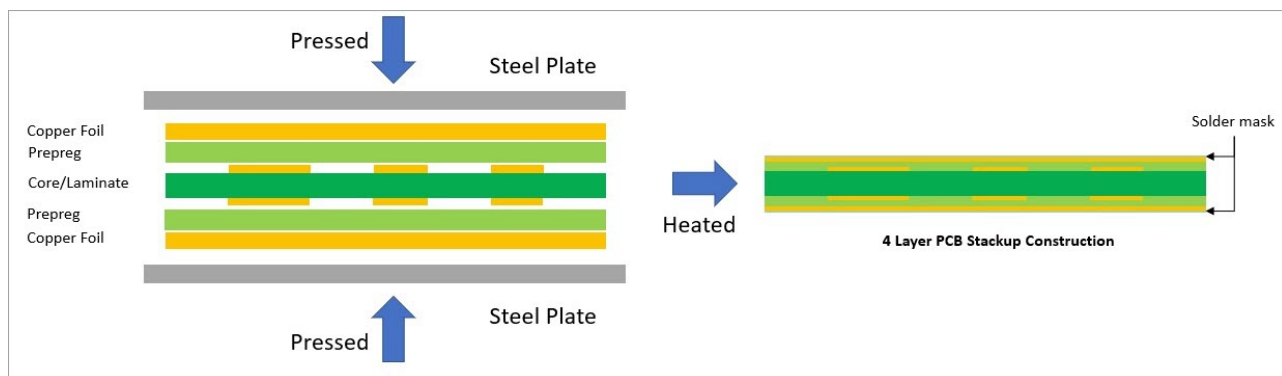
- **Conductor:** The layers between two dielectric sheets made of conducting material, providing electrical connection between various components on the board. The conductor also provides mechanical stability along with glass fibers in the laminate layers.
- **Reinforcement:** The laminate and prepreg of the printed circuit board that are composed of woven glass fibers and epoxy that provide structural support and electrical insulation. Other materials such as impregnated cotton paper are sometimes used, but glass fibers dominate the market.
- **Matrix (Resin):** Typically a thermosetting epoxy that holds everything together, although other materials such as polyimide and Teflon are also used in special applications. The amount of resin is

defined by a resin content percentage by weight. Resin also determines the thickness of a given layer.

A simple four-layer printed circuit board is shown in [Figure 9.1 \(p. 236\)](#). The layers described above are stacked and loaded into a lamination press where pressure, temperature, and vacuum are applied. The press conditions depend on the resin system, the resin's degree of cure, among other factors. The stackup starts with a core laminate layer. This layer is followed either by a single layer or multiple layers of prepreg (depending on the layup), followed by the outer copper foil. The outer copper foil is called "copper on prepreg." The core layer, as mentioned earlier, is a fully cured epoxy impregnated glass fabric with copper patterns etched on either side. The core layer and prepreg are alternated according to design specifications. The final step is placing the copper foil on top of the stackup.

The stackup is placed between two press plates (usually steel or aluminum) in the lamination press and heated by applying vacuum and pressure. During heating, the partially cured resin from the prepreg flows into the gaps between the copper pattern on either side of the cores, holding everything together. The copper on the top and bottom faces are later etched—often using cupric chloride as the etchant—to form the necessary trace patterns. Finally, the solder mask layer is applied to insulate the copper traces. Although this simplified explanation seems straight forward, the PCB fabrication is far more complicated, involving many other variables that influence the quality and performance of the final product.

Figure 9.1: PCB Stack-Up Construction



You can import, create, or edit a stackup in Sherlock as shown in [Figure 9.2 \(p. 237\)](#). Sherlock can then compute the mechanical and thermal properties based on the stackup's construction. Calculating the mechanical behavior of a printed circuit board requires knowing its constituent materials and their properties. Typically, the material properties of the conductor and the reinforcement (glass fibers) are readily available. However, the properties of the resin (matrix) are often not known since their composition is proprietary. Due to limited information, Sherlock computes resin properties from other constituents of the laminate.

