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`Finite Element Analysis for a CubeSat Mounted on the International Space Station

by

Zachary Lee Burkhardt

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Date

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Abstract

A finite element model (FEM) was created of ACES RED, an International Space Station (ISS) mounted CubeSat being developed by the U.S. Army's Space and Missile Defense Command (SMDC). The finite element model was used to evaluate the response of the CubeSat's structure to a variety of loads. The results of this analysis demonstrated that the CubeSat would comply with all mission requirements that could be verified using the finite element method, including ISS applied force restrictions and launch loads. However, analysis of reaction wheel induced vibrations was determined to be impossible without experimental testing and prediction of workmanship vibration testing was found to be infeasible using the available finite element software.

Introduction

SMDC is developing a CubeSat called ACES RED. The goal of ACES RED is to demonstrate and test the functionality of technologies being considered for wider use by SMDC. Figure 1 shows the CubeSat with a transparent surface to allow the interior to be viewed. This CubeSat will be mounted to the outside of the ISS and must comply with requirements created by the ISS program to ensure the safety of the astronaut on board. Additionally, the CubeSat may experience hazards related to extravehicular activities (EVAs) conducted in its vicinity.

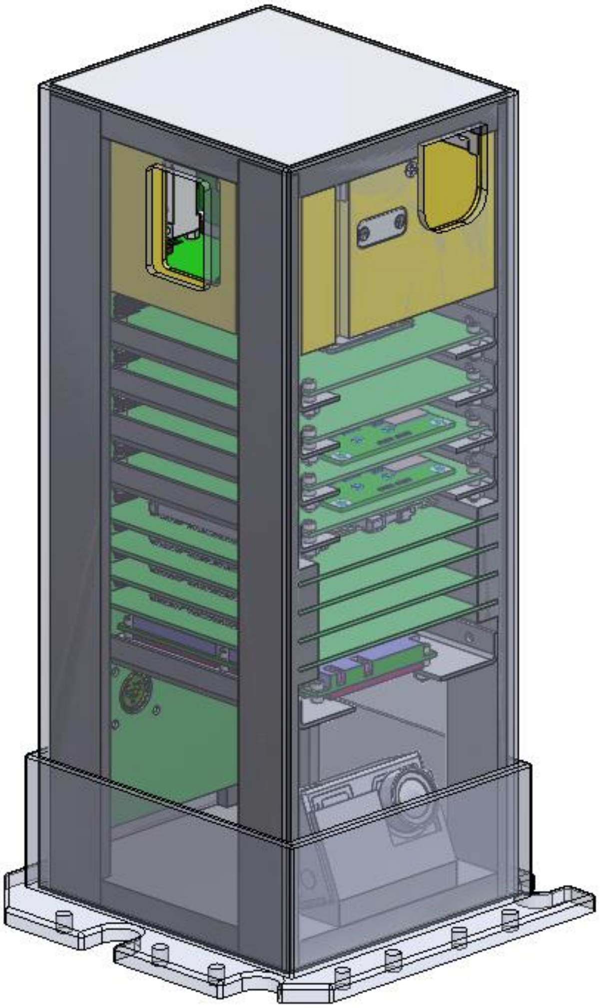

Figure 1: ACES RED CAD Model

SMDC requested the creation of a finite element model to demonstrate that ACES RED complied with its structural requirements and that it would survive all loads encountered during its mission. Table 1 shows the analyses requested by SMDC.

Table 1: FEA Objectives

Number	Analysis Objective
1	Show that the CubeSat will apply an impulse of no greater than 44 N*s to the ISS over any 10 second period.
2	Show the frequency response of the CubeSat to ADCS induced vibrations.
3	Show that the CubeSat will not apply a force of greater than 4448 N to the ISS at any time.
4	Calculate natural frequency data for the workmanship vibration testing to be conducted on the CubeSat. This testing will use vibrations of 0.25 g magnitude following a frequency sweep from 20 Hz to 2000 Hz.
5	Predict the results of the vibration testing.
6	Show that the CubeSat will survive loads experienced during launch. These loads are described in Appendix B.
7	Show that the CubeSat will withstand all loads experienced while attached to the ISS.
8	Create high quality renderings of the CubeSat.

To perform these analyses, a model of the CubeSat structure was created in Patran. Patran is a software package developed by MSC that allows for the creation of models to be analyzed with Nastran, the program which actually conducts the finite element analysis (FEA). The analysis was conducted based on a variety of load magnitudes and locations that the CubeSat could encounter.

Background

ISS and CubeSats

A CubeSat is a small satellite made up over one or more 10x10x10 cm cubic units. CubeSats are generally designed and intended to be launched as secondary payloads on rocket launches with other primary purposes. This allows for significant savings on the cost of launching a satellite, allowing a wide variety of organizations access to space at a much lower price point. This also makes CubeSats ideal for testing new technologies in space because the low cost reduces the financial risk of the project (Lee et al. 2014, 5).

Recently, the International Space Station (ISS) has become involved with numerous CubeSat projects. Two systems have been installed to deploy CubeSats into orbit from within the space station, the NanoRacks CubeSat Deployer and the Japanese Experiment Module Small Satellite Orbital Deployer. Many CubeSat projects have begun to favor this method because it is more reliable than previous deployment methods. ACES RED is the first CubeSat designed to be attached to the outside of the ISS, rather than deployed using one of these deployment systems.

