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Predicting Fatigue Failure of a Circuit Board in Random Vibration: The Reference Model

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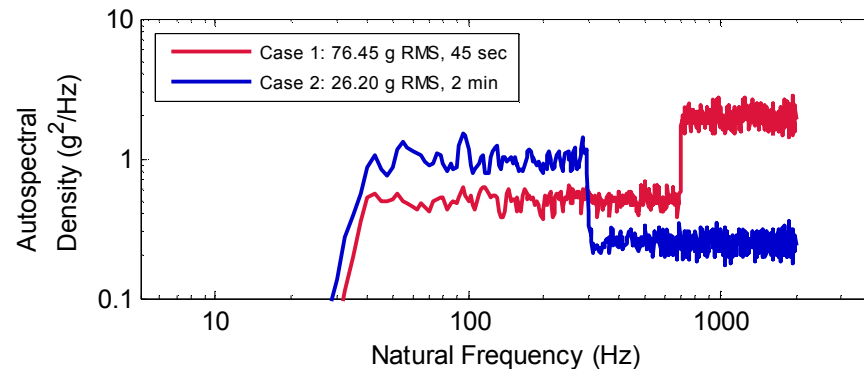
Presentation Outline

- Introduction and Project Objective
 - Printed Circuit Board Specimen
 - Failure Criterion
- The Reference Model
 - Building S-N curves from random data
- Test Description
 - Vibration Test
 - Strain Measurements
- Results
- Conclusions

Introduction

■ Energy Based Failure Prediction Methods

- Use modal energy as an intensity measure for predicting structural failure
- Requires approx. linear structure, fixed-base modal properties, base input
- Key Advantage: Once failure model is built, arbitrary input profiles can be assessed for relative severity – hedge against environmental uncertainty.



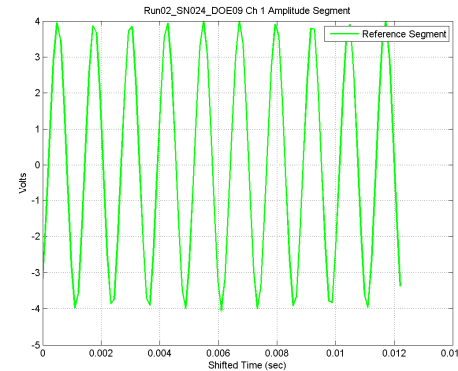
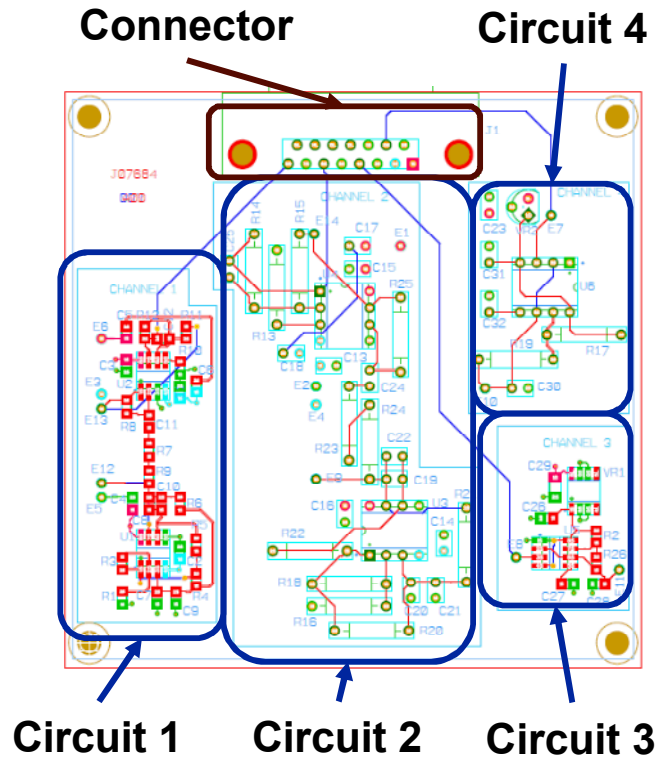
Which is more severe?

■ Project Objective

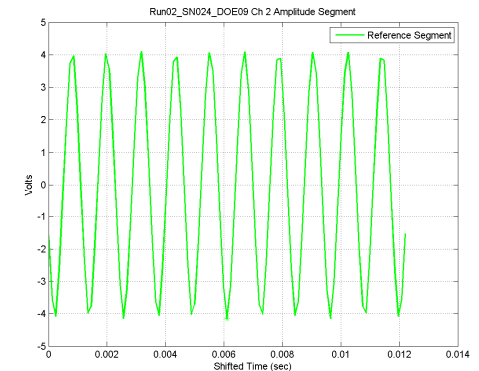
- To compare the prediction efficiency of energy-based fatigue failure models to a traditional fatigue failure model.