Figure 9.2: A- PCB Stackup. B- PCB Stackup in Sherlock

A			B				
			Layer	Type	Material	Construction	Thickness
Copper	Copper (91.7%)	35.6 μm	1	SIGNAL	COPPER (91.7%) / RM_L01		35.6 micron
Prepreg	1080 : RC 51%	210 μm	2	Laminate	Generic FR-4 / COPPER (0.5%) / Resin Content (51.0%)	1080x1+2113x1	210 micron
Prepreg	2113 : RC 51%		3	SIGNAL	COPPER (89.9%) / RM_L03		35.6 micron
Copper	Copper (89.9%)	35.6 μm	4	Laminate	Generic FR-4 / COPPER (0.3%) / Resin Content (42.0%)	2116	711.2 micr...
Core	2116 : RC 42%	711.2 μm	5	SIGNAL	COPPER (87.5%) / RM_L05		35.6 micron
Copper	Copper (87.5%)	35.6 μm	6	Laminate	Generic FR-4 / COPPER (0.1%) / Resin Content (47.0%)	7628	210 micron
Prepreg	7628 : RC 47%	210 μm	7	SIGNAL	COPPER (87.5%) / RM_L07		35.6 micron
Copper	Copper (87.5%)	35.6 μm	8	Laminate	Generic FR-4 / COPPER (0.3%) / Resin Content (42.0%)	2116	711.2 micr...
Core	2116 : RC 42%	711.2 μm	9	SIGNAL	COPPER (89.9%) / RM_L09		35.6 micron
Copper	Copper (89.9%)	35.6 μm	10	Laminate	Generic FR-4 / COPPER (0.5%) / Resin Content (51.0%)	1080x1+2113x1	210 micron
Prepreg	2113 : RC 51%		11	SIGNAL	COPPER (91.7%) / RM_L11		35.6 micron
Prepreg	1080 : RC 51%	210 μm					
Copper	Copper (91.7%)	35.6 μm					

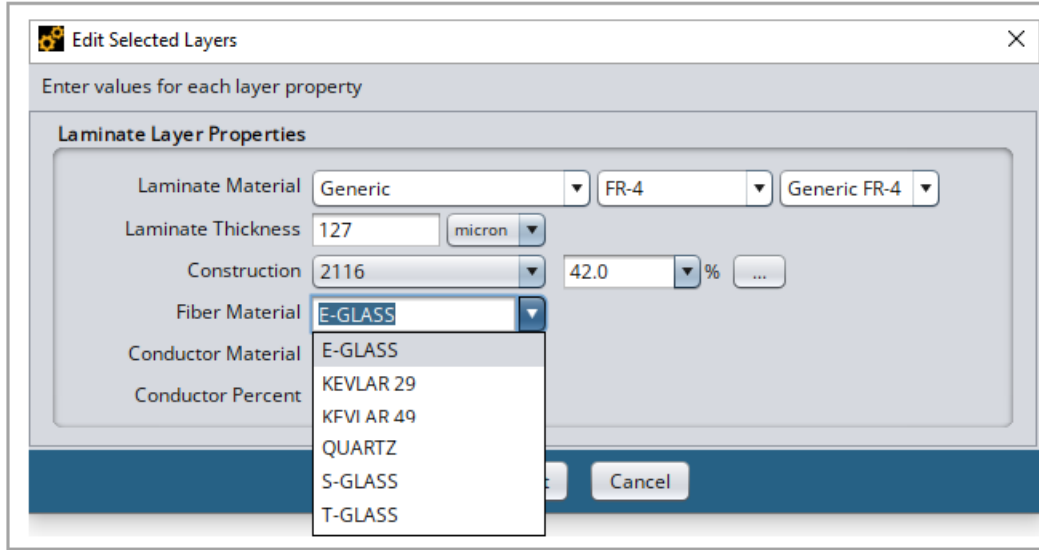
Because Sherlock stores the material properties for the matrix/resin, glass fiber, and copper, it is able to quantify the effect of each element that comprises the PCB. This document presents the theory and formulation behind the method Sherlock uses to determine the mechanical properties of the stackup.

