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Methods to predict fatigue in CubeSat structures and mechanisms

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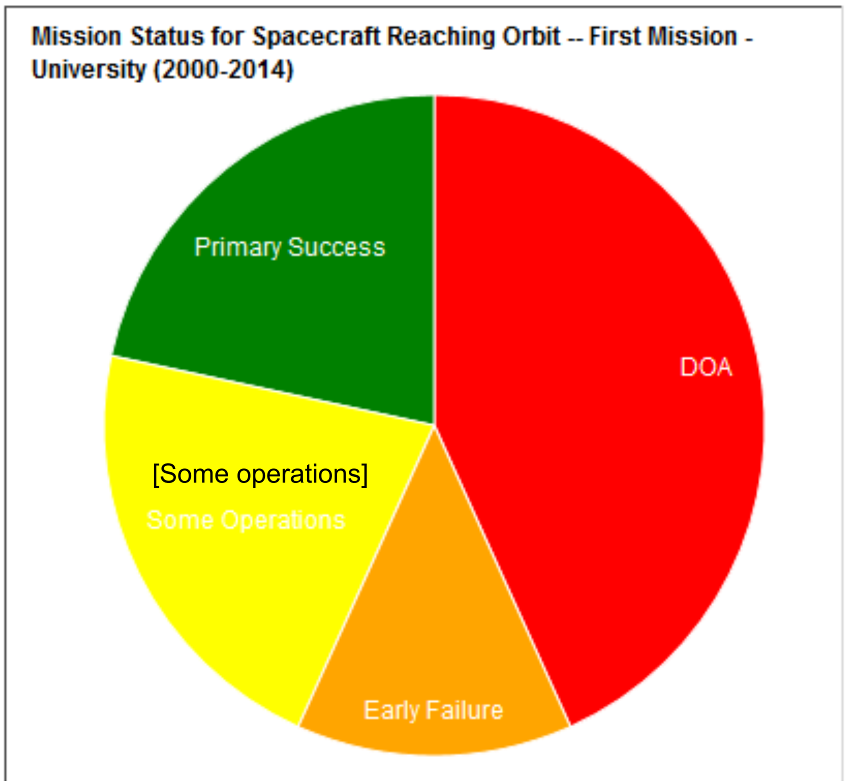
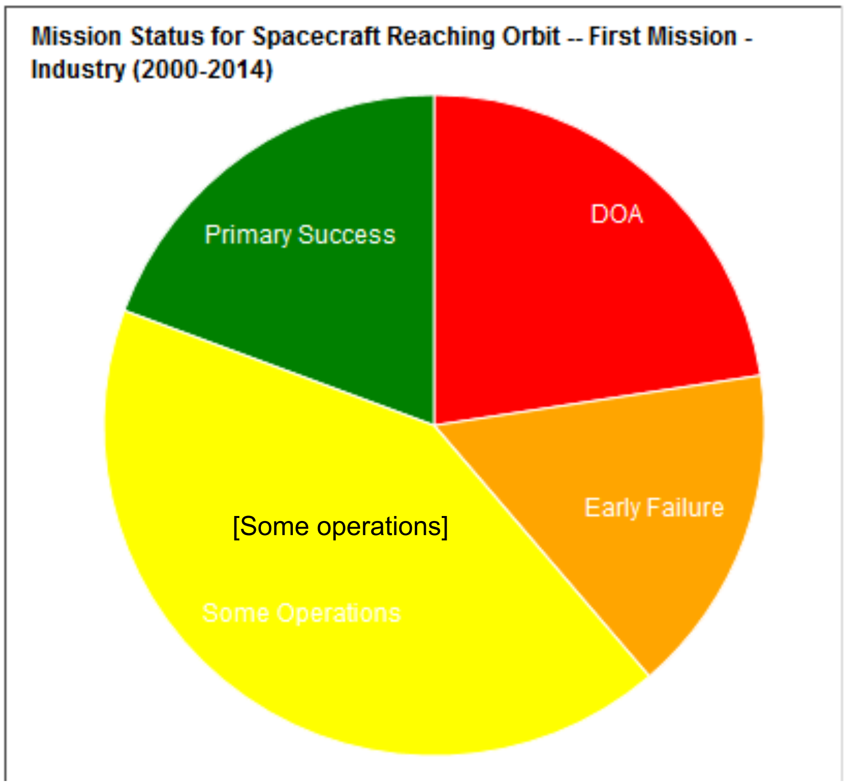
Outline

- Problem Statement
- What is fatigue?
- Cyclic loading and strength
- What is sensitive?
- Steps 1-8
- What is preload?
- Summary

