OMEN Structural Analysis 3

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Introduction:

This document is a thorough analysis of the OMEN cube satellite primary and secondary structure. The OMEN engineering unit is a 3U sized cube satellite created specifically for Saint Louis University's DORRE mission. Space Systems Research Lab has chosen a NanoAvionics 3U Frame to serve as the skeleton of the cube satellite.

General Test Procedure Background:

The purpose of the verification test is to ensure that OMEN will survive Launch Vehicle loading conditions. The tests required (as taken from UNP 10-4 and UNP 10-5, UNP NS10 User's Guide) are an acceleration loading analysis followed by a random vibration analysis. The tests will be simulated with the FEA software ANSYS using the Static Structural, Modal, and Random Vibration analysis tools.

Assembly

Below is an image of the assembly imported into ANSYS. The assembly includes the cube satellite's primary structure, secondary structure, and relevant fasteners. Many components were excluded from this analysis, as their inclusion would have increased the complexity of the analysis and therefore lengthened solve times.

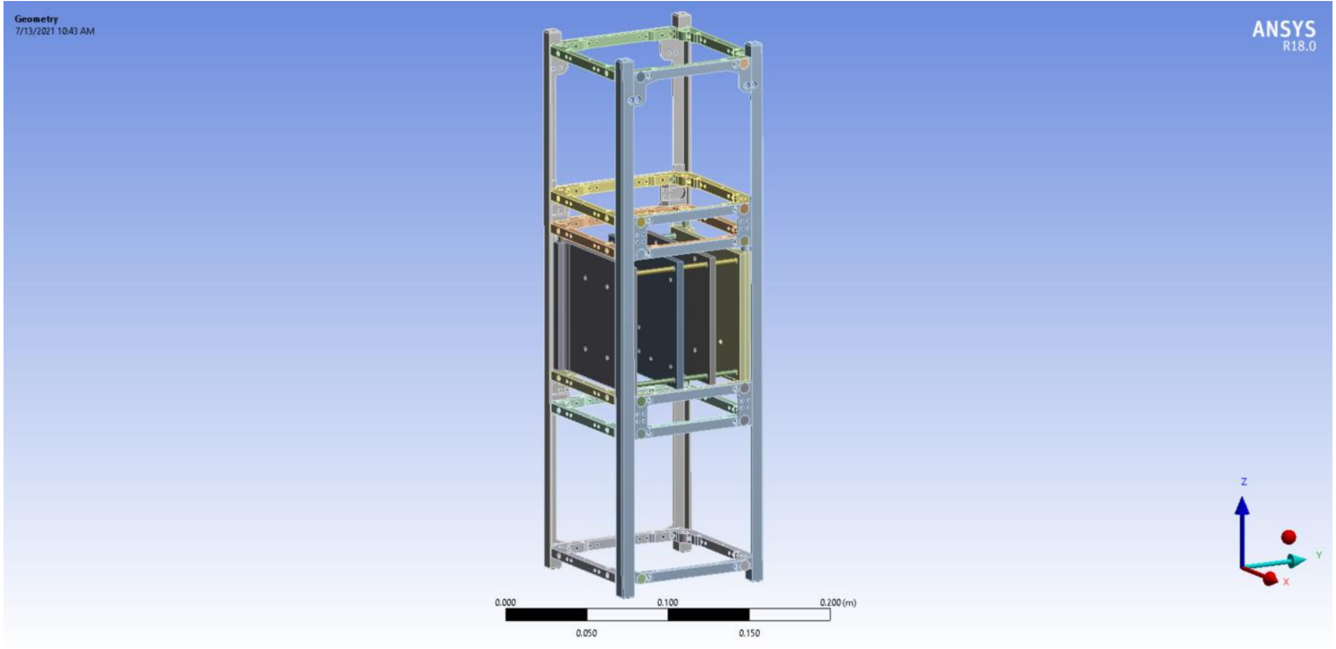


Figure 1: Assembly

The cube satellite's primary structure is pictured below on the left. It consists of two 3U walls as well as six structural ribs (the hollow squares). All primary structure components are made of aluminum 6061. The purpose of the primary structure is to constrain all the hardware on the cube satellite. The secondary structure is pictured below in the middle. It consists of four aluminum 6061 plates as well as 4 aluminum 6061 mounting rods. The plates will serve as a mount for several pieces of hardware, and the rods will constrain the plates. Lastly, all the fasteners that constrain the components of the primary and secondary structure relative to each other are pictured below on the right. All fasteners are made of steel. The form of all fasteners was simplified substantially; for instance, all threads were completely removed. This change was made to simplify the connections between objects in the assembly. This alteration will not alter the behavior of the assembly, but it will make stress results in the fasteners themselves unrealistic. Therefore, this test will focus only on loads experienced by the primary and secondary structures.

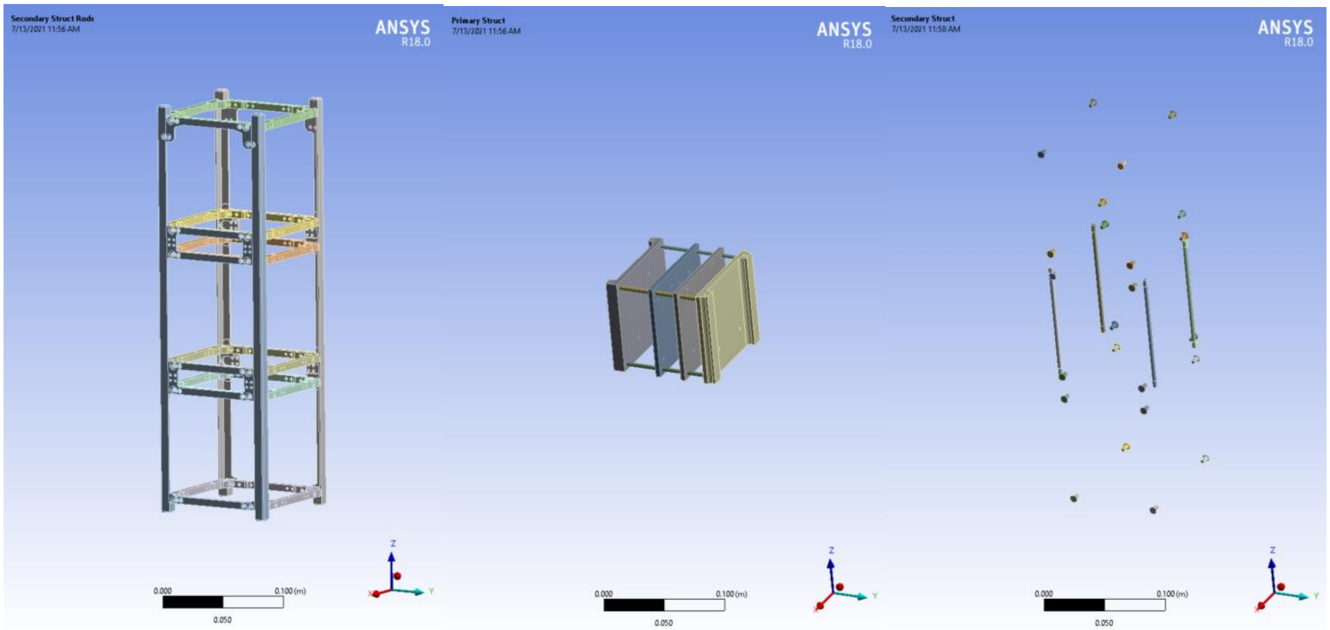


Figure 2: Primary Structure (left), Secondary Structure (middle), and Fasteners (right)

FEA Mesh

Below is an image of the Mesh generated for the FEA analysis. Note that in the bottom of the image , a graph describing the elements is included. The x axis is element quality, which ranges from zero (which describes an extremely distorted element) to one (which describes an element that is a perfect tetrahedron, hexahedron, or another element shape). The y axis is the distribution of elements. Note that the distribution is centered at a quality value of 0.85, so this is a quality mesh. However, an even finer mesh with more high-quality elements was not generated, as it would have increased solution times.