This talk is about the reference fatigue model

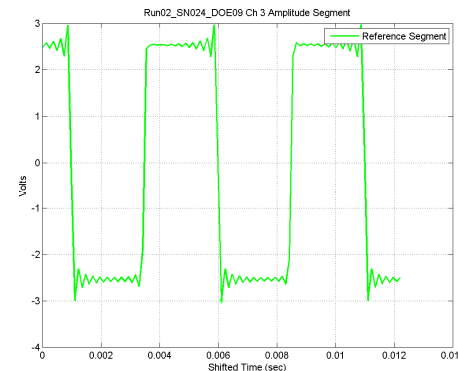
Printed Circuit Board



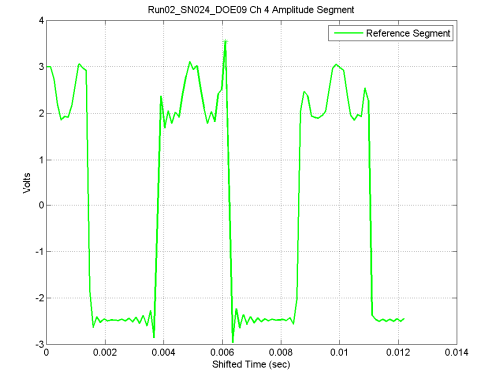
Circuit 1



Circuit 2



Circuit 3



Circuit 4

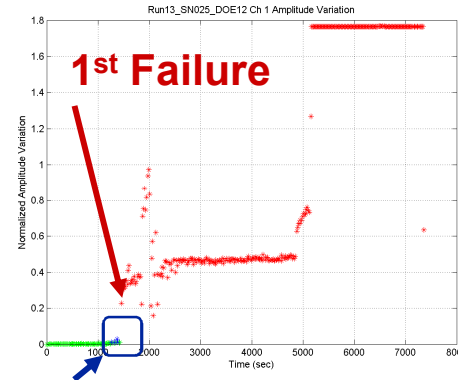
Quasi-isotropic Material Properties

$E = 3.795 \times 10^6$ psi

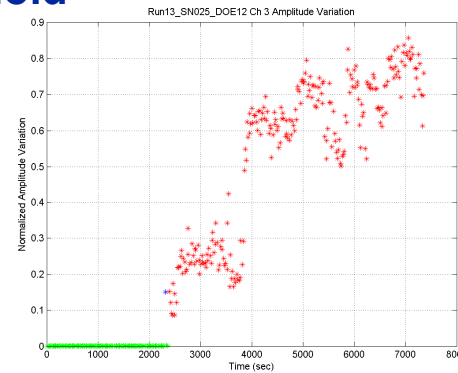
$\nu = 0.266$

Circuit Failure Criterion

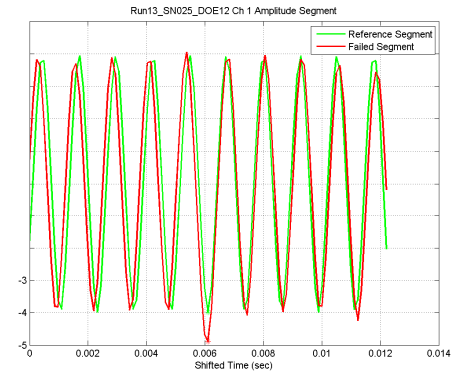
- Failure was based on the outputs of the PCB circuits
- The signals were subdivided into 20 sec segments
 - The 2nd segment is the reference segment
- Circuit failure criterion:
 - Peak response exceeds the reference value by 1% in at least 3 consecutive segments



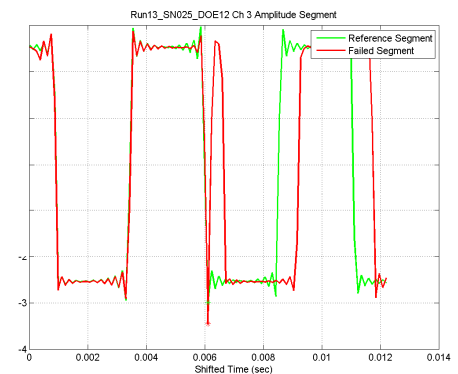
Amplitude exceeds threshold



Circuit 1



Circuit 3



The Reference Model

- A standard technique for approximating the fatigue life of a structure subjected to vibratory loads is Miner's method.
 - It is based on the assumption that every structural component has a specific fatigue life and every stress cycle uses up a portion of that fatigue life.

$$D = \sum_{j=1}^M \frac{n_j}{N_j}$$

D = fraction of consumed fatigue life;
 n_j = number of cycles experienced by the structure at stress S_j ;
 N_j = number of cycles to failure at stress S_j determined from S-N curves.

- **$D = 0.3$** for critical life-cycle electronics
- **$D = 0.7$** for typical structures

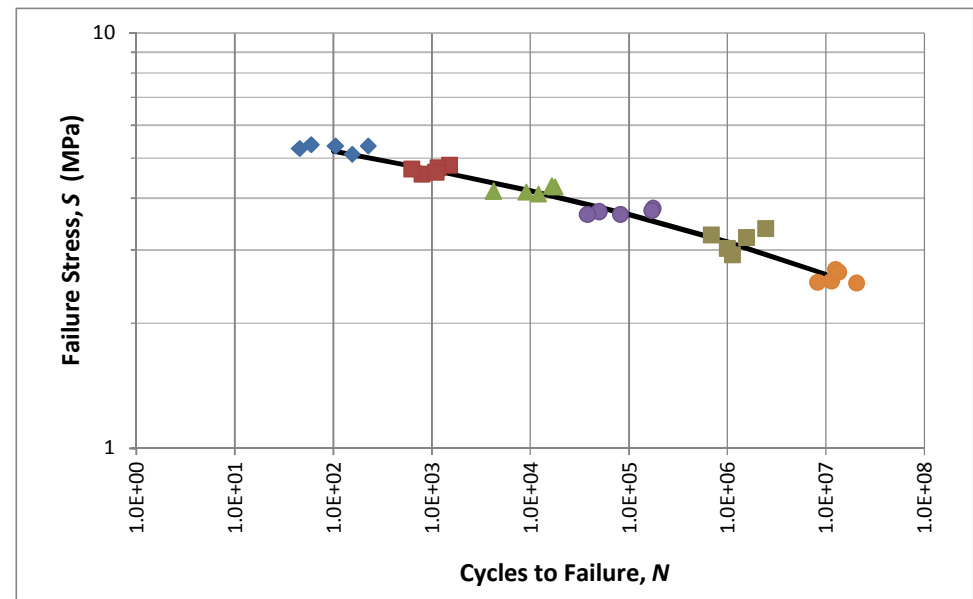
The key to using Miner's method is the S-N curve

S-N Curves

- S-N curves are failure definition specific
 - Failure is not necessarily physical failure / breakage
 - It can be some change in a structural property like loss of stiffness
- S-N curves are based on sinusoidal loading
 - Experimental determination can be time consuming and expensive
- Basic assumption: Fatigue strength is a linear function in log-log space

$$NS^b = A$$

- N, S are measured
- A, b are empirically derived constants



Notional S-N curve

The Challenge

- No S-N curves exist for the PCB and the conditions of interest
- The first part of the study generated failure data with which to characterize the fatigue endurance of the PCB
- Preliminary experiments indicated that at the environment of interest the long duration exposures were necessary
- Sinusoidal testing was not feasible

The Challenge: Develop fatigue damage properties from broadband random vibration data measured during test to failure.

