ART-001
Characterization of Emerging Technologies in Military Systems

Sponsor: CCDC-AC

Pradeep Lall
MacFarlane Endowed Distinguished Professor
Auburn University
NSF-CAVE3 Electronics Research Center
Auburn, AL 36849
Tele: +1(334)844-3424; E-mail: lall@auburn.edu

AUBURN UNIVERSITY

12th Annual SERC Sponsor Research Review
HOSTED VIRTUALLY ON: November 18, 2020
www.sercuarc.org

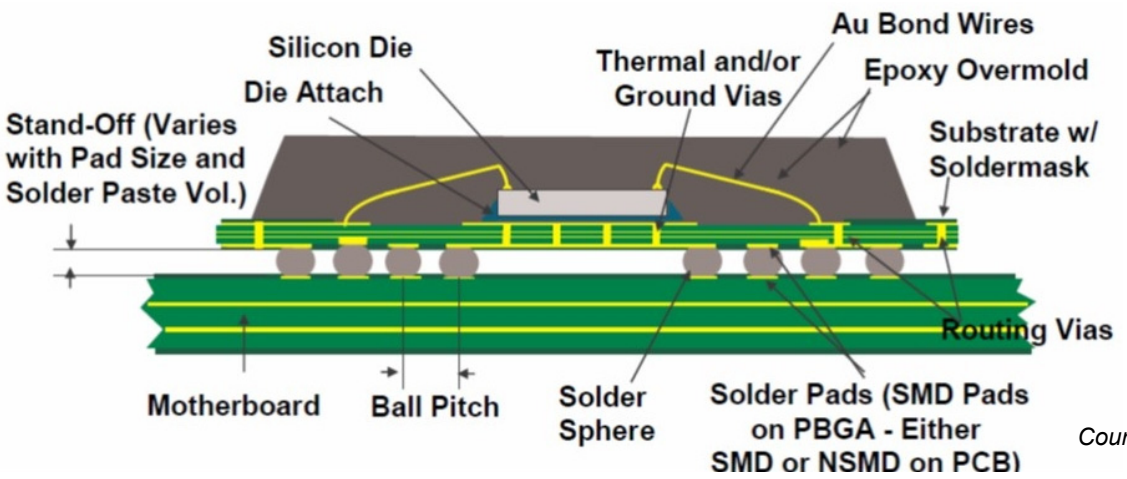
Emerging Technologies

- Leadfree Electronics Solder Interconnects under High Strain Rate Operation and Sustained High and Low Temperature.

  - Strain Rate of 1-100 sec^{-1}
  - Sustained Low-Temperature (-65°C)
  - Sustained High-Temperature (+200°C)
  - Prolonged Storage up to 1-year

- Prognostics Health Management Methods for Early Identification of Impending Failure.

Motivation

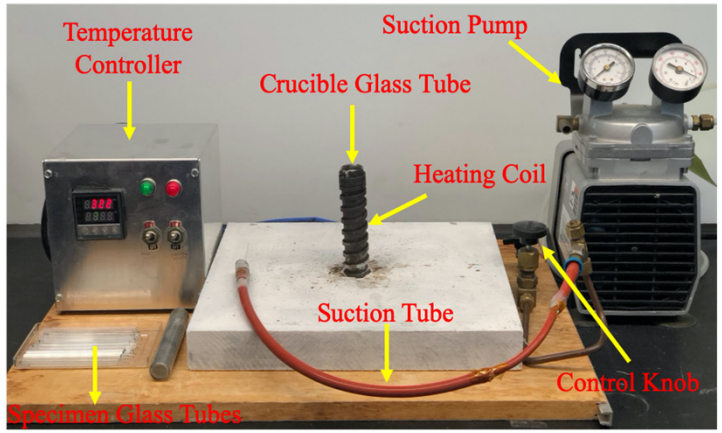


Courtesy of NXP

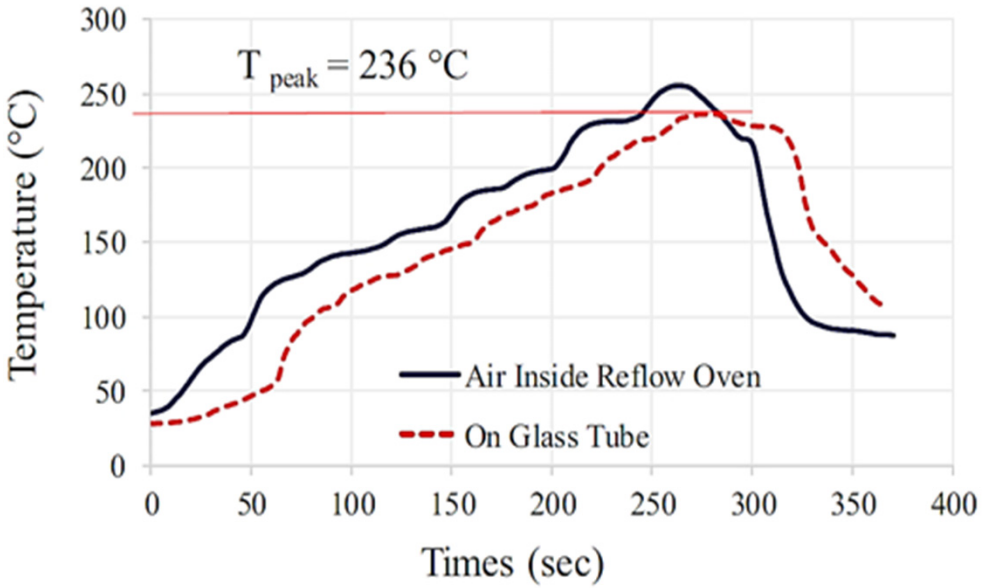
- In aerospace and defense applications, the electronic components may get exposed to extreme temperatures ranging from -65°C to 200°C in addition to sustained periods of aging in non-climate controlled enclosures.
- Electronics may be subjected to high strain-rates in the neighborhood of 1-100 sec^{-1} during storage, transport and deployment of systems.
- Analysis tools lag the introduction of new leadfree alloys which percolating into the commercial supply-chain and impact defense electronics which increasingly relies on COTS parts.

Sample Preparation Procedure

Specimen Preparation Setup

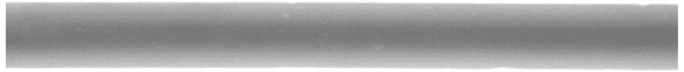


Reflow Profile



Samples Formed in Glass Tubes

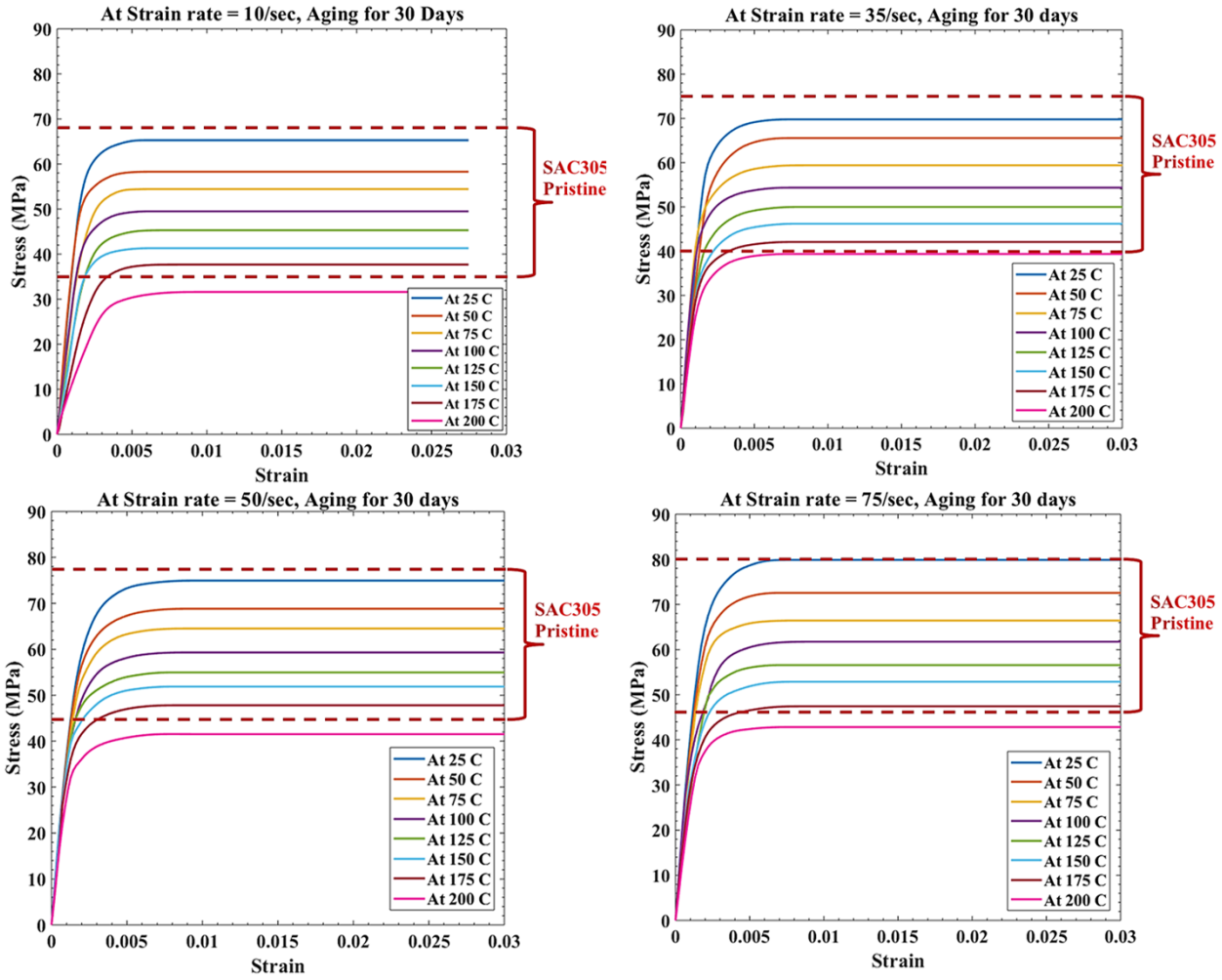
Specimen under X-ray inspection



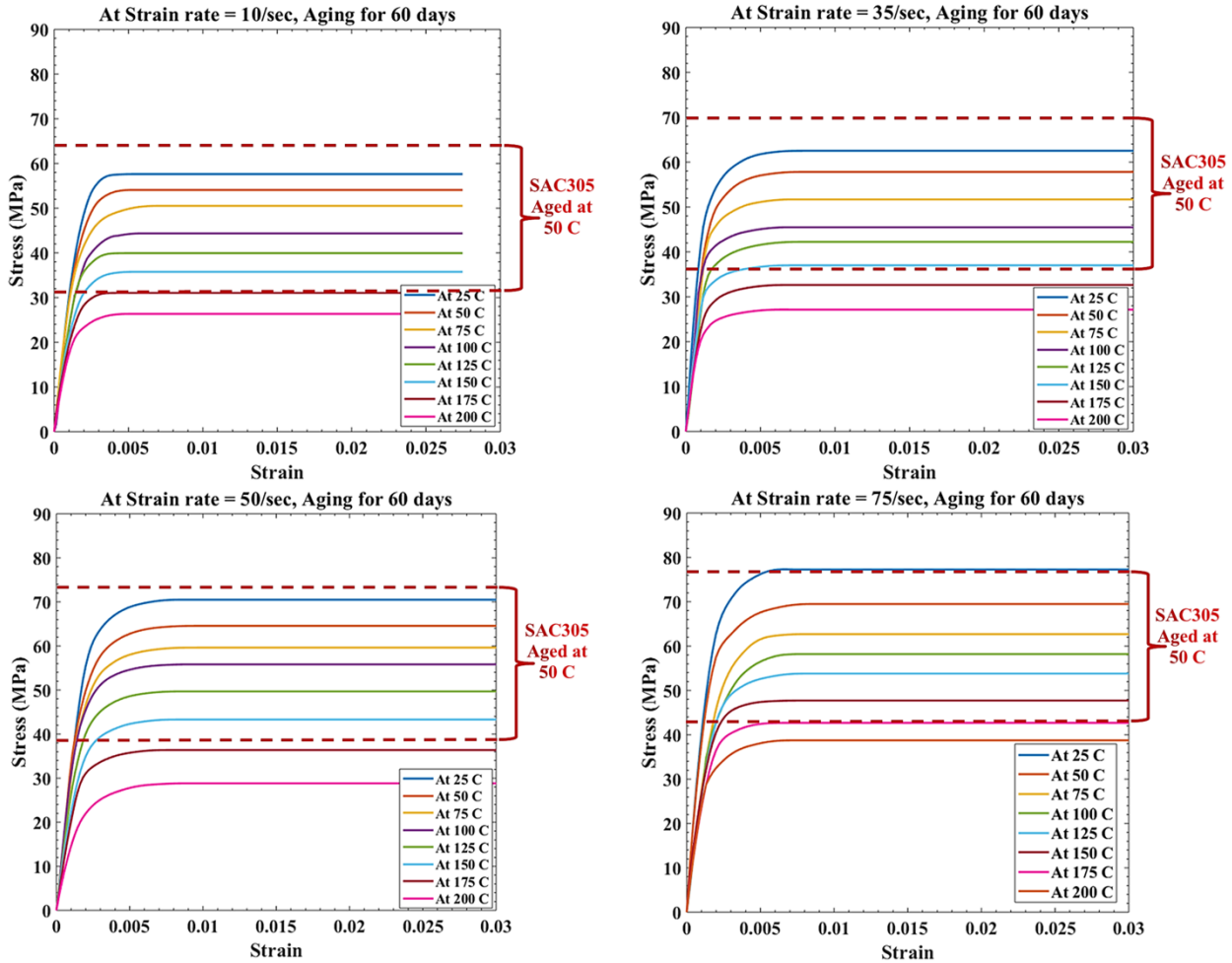
Test Matrix for High Strain-Rate SAC305, SAC-Q and SAC-R

T(°C)	Strain Rate (sec^{-1})				Aging Duration @100°C (Days)
	10	35	50	75	
-65,	X	X	X	X	Up to 1-Year of Storage
-55,	X	X	X	X	
-40,	X	X	X	X	
0,	X	X	X	X	
25,	X	X	X	X	
50,	X	X	X	X	
75,	X	X	X	X	
100,	X	X	X	X	
125,	X	X	X	X	
150,	X	X	X	X	
175,	X	X	X	X	
200					

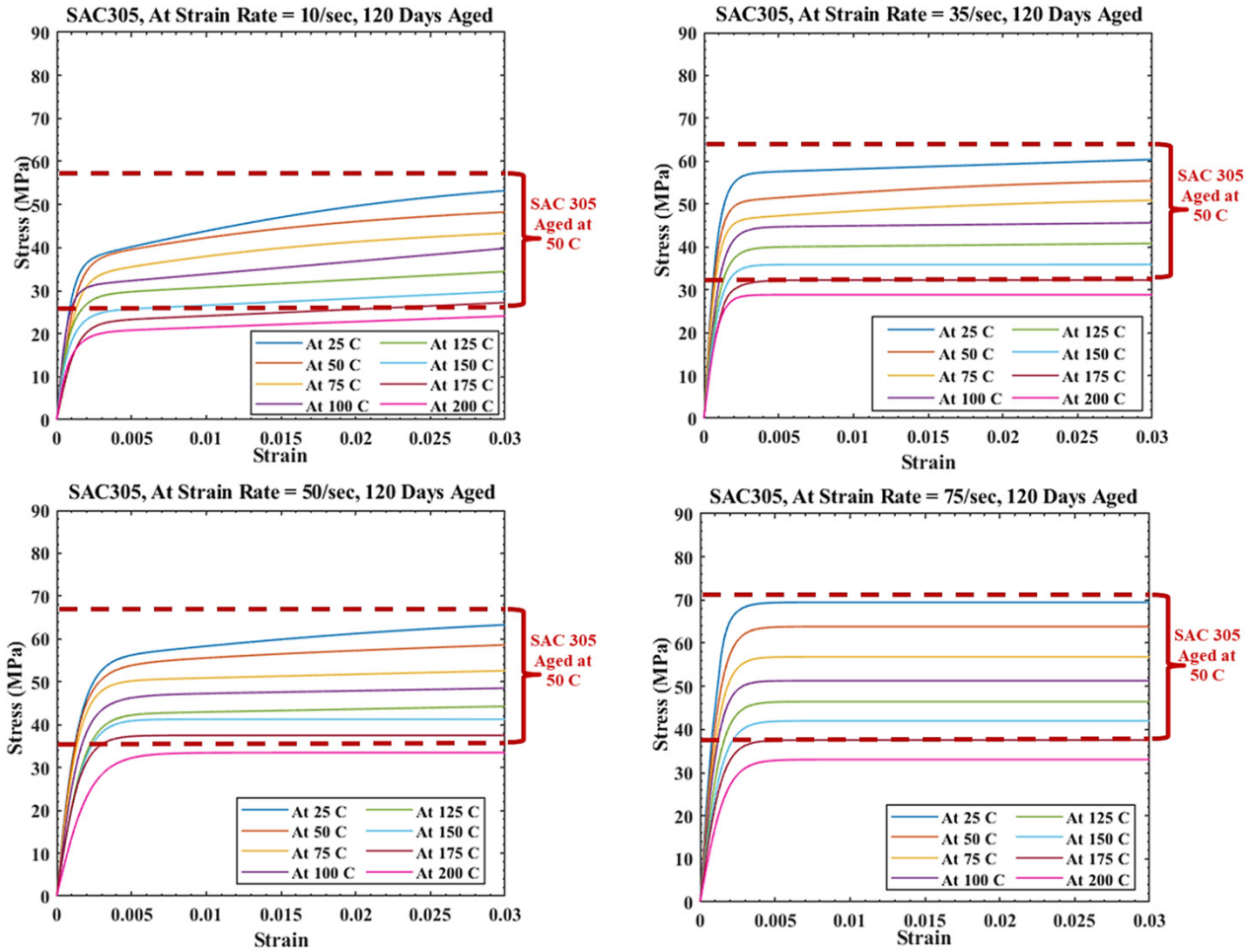
SAC305 Stress-Strain curves – 30 Days @100C