The need to protect the crew of ISS necessitates additional safety requirements with which any ISS related CubeSat project must comply. These requirements are designed to protect the crew from any harmful exposure related to the materials used in the CubeSat (Kelley 2015, 3). While the ACES RED CubeSat is not using any of these deployment systems, it must still meet these requirements to ensure crew safety. Additionally, it must comply with a special set of requirements that applies to any object mounted to the outside of ISS. These requirements are intended to ensure that it can survive a variety of possible contacts with astronauts performing EVAs, and to ensure that it poses no risk to the structure of ISS or the operation of its control systems. A table summarizing some of these requirements can be found in Appendix A.

Spacecraft Systems

The design of a spacecraft is generally broken down into several subsystems. The primary subsystems of ACES RED that are of interest to this project are the structure and the attitude determination and control system (ADCS). The structure is responsible for holding the CubeSat together and protecting it from any forces experienced. On most satellites, the ADCS system is responsible for determining and controlling the orientation and position of the spacecraft. Because ACES RED will be fixed in place on the ISS, the ADCS will exert loads upon it that the structure must be able to withstand (Brown 2003). The inner structure of ACES RED without the outer casing is shown in Figure 2.

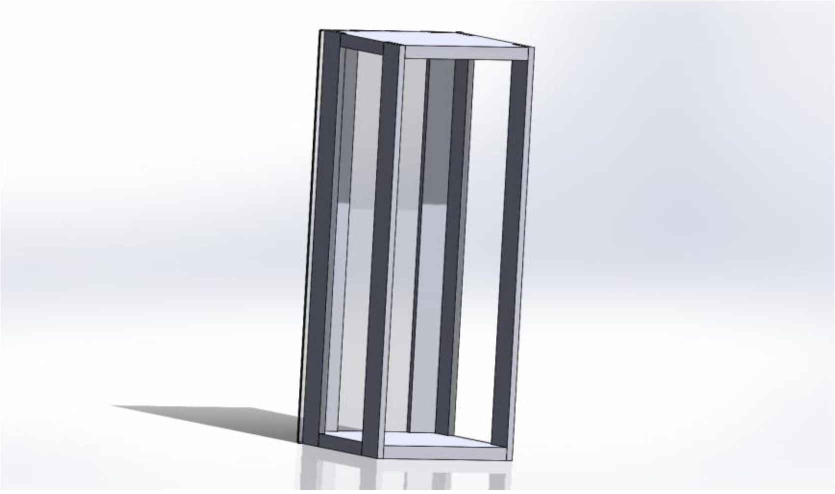

Figure 2: Internal Structure of ACES RED

U.S. Army Space and Missile Defense Command (SMDC)

SMDC has existed since 1985, although it has undergone several name changes since then. The goal of SMDC is to develop countermeasures to missile weaponry and to use space technologies to provide support to the Army's ground operations (Hubbs 2007, 1). Despite this goal, SMDC did not begin developing their own satellites until 2010. Since then, SMDC has designed 11 CubeSats and put them into orbit. They are currently developing several additional satellites to be completed within the next few years.

ACES RED Project

The ACES RED project is one of these ongoing developments. ACES RED stands for Army Cost Efficient Spaceflight Research Experiments and Demonstrations. The goal of the ACES RED program is to develop and flight test space technologies of interest to SMDC. One particular goal is the flight testing of the MAI-400 ADCS system that ACES RED has on board.

The CubeSat will be mounted to the outside of the international space station using 14 bolts. This configuration adds many requirements to the project, as it must not interfere with the operations or safety of ISS. Some of these requirements are described in Table 1 and in Appendix A (Johnson et al. 2016).

Finite Element Analysis

Finite element analysis (FEA) is a method used to analyze the mechanical behaviors of complex structures. FEA is conducted by creating a finite element model of a structure. The FEM breaks down the structure into nodes or grid points. These nodes are connected to make shapes called elements. Loads and constraints can then be applied to this model to simulate the response of the structure to physical conditions. The more nodes and elements used, the more accurate the calculated response; unfortunately, this also leads to significantly increased computational time.

Mathematically, FEA considers each element to have a spring like behavior. Each element has a stiffness matrix K defined by its material properties and geometry. This stiffness matrix is used to solve for the displacement vector of each node based on the applied force. This relationship is described by Equation 1, seen below.

$$\{u\} = [K]^{-1} * F \tag{1}$$

From the displacement of each node, stresses and strains can be calculated based on Hooke’s law. For any FEM that is not extremely simple, the solution of Equation 1 becomes nearly impossible to achieve by hand. Because of this many programs exist to implement FEA (Fikes August 2016). In this analysis, the programs Patran and Nastran developed by MSC were used.

Normal Modes

Normal modes describe the frequencies at which a system naturally oscillates. In the case of structures, the normal modes describe the natural frequencies at which vibrations propagate through the body. Knowledge of these modes can be important to understanding the transient response of the structure to any force or impact that induces vibrations. If a load that oscillates at the same frequency as one of the structure's normal modes is applied, vibrations could potentially create very high stresses in the structure. Because of this, it is important to be aware of the structure's normal modes. Nastran is able to calculate the normal modes of a structure using FEA (Fikes October 2016).