RMS Stress Approach

- Replace the S-N curve with a $\sigma - N_T$ curve
 - σ - stress standard deviation
 - N_T - total number of cycles to failure
- Advantages
 - Straightforward computation
- Disadvantages
 - Cannot account for combined loading

Cumulative Damage Index Approach Sandia National Laboratories

- Assume M units have been tested to failure with random excitation and the stress amplitude distribution has been determined for each unit
- Discretize each distribution into at most M bins, centered on stress levels S_1, S_2, \dots, S_M to obtain the rainflow cycles at each stress, n_1, n_2, \dots, n_M .
- The number of cycles to failure at each stress level, N_1, N_2, \dots, N_M can be estimated with Miner's Equation

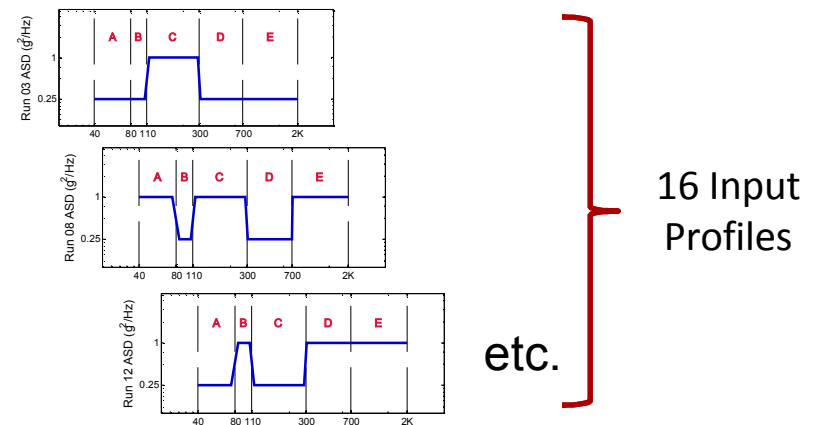
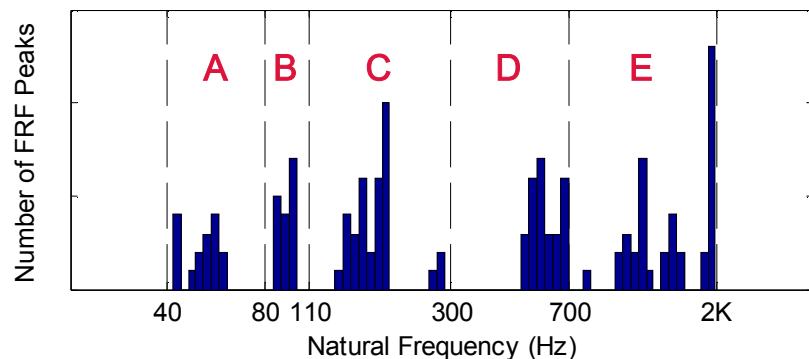
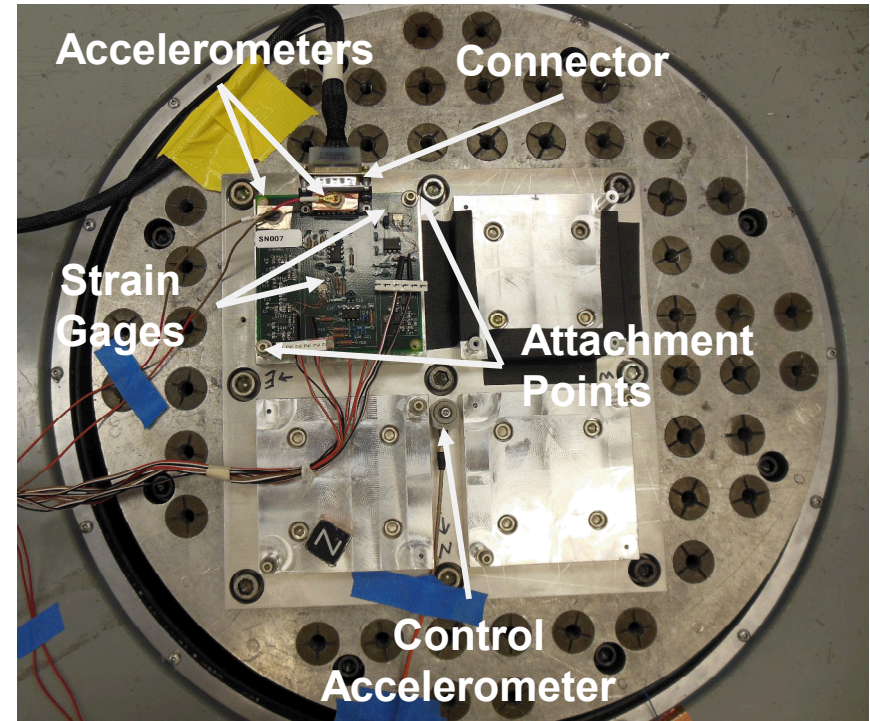
$$\begin{matrix} \begin{bmatrix} n_1^1 & \dots & n_M^1 \\ \vdots & \ddots & \vdots \\ n_1^M & \dots & n_M^M \end{bmatrix} & \begin{Bmatrix} \frac{1}{N_1} \\ \vdots \\ \frac{1}{N_M} \end{Bmatrix} & = & \begin{Bmatrix} D \\ \vdots \\ D \end{Bmatrix} \\ [n] & \left\{ \frac{1}{N} \right\} & & \{D\} \end{matrix}$$