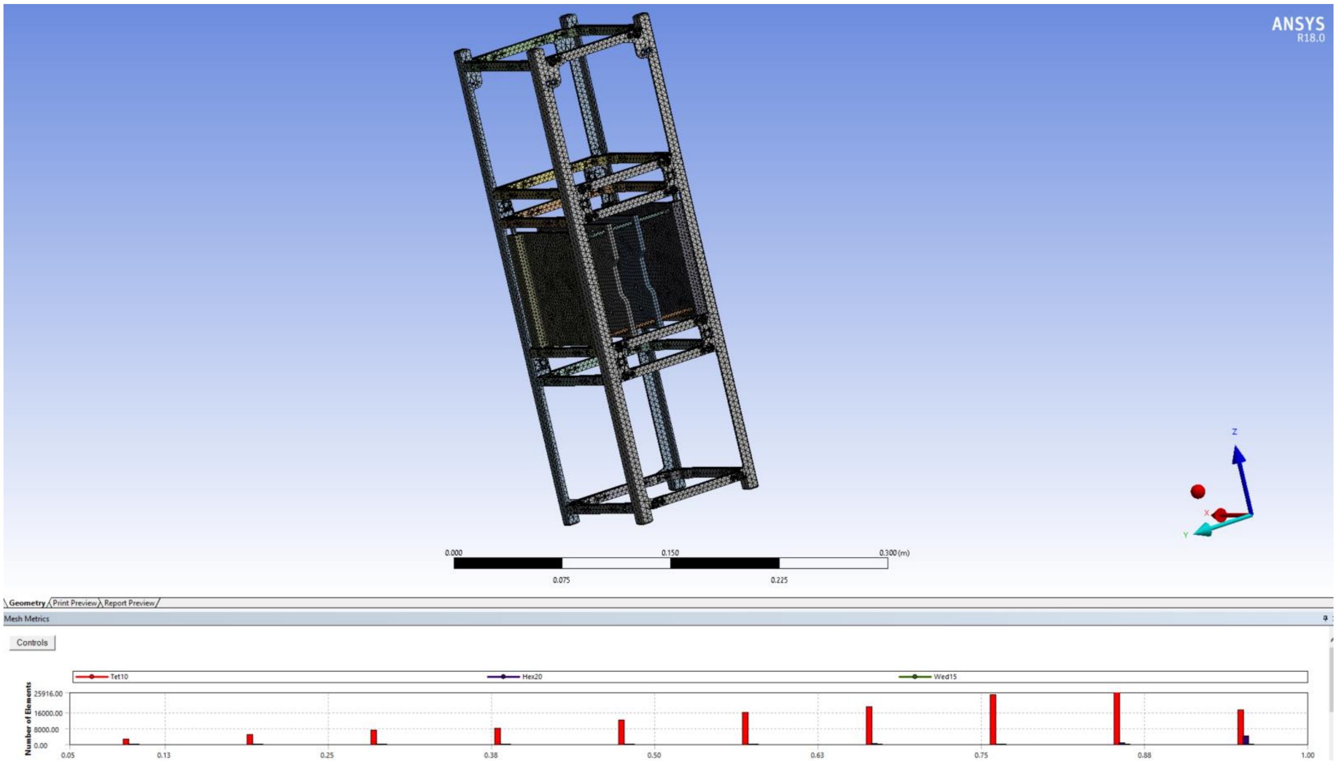


Figure 3: Mesh

Acceleration Loading Conditions

Each acceleration load was required to be applied independently of the others (UNP 10-4). Therefore, the structural analysis needed to be divided into three parts: one for x-axis acceleration loading, one for y-axis acceleration loading, and one for z-axis acceleration loading. Note that the assembly and mesh pictured above were used in all three analyses. In each of the three analyses, 30 G's, or 294.3 m/s^2, was applied through the center of mass on each separate axis (From UNP10-4). The loading conditions, as applied to the assembly in Ansys Static Structural, are pictured below.

