DfR Solutions

reliability designed, reliability delivered

Thermo-Mechanical and Mechanical Reliability of Electronics

IEEE CPMT Webinar

November 13, 2013

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What is Thermo/Mechanical Reliability?

- Describes the potential for product failure when subjected to periodic changes in environmental stress or an overstress event that are thermal or mechanical in nature

- What types of thermal or mechanical stress could cause failure in today's electronics?

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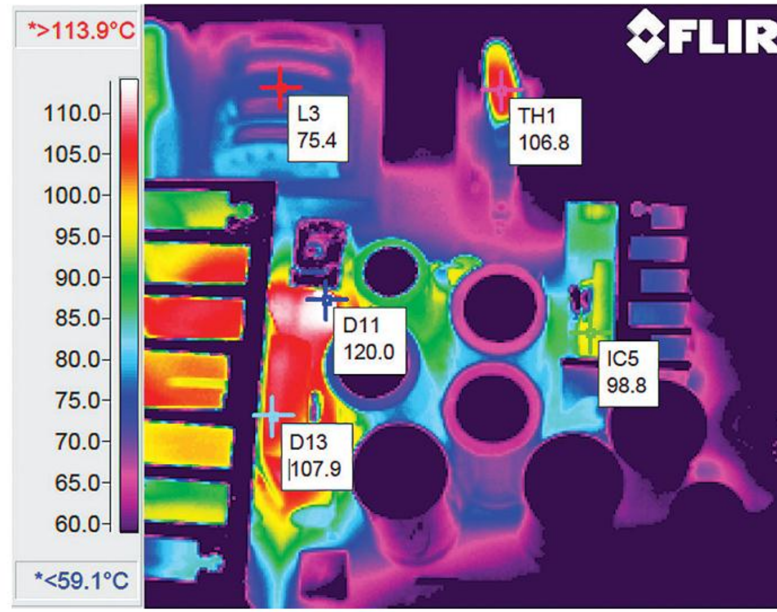
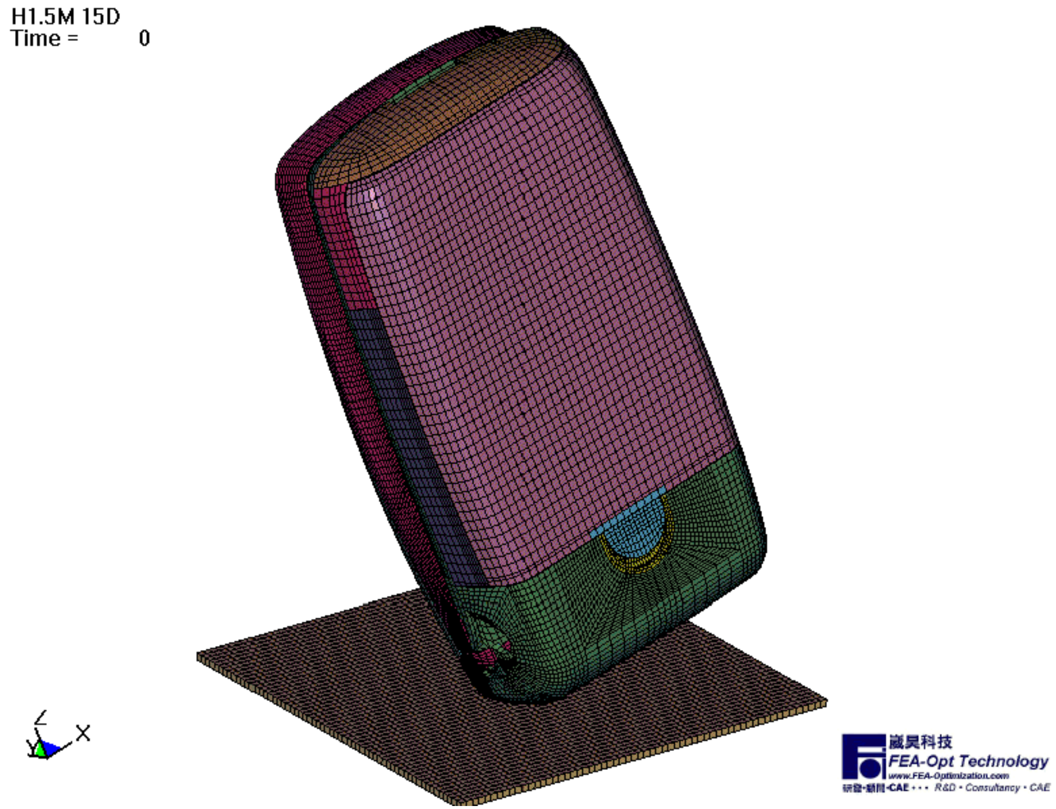
Thermal Cycling

Due to Solar Loading



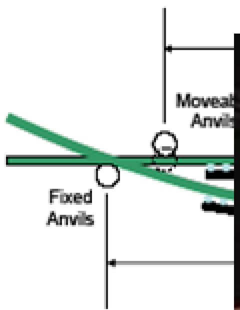
Due to Power Dissipation

Drop / Mechanical Shock

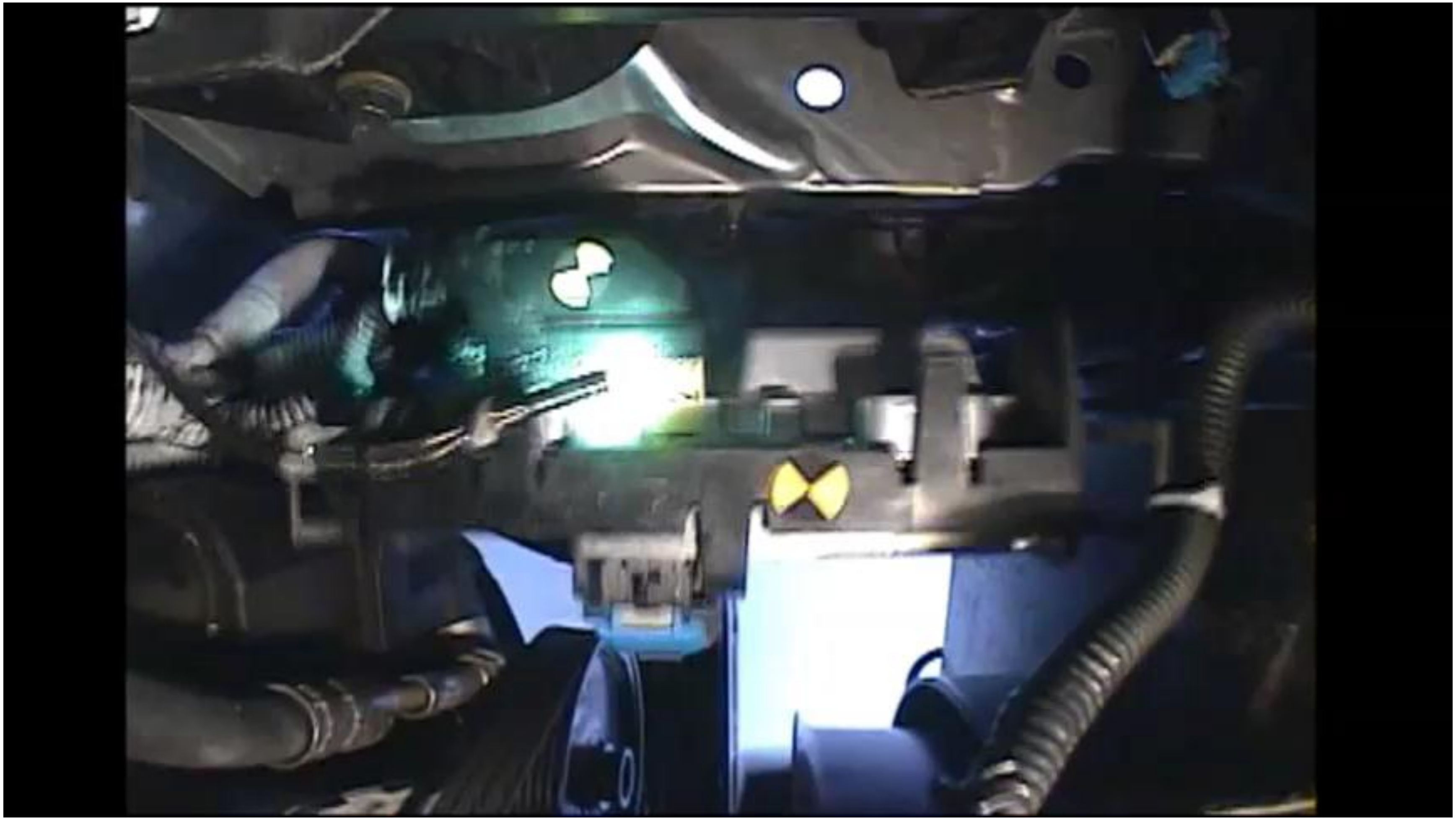


Drop (Mechanical Shock)

Bending



Vibration



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Why Care About Thermal/Mechanical Reliability?

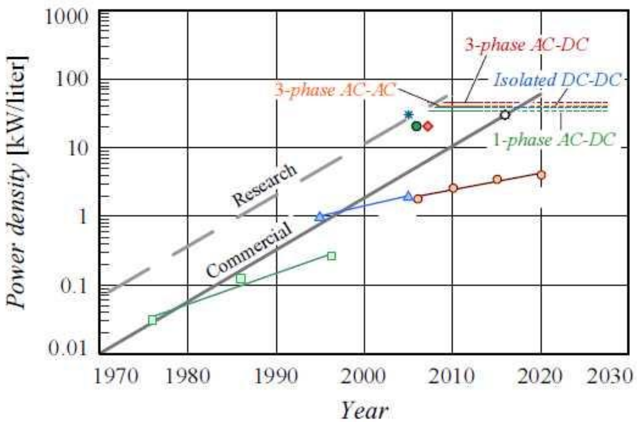
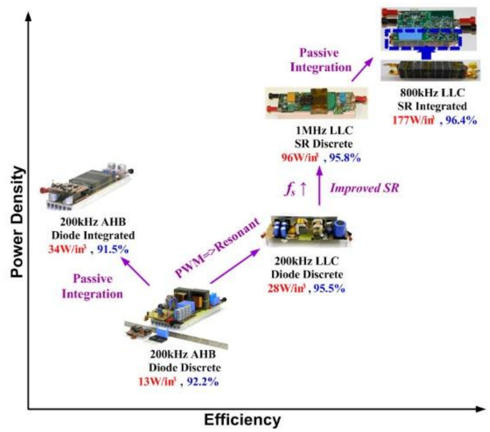


Figure 2. Power density trends of commercial and research systems and the Power Density Barriers.

Everything is Hot



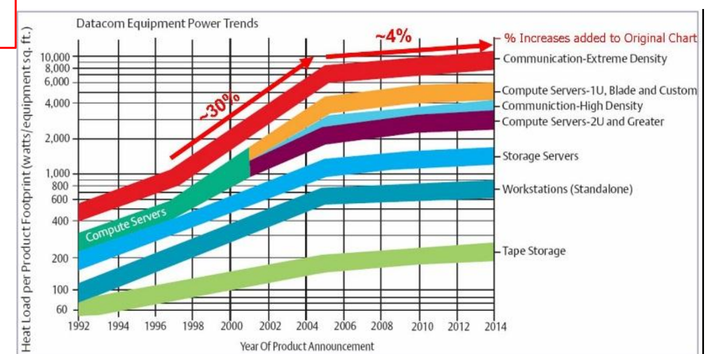


Figure 1. Equipment densities are rising even faster than once predicted.
© 2005 ASHRAE TC 9.9 Datacom Equipment Power Trends & Cooling Applications

Everything is Mobile

Everything is Everywhere

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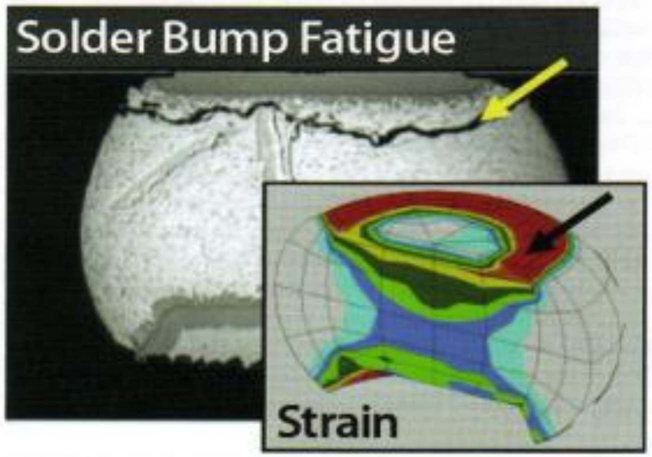
Why Care About Thermal/Mechanical Reliability? (cont.)

- Failures are not always about electrical overstress (EOS)!
- Recent studies suggest that the majority of electronic failures are thermo-mechanically related*

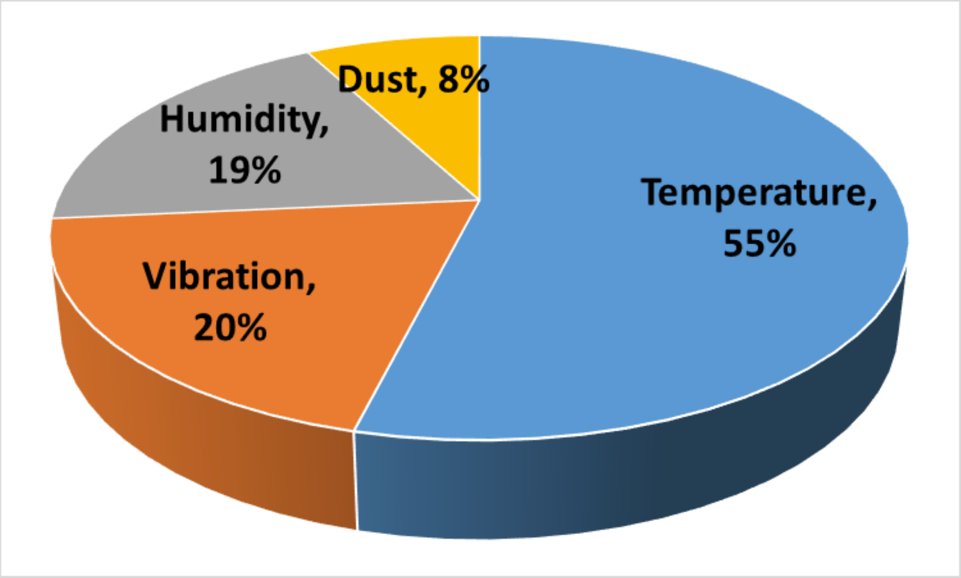


*Wunderle, B. and B. Michel, "Progress in Reliability Research in Micro and Nano Region", Microelectronics and Reliability, V46, Issue 9-11, 2006.

A. MacDiarmid, "Thermal Cycling Failures", RIAC Journal, Jan., 2011.

Why Care About Thermal/Mechanical Reliability? (cont.)

- According to U.S Air-Force statistics, twenty (20%) percent of all failures observed in electronic equipment were due to vibration problems



Steinberg D.S. Vibration analysis for electronic equipment. John Wiley & Sons, 2000.

Why Care About Thermal/Mechanical Reliability? (cont.)

- Automotive manufacturers are now requiring Tier 1 suppliers to provide thermal and mechanical reliability predictions for <u>every component</u> in the assembly

- Avionic manufacturers are considering adopting this requirement

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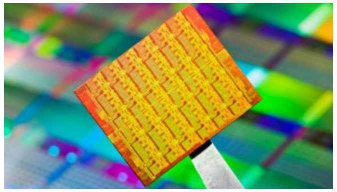
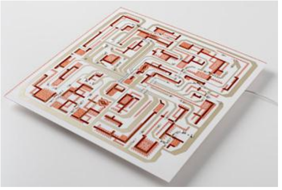
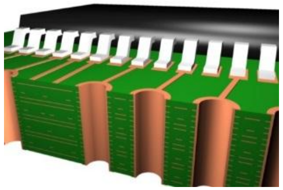
Thermo-Mechanical

Why Do Electronics Fail Under Thermal Cycling?

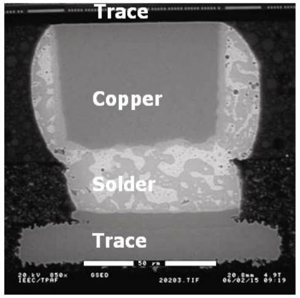
- A. We use lots of different materials
  - Semiconductors, Ceramics, Metals, Polymers

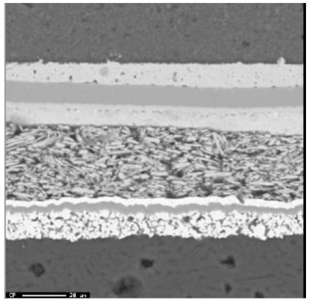






- B. We bond these different materials together
  - Plating, **Solder**, Adhesive





- C. These materials expand/contract at different rates

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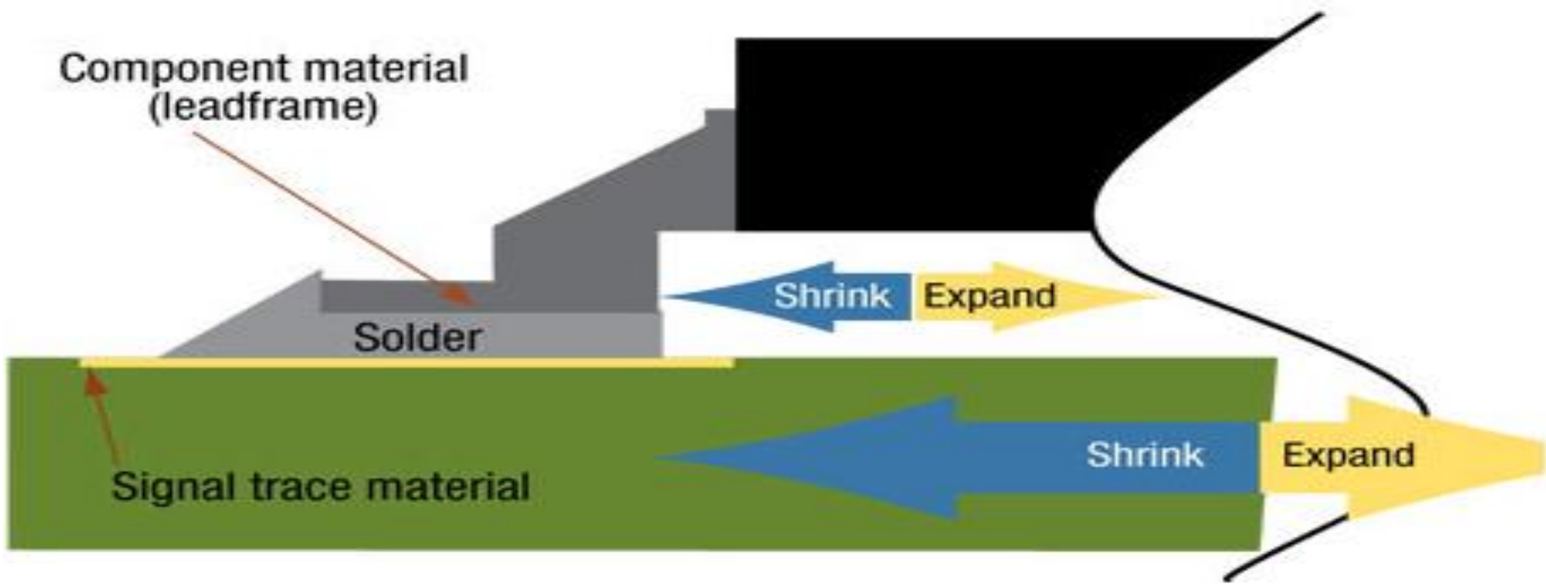
Why Do Electronics Fail Under Thermal Cycling? (cont.)

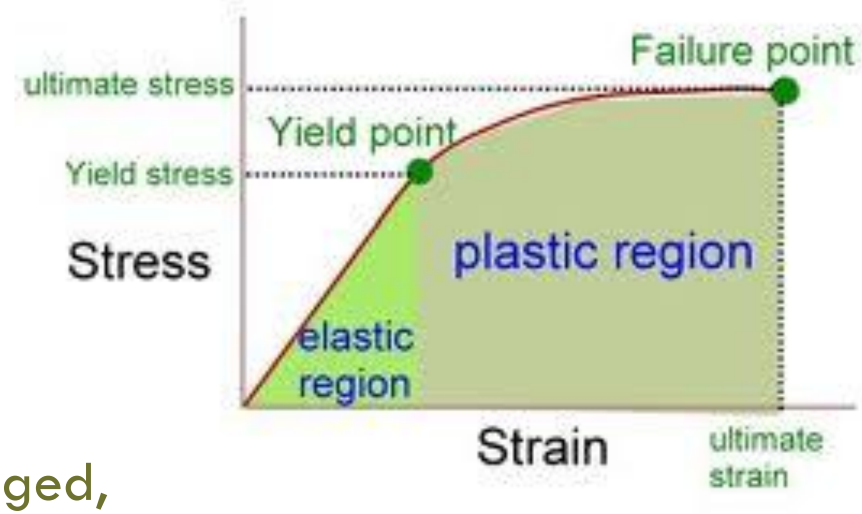
- Two different expansion/contraction behaviors
  - Because solder is connecting two materials that are expanding / contracting at different rates (GLOBAL)
  - Because solder is expanding / contracting at a different rate than the material to which it is connected (LOCAL)



How Do Electronics Fail Under Thermal Cycling? (cont.)

- This differential expansion and contraction introduces stress into the solder joint
  - This stress causes the solder to deform (aka, elastic and plastic strain)

- The extent of this strain (that is, strain range or strain energy) tells us the lifetime of the solder joint
  - The higher the strain, the more the solder joint is damaged, the shorter the lifetime



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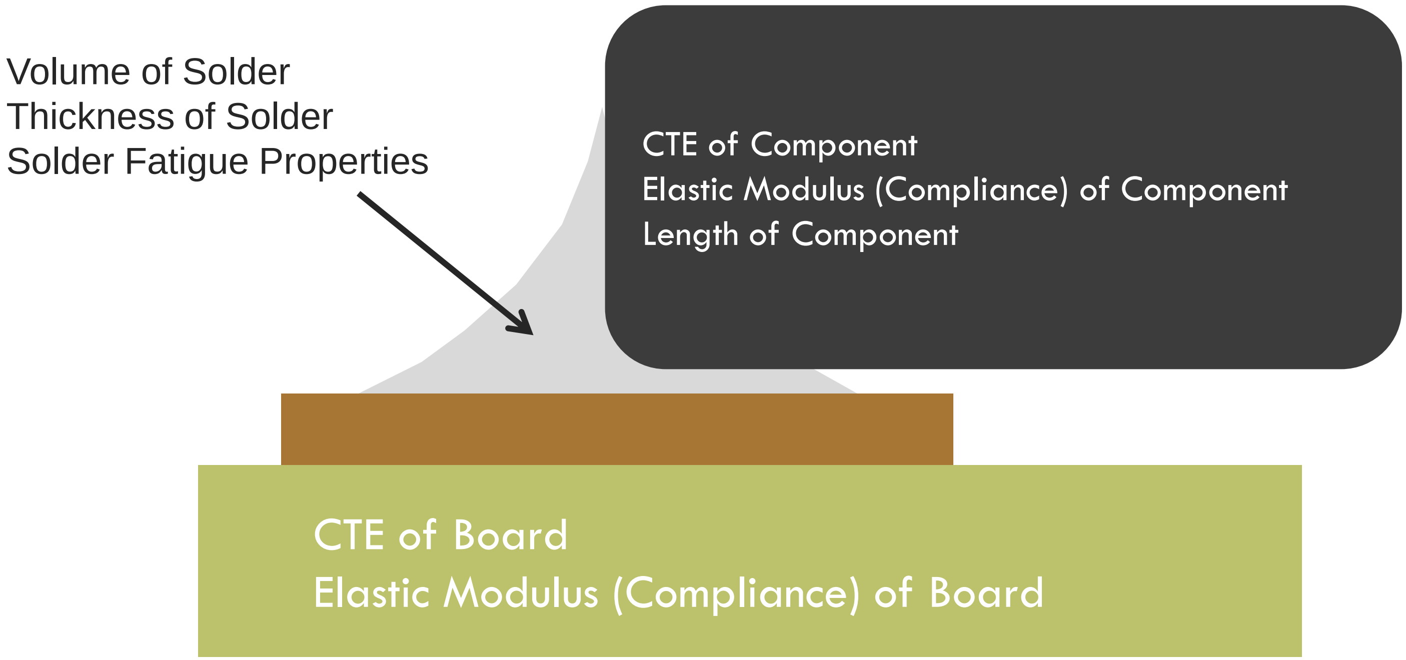
Drivers for Solder Joint Thermo-Mechanical Failures

- Knowing the critical drivers for solder joint fatigue, we can develop predictive models and design rules



Predictive Models – Physics of Failure (PoF)

- Modified Engelmaier for Pb-free Solder (SAC305)
  - Semi-empirical analytical approach
  - Energy based fatigue
- Determine the strain range ($\Delta\gamma$)

$$\Delta\gamma = C\frac{L_D}{h_s}\Delta\alpha\Delta T$$

- C is a correction factor that is a function of dwell time and temperature, L_D is **diagonal distance**, α is coefficient of thermal expansion (**CTE**), ΔT is temperature cycle, h is **solder joint height**

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Predictive Models – Physics of Failure (PoF)(cont.)

- Determine the shear force applied to the solder joint

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

  - F is shear force, L is **length**, E is **elastic modulus**, A is the area, h is thickness, G is shear modulus, and a is edge length of bond pad
  - Subscripts: 1 is **component**, 2 is **board**, s is solder joint, c is bond pad, and b is board

- Takes into consideration foundation stiffness and both shear and axial loads

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Predictive Models – Physics of Failure (PoF)(cont.)

- Determine the strain energy dissipated by the solder joint

$$\Delta W = 0.5 \cdot \Delta\gamma \cdot \frac{F}{A_s}$$

- Calculate cycles-to-failure (N_{50}), using energy based fatigue models

$$N_f = \left(0.0019 \cdot \Delta W\right)^{-1}$$

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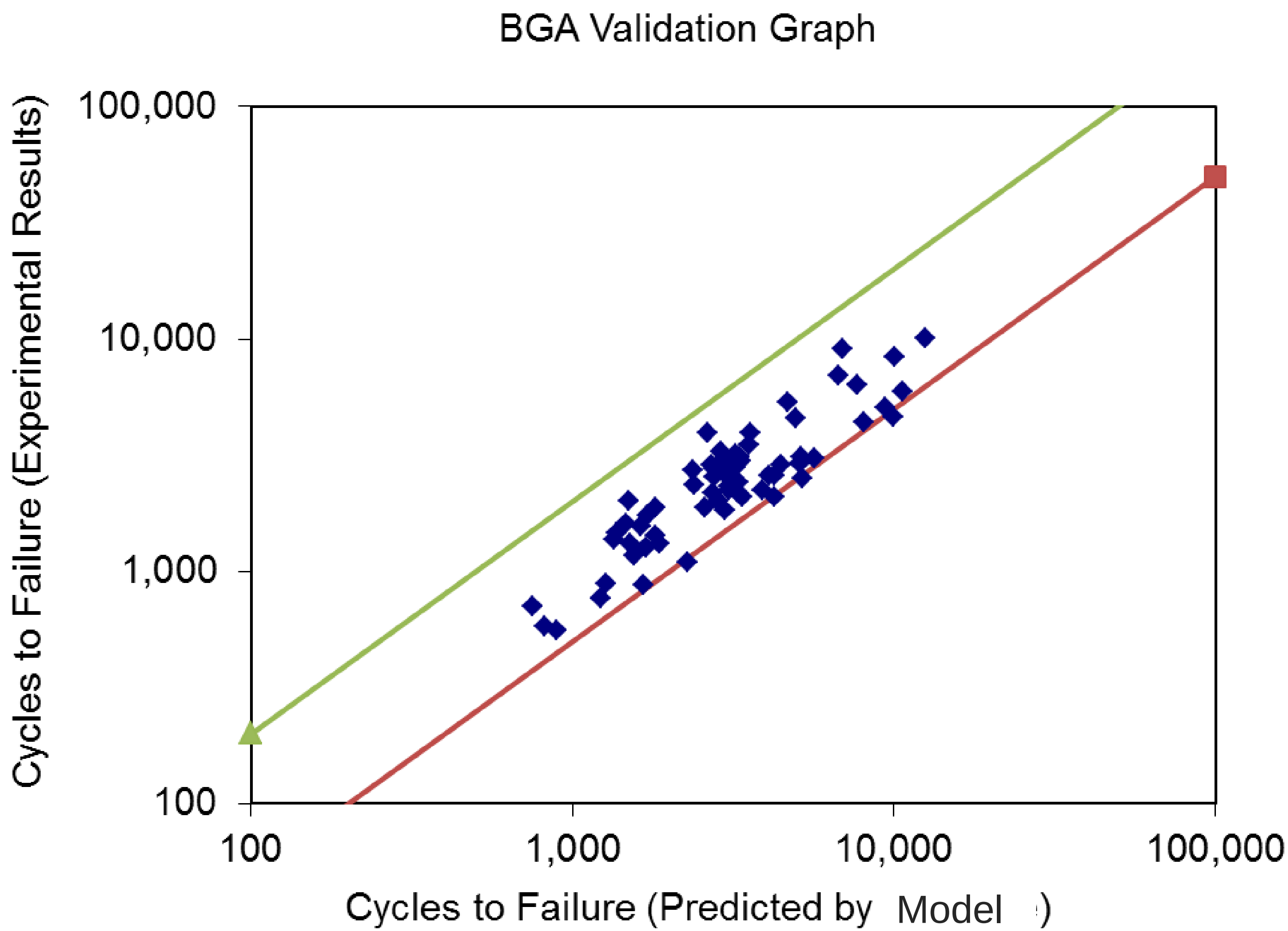
And It Works!



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Thermo-Mechanical Design Rules

- Knowing the drivers and how to predict provides powerful insight to the design process
- Identify which designs and environments are at potential risk of solder joint fatigue
- Quantitatively benchmark material changes
- Develop accurate accelerated life tests

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Thermo-Mechanical Design Rules - Components

- Large components
  - Quad Flat Pack No-Lead (QFN): Greater than 7mm x 7mm
  - Ball Grid Array (BGA): Greater than 20mm x 20mm
- Components with CTE far below or far above PCB CTE (typically 14-17 ppm)
  - Chip scale packages (CSP)
  - Chip resistors
- Components with a low compliance
  - High modulus, thick components (ceramic)
  - Leads with high stiffness (thick, short, encapsulated, no bend)
  - Leadless (QFN, BGA, CSP)

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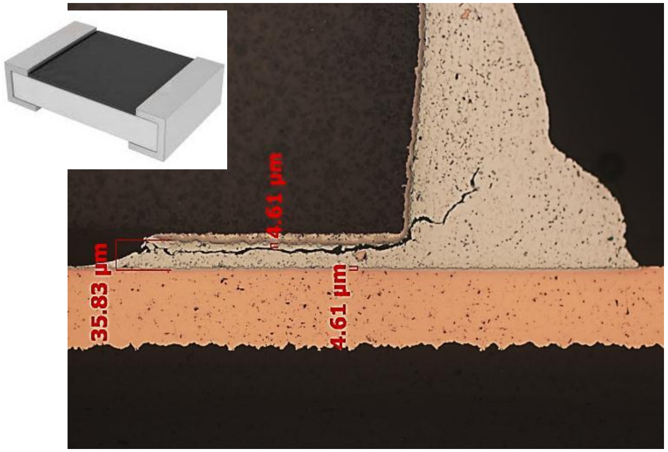
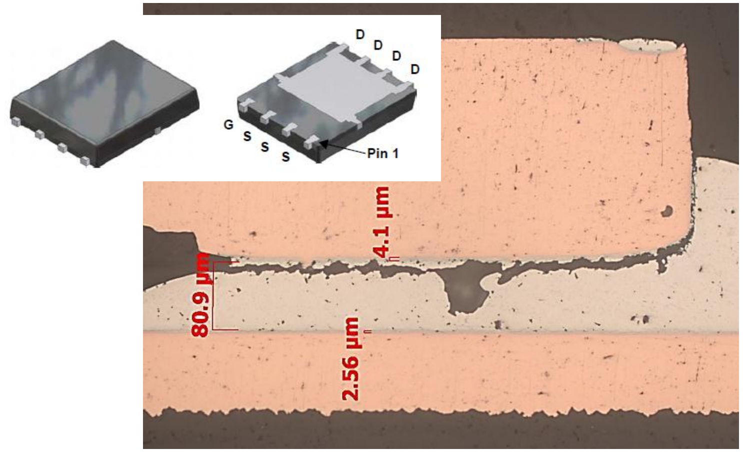
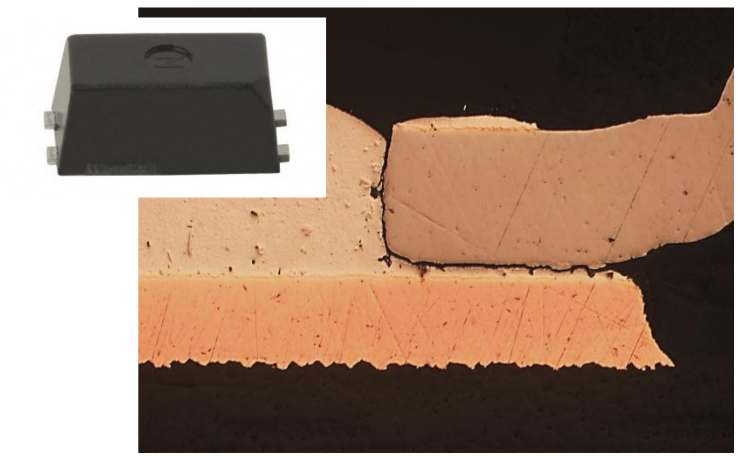
Avoiding Thermo-Mechanical Failures



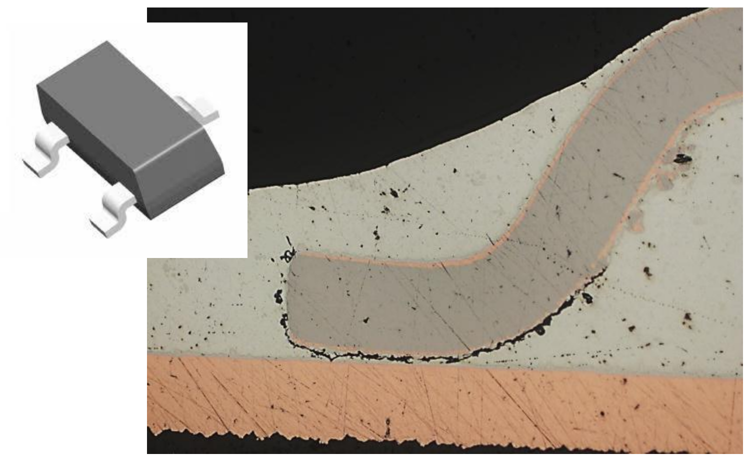
Chip Resistor



QFN



SOT Alloy 42



SOT Alloy 42

Thermo-Mechanical Design Rules - PCB

- Thick boards
  - Most qualification of thermo-mechanical reliability is done on thin boards (1.5mm or less)
  - Higher thickness (i.e., 2.5mm) reduces the compliance
    - Compliance is length over the product of area and modulus (L/AE) (inverse of stiffness)(A = thickness x width)
  - Lower compliance means more stress in the solder joint

- Boards well-bonded to large metal structures (heat spreaders, stiffeners, etc.)
  - Can greatly increase PCB CTE (especially if metal is aluminum)

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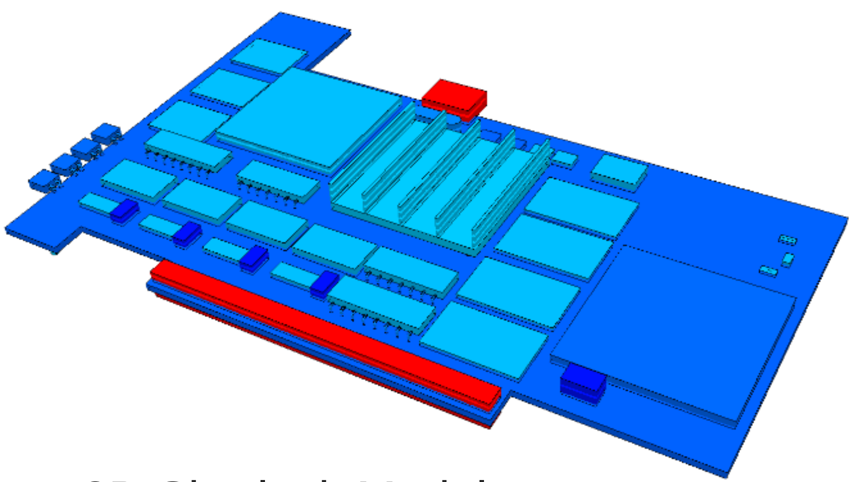
Thermo-Mechanical Design Rules - Environment

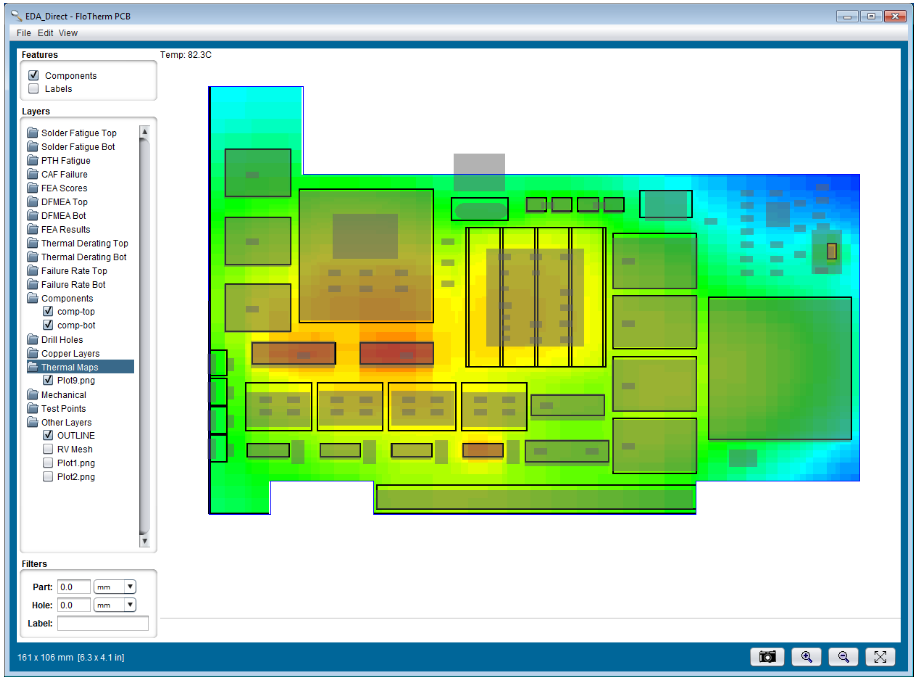
- Environments of No Concern
  - Home/Office Environments with no power cycling
- Environments of Less Concern
  - Diurnal with low power dissipation (ΔT of 25C, 1 cycle/day)
  - Lifetime of less than 10 years
- Environments of Higher Concern
  - Diurnal heat sources with sufficient fluctuation (Δ40C)
  - Diurnal power dissipation of Δ40C and greater
  - Power cycling greater than 4 cycles/day (mini-cycling)
  - Long lifetimes (>15 years)

Thermo-Mechanical Design Rules Through Prediction

More specific design rules requires performing a higher level of analysis (especially for power cycling)



3D Sherlock Model



Thermal Analysis Results

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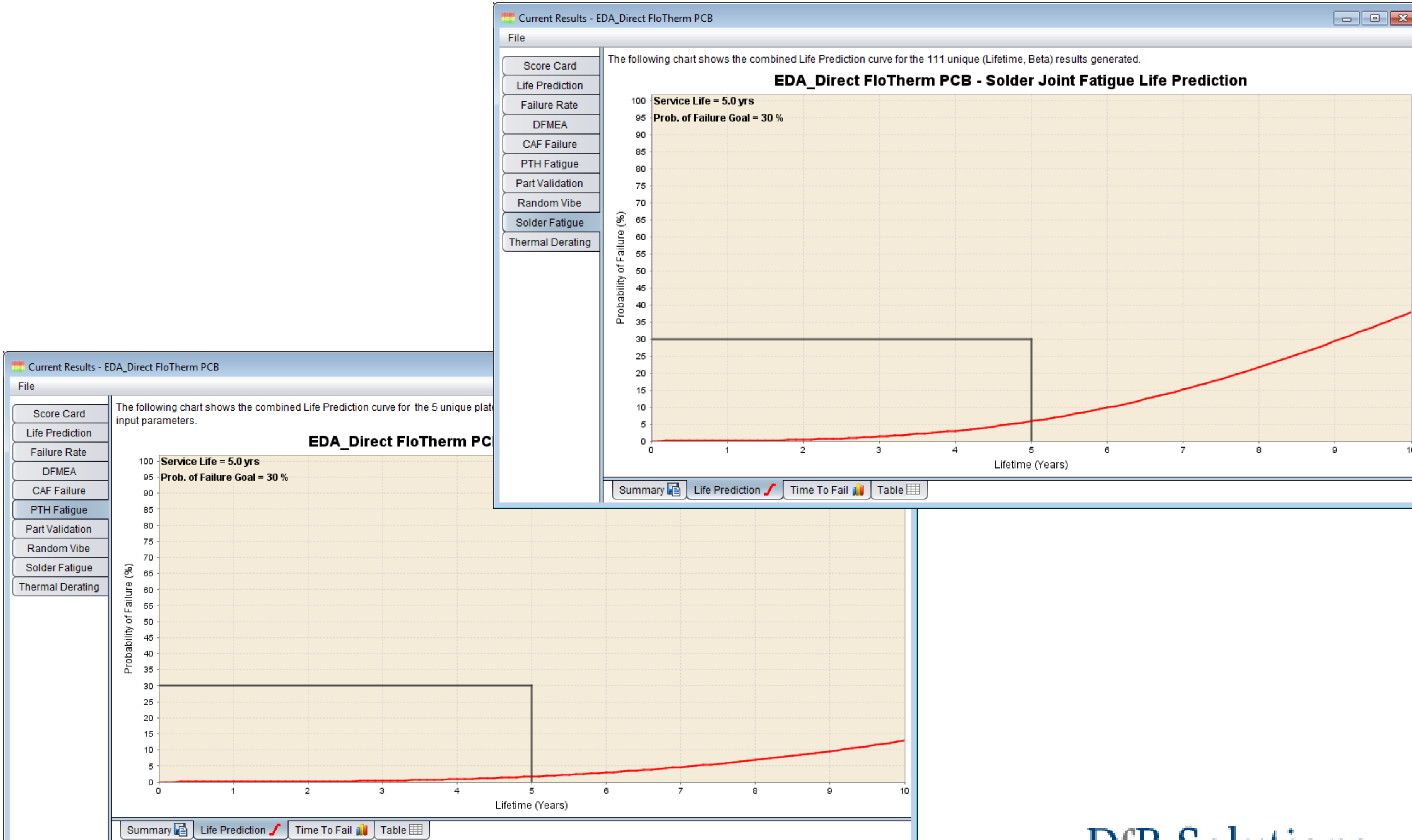
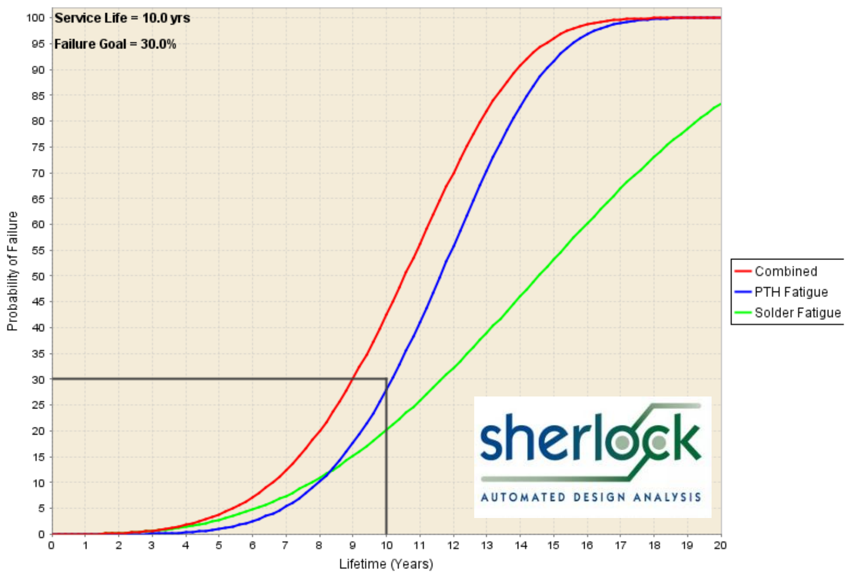
Design Rules Through Prediction (cont.)

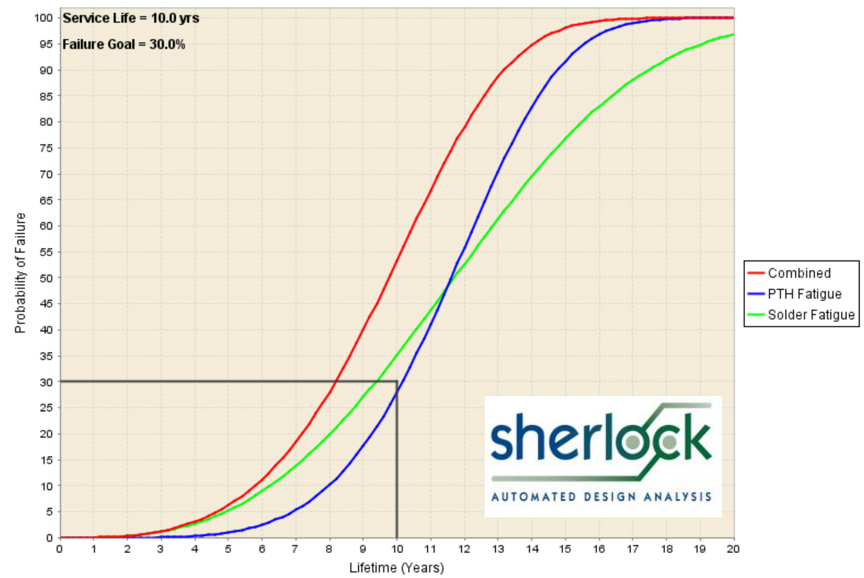


Benchmarking Different Materials

SnPb Assembly

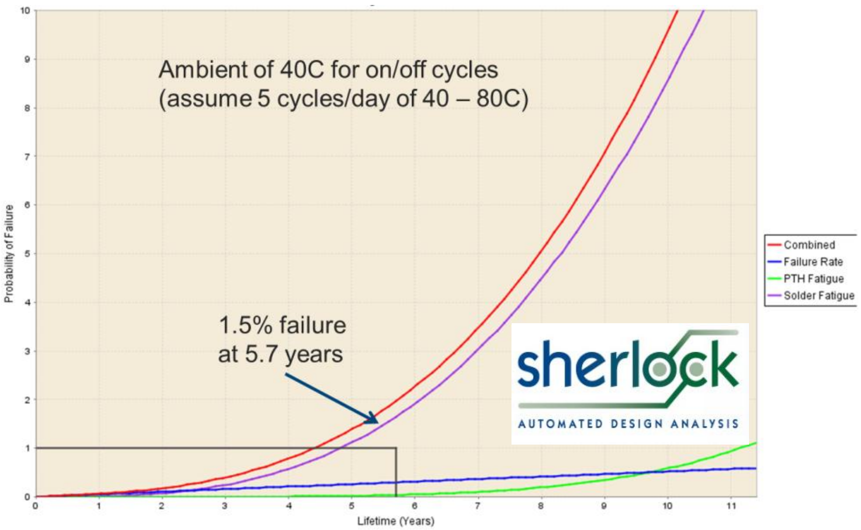


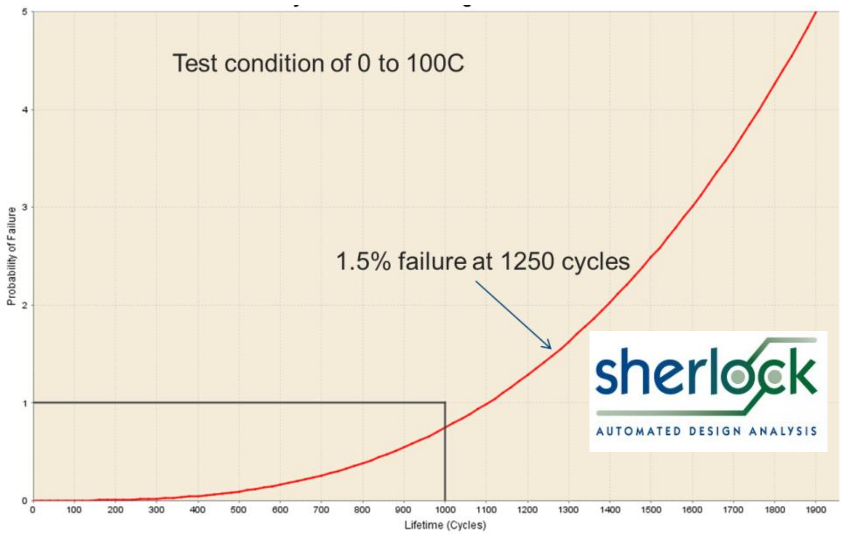
SAC305 Assembly



- Demonstrated to avionics customer that transition to Pb-free would have a detrimental impact to product performance
  - Driven by severe use environment

Developing Accurate Accelerated Life Tests (ALT)





- Lighting products customer was attempting to develop a product qualification plan
- Sherlock identified appropriate test time and test condition based on field environment and likely failure mechanism

Mechanical

Mechanical – Background

- There are three mechanical loading conditions of concern to modern electronics

- **Mechanical Shock / Drop**
- **Bending (Cyclic or Overstress)**
- **Vibration**

- Mechanical failures occur due to either overstress/low cycle/high amplitude events (shock/bending) and high cycle/low amplitude events (vibration/bending)

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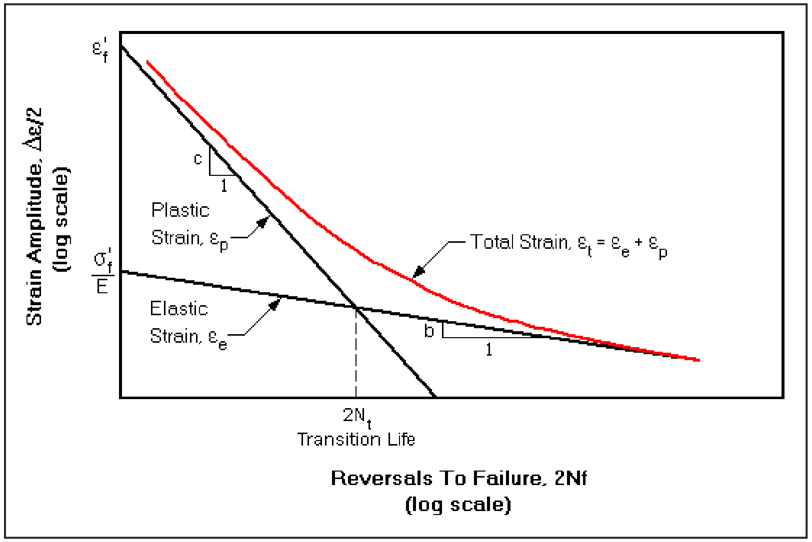
Mechanical Failures

- Low cycle fatigue (LCF) is driven by inelastic strain (Coffin-Manson)
  - Difficult to provide predictions under 100 events/cycles
  - Considered relevant out to 10,000 cycles



- High cycle fatigue (HCF) is driven by elastic strain (Basquin)
  - Primarily vibration, but can be bending as well
  - Failures above 100,000 cycles

$$\varepsilon_e = \frac{\sigma_f}{E}\left(2N_f\right)^b$$

-0.05 < b < -0.12; 8 < -1/b < 20

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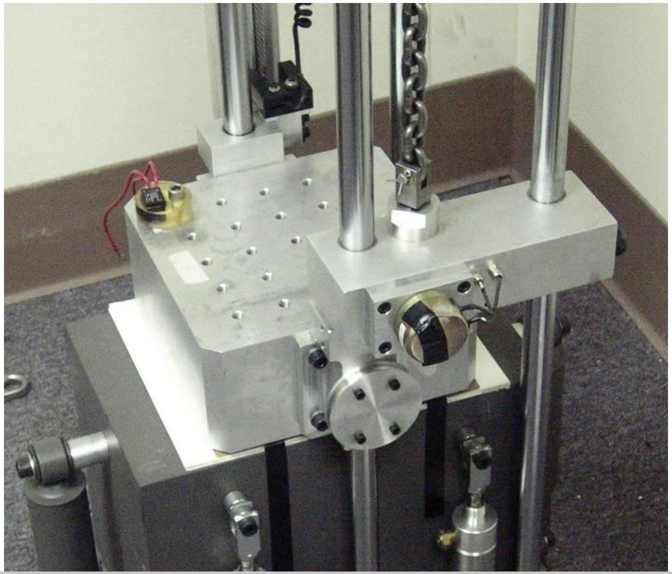
Mechanical Shock / Drop

- Initially driven by experiences during shipping and transportation
- Increasing importance with use of portable electronic devices
  - A surprising concern for portable medical devices
  - Floor transitions (1 to 5 inch 'drop')
- Environmental definitions
  - Height or G levels
  - Surface (e.g., concrete)
  - Orientation (corner or face)
  - Number of drops



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Environmental Definitions (Example)

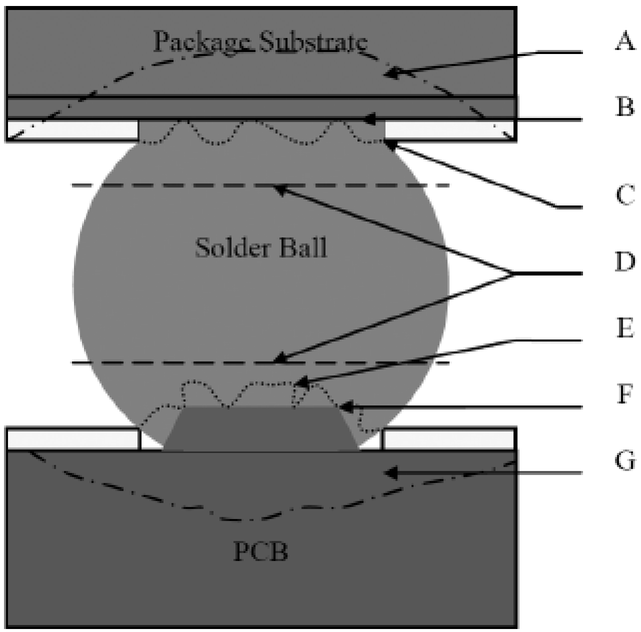
JESD22-B110A, Subassembly Mechanical Shock

Table 2a — Portable subassembly service condition test levels (English units)

Service condition	Equivalent drop height (in) max / reduced	Velocity change (in/s) max / reduced	Peak acceleration (G) max / reduced	Pulse duration (ms) max / reduced
P1	59 / 32	214 / 157	235 / 188	3.7 / 3.4
P2	51 / 28	199 / 147	225 / 181	3.6 / 3.3
P3	44 / 24	184 / 136	214 / 173	3.5 / 3.2
P4	36 / 18	167 / 118	199 / 153	3.4 / 3.1
P5	30 / 12	152 / 96.3	188 / 130	3.3 / 3.0
P6	24 / 10	136 / 87.9	173 / 123	3.2 / 2.9
P7	18 / 8	118 / 78.6	153 / 114	3.1 / 2.8
P8	12 / 6	96.3 / 68.1	130 / 102	3.0 / 2.7
P9	10 / 4	87.9 / 55.6	123 / 87	2.9 / 2.6
P10	8 / 2	78.6 / 39	114 / 61	2.8 / 2.6
P11	6 / 2	68.1 / 39	102 / 61	2.7 / 2.6
P12	4 / 1	55.6 / 28	87 / 43	2.6 / 2.6
P13	3 / 1	48.1 / 28	75 / 43	2.6 / 2.6
P14	2 / 1	39.3 / 28	61 / 43	2.6 / 2.6

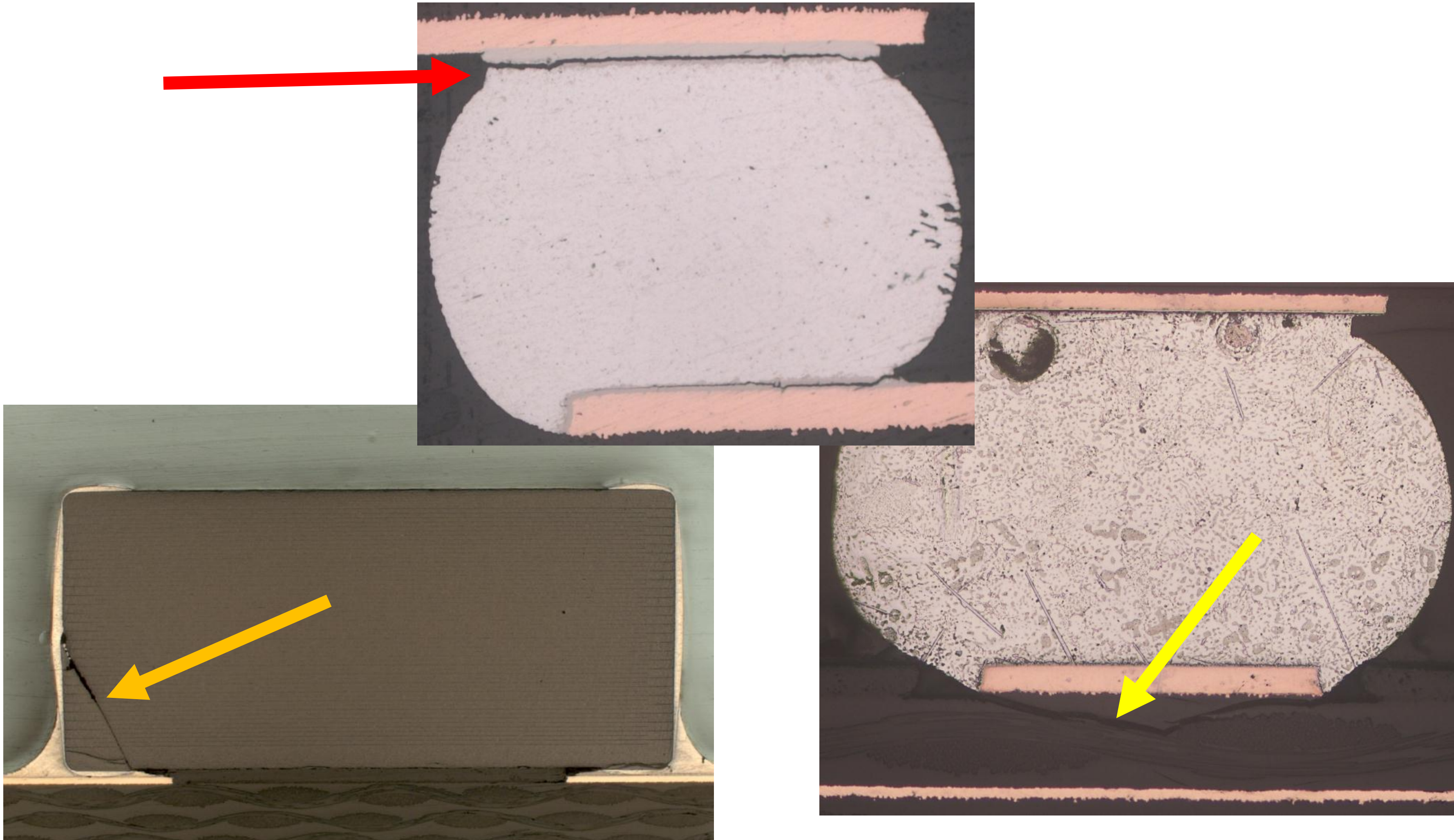
Mechanical Shock Failures

- Due to today's low profile surface mount components, shock failures are primarily driven by board flexure
  - BGAs don't care about in-plane shock
- Specific failure modes are
  - Pad cratering (A,G)
  - Intermetallic fracture (B, F)
  - Component cracking
- Shock tends to be an overstress event (though, not for car doors)
  - Failure distribution is 'random'



Legend
A Package Pad Lift/Crater
B Pkg Base Metal/IMC Interface Fracture
C Pkg IMC/Solder Interface Fracture
D Bulk Solder Fracture
E PCB IMC/Solder Interface Fracture
F PCB Solder pad/IMC Interface Fracture
G PCB Pad Lift/Crater

Mechanical Shock Failure Modes



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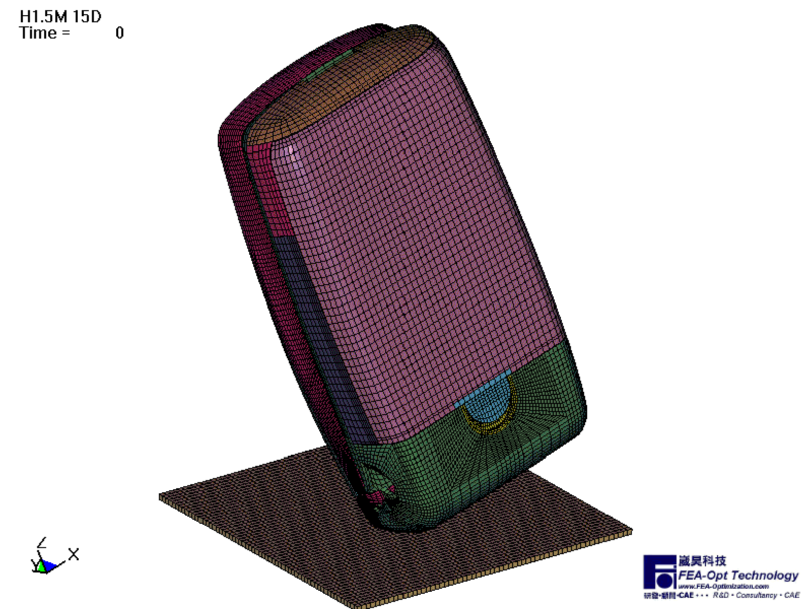
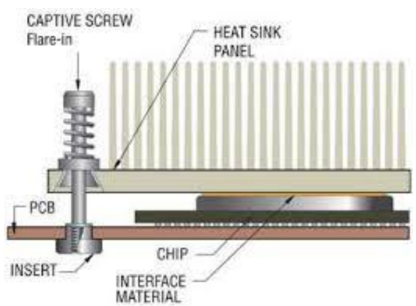
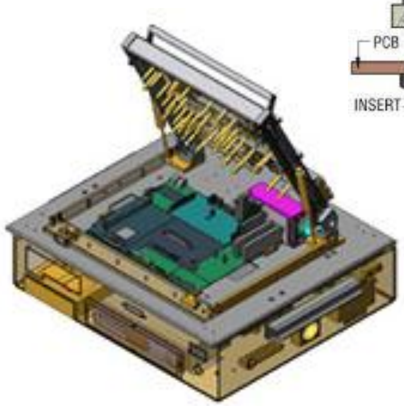
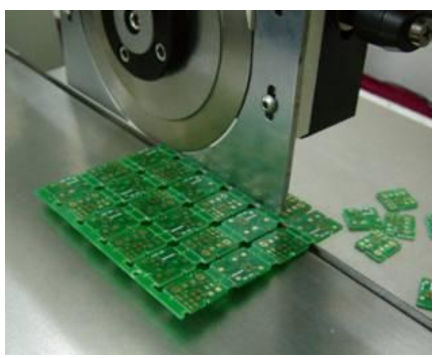
Mechanical Shock Events

- Tend to be overly focused on drop, but excessive flexure can occur at multiple points post-assembly







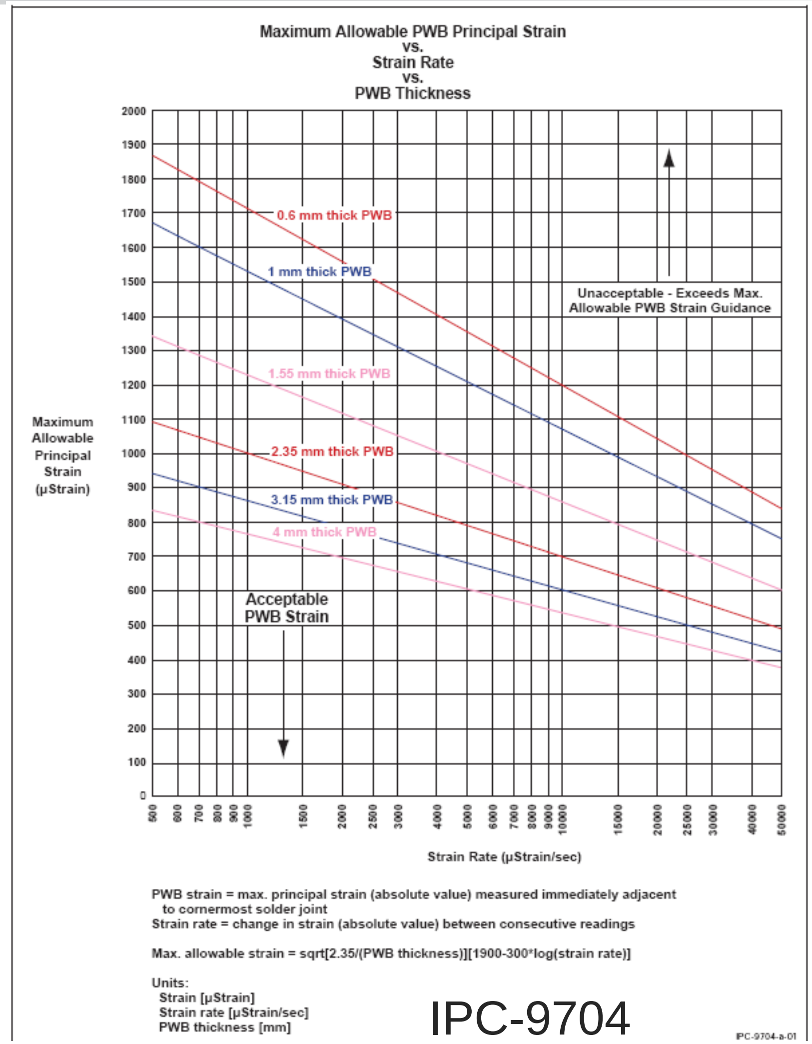


Predicting Mechanical Shock Failures

- Currently no methodology for predicting number of shocks/drops to failure
  - Assessment is go/no-go
- Based on a critical board level strain
  - Varies based on component type and strain rate

$$\varepsilon_c = \frac{\zeta}{c\sqrt{L}}$$

Initially developed by Steinberg



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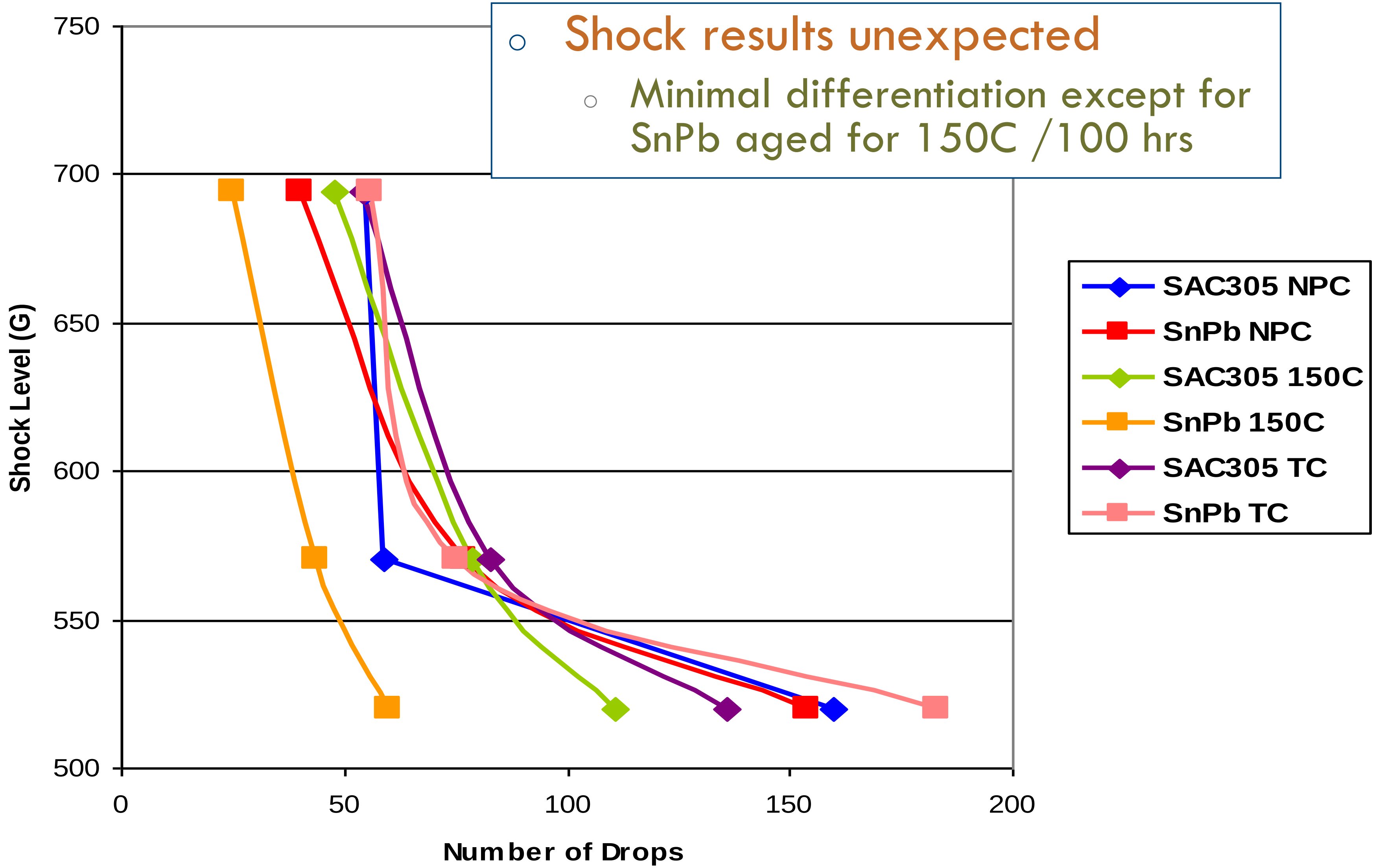
- Shock results unexpected
  - Minimal differentiation except for SnPb aged for 150C /100 hrs



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Shock Analysis – Curvature

Curvature deflection relationship

$$\kappa = \frac{-Z \cdot \pi^2}{B^2}$$

Curvature strain relationship

$$\varepsilon = \frac{\kappa \cdot t}{2}$$

B = board length
Z = board deflection
κ = board curvature
ε = board strain
t = board thickness

Shock induced strains

Pulse	Time	Frequency	G	Board Strain	Board Strain limit
1500 G	0.5 mS	1000 Hz	570	1614 με	1400 με, C=1 622 με, C=2.25
1000 G	1.00 mS	500 Hz	694	1950 με	
750 G	1.00 mS	500 Hz	520	1445 με	

- Critical board strain is 622 με for BGAs
  - Board strain should not exceed this for either solder
  - In line with IPC recommendations

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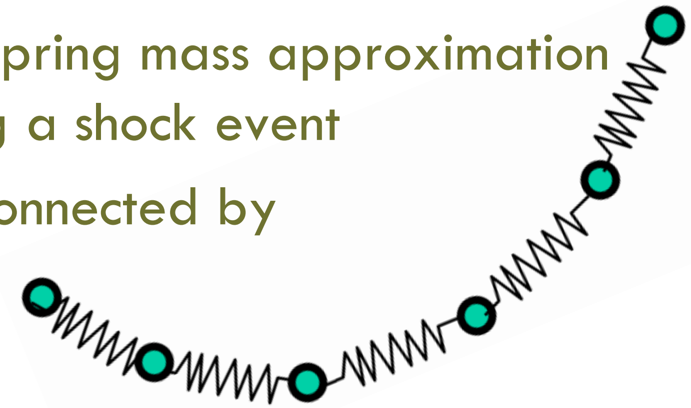
Calculating Board Level Strain

- Except for really simple structures, you need finite element analysis (FEA)
  - There are techniques that use simple spring mass approximation to predict the board deflection during a shock event
  - Spring/mass models assume masses connected by ideal weightless springs



- FEA simulations are usually transient dynamic
  - DfR (Sherlock) utilizes an implicit transient dynamic simulation (useful when solving linear/elastic)

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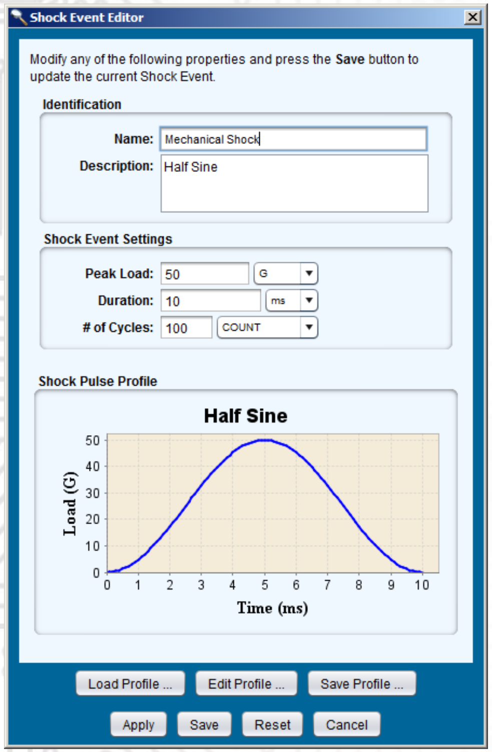
Calculating Board Level Strain

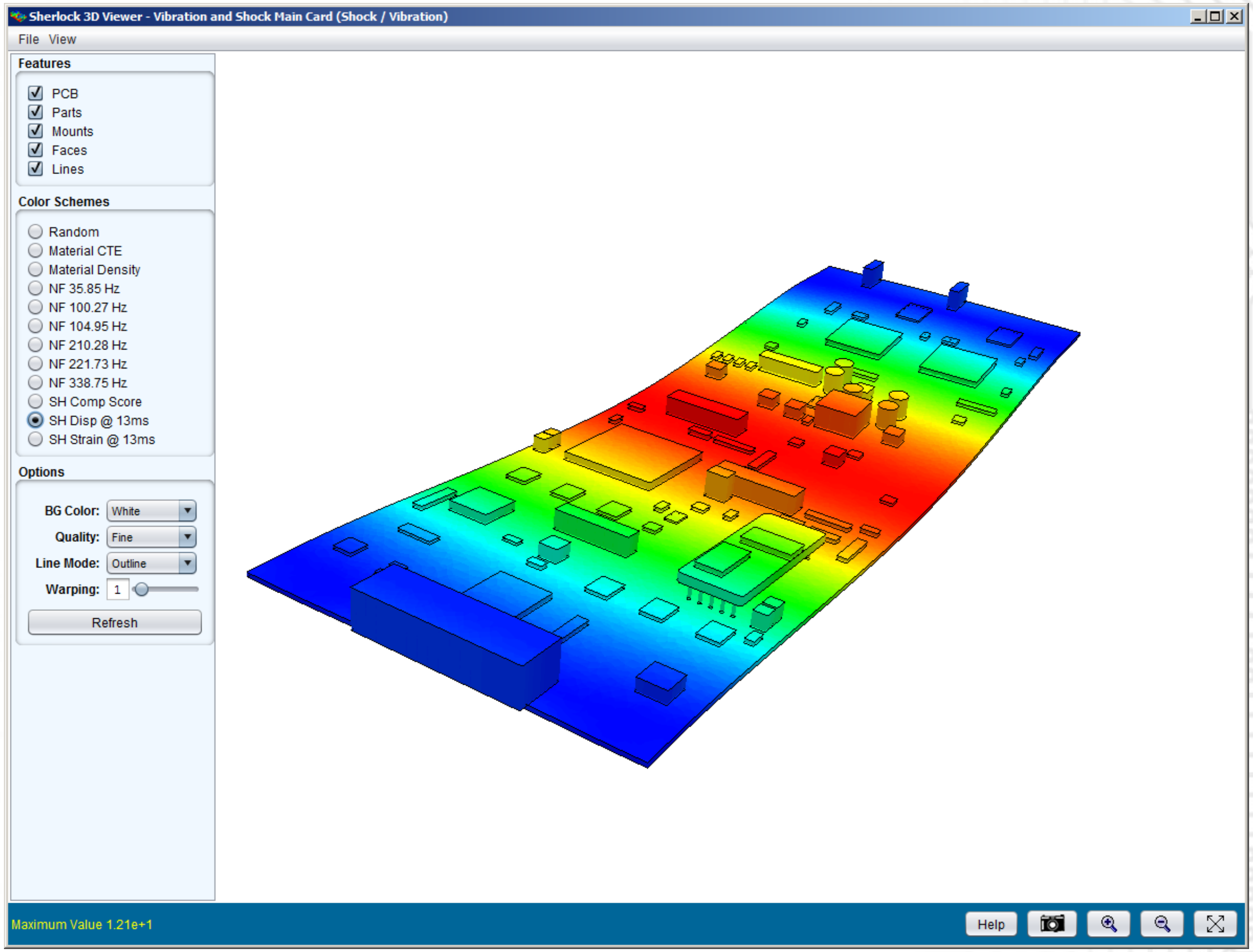
- Shock pulse is transmitted through the mounting points into the board

- The resulting board strains are extracted from the FEA results and used to predict robustness under shock conditions

CPU Card with DC/DC Converter

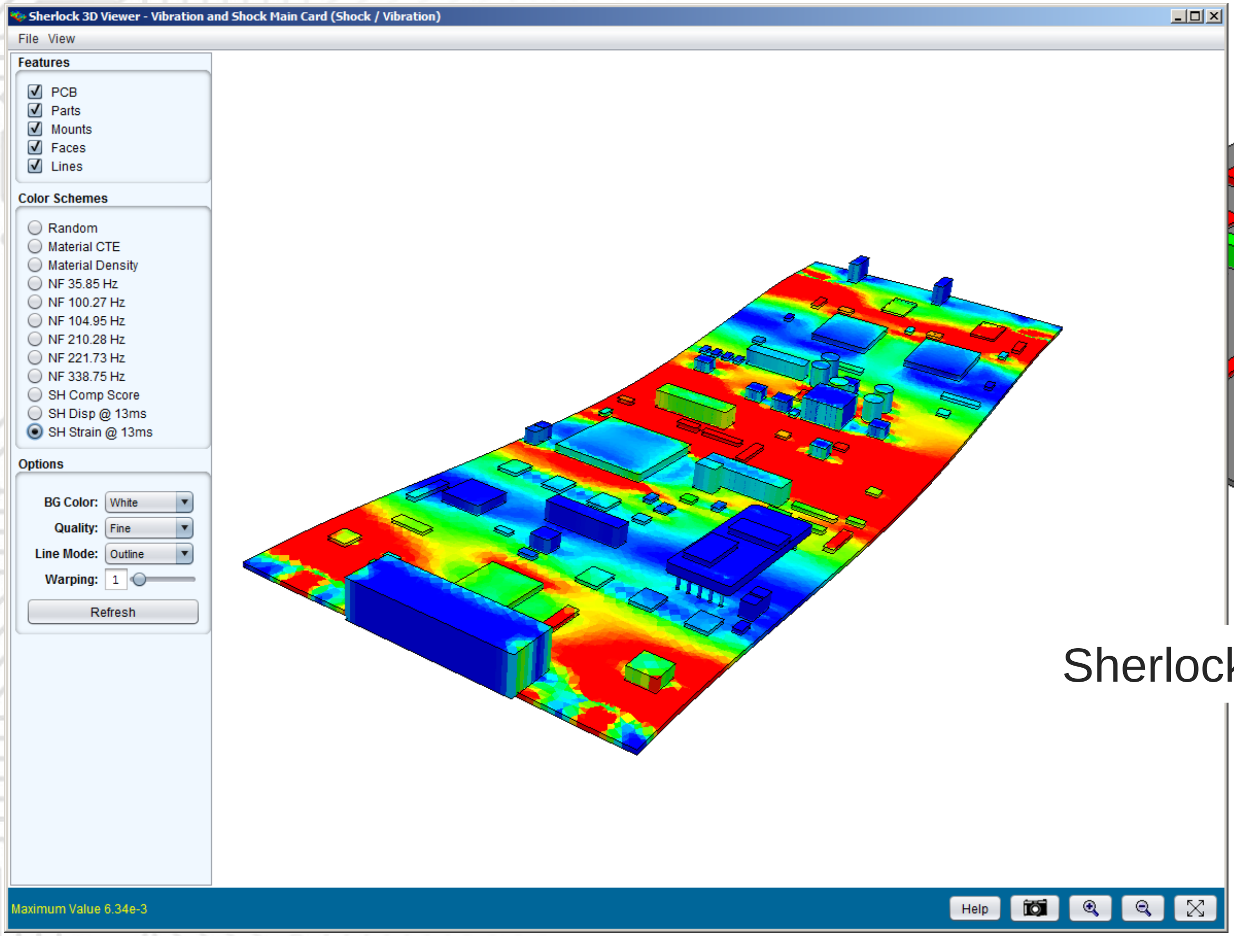
- 50G shock pulse
- Results in 12 mm deflection (severe)

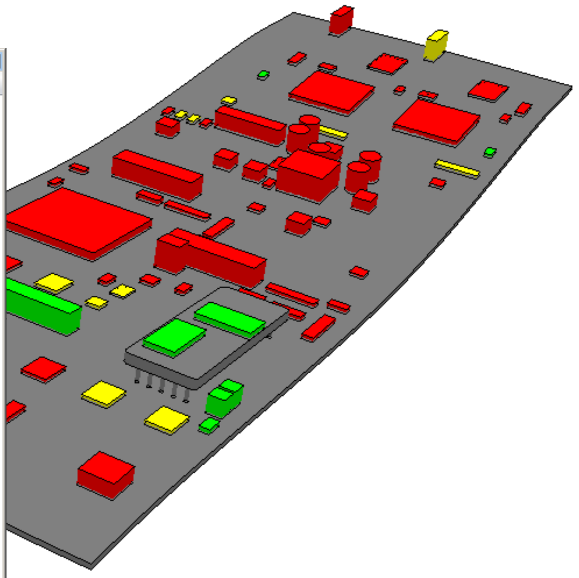




Shock Failure Predictions

- Excessive bending strains



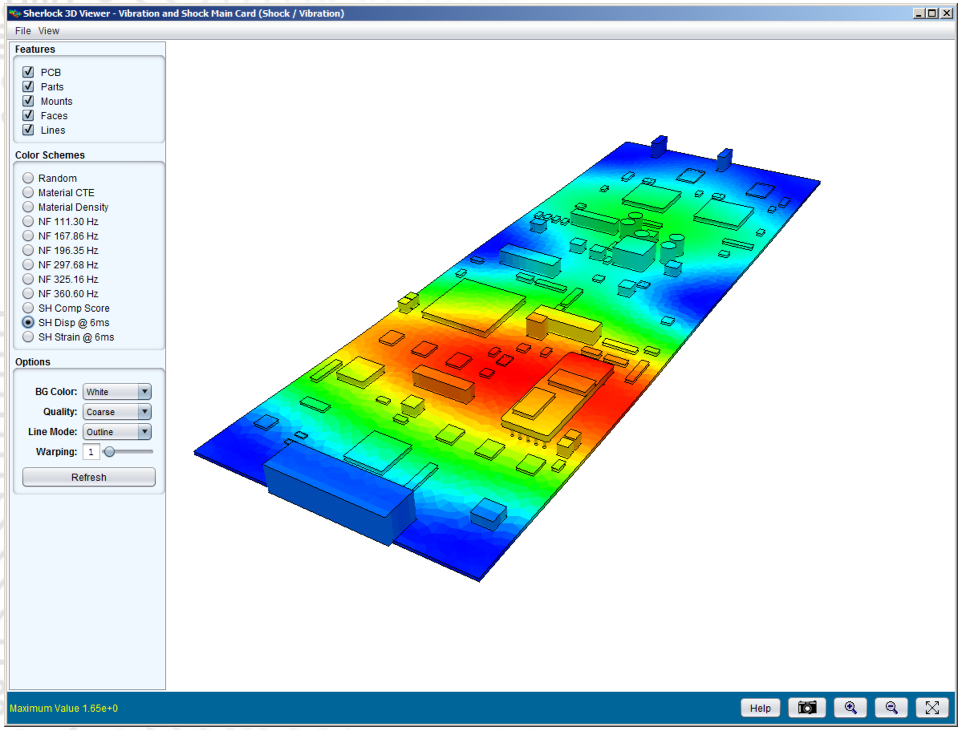


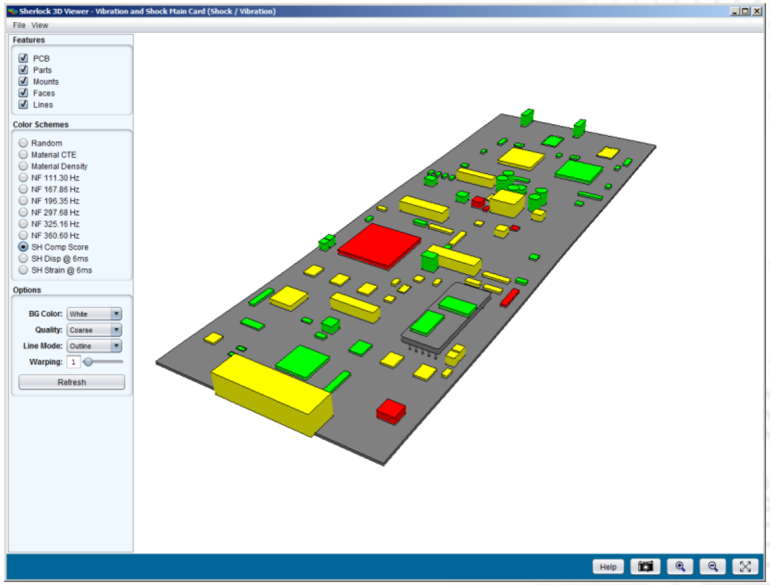
Sherlock scoring on deformed plot

sherlock
AUTOMATED DESIGN ANALYSIS

Model Modification Shock

- Two additional mounting points added mid-span
- Deflection drops from 12 mm to 1.65 mm



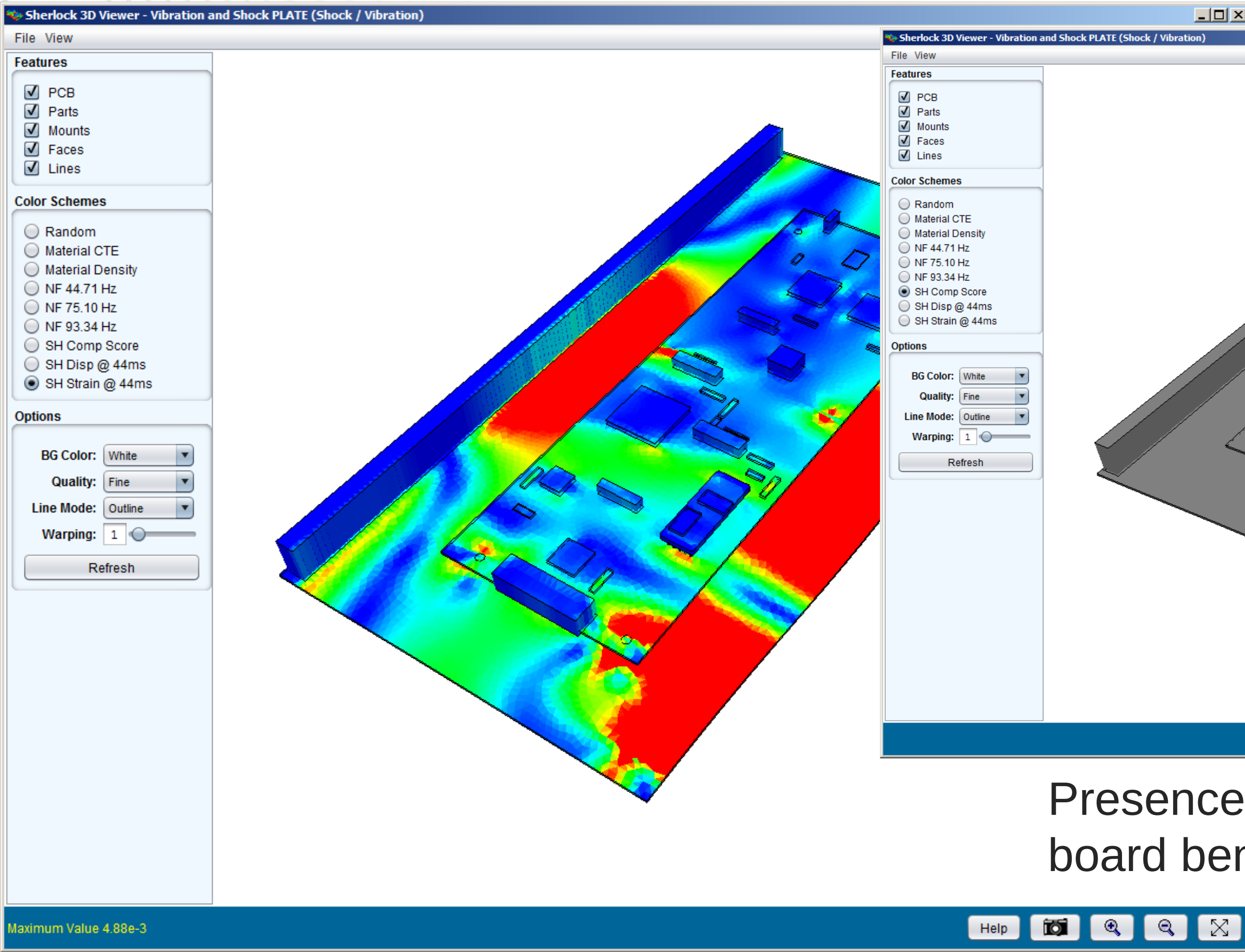


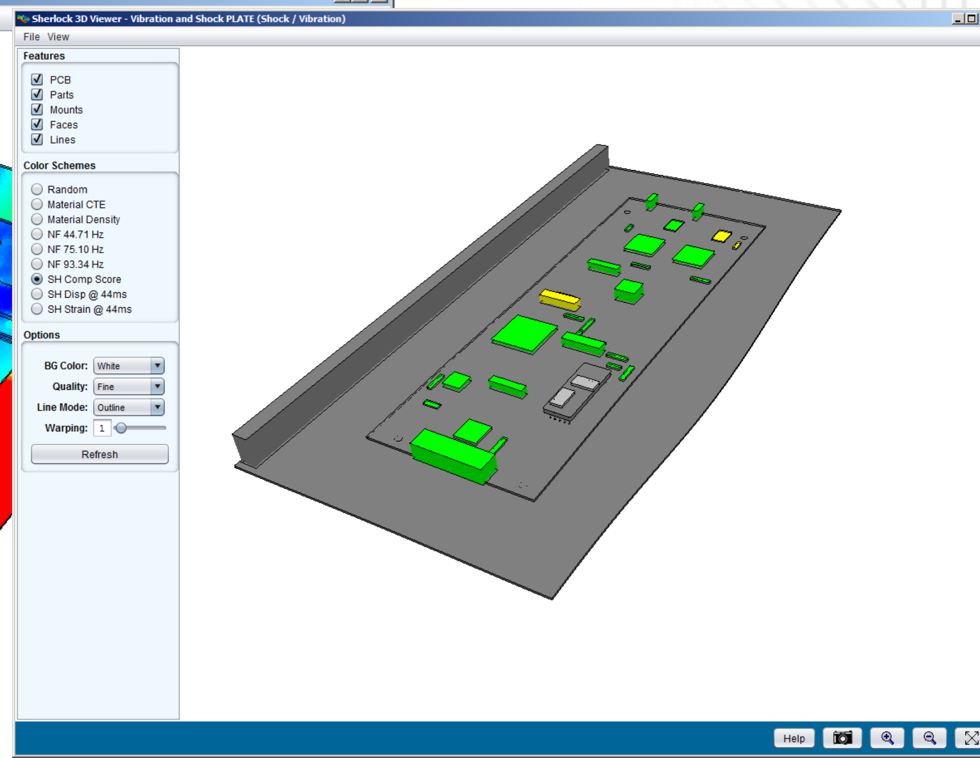
Still some component failures more support is needed

DfR Solutions
reliability designed, reliability delivered

Model Modification Shock

- Board mounted to a chassis plate





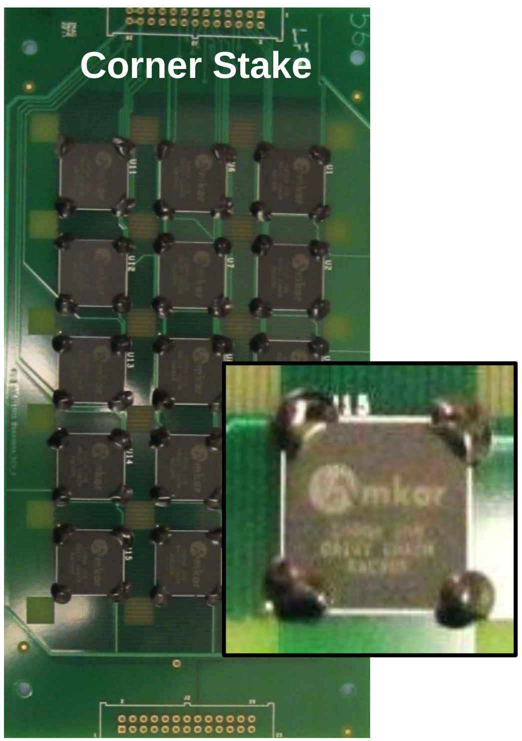
Presence of chassis reduces board bending

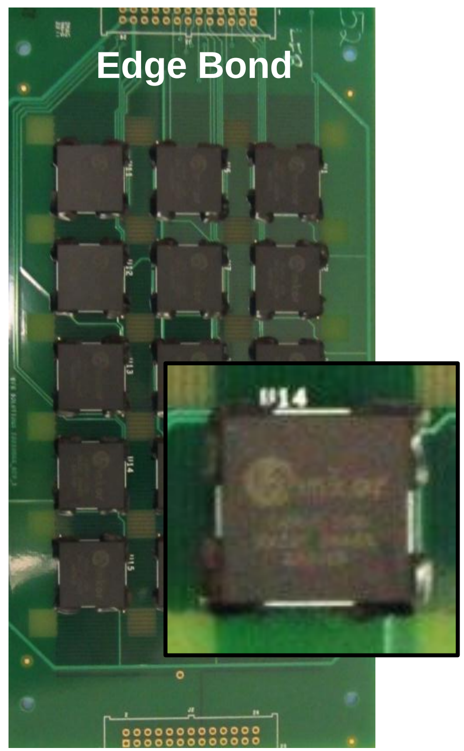
How to Mitigate Shock/Drop?

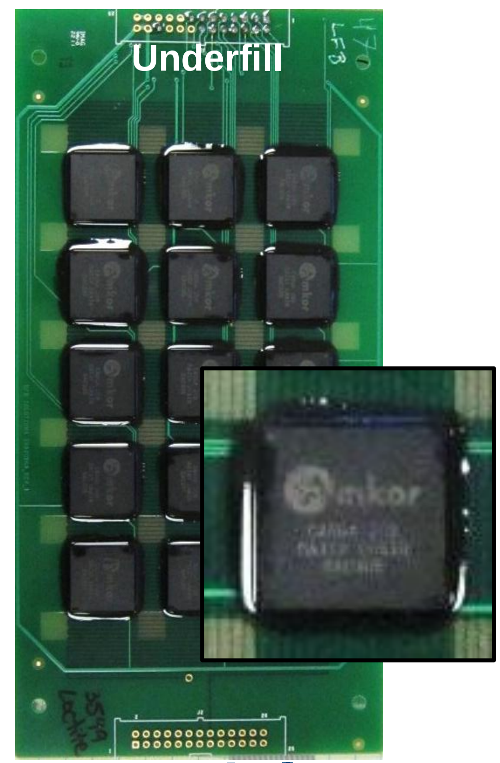
- Option One: Stop the board from bending!
  - Mount points, standoffs, epoxy bonding, thicker board, etc.
- Option Two: Give your part flexibility
  - Flexible terminations on ceramic capacitors
- Option Three: Strengthen your part (BGA / CSP)
  - Corner Staking
  - Edge Bonding
  - Underfill

Experimental Design - Mitigation

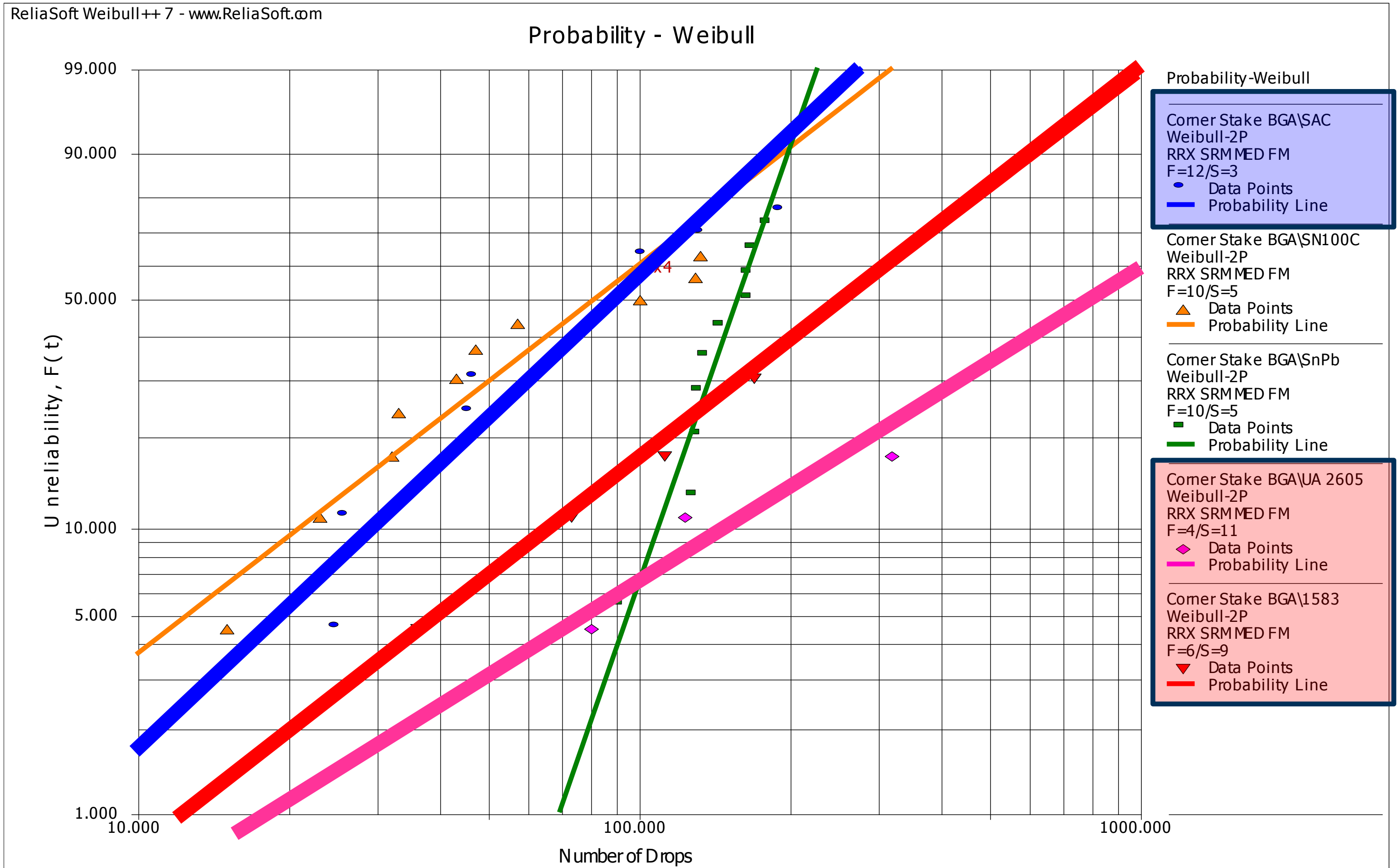
- Edge bond/Corner Stake: Zymet UA 2605 & Namics XR1583-2
- Underfill: Loctite 3549 & Namics SUF1589-1 (BGAs only)







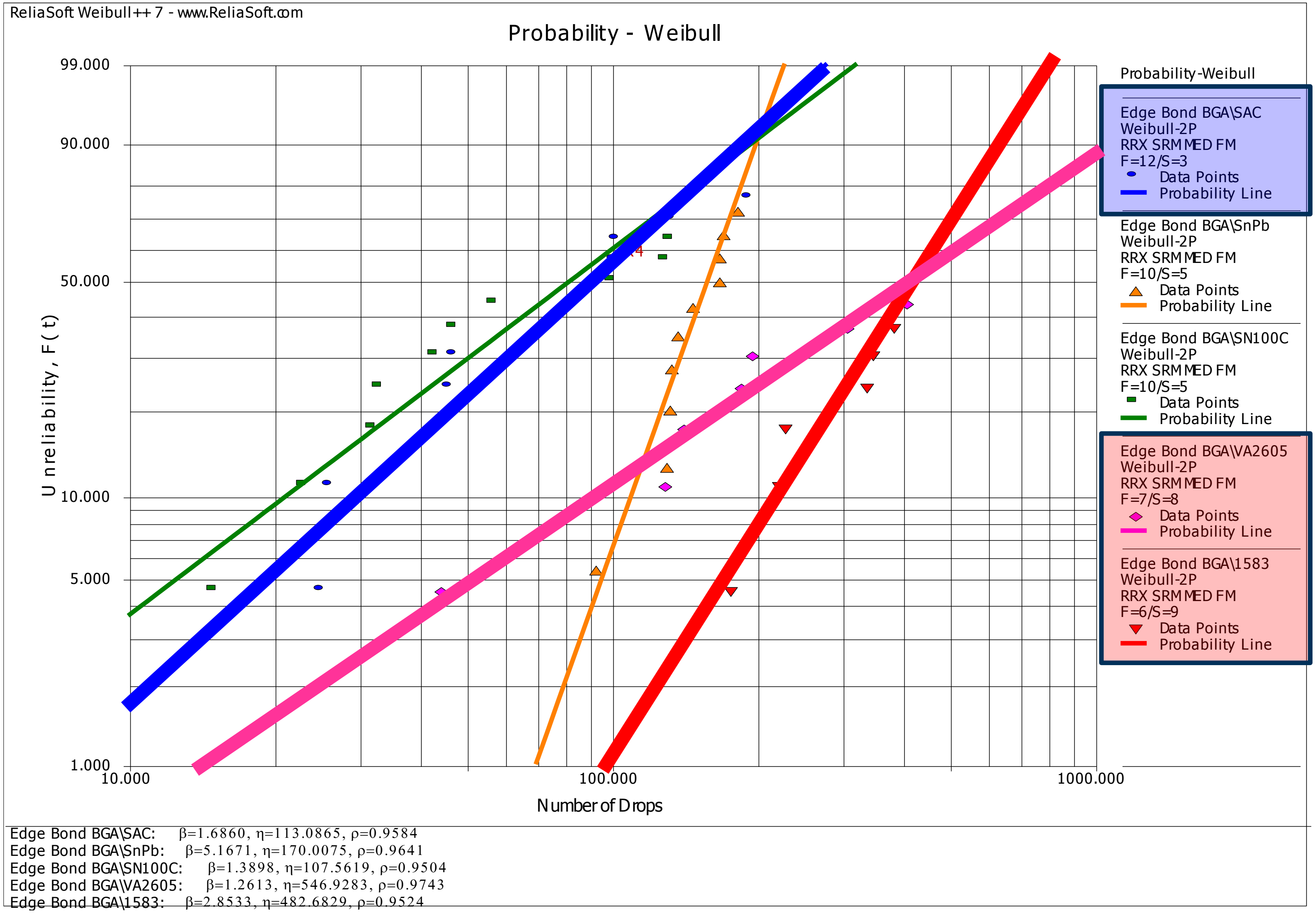
Shock/Drop and Corner Staking



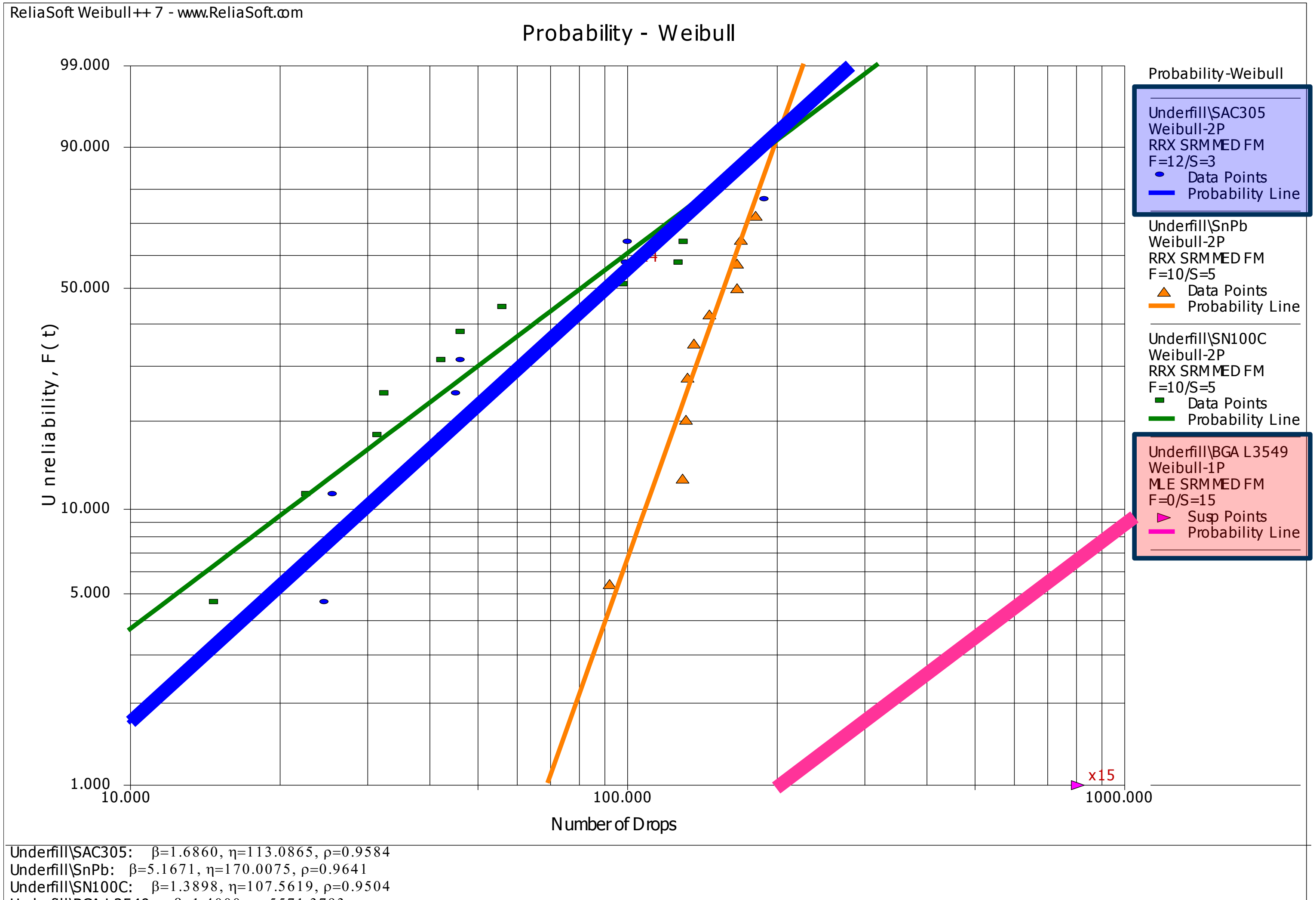
Corner Stake BGA\SAC: β=1.6860, η=113.0865, ρ=0.9584
Corner Stake BGA\SN100C: β=1.3898, η=107.5619, ρ=0.9504
Corner Stake BGA\SnPb: β=5.1671, η=170.0075, ρ=0.9641
Corner Stake BGA\UA 2605: β=1.1227, η=1121.6403, ρ=0.9543
Corner Stake BGA\1583: β=1.3737, η=347.1600, ρ=0.9977

DfR Solutions

Shock/Drop and Edge Bonding



Shock/Drop and Underfill



DfR Solutions

Mechanical - Vibration

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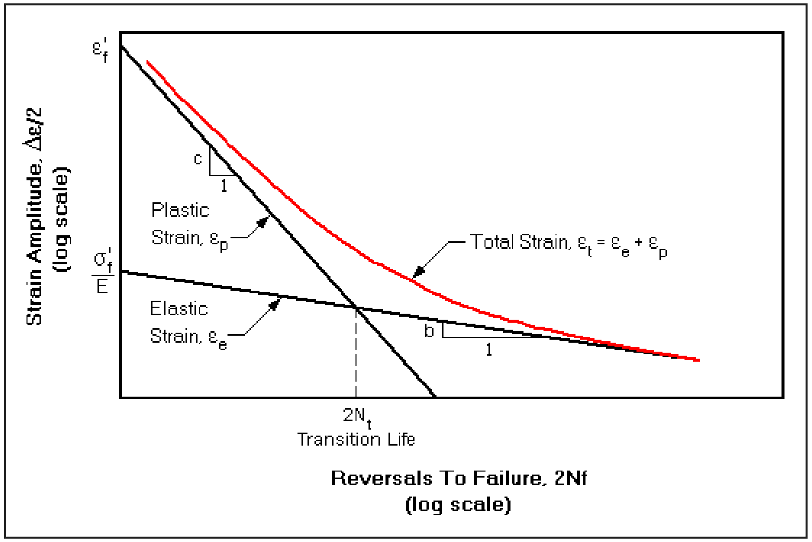
Mechanical Failures

- Low cycle fatigue (LCF) is driven by inelastic strain (Coffin-Manson)
  - Difficult to provide predictions under 100 events/cycles
  - Considered relevant out to 10,000 cycles

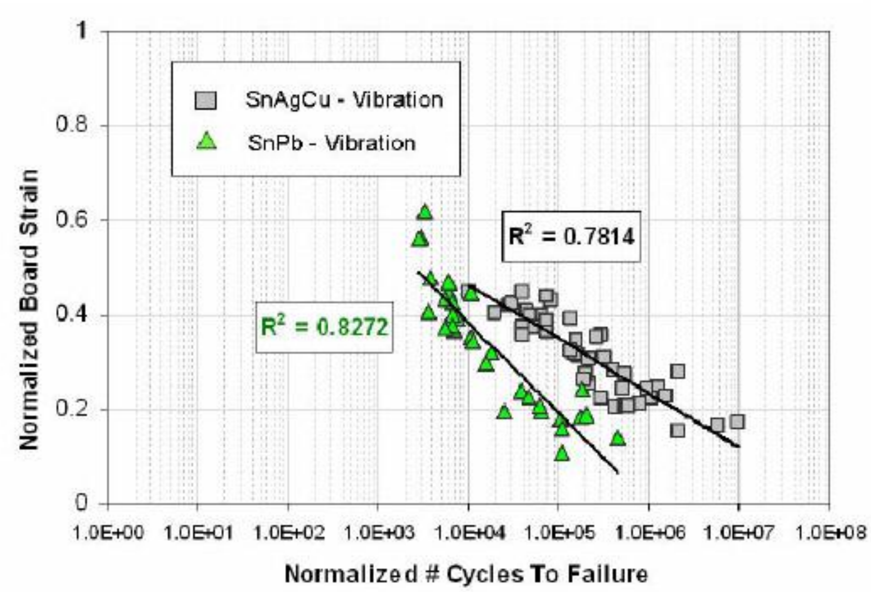


- High cycle fatigue (HCF) is driven by elastic strain (Basquin)
  - Primarily vibration, but can be bending as well
  - Failures above 100,000 cycles

$$\varepsilon_e = \frac{\sigma_f}{E}\left(2N_f\right)^b$$

-0.05 < b < -0.12; 8 < -^{1}/b < 20

Vibration is Difficult (example)



- Sinusoidal Vibration
  - 0.75g to 4.0g input
- Note change in Pb-free behavior at high loads, compared to SnPb
  - Similar behavior observed at DfR

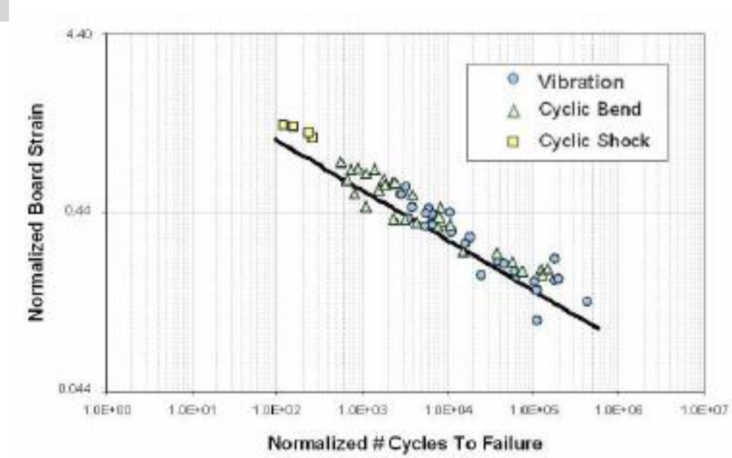


Figure 8: Mechanical fatigue curve of SnPb solder system.

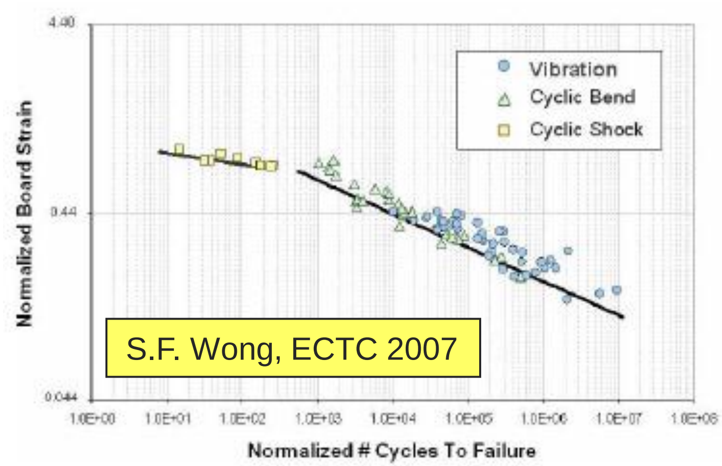


Figure 9: Mechanical fatigue curves of SnAgCu solder system..

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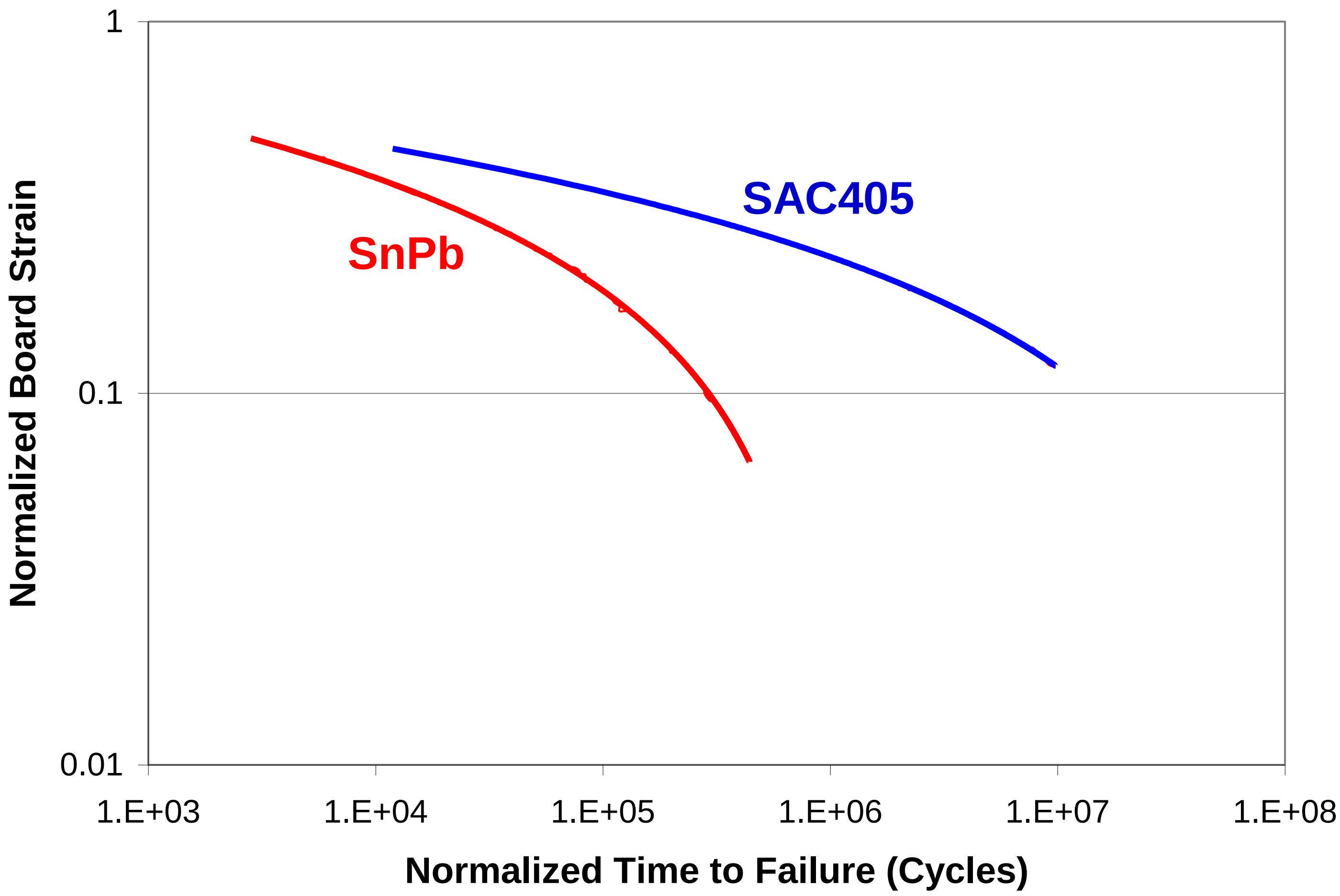
Vibration is Difficult (cont.)



Results do not display power-law behavior

When Does Vibration Occur?

- Primarily affiliated with transportation
  - Shipping (very short part of the life cycle)
  - Automotive, trains, avionics, etc.

- Also a concern with rotating machinery (motors)
  - Transportation, appliances, HVAC, pipelines

- The two environments produce two very different forms of vibration
  - Harmonic (sinusoidal) and Random

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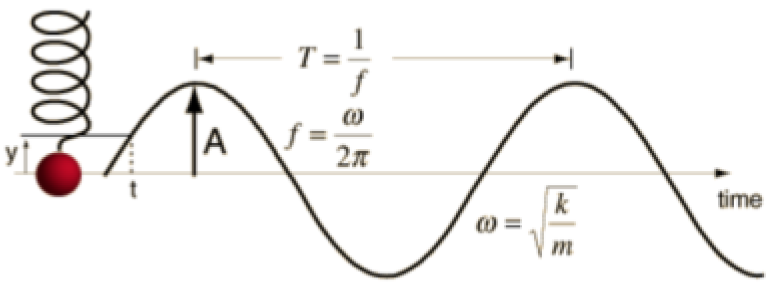
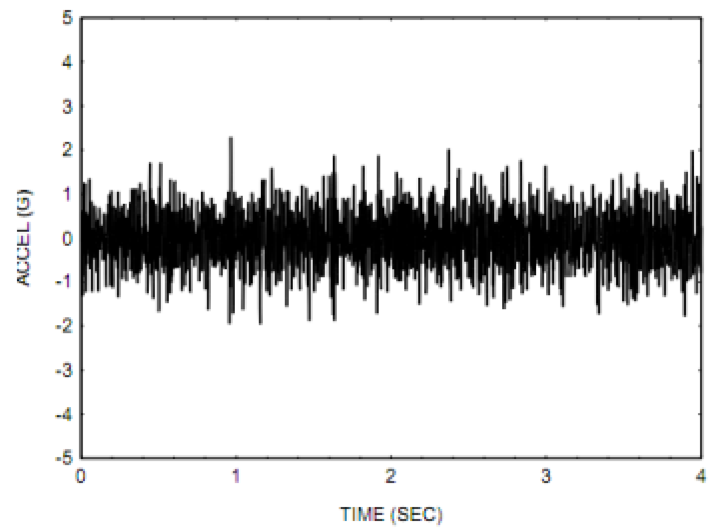
Forms of Vibration

- Single frequency



- Random vibration is a continuous spectrum of frequencies



General equivalence. Sine and random characterizations of vibration are based on distinctly different sets of mathematics. In order to compare the effects of given random and sine vibration on materiel, it is necessary to know the details of materiel dynamic response. A general definition of equivalence is not feasible.

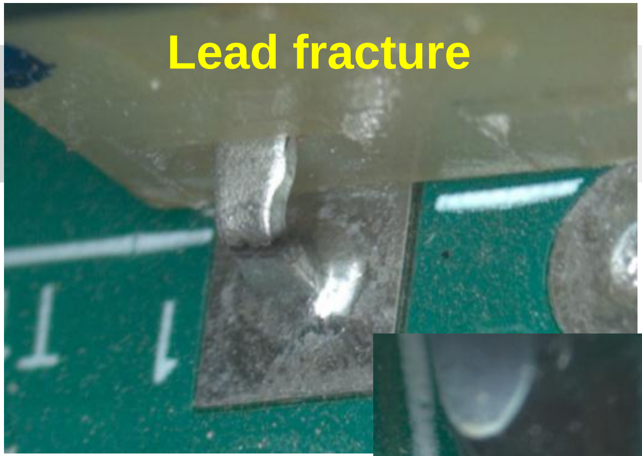
Grms. Often, attempts are made to compare the peak acceleration of sine to the rms acceleration of random. The only similarity between these measures is the dimensional units that are typically acceleration in standard gravity units (g). Peak sine acceleration is the maximum acceleration at one frequency (see paragraph 2.3.2). Random rms is the square root of the area under a spectral density curve (see paragraph 2.3.1). **These are not equivalent!**

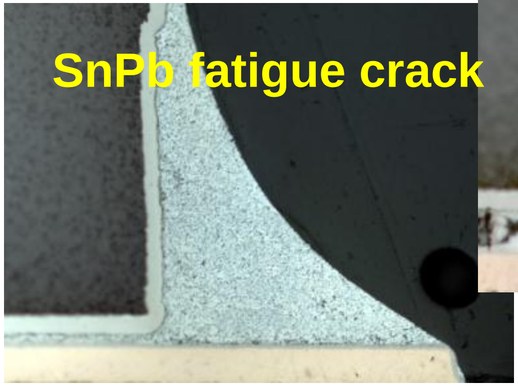
MIL-STD-810G

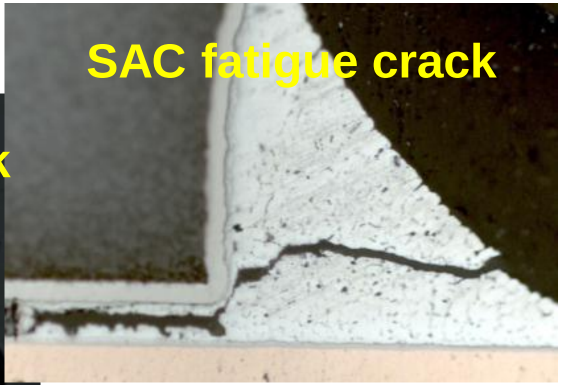
AN INTRODUCTION TO RANDOM VIBRATION – Tom Irvine

Vibration Failure Sites

- Failure sites may occur in the lead or solder (or even PCB traces)
  - Lead failures often affiliated with tall components and in-plane vibration
- Crack propagation usually in the bulk material
  - Cracks along the interface, typically either indicate a much higher stress application (such as shock) or manufacturing defect







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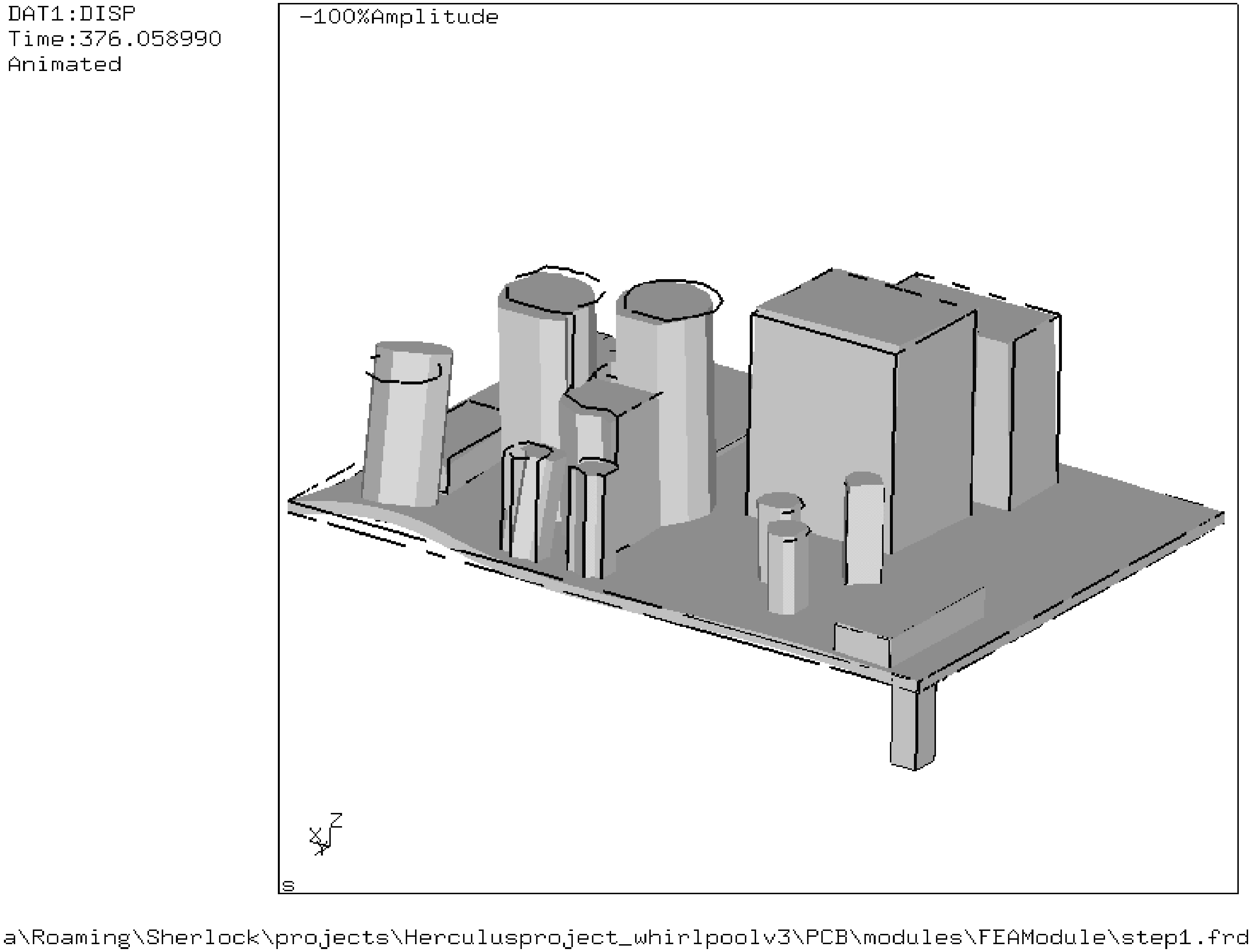
In-Plane Component Vibration

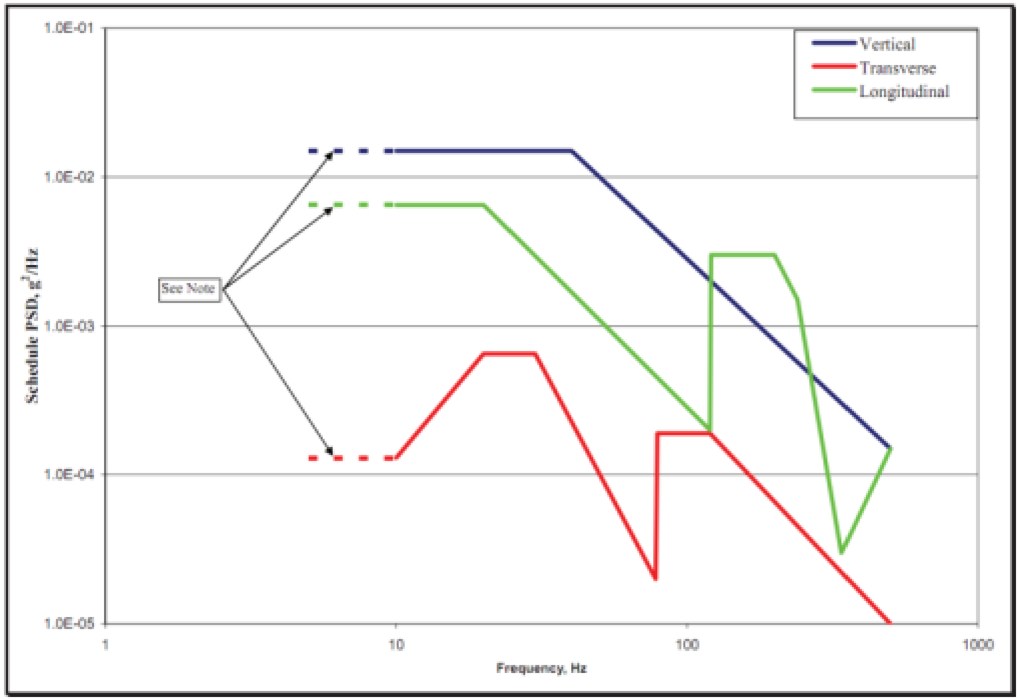


Vibration Environments (Examples)

Harmonic

Steinberg D.S. Vibration analysis for electronic equipment. John Wiley & Sons, 2000.

Equipment	Frequency range (Hz)	Acceleration level (*G*)
Ships and Submarines	1-50	1-3
Automobiles, trucks, and tanks	15-40	15-19
Airplanes	3-1000	1-5
Helicopters	3-500	0.5-4
Missiles	5-5000	5-30



Random

MIL-STD-810G Figure 514.6C-1
US Highway truck vibration exposure

1 hour is equivalent to 1000 miles

DfR Solutions

Vibration Environments (cont.)

- Exposure to vibration loads can result in highly variable results
  - Vibration loads can vary by orders of magnitude (e.g., 0.001 g^2/Hz to 1 g^2/Hz)
  - Time to failure is very sensitive to vibration loads ($t_f \propto W^4$)

- Very broad range of vibration environments
  - MIL-STD-810 lists 3 manufacturing categories, 8 transportation categories, 12 operational categories, and 2 supplemental categories

Bending vs. Vibration

- Bending is equivalent to out-of-plane vibration with two key caveats

- 1. Most test results plot life as a function of board-level strain
  - Equivalent to solder strain only in the elastic regime (high enough bending can drive solder strain into the plastic regime)

- 2. Bend cycling is ½ to ¼ less severe than vibration
  - Because bending is not fully reversed

Predicting Vibration Failures (Steinberg)

- The board displacement is modeled as a single degree of freedom system (spring, mass) using an estimate (or measured) of the natural frequency
  - Allows for calculation of maximum deflection (Z_0)

$$Z_0 = \frac{9.8 \times 3\sqrt{\pi/2 \cdot PSD \cdot f_n \cdot Q}}{f_n^2}$$

Random

- Variables
  - PSD is the power spectral density (g^2/Hz)
  - f_n is the natural frequency of the CCA
  - G_{in} is the acceleration in g
  - Q is transmissibility (assumed to be square root of natural frequency)

$$Z_0 = \frac{9.8 \times G_{in} \times Q}{f_n^2}$$

Harmonic

Steinberg D.S. Vibration analysis for electronic equipment. John Wiley & Sons, 2000.

Predicting Vibration Failures (cont.)

- Calculate critical displacement
  - This is the displacement value at which the component can survive 10 to 20 million cycles (harmonic, random)

- Variables
  - B is length of PCB parallel to component
  - c is a component packaging constant
    - 1 to 2.25
  - h is PCB thickness
  - r is a relative position factor
    - 1.0 when component at center of PCB
  - L is component length

$$Z_c = \frac{0.00022B}{chr\sqrt{L}}$$

Steinberg D.S. Vibration analysis for electronic equipment.
John Wiley & Sons, 2000.

DfR Solutions

Predicting Vibration Failures (cont.)

- Life calculation
  - Nc is 10 or 20 million cycles

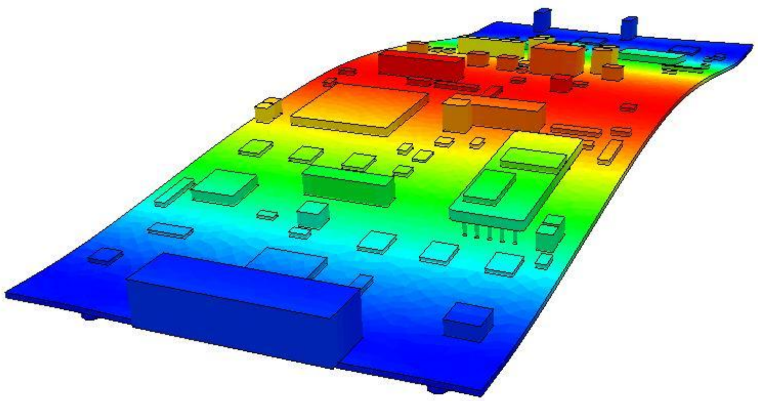
$$N_0 = N_c \left(\frac{Z_c}{Z_0} \right)^{6.4}$$

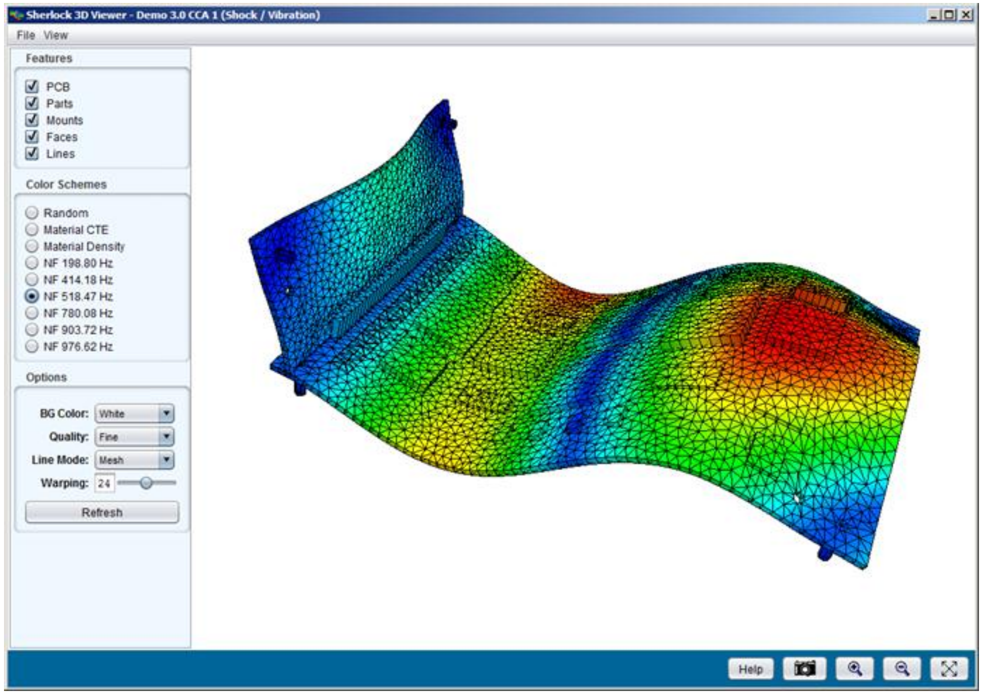
- Several assumptions
  - CCA is simply supported on all four edges
  - More realistic support conditions, such as standoffs or wedge locks, can result in a lower or higher displacements
  - Chassis natural frequency differs from the CCA natural frequency by at least factor of two (octave)
  - Prevents coupling
  - Does not consider printed circuit board bending (components can have zero deflection but still be subjected to large amounts of bending)

Steinberg D.S. Vibration analysis for electronic equipment.
John Wiley & Sons, 2000.

FEA Based Vibration Predictions

- Finite Element Analysis can be used to capture more complex geometries, loadings and boundary conditions



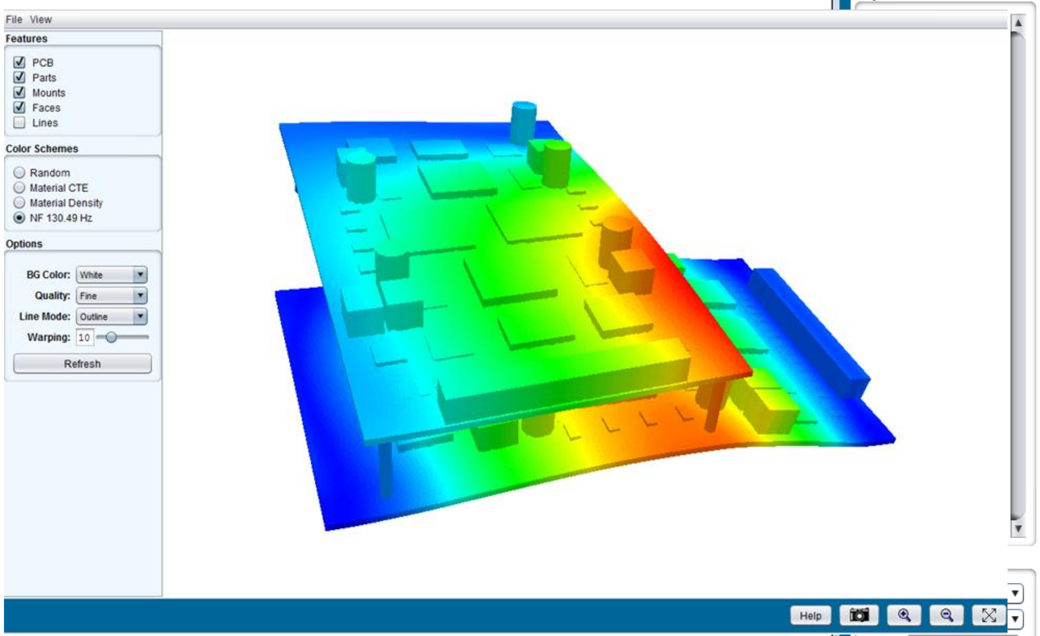


DfR Solutions

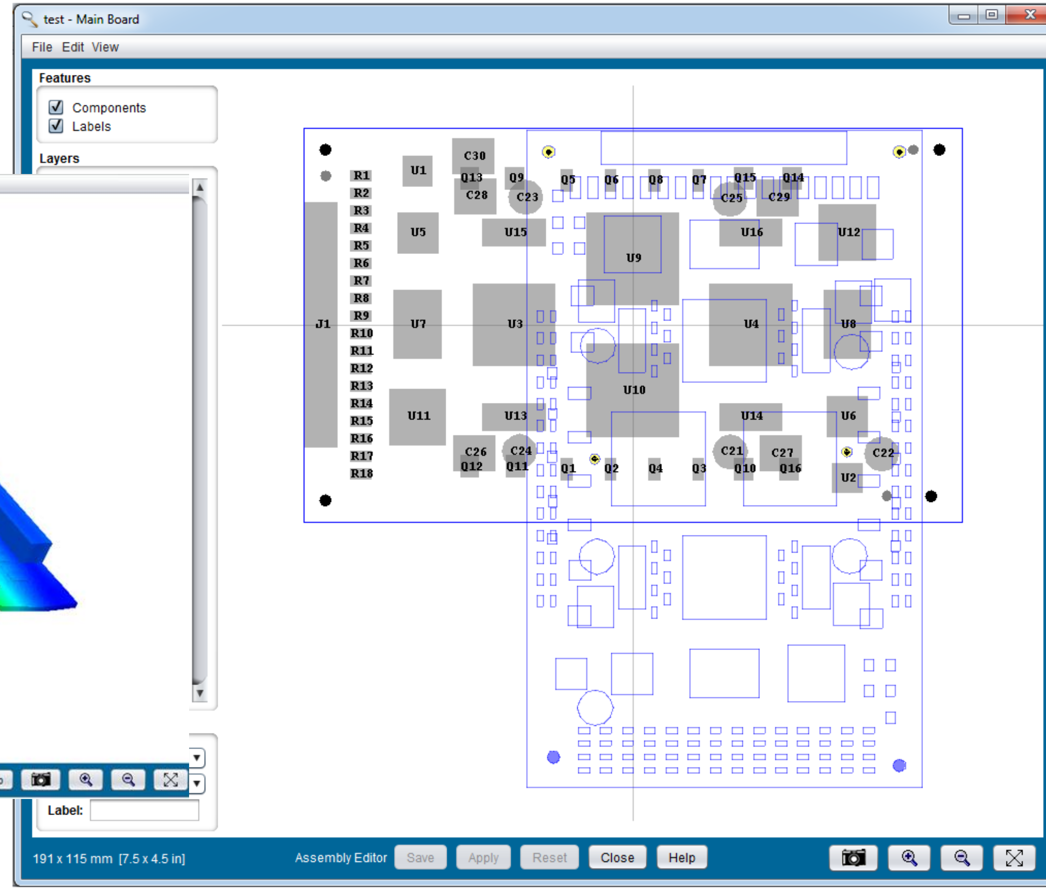
FEA Based Vibration Predictions (cont.)

Example:

Mezzanine and Daughter cards



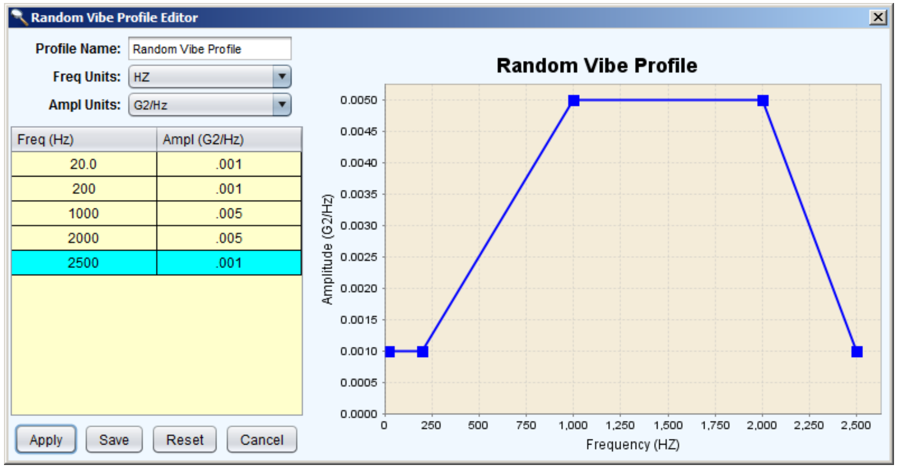
Sherlock 3.0



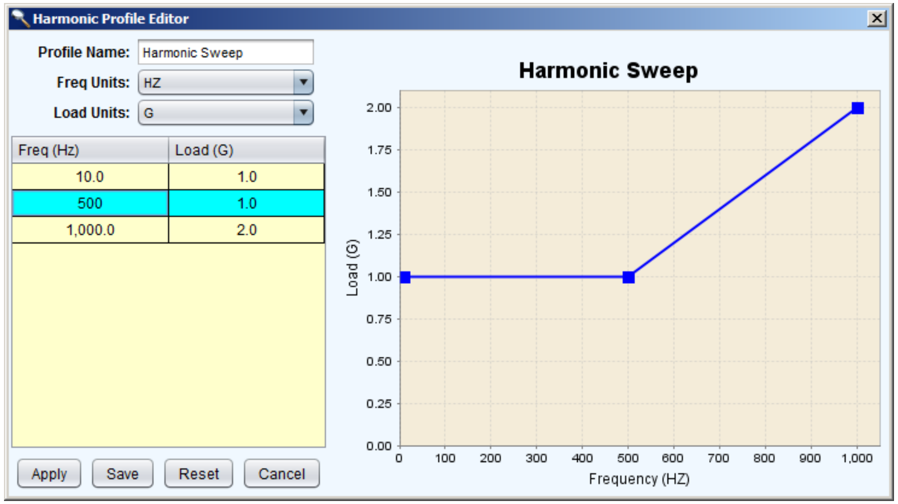
Sherlock 3.0

DfR Solutions

FEA Modeling Loads



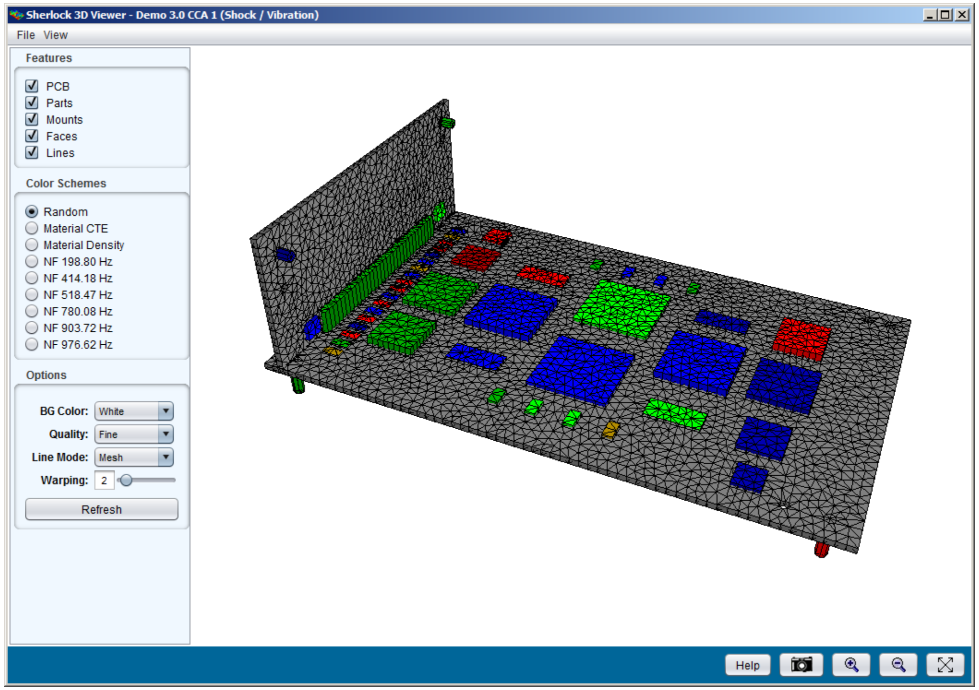
- Loading can be applied to the model directly from the specification
- Vibration is applied to the structure through the standoffs/mount points



DfR Solutions

FEA Vibration Simulation

- Determining the response of the structure to a vibration load is commonly done using a Modal Dynamic Analysis
  - It is necessary to do a modal analysis before conducting this analysis
  - Determines the eigenvalues and eigenmodes (natural frequencies)
  - Calculates the stiffness and mass matrices



DfR Solutions

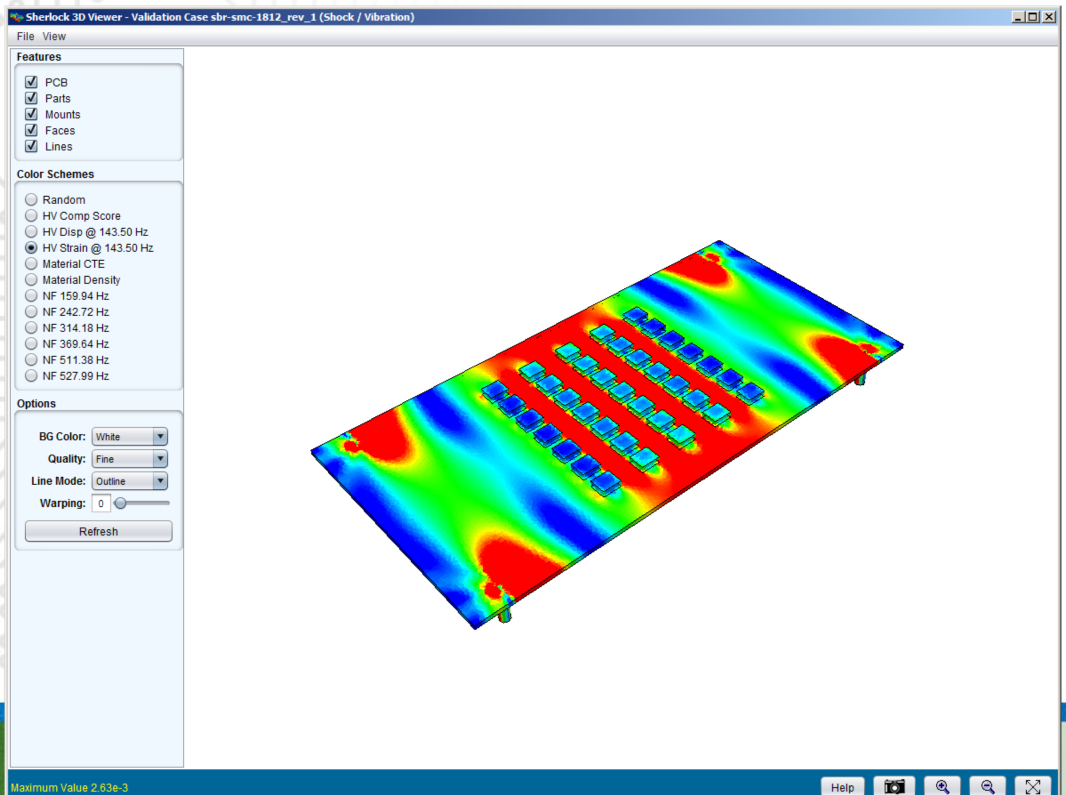
FEA Failure Prediction

- During vibration the board strain is proportional to the solder or lead strains and therefore can be used to make time to failure predictions
- This requires converting the cycles to failure displacement equations (Steinberg) to use strain
- The strain for the components is now pulled from the FEA results
- The critical strain for the package types is a function of package style, size, lead geometry

$$\varepsilon_c = \frac{\zeta}{c\sqrt{L}}$$

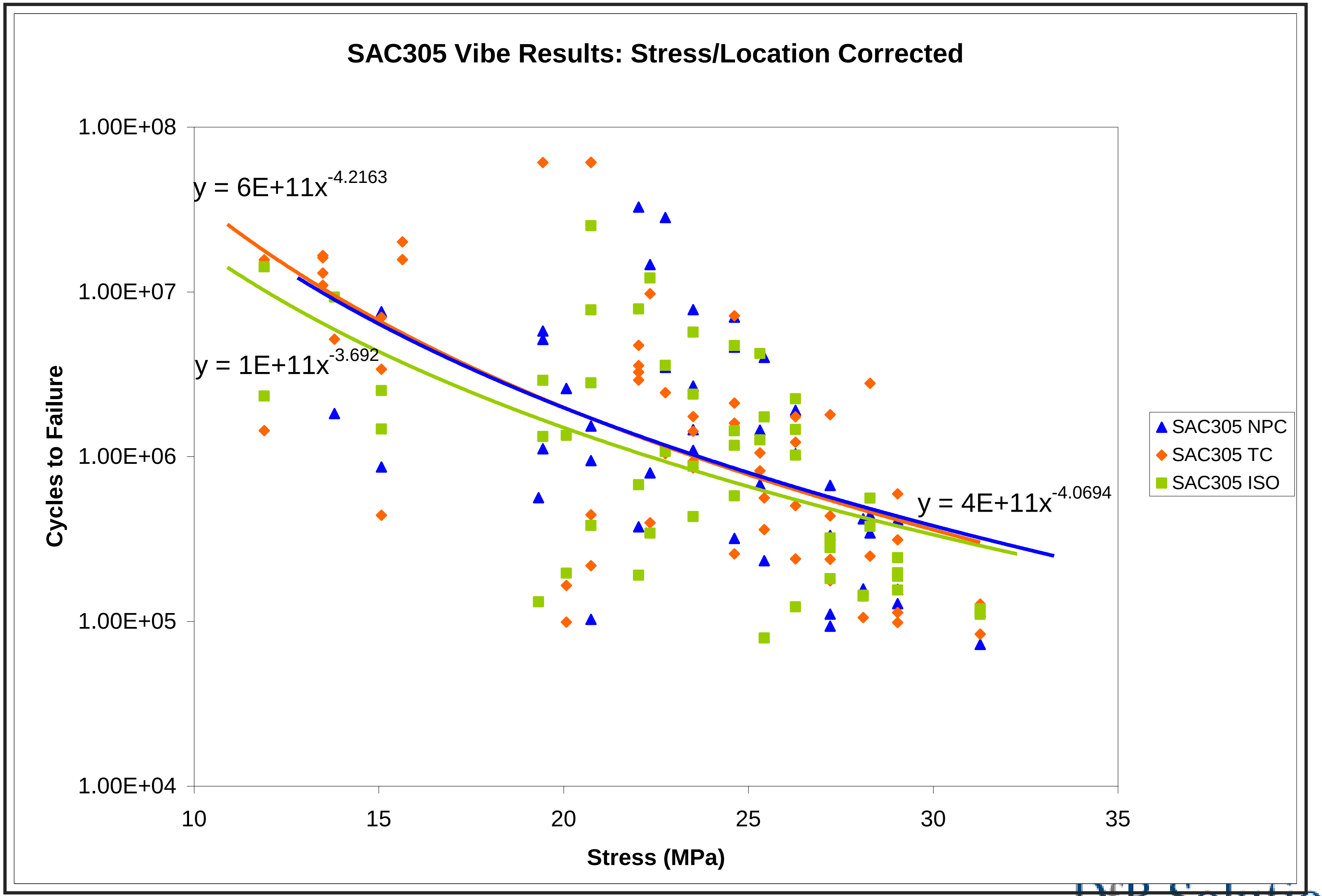
ζ is analogous to 0.00022B but modified for strain
c is a component packaging function
L is component length

$$N_0 = N_c \left(\frac{\varepsilon_c}{\varepsilon_0} \right)^n$$

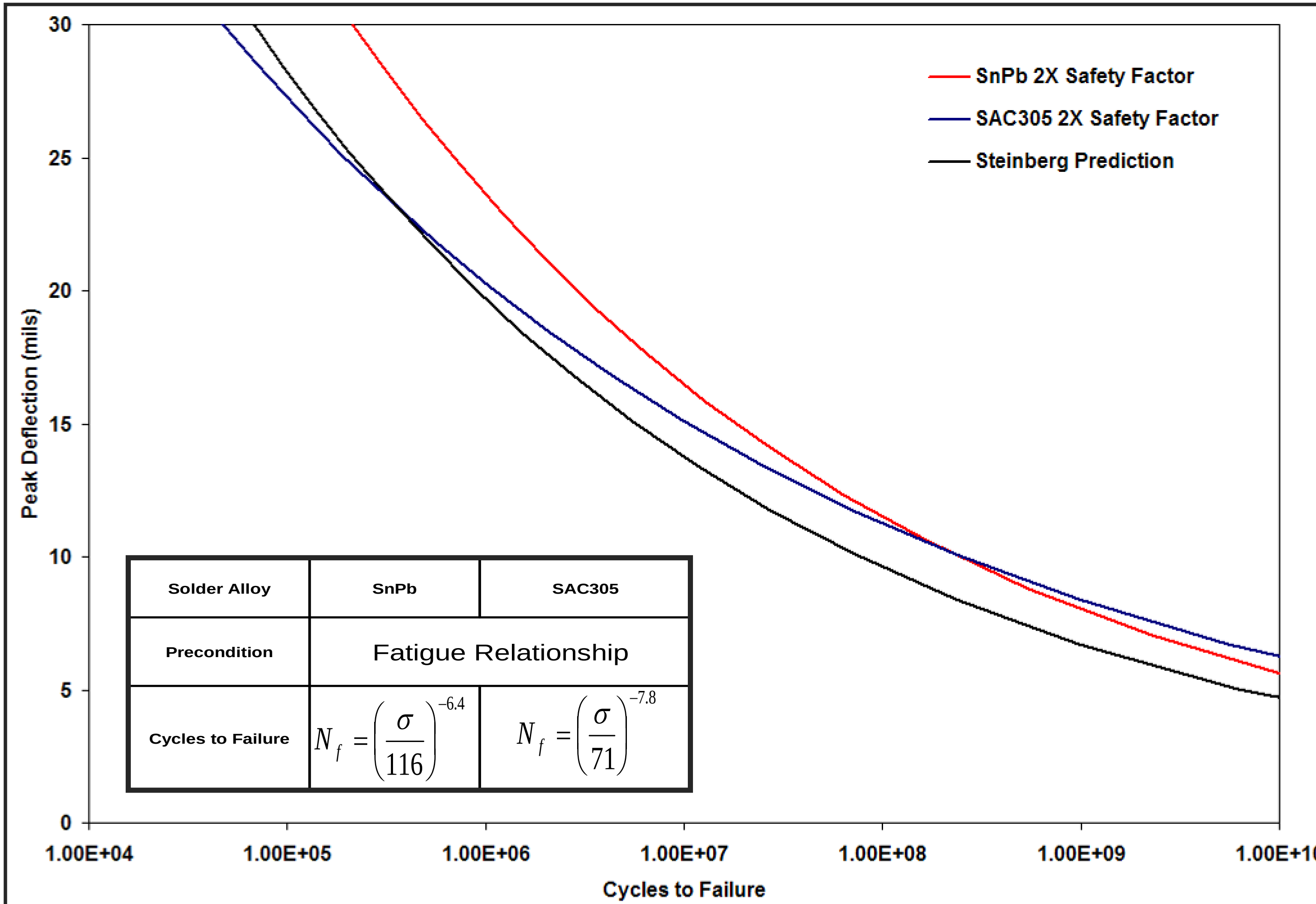


Sherlock 3.0

Examples of Vibration Testing



Vibration Behavior of Solders



Solder Alloy	SnPb	SAC305
Precondition	Fatigue Relationship	
Cycles to Failure	$N_f = \left(\frac{\sigma}{116}\right)^{-6.4}$	$N_f = \left(\frac{\sigma}{71}\right)^{-7.8}$

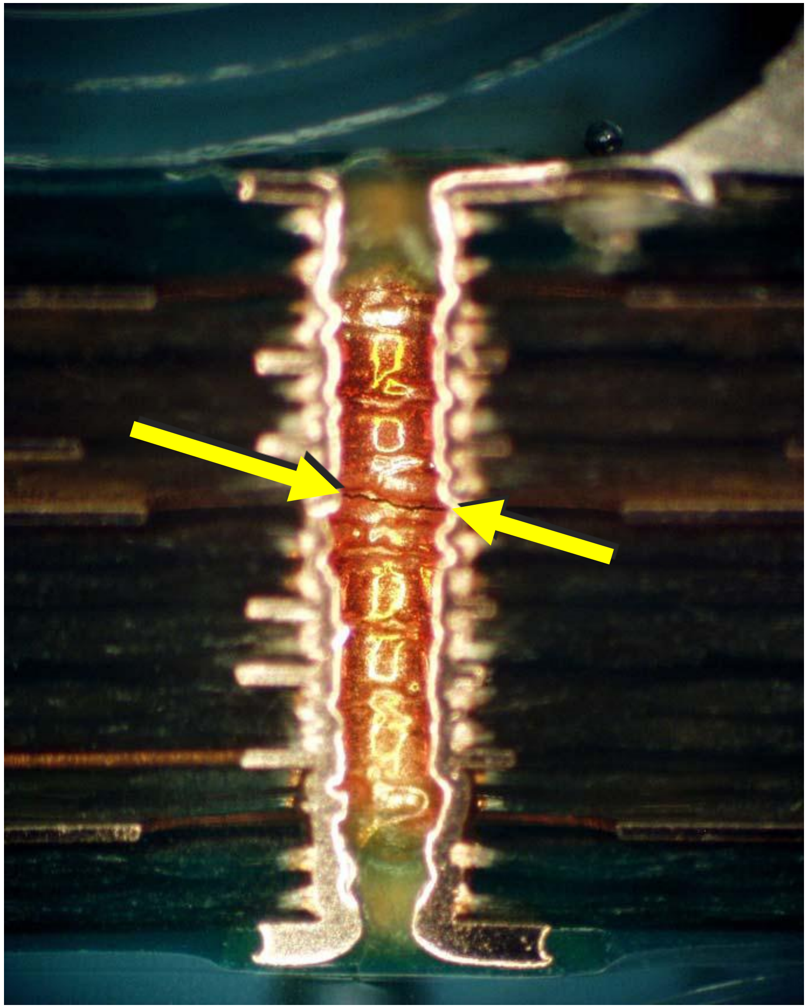
Conclusions

- Understanding and mitigating thermal and mechanical is just as important as electrical for ensuring reliability
- There are very robust methods for predicting the performance of electronics under a variety of thermo-mechanical and mechanical environments
  - Automation can accelerate and improve the accuracy of these calculations
- Design rules are a good start, but not the way to win!

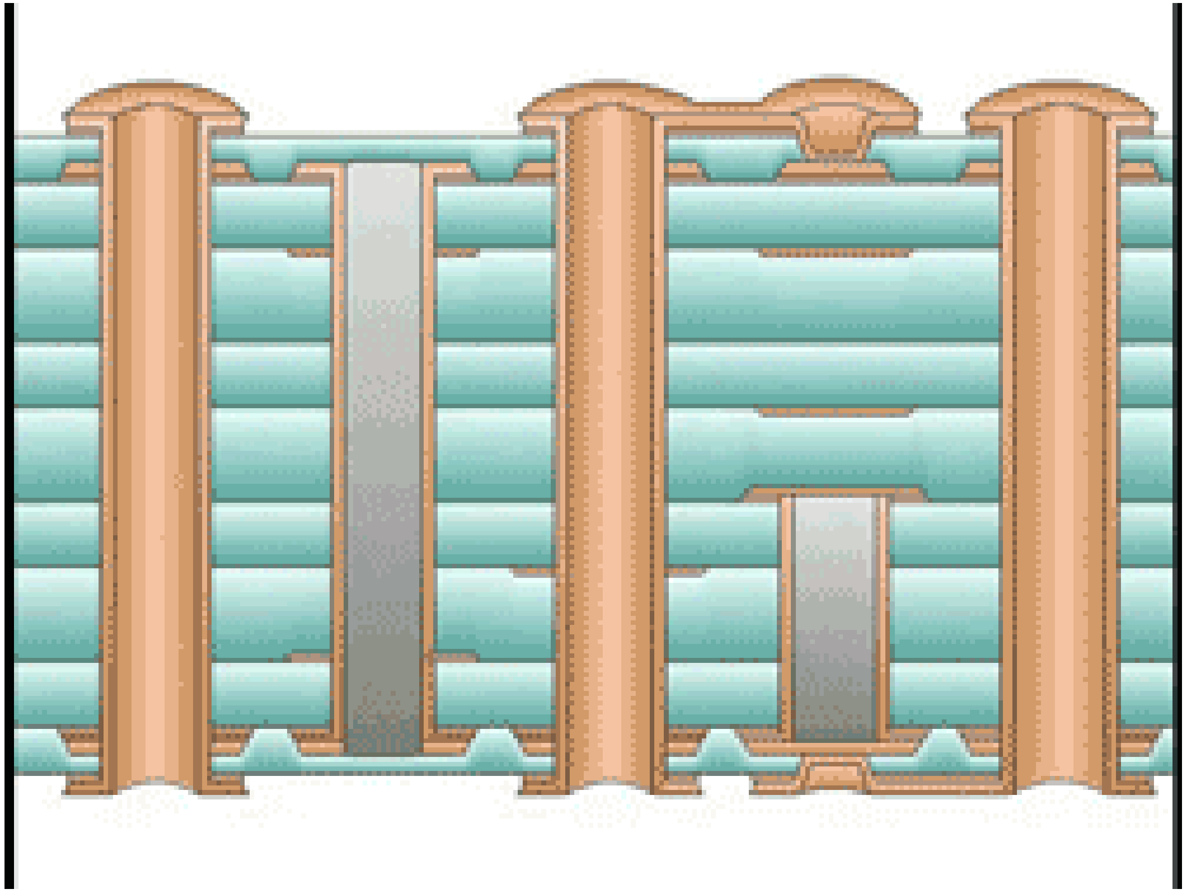
Appendix

Plated Through Vias (PTV) and Thermo-Mechanical

- The dominant failure mode in PTV tends to be barrel fatigue
- Barrel fatigue is the circumferential cracking of the copper plating that forms the PTV wall
- Driven by differential expansion between the copper plating (~17 ppm) and the out-of-plane CTE of the printed board (~70 ppm)

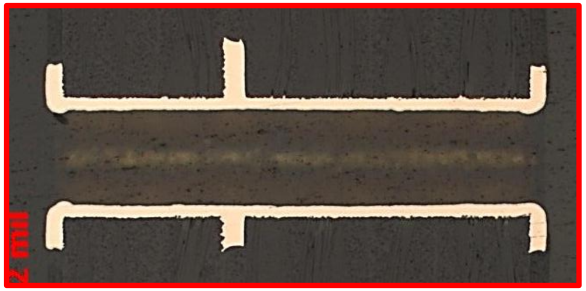


Plated Through Vias (PTV) and Thermo-Mechanical



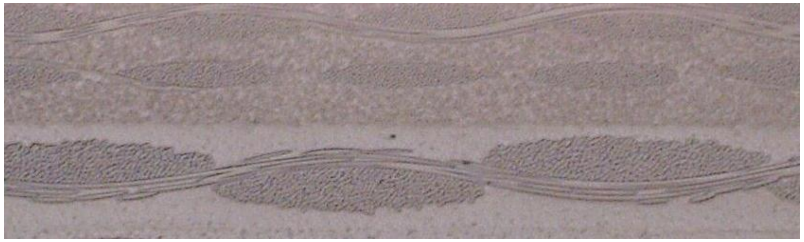
Drivers for PTV Failures

PTV Architecture
(height / diameter)



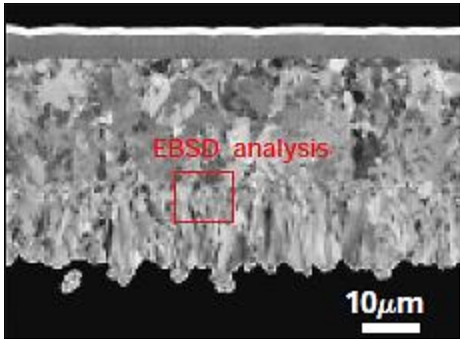
+

PCB Material
(modulus / CTE)



+

Plating
(thickness / material)



DfR Solutions

IPC TR-579 (cont.)

- Determine stress applied (σ)
  - Assumes perfectly elastic deformation when below yield strength (Sy)
  - Linear stress-strain relationship above Sy

$$\sigma = \frac{(\alpha_E - \alpha_{Cu})\Delta T A_E E_E E_{Cu}}{A_E E_E + A_{Cu} E_{Cu}}, \text{for } \sigma \le S_y$$

$$\sigma = \frac{\left[(\alpha_E - \alpha_{Cu})\Delta T + S_y \frac{E_{Cu} - E'_{Cu}}{E_{Cu} E'_{Cu}}\right] A_E E_E E'_{Cu}}{A_E E_E + A_{Cu} E'_{Cu}}, \text{for } \sigma > S_y$$

$$A_E = \frac{\pi}{4}\left[(h + d)^2 - d^2\right]$$

$$A_{Cu} = \frac{\pi}{4}\left[d^2 - (d - 2t)^2\right]$$

h	PTV Height
d	PTV Diameter
t	Plating Thickness
E	Elastic Modululs
α	Coefficient of Thermal Expansion
T	Temperature (oC)

IPC TR-579 (cont.)

- Determine strain range (Δε)

$$\Delta\varepsilon = \frac{\sigma}{E_{Cu}}, \text{ for } \sigma < S_y$$

$$\Delta\varepsilon = \frac{S_y}{E_{Cu}} + \frac{\sigma - S_y}{E'_{Cu}}, \text{ for } \sigma > S_y$$

IPC-TR-579 (Calibration Constants)

- Strain distribution factor, Kd (2.5 –5.0)
  - 2.5 recommended
- Quality index, K_Q (0 –10)
  - Extraordinary (K_Q = 10)
  - Superior (K_Q = 8.7)
  - Good (K_Q = 6.7)
  - Marginal (K_Q = 4.8)
  - Poor (K_Q = 3.5)

$$\Delta\varepsilon_{eff} = \Delta\varepsilon\left(K_d \frac{10}{K_Q}\right)$$

- Some companies assume K_Q = 5

PTH Quality Index

Reference	IPC	IPC	Alcatel	Intel	Cisco
Year	1988	1988	1997	2000	2002
Via Diameter (mm)	0.25	0.33	0.35	0.30	0.34
Plating Thickness (mm)	20	32	25	30	25
PCB Thickness (mm)	2.28	2.28	1.5	1.5	2.36
Out of Plane CTE (ppm/C)	70	83	63	50	N/A
Mean Time to First Failure (thermal cycles)					
-35 / 125C	300	N/A	N/A	N/A	N/A
-40 / 125C	N/A	N/A	N/A	N/A	750
-55 / 125C	N/A	N/A	925	2190	N/A
-65 / 125C	N/A	371	N/A	N/A	N/A
Quality Index (calculated)	6.0	8.0	7.5	7.2	9.0

IPC TR-579 (cont.)

- Iteratively calculate cycles-to-failure (Nf)

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

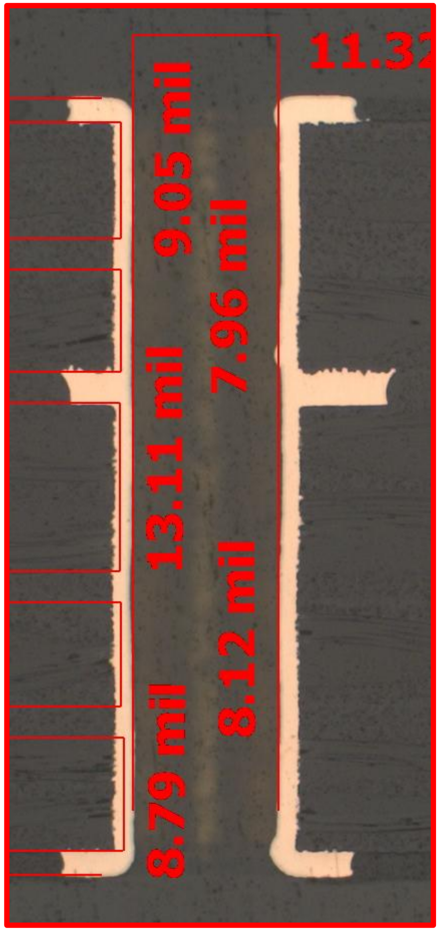
Two key plating properties

Df	Elongation (assumed ~30%)
Su	Tensile Strength (assumed ~40,000 psi)

DfR Solutions

PTV Architecture

- PTV Height
  - Driven by the PCB thickness
  - 30 mil (0.75 mm) to 250 mil (6.25 mm)
- PTV Diameter
  - Driven by component pitch/spacing
  - 6 mil (150 micron) to 20 mil (500 micron)
- Key Issues
  - Be aware that PCB manufacturing has cliffs
  - Quantify effect of design parameters using IPC TR-579



DfR Solutions

The Effect of Design Parameters (Height / Diameter)

- Reduce the PTV Height (PCB Thickness)
  - Reduce laminate/prepreg thickness (2.7 to 4 mil is current limitation)
  - Results in minimal cost changes and minimal effect on design
  - Has the least effect on PTH reliability

- Increase PTV Diameter
  - Typically not an option due to spacing issues
  - An important, but significant effect (dependent on a number of other variables)
  - Example: Moving from 10 mil to 12 mil diameter on a 120 mil board, 50C temp cycle, will result in approximately 20% improvement

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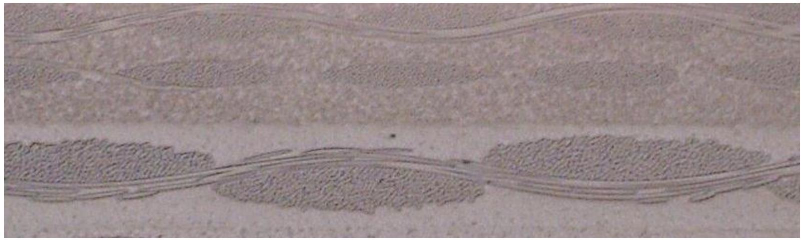
PCB Materials and PTV Reliability

- Historically, two material properties of concern
  - Out-of-plane coefficient of thermal expansion (CTE_z)
  - Out-of-plane elastic modulus ('stiffness')(E_z)

- Key Assumption: No exposure to temperatures above the glass transition temperature (Tg)

- The two material properties (CTE and E) are driven by choices in resin, glass style, and filler



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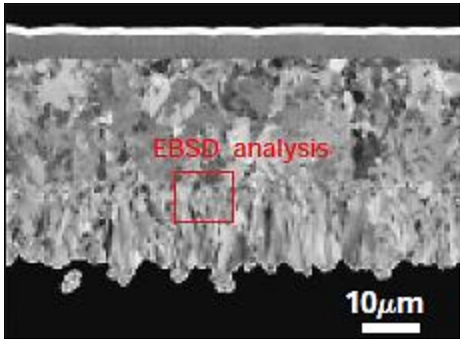
Plating (Thickness and Material Properties)



- Considered to be the number one driver for PTV barrel fatigue
- Classic engineering conflict
  - Better properties (greater thickness, higher plating strength, greater elongation) typically require longer time in the plating bath
  - Longer time in the plating bath reduces throughput, makes PCBs more expensive to fabricate
- PCB fabricators, low margin business, try to balance these conflicting requirements
  - Key parameters are thickness, strength, and elongation (ductility)

About the Presenter

Dr. Craig Hillman is the CEO of DfR Solutions. DfR Solutions provides engineering services and tools that allow the electronic supply chain to meet customer expectations in regards to quality, reliability, and safety.

Dr. Hillman has put together an a comprehensive group of subject matter experts in a number of different fields, including semiconductors, electronic design and fabrication, and systems engineering, and has overseen the release of the first Automated Design Analysis software to the EDA/CAE marketplace.

DfR Solutions is now the largest organization of its kind in the world and has offices across North America and Europe. Dr. Hillman holds two patents, has over 100 publications, is a guest columnist for Global SMT & Packaging, has been a course instructor at IPC, SMTA, IMAPS and IEEE conferences, was identified by the US DoD as a subject matter expert in Pb-free technology, and has presented on a wide variety of reliability issues to over 500 companies and organizations.

He holds a B.S. in Metallurgical Engineering and Materials Science and Engineering and Public Policy and a PhD in Materials Science

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