- [Section 9.1 \(p. 237\)](#) and [Section 9.2 \(p. 242\)](#) go through the laminate and copper layer properties in Sherlock.
- [Section 9.3 \(p. 244\)](#) explains the methods behind Sherlock's effective stackup calculator.

9.1. Laminate Layer Material Properties in Sherlock

With a completed PCB stackup, the mechanical properties of a core/prepreg laminate layer mostly depends on the glass type, fiber-resin content, and their respective material properties. A core/prepreg laminate layer in electronics is a composite layer made of woven glass fiber and a resin matrix. In literature, there are several models available for determining the properties of a composite layer. Sherlock uses the Hashin model for the in-plane laminate modulus ([Hashin, 1974a \(p. 245\)](#) and [Hashin, 1974b \(p. 245\)](#)) and the rule of mixture model for the out-of-plane modulus.

Sherlock assumes all laminates in its library are composed of 50% resin by weight. Sherlock then back calculates the resin modulus and CTE, taking into account user-defined laminate layer properties entered into the **Edit Select Layers** dialog shown in [Figure 9.3 \(p. 238\)](#).

Figure 9.3: Fiber Material in Sherlock

Respectively, [Equation 9.1 \(p. 238\)](#) and [Equation 9.2 \(p. 238\)](#) provide the in-plane and out-of-plane moduli used in Sherlock. Similar to moduli properties calculation, the coefficient of thermal expansion (CTE) and density for laminate layer is also based on the rule of mixture as shown in [Equation 9.3 \(p. 239\)](#) through [Equation 9.5 \(p. 239\)](#).

In-Plane Modulus

$$E_{xy} = a \left(V_f E_f + V_r E_r + \left\{ \frac{4V_f V_r (v_f - v_r)^2 G_f G_r \frac{E_r}{2(1-v_r)}}{(G_f + \frac{E_r}{2(1+v_r)}) G_r + (G_f - G_r) \frac{E_r V_f}{2(1+v_r)}} \right\} \right) \quad (9.1)$$

Out-of-Plane Modulus

$$E_z = \frac{E_f E_r}{V_f E_f + V_r E_r} \quad (9.2)$$

where

E_{xy} is the in-plane modulus

E_z is the out-of-plane modulus

v_f, v_r are the fiber and resin volume fractions

E_f, E_r are the fiber and resin Young's moduli

v_f, v_r are the fiber and resin Poisson's ratios

G_f, G_r are the fiber and resin shear moduli

a is the experimental correlation factor to account for undulations in the weave pattern

In-Plane CTE

$$\alpha_{xy} = \frac{V_f \alpha_f E_f + V_r \alpha_r E_r}{V_f E_f + V_r E_r} \quad (9.3)$$