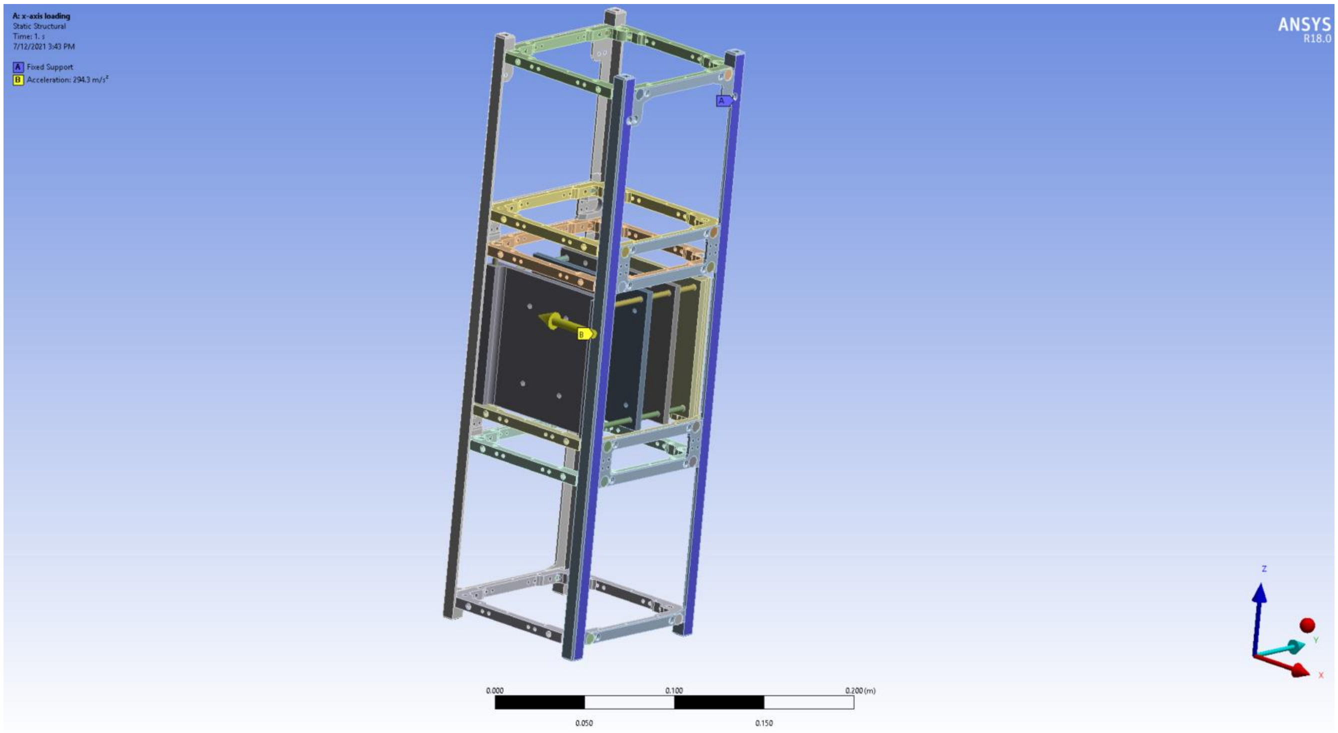


Figure 4: Loading Conditions for X-Axis Structural Analysis

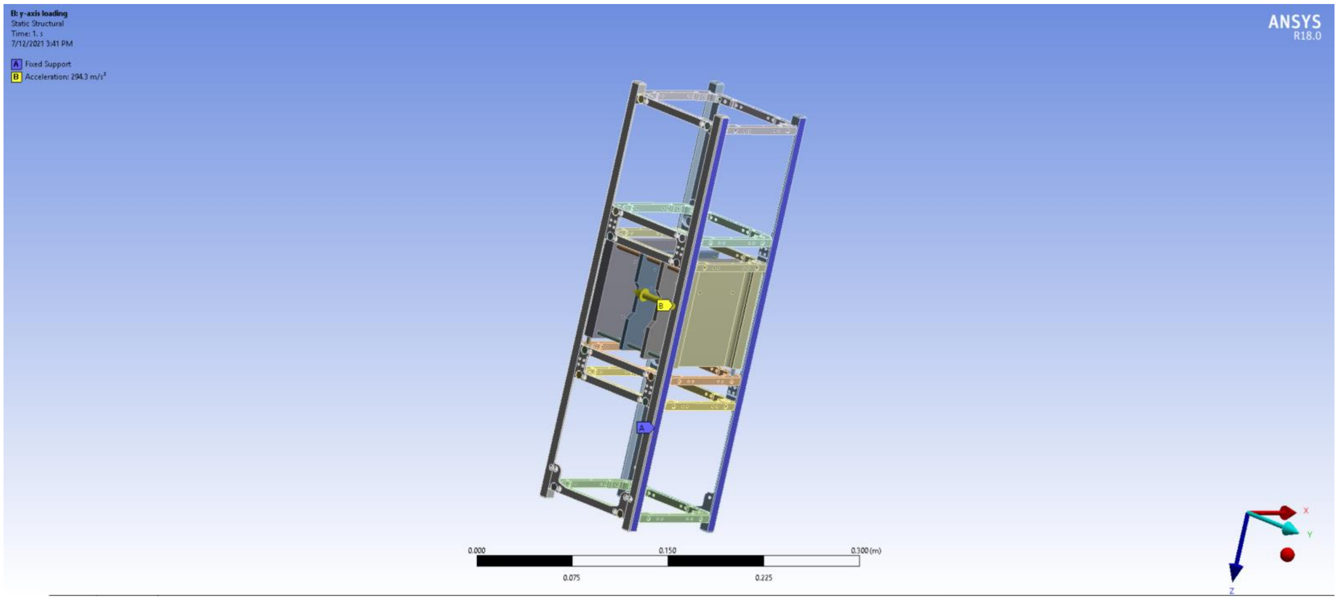


Figure 5: Loading Conditions for Y-Axis Structural Analysis

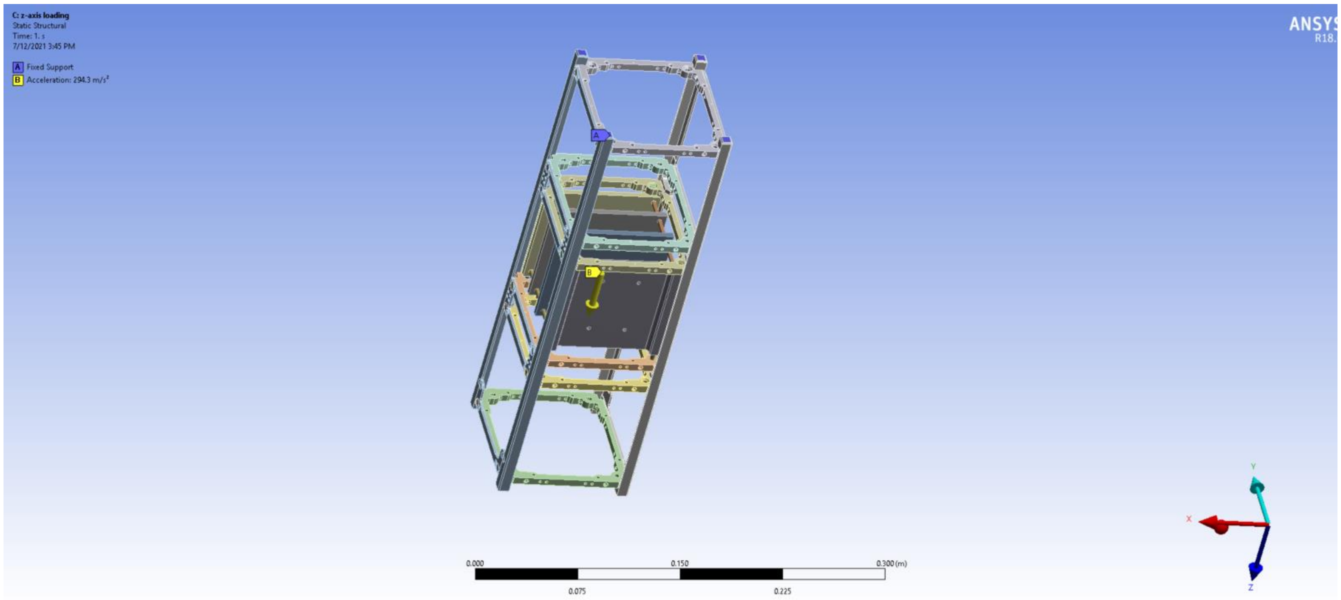


Figure 6: Loading Conditions for Z-Axis Structural Analysis

Acceleration Loading Results

The loading conditions pictured above caused the stress and deformation that are represented in the figures below. Note that the deformation is exaggerated by a factor of about 1000-2000 for emphasis. With a true scale there is no visible deformation due to the acceleration loading. During x-axis acceleration loading, the max equivalent stress was 42.309 MPa. During y-axis acceleration loading, the max equivalent stress was 22.008 MPa. During z-axis acceleration loading, the max equivalent stress was 37.112 MPa. Because the yield strength of Aluminum 6061 (241 MPa [1]) is well above any induced stress, it can be concluded that the acceleration loading through the primary axes will not compromise the OMEN structure, especially because 30G's is likely an over estimation of the acceleration loading. Note also that the maximum stresses mentioned above occurred only in small areas in the assembly, often in the secondary structure rods.