Problem Statement

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

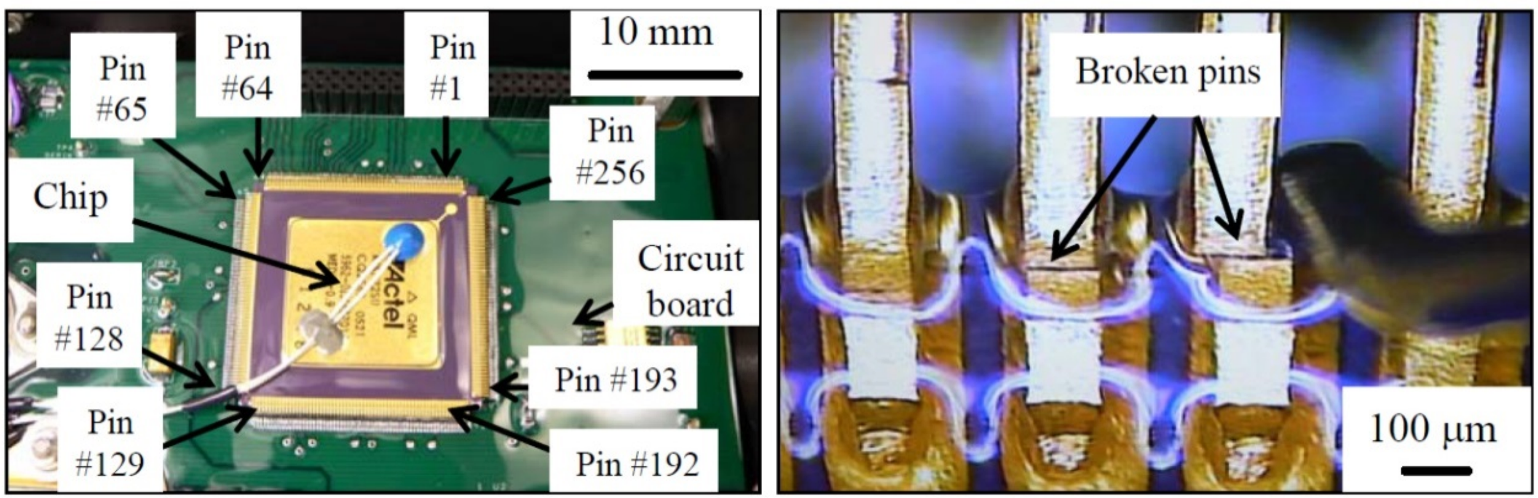




Source: Swartwout, Michael
Parks College of Engineering, Aviation & Technology
Saint Louis University
https://script.google.com/macros/s/AKfycbynG51p-33r5fBqV-uuNv4Sm3dz4XYThZkPx5pdIT-Wtjmi-Y9X/exec?source=P3

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

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

Figure 1. Photographs of failed electrical connector pins.

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

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Cyclic loading reduces material strength by about 50 percent

- Typical Stress Versus Life (S-N) Curve

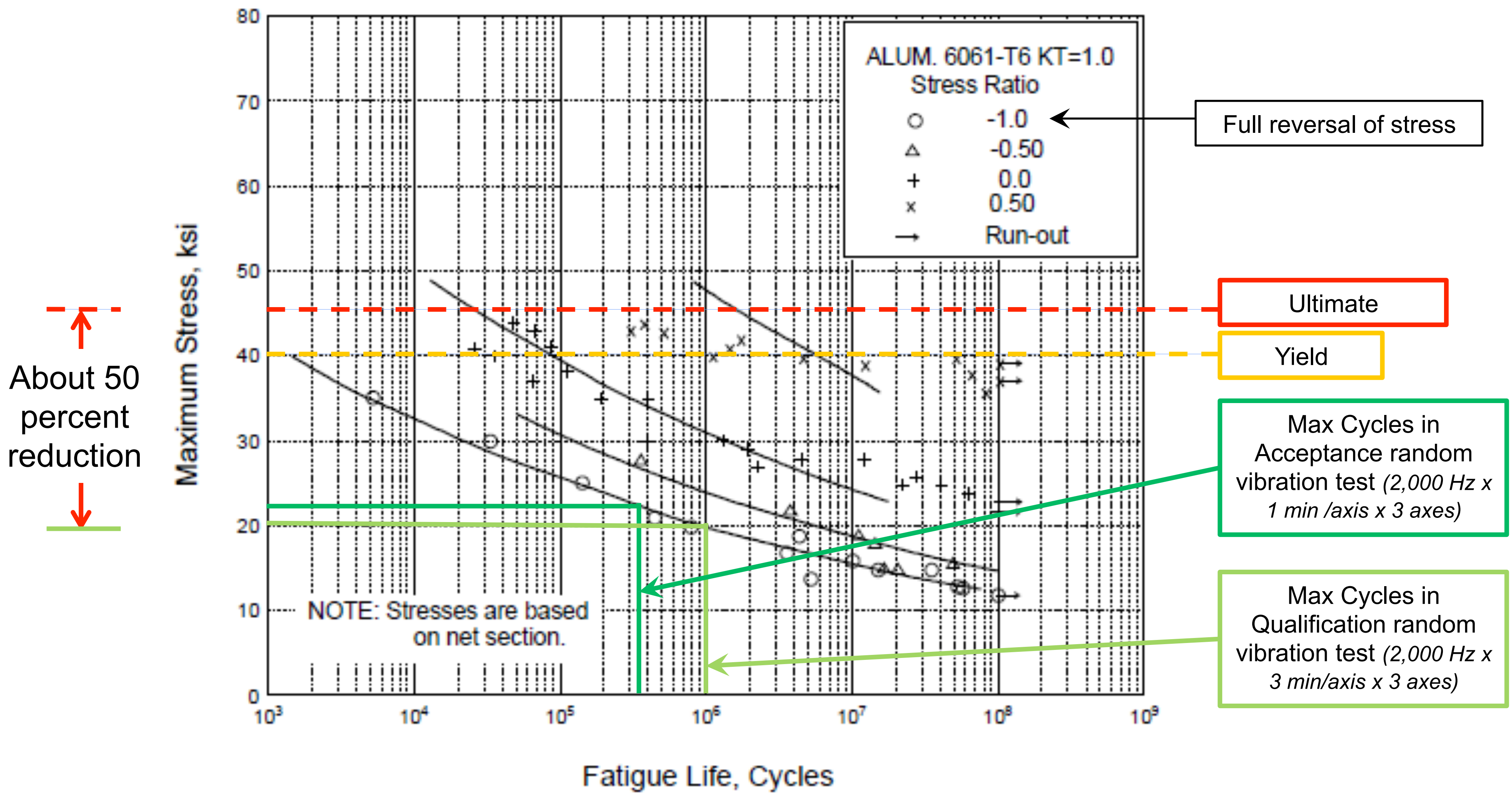
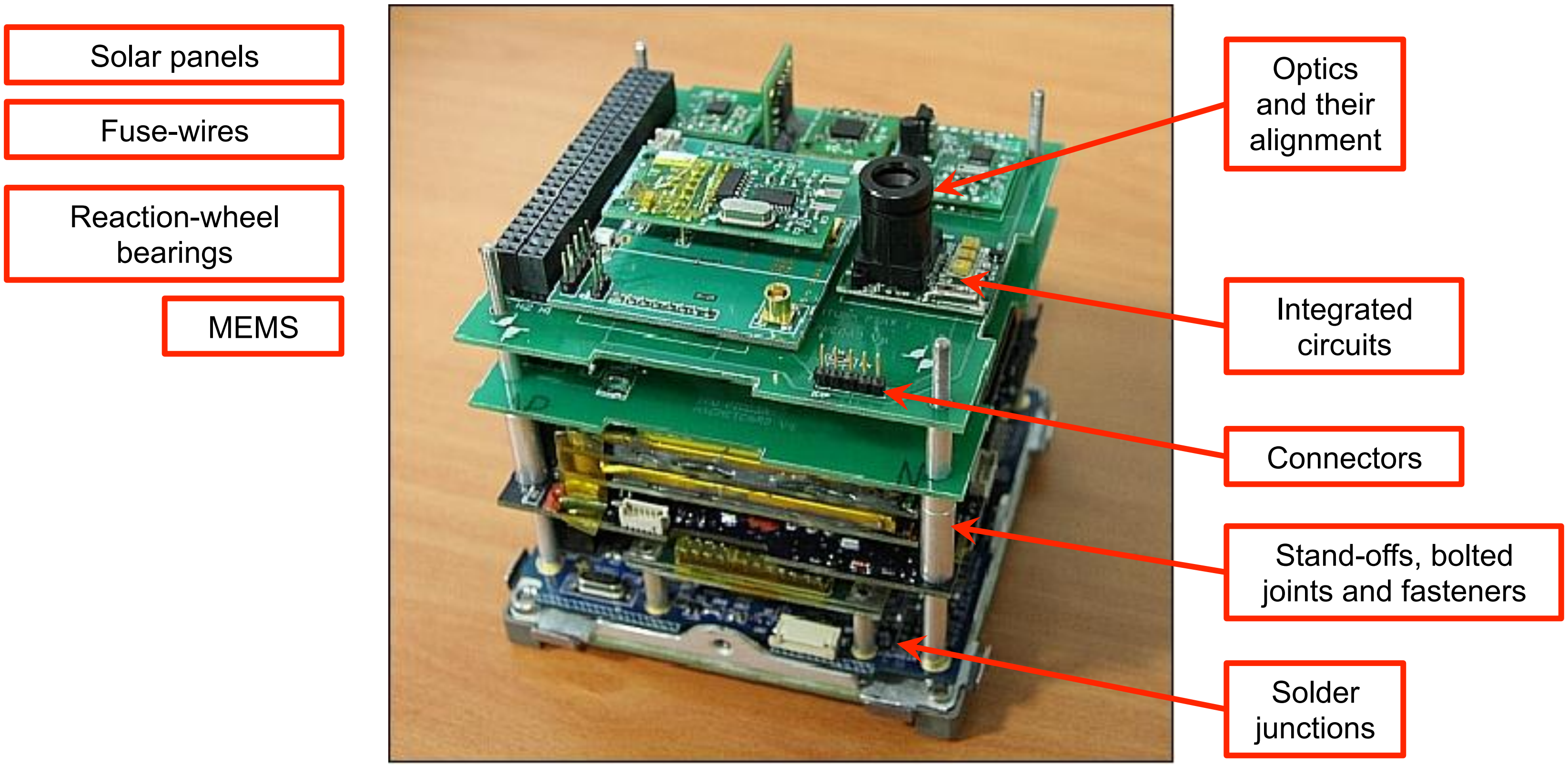