Out-of-Plane CTE

$$\alpha_z = V_f \alpha_f + V_r \alpha_r \quad (9.4)$$

where

α_{xy} is the in-plane CTE

α_z is the out-of-plane CTE

V_f, V_r are the fiber and resin volume fraction

E_f, E_r are the fiber and resin Young's moduli

Effective Laminate Density

$$\rho_{\text{lam}} = V_f \rho_f + V_r \rho_r \quad (9.5)$$

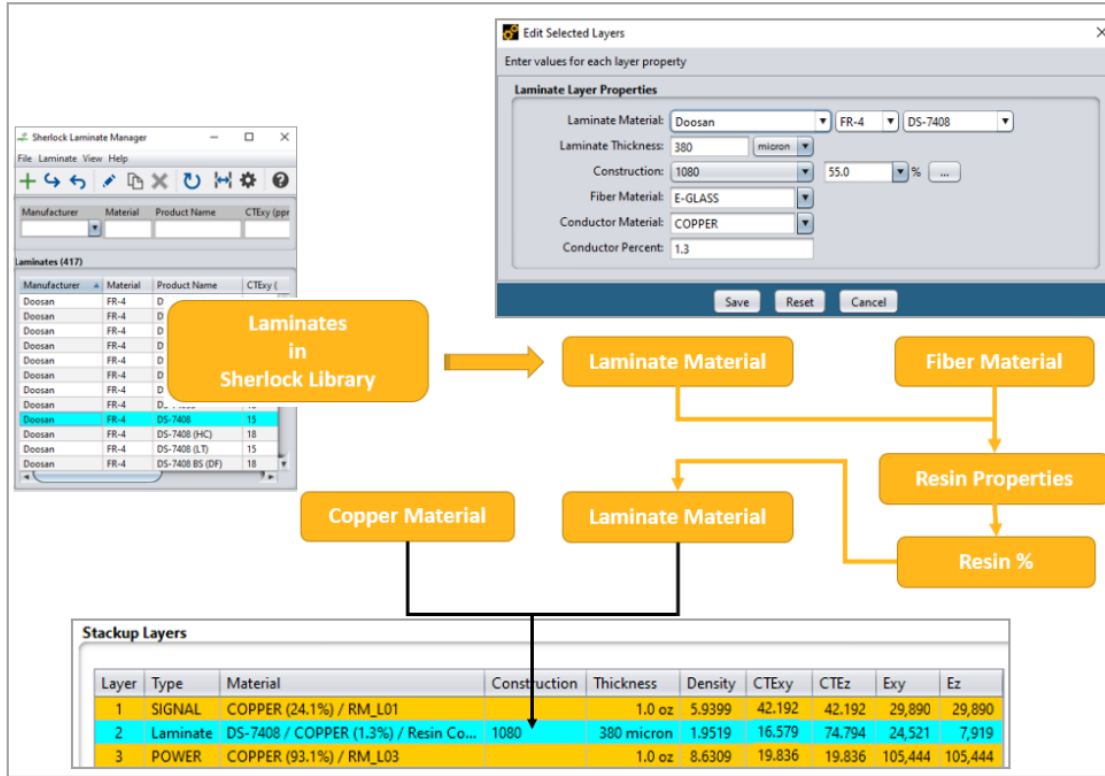
where

ρ_{lam} is the laminate density

V_f, V_r are the fiber and resin volume fractions

ρ_f, ρ_r are the fiber and resin density

The laminate properties are then combined with copper properties to determine the effective laminate properties used in the stackup. The flow of calculations is represented in [Figure 9.4 \(p. 240\)](#).

Figure 9.4: Laminate Properties Update

Using the composite laminate properties from the Sherlock library, the resin modulus and CTE can be calculated from Equation 9.1 (p. 238) and Equation 9.3 (p. 239) respectively. Equation 9.1 (p. 238) when solved for resin modulus will yield a quadratic solution. For completeness, the quadratic equation from Equation 9.1 (p. 238) is provided in Equation 9.6 (p. 240) below. CTE from Equation 9.3 (p. 239) can be described from Equation 9.7 (p. 240)

$$V_r^2 E_r^2 + (V_r K_f B C + V_f E_f V_r - E_{xy} V_r) E_r + (A E_r K_f + V_f E_f K_f B C - E_{xy} K_f B C) = 0 \quad (9.6)$$

where

$$A = 4 V_f V_r (v_f - v_r)^2$$

$$B = 2 V_f (1 - 2 v_r) (1 + v_r)$$

$$C = 2 (1 + v_r)$$

E_{xy} is the in-plane laminate modulus from Sherlock Library

V_f, V_r are fiber and resin volume fractions, $V_f = \frac{w_f}{\rho_f}$, fiber weight over fiber density

E_f, E_r are the fiber and resin Young's Moduli

v_f, v_r are the fiber and resin Poisson's ratio

K_f are the fiber and resin bulk modulus

$$\alpha_r = \frac{\alpha_{xy} (V_f E_f + V_r E_r) - V_f \alpha_f E_f}{V_r E_r} \quad (9.7)$$