- This yields a constrained least squares optimization problem

$$\min_{N_i} \left\| \{D\} - [n] \left\{ \frac{1}{N} \right\} \right\|_2^2 \text{ subject to } N_i > \max_{k=1 \dots M} n_i^k > 0$$

Vibration Test

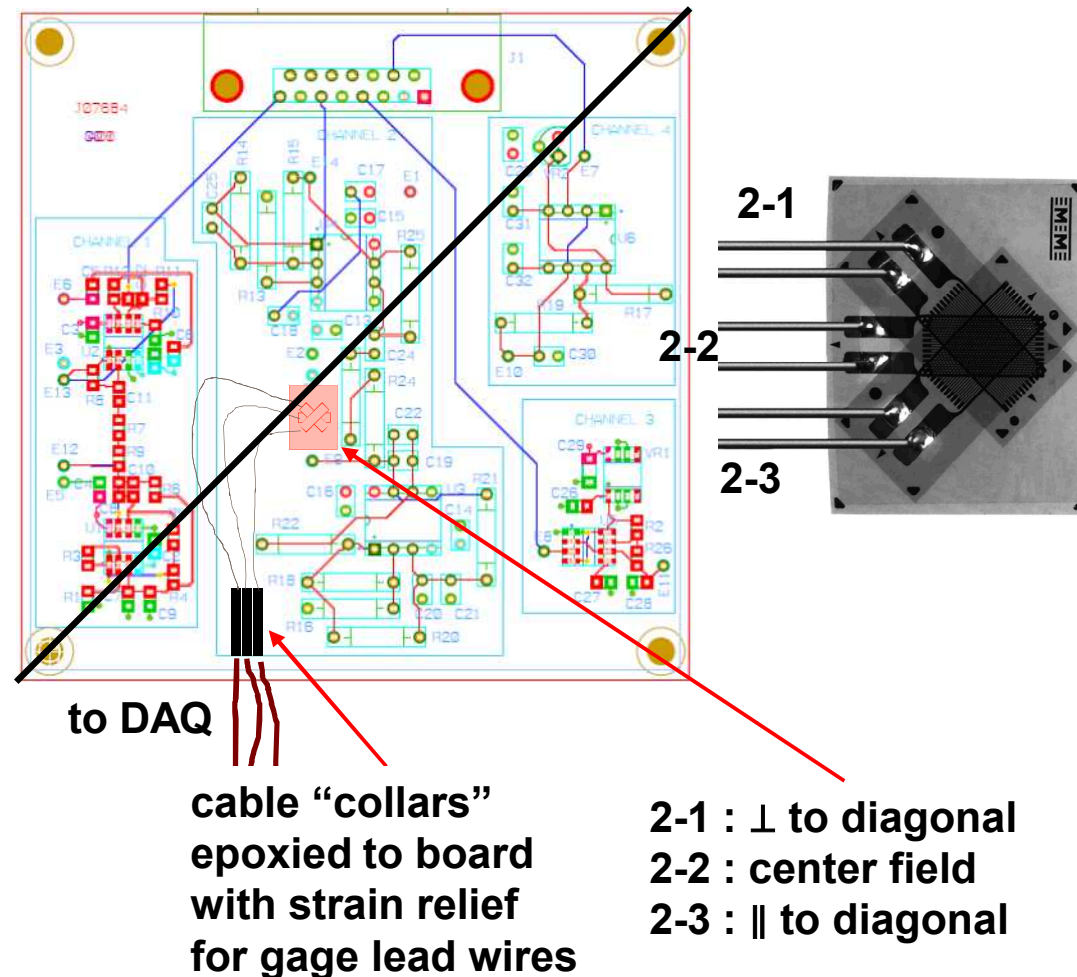
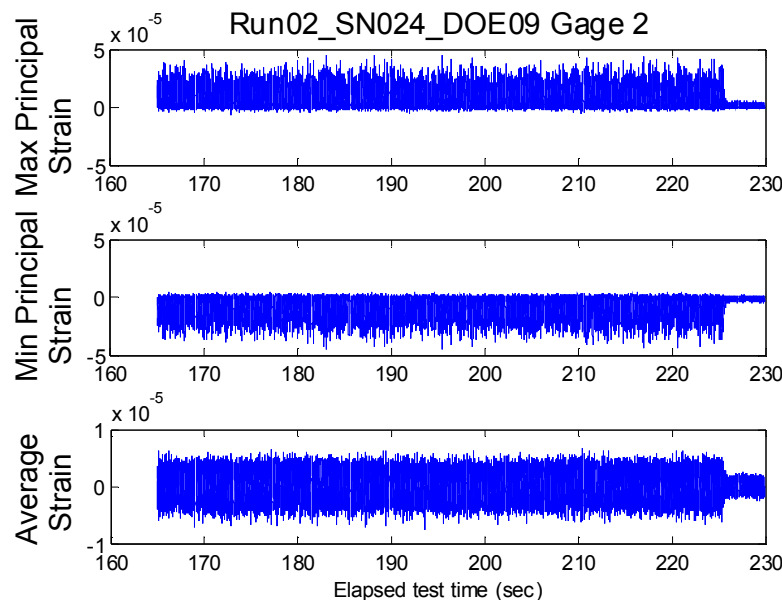
- Each PCB was mounted to a fixture on a shaker via two standoffs diagonally
- Vertical excitation
- Bandwidth: 40 Hz – 2000 Hz
- 16 PCBs were tested, each with a unique excitation profile (2_V^{5-1} Design)



Strain Gage Measurements

- The center strain gage (Gage 2) was used for making the reference model
- Average stress was the quantity of interest