Analysis

Finite Element Model

A finite element model of the ACES RED CubeSat was constructed in Patran to attempt the analysis goals described in Table 1. To prevent errors from occurring within Patran and to speed computation, a simplified model of the CubeSat was created. All components without significant structural load bearing contributions were neglected. This left the outer shell of the CubeSat, the inner rails, the ISS attachment flange, and the top and bottom plates. The structure was treated as a hollow rectangular prism with two dimensional plates as each surface and the flange on the bottom with holes removed to represent the major gaps in the structure. This resulted in a FEM consisting of 6584 nodes and 6581 elements. All of the considered parts were made out of Aluminum-6061, so the material properties of Aluminum 6061 were defined. Two-dimensional plate properties were then given to the structure on a section by section basis with aluminum material properties; the thickness of the plate at a given location was taken to be the total combined thickness from the outer shell, rails, and flange at that location. This should be an accurate method for modeling the design as no significant gaps are projected to exist between the shell and the rails. Boundary conditions were applied to the bottom flange to represent the bolts attaching the CubeSat to the ISS. Additionally, all applied forces were modeled as applying at a single point. While this is not true in reality, it produces results that are more conservative and is simpler. The CubeSat is more likely to fail from these approximated loads than it would be from the real loads. Figure 3 shows the FEM of the CubeSat in Patran.

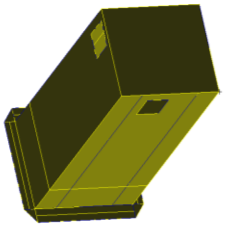

Figure 3: Simplified Patran Model

Normal Modes and Vibration

Analysis objectives 2, 4, and 5 shown on Table 1 were all related to vibrations and frequency responses of the system. To begin this analysis, the Patran FEM was used to determine the normal modes of the system. These modes are shown in Table 2 below.

Table 2: First 10 Normal Modes

Mode	f (Hz)
1	730.71
2	822.18
3	988.79
4	1517
5	1530.4
6	1584.3
7	1833.4
8	1907.5
9	2009.2
10	2075.6

Notably, the first eight normal modes of the CubeSat are below the maximum frequency that will be encountered in the random vibration test that the CubeSat must undergo. This could potentially indicate that the CubeSat will be damaged in the random vibration testing if the damping ratios for these modes are not high enough.

Unfortunately, the method that Nastran uses does not allow for computation of damping ratios for these modes. Similarly, a detailed prediction of the random vibration test proved impossible using Nastran as properly representing a vibration frequency of 2000 Hz requires over 4000 data points per second. Since a single data point requires files taking a total of 0.1 MB of space, a simulation of the vibration test would require 314.9 GB of data. Therefore, Patran is not suitable for vibration test simulation nor is any other program for which a license is available at UAH.

Analysis objective 2 from Table 1 could also not be completed. Vibrations induced by the ADCS system are a function of the manufacturing of the reaction wheels used in the system. No two reaction wheels will be the same (Liu 2008, 2). As such, it is impossible to model this without experimental data describing the wheels' actual performance. Since a test would be needed to gather such data in any case, it makes more sense to validate reaction wheel vibration related requirements experimentally.

EVA Loads

Analysis objective 7 from Table 1 deals with EVA loads. While mounted to the ISS, the CubeSat may come into contact with astronauts performing EVA. The astronauts may attempt to use the CubeSat as a hand hold or as a launching point for maneuvering. The CubeSat must be able to withstand these loads.

Astronaut Hand Hold

An astronaut could potentially grab the CubeSat to secure themselves. The CubeSat must not break or separate from the ISS if this occurs. Five different astronaut hold cases were modeled, one on the top surface, one on a corner, one on a side, and one on each of the holes in the CubeSat side panels. Each case used a net force of 200.17 N (45 lbf). The results of these analyses are shown in Table 3. Figure 4 is an example Patran plot of the stresses induced by a hand hold.

Table 3: EVA Astronaut Hold Results

Case	Max Stress (MPa)	Factor of Safety	Maximum Displacement (mm)
Hold Corner	7.04	71.44886364	0.0116
Hold Hole 2	21.0	23.95238095	0.0391
Hold Side	32.5	15.47692308	0.0742
Hold Top	13.4	37.53731343	0.00977