where

α_{xy} is the in-plane Laminate CTE from Sherlock Library

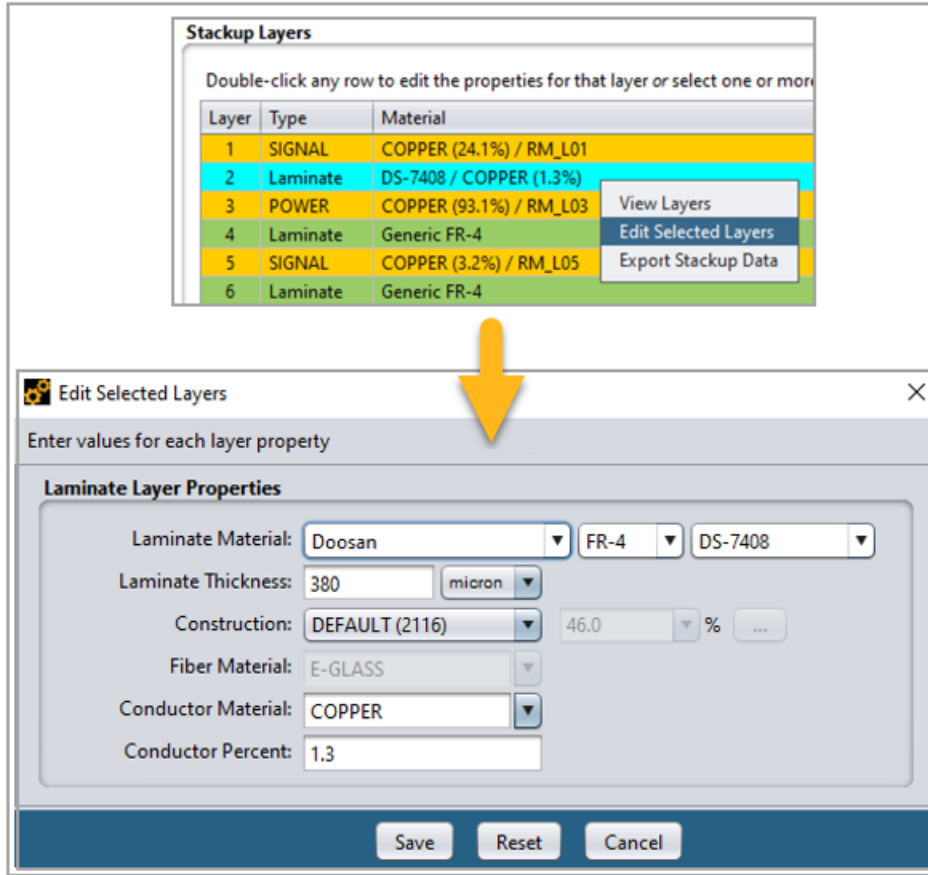
α_z is the out-of-plane CTE

V_f, V_r are the fiber and resin volume fractions

E_f, E_r are the fiber and resin Young's Moduli

Vias and/or plated through holes in a laminate form the overall conductor distribution in that layer. Sherlock captures these features by enabling you to define the conductor percentage in each individual layer making up the stackup as shown in [Figure 9.5 \(p. 241\)](#).

Figure 9.5: Conductor Distribution in Stackup Laminate Layer



A layer constituting fiber and resin, along with the copper definition, completely defines any laminate in a given stackup. The effect of copper in the layer is based on volume averaging from the defined copper percentage for both in-plane and out-of-plane direction as shown in [Equation 9.8 \(p. 241\)](#) and [Equation 9.9 \(p. 241\)](#) respectively.

$$E_{xy/z}^{\text{Layer}} = (1 - V_{\text{cond}}) E_{xy/z}^{\text{Lam}} + V_{\text{cond}} E_{\text{cond}} \quad (9.8)$$

$$\alpha_{xy/z}^{\text{Layer}} = (1 - V_{\text{cond}}) \alpha_{xy/z}^{\text{Lam}} + V_{\text{cond}} \alpha_{\text{cond}} \quad (9.9)$$

where

$E_{xy/z}^{\text{Layer}}$ is the stackup layer modulus

$E_{xy/z}^{\text{Lam}}$ is the laminate modulus

E_{cond} is the conductor modulus

V_{cond} is the conductor volume fraction in the layer (%)