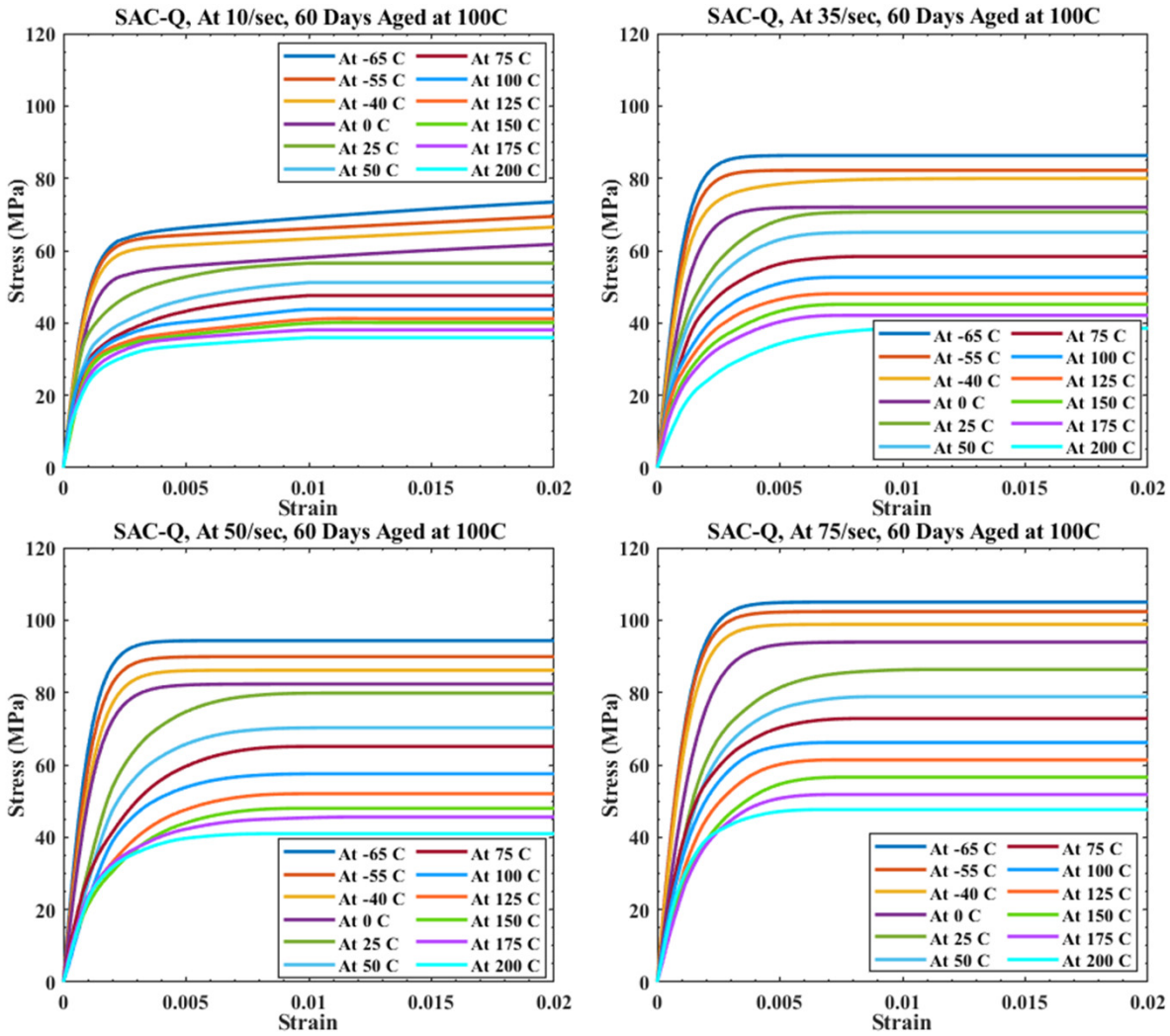
SAC305 Stress-Strain curves – 60 Days @100C



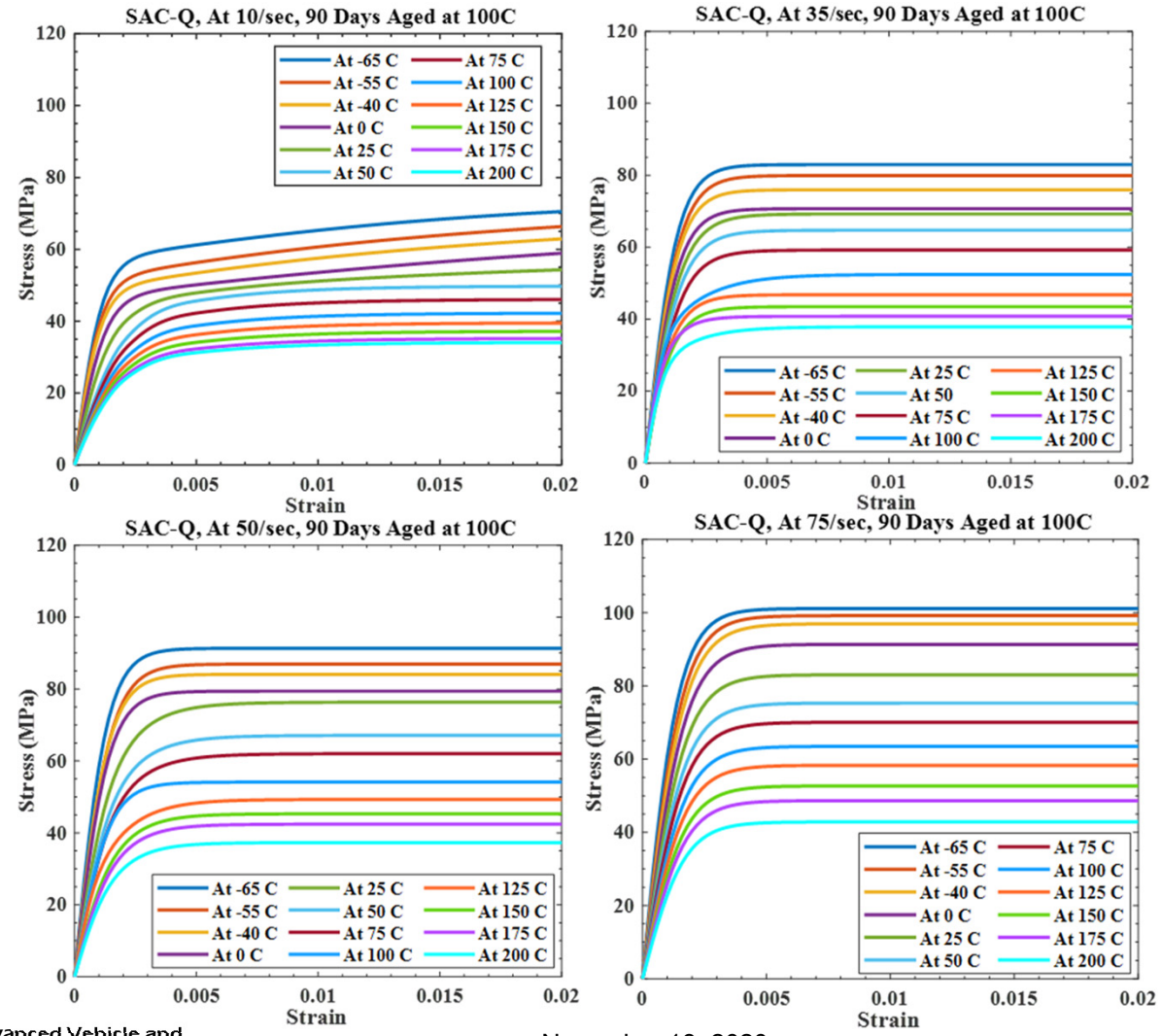
SAC305 Stress-Strain curves – 120 Days @100C



SAC-Q Stress vs Strain Curves - 60 days @100C



SAC-Q Stress vs Strain Curves - 90 days @100C



Anand Model

Flow Equation:

$$\dot{\varepsilon}_p = A\, exp\left(-\frac{Q}{RT}\right)\left[\sinh\left(\xi\frac{\sigma}{s}\right)\right]^{\frac{1}{m}}$$

$$c = \frac{\sigma}{s}$$

Invers
e

$$c = (\dot{\varepsilon}_p, T) = \left(\frac{1}{\xi}\right)\sinh^{-1}\left\{\left[\frac{\dot{\varepsilon}_p}{A}\, exp\left(\frac{Q}{RT}\right)\right]^m\right\}$$

Substitute

Stress Equation: $\sigma = cs; c < 1$

$$\sigma = \left(\frac{s}{\xi}\right)\sinh^{-1}\left\{\left[\frac{\dot{\varepsilon}_p}{A}\, exp\left(\frac{Q}{RT}\right)\right]^m\right\}$$

Anand Model Constants:

A: Pre-exponential factor,
Q: Activation energy,
R: Universal gas constant,
m: Strain rate sensitivity of stress,
n: Exponent of deformation resistance,
ξ: Stress Multiplier,
$\hat{s}$: Coefficient of deformation resistance saturation value,
h_0: Hardening/Softening constant,
a: Strain rate sensitivity for hardening/softening,
s_0: Initial value of deformation resistance

Anand Model

$$B = 1 - \frac{s}{s^*}$$

Substitute

Evolution Equation:

$$\dot{s} = \left\{ h_0 (|B|)^a \frac{B}{|B|} \right\} \dot{\varepsilon_p}; (a > 1)$$

Integrate

$$s = s^* - \left\{ (s^* - s_0)^{(1-a)} + (a-1)\left[h_0 (s^*)^{-a} \varepsilon_p \right] \right\}^{\frac{1}{1-a}}$$

Substitute

$$s^* = \hat{s} \left[\frac{\dot{\varepsilon_p}}{A} exp\left(\frac{Q}{RT} \right) \right]^n$$

$$s = \hat{s} \left[\frac{\dot{\varepsilon_p}}{A} exp\left(\frac{Q}{RT} \right) \right]^n - \left\{ \left(\hat{s} \left[\frac{\dot{\varepsilon_p}}{A} exp\left(\frac{Q}{RT} \right) \right]^n - s_0 \right)^{(1-a)} + (a-1) \left[h_0 \left(\hat{s} \left[\frac{\dot{\varepsilon_p}}{A} exp\left(\frac{Q}{RT} \right) \right]^n \right)^{-a} \varepsilon_p \right] \right\}^{\frac{1}{1-a}}$$

Anand Model Constants:

A: Pre-exponential factor,
Q: Activation energy,
R: Universal gas constant,
m: Strain rate sensitivity of stress,
n: Exponent of deformation resistance,
ξ: Stress Multiplier,
$\hat{s}$: Coefficient of deformation resistance saturation value,
h_0: Hardening/Softening constant,
a: Strain rate sensitivity for hardening/softening,
s_0: Initial value of deformation resistance

SAC305 Anand Constants

Constant No.	Anand Constants	Unit	30 Days Aging (At 100°C)	60 Days Aging (At 100°C)	90 Days Aging (At 100°C)	120 Days Aging (At 100°C)
1	A	sec^{-1}	1192.17	1459.75	1697	1800
2	Q/R	1/K	4500	4500	4500	4500
3	m	-	0.697	0.995	0.88	1
4	n	-	0.00113	0.01130	0.0087	0.0127
5	ξ	-	6.7	6.7	6.7	6.7
6	$\hat{s}$	MPa	52.97	54.95	64.28	61.819
7	h_0	MPa	64992.50	57074.03	77300	73140
8	a	-	1.0151	1.0082	1.1018	1.407
9	s_0	MPa	0.01331	0.00012	0.00913	0.0409

A: Pre-exponential factor,
Q: Activation energy,
R: Universal gas constant,
m: Strain rate sensitivity of stress,
n: Deformation resistance

ξ: Stress Multiplier,
$\hat{s}$: Coefficient of deformation resistance saturation value,
h_0: Hardening/Softening constant,
a: Strain rate sensitivity for hardening/softening,
s_0: Initial value of deformation resistance

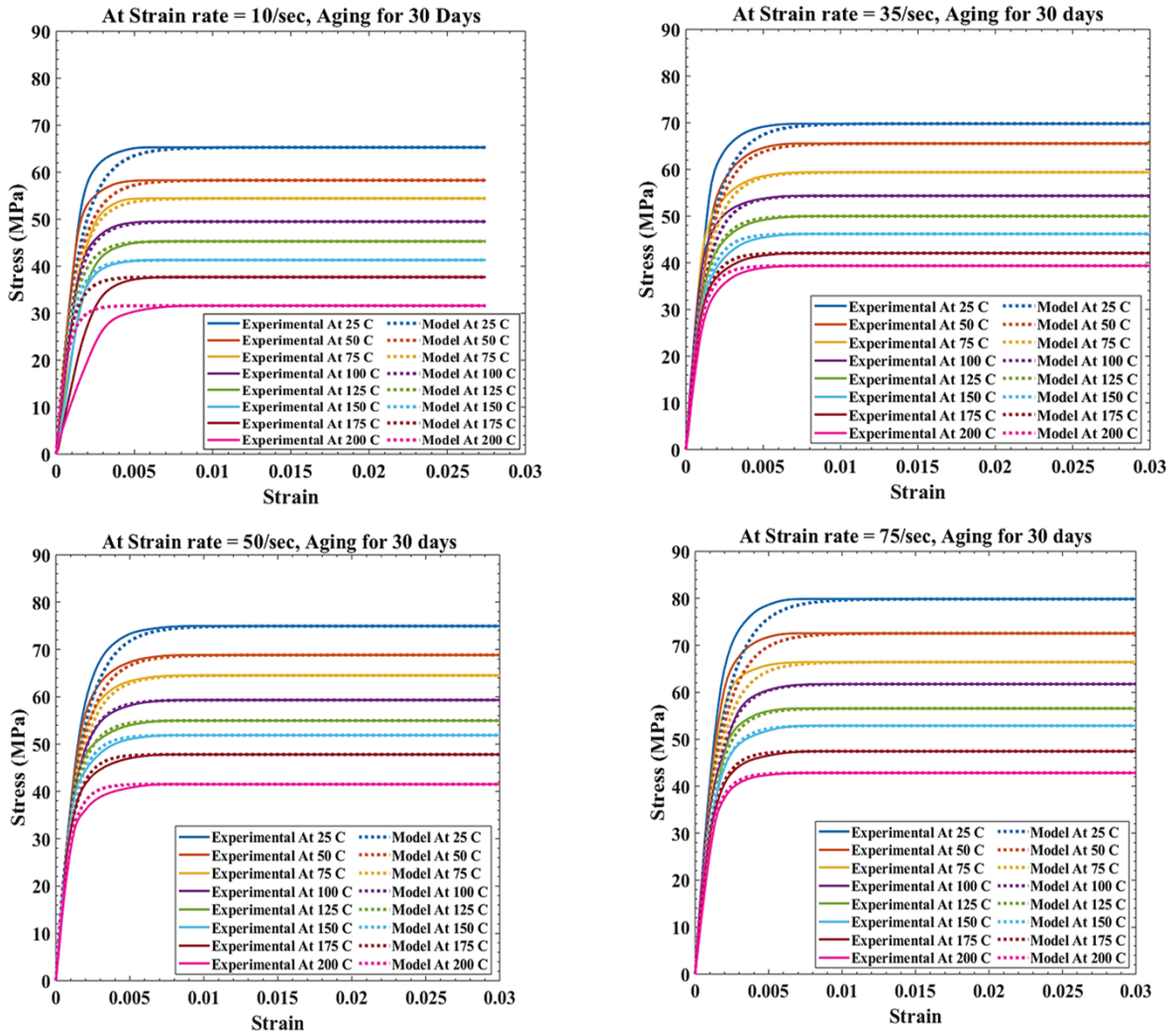
SAC-Q Anand Constants

Constant No.	Anand Constants	Unit	30 Days Aging (At 100°C)	60 Days Aging (At 100°C)	90 Days Aging (At 100°C)
1	Q/R	sec^{-1}	8444	8444	8444
2	ξ	1/K	4.28	4.28	4.28
3	A	-	6230	7110	7375
4	m	-	0.303	0.355	0.361
5	n	-	0.00269	0.0009	0.0022
6	h_0	MPa	93350	92770	88850
7	a	MPa	1.29	1.32	1.36
8	s_0	-	0.783	0.697	0.73
9	$\hat{s}$	MPa	47.54	43.95	40.42