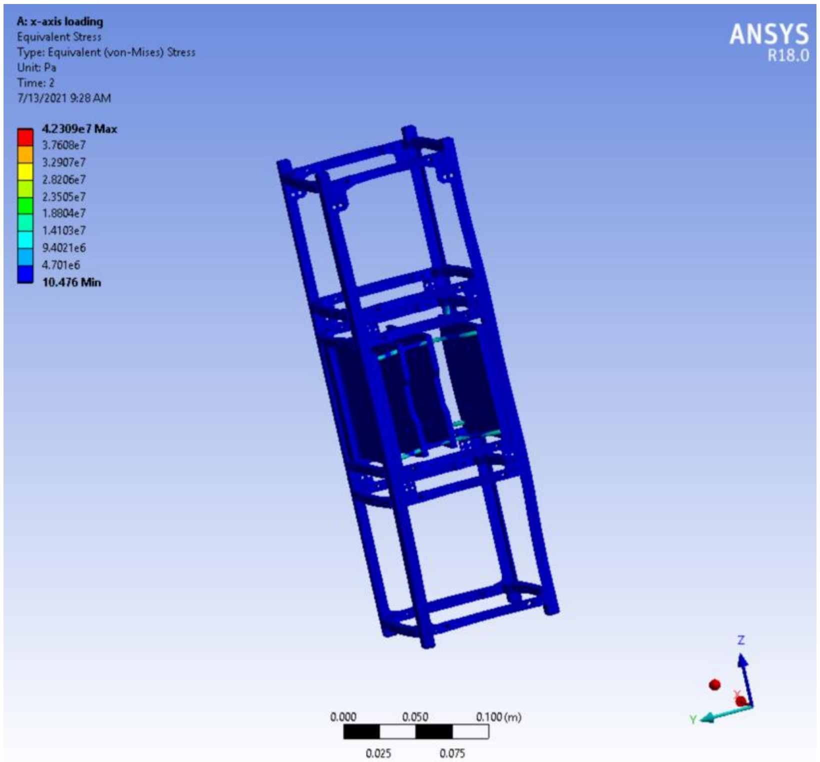


Figure 7: Equivalent Stress During X-Axis Acceleration Loading

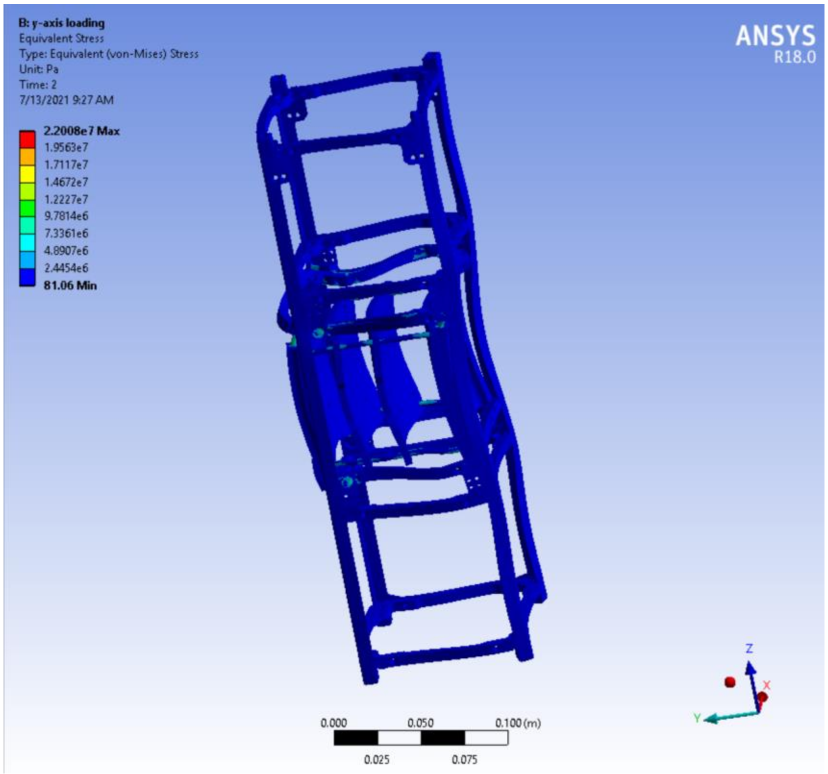


Figure 8: Equivalent Stress During Y-Axis Acceleration Loading

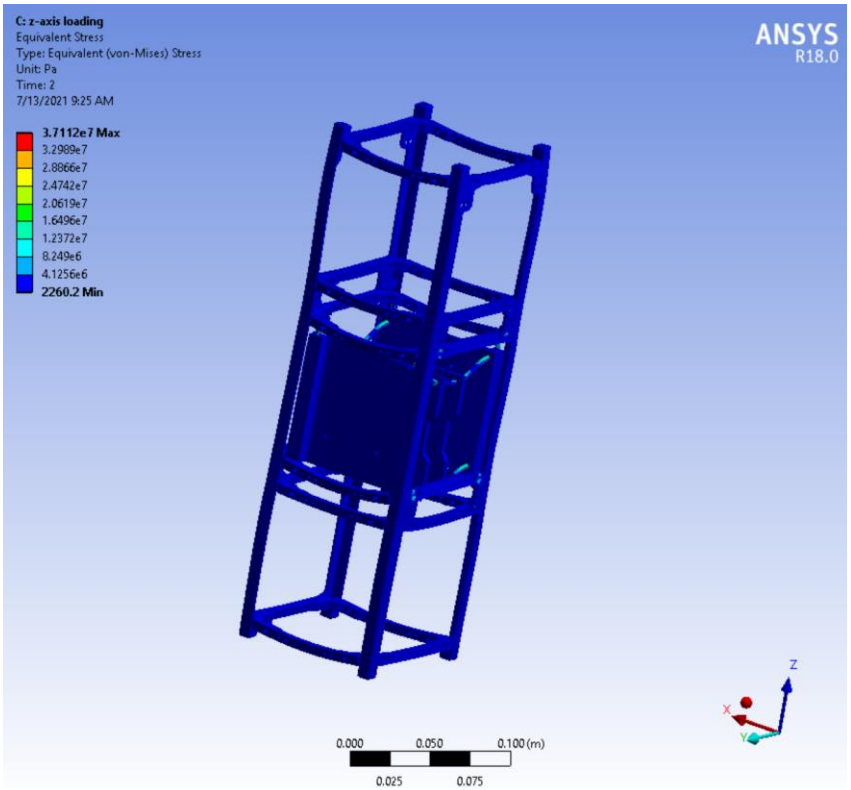
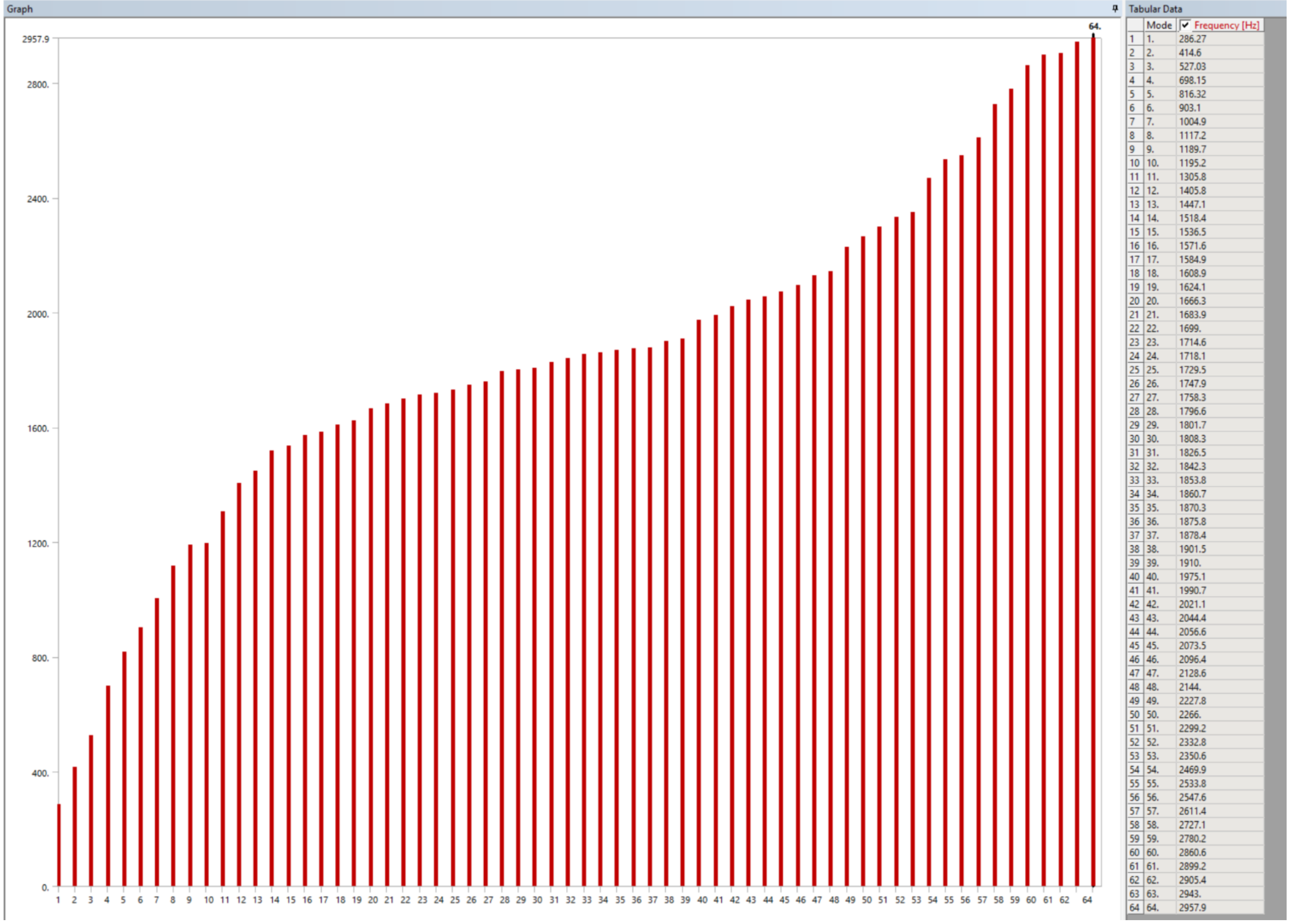