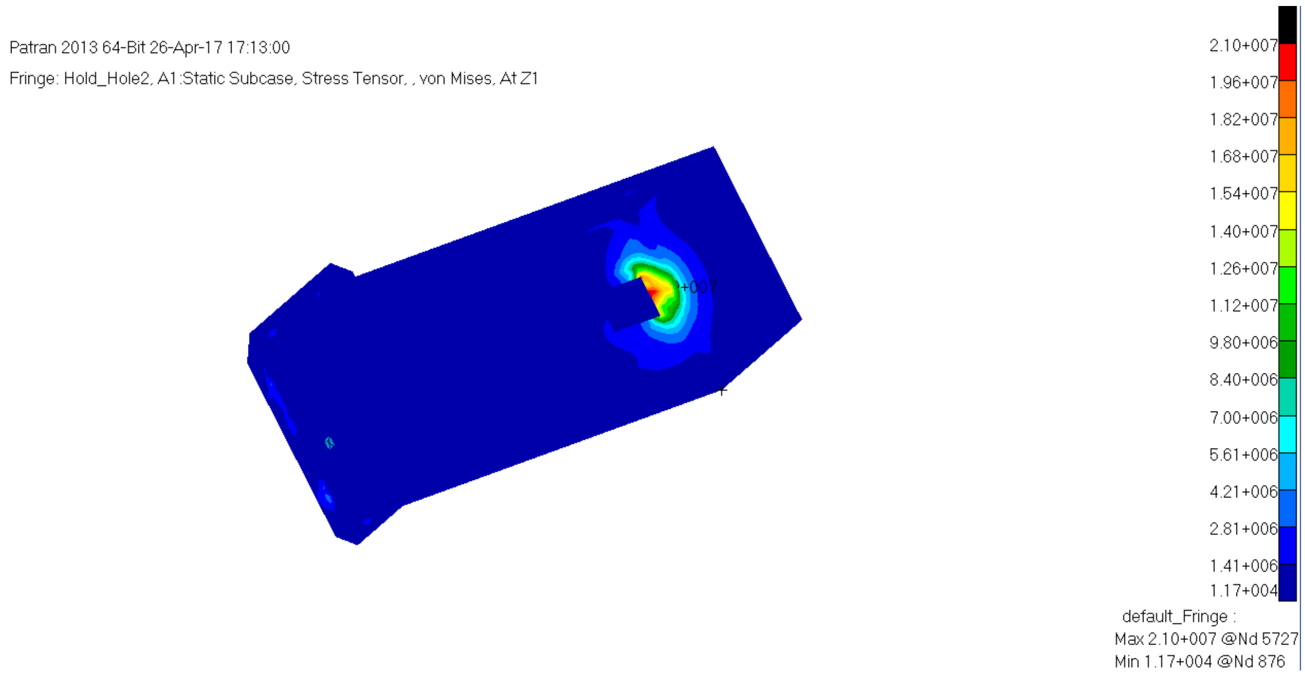

Figure 4: Hole Hold Stress Distribution

Factor of safety refers to the ratio of the yield stress of the material to the experienced stress. The yield stress of the aluminum used in ACES RED is 503 MPa. All of these load cases produce stresses well below the yield stress, indicating that the structure will survive these loads.

Astronaut Kick

An astronaut may kick the CubeSat to propel themselves away from it. This would be a much larger force than the previous cases; as seen in Appendix 1, the kick force is approximately 890 N (200 lbf). Three different kick cases were modeled, one at the top corner of the CubeSat, one on an edge near one of the holes, and one in the middle of one of the sides. The results of these analyses are shown in Table 4. Figure 5 is the Patran plot of the stresses induced by a side kick.

Table 4: EVA Kick Results

Case	Max Stress (MPa)	Factor of Safety	Maximum Displacement (mm)
EVA Kickoff Top Corner	23.9	21.0460251	0.0393
EVA Kickoff Edge	34.3	14.66472303	0.0565
EVA Kickoff Side	157	3.203821656	0.443

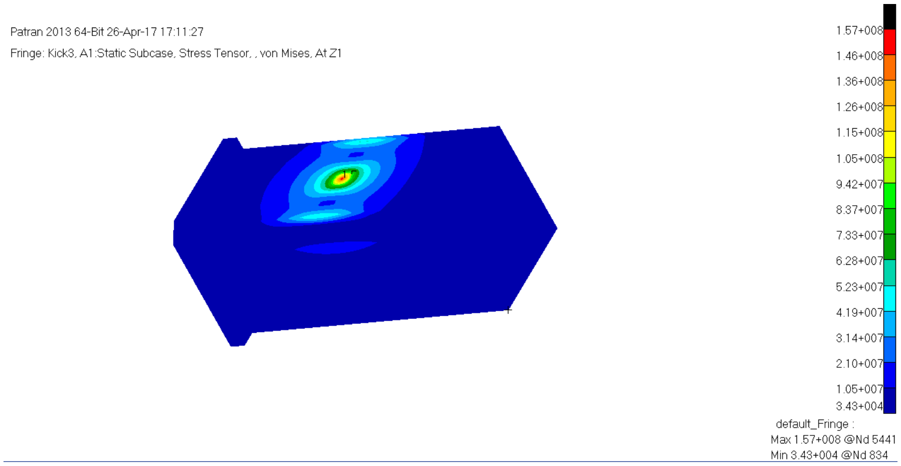

Figure 5: Side Kick Stress Distribution

Tool Impact

Another possible on-orbit hazard is an impact with a tool dropped by an astronaut. This would apply a force of 556 N (125 lbf). Five tool impact cases were modeled. The results of this are shown in Table 5. Figure 6 is a Patran plot of stresses resulting from a tool impact on the side of the CubeSat.

Table 5: Tool Impact Results

Case	Max Stress (MPa)	Factor of Safety	Maximum Displacement (mm)
Tool Impact Side	88.9	5.658042745	0.217
Tool Impact Side Edge	17.3	29.07514451	0.061
Tool Impact Side Bottom	67.3	7.473997028	0.147
Tool Impact Side Top	96.5	5.212435233	0.229
Tool Impact Top Edge	50.9	9.882121807	0.0717