Figure 3.6.2.2.8. Best-fit S/N curves for unnotched 6061-T6 aluminum alloy, various wrought products, longitudinal direction.

Source: Battelle-MMPDS Metallic Materials Properties Development and Standardization

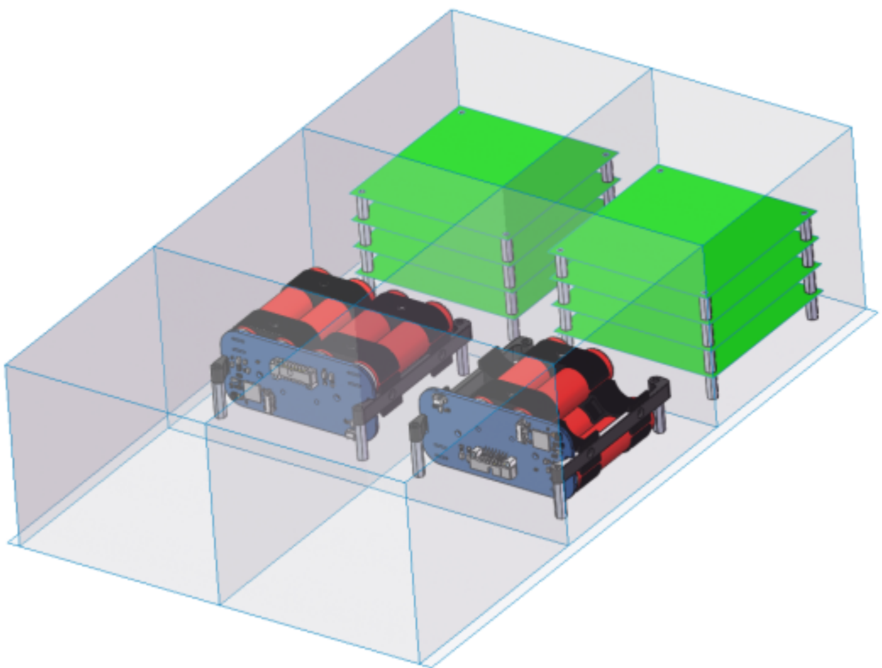
What items are sensitive to fatigue?

