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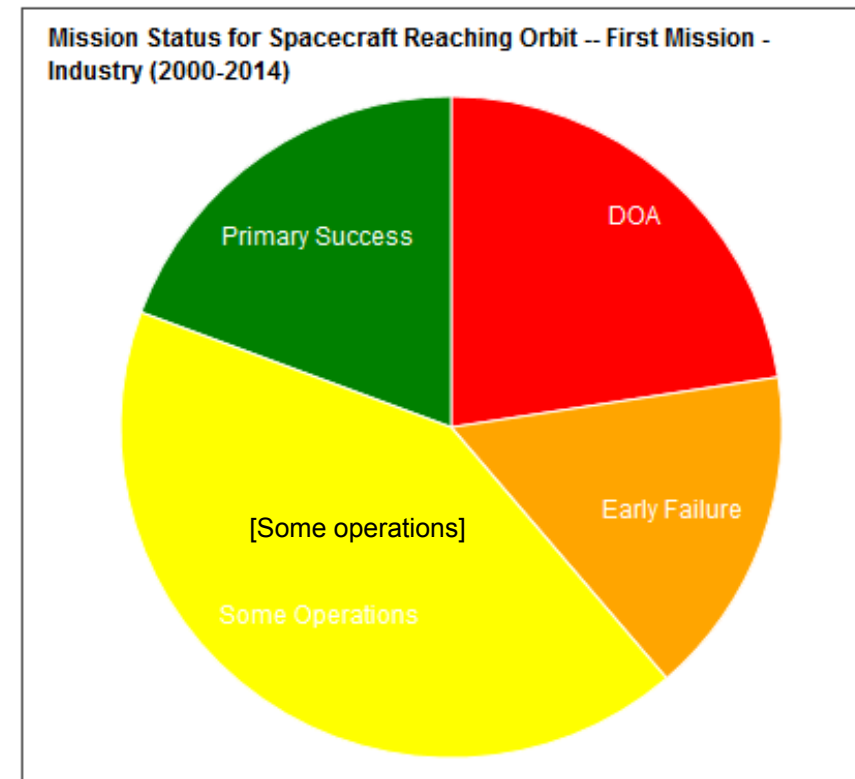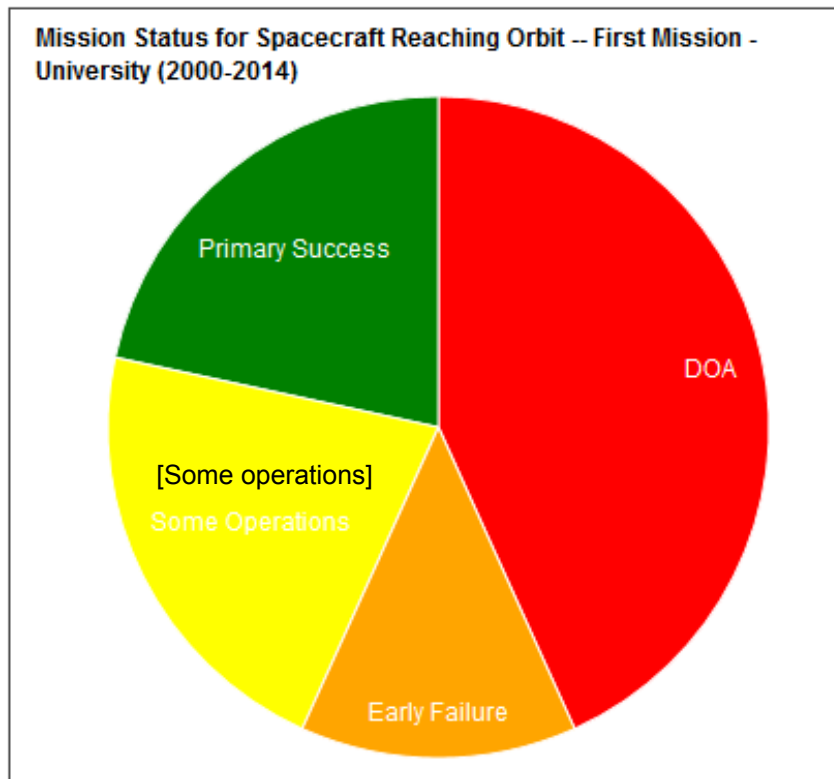# Methods to predict fatigue in CubeSat structures and mechanisms

By Walter Holemans (PSC), Floyd Azure (PSC) and Ryan Hevner (PSC)

08-09 August 2015 12th Annual Summer CubeSat Developers' Workshop

- Problem Statement

- What is fatigue?

- Cyclic loading and strength

- What is sensitive?

- Steps 1-8

- What is preload?

- Summary

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- Why do CubeSats fail 30 to 50 percent of the time?
- One failure mode may be **fatigue failure**

Source: Swartwout, Michael
Parks College of Engineering, Aviation & Technology
Saint Louis University
https://script.google.com/macros/s/AKfycbynG51p-33r5fBqV-uuNv4Sm3dz4XYThZkPx5pdIT-Wtjmi-Y9X/exec?source=P3

What is fatigue?

- Fatigue is the process of damage and failure due to cyclic loading

- Cyclic loading may come from:
  - Oscillating acceleration like random vibration and shock
  - Oscillating thermal loading from orbital period or heating cooling cycles of components turned OFF and ON
  - Pressure and vacuum cycling
  - Humidity cycling
  - Assembly cycles
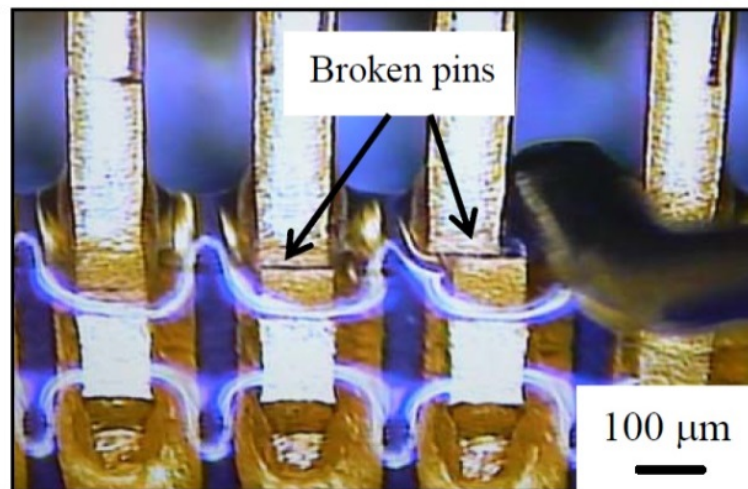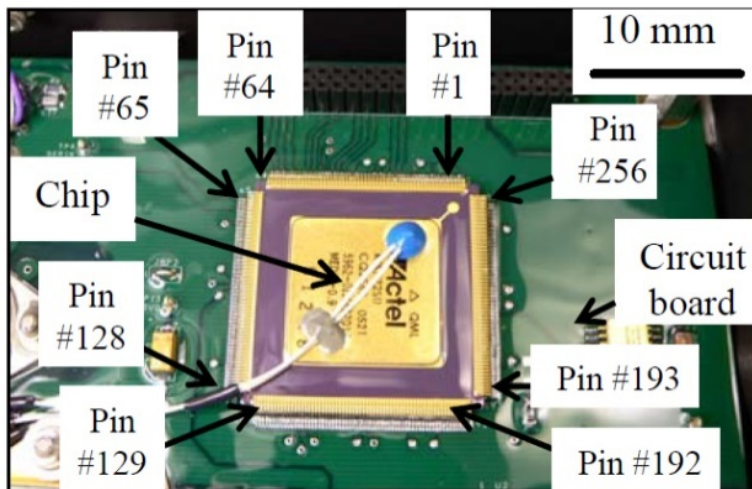
(a) Photograph of processing chip on circuit board