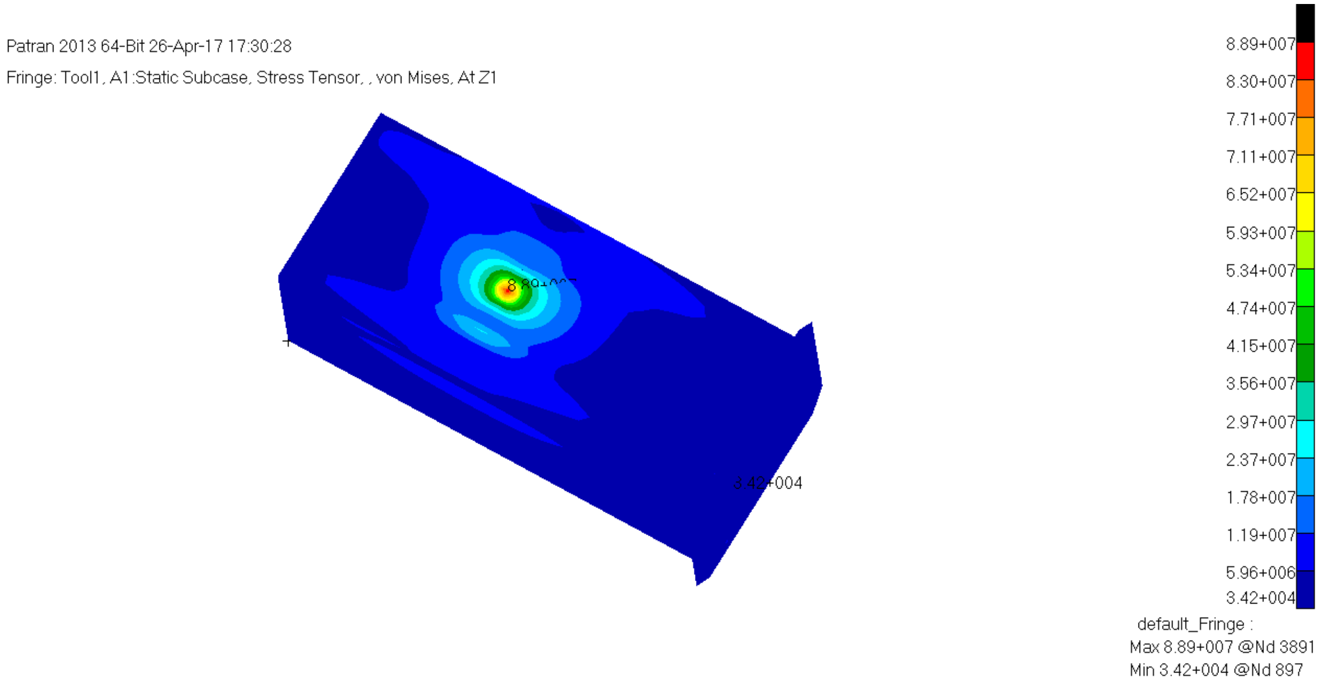

Figure 6: Side Tool Impact Stress Distribution

Launch Loads

The CubeSat will experience its highest loads during launch. For specific details on the magnitudes of these loads, see Appendix B. The launch loads were modeled as being distributed across the faces of the CubeSat that are aligned in the same direction as the load. This resulted in a maximum stress of 14 MPa and a maximum displacement of 0.0366 mm. This load case has a factor of safety of 35.9, indicating that the CubeSat is more than capable of surviving launch. The launch stress distribution given by Patran is shown in Figure 7.

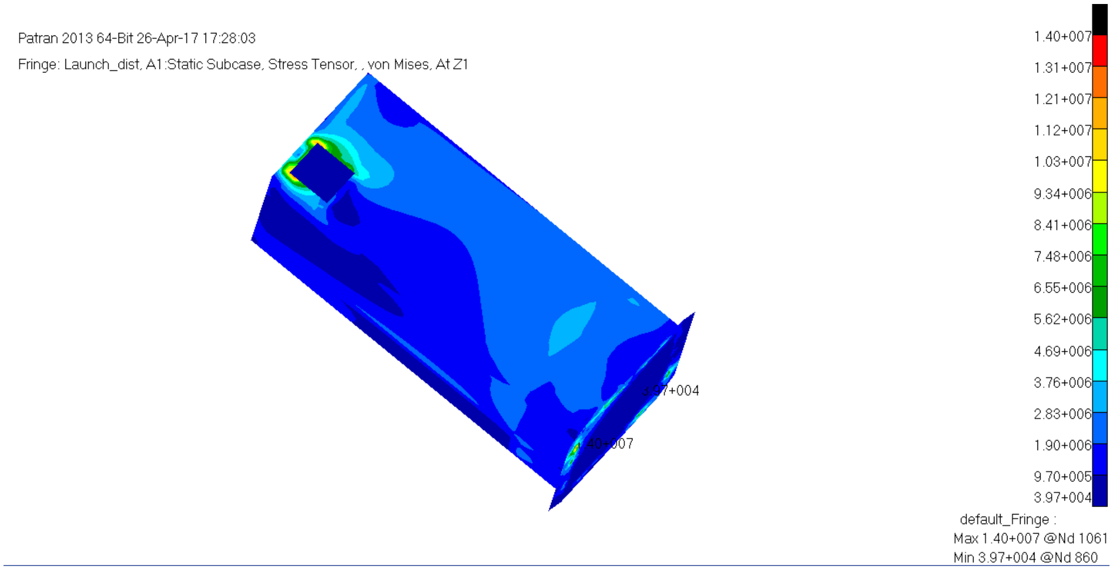

Figure 7: Launch Stress Distribution

ADCS Loads

The loads induced on the structure by the ADCS system will be torques. However, since the FEM of the CubeSat is two dimensional, torques do not always work as expected. As such, the ADCS torque was modeled as a force couple acting on opposite faces of the CubeSat. The MAI-400 ADCS system exerts 0.635 mNm of torque. This small torque produces minuscule stresses in the CubeSat. The peak stress resulting from ADCS operation is just 235 Pa. To provide more perspective about the negligible size of this effect, this produces a maximum deflection of just 0.1 nm. The stress distribution resulting from ADCS operation is shown in Figure 8.