Figure 9: Equivalent Stress During Z-Axis Acceleration Loading

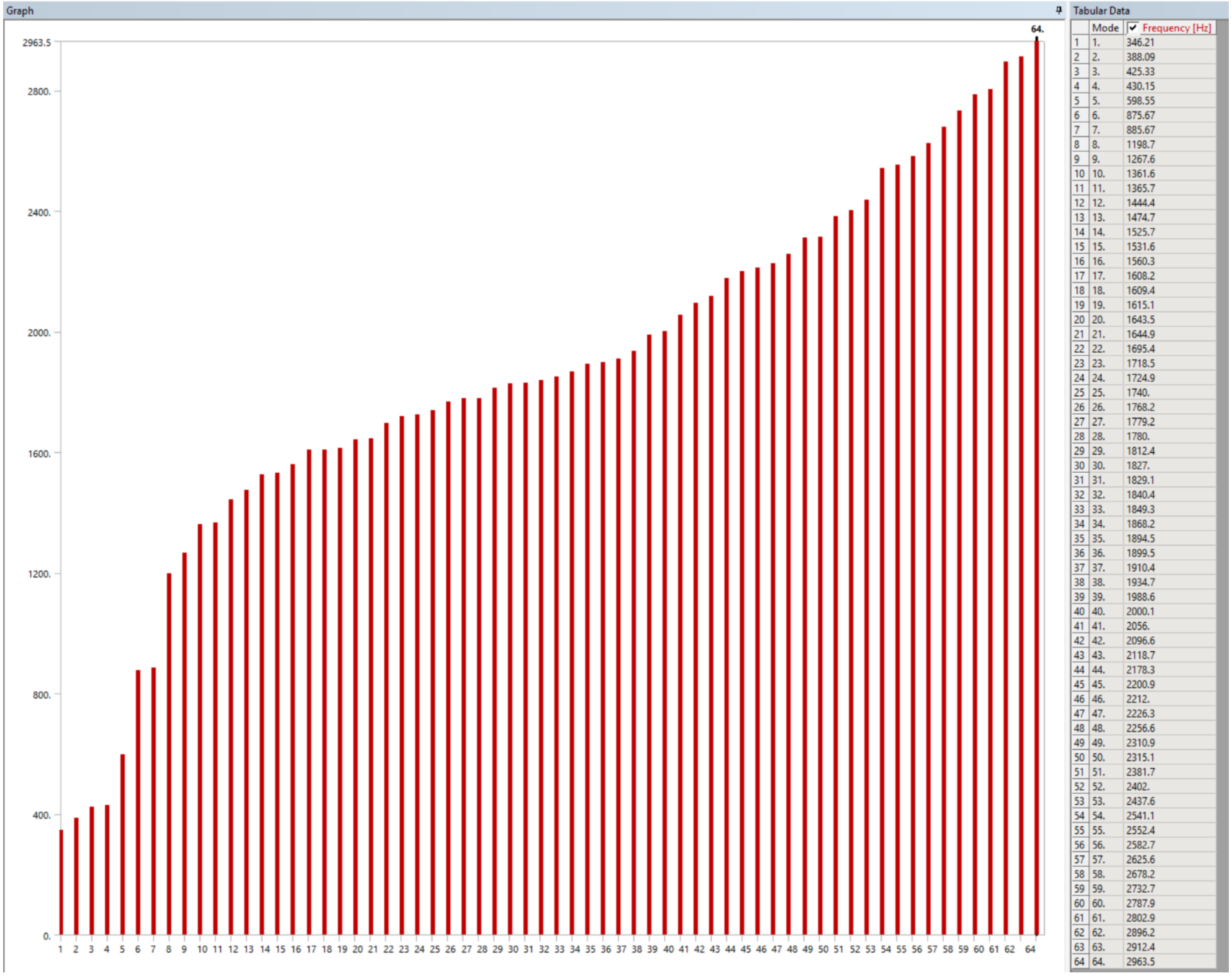
Modal Analysis

The lowest natural frequencies of the structure under each of the three acceleration loading conditions were found using the Ansys Modal Analysis tool. The frequencies as well as their associated mode number are shown in the figures below. Note that the modes for each natural frequency were found during analysis, but images of the modes will not be included in this document for the sake of brevity.



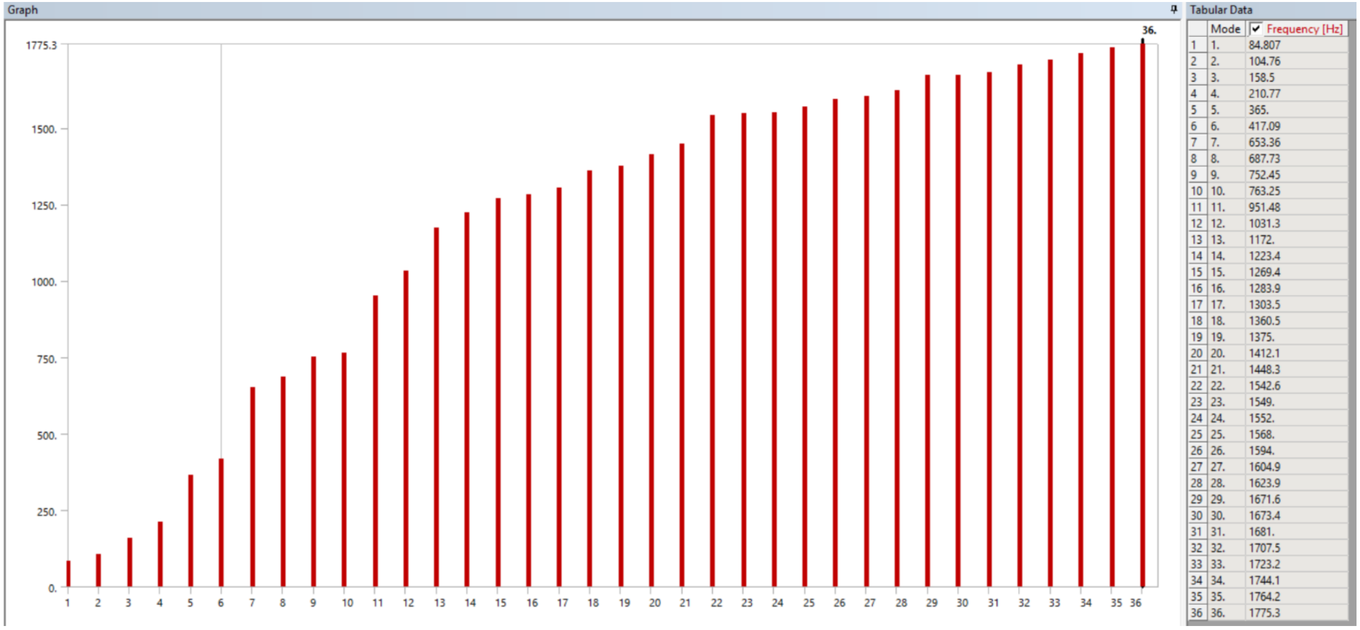
	Mode	☑ Frequency [Hz]
1	1.	286.27
2	2.	414.6
3	3.	527.03
4	4.	698.15
5	5.	816.32
6	6.	903.1
7	7.	1004.9
8	8.	1117.2
9	9.	1189.7
10	10.	1195.2
11	11.	1305.8
12	12.	1405.8
13	13.	1447.1
14	14.	1518.4
15	15.	1536.5
16	16.	1571.6
17	17.	1584.9
18	18.	1608.9
19	19.	1624.1
20	20.	1666.3
21	21.	1683.9
22	22.	1699.
23	23.	1714.6
24	24.	1718.1
25	25.	1729.5
26	26.	1747.9
27	27.	1758.3
28	28.	1796.6
29	29.	1801.7
30	30.	1808.3
31	31.	1826.5
32	32.	1842.3
33	33.	1853.8
34	34.	1860.7
35	35.	1870.3
36	36.	1875.8
37	37.	1878.4
38	38.	1901.5
39	39.	1910.
40	40.	1975.1
41	41.	1990.7
42	42.	2021.1
43	43.	2044.4
44	44.	2056.6
45	45.	2073.5
46	46.	2096.4
47	47.	2128.6
48	48.	2144.
49	49.	2227.8
50	50.	2266.
51	51.	2299.2
52	52.	2332.8
53	53.	2350.6
54	54.	2469.9
55	55.	2533.8
56	56.	2547.6
57	57.	2611.4
58	58.	2727.1
59	59.	2780.2
60	60.	2860.6
61	61.	2899.2
62	62.	2905.4
63	63.	2943.
64	64.	2957.9

Figure 10: Natural Frequencies and Modes during X-Axis Acceleration Loading



	Mode	☑ Frequency [Hz]
1	1.	346.21
2	2.	388.09
3	3.	425.33
4	4.	430.15
5	5.	598.55
6	6.	875.67
7	7.	885.67
8	8.	1198.7
9	9.	1267.6
10	10.	1361.6
11	11.	1365.7
12	12.	1444.4
13	13.	1474.7
14	14.	1525.7
15	15.	1531.6
16	16.	1560.3
17	17.	1608.2
18	18.	1609.4
19	19.	1615.1
20	20.	1643.5
21	21.	1644.9
22	22.	1695.4
23	23.	1718.5
24	24.	1724.9
25	25.	1740.
26	26.	1768.2
27	27.	1779.2
28	28.	1780.
29	29.	1812.4
30	30.	1827.
31	31.	1829.1
32	32.	1840.4
33	33.	1849.3
34	34.	1868.2
35	35.	1894.5
36	36.	1899.5
37	37.	1910.4
38	38.	1934.7
39	39.	1988.6
40	40.	2000.1
41	41.	2056.
42	42.	2096.6
43	43.	2118.7
44	44.	2178.3
45	45.	2200.9
46	46.	2212.
47	47.	2226.3
48	48.	2256.6
49	49.	2310.9
50	50.	2315.1
51	51.	2381.7
52	52.	2402.
53	53.	2437.6
54	54.	2541.1
55	55.	2552.4
56	56.	2582.7
57	57.	2625.6
58	58.	2678.2
59	59.	2732.7
60	60.	2787.9
61	61.	2802.9
62	62.	2896.2
63	63.	2912.4
64	64.	2963.5

Figure 11: Natural Frequencies and Modes during Y-Axis Acceleration Loading



	Mode	☑ Frequency [Hz]
1	1.	84.807
2	2.	104.76
3	3.	158.5
4	4.	210.77
5	5.	365.
6	6.	417.09
7	7.	653.36
8	8.	687.73
9	9.	752.45
10	10.	763.25
11	11.	951.48
12	12.	1031.3
13	13.	1172.
14	14.	1223.4
15	15.	1269.4
16	16.	1283.9
17	17.	1303.5
18	18.	1360.5
19	19.	1375.
20	20.	1412.1
21	21.	1448.3
22	22.	1542.6
23	23.	1549.
24	24.	1552.
25	25.	1568.
26	26.	1594.
27	27.	1604.9
28	28.	1623.9
29	29.	1671.6
30	30.	1673.4
31	31.	1681.
32	32.	1707.5
33	33.	1723.2
34	34.	1744.1
35	35.	1764.2
36	36.	1775.3

Figure 12: Natural Frequencies and Modes during Z-Axis Acceleration Loading

Mass Participation Factor

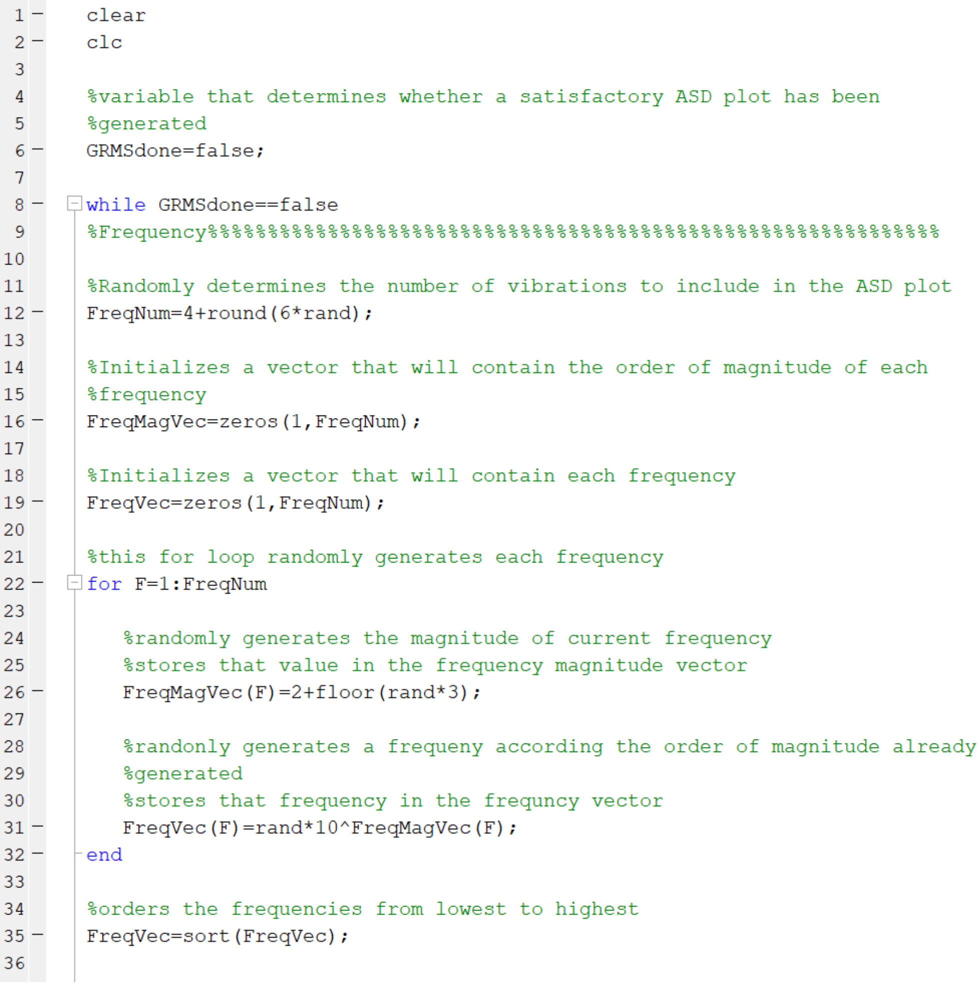
The vibrations induced by the natural frequencies displayed in the figures above yielded mass participation ratios that can be seen in the table below. Because the ratios of the effective mass (the sum of the mass associated with each mode) to the total mass are close to 1, enough modes have been extracted. A common standard for a modal analysis mass ratio is 0.9 or higher, which this test for the most part did not meet. As with other trade-offs in this analysis, this comprise was made to reduce solution time. Lastly, only 36 modes were extracted for the z-axis acceleration loading, as the mass participation factors during that analysis were near 0.9, so 36 modes were deemed sufficient.

Loading Conditions	***Direction***	***Ratio of effective mass to total mass***
X-axis acceleration loading	*x*	*0.733*
	y	*0.811*
	z	*0.819*
Y-axis acceleration loading	*x*	*0.850*
	y	*0.686*
	z	*0.857*
Z-axis acceleration loading	*x*	*0.941*
	y	*0.933*
	z	*0.886*

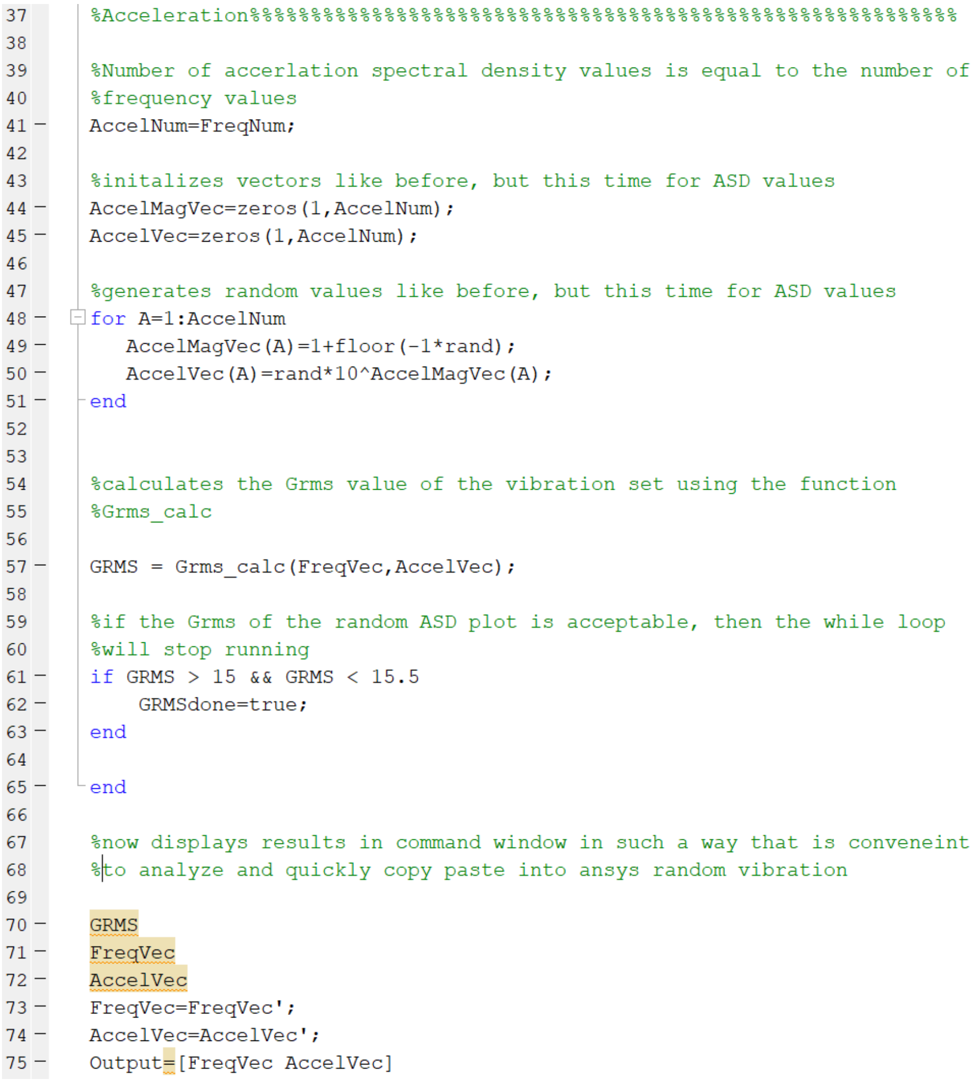
Figure 13: Participation Factor Summary Table