(b) Photograph of broken electrical connector pins

Figure 1. Photographs of failed electrical connector pins.

"The results of this study show that the pins failed as a result of fatigue loading."

Source: Failure Analysis of Electrical Pin Connectors, NASA/TM-2008-215531, October 2008 [Mars Science Laboratory]

Cyclic loading reduces material strength by about 50 percent

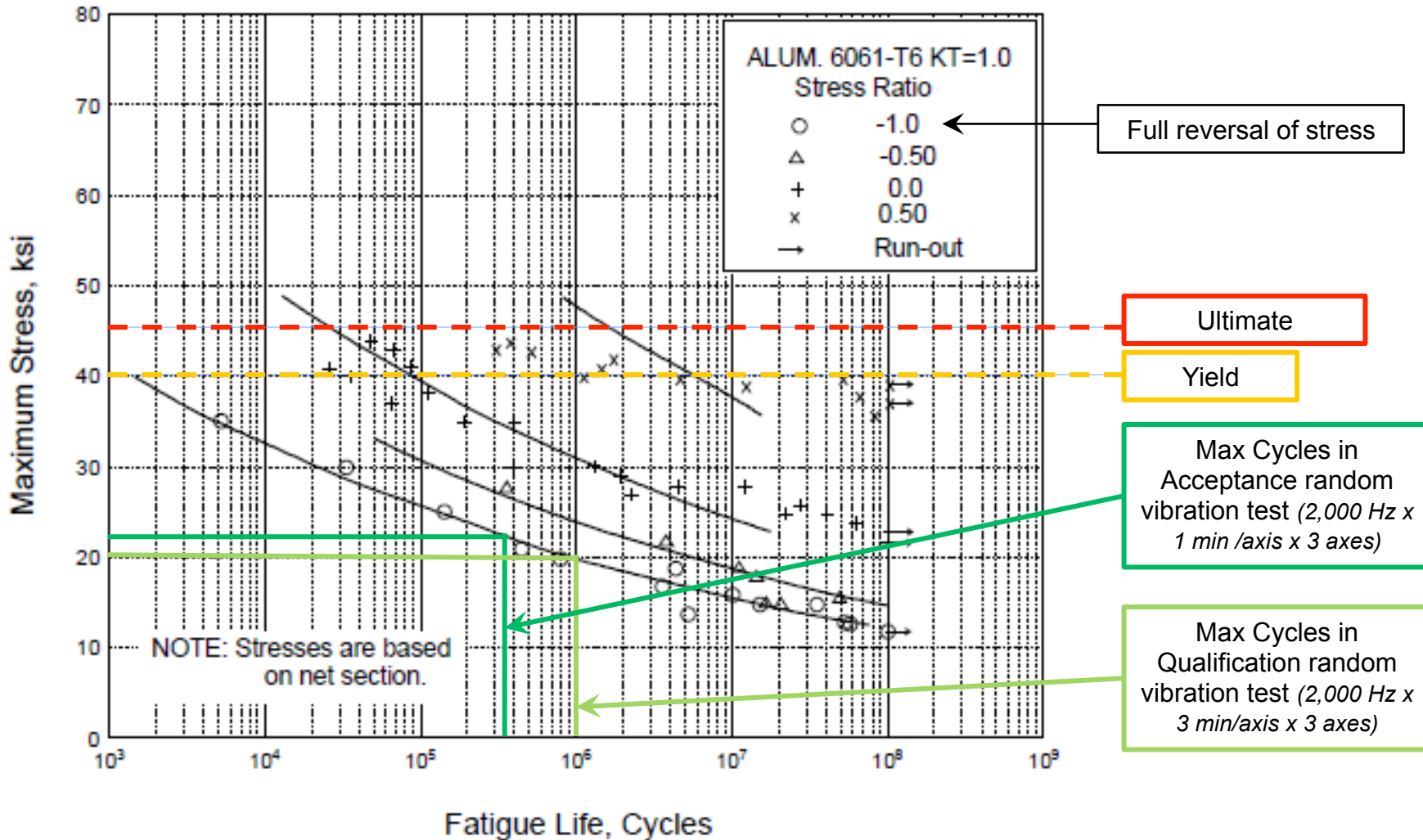- Typical Stress Versus Life (S-N) Curve

Figure 3.6.2.2.8. Best-fit S/N curves for unnotched 6061-T6 aluminum alloy, various wrought products, longitudinal direction.