$\alpha_{xy/z}^{\text{Layer}}$ is the stackup layer CTE

$\alpha_{xy/z}^{\text{Lam}}$ is the laminate CTE

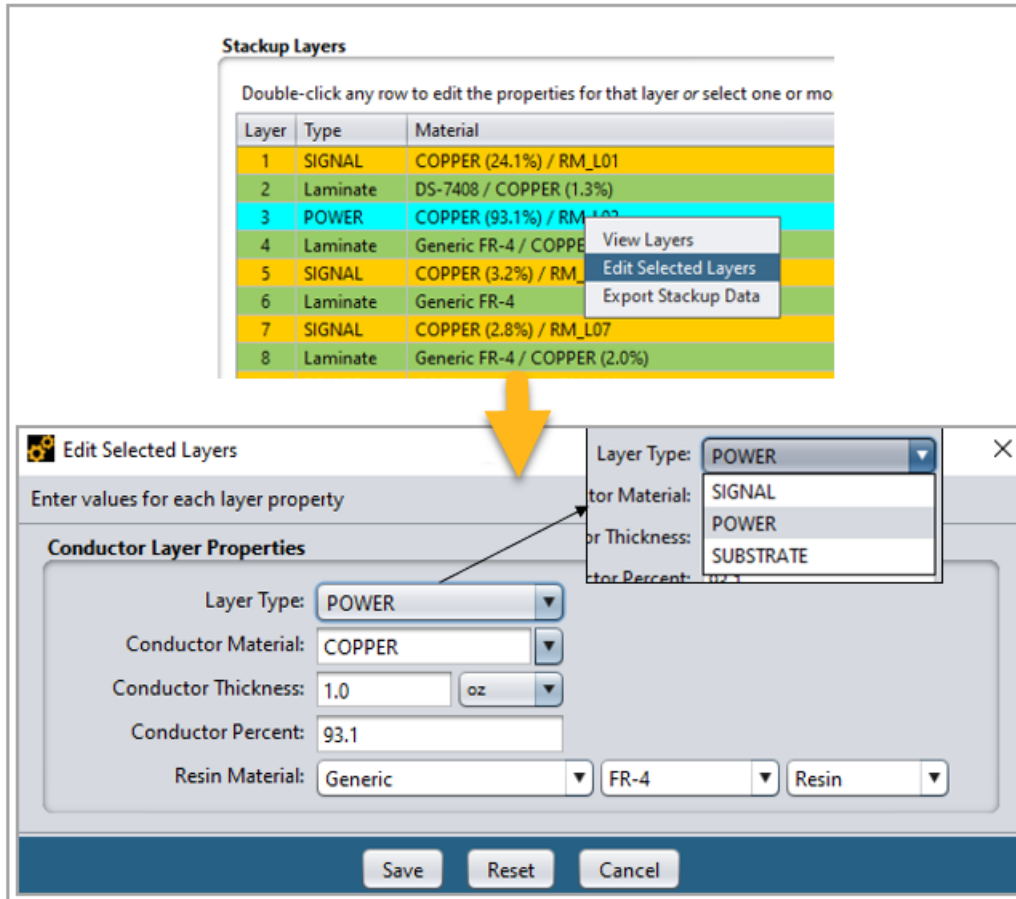
α_{cond} is the conductor CTE

Summary

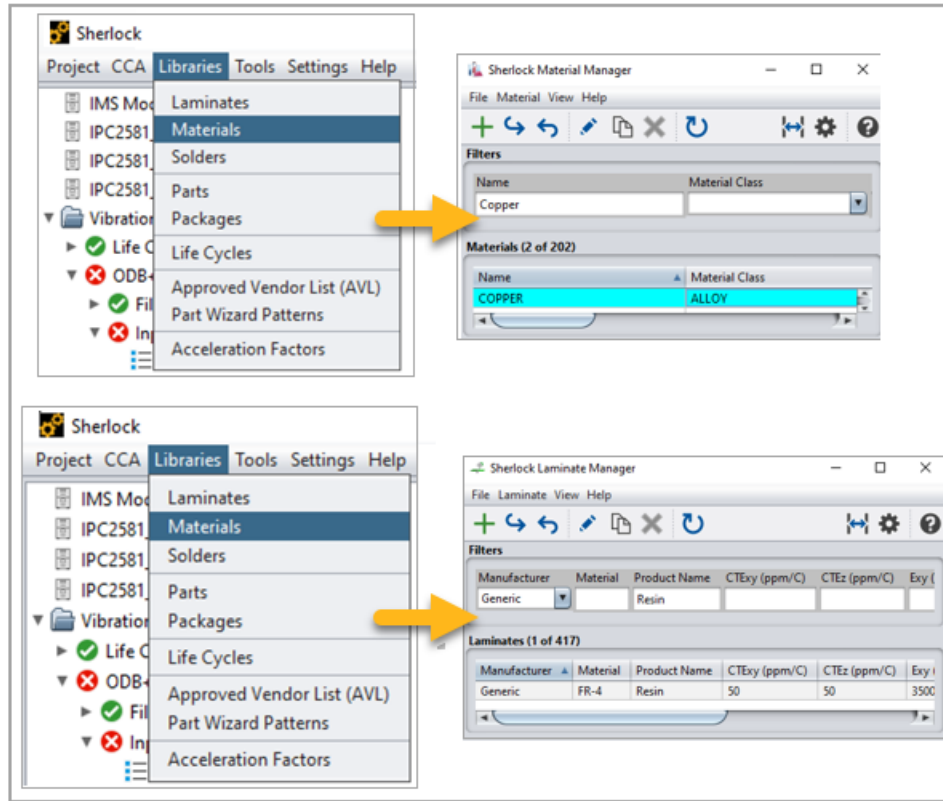
1. A prepreg layer contains glass fiber and resin. Mechanical properties of the glass fibers are readily available, but the resin properties rarely are. To have an accurate set of mechanical properties, you must obtain the resin properties.
2. The literature offers a number of different models for calculating the modulus and CTE of composite lamina. Sherlock uses the Hashin and Rosen model for the in-plane modulus and Reuss's rule of mixture model for the out-of-plane modulus. The coefficient of thermal expansion for the lamina is also based on rule of mixture.
3. Sherlock offers several laminate properties from its extensive [Laminate Library](#).
4. When determining the resin properties (modulus and CTE) from the laminates, Sherlock assumes 50% resin by weight.
5. Sherlock uses the standard fiber properties—as well as the resin properties determined from the laminate—to update the laminate properties with the new resin percentage provided by the user.
6. Effective layer properties containing the laminate in the stackup are calculated based on volume averaging using laminate and the conductor properties.

9.2. Copper Layer Material Properties

A conductor layer in the PCB is mostly made of ED (electrodeposited) copper and resin that fills the negative space between adjacent prepreg layers during pressing. Both materials are treated as isotropic mediums and are combined based on volume averaging, similar to how laminates are handled. [Figure 9.6 \(p. 243\)](#) shows the input fields where you can enter the conductor percentage of the conductor layer similar to [Figure 9.5 \(p. 241\)](#) for laminate layers. In keeping with labeling standards, you can assign a **Layer Type** as shown below.

Figure 9.6: Conductor Distribution in Stackup Conductor Layer

You can define the resin and conductor material of the layer under **Edit Selected Layers** based on the **Conductor Percent** input. Sherlock combines the materials based on volume averaging scheme. Equation 9.10 (p. 244) and Equation 9.11 (p. 244) show the effective material properties for the modulus and CTE. To edit or define the conductor material, use the **Sherlock Material Manager**. Editing or defining the resin material, however, must be done in the Laminate Library as shown in Figure 9.7 (p. 244). Earlier versions of Sherlock let you define resin material using the Material Manager, but that is no longer the case.