RANDOM VIBRATION

Requirement UNP10-5 states that the cube satellite should be designed to withstand a 15 Grms vibroacoustic environment. Because there is no one unique set of vibrations that create such an environment, it was determined that a set of acceleration spectral density (ASD) plots should be randomly generated and used during the random vibration analysis. Such a method reduced bias. The MATLAB script pictured below was used to generate the random ASD plots. The code randomly generates a set of frequencies as well as associated acceleration spectral densities. It then calculates the root mean square acceleration of the set of vibrations. If the Grms value is between 15 and 15.5, the code will output the random ASD plot. If the Grms value is not satisfactory, the code will continue generating ASD plots until one has an appropriate Grms value.



```
clear
clc

%variable that determines whether a satisfactory ASD plot has been
%generated
GRMSdone=false;

while GRMSdone==false
%Frequency%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Randomly determines the number of vibrations to include in the ASD plot
FreqNum=4+round(6*rand);

%Initializes a vector that will contain the order of magnitude of each
%frequency
FreqMagVec=zeros(1,FreqNum);

%Initializes a vector that will contain each frequency
FreqVec=zeros(1,FreqNum);

%this for loop randomly generates each frequency
for F=1:FreqNum

   %randomly generates the magnitude of current frequency
   %stores that value in the frequency magnitude vector
   FreqMagVec(F)=2+floor(rand*3);

   %randonly generates a frequeny according the order of magnitude already
   %generated
   %stores that frequency in the frequncy vector
   FreqVec(F)=rand*10^FreqMagVec(F);
end

%orders the frequencies from lowest to highest
FreqVec=sort(FreqVec);

```



```
%Acceleration%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Number of accerlation spectral density values is equal to the number of
%frequency values
AccelNum=FreqNum;

%initalizes vectors like before, but this time for ASD values
AccelMagVec=zeros(1,AccelNum);
AccelVec=zeros(1,AccelNum);

%generates random values like before, but this time for ASD values
for A=1:AccelNum
   AccelMagVec(A)=1+floor(-1*rand);
   AccelVec(A)=rand*10^AccelMagVec(A);
end


%calculates the Grms value of the vibration set using the function
%Grms_calc

GRMS = Grms_calc(FreqVec,AccelVec);

%if the Grms of the random ASD plot is acceptable, then the while loop
%will stop running
if GRMS > 15 && GRMS < 15.5
    GRMSdone=true;
end

end

%now displays results in command window in such a way that is conveneint
%to analyze and quickly copy paste into ansys random vibration

GRMS
FreqVec
AccelVec
FreqVec=FreqVec';
AccelVec=AccelVec';
Output=[FreqVec AccelVec]
```

Figure 14: Random ASD Generator Code

Random Acceleration Spectral Density Plots

The code pictured above was used to randomly generate the frequency sets pictured below.

Vibration Group 1		Vibration Group 2		Vibration Group 3		Vibration Group 4		Vibration Group 5		Vibration Group 6	
Frequency (Hz)	ASD (g^2/ Hz)	Frequency (Hz)	ASD (g^2/ Hz)	Frequency (Hz)	ASD (g^2/ Hz)	Frequency (Hz)	ASD (g^2/ Hz)	Frequency (Hz)	ASD (g^2/ Hz)	Frequency (Hz)	ASD (g^2/ Hz)
57.694	0.0351	25.024	0.1218	70.815	0.8492	22.304	0.0989	34.7	0.0395	90.906	0.2786
88.908	0.6050	30.580	0.8388	105.70	0.3382	29.352	0.3668	97.897	0.0317	795.32	0.0600
98.637	0.3937	97.298	0.5814	445.35	0.4874	61.915	0.8102	320.81	0.1093	938.76	0.3402
935.26	0.0324	389.47	0.2448	547.51	0.9418	188.63	0.7657	469.07	0.1471	2676.9	0.0143
1525.7	0.7006	706.70	0.2727			456.32	0.0345	1867.9	0.0727		
						2486.2	0.0188	3000.6	0.0411		
						2730.4	0.1424				

Figure 15: Random ASD Data Generated

Random Vibration Loading Conditions

The vibration groups were applied independently to the assembly while it was undergoing each acceleration loading condition. That made for a total of 18 random vibration analyses, six per each acceleration loading condition. In each analysis, the vibrations were applied in the same direction as the direction of acceleration. It was determined that this would most accurately represent launch conditions.

Random Vibration Results

To reiterate, a total of 18 different loading condition combinations were applied to the structure during this test: 3 different acceleration loads along with 6 different random vibration loads. Furthermore, within each loading combination, the stress within the primary structure and secondary was analyzed independently. Therefore, for the sake of brevity, tables summarizing the results are included instead of images that show the stress throughout a body.

X-Axis Acceleration and Vibration Loading			
	Primary Structure (Aluminum)	Secondary Structure Plates (Aluminum)	Secondary Structure Rods (Aluminum)
Maximum Stress from Vibration Group 1 (MPa)	59.593	64.502	109.15
Maximum Stress from Vibration Group 2 (MPa)	51.109	36.647	70.089
Maximum Stress from Vibration Group 3 (MPa)	24.737	26.219	47.903
Maximum Stress from Vibration Group 4 (MPa)	45.764	54.778	94.111
Maximum Stress from Vibration Group 5 (MPa)	84.017	104.67	176.56
Maximum Stress from Vibration Group 6 (MPa)	70.409	92.867	157.18
Yield Strength (MPa)	241	241	241

Figure 16: X-Axis Vibration Loading Results

Y-Axis Acceleration and Vibration Loading			
	Primary Structure (Aluminum)	Secondary Structure Plates (Aluminum)	Secondary Structure Rods (Aluminum)
Maximum Stress from Vibration Group 1 (MPa)	72.338	82.835	106.27

Maximum Stress from Vibration Group 2 (MPa)	10.433	11.733	13.666
Maximum Stress from Vibration Group 3 (MPa)	10.296	11.568	35.744
Maximum Stress from Vibration Group 4 (MPa)	30.195	34.613	44.561
Maximum Stress from Vibration Group 5 (MPa)	56.322	64.631	83.778
Maximum Stress from Vibration Group 6 (MPa)	86.822	119.29	227.10
Yield Strength (MPa)	241	241	241

Figure 17: Y-Axis Vibration Loading Results

Z-Axis Acceleration and Vibration Loading			
	Primary Structure (Aluminum)	Secondary Structure Plates (Aluminum)	Secondary Structure Rods (Aluminum)
Maximum Stress from Vibration Group 1 (MPa)	60.279	73.854	158.74
Maximum Stress from Vibration Group 2 (MPa)	44.768	51.832	127.69
Maximum Stress from Vibration Group 3 (MPa)	20.902	19.939	50.873
Maximum Stress from Vibration Group 4 (MPa)	44.145	53.552	120.16
Maximum Stress from Vibration Group 5 (MPa)	83.878	104.31	233.55
Maximum Stress from Vibration Group 6 (MPa)	65.641	83.911	185.91
Yield Strength (MPa)	241	241	241

Figure 18: Z-Axis Vibration Loading Results

The stresses that occurred in the primary structure and secondary structure plates were all relatively minor; none of these stresses resulted in a factor of safety below two, and most of these safety factors were much higher. The stress experienced by the secondary structure rods was more substantial, but it was never as high as the yield strength of aluminum 6061, 241 MPa [1]. Therefore, the factor of safety was always greater than one in the Secondary Structure Rods.