Source: Battelle-MMPDS Metallic Materials Properties Development and Standardization
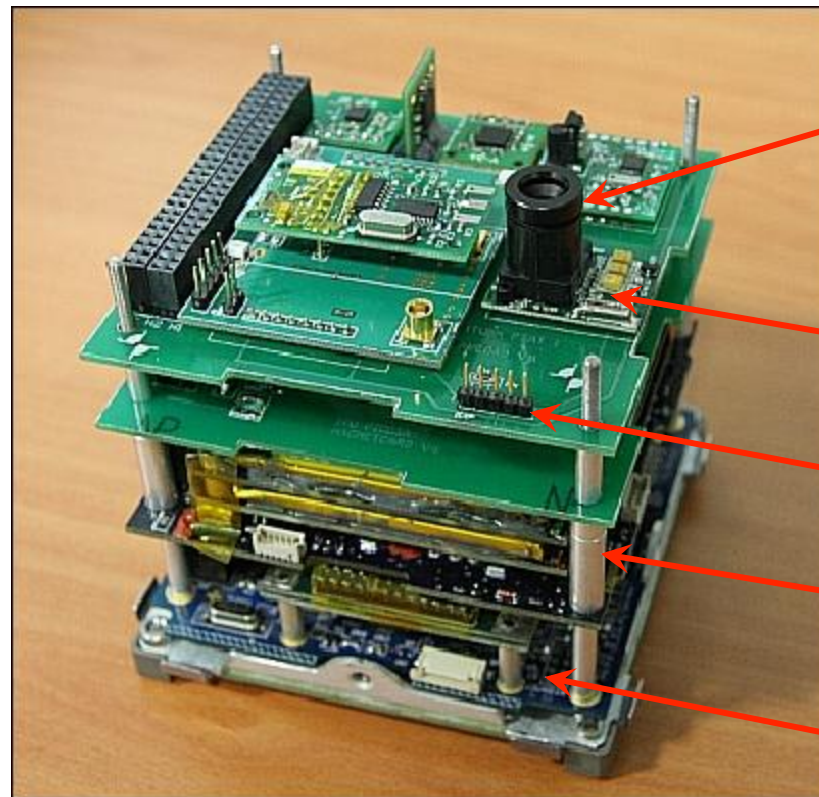
- All solid state materials of **any size**

Solar panels

Fuse-wires

Reaction-wheel bearings

MEMS

Optics and their alignment
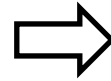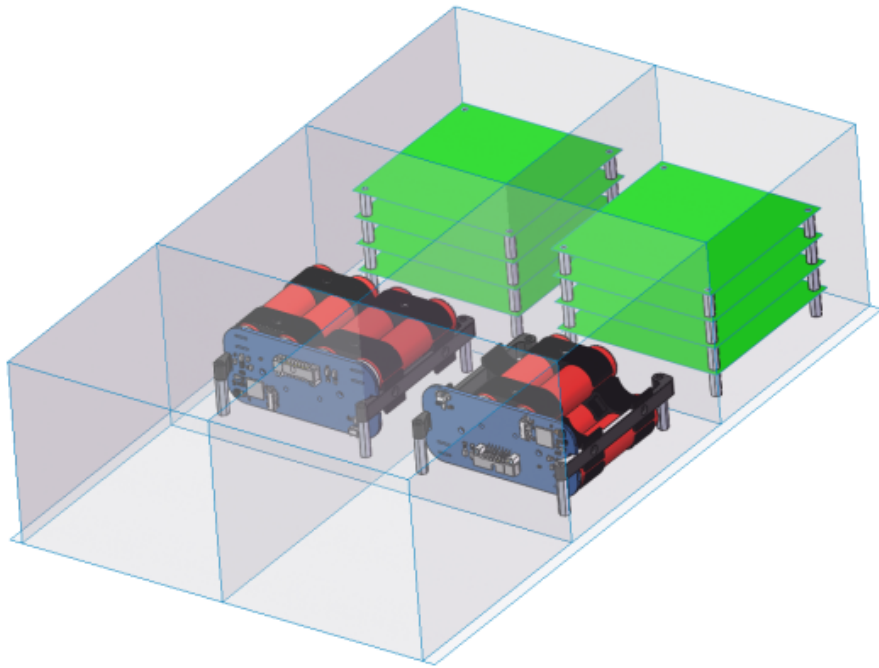
Integrated circuits