- All solid state materials of **any size**

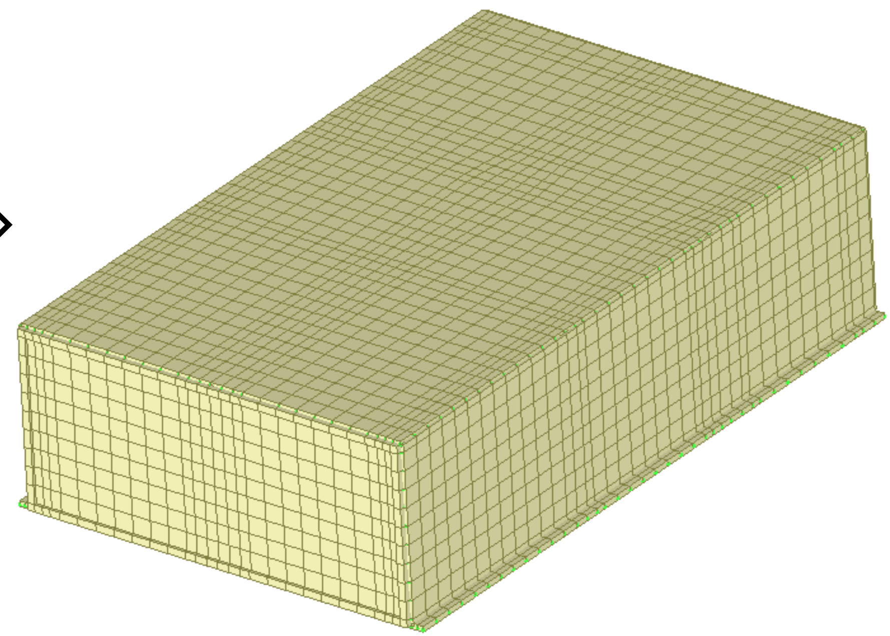


Step 1: Build Finite Element Model (FEM) of CubeSat

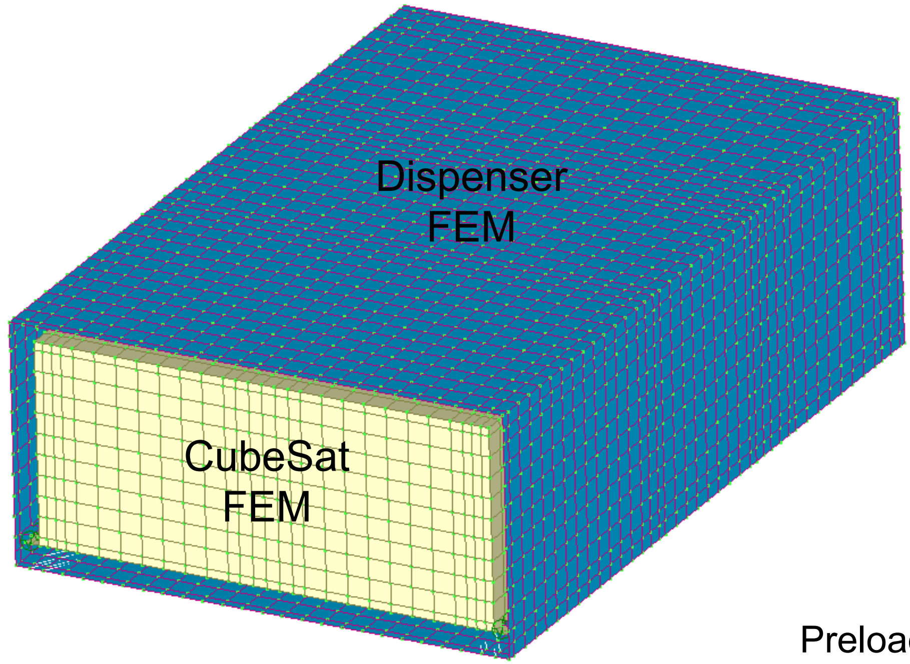
Model



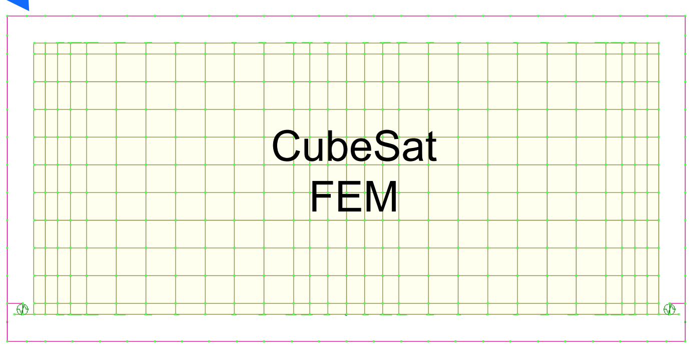
CubeSat
FEM



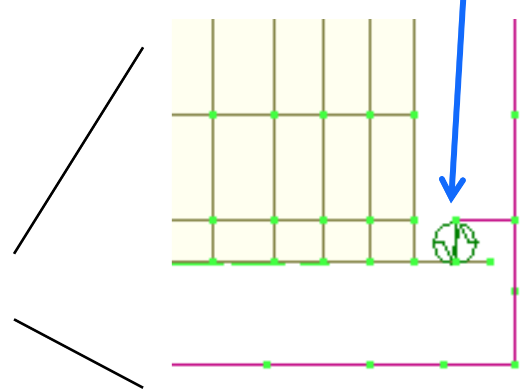
Step 2: Join CubeSat FEM to Dispenser FEM



Dispenser
FEM

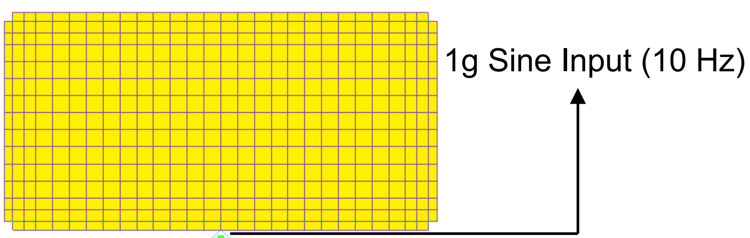


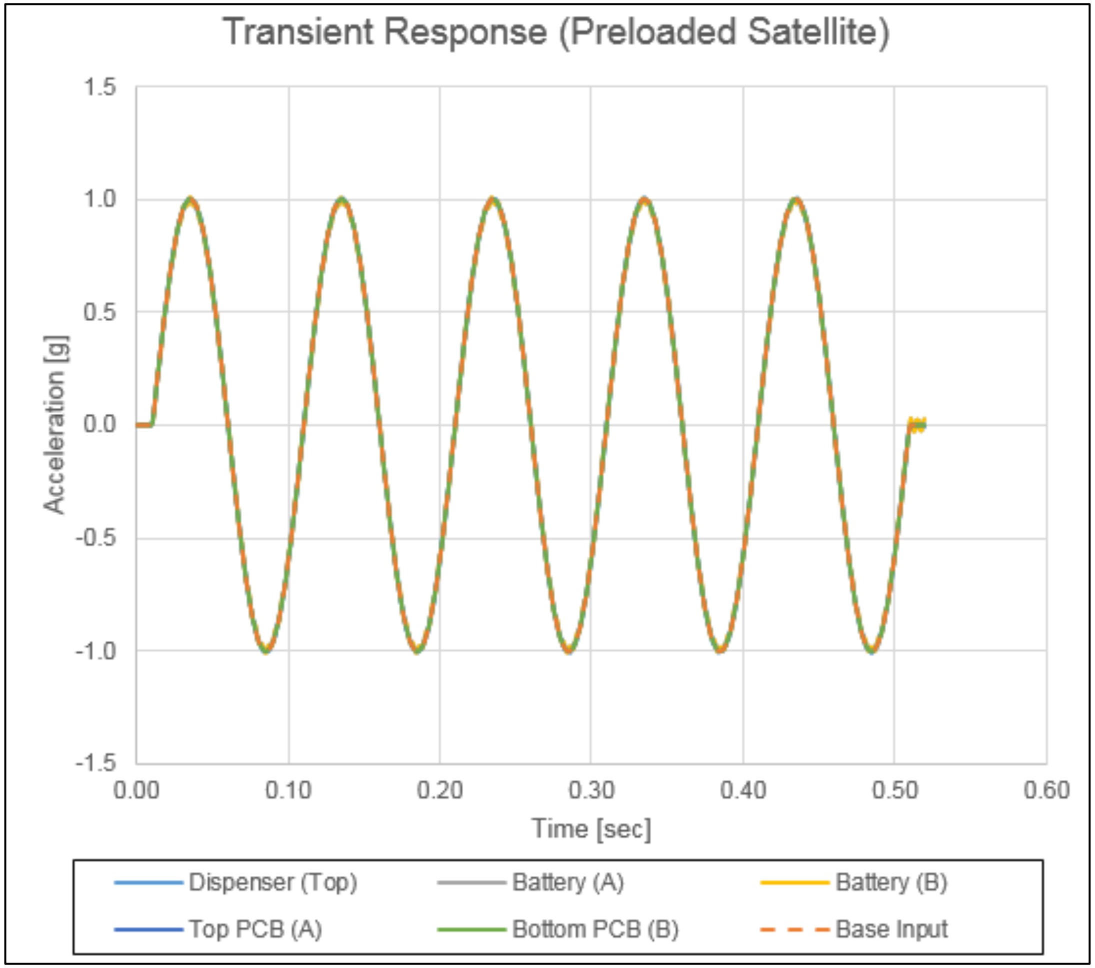
Preloaded junction (a spring element) joins CubeSat to Dispenser FEM



Step: 3 Verify model is Linear

- 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

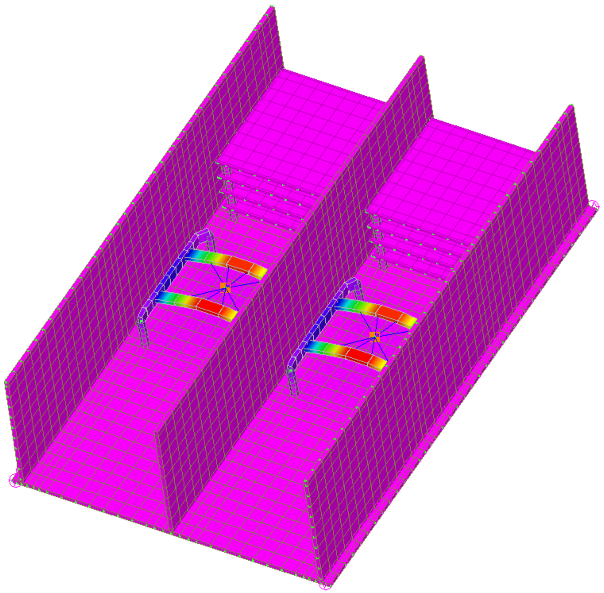




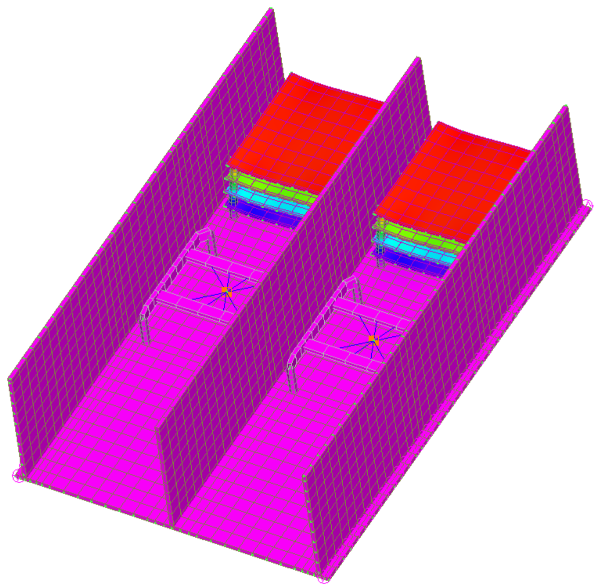
Step 4: Normal Modes Analysis

- The base of the Dispenser (not shown) is fixed

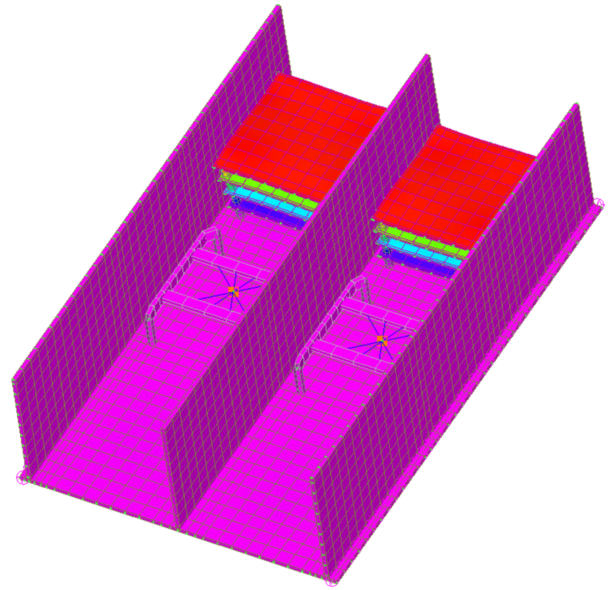
Batteries (329Hz)



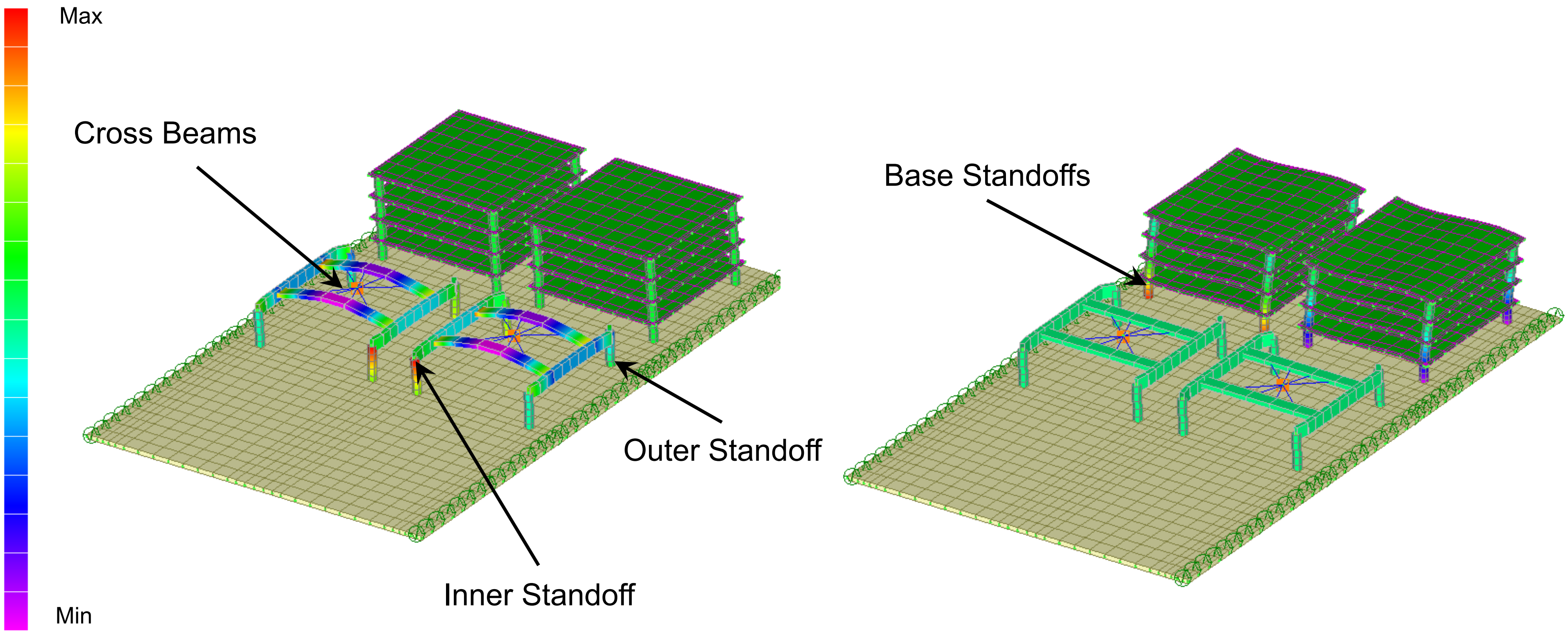
PCB Stack (1,295Hz)



PCB Stack (1,297Hz)



Step 5: Identify Elements with high stress or strain



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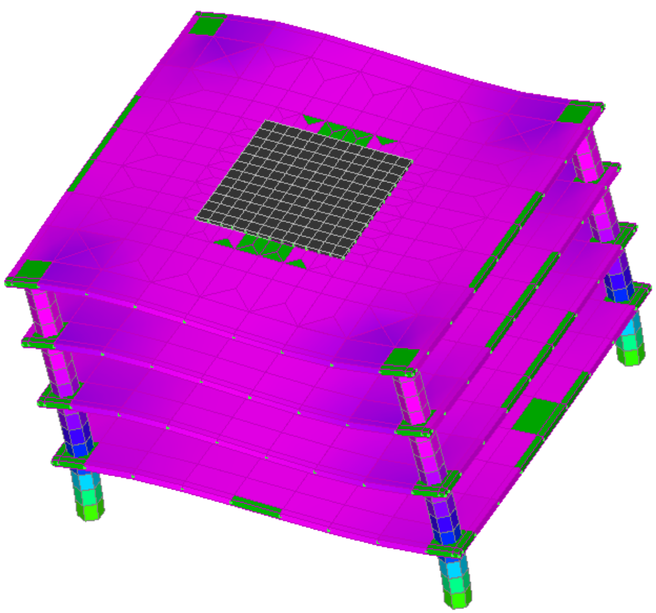
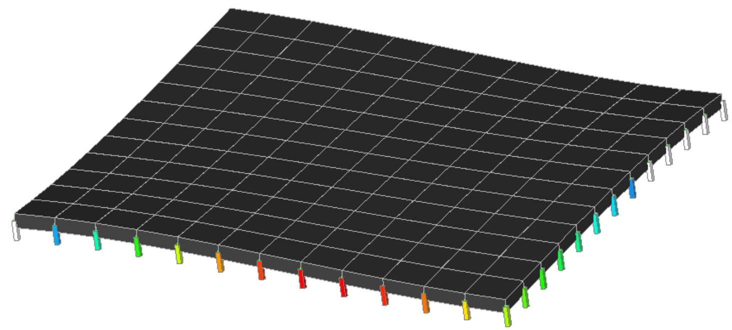
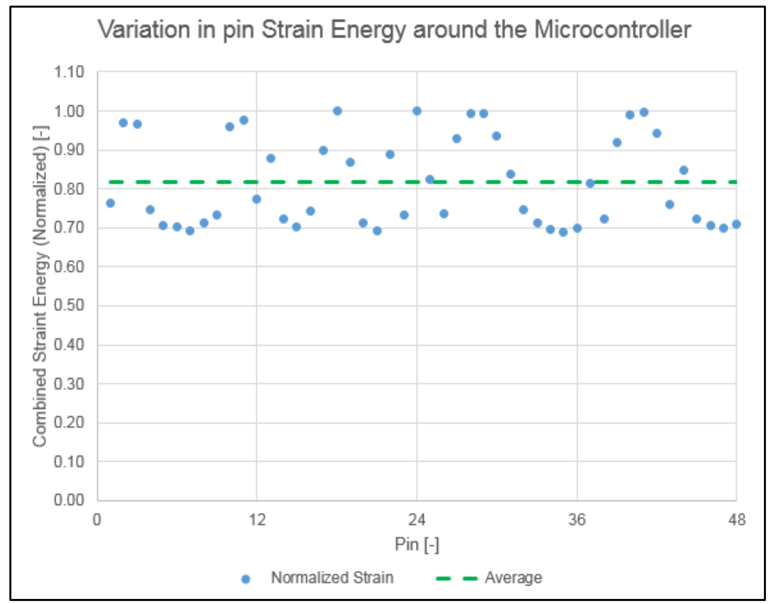
A Microcontroller's pins may be modelled