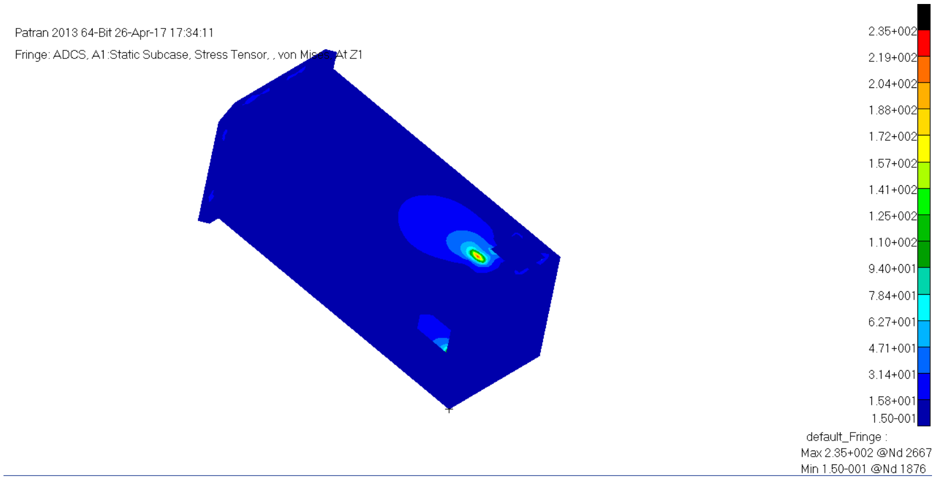

Figure 8: ADCS Stress Distribution

Combined Load Cases

The unlikely event of the CubeSat experiencing combined load cases was also considered. Several such loadings were modeled, one with an astronaut grabbing the CubeSat by both holes at once, an astronaut kicking off of the CubeSat while the ADCS is running, and two others with an astronaut grabbing the CubeSat and losing control of a tool which then hits the CubeSat while the ADCS is running. Table 6 shows the results of these analyses and Figure 9 shows the output of the hold and side impact load case.

Table 6: Combined Load Results

Case	Max Stress (MPa)	Factor of Safety	Maximum Displacement (mm)
Hold Both Holes	36.6	13.7431694	0.0408
Hold Hole With Simultaneous Impact	50.4	9.98015873	0.0682
Hold Hole with Side Impact	89.9	5.658042745	0.217
Kick and ADCS	157	3.203821662	0.478