Connectors

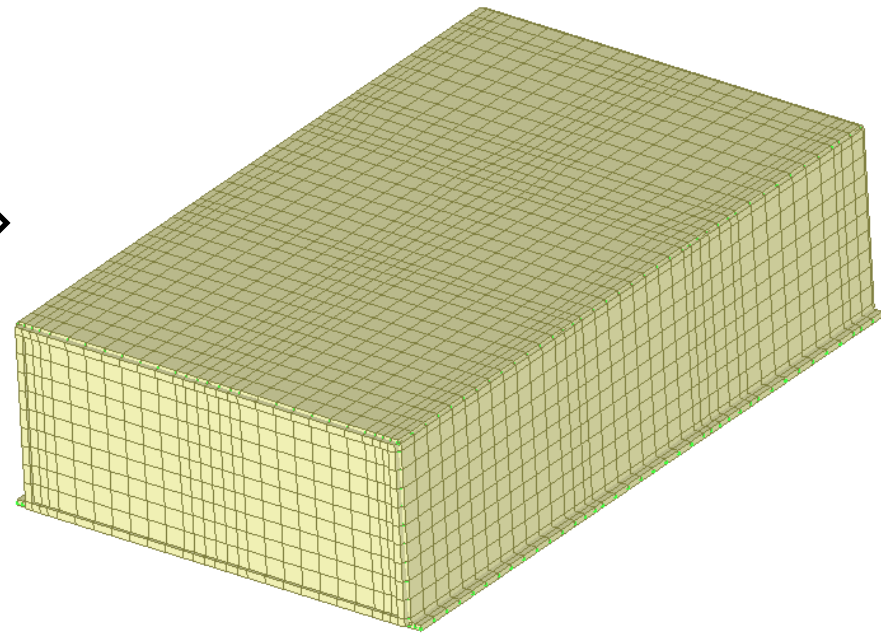Stand-offs, bolted joints and fasteners

Solder junctions

Step 1: Build Finite Element Model (FEM) of CubeSat

Model

CubeSat
FEM

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Dispenser FEM

CubeSat FEM

Dispenser FEM

CubeSat FEM

Preloaded junction (a spring element) joins CubeSat to Dispenser FEM

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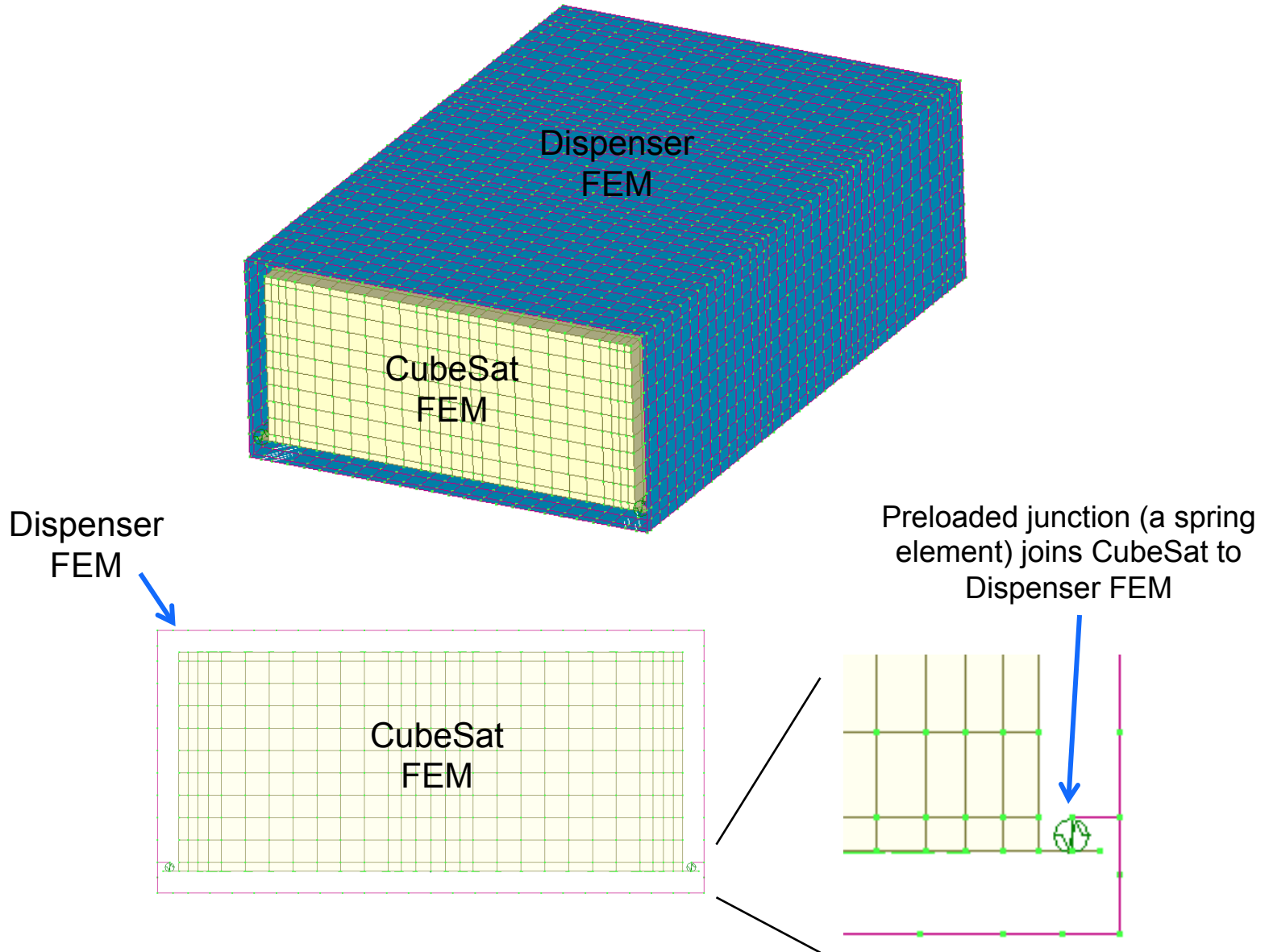
- Compared the response of each component to the base input. Peak values were:
  - Base input [g] = 1.01
  - Battery A [g] = 1.01
  - Bottom PCB [g] = 1.00

1g Sine Input (10 Hz)

Transient Response (Preloaded Satellite)
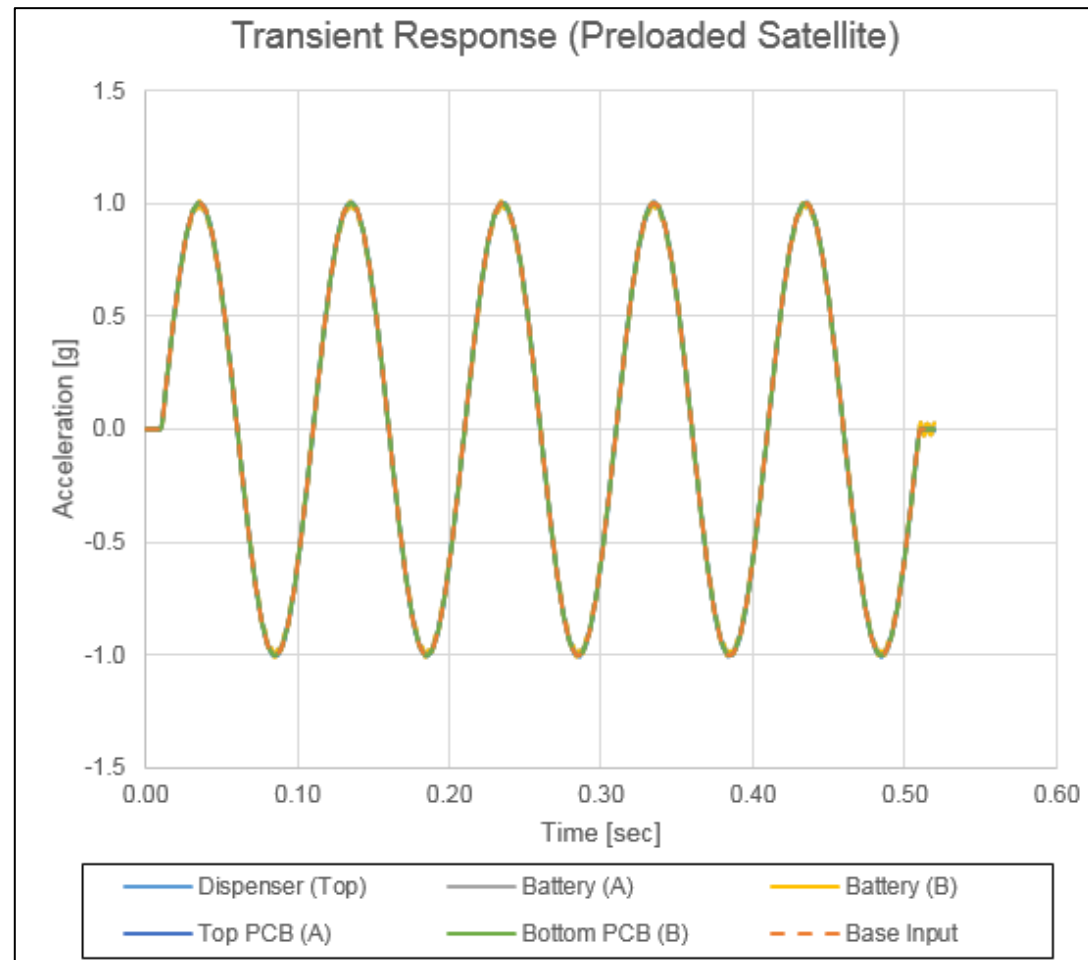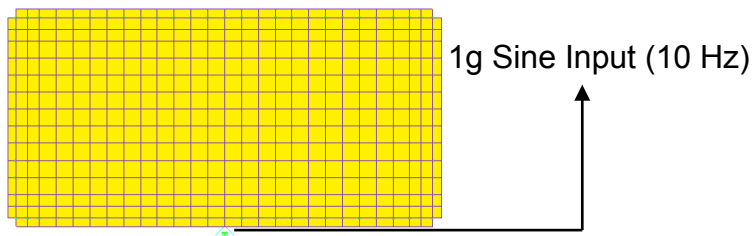
Step 4: Normal Modes Analysis

- The base of the Dispenser (not shown) is fixed
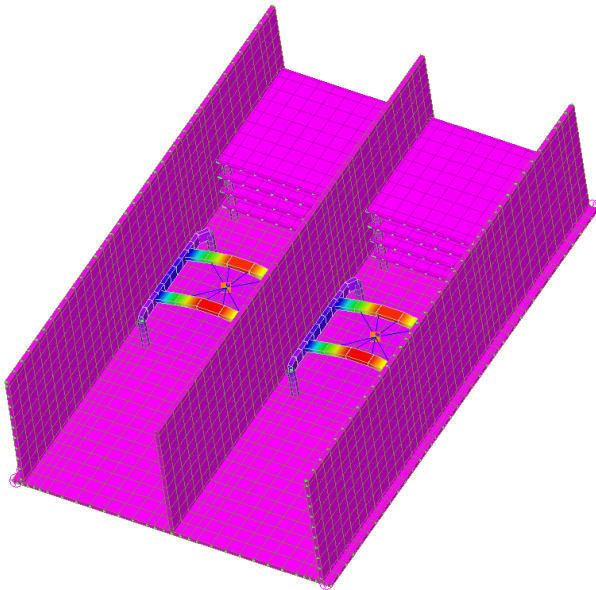
Batteries (329Hz)   PCB Stack (1,295Hz)   PCB Stack (1,297Hz)
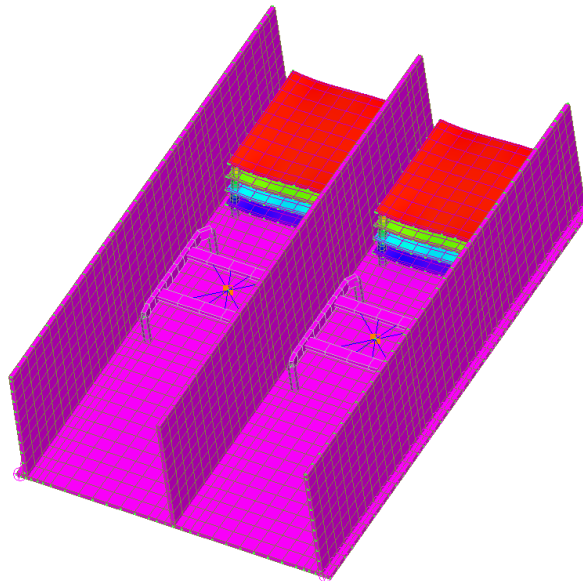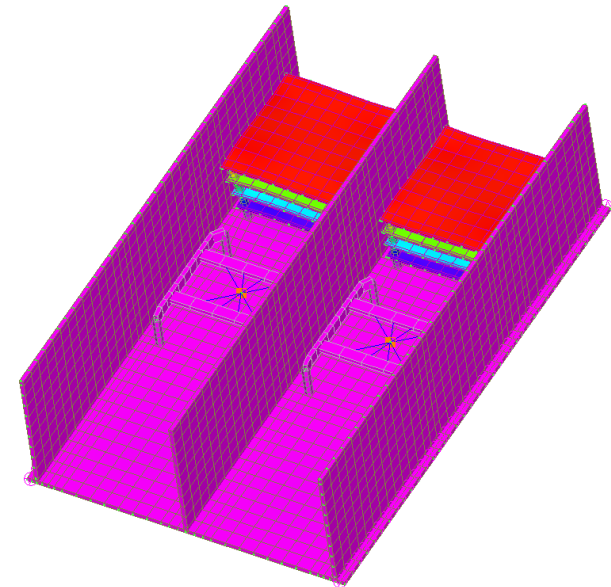
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Max

Cross Beams

Base Standoffs

Outer Standoff

Inner Standoff

Min

A Microcontroller's pins may be modelled

Strain Energy Density

1st Mode (1,002Hz)

Variation in pin Strain Energy around the Microcontroller
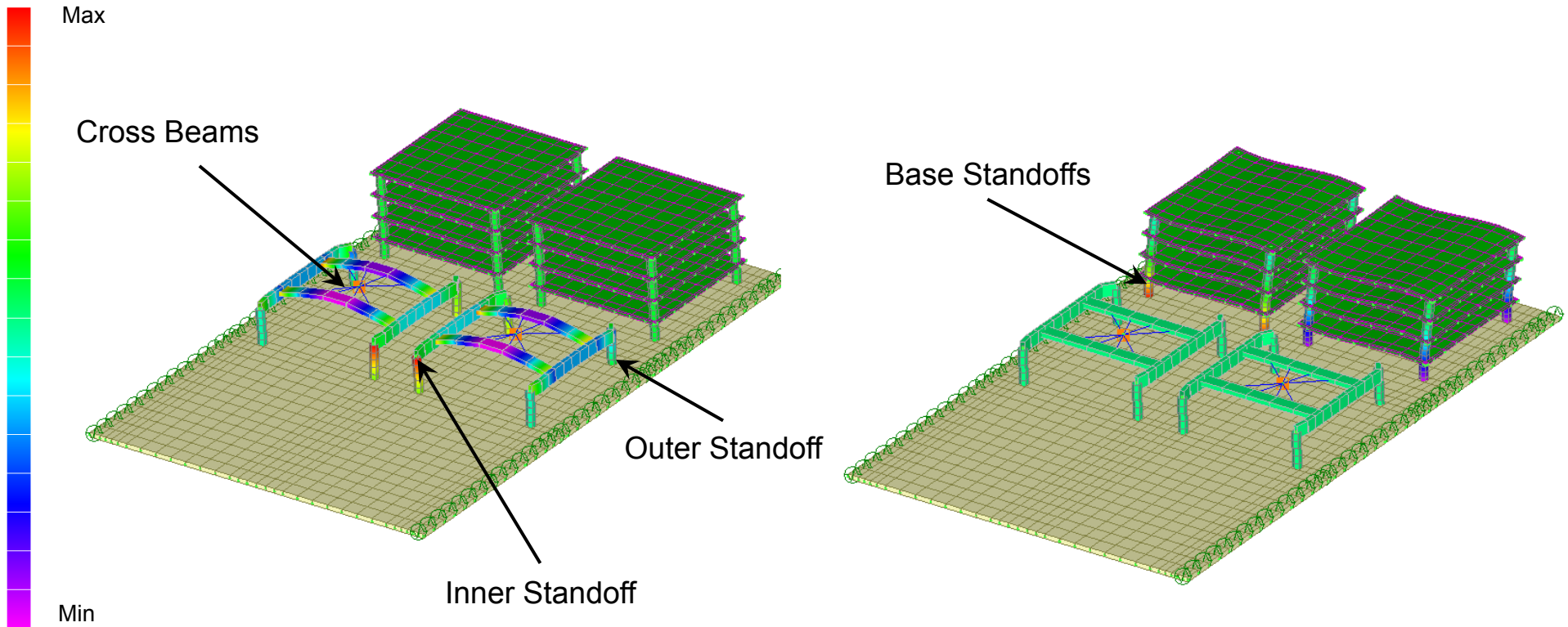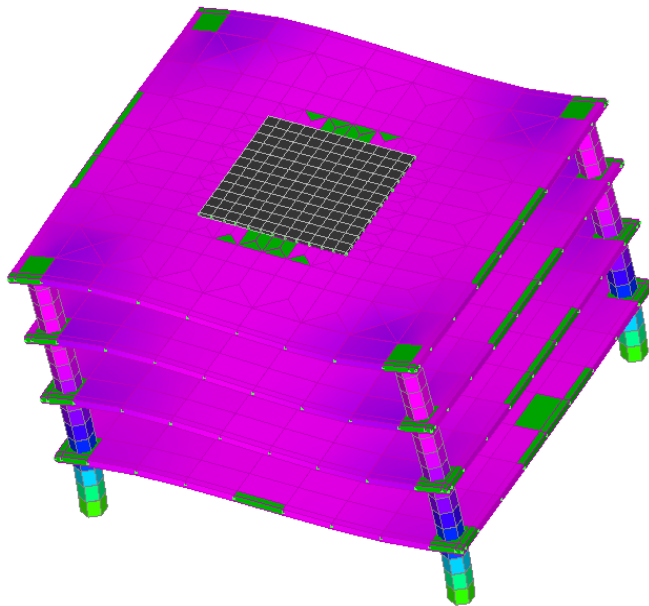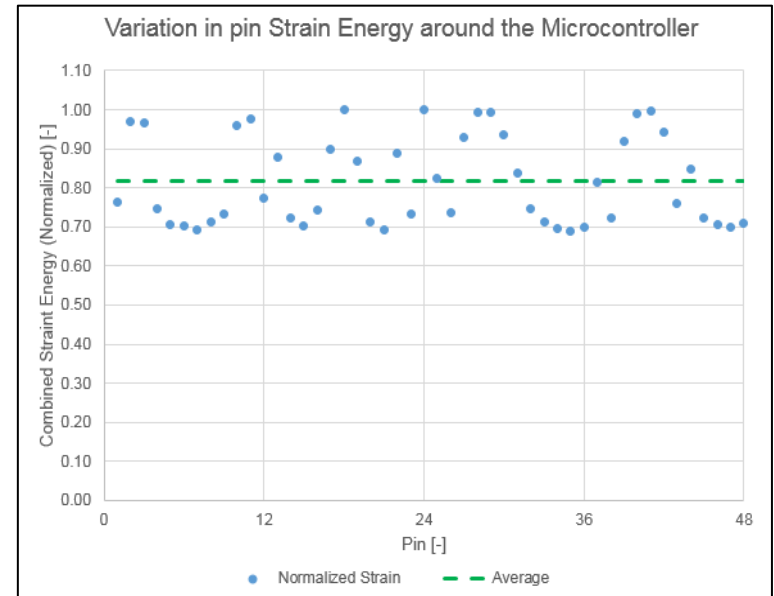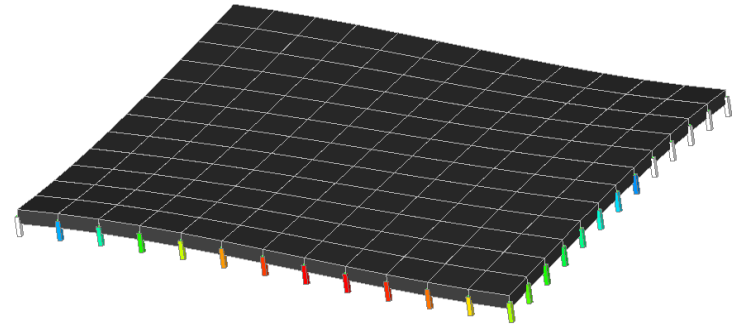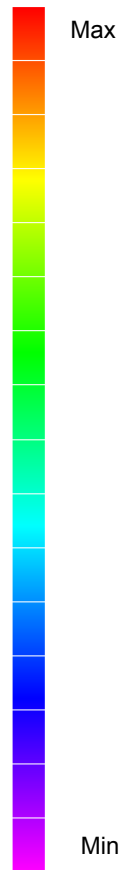
Also see Solomon, H. D. et. al. **Prediction of Solder Joint Fatigue Life,** Air Force Wright Aeronautical Laboratories, April 1988

Step 6: Random Vibration Analysis

- The input vibration is at the base of the dispenser

- Are the responses exceeding specification?

  – Example: Is Battery A being exposed to random vibration (cyclic loading) in excess of its specification?

Random Vibration Test Predictions

Is Battery A going to fail if this response exceeds its specification?

- Top of Satellite (23.3 grms)
- Base input (14.1 grms)
- Battery A (29.8 grms)
- Top PCB (25.1 grms)
- Bottom PCB (24 grms)

Random Vibration Standoff Stress Results

- Inner Standoff (1,309 psi rms)
- Cross Beam (2,013 psi rms)
- Inner Base Standoff (261 psi rms)
- Outer Base Standoff (163 psi rms)
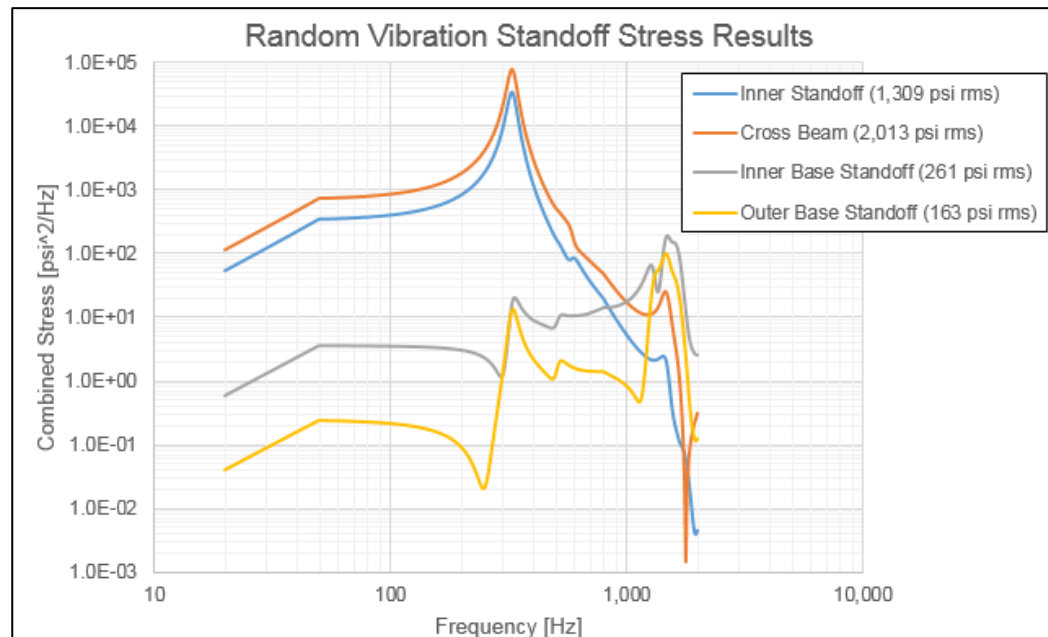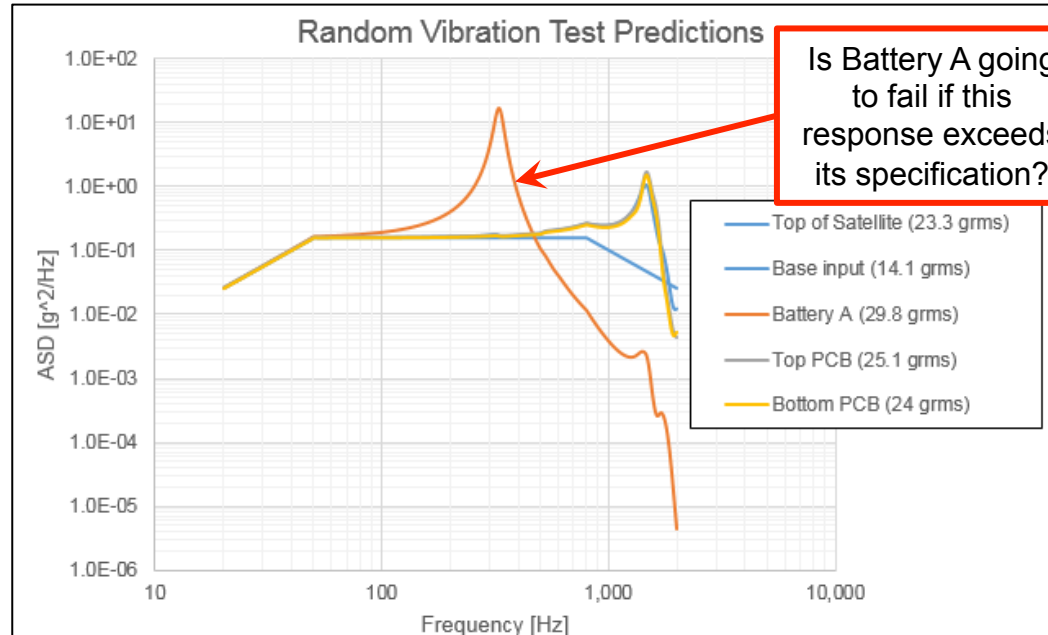
Step 7: Predict fatigue damage

- Using the Rms stress from **Step 6**, and assume a full stress reversal
- Use Miner's Rule to compute **Fatigue damage ratio.**
  - Values less than 1.0 are indicate **no fatigue failure**

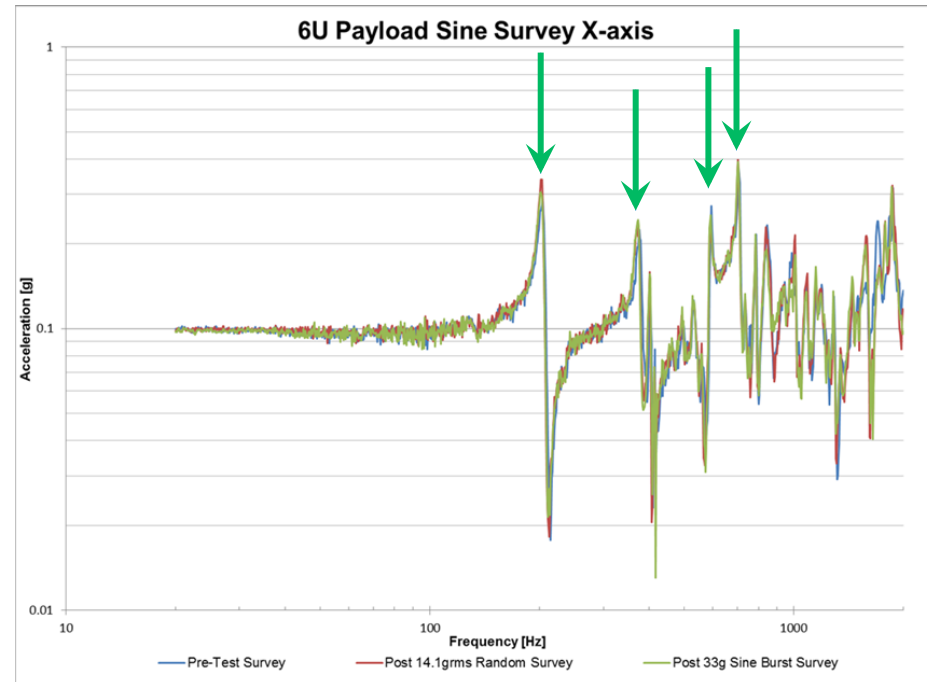|	Inner Standoff	Cross Beam	Inner Base Standoff	Outer Base Standoff
Resonant Frequency [Hz]	329	329	1,295	1,296
Duration [sec]	120	120	120	120
Trials [-]	1	1	1	1
Total Duration [sec]	120	120	120	120
Duration Cycle [sec]	0.0030	0.0030	0.0008	0.0008
Total Cycles [-]	39,480	39,480	155,400	155,520
Stress (1-sigma) [psi]	1,309	2,013	261	163
Stress (2-sigma) [psi]	2,619	4,026	522	326
Stress (3-sigma) [psi]	3,928	6,040	782	488
Time Stress Occurs (1-sigma) [-]	68.3%	68.3%	68.3%	68.3%
Time Stress Occurs (2-sigma) [-]	27.2%	27.2%	27.2%	27.2%
Time Stress Occurs (3-sigma) [-]	4.3%	4.3%	4.3%	4.3%
Number of Cycles (1-sigma) [-]	26,953	26,953	26,953	26,953
Number of Cycles (2-sigma) [-]	10,731	10,731	10,731	10,731
Number of Cycles (3-sigma) [-]	1,690	1,690	1,690	1,690
Fatigue Limit (1-sigma) [-]	1.00E+08	1.00E+08	1.00E+08	1.00E+08
Fatigue Limit (2-sigma) [-]	1.00E+08	1.00E+08	1.00E+08	1.00E+08
Fatigue Limit (3-sigma) [-]	1.00E+08	1.00E+08	1.00E+08	1.00E+08
Fatigue Damage Ratio [-]	3.94E-04	3.94E-04	3.94E-04	3.94E-04