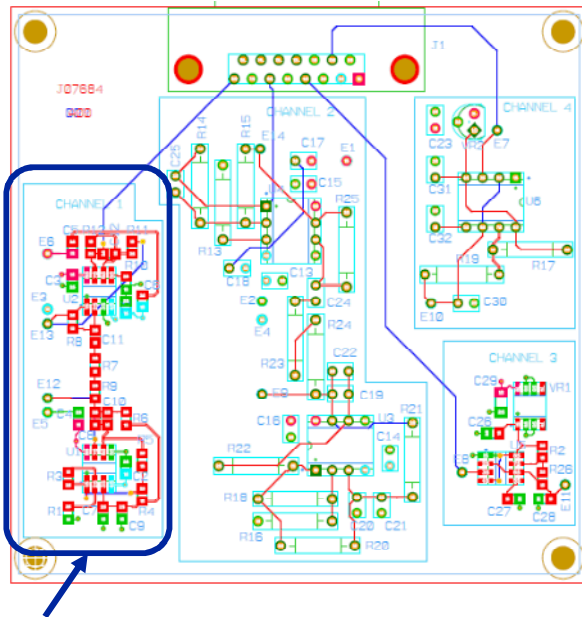
$$\sigma_{P,Q} = \frac{E}{2} \left[\frac{\varepsilon_1 + \varepsilon_3}{1 - \nu} \pm \frac{\sqrt{2}}{1 + \nu} \sqrt{(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2} \right]$$



Results

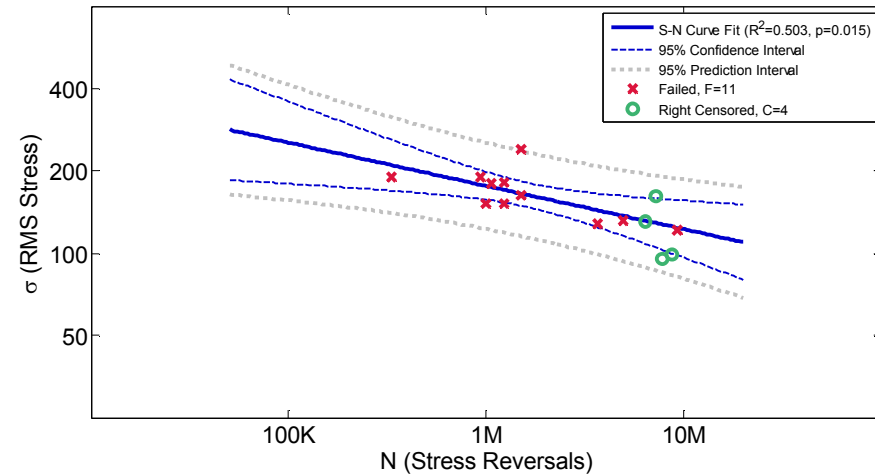
Test	Input RMS (g)	Gage 2 Avg Stress RMS (psi)	Circuit 1		Circuit 2		Circuit 3		Circuit 4	
			Time to Failure (min)	# of Cycles to Failure	Time to Failure (min)	# of Cycles to Failure	Time to Failure (min)	# of Cycles to Failure	Time to Failure (min)	# of Cycles to Failure
Run01 SN021 DOE01	38.26	101.14	1.18	-91554	No Failure	9584543	16.96	1165361	2.16	-14120
Run02 SN024 DOE09	22.78	95.22	No Failure	7730505	No Failure	7730505	No Failure	7730505	No Failure	7730505
Run03 SN029 DOE03	25.12	152.49	21.86	989869	32.10	1508675	No Failure	6089038	118.65	5896048
Run04 SN027 DOE04	43.67	239.93	25.19	1501047	66.32	4242794	79.75	5137359	No Failure	8007150
Run05 SN014 DOE14	28.98	132.06	90.64	4887099	90.64	4887099	90.64	4887099	57.89	3068032
Run06 SN015 DOE02	28.08	130.9	No Failure	6364557	No Failure	6364557	No Failure	6364557	No Failure	6364557
Run07 SN028 DOE07	25.56	152.43	23.97	1220546	35.70	1892196	No Failure	7042003	35.18	1862498
Run08 SN026 DOE11	40.42	180.49	16.90	1052013	25.94	1705100	No Failure	8703575	16.67	1035335
Run09 SN030 DOE10	42.35	161.64	No Failure	7230877	No Failure	7230877	No Failure	7230877	No Failure	7230877
Run10 SN017 DOE16	44.27	190.04	16.32	936524	84.67	5510966	53.30	3411678	36.90	2313535
Run11 SN022 DOE15	26.16	162.78	22.99	1497379	53.65	3756436	74.27	5275618	15.99	981344
Run12 SN013 DOE06	42.25	128.33	50.98	3627986	No Failure	8916185	No Failure	8916185	49.33	3506343
Run13 SN025 DOE12	30.98	182.33	24.31	1226594	56.59	3085377	39.94	2126822	21.03	1038277
Run14 SN018 DOE13	38.93	121.92	120.55	9279470	No Failure	9428775	No Failure	9428775	84.52	6458859
Run15 SN016 DOE05	22.6	98.90	No Failure	8700199	No Failure	8700199	No Failure	8700199	No Failure	8700199
Run16 SN020 DOE08	30.88	190.87	10.66	331473	106.21	4859450	0.85	-133293	9.72	286692
	No failure									
	Circuit failed before full level									

Results: Circuit 1

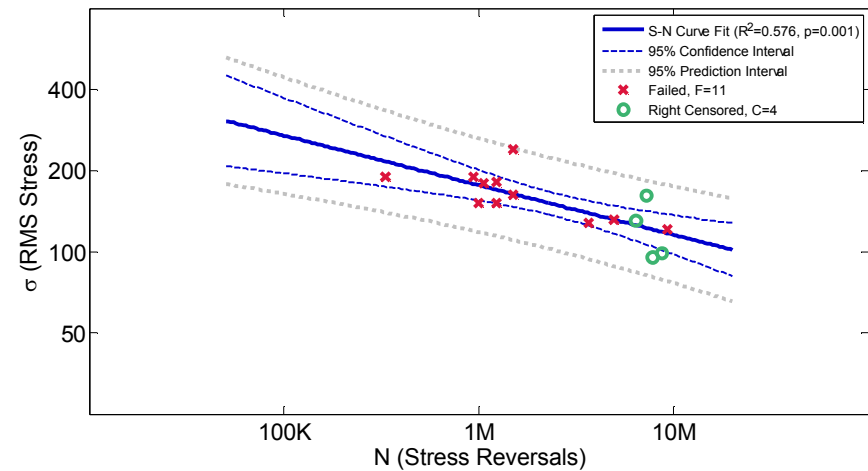


Circuit 1

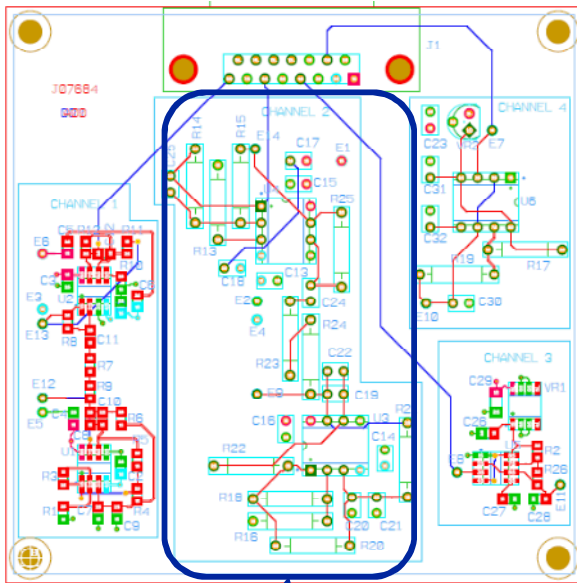
Circuit 1, Censored Values Omitted from Regression



Circuit 1, Censored Values Included as Failures in Regression

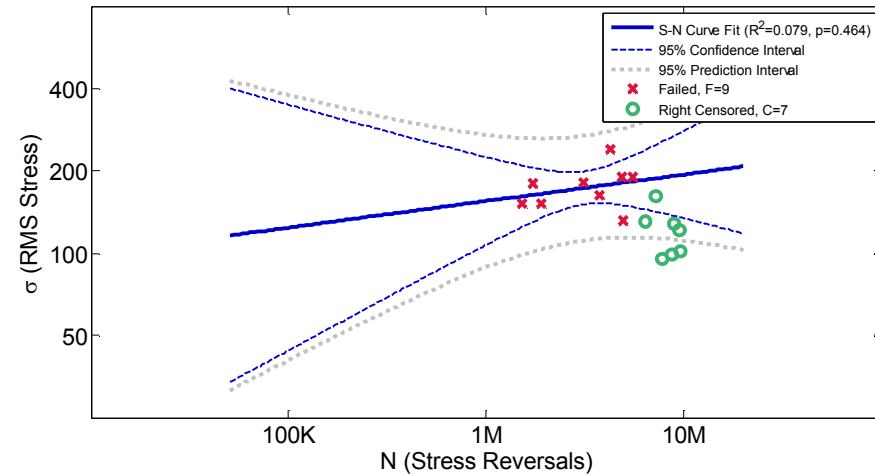


Results: Circuit 2

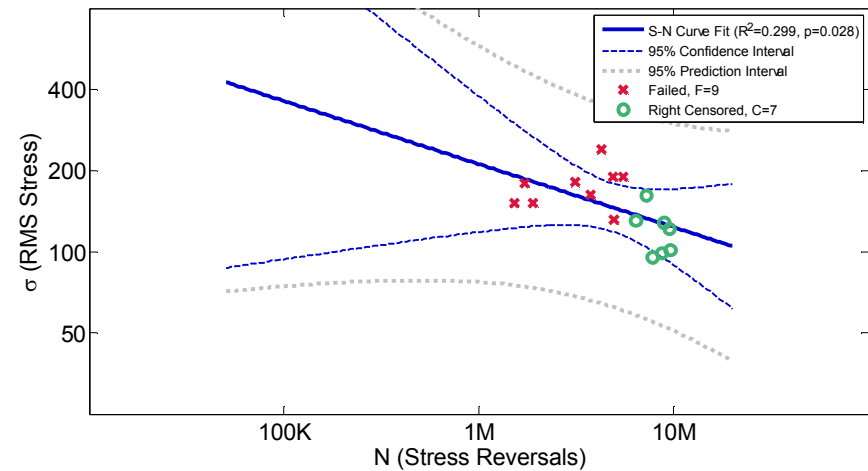


Circuit 2

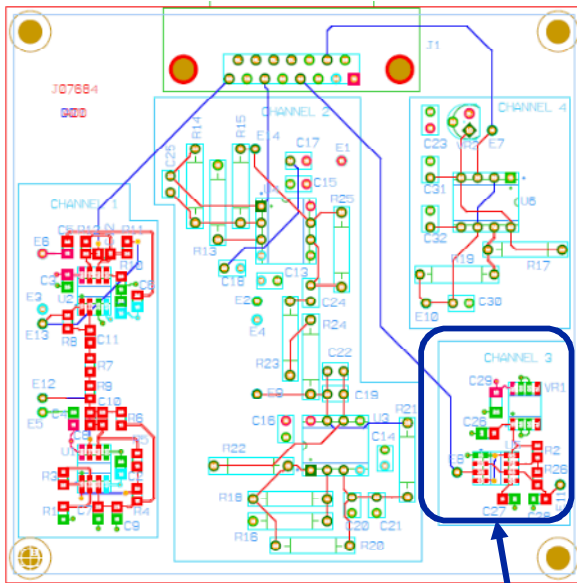
Circuit 2, Censored Values Omitted from Regression