1st Mode (1,002Hz)



Strain Energy Density





Also see Solomon, H. D. et. al. **Prediction of Solder Joint Fatigue Life,** Air Force Wright Aeronautical Laboratories, April 1988

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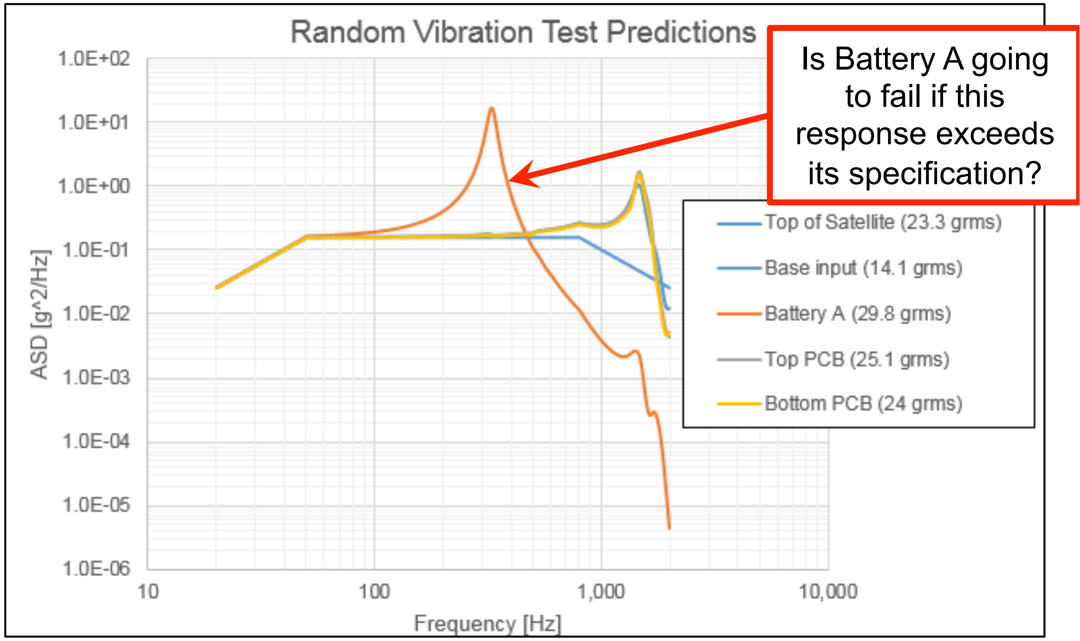
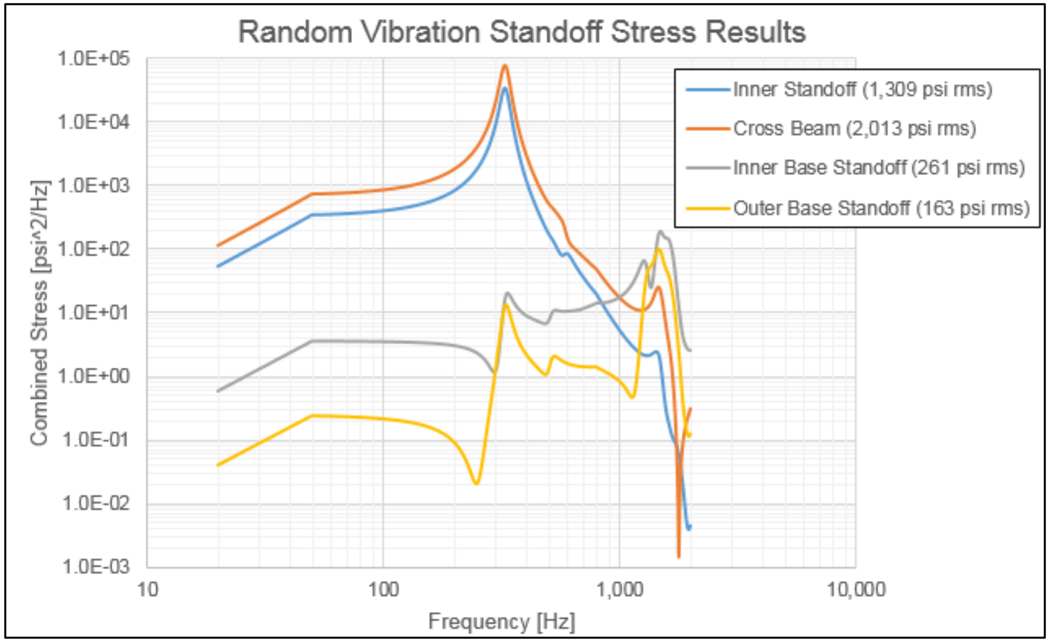
Step 6: Random Vibration Analysis

- 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?





Step 7: Predict fatigue damage

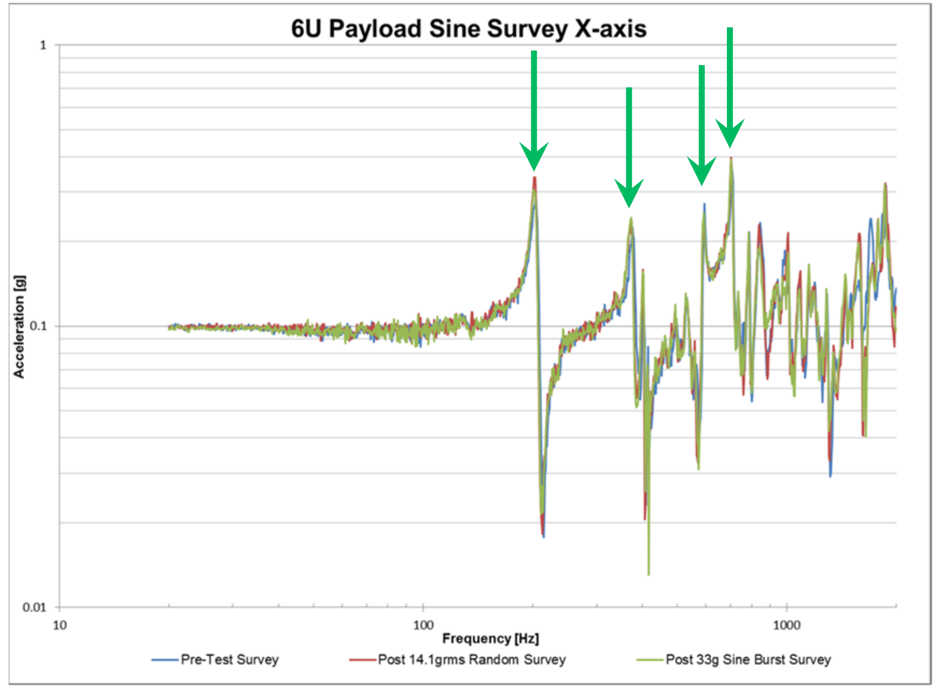
- Using the Rms stress from **Step 6**, and assume a full stress reversal
- Use Miner's Rule to compute **Fatigue damage ratio.**
  - Values less than 1.0 are indicate **no fatigue failure**

	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

Step 8: Test Verification

- 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



What is a preloaded junction?

- 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

Fatigue cannot be predicted with un-preloaded CubeSats

- 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…

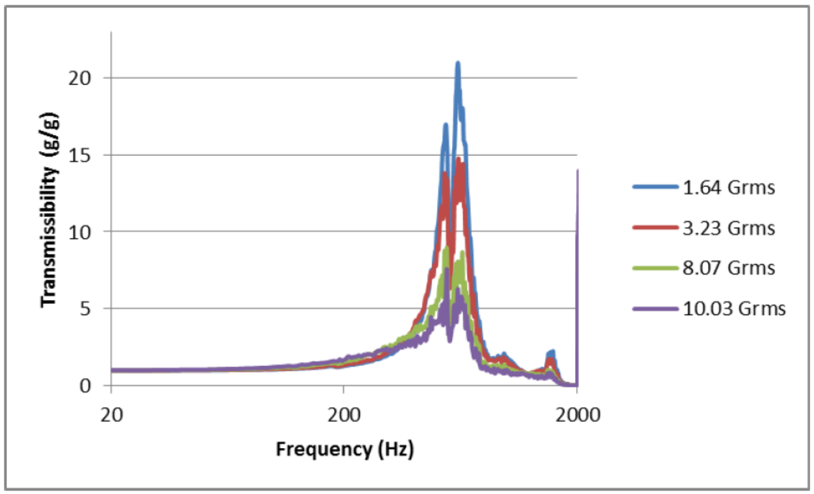


Figure 10: Transmissibility of CubeSat in X axis of 1U TestPOD with variable loads (test 1 during ramp-up).

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

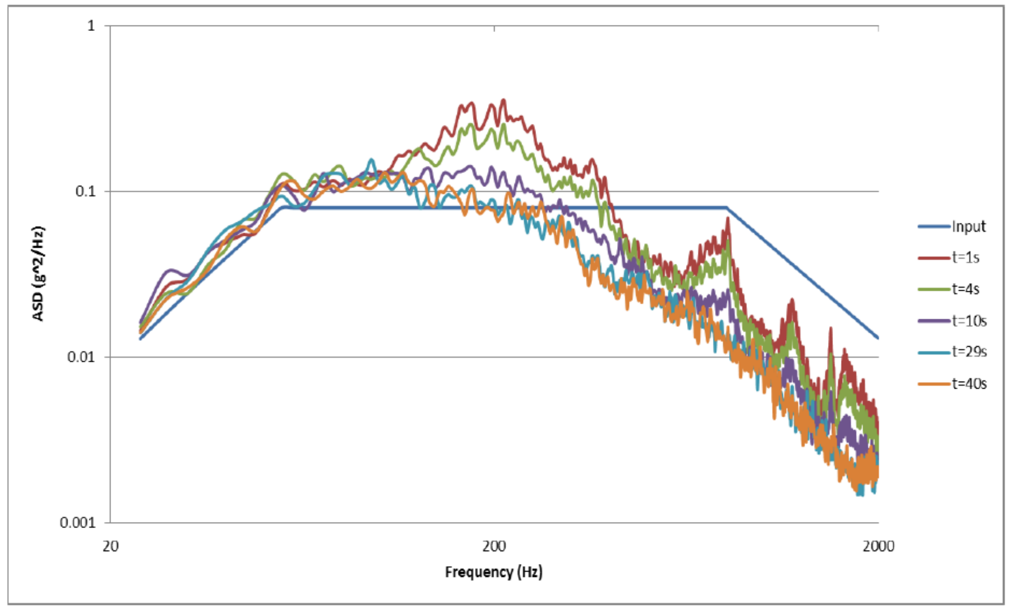


Figure 5: X axis response of CubeSat in 3U TestPOD over time (test 3-3).

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*

Summary

- 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

Thank You

- Questions?