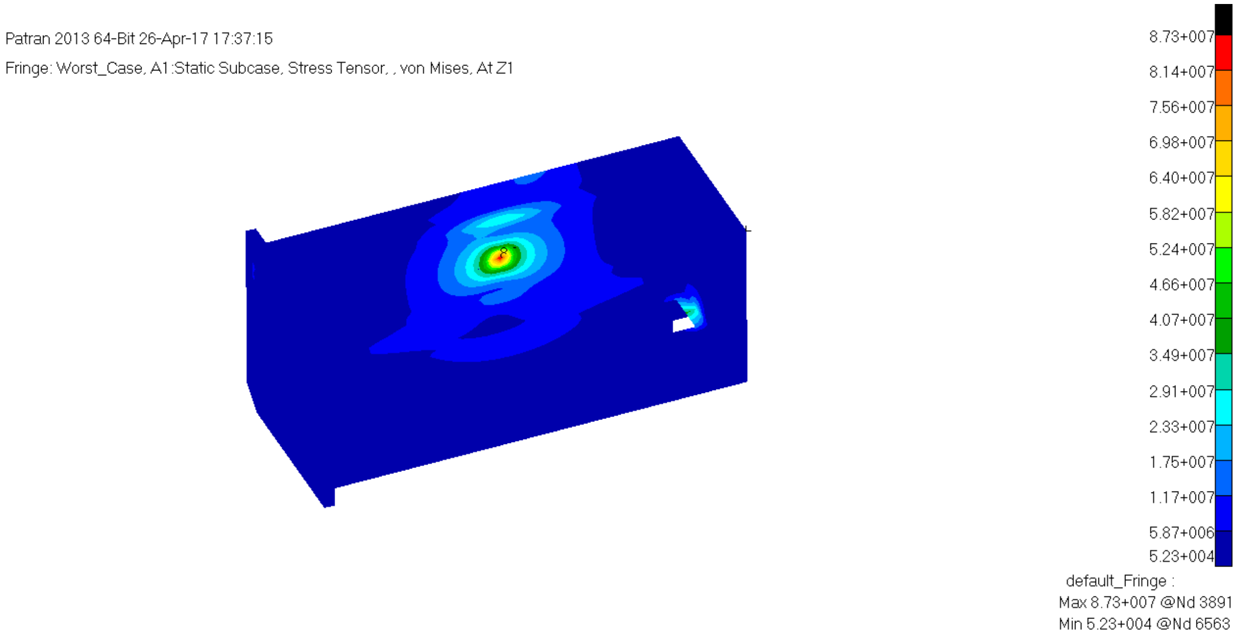

Figure 9: Simultaneous Impact and Hold Stress Distribution

ISS Reaction Forces

To ensure that the spacecraft does not cause any damage to the ISS, the reaction force at the ISS boundary condition was determined for each previously analyzed load case. As seen in Table 1, this force must never exceed 4448 N for the spacecraft to be in compliance with the requirements. Because the spacecraft is in static equilibrium relative to the ISS, the reaction forces applied to the ISS equal the forces applied to the CubeSat in each case where an external load is applied. As these loads never exceed 4448 N, the reaction force will also never exceed 4448 N due to these loads. The only load of interest, therefore is the load induced by the ADCS system as this load is internal to the spacecraft. The Patran results were used to determine the reaction forces caused by the ADCS operation. This force was 21.1 mN, indicating that the requirement is satisfied. Additionally, because this is the only continuous force exerted by

CubeSat on the ISS in its operation, the maximum total impulse applied over a hypothetical 10 second window is 211 mN*s, which is much less than the 44 N*s maximum impulse.

CubeSat Renderings

Lastly, SMDC requested the creation of a rendering of the CubeSat. Figure 10 is a rendering of the CubeSat created in Solid Edge. Several other renderings have been created, and more could be created pending further specification of SMDC's desires.

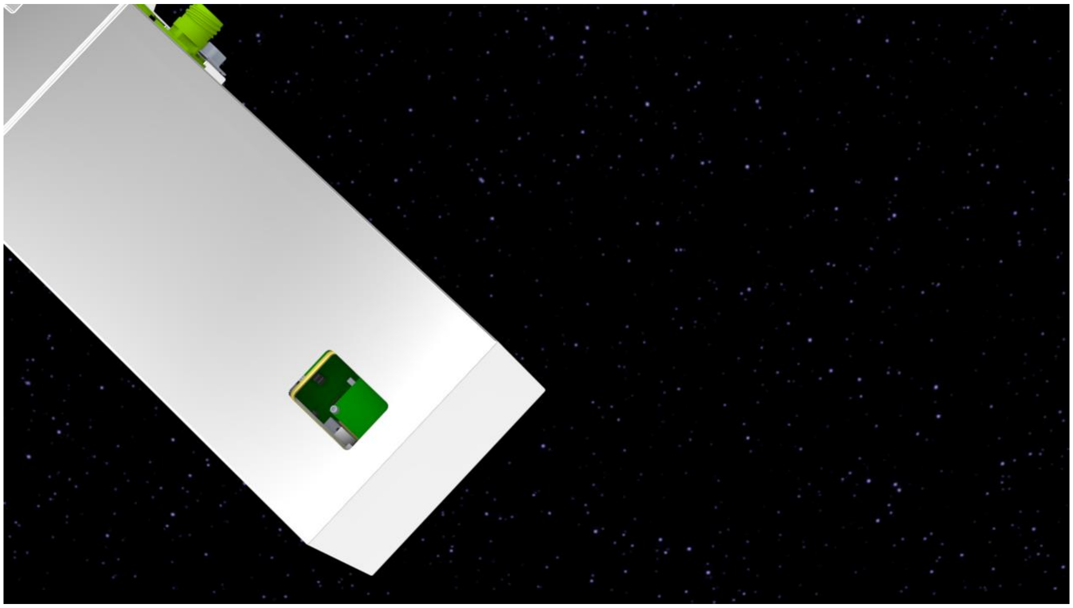

Figure 10: Render of ACES RED with Stars in Background

Conclusion

ACES RED is a CubeSat under development as a technology testbed for SMDC. It will be mounted to the exterior of the ISS, which imposes a special set of environmental requirements on the structure of the CubeSat. A finite element model was established to validate the CubeSat's compliance with these and other requirements.

The results of the FEA showed that the CubeSat would comply with all requirements that could be successfully evaluated by this modeling technique. All applied load cases produced stresses sufficiently below the yield stress of the aluminum structure, resulting in a factor of safety of at least 3. The reaction forces applied to the ISS were below 4448 N in every case, and the ADCS produced applied an impulse of 211 mN*s, which was well below the maximum of 44 N*s.

The system's performance during the workmanship vibration test could not be calculated due to the high frequencies involved which would have necessitated an infeasible amount of Nastran calculations. Additionally, the effects of this test could be very dependent on components that were neglected in the analysis. Circuit boards could jostle loose for example. A normal modes analysis was performed on the system to determine whether the vibration test would correspond to any natural frequencies of the system. The first 8 normal modes fell within the range to be tested during the vibration test. This could potentially cause high stresses in the structure if the damping ratios of the structure are small and the test is run at those frequencies for sufficiently long.