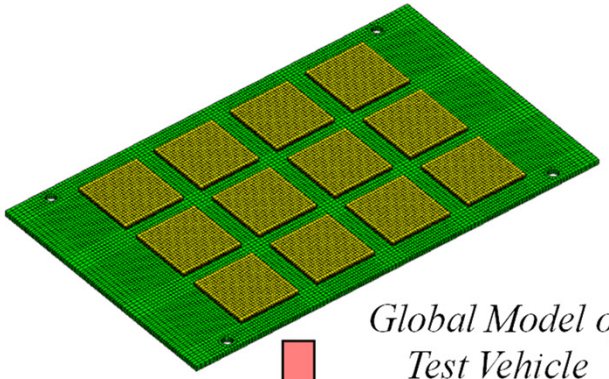
A: Pre-exponential factor,
Q: Activation energy,
R: Universal gas constant,
m: Strain rate sensitivity of stress,
n: Exponent of Deformation resistance

ξ: Stress Multiplier,
$\hat{s}$: Coefficient of deformation resistance saturation value,
h_0: Hardening/Softening constant,
a: Strain rate sensitivity for hardening/softening,
s_0: Initial value of deformation resistance

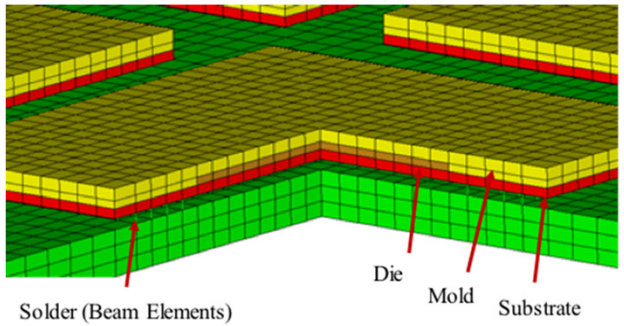
Model Verification - Aging @ 100 °C for 30 days



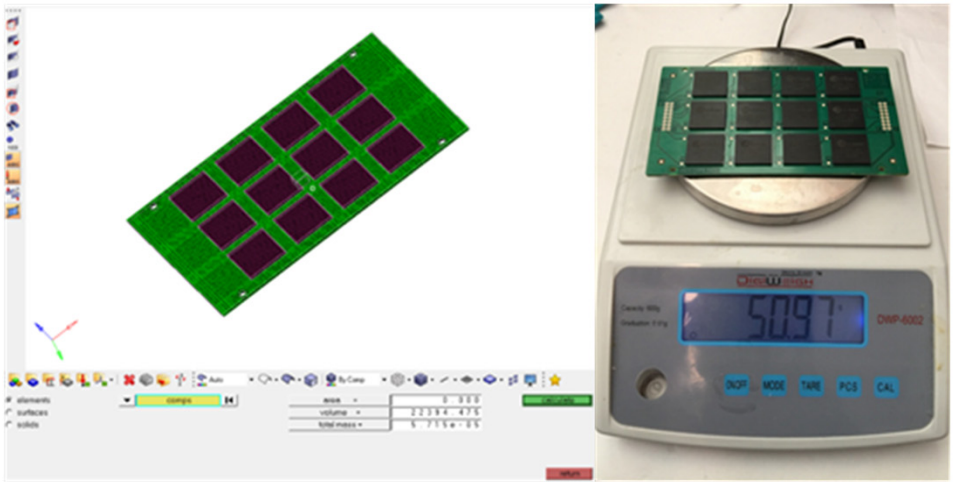
Actual Mass vs Global FE Model



Global Model of Test Vehicle



Cut-Section View of CABGA288.

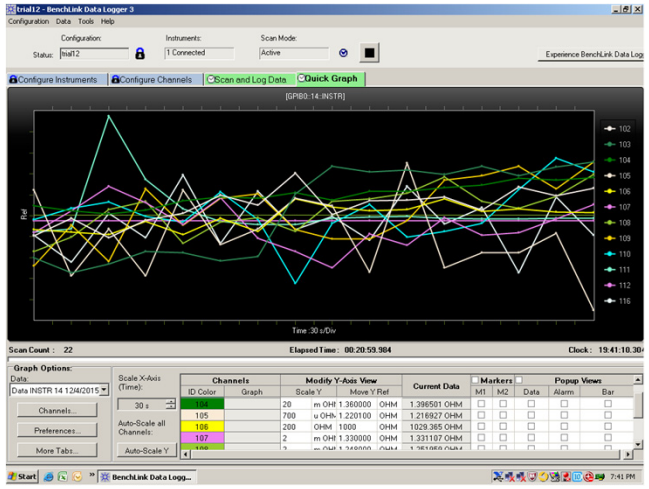


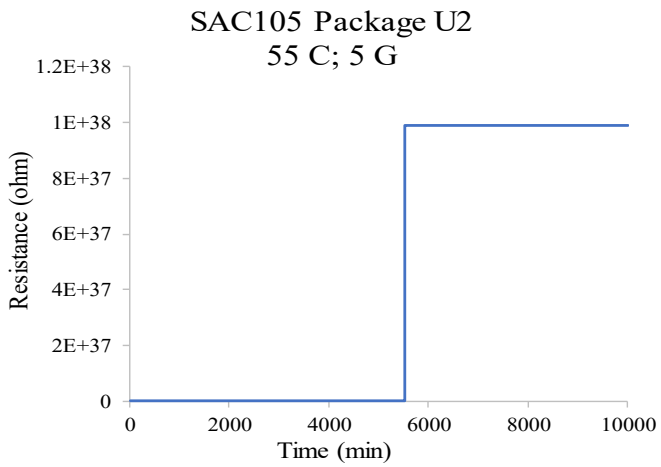
Weight comparison of Test Vehicle

Material Properties

Package Assembly	E (MPa)	Poisson's Ratio	Density (tonne/mm^3)	Element Type
Solder Joints	42000	0.34	8.40E-09	VISCO107
EMC	23500	0.25	1.65E-09	SOLID 45
Silcon Die	162000	0.28	2.33E-09	SOLID 45
Die Attach	2760	0.35	7.80E-09	SOLID 45
BT Substrate	17400	0.28	1.80E-09	SOLID 45
Copper Pad	129000	0.34	8.82E-09	SOLID 45
PCB	23.8	0.39	1.80E-09	SOLID 45

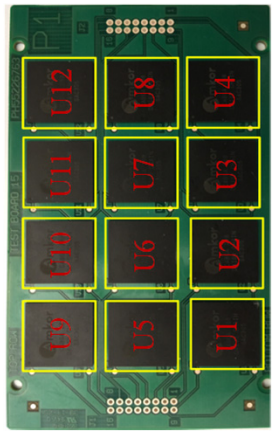
Resistance Measurement Set-up

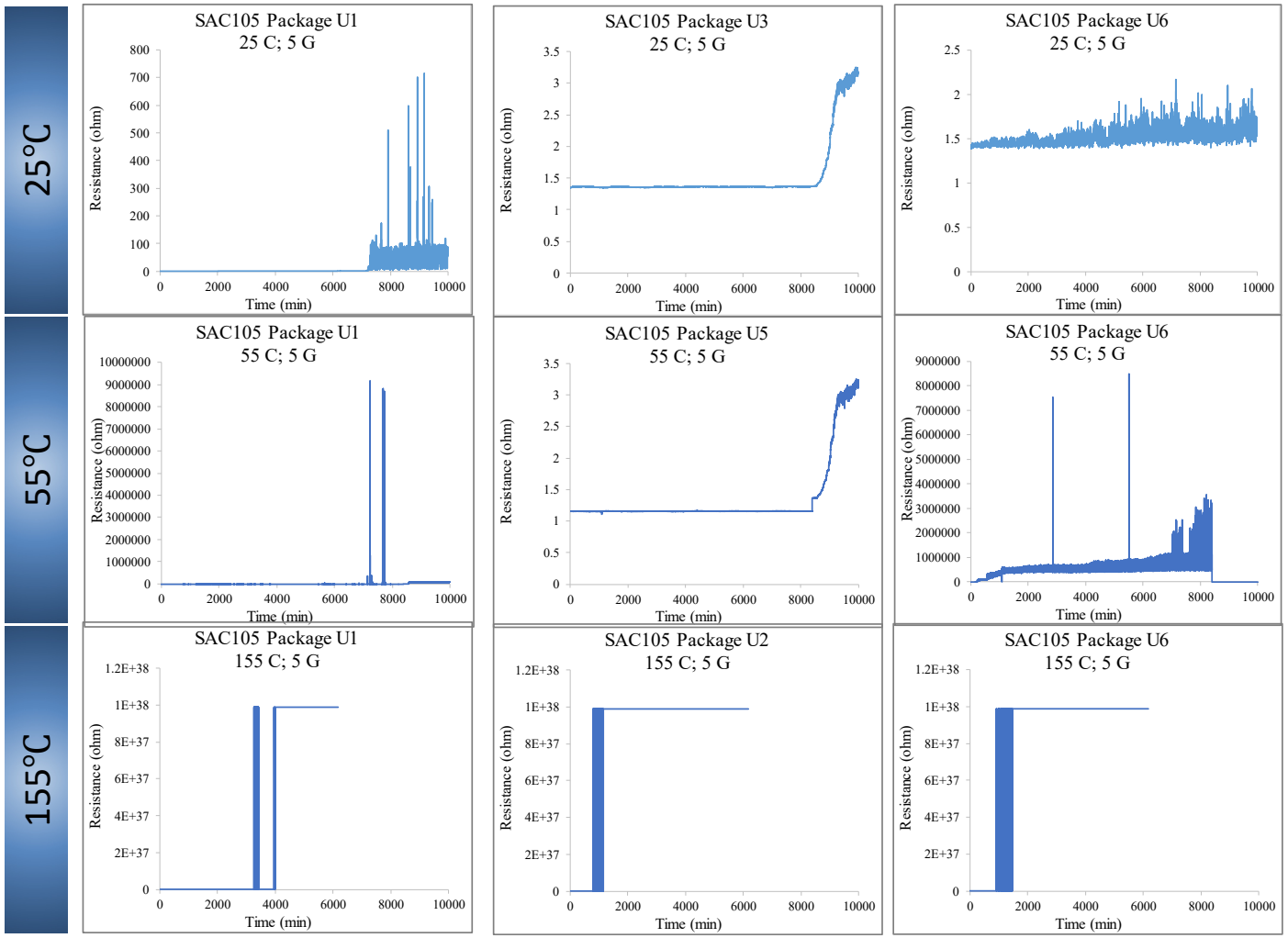




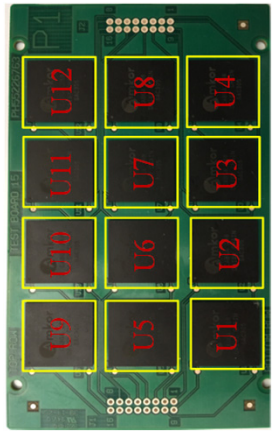
Typical Resistance Data

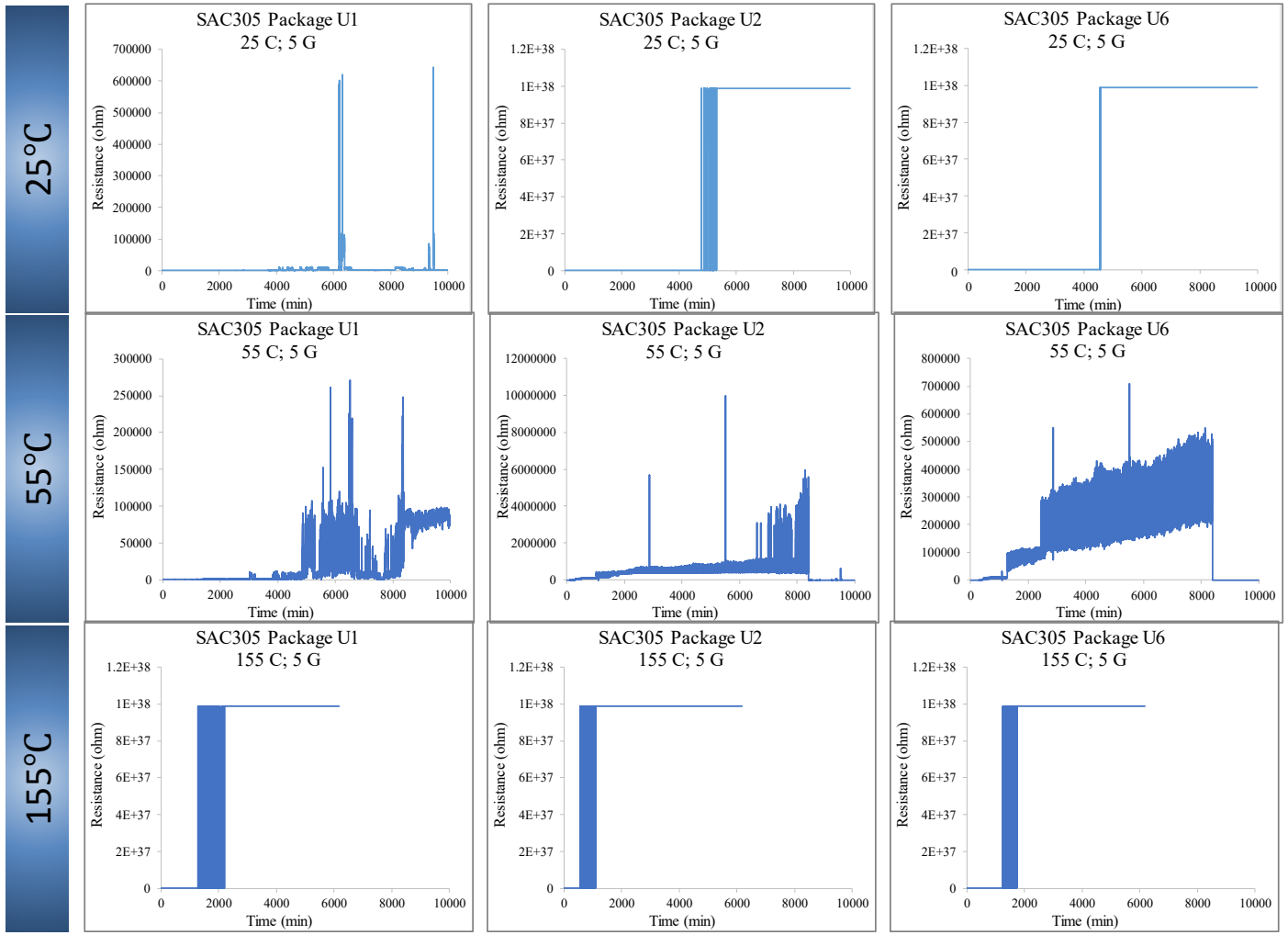
Life-Resistance Data: SAC105 @ 5g



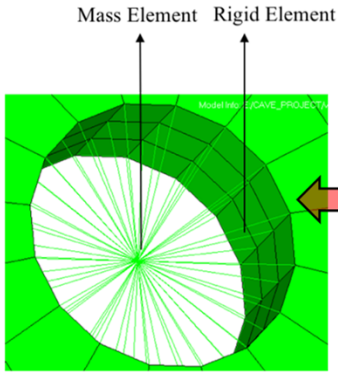


Life-Resistance Data: SAC305 @ 5g

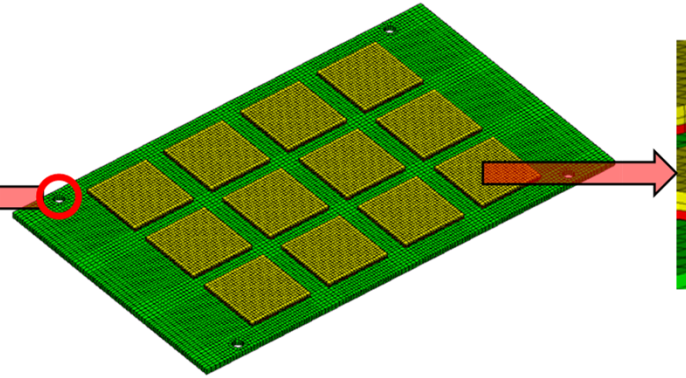




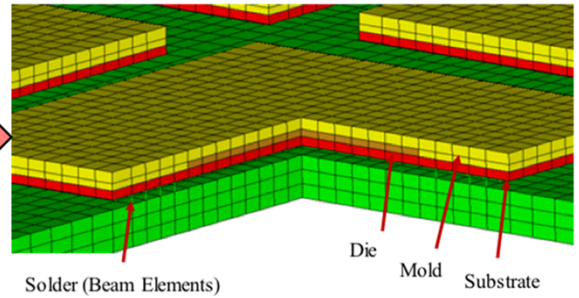
FE-Global Model



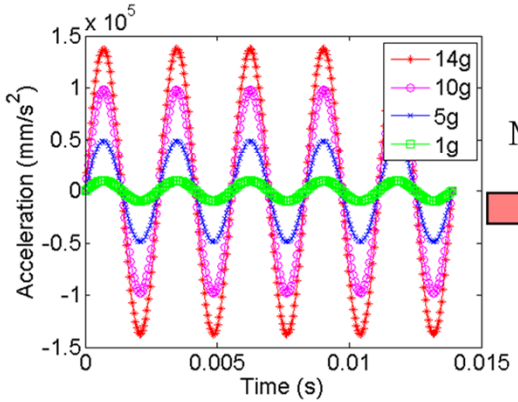
Mass and Rigid Element at Screw holes of PCB



Global model of Test Vehicle

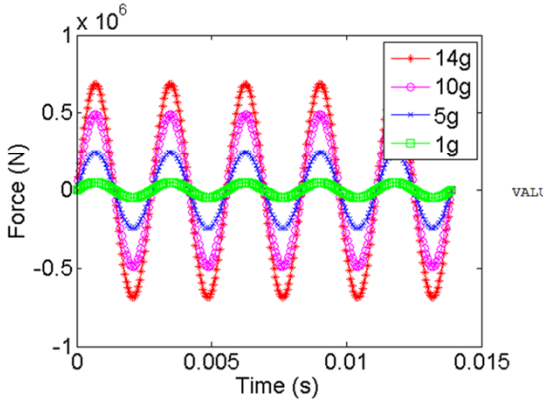


Cut-Section View of CABGA288

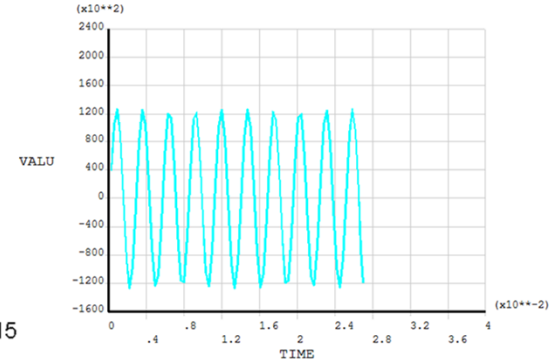


Desired Input Excitation

Multiply by mass

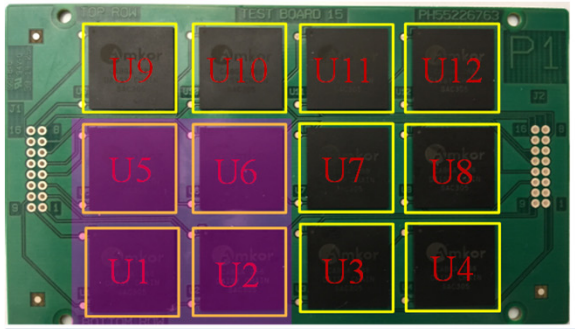


Input Tabular Force Data

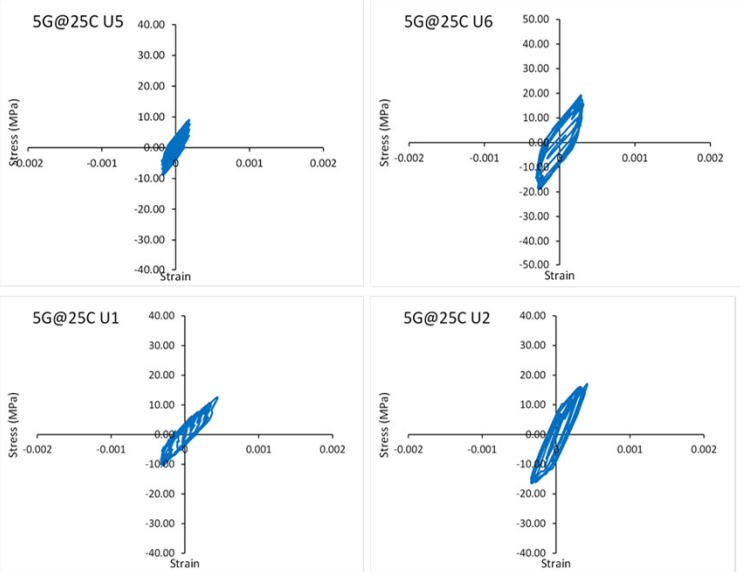


Output Acceleration from the Mass node at 14g and 360Hz

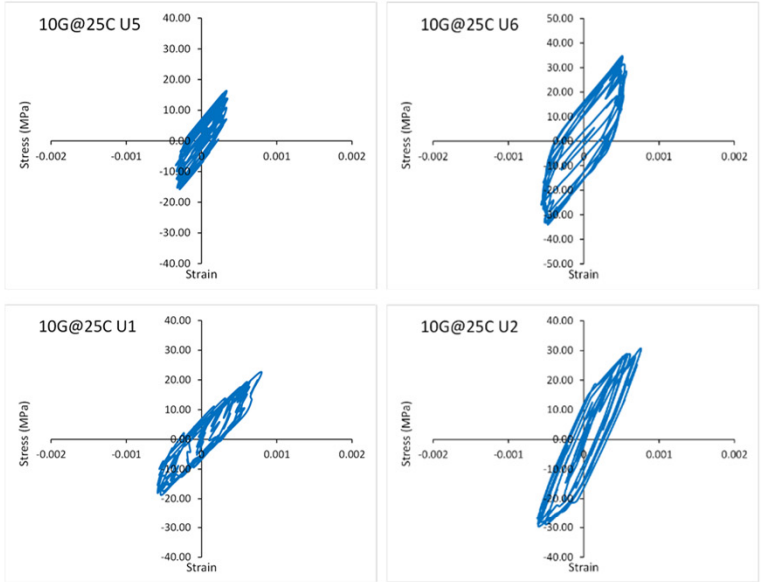
Hysteresis Loop of Critical Solder Joint



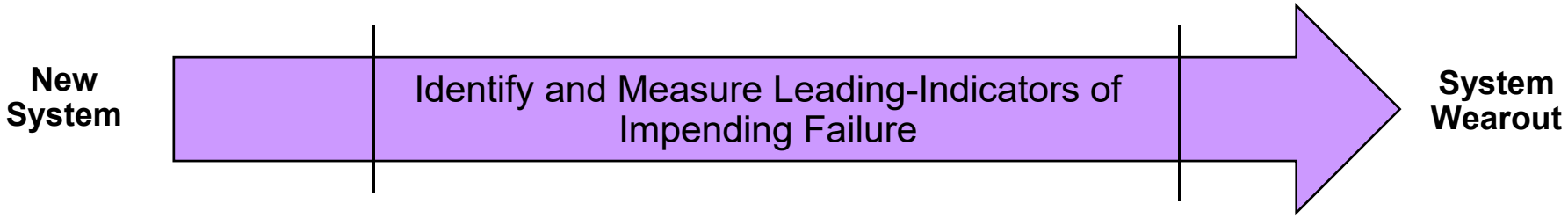
5g



10g



Prognostics for Risk Mitigation



- **Sensitivity of sensor locations** in predicting failure during Vibration
- Study the changes in the **two selected feature vectors at different locations** of the PCB during vibration
- Investigating the importance of **different strain components** in predicting failure
- Comparison of the effect of prognostication based on sensor location for **two board assemblies**

Prognostics State-of-Art

Author	Reported Methods
Jie Gu 2008	Prognostics and Health management using **Physics of Failure approaches**
Scwabacher 2009, Vicare 2006	**Data driven approaches** using statistics and probability techniques
Lall 2009, Lall 2012, Lall 2014	Prognostics based on **Resistance Spectroscopy** measurements
Lall 2017	Health Monitoring of electronic components from **Strain Measurements**
Liu J 2009	**Model based approaches**

Test Setup for Test board-1

Figure 1: Shaker with the heating chamber on top

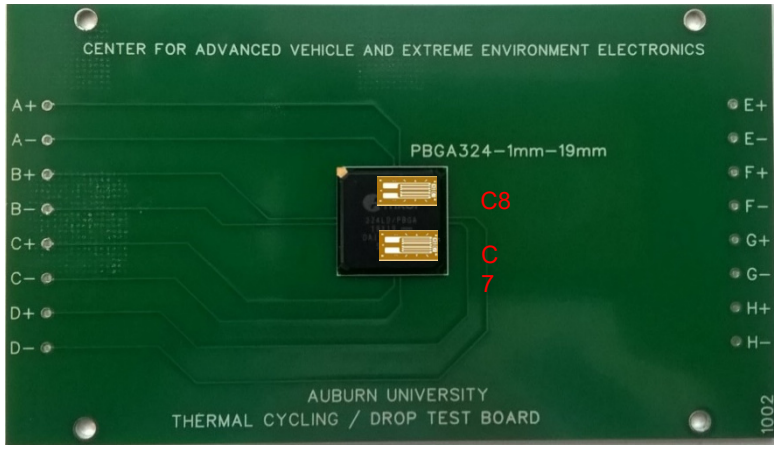


Figure 2: Front side of the test board -1

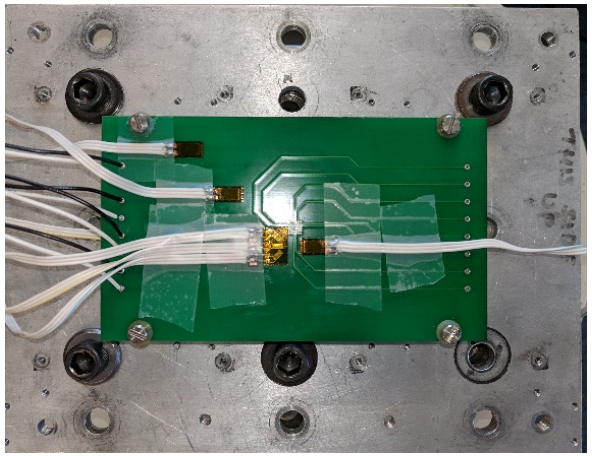


Figure 5: PCB board inside the heating chamber with strain gauge

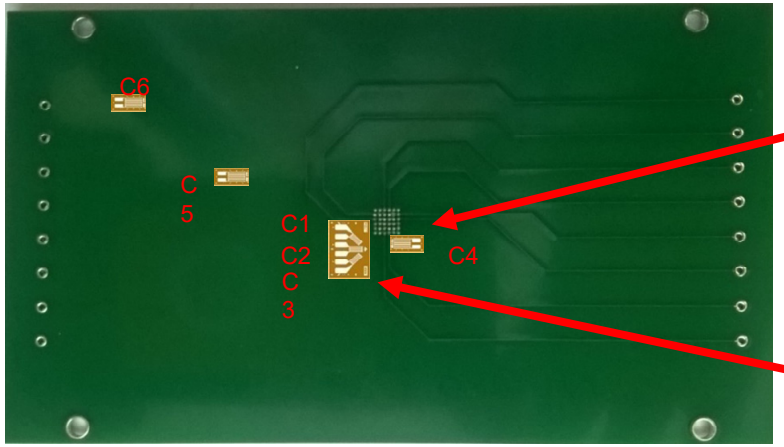


Figure 2: Back side of the test board -1

Strain gauge fixed on back side of the PCB

Strain rosette fixed on back side of the PCB

- **Natural frequency- 340 Hz**
- **Frequency Range of vibration from 330 Hz to 350 Hz**

Test Setup for Test Board-2

Figure 1: Shaker with the heating chamber on top

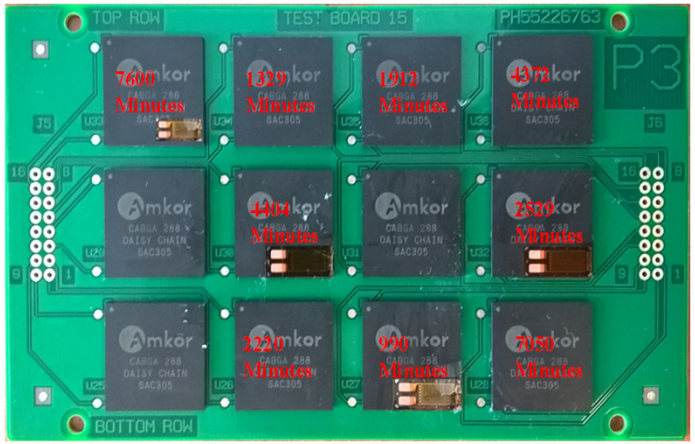


Figure 2: PCB board with packages

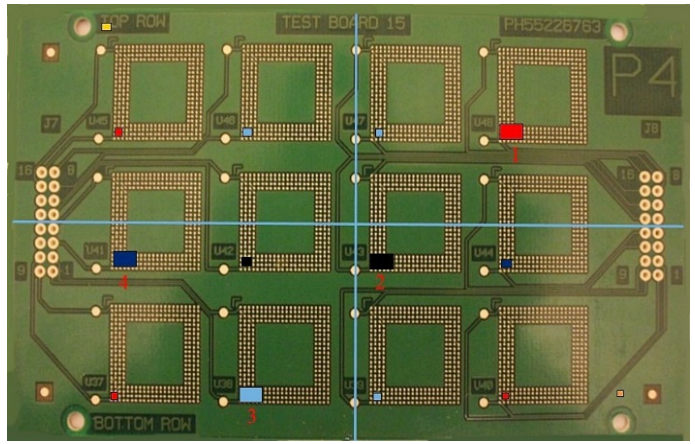


Figure 3: Schematic diagram of the symmetric position of strain gauges on the packages

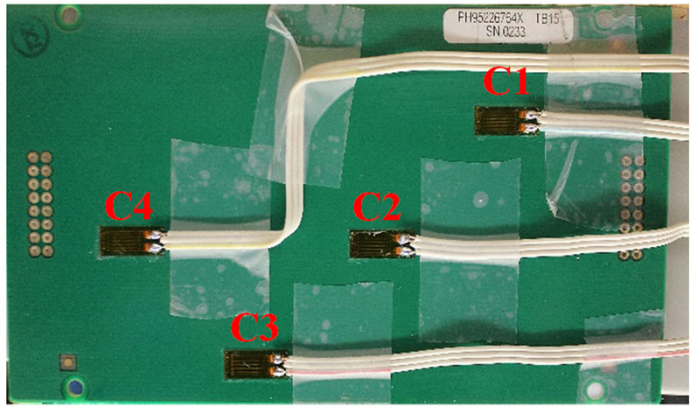


Figure 4: PCB board with strain gauges fixed to the back side of the board

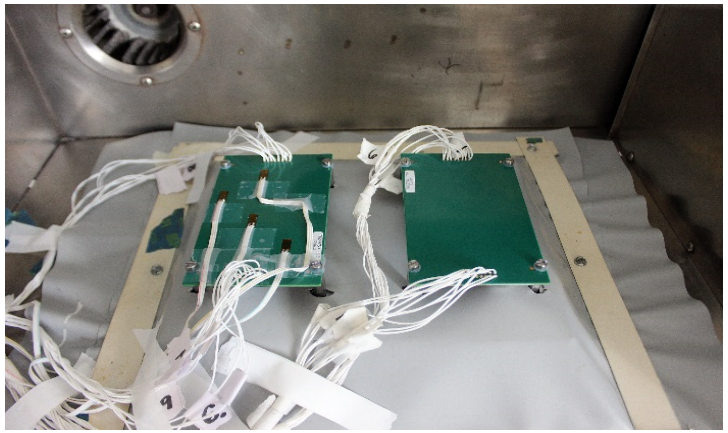


Figure 5: PCB board inside the heating chamber

- **Natural frequency- 380 Hz**
- **Frequency Range of vibration from 370 Hz to 390 Hz**

Data Acquisition

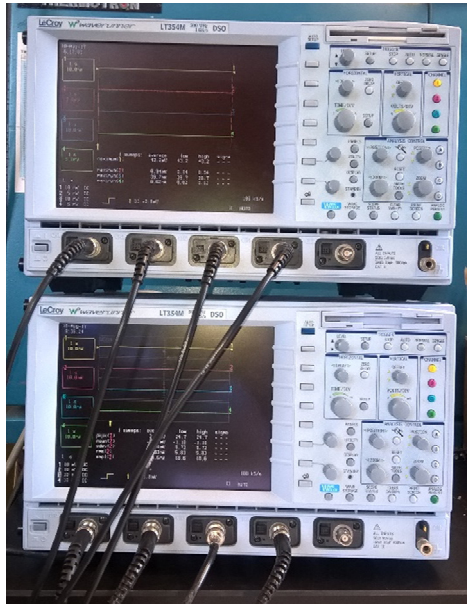


Figure 6: Oscilloscope for Data Acquisition

Figure 7: Signal condition Amplifier

- There are **50 strain signals** captured at different **instances of vibration**
- The **Red instances** represent the strain signal captured **before failure** of electronic package
- The **blue represents** after **failure strain** signals

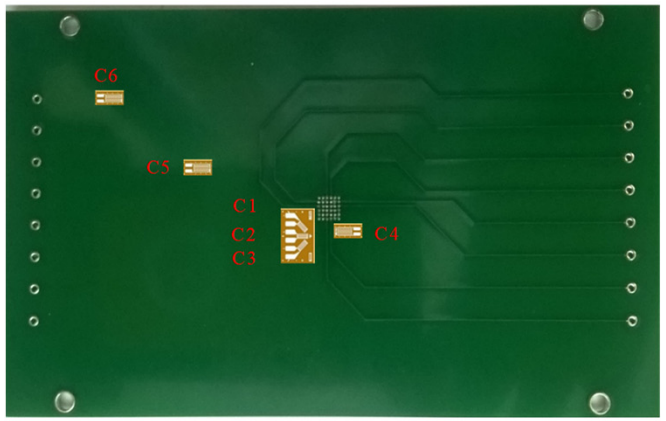
Table 1: Time Series taken for analysis

SL:No	Time (Minutes)
1	0
2	1
3	4
.	.
.	.
34	420
35	450
36	480
.	.
.	.
48	840
49	870
50	900

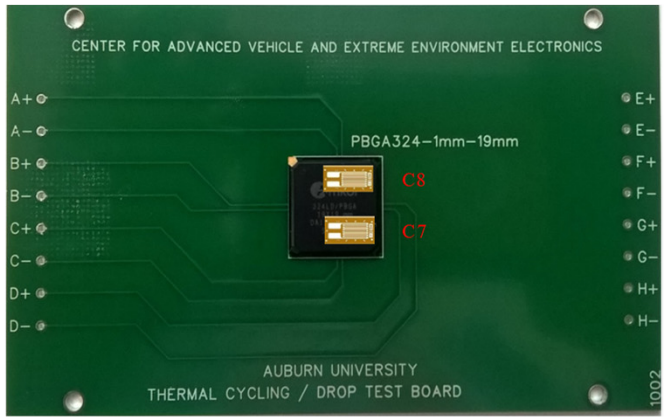
Red Series- Before Failure
Blue Series- After Failure

- **Vibration Acceleration level- 5G**
- **Ambient Temperature-25 Degree Celsius**

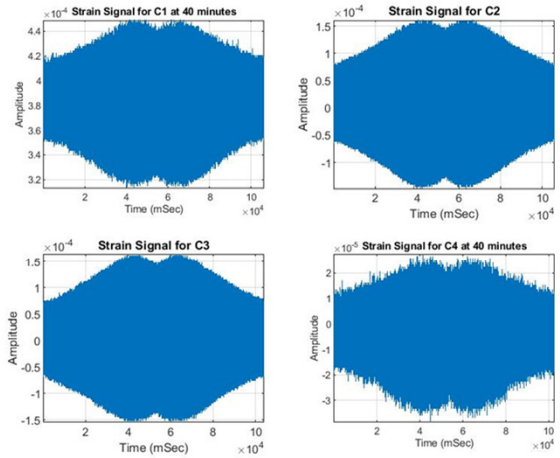
Strain Signals for Test Board-1



C1-C6 from the **back side**

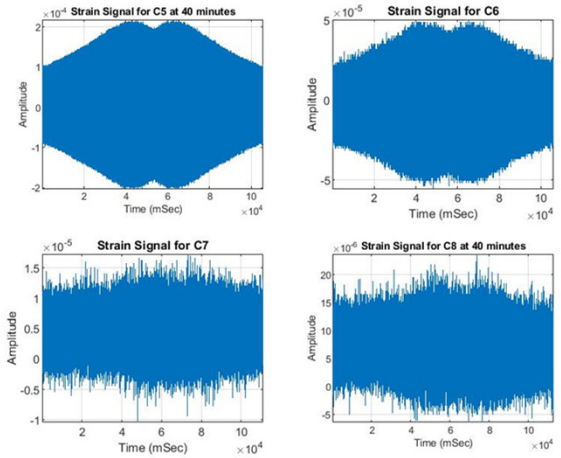


C7 and C8 from the **front side**



C1-C3 are the strain signals from strain rosette

C4-C8 are the strain signals from strain gauges

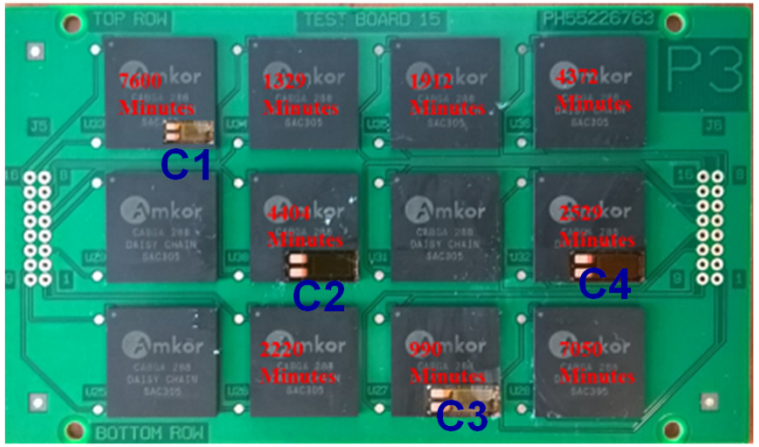


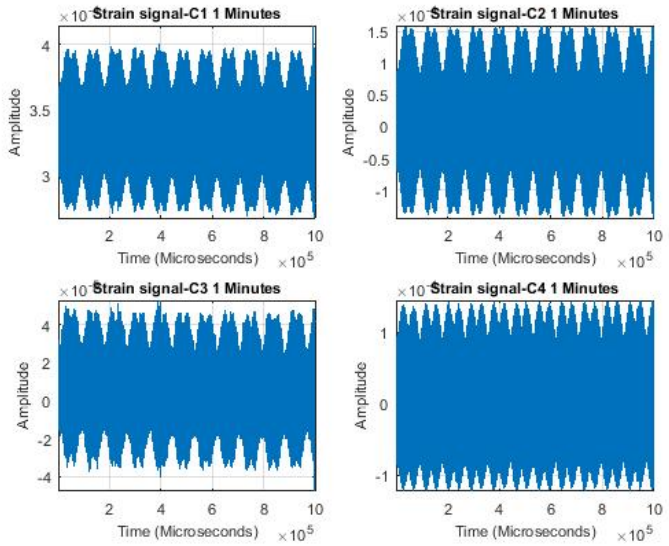
Strain signals C1 to C4 from the **back side**

Sampling frequency is at 10,000 Hz and Sampling Time is for 100 Sec

Strain signals C5 to C8 from the **back and front side**

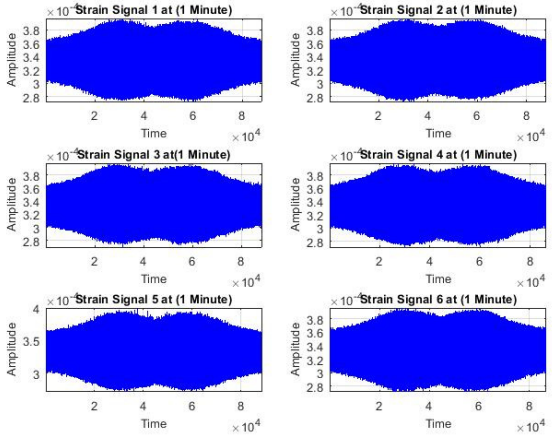
Strain Signals for Test Board-2





C1, C2, C3 and C4 are strain signals from **different locations** of test board-2

Sampling frequency is at 10,000 Hz and Sampling Time is for 100 Sec



Splitting of each strain signal (C1 to C4)

Test Matrix and FFT of the Strain Signals

- **Peak Frequency Amplitudes** are same for (C1 to C4).
- Peak frequency is seen at the **Natural Frequency** of the board
- **Low Amplitude frequency** components are not visible

$$DFT = \sum_{N} x_N[n] \cdot e^{-i2\pi \frac{kn}{N}}$$

N= Number of samples
n= sum over n sequence of length N
k= integer from 0 to N

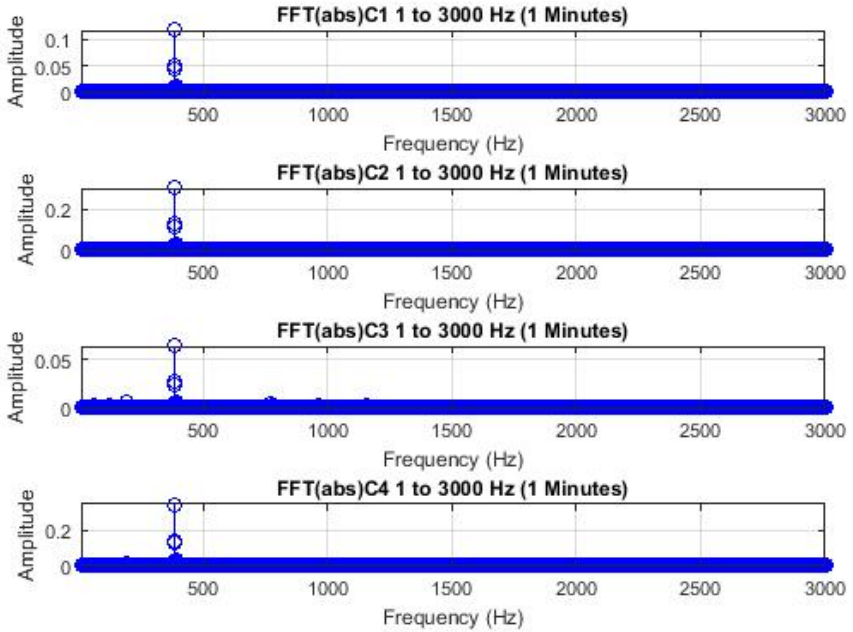


*Figure 11: FFT (Abs) of the strain signal (C1-C4) from **1- 3000 Hz** at 1 Minute*

Test Matrix (X)-Strain Signal

$$\begin{matrix} Row: 1 & Strain\ Signal\ at\ SL\ No:\ 1 \\ \vdots & \vdots \\ Row: 50 & Strain\ Signal\ at\ SL\ No: 50_{50\times10^6} \end{matrix}$$

Test Matrix (F)- FFT(Strain Signal)

$$\begin{matrix} Row: 1 & FFT\ at\ SL\ No:\ 1 \\ \vdots & \vdots \\ Row: 50 & FFT\ at\ SL\ No: 50_{50\times10^4} \end{matrix}$$

FFT of Strain Signals (C1-C4)

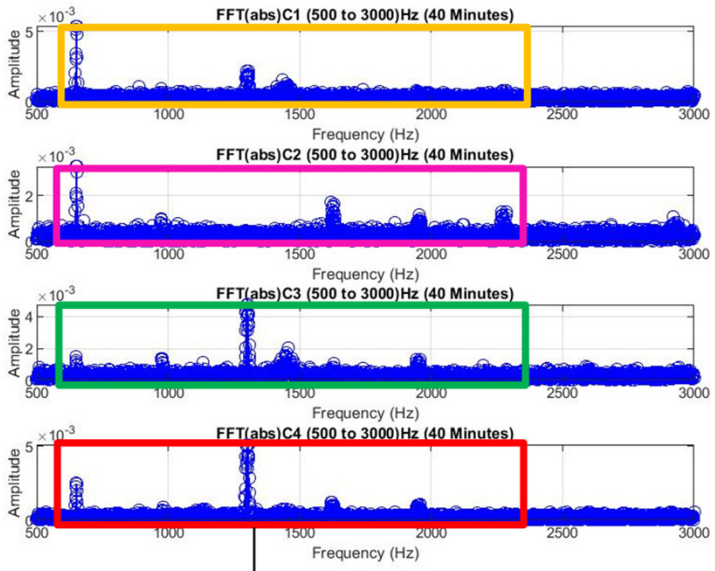


*Figure 12: FFT (Abs) of the strain signal (C1-C4) from **500- 3000 Hz** at **40 Minute***

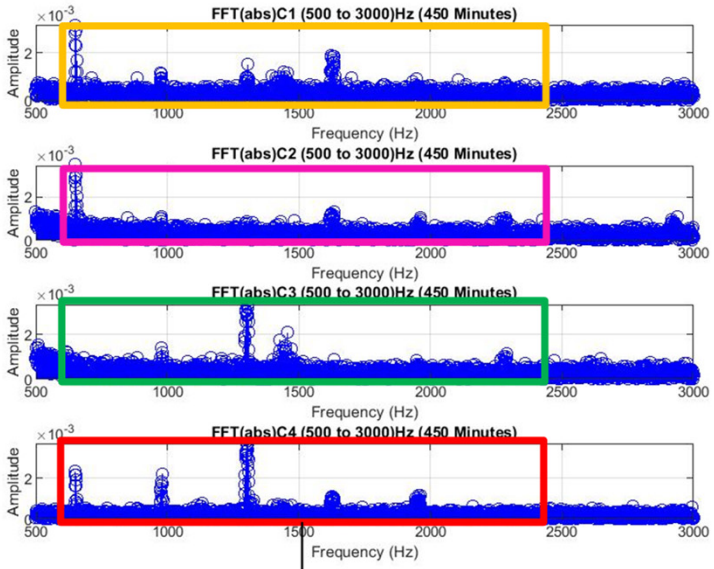


*Figure 13: FFT (Abs) of the strain signal (C1-C4) from **500- 3000 Hz** at **450 Minute***

FFT of Before failure Strain Signal

- Corresponding frequency components for strain signal C4 at **40 and 450 minutes of vibration**
- **Lower frequency components** change considerably with vibration time
- This behavior is **same for C1, C2, and C3** as well.

FFT of After failure Strain Signal

FFT of Strain Signals (C5-C8)

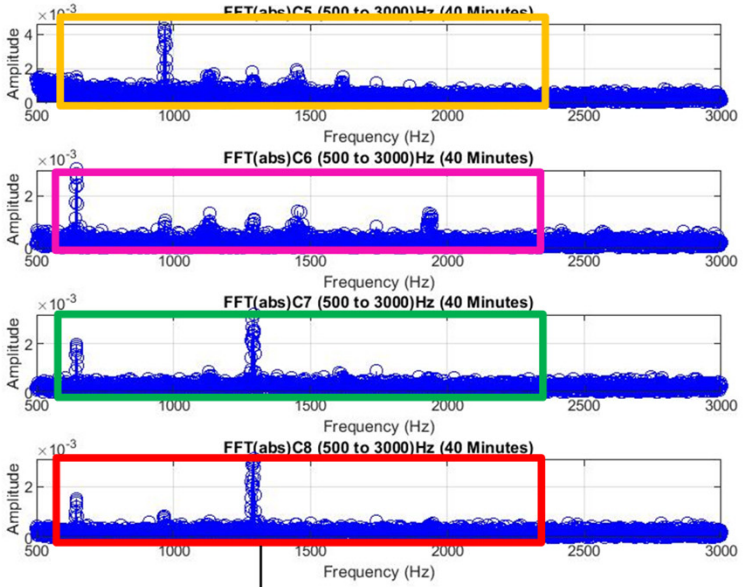


*Figure 12: FFT (Abs) of the strain signal (C5-C8) from **500- 3000 Hz** at **40 Minute***

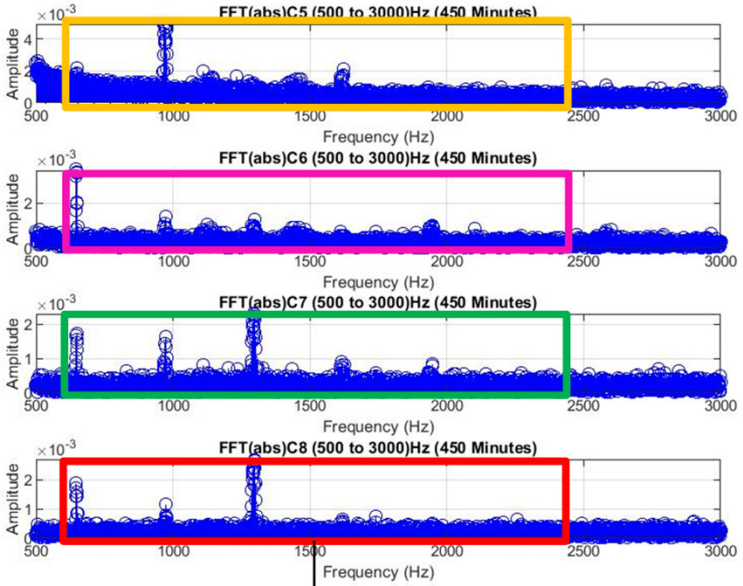


*Figure 13: FFT (Abs) of the strain signal (C5-C8) from **500- 3000 Hz** at **450 Minute***

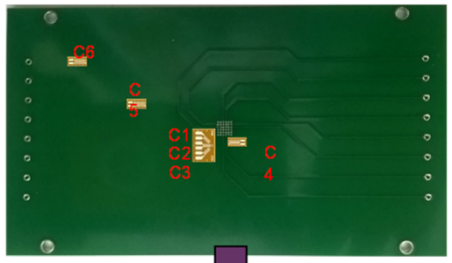
FFT of Before failure Strain Signal

- Corresponding frequency components for strain signal C8 at **40 and 450 minutes of vibration**
- **Lower amplitude frequency components** change considerably with vibration time

FFT of After failure Strain Signal

Feature Vectors Used in the Analysis

Each strain signal is analyzed in the following manner to find the pattern for the two feature vectors



Test Matrix (X)-Strain Signal C1

$Row: 1 \quad Strain\ Signal\ at\ SL\ No:\ 1$
$\vdots \qquad \vdots$
$Row: 50 \quad Strain\ Signal\ at\ SL\ No: 50_{50\times10^6}$

Calculation for Instantaneous Frequency(IF)

Let the signal be $x(t)$ and the $Z(t)$ analytical equivalent of the signal is

$$Z(t) = x(t) + jH\{x(t)\} = a(t)e^{i\phi(t)}$$

$H\{x(t)\}$ Hilbert transform of $x(t)$

Instantaneous Amplitude = $a(t)$

Instantaneous Phase = $\phi(t)$

Instantaneous Frequency $\omega(t) = \phi'(t)$

Test Matrix (F1)- FFT of Strain Signal)

$Row: 1 \quad FFT\ at\ SL\ No:\ 1$
$\vdots \qquad \vdots$
$Row: 50 \quad FFT\ at\ SL\ No: 50_{50\times10^4}$

PCA Analysis on F1

Feature Vector-1

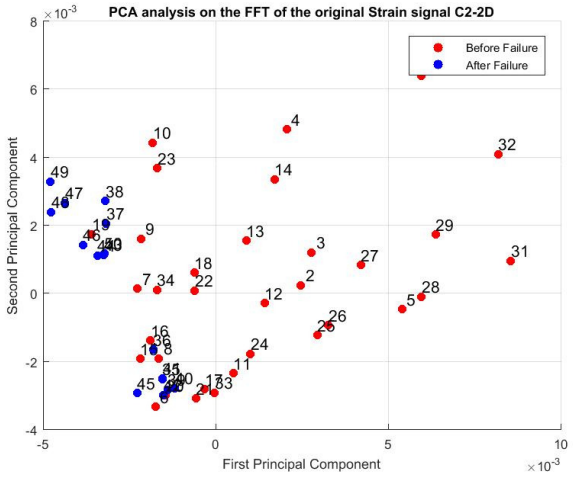
Test Matrix (F2)- IF of Strain Signal

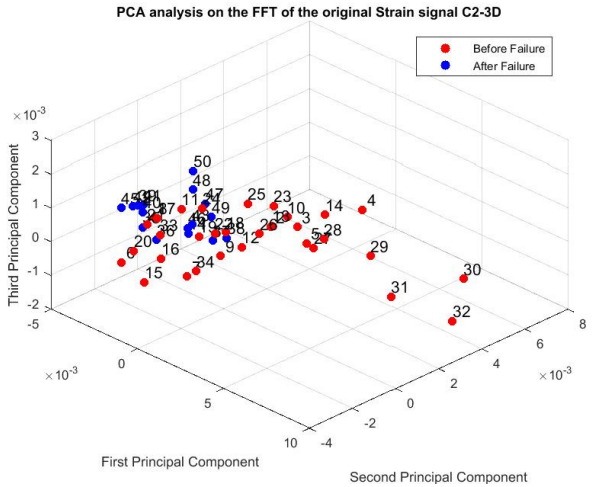
$Row: 1 \quad IF\ at\ SL\ No:\ 1$
$\vdots \qquad \vdots$
$Row: 50 \quad IF\ at\ SL\ No: 50_{50\times10^4}$

PCA Analysis on F2

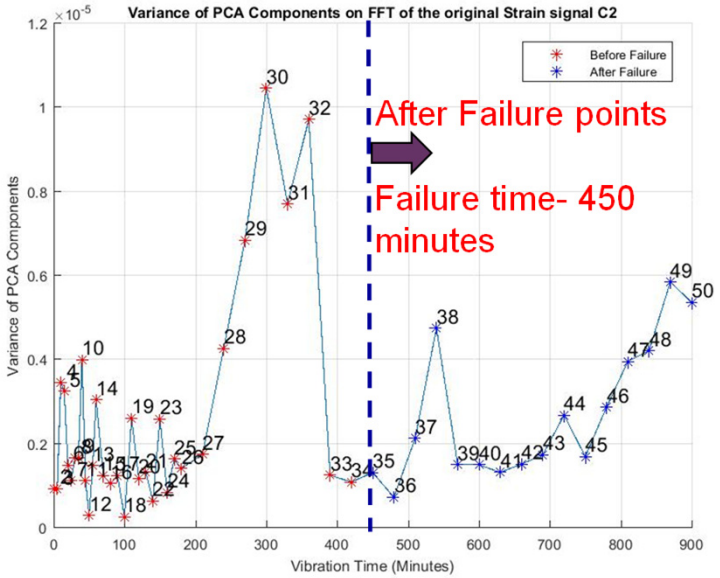
Feature Vector-2

Feature Vectors-1 Used in the Analysis



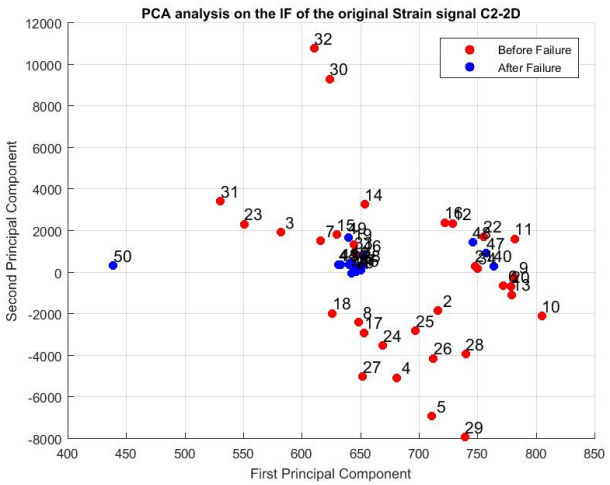


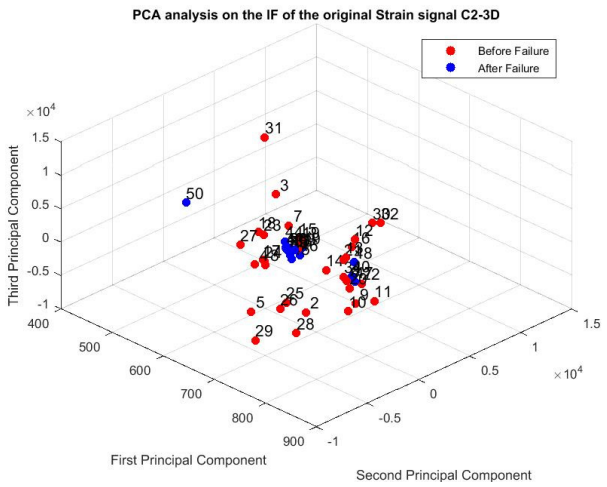
Shows the variation of the **first and second principal components** for feature vector-1



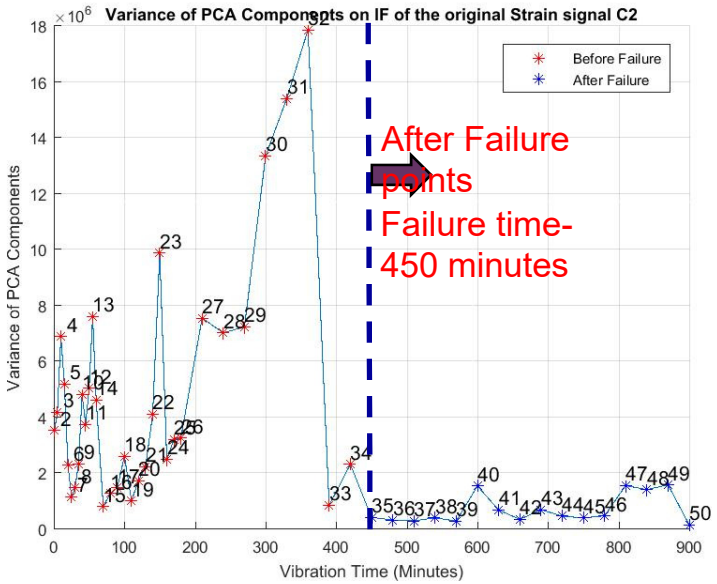
The variance of the **first 10 principal components** are plotted with vibration time.

Feature Vectors-2 Used in the Analysis





Shows the variation of the **first and second principal components** for feature vector-2

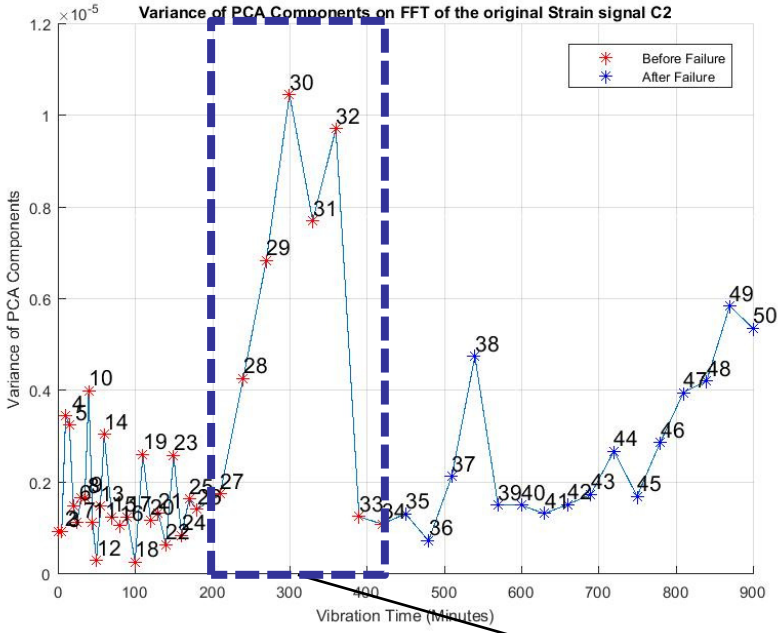


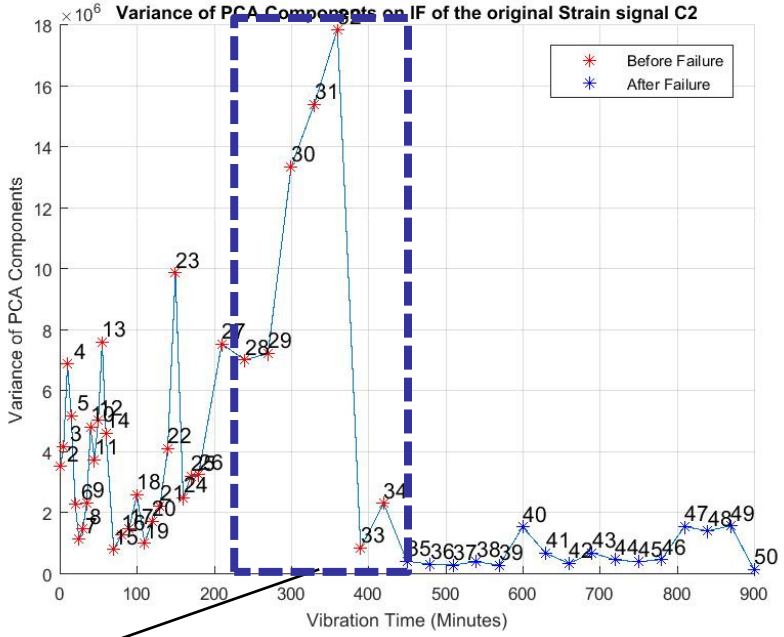
The variance of the **first 10 principal components** are plotted with vibration time.

Two Feature Vectors Used in the Analysis

Feature Vector-1
PCA on FFT (500-2000)Hz

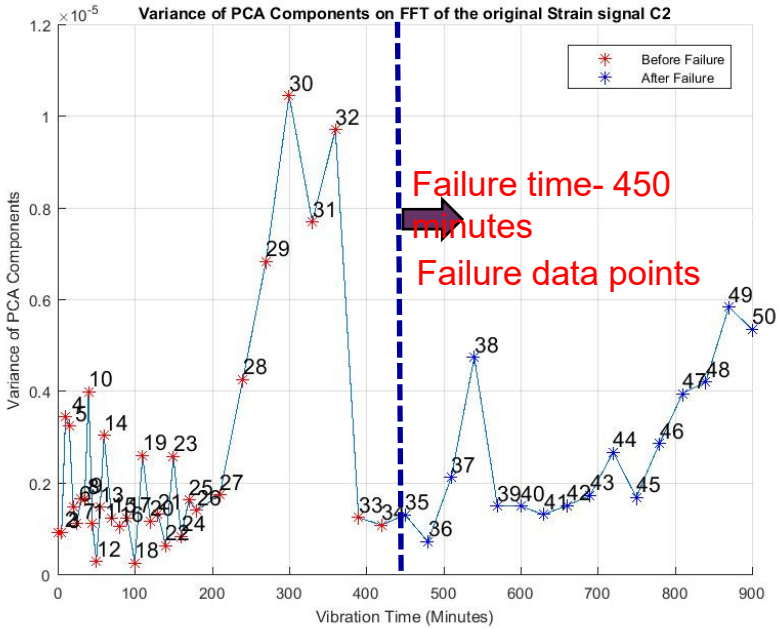
Feature Vector-2
PCA on IF of the Signal

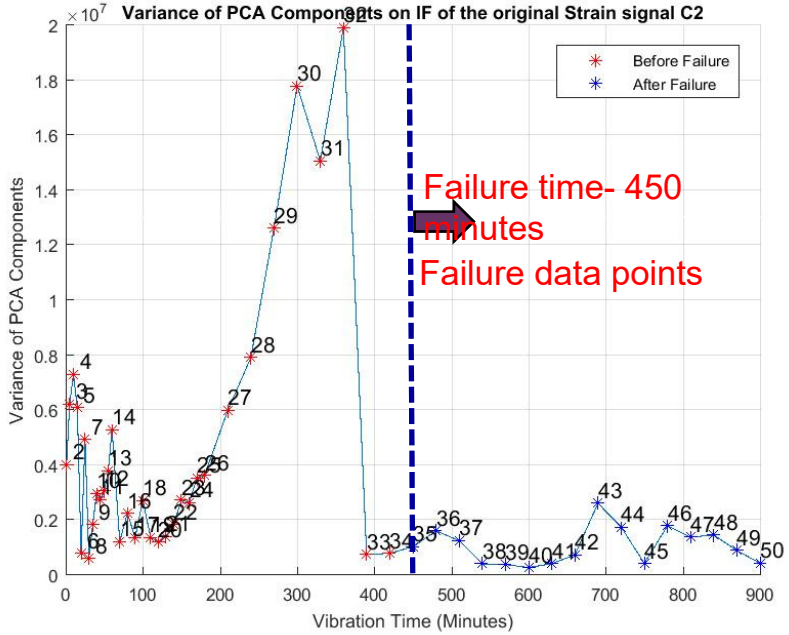




The **sudden increase in the variance** values just before failure is taken as the identification for failure.

Analysis-1 (Analysis on the Strain Rosette Signals)

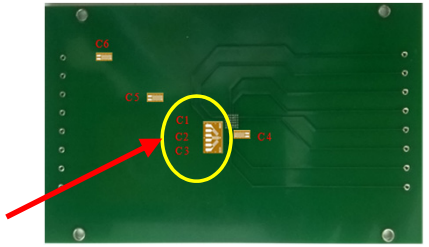




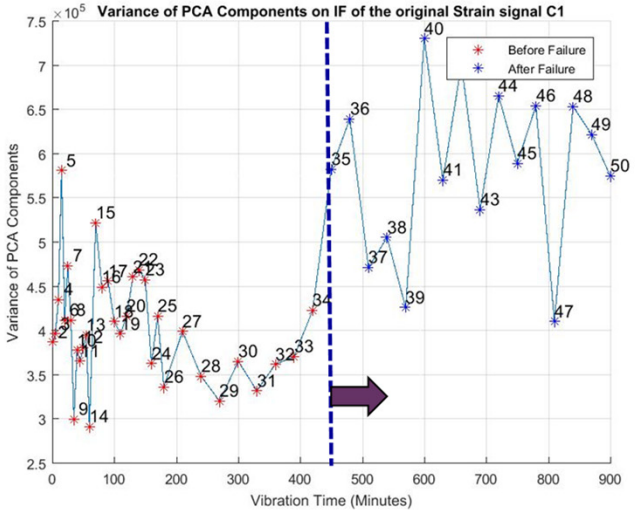
Analysis-1

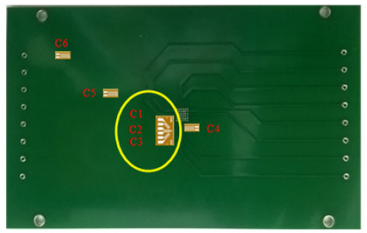
Studies the variation of the feature vectors-1 and 2 for **normal and shear strain** using strain rosette

- **Comparison Analysis** on Strain signal C1, C2 and C3
- **C1 and C3 shear strain components** whereas **C2 is normal strain**

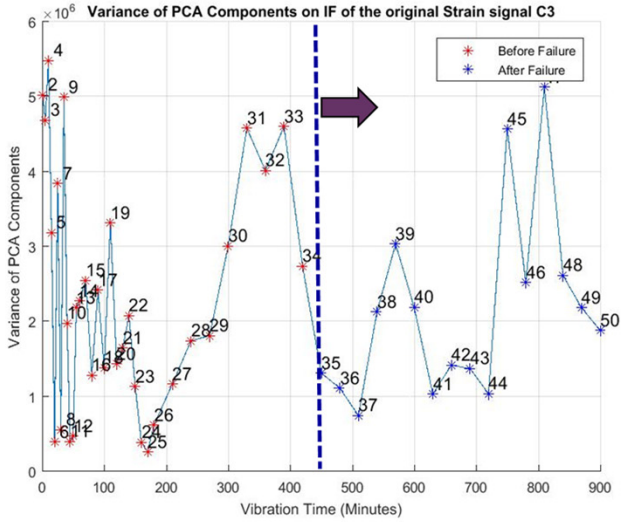


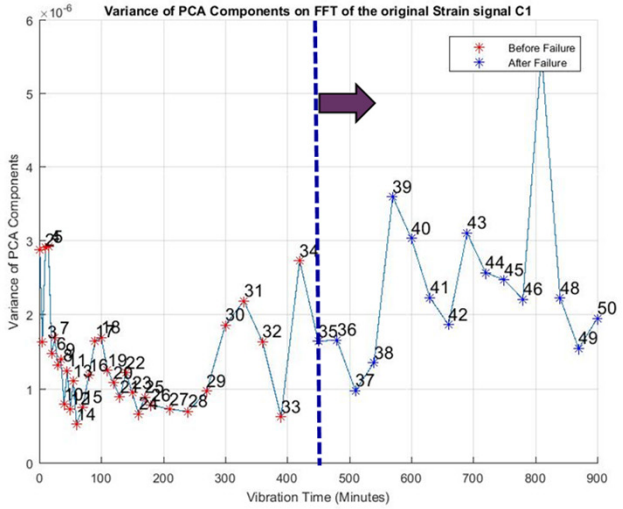
Analysis-1 (Analysis on the Strain Rosette Signals)



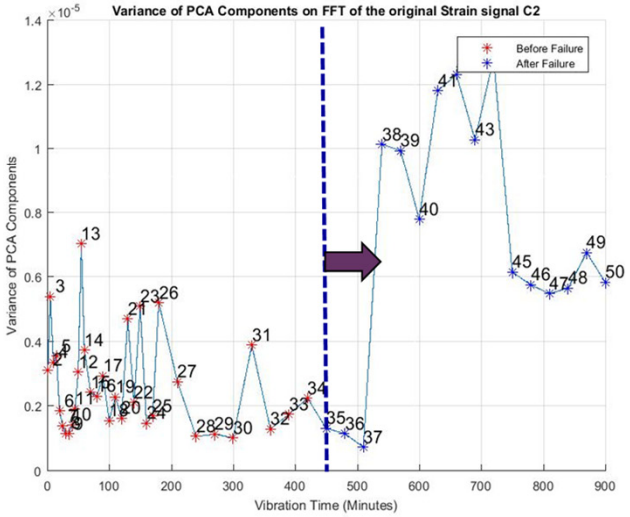


Feature vector variation for C1 and C3

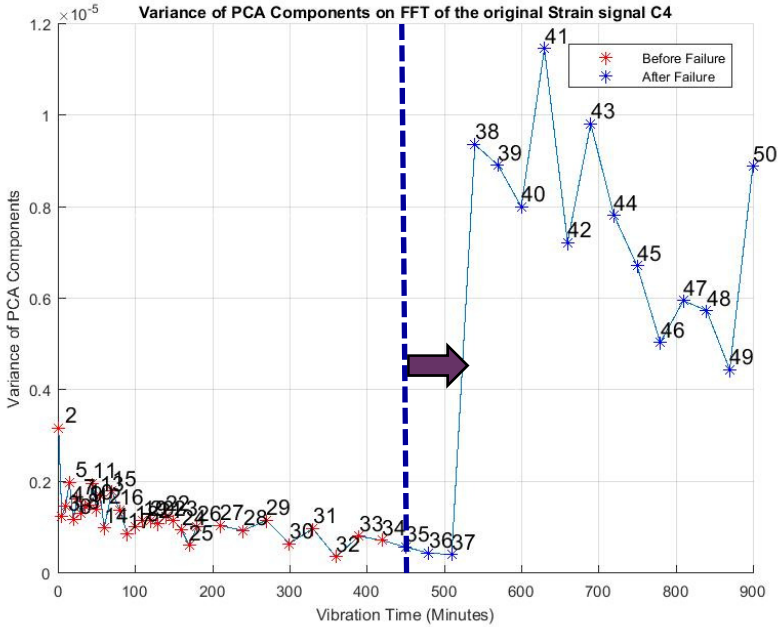


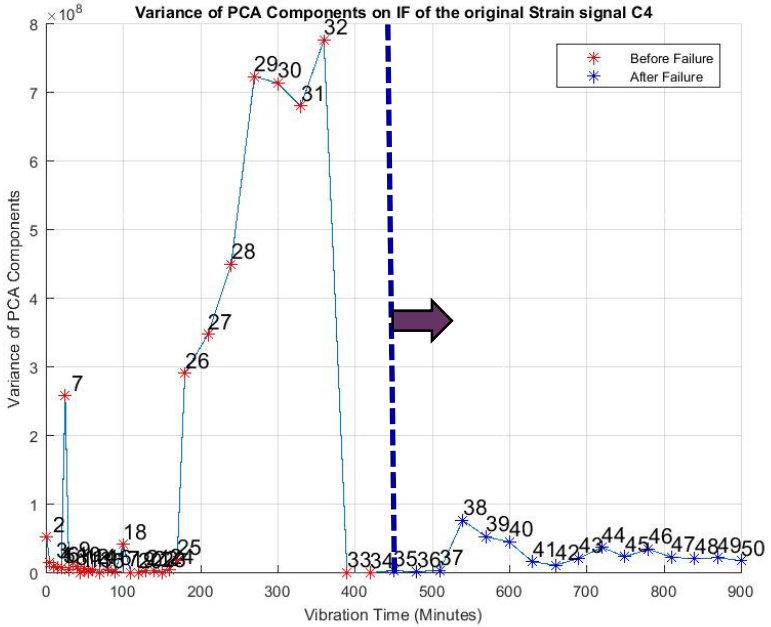


The **shear strain components** were not able to pattern indicating failure



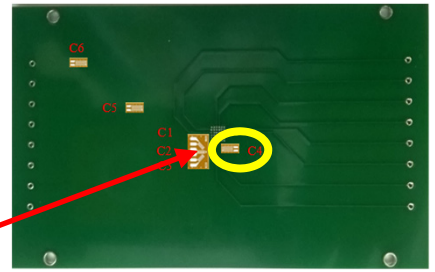
Analysis-2 (Analysis on the Strain Signals C4





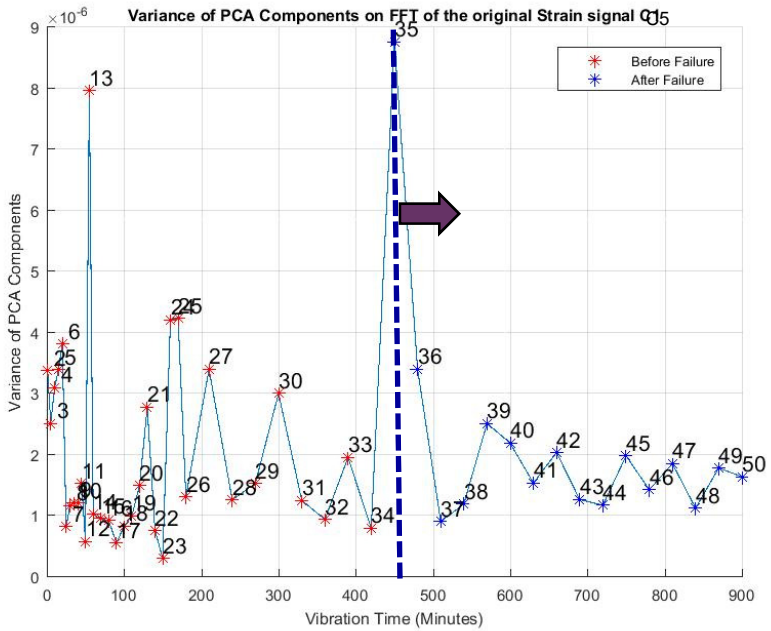
Analysis-2

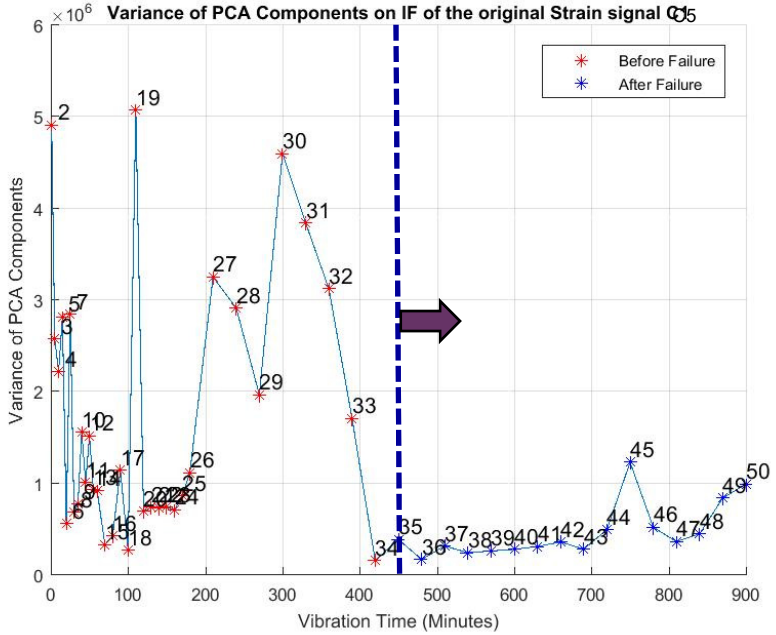
- Studies the variation of the feature vectors-1 and 2 with different distances from the package
- C4 is exact opposite position to the package on the back side of the PCB



Comparison Analysis on Strain signal C4

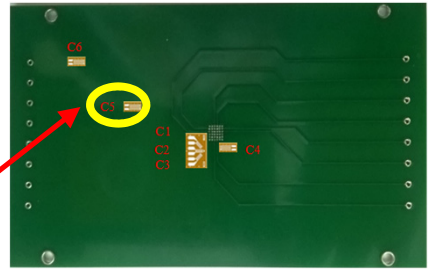
Analysis-2 (Analysis on the Strain Signals C5)





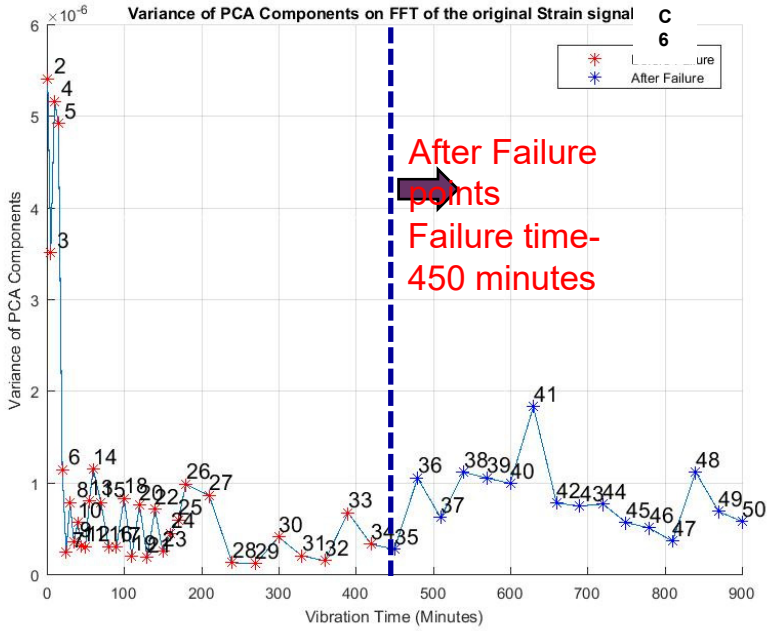
Analysis-2

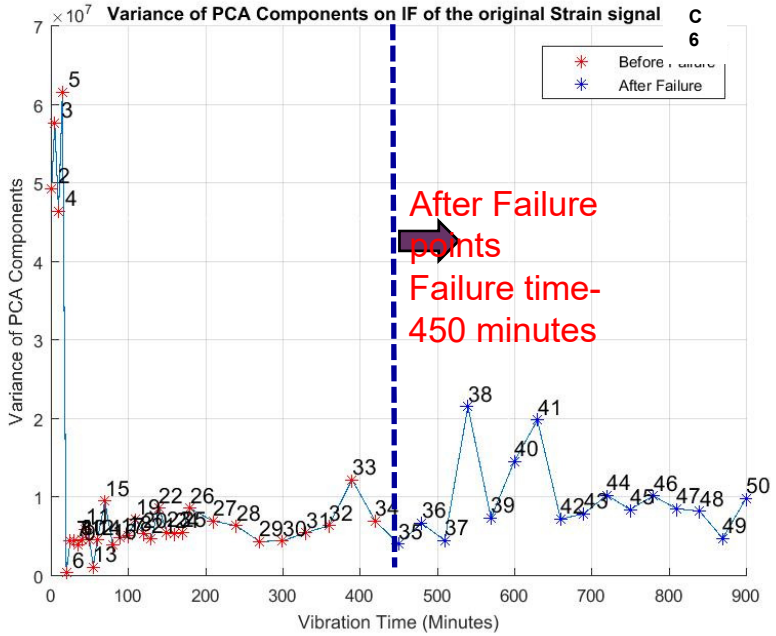
- C5 is middle position from the package to the fixture on the back side of PCB



Comparison Analysis on Strain signal C5

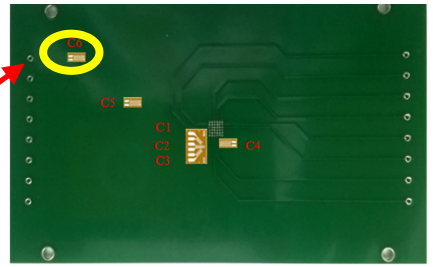
Analysis-2 (Analysis on the Strain Signals C6)





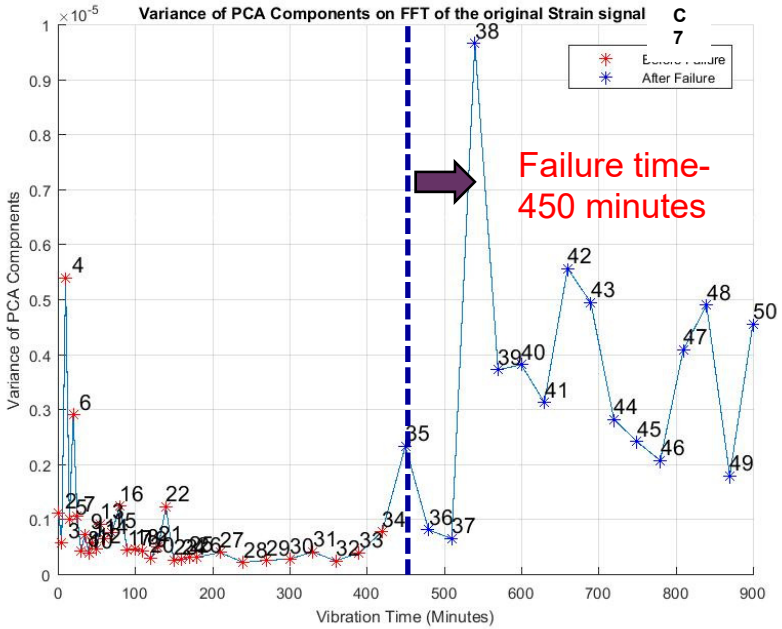
Analysis-2

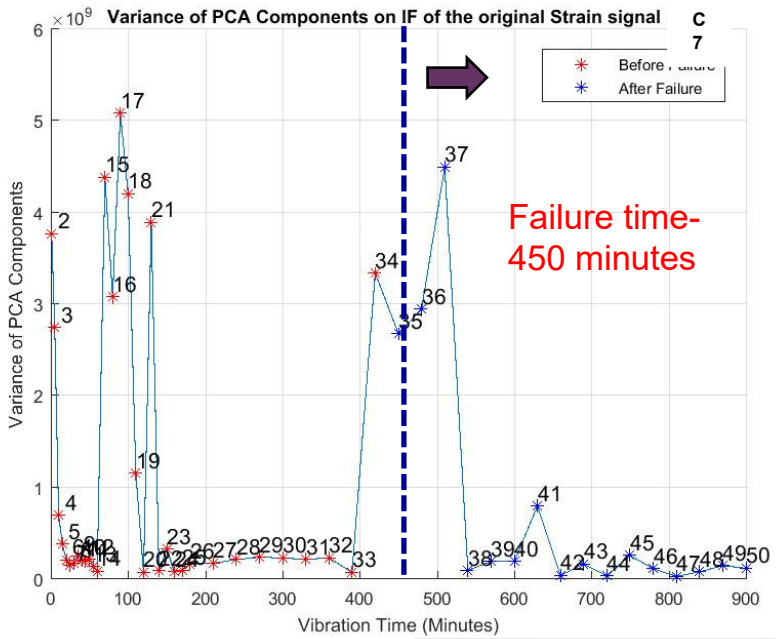
C6 is farthest position from the package and close to the fixture on the back side of PCB



Comparison Analysis on Strain signal C6

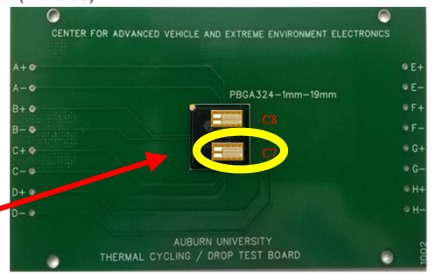
Analysis-3 (Analysis on the Strain Signals C7)





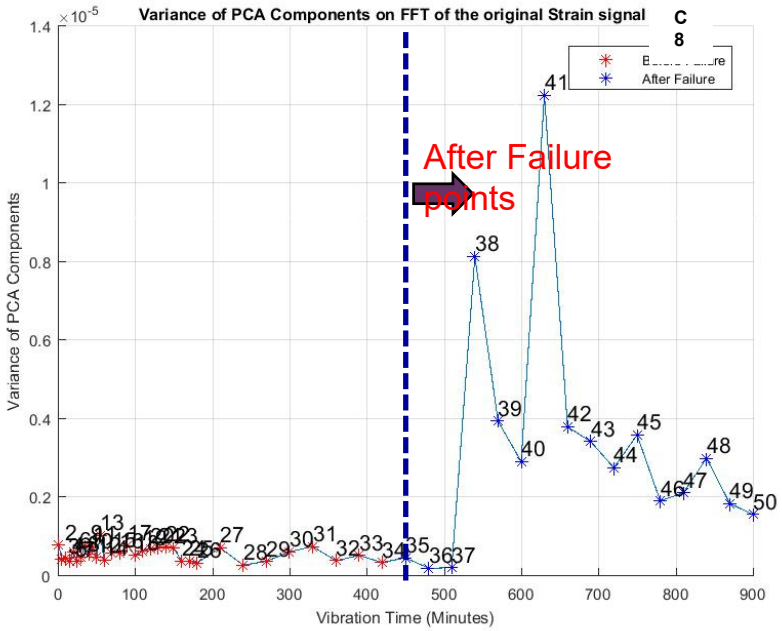
Analysis-3

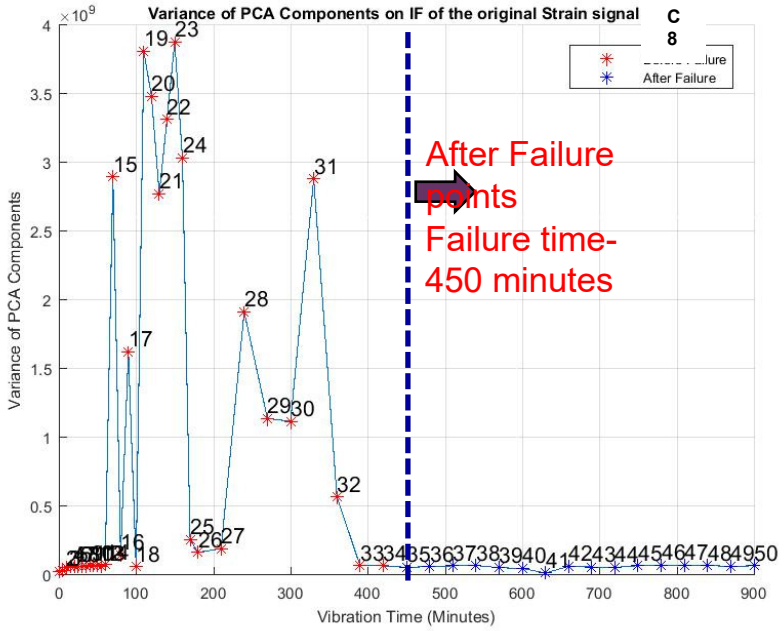
- Studies the variation of the feature vectors-1 and 2 for strain signals from on the package
- C7 is corner position of the package on the front side of the PCB



Comparison Analysis on Strain signal C7

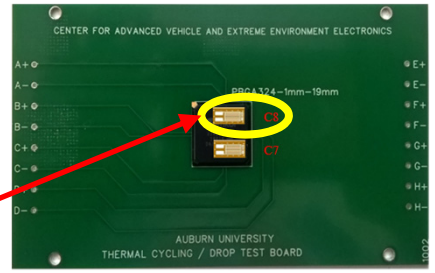
Analysis-3 (Analysis on the Strain Signals C8)





Analysis-3

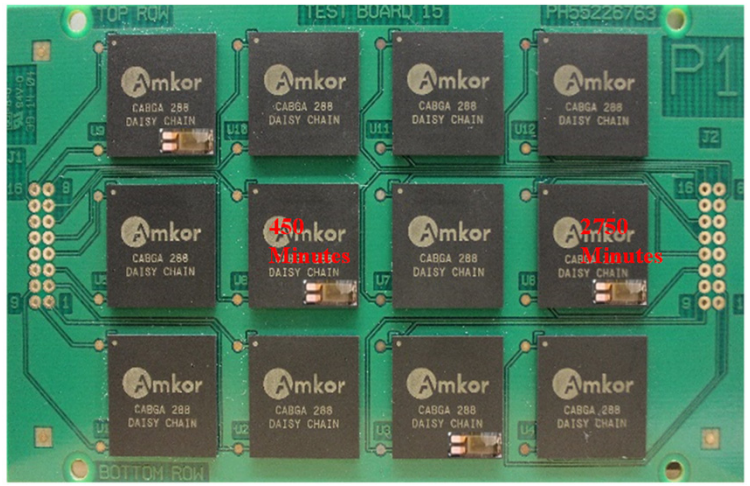
C8 is corner position of the package parallel to C7 on the front side of the PCB



Comparison Analysis on Strain signal C8

Analysis on test board-2

Case-1



Failure time of the packages

C2- 450 minutes

C4- 2750 minutes

- Only **two packages failed** and are captured by the strain gauges
- They are not close enough

Case-2

Failure time of the packages

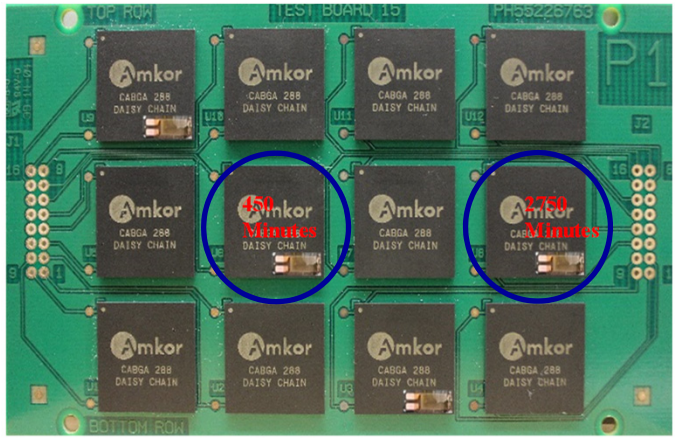
C1- 600 minutes

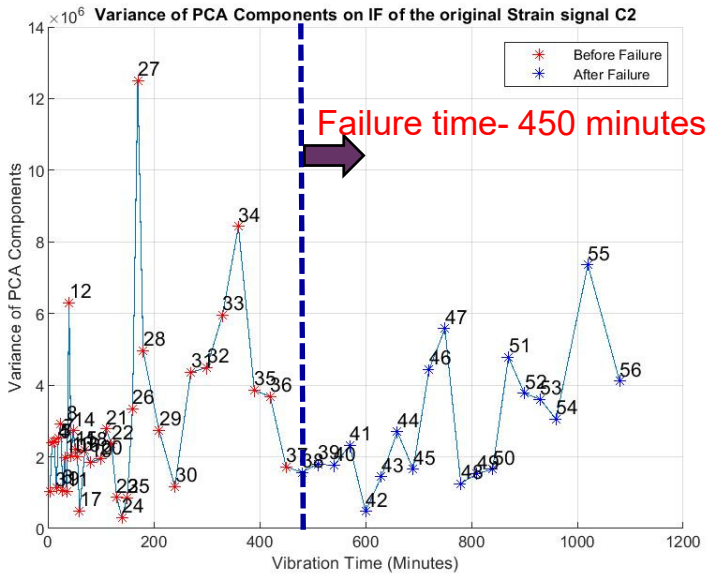
C2- 270 minutes

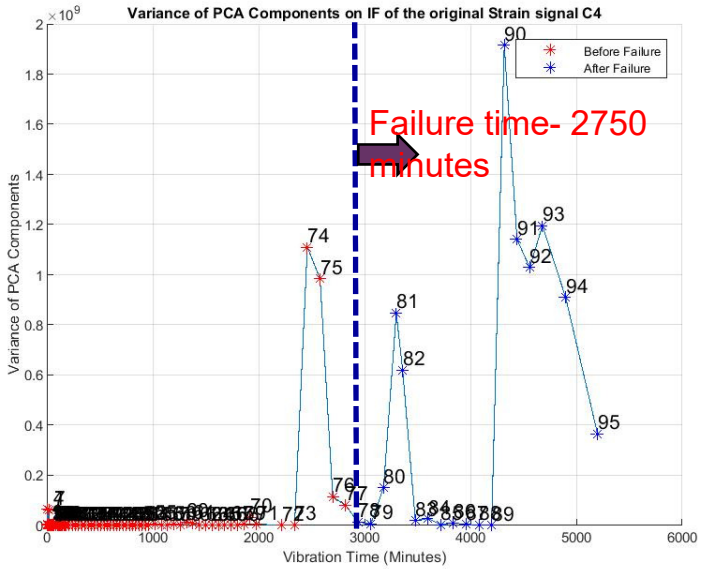
C3- 27 minutes

- **Seven packages failed** and three are captured by the strain gauges
- The failures are close enough and other packages fail close by as well

Analysis with Test Board-2 for Case-1







- Feature vector for C2 has increasing behavior with some noise present
- Feature vector for C4 is the perfect behavior for identification of failure

Summary and Conclusions

High Strain-Rate Properties after Prolonged Storage

- Low-and-high temperatures effects on mechanical properties of solder-alloys have been characterized.
- Measurements indicate that material properties are sensitive to both operational temperature and strain rate.
- Exposure to lower temperatures in the neighborhood of -65°C resulted in an increase in the UTS and YS values.
- UTS and YS values show a reduction with the increase aging time.
- 9-anand parameters extracted from stress-strain data.

Feature Vectors for PHM Under Overlapping Stresses

- Demonstrated strain-based feature vectors from the PCB surfaces.
- Data shows the importance of variance of the PCA and IF based feature vectors on the identification of impending failure.
- Fidelity of the feature vectors with distance of the strain signals from package failure-locations has been quantified.
- Case-1 of test board-2 looked at the behavior feature vectors when there are not many packages fail - FV is able to predict failure
- Case-2 of test board-2 looked at the behavior feature vectors when there are many packages fail - increasing variation of FV