- In the actual test, response accelerometers are used to correlate the FEM
    - Damping and stiffness are modified in the FEM to best mimic test response
- If pre and post sine sweeps are substantially different, fracture may have occurred changing the load path and so changing the response frequency and amplitude
- A fractured electrical junction may not be detected until thermal or operations testing
    - At temperature extremes, an already cracked circuit element may OPEN as the materials contract
        - So it is valuable to follow vibration testing with thermal vacuum testing

If the load path changed because of fatigue, one would see a change in frequency or amplitude

6U Payload Sine Survey X-axis

Pre-Test Survey — Post 14.1grms Random Survey — Post 33g Sine Burst Survey

- A compressive load to join parts wherein the compressive load is greater than external load
  - Because the junction does not slip it behaves as if it were welded together
- Examples of preloaded junctions
  - Tightened bolts holding a wheel to a car
  - Tightened C-clamp holding two pieces of wood together
  - Straps holding cargo inside a plane
- Examples of un-preloaded junctions
  - Untightened bolts holding a wheel to a car
    - The wheels will jiggle and wreck the bolts. Then the wheel will fall off.
  - Untightened C-clamp holding two pieces of wood together
    - One piece of wood will slip away
  - Cargo moving around the inside of a plane

- In un-preloaded CubeSats, response changes with applied load and time
  - Very non-linear = impractical to usefully model
    - So model correlation is impractical as well
  - Non-linearities are (also) consistent with fatigue!
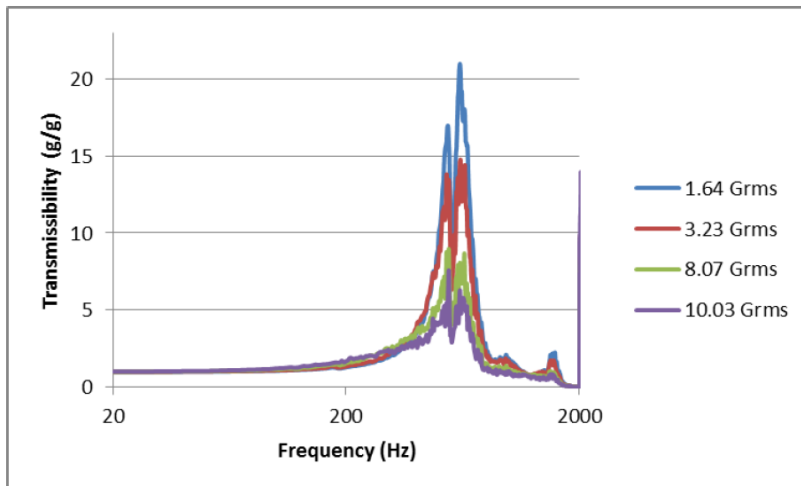   - So CubeSats may have suffered a fatigue failure, but engineers can't tell…

Figure 10: Transmissibility of CubeSat in X axis of 1U TestPOD with variable loads (test 1 during ramp-up).

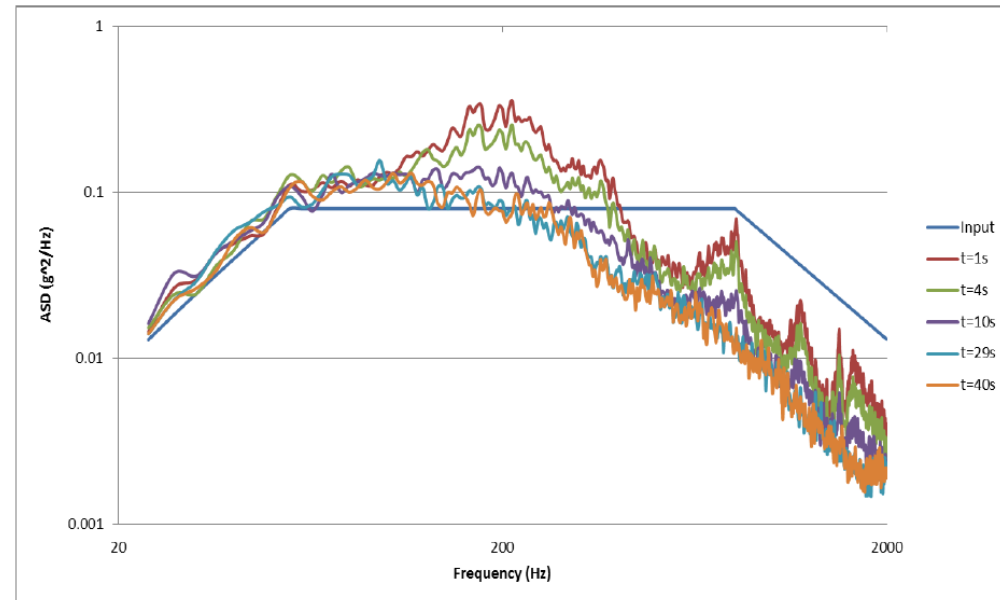*Non-linearity # 1: The higher the loading, the lower the transmissibility*

Figure 5: X axis response of CubeSat in 3U TestPOD over time (test 3-3).

Non-linearity # 2: Response is changing with time

*Source: Furger, S. **Development of Random Vibration Profiles for Test Deployers to Simulate the Dynamic Environment in the Poly-Picosatellite Orbital Deployer**, California Polytechnic, San Luis Obispo, 2013*

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- Analysis can be used to predict fatigue life allowing engineers to avoid failure modes associated with fatigue and focus on predicted weaknesses
- Un-preloaded CubeSats cannot be practically analyzed for fatigue life
  - Un-preloaded (jiggling) Cubesats may be masking useful data about fatigue failure

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- Questions?