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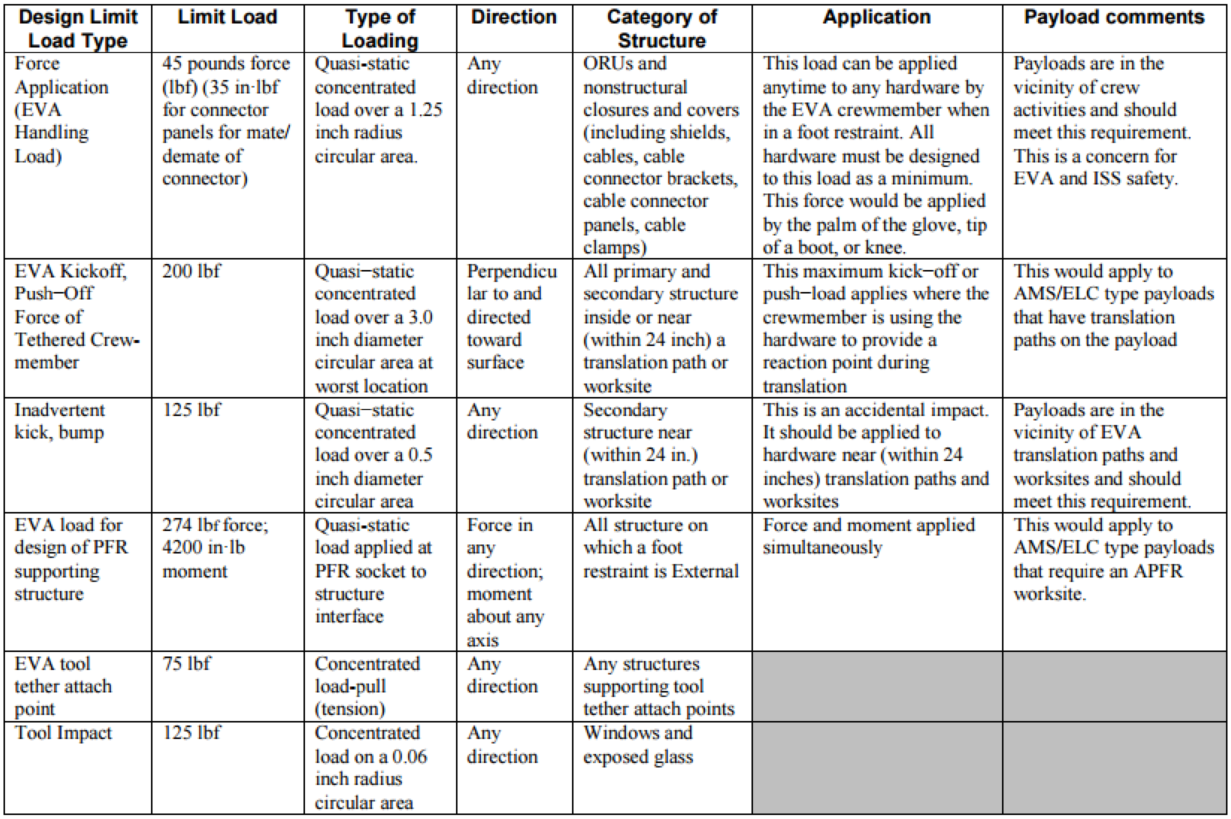
Appendix A

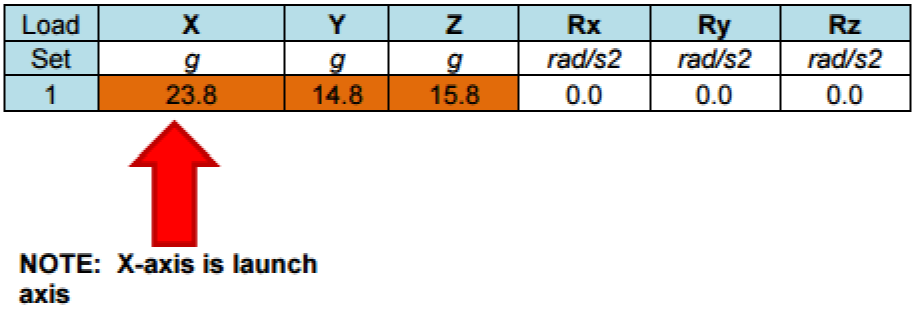
The table below shows the EVA loads that the CubeSat must withstand.



Design Limit Load Type	Limit Load	Type of Loading	Direction	Category of Structure	Application	Payload comments
Force Application (EVA Handling Load)	45 pounds force (lbf) (35 in-lbf for connector panels for mate/ demate of connector)	Quasi-static concentrated load over a 1.25 inch radius circular area.	Any direction	ORUs and nonstructural closures and covers (including shields, cables, cable connector brackets, cable connector panels, cable clamps)	This load can be applied anytime to any hardware by the EVA crewmember when in a foot restraint. All hardware must be designed to this load as a minimum. This force would be applied by the palm of the glove, tip of a boot, or knee.	Payloads are in the vicinity of crew activities and should meet this requirement. This is a concern for EVA and ISS safety.
EVA Kickoff, Push–Off Force of Tethered Crew-member	200 lbf	Quasi–static concentrated load over a 3.0 inch diameter circular area at worst location	Perpendicular to and directed toward surface	All primary and secondary structure inside or near (within 24 inch) a translation path or worksite	This maximum kick–off or push–load applies where the crewmember is using the hardware to provide a reaction point during translation	This would apply to AMS/ELC type payloads that have translation paths on the payload
Inadvertent kick, bump	125 lbf	Quasi–static concentrated load over a 0.5 inch diameter circular area	Any direction	Secondary structure near (within 24 in.) translation path or worksite	This is an accidental impact. It should be applied to hardware near (within 24 inches) translation paths and worksites	Payloads are in the vicinity of EVA translation paths and worