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
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.

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

![Image](image.png)

Figure 1. Photographs of failed electrical connector pins.

Cyclic loading reduces material strength by about 50 percent

- Typical Stress Versus Life (S-N) Curve

![Diagram showing typical stress versus life (S-N) curve for aluminum 6061-T6 alloy with stress ratio and cycles indicated.](source: Battelle-MMPDS Metallic Materials Properties Development and Standardization)
What items are sensitive to fatigue?

- 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
Step 2: Join CubeSat FEM to 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

Max

Cross Beams

Inner Standoff

Outer Standoff

Base Standoffs

Min
A Microcontroller’s pins may be modelled

1\textsuperscript{st} Mode (1,002Hz)

Strain Energy Density

Max

Min

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

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

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

Non-linearity # 2: Response is changing with time

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?