Figure 9.7: Material and Laminate Library in Sherlock

$$E_{\text{Layer}} = (1 - V_{\text{cond}}) E_{\text{resin}} + V_{\text{cond}} E_{\text{cond}} \quad (9.10)$$

$$\alpha_{\text{Layer}} = (1 - V_{\text{cond}}) \alpha_{\text{resin}} + V_{\text{cond}} \alpha_{\text{cond}} \quad (9.11)$$

where

E_{layer} is the stackup conductor layer modulus

E_{resin} is the conductor layer resin modulus

E_{cond} is the conductor layer conductor modulus

V_{cond} is the conductor volume fraction in the conductor layer (%)

α_{layer} is the stackup conductor layer CTE

α_{resin} is the resin CTE

α_{cond} is the conductor CTE

9.3. PCB Stackup Calculation

Almost all materials exhibit a change in physical dimensions when subjected to temperature changes. The Young's modulus (E) and coefficient of thermal expansion (CTE) are critical because when two materials with different CTE and E are joined, the displacement mismatch creates stress. This is the main driver of thermal-mechanical fatigue in electronic components. When a temperature change occurs, the component and printed circuit board expand or contract by dissimilar amounts due to the CTE and E differences. This difference in expansion or contraction will place the second-level solder joint under

a shear load. Typically, this load or stress is far below the strength of the solder joint. However, repeated exposure to temperature changes, as happens with power on/off or diurnal cycles, can damage the bulk solder. Therefore, obtaining accurate moduli and CTE's for the PCB and components is vital.

Sherlock uses the Voigt composite model and the Reuss composite model to evaluate the modulus and CTE for a complete stackup. As discussed in the previous sections, PCBs are composed of alternating layers of prepregs (laminates/core) and conductor layers. Also covered were Sherlock's approach to calculating properties of individual laminate layers and conductor layers. The formulation for modulus and CTE from rule of mixture models are shown in Equation 9.12 (p. 245) through Equation 9.15 (p. 245).

$$\text{Voigt Composite: } E_{xy}^{\text{PCB}} = \frac{t_{\text{Layer1}}}{t_{\text{PCB}}} E_{xy}^{\text{Layer1}} + \frac{t_{\text{Layer2}}}{t_{\text{PCB}}} E_{xy}^{\text{Layer2}} + \dots + \frac{t_{\text{LayerN}}}{t_{\text{PCB}}} E_{xy}^{\text{LayerN}} \quad (9.12)$$

$$\text{Reuss Composite: } \frac{1}{E_z^{\text{PCB}}} = \frac{t_{\text{Layer1}}}{t_{\text{PCB}}} \frac{1}{E_z^{\text{Layer1}}} + \frac{t_{\text{Layer2}}}{t_{\text{PCB}}} \frac{1}{E_z^{\text{Layer2}}} + \dots + \frac{t_{\text{LayerN}}}{t_{\text{PCB}}} \frac{1}{E_z^{\text{LayerN}}} \quad (9.13)$$

$$\frac{1}{\alpha_{xy}^{\text{PCB}}} = \frac{t_{\text{Layer1}}}{t_{\text{PCB}}} \frac{1}{\alpha_{xy}^{\text{Layer1}}} + \frac{t_{\text{Layer2}}}{t_{\text{PCB}}} \frac{1}{\alpha_{xy}^{\text{Layer2}}} + \dots + \frac{t_{\text{LayerN}}}{t_{\text{PCB}}} \frac{1}{\alpha_{xy}^{\text{LayerN}}} \quad (9.14)$$

$$\alpha_z^{\text{PCB}} = \frac{t_{\text{Layer1}}}{t_{\text{PCB}}} \alpha_z^{\text{Layer1}} + \frac{t_{\text{Layer2}}}{t_{\text{PCB}}} \alpha_z^{\text{Layer2}} + \dots + \frac{t_{\text{LayerN}}}{t_{\text{PCB}}} \alpha_z^{\text{LayerN}} \quad (9.15)$$

where

E_{xy}^{PCB} is the in-plane PCB modulus

E_{xy}^{Layer1} is the in-plane modulus of Layer 1 in the stackup

E_z^{PCB} is the out-of-plane PCB modulus

E_z^{Layer1} is the out-of-plane modulus of Layer 1 in the stackup

α_{xy}^{PCB} is the in-plane PCB CTE

α_z^{PCB} is the out-of-plane PCB CTE

$\alpha_{xy}^{\text{Layer1}}$ is the in-plane CTE of Layer 1 in the stackup

α_z^{Layer1} is the out-of-plane CTE of Layer 1 in the stackup

t_{Layer1} is the Layer 1 thickness

t_{PCB} is the PCB thickness

9.4. References

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