Circuit 2, Censored Values Included as Failures in Regression

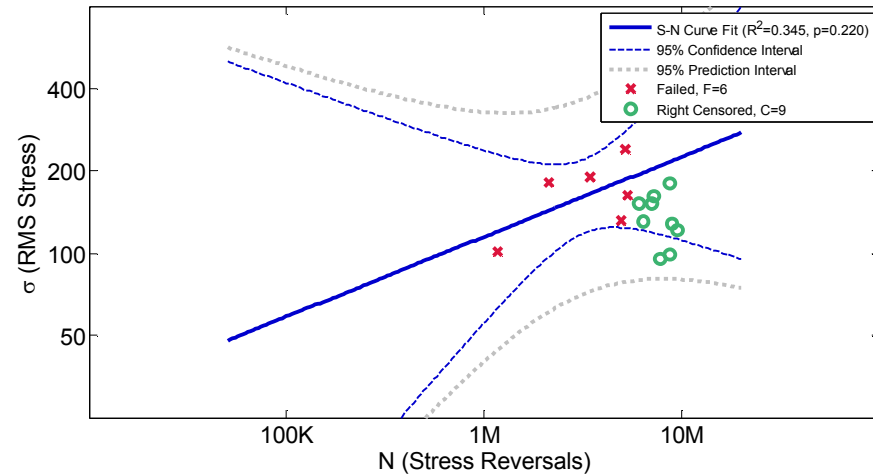


Results: Circuit 3

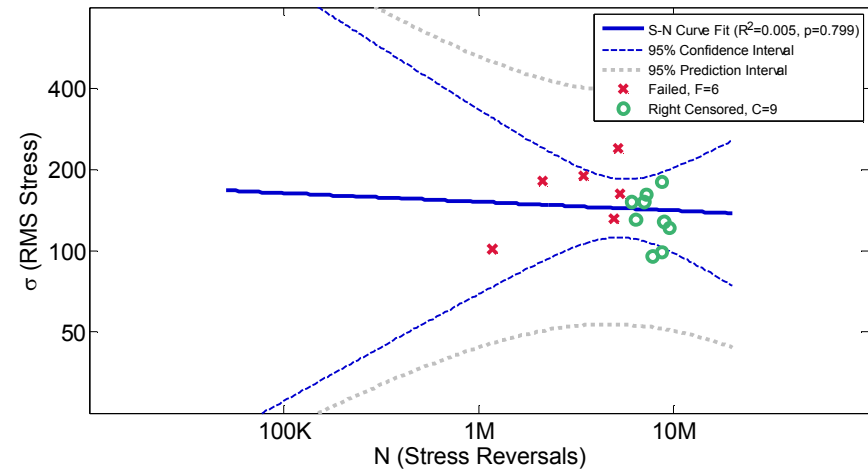


Circuit 3

Circuit 3, Censored Values Omitted from Regression

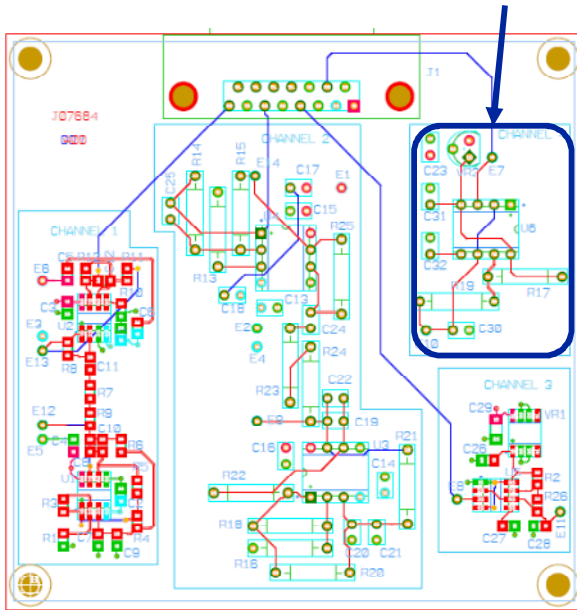


Circuit 3, Censored Values Included as Failures in Regression

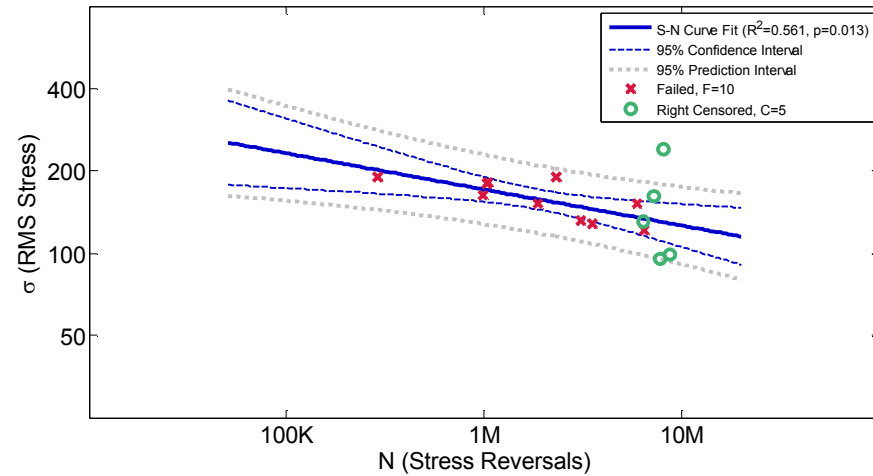


Results: Circuit 4

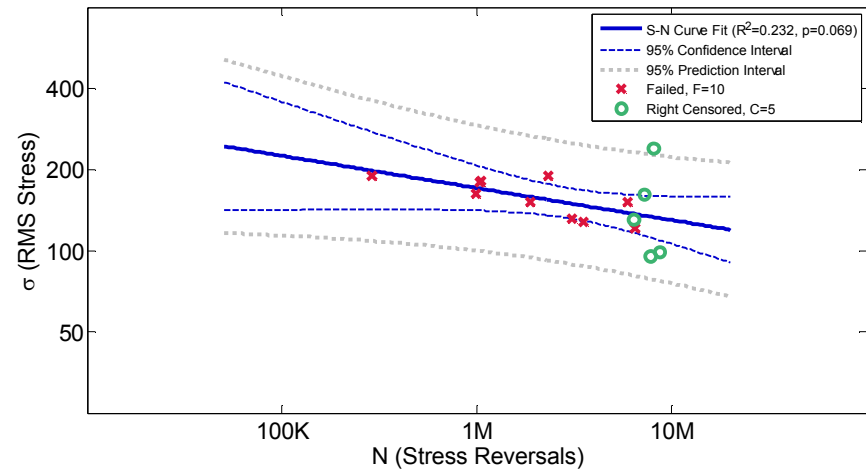
Circuit 4



Circuit 4, Censored Values Omitted from Regression



Circuit 4, Censored Values Included as Failures in Regression



Conclusions

- Circuit 1
 - Cycles to failures correlated reasonably well with RMS stress
- Circuit 2 was surprisingly robust
 - Data did not show typical S-N trend
- Circuit 3 was very robust
 - Not enough data were collected to estimate a damage index
- Circuit 4
 - Cycles to failures correlated reasonably well with RMS stress
- A bounding damage index line was generated for Circuits 1 and 4
- High frequency modes did not contribute to the response very much
- Much of the response was characteristic of a SDOF system

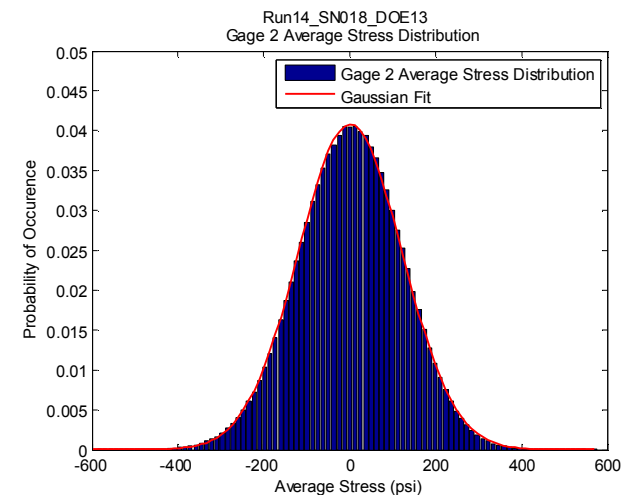
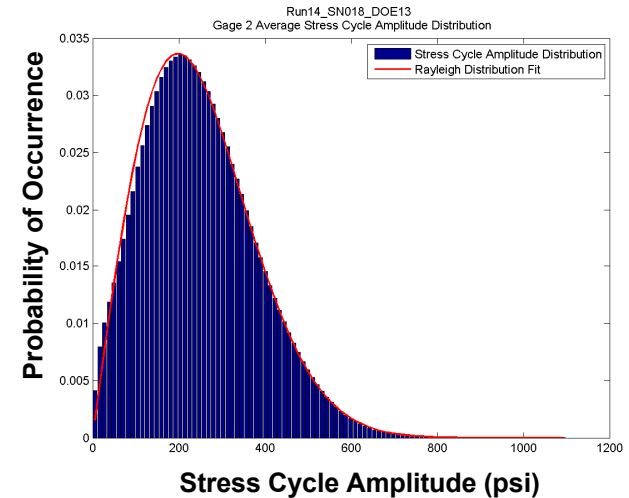
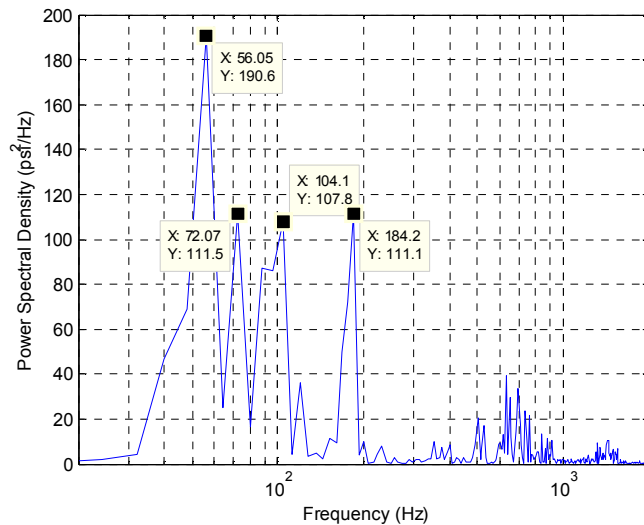
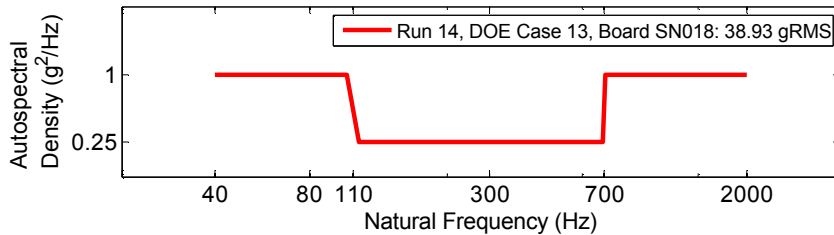
Acknowledgement

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- Management
 - Tim Edwards, David Epp
- Testing
 - Ron Coleman, Bob Cordova, Jack Heister, Alex Hielo, John Hofer, Norm Hunter, Sharlotte Kramer, John Laing, Tano Mendoza, Martin Sanchez, Eric Stasiunas, Gerald Thomason, Brandon Zwink

BACKUP SLIDES

Results

- In most of the 16 cases the response seemed to have narrow band characteristics dominated by a single mode



Results

- High frequency modes contribute little to the response