Random Vibration Image Result Example

Three images are included in addition to the tables to give an example of the image results. The images are from vibration group 4 being applied to the structure under y-axis acceleration loading. Note that the tables only include the maximum stress experienced by the specified group of bodies. As can been seen in the example images below, these maximum stress values only occur in small pockets in the primary structure and the secondary structure plates, and a vast majority of these bodies are in a much lower stress state. However, the stress distribution in the secondary structure rods is more varied. In the other 17 combinations of acceleration and vibration loading conditions, stress was distributed among the assembly bodies in a comparable way.

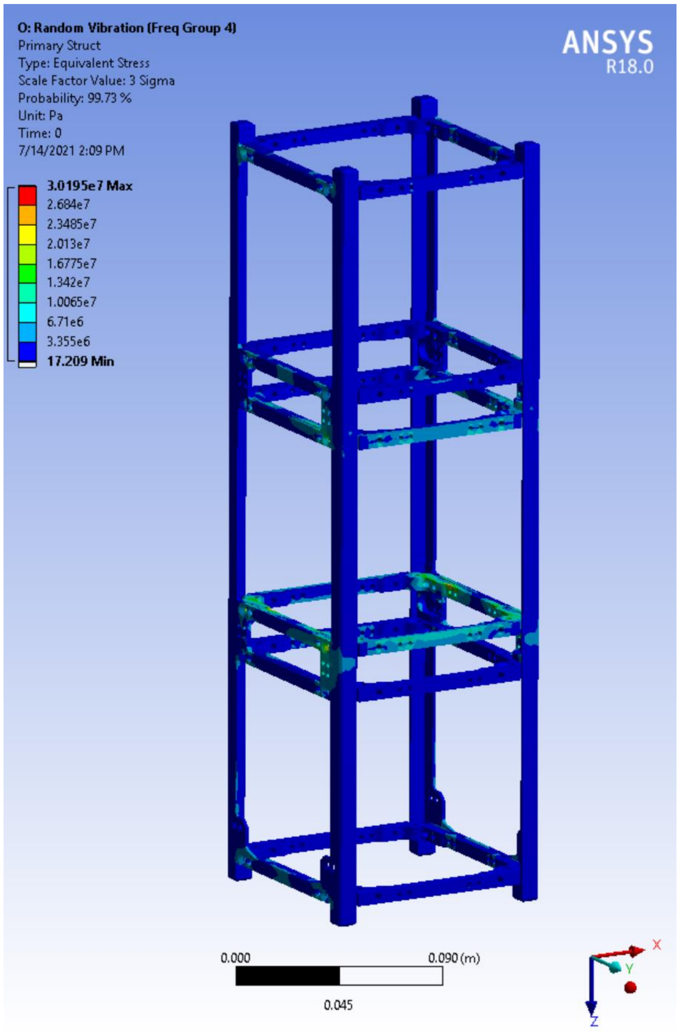


Figure 19: Example Primary Structure Vibration Loading Results

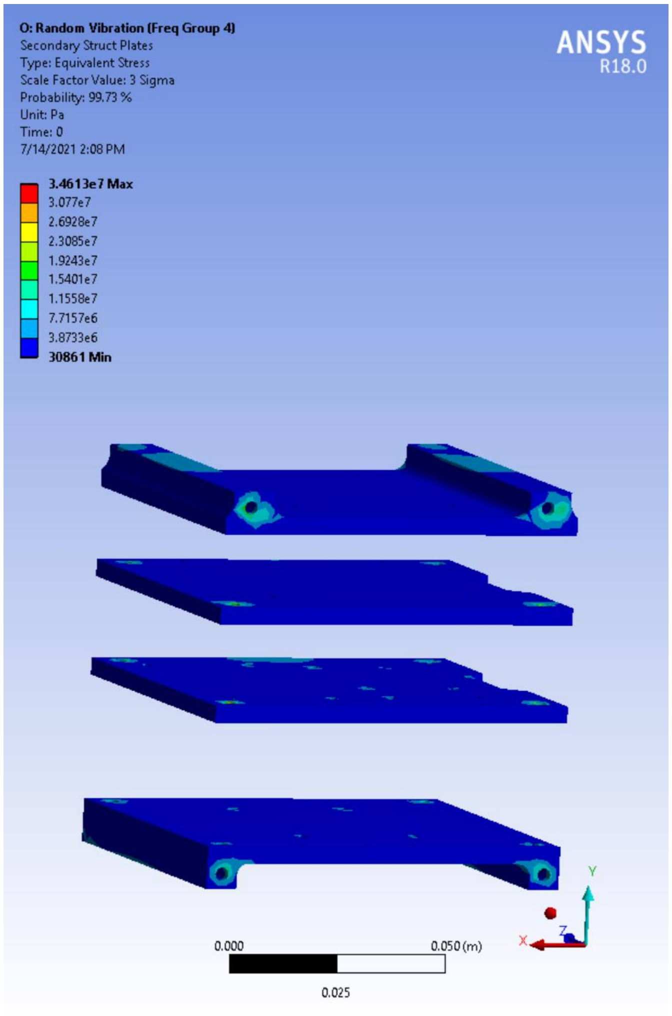


Figure 20 Example Secondary Structure Plates Vibration Loading Results

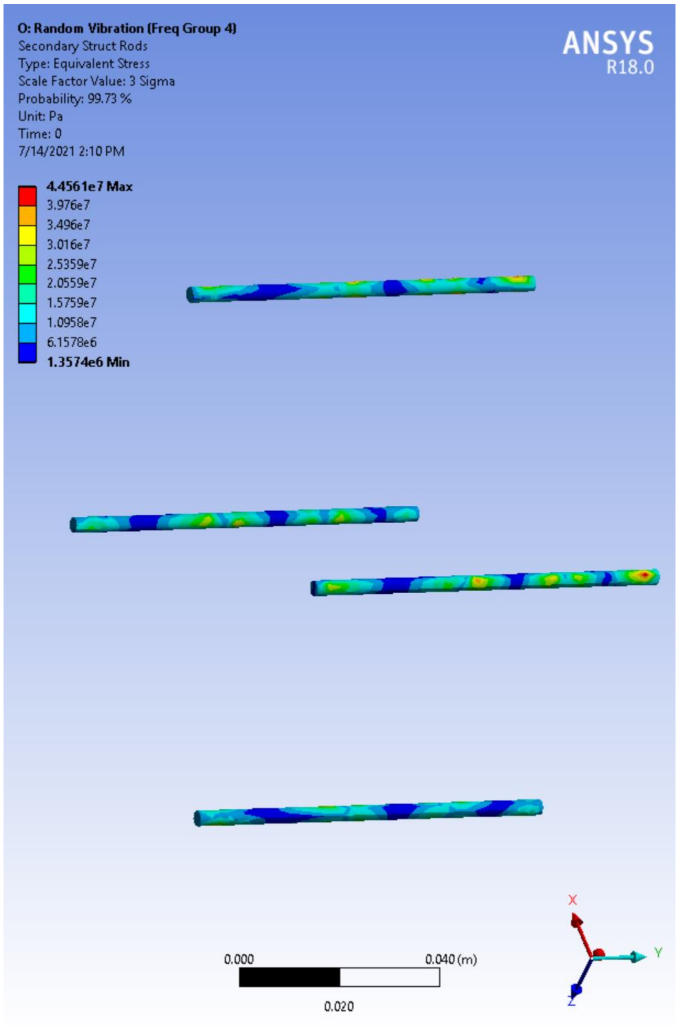


Figure 21: Example Secondary Structure Rods Vibration Loading Results

Conclusion

Because all the vibration loads experienced by the primary and secondary structure induced stresses less than the yield strength of aluminum 6061, it can be concluded that the structure will not fail when exposed to a combination of acceleration and vibration loading. Such a conclusion has extra certainty because many different loading condition combinations were tested, and relatively high stresses (those that yield a factor of safety less than two) occurred infrequently. Most stresses were well below the yield strength of the structure. Lastly, both the acceleration and vibration loads in this test are deemed to be extreme conditions that the cube satellite will likely never experience. If minor changes were to be made to the structure, the secondary structure rods could be made thicker, as those components experienced the most severe stress states.

Bibliography

[1] “Aluminum Alloys - Mechanical Properties.” Engineering ToolBox, www.engineeringtoolbox.com/properties-aluminum-pipe-d_1340.html.