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Predicting the Reliability Of Package-on-Package Interconnections Using Computational Modeling

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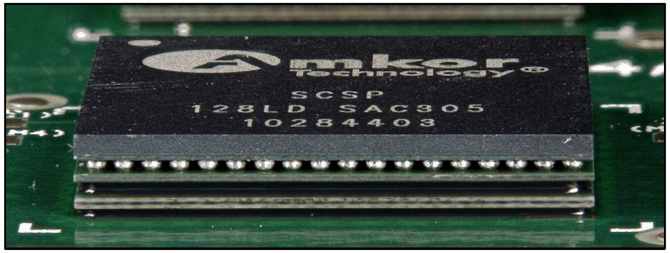
Introduction

- There is the need to reduce the size, weight, and power – SWaP - of military, space, satellite and other high-reliability electronics.

- Three-dimensional (3-D) packaging - stacked die or package-on-package (PoP) – provides an attractive methodology.

- Package-on-package (PoP) is the preferred approach at present because:
  - Known-good-dice minimize the likelihood of infant and latent failures,
  - Signal I/Os are available in order to confirm package functionality,
  - Assembly infrastructure is already in place to minimize capital investment.

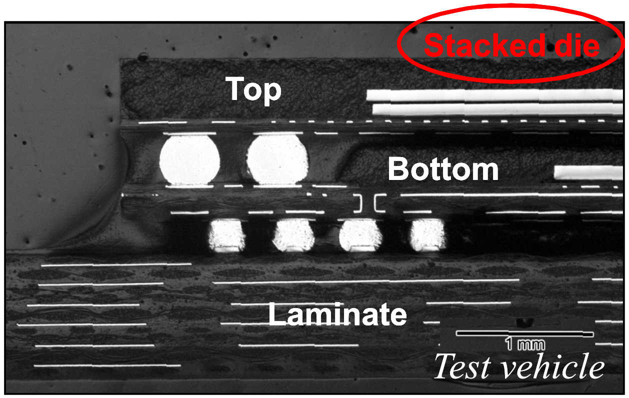


Courtesy of Sandia National Laboratories

Introduction

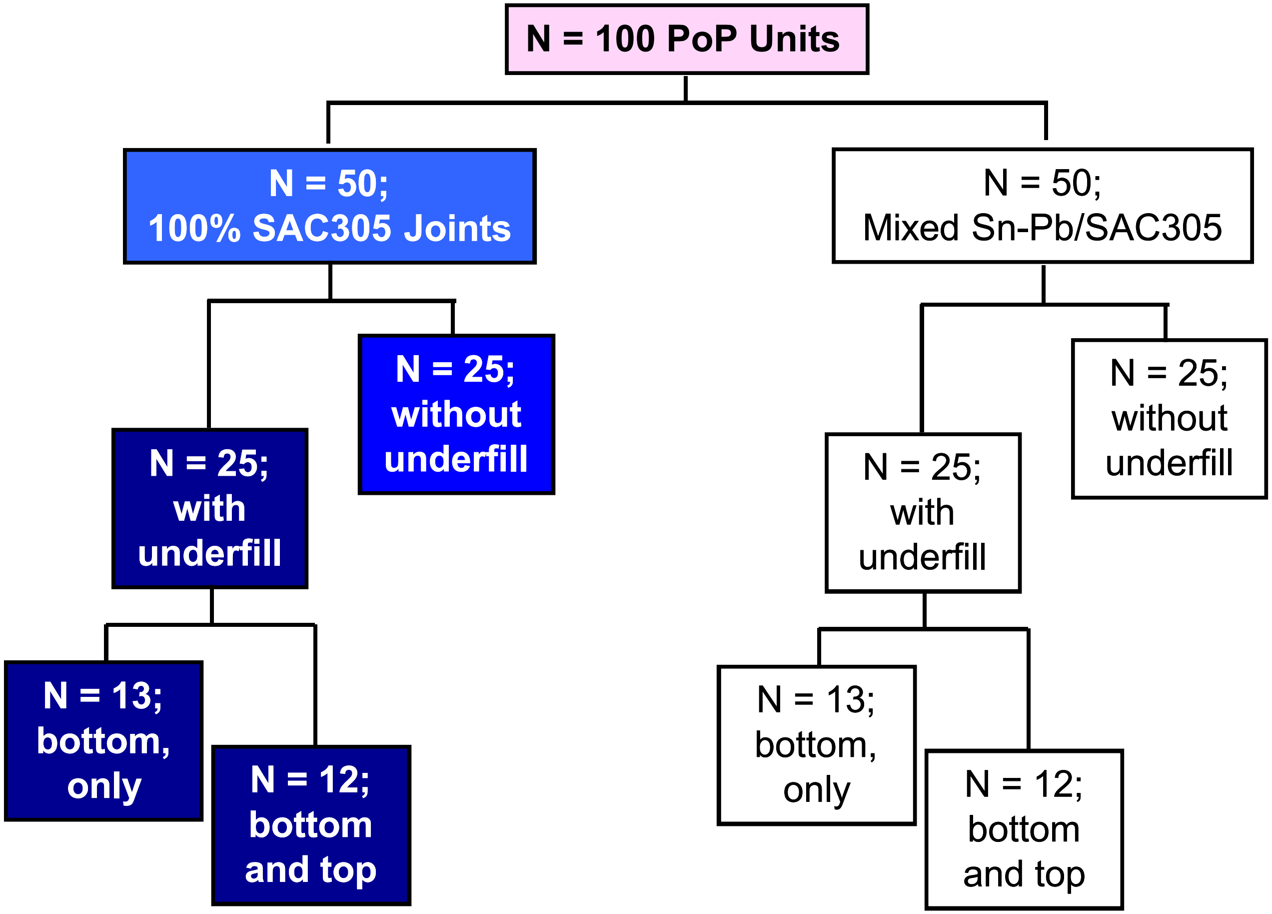
- Military, space, and satellite systems are frequently exposed to harsh environments that include shock, vibration and cycles between severe temperature extremes.

- The applicability of PoP technology in high-reliability systems requires an understanding of thermal-mechanical fatigue (TMF) behavior by the solder joints ….. *both rows of them !*



Introduction

- **An extensive empirical study was performed that examined TMF as a function of several test vehicle configurations*.**

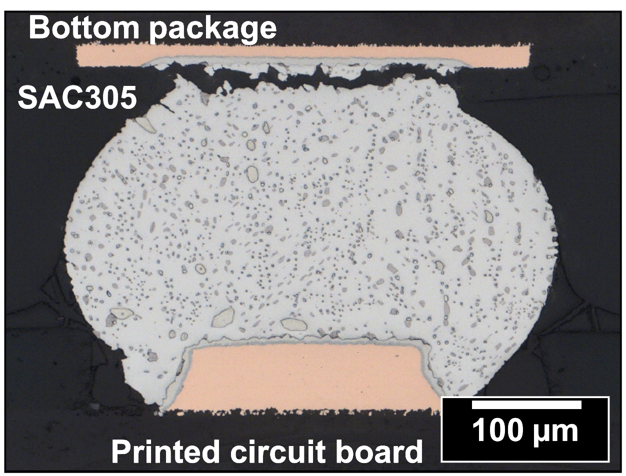


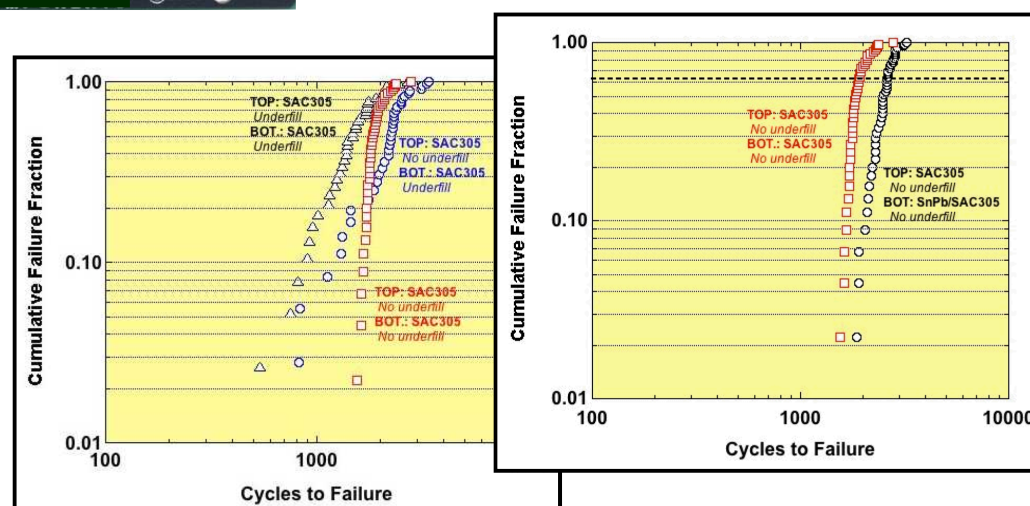
*P. Vianco, et al., *Proc. SMTAI* (2010)

Introduction

- **Accelerated aging experiments generated failure event data, which was further augmented by failure mode analyses (FMA).**

-55°C / 125°C;
10 min hold times;
20°C/min;
7500 cycles

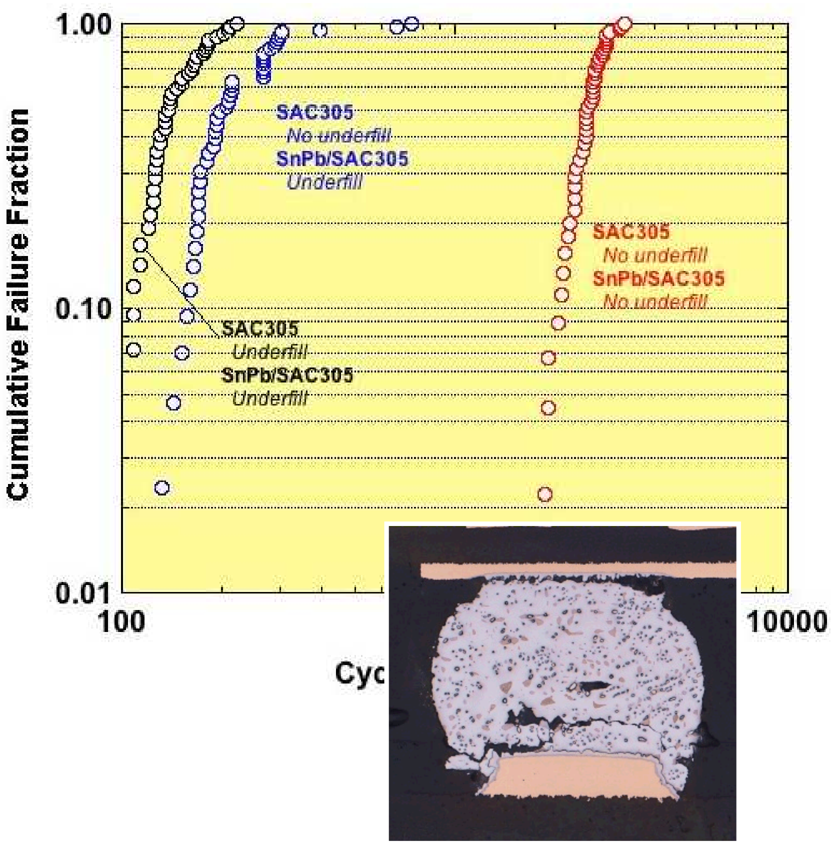




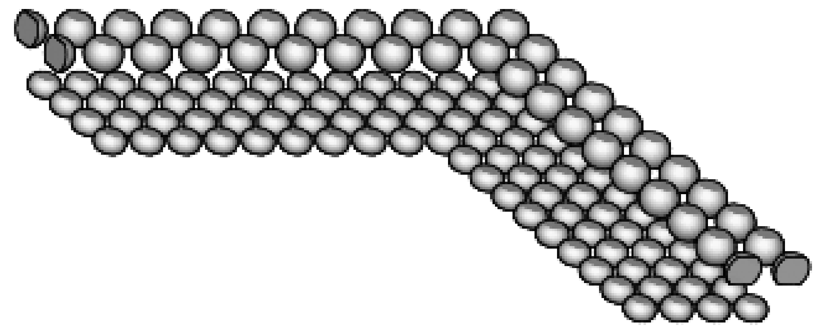
Objective

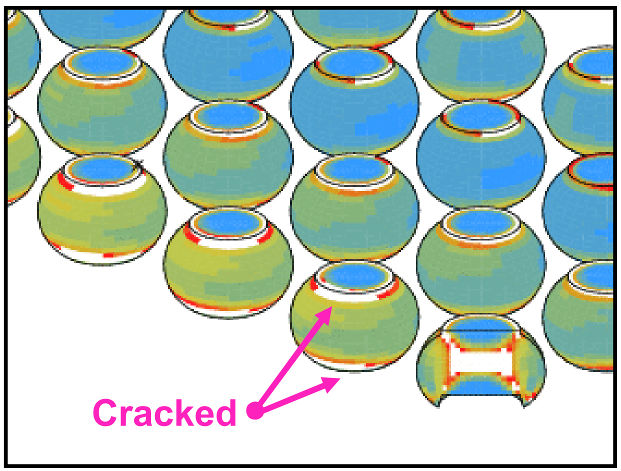
- **This study provided an opportunity to validate the TMF model against the empirical data from a *very complex package system*.**

Empirical data



Computational model

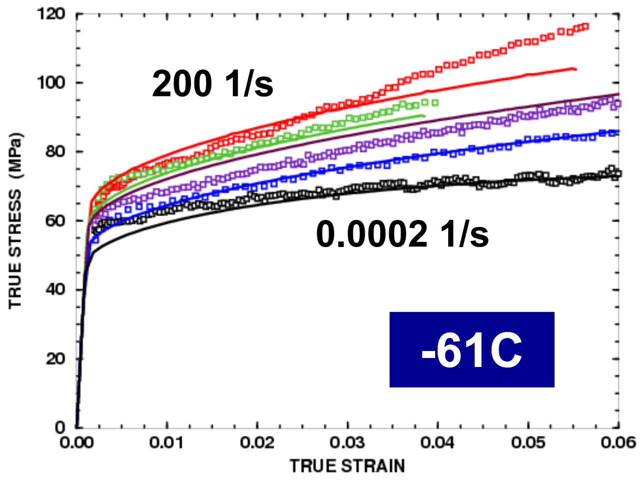


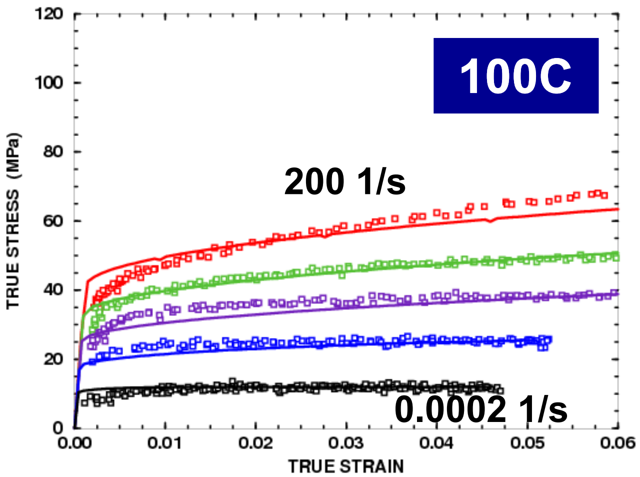


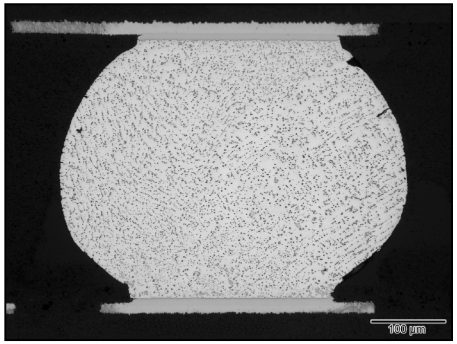
Approach

- **Construct a computational model that provided the highest fidelity of thermal-mechanical fatigue (TMF) predictions.**
  - **Constitutive relationship of the solder (model)**

$$\dot{\boldsymbol{\varepsilon}}^{in} = \frac{3}{2}\dot{\gamma}\,\mathbf{n} = \frac{3}{2} f \sinh^{p}\left(\frac{\tau}{D(1-cw)}\right)\mathbf{n}$$

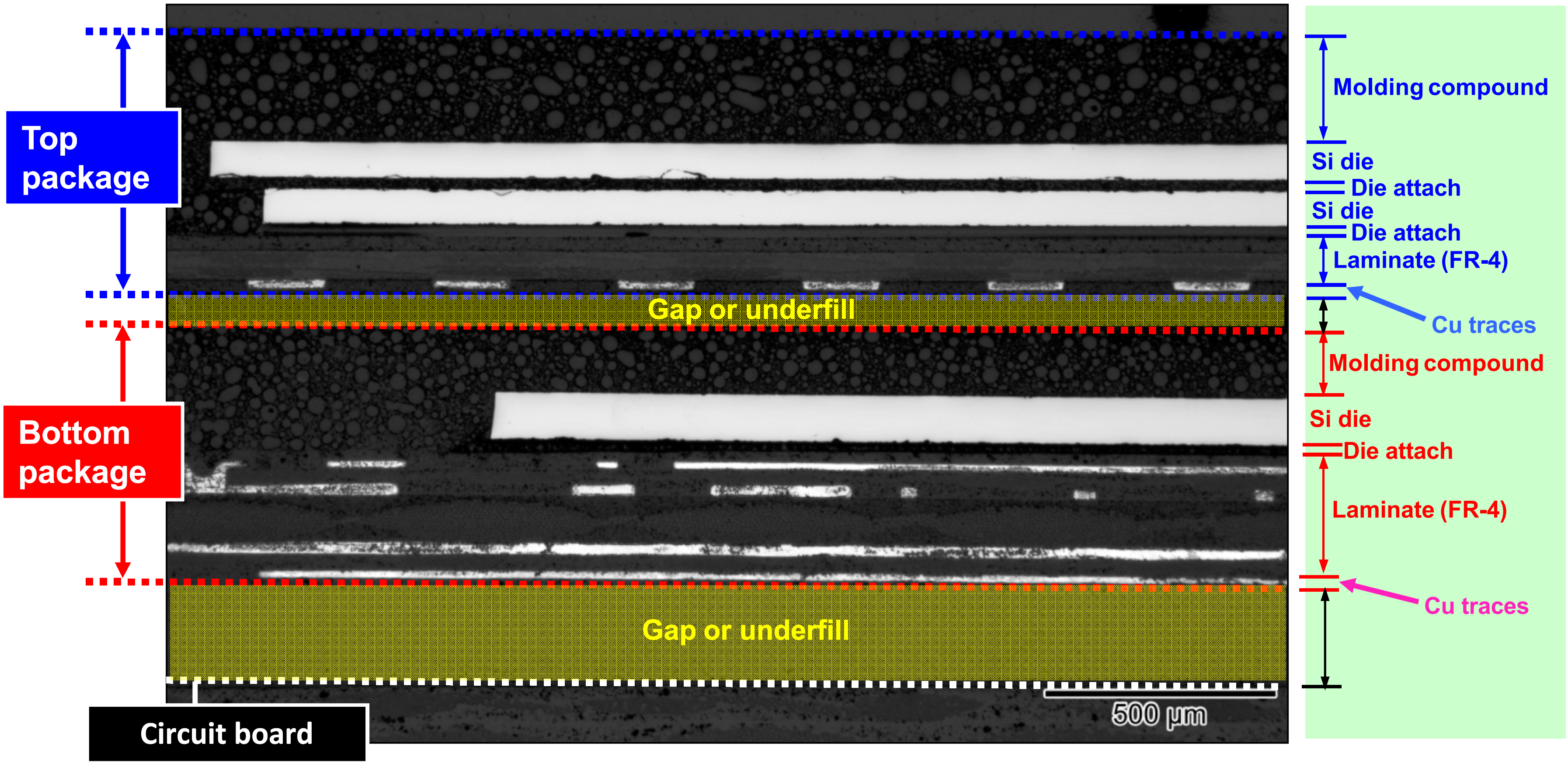






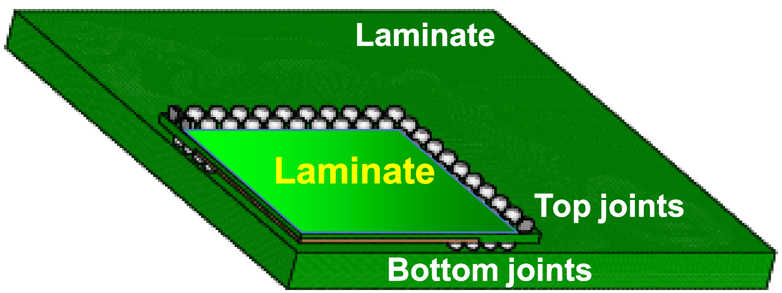
Approach

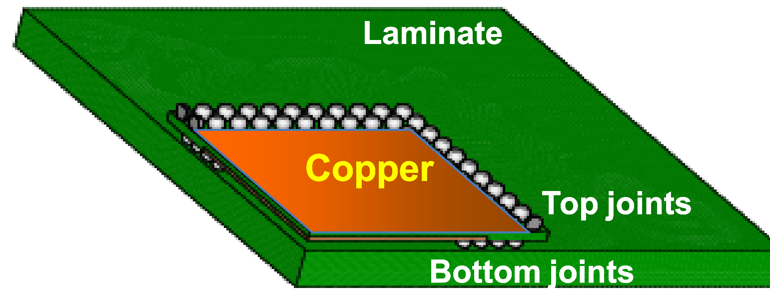
- **Numerical building blocks** *(con't)*:
  - Finite element geometry (model)
  - Mechanical and physical properties of package and PCB materials



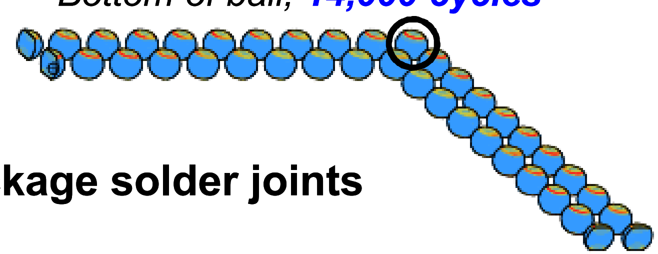
Approach – *Bottom Package Layout*

- **The interposer layout significantly affected the TMF experienced by bottom *and top* rows of joints. Here are the two limiting cases:**

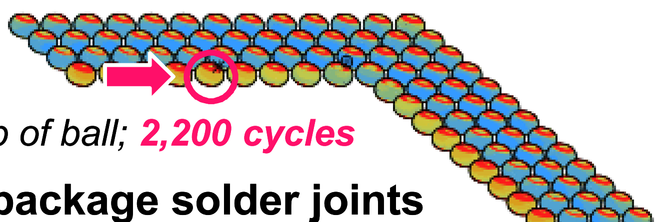




Bottom of ball; ***14,000 cycles***

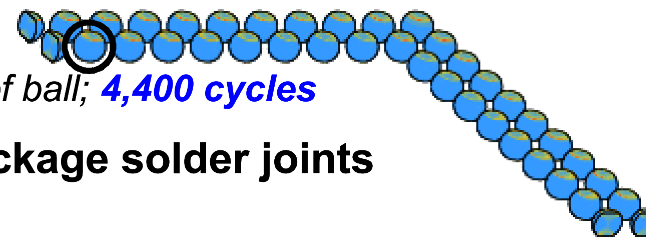


Top package solder joints



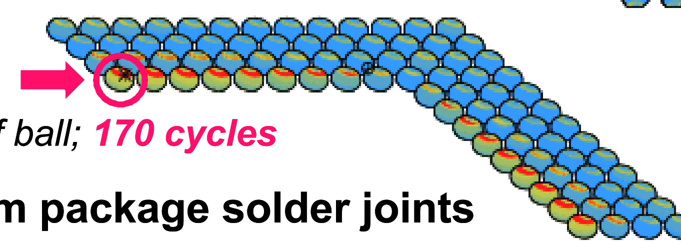
Top of ball; ***2,200 cycles***

Bottom package solder joints



Bottom of ball; ***4,400 cycles***

Top package solder joints

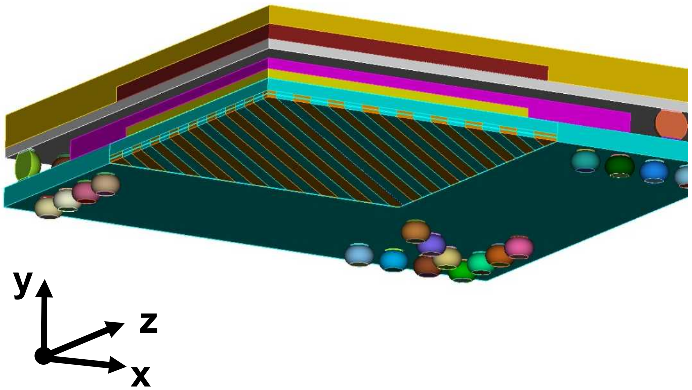


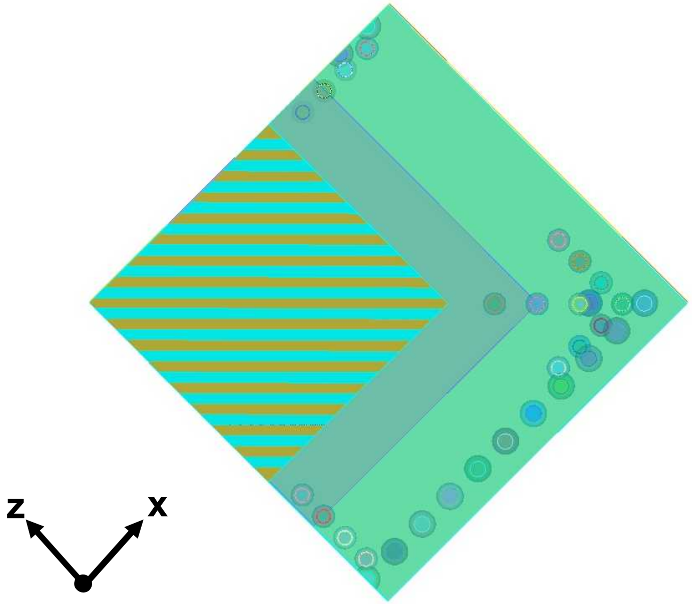
Top of ball; ***170 cycles***

Bottom package solder joints

Approach – *Bottom Package Layout*

- The following single row-hatch geometry was observed in other PBGAs by means of destructive physical analysis.

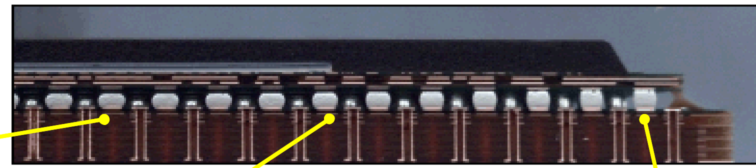


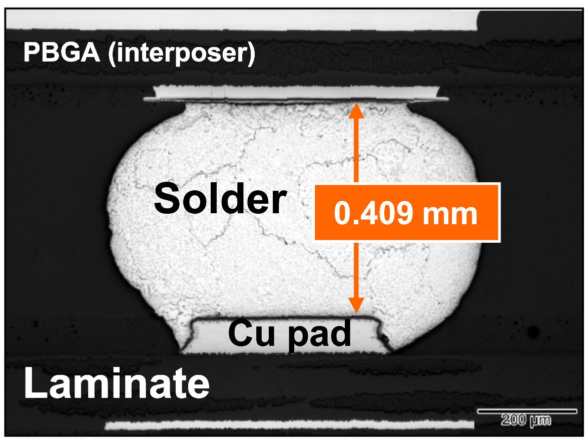


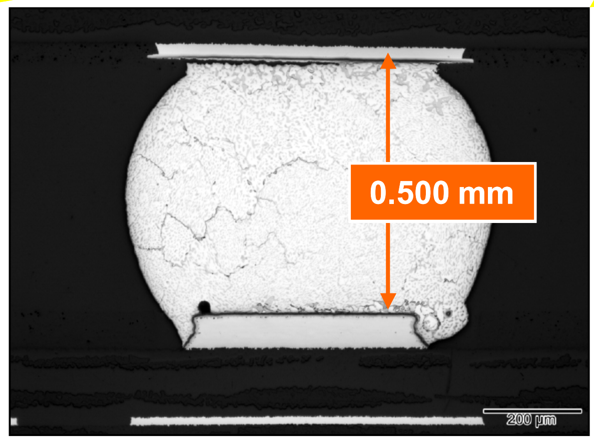
- There was no difference between the single row and cross hatched cases.
- The single row hatch (30% Cu) was used in the parameterization, PoP computational modeling analyses.

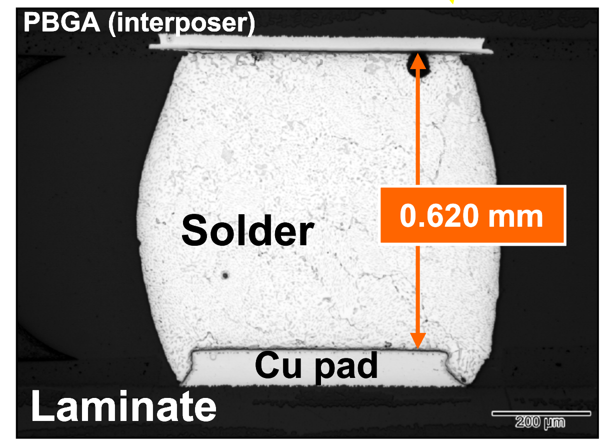
Approach – *Solder Joint Distortion*

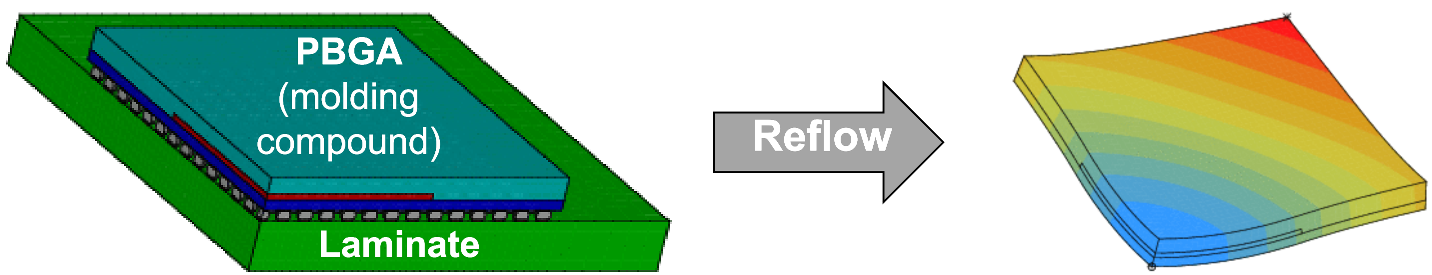
- The PoP construction generates **residual stresses** that result in **package warpage** after reflow.







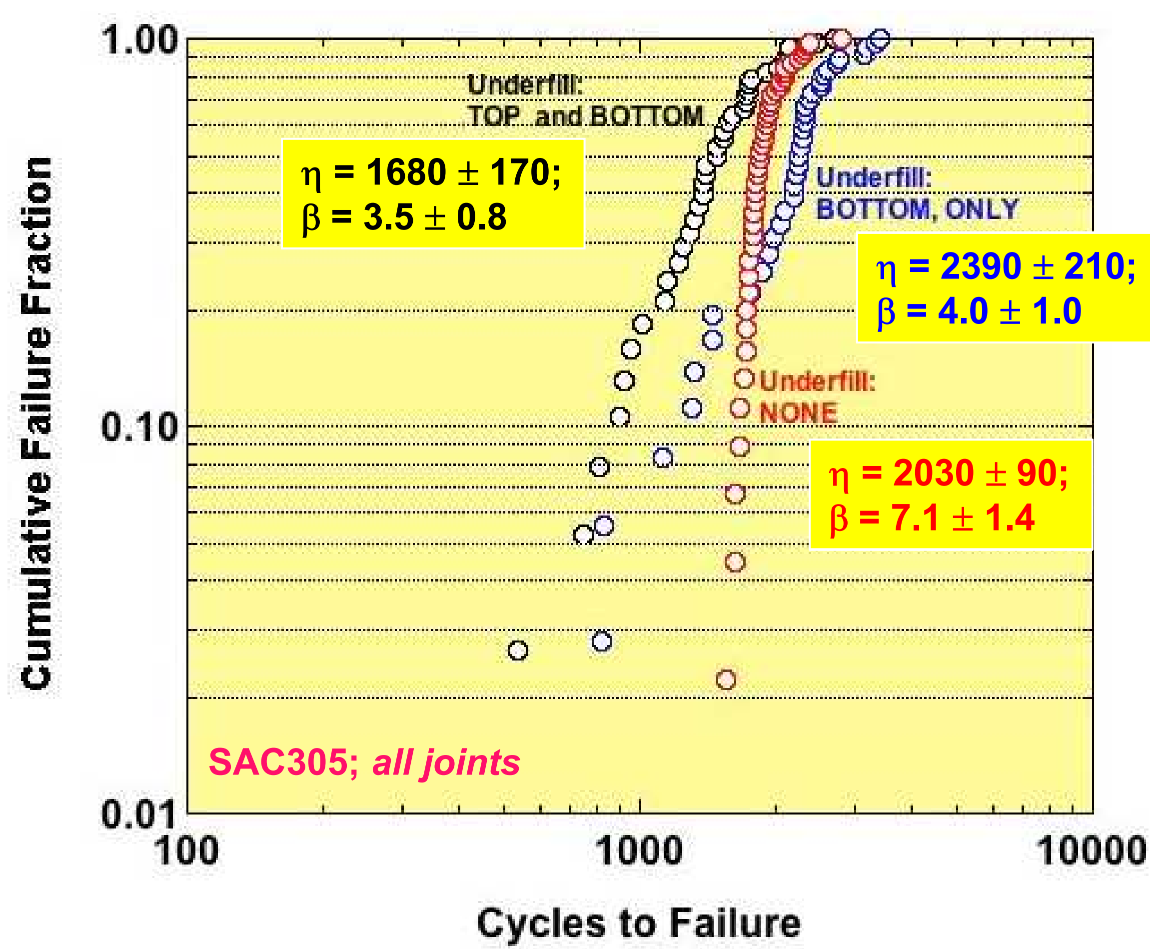




- **The computational model predicted only a 6% change to N_f and no change to the failure mode.**

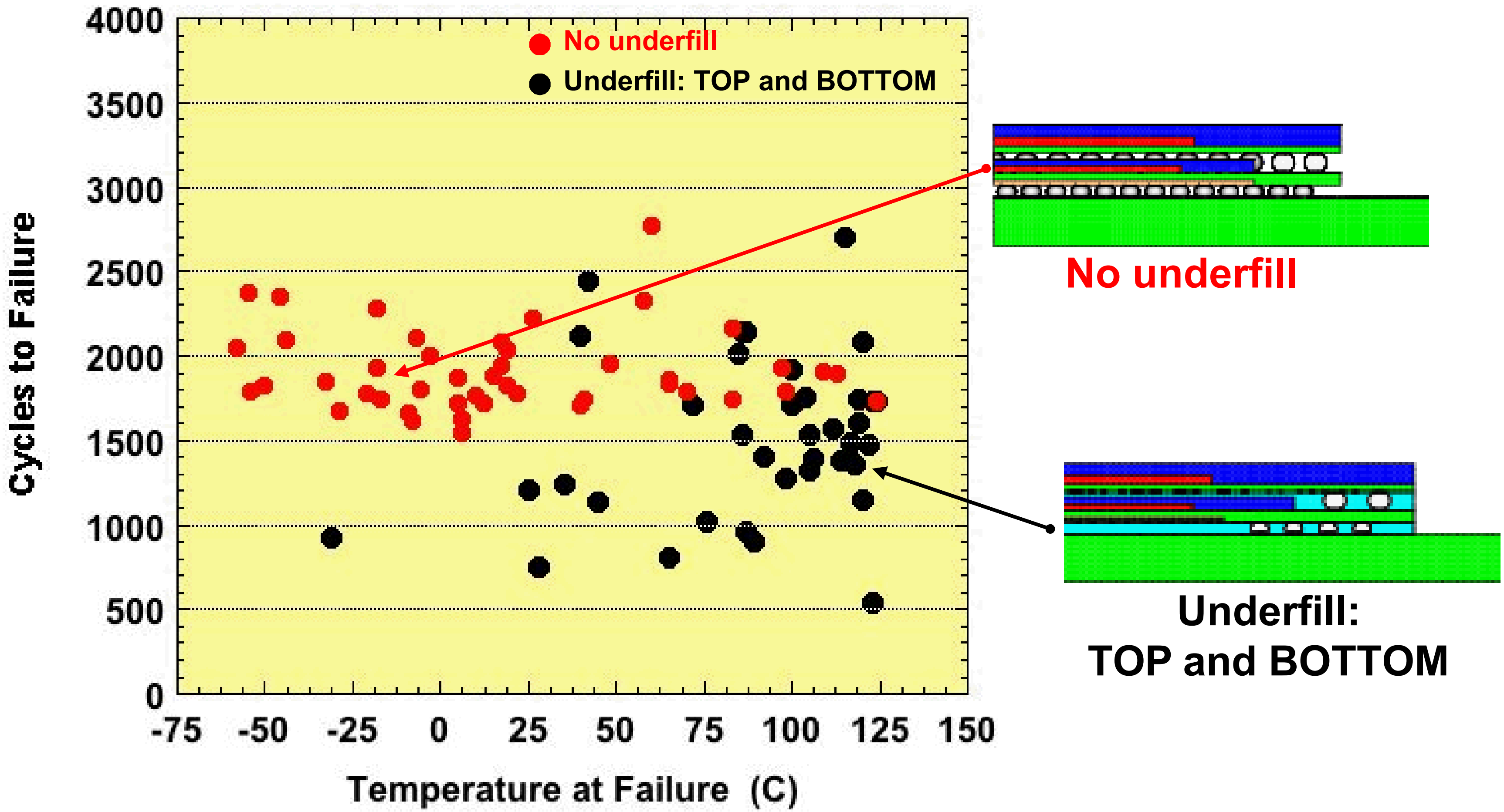
Model Validation

- The empirical data clearly indicated that the PoP construction – materials and geometry – had a complex effect on TMF behavior.



Model Validation

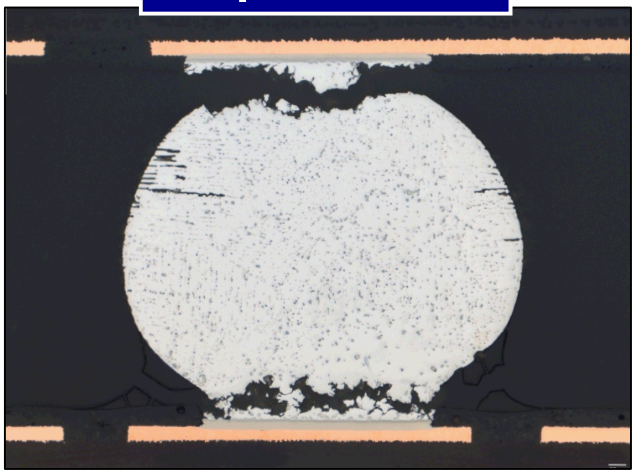
- The effect of the underfill was also apparent when a compilation was made of the temperatures at which N_f took place.



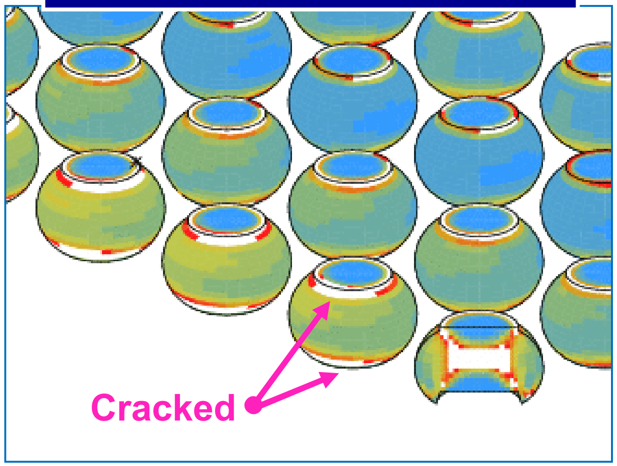
Model Validation

- It was first necessary to identify an empirical metric that could be used to correlate to the model predictions.

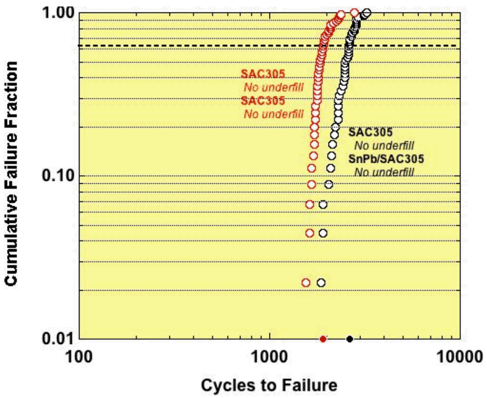
Empirical data



Computational model

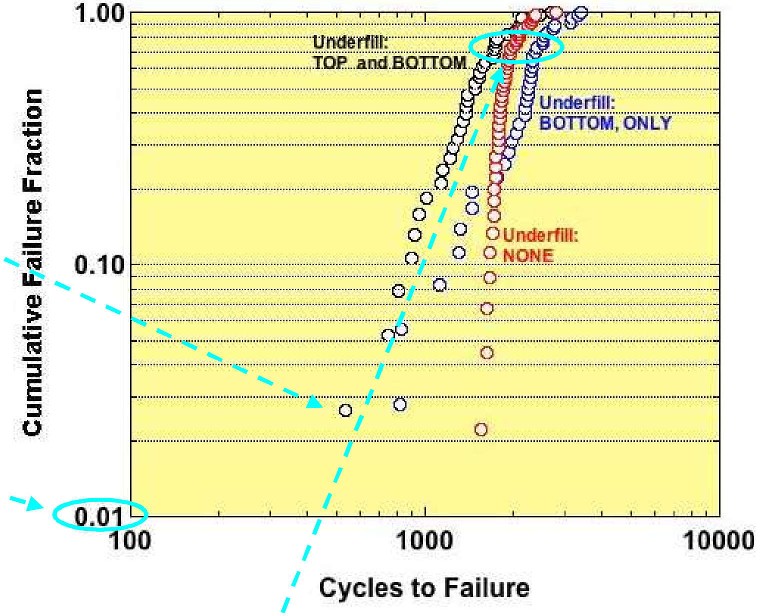


- There were three candidate
  - Cycles to first failure
  - Cycles to 1% failure, $N_{f,\,0.01}$
  - Characteristic lifetime (η), $N_{f,\,0.01}$



Model Validation

- **The three parameters were less-than-favorable for the following reasons:**
  - **Cycles to first failure**
    - **Limited accuracy because could include premature failures.**
  - **Cycles to 1% failure, $N_{f,\ 0.01}$**
    - **Front-tail of the distribution is too conservative because it does not capture the bulk of the distribution.**
  - **Characteristic lifetime (η), $N_{f,\ 0.62}$**
    - **Occurs late in the distribution so that slope effects can skew the results.**



The chosen convention was that the range, $N_{f,\ 0.10}$ - $N_{f,\ 0.25}$, would represent the empirical data in the model validation.

Model Validation

- A direct comparison was drawn between the empirical data range, $N_{f,\,0.10} - N_{f,\,0.25}$, and the computational model predictions.

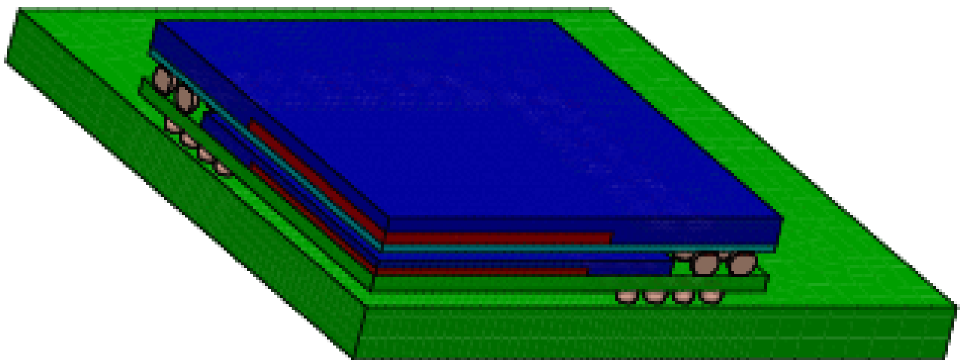
Underfill, Top	Underfill, Bottom	Empirical data: $N_{f,\,0.10} - N_{f,\,0.25}$ Range (cycles) *Top*	Empirical data: $N_{f,\,0.10} - N_{f,\,0.25}$ Range (cycles) *Bottom*	Computational model: Cycles to Crack Initiation* *Top*	Computational model: Cycles to Crack Initiation* *Bottom*
None	None		1400 – 1700	39000	1200
None	Present	1300 – 1800		960	2400
Present	Present		800 – 1200	2100	2200

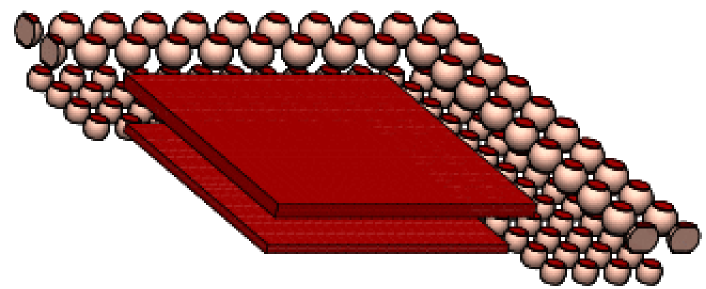
*Cross hatched interposer, 30% Cu

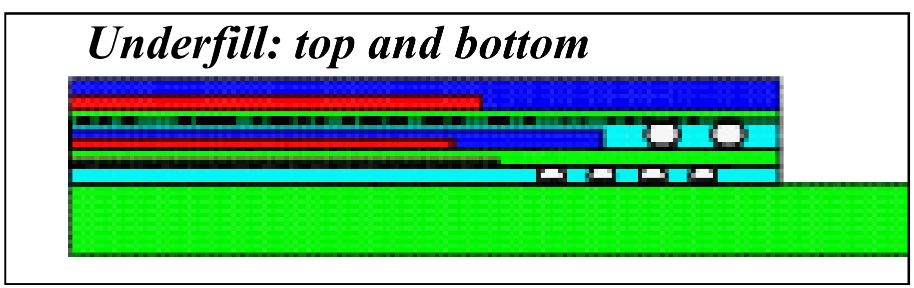
- Observations from the failure mode analysis:
  - *No underfill:* The preference was indisputable for bottom joint failure.
  - *Underfill, bottom only:* Top joints were preferred to fail first.
  - *Underfill, both:* Bottom joints were slightly preferred as first-failure.

Model Validation

- **Validation of the computational model predictions was deemed to have been "satisfactory," at-best.** ***Where were the discrepancies?***
- **The warpage effect was given a critical examination to determine the extent of its root cause(s) impacted solder joint TMF.**



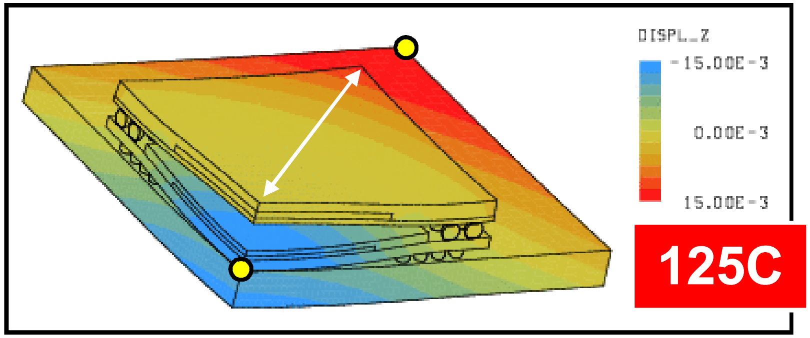


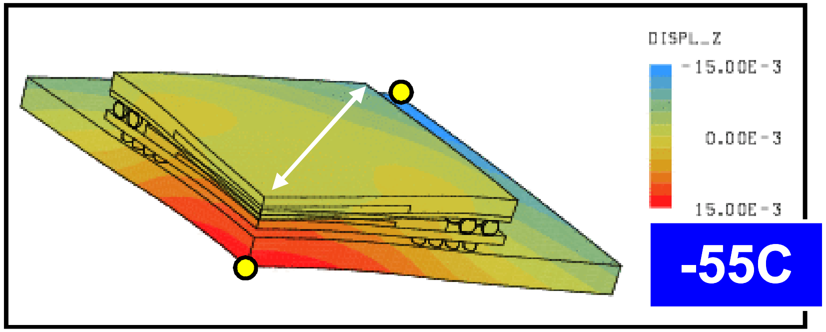


Model Validation

- The warpage of the PoP assembly was examined for two cases:

Case #1: No underfill

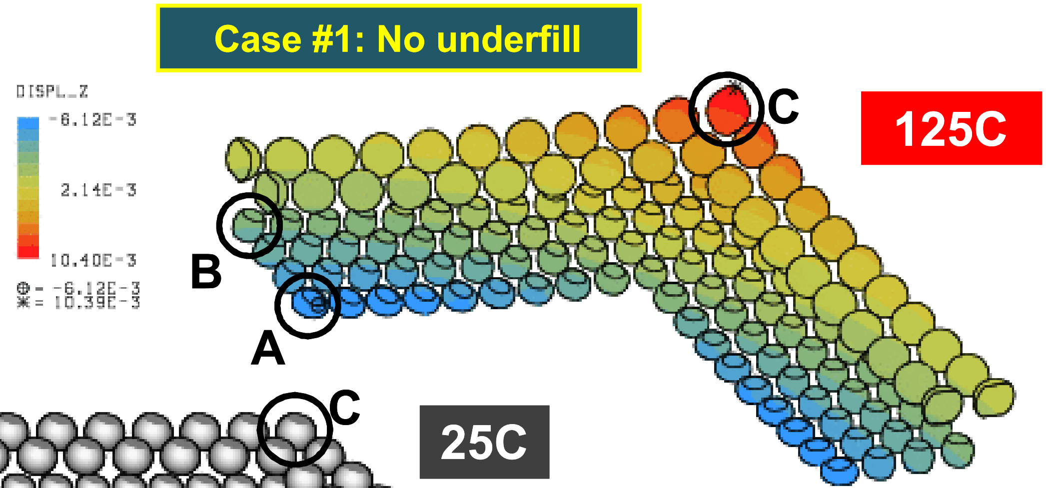


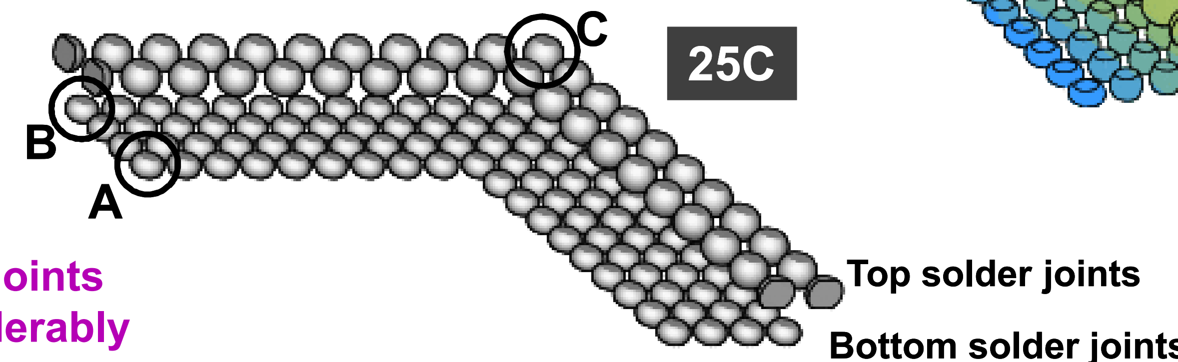


- **Map contours are absolute displacements, magnified 20x.**
- **Yellow dots (○) are the maximum +z and –z displacements and were located on the PCB.**
- **The bottom package and PCB exhibited significant warpage, *together*.**
- **The top package exhibited very little warpage across it (white arrow).**

Model Validation

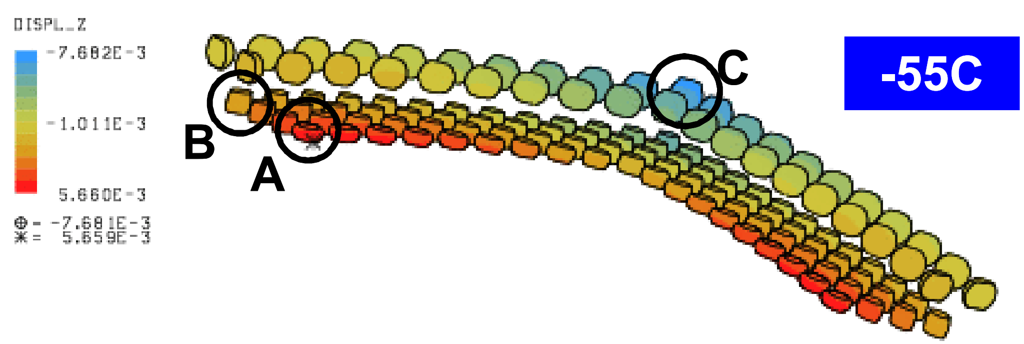
- **The displacement caused formation of a complex pattern of strains to occur in the solder joints.**





- **The bottom solder joints experienced considerably more strain than the top solder joints.**

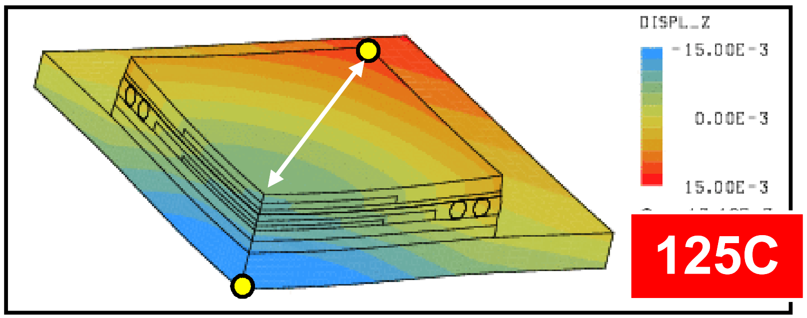
- **The bottom solder joints experienced approximately equivalent strains at -55°C *and* 125°C.**

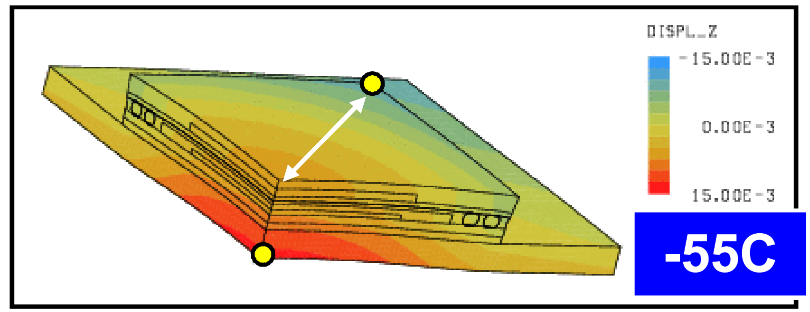


Model Validation

- The second case is:

Case #2: Underfill in both gaps



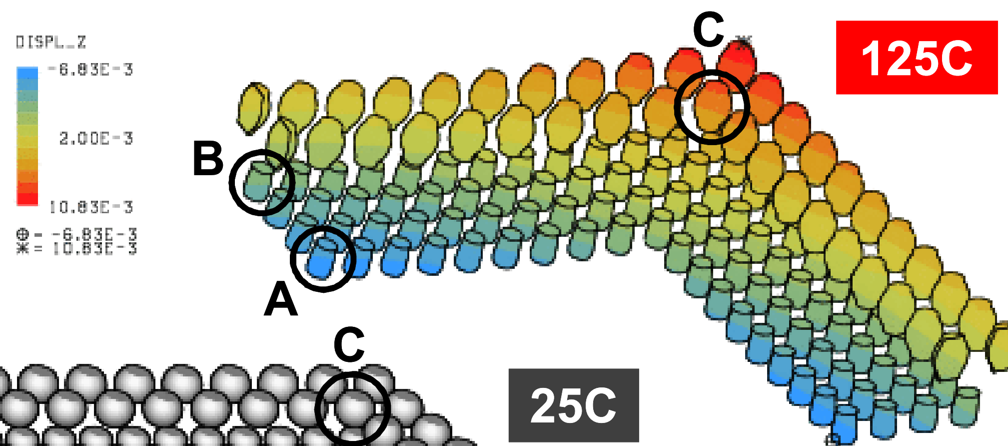


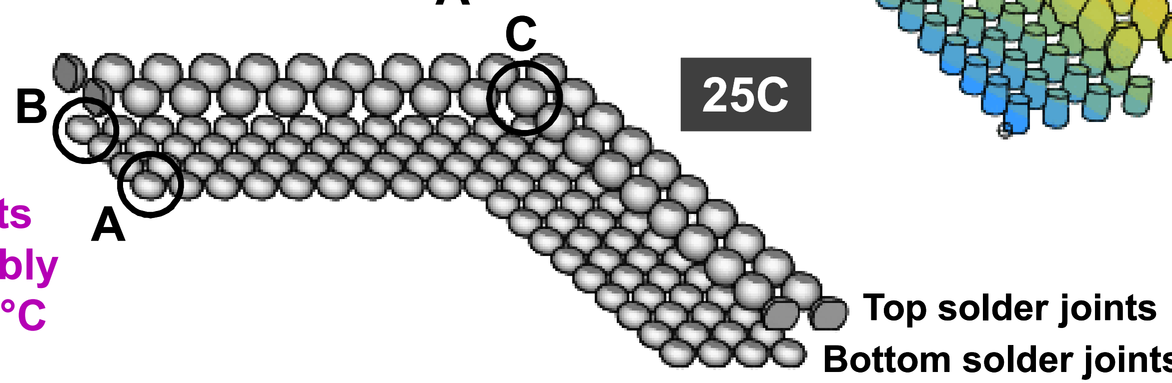
- **Overall, the maximum vertical displacements were significantly reduced with underfill.**
- **However, there was a higher displacement gradients across both the top and bottom packages (arrows).**
- **The top and bottom packages as well as PCB exhibited similar warpage.**

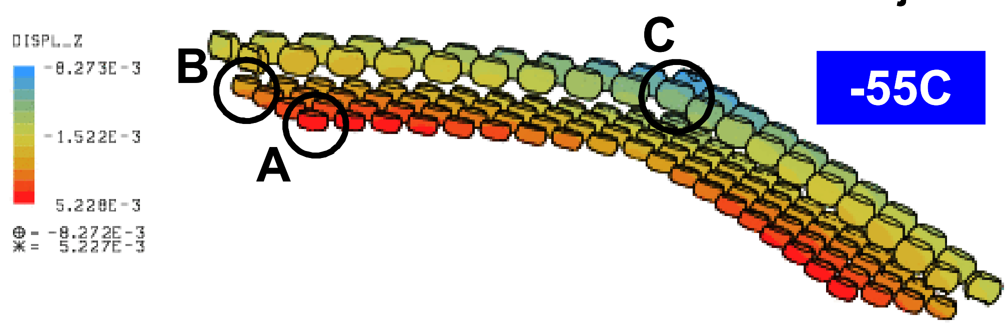
Model Validation

- **The displacements traced no-less of a complicated strain pattern with the presence of underfill.**
  - **The bottom solder joints experienced considerably more elongation at 125°C than at -55°C.**
  - **The top and bottom joints experienced about equivalent elongation at 125°C, but the top less at -55°C, for a net higher TMF strain in the bottom joints.**

Case #2: Underfill in both gaps







Model Validation

- **Qualitatively, the model predictions corroborate the failure mode analysis.**

The PoP configuration has been set up correctly.

- **Quantitatively, the discrepancy between the model predictions and data was considered with respect to of CTE and elastic modulus for the organic materials – molding compound and underfill.**

- **A parameterization study analyzed the underfill CTE and modulus, using values representing a typical envelop of filled epoxies:**

Case 1: E = 5600 MPa; CTE = 45 ppm/°C

Case 2: E = 9500 MPa; CTE = 22 ppm/°C

Model Validation

Underfill, Top	Underfill, Bottom	Case 1: E = 5600 MPa; CTE = 45 ppm/°C Top	Case 1: Bottom	Case 2: E = 9500 MPa; CTE = 22 ppm/°C Top	Case 2: Bottom
None	Present	960	2300	1400	57,000
	Empirical data	1300 – 1800			
Present	Present	2100	2200	34,000	61,000
		Empirical data	800 – 1200		

- In the ***underfill, bottom only*** case, the underfill had smaller effect on the top solder joints, which controlled the PoP TMF.

  … but, the model predictions were closer to the empirical data.

- Unfortunately, the discrepancy worsened for the case of having both gaps filled with underfill.

Summary

- An extensive experimental study was completed that investigated the thermal mechanical fatigue of PoP SAC305 interconnections.
- These data provided an opportunity to validate the predictions obtained from a computational model of the PoP system.
- Three configurations were the subject of the study:
  - No underfill
  - Underfill, bottom gap only
  - Underfill, both gaps.
- The correlation was deemed to be only *satisfactory*.

Further analysis and model predictions indicated clearly the need for accurate physical and mechanical properties of the organic materials contained in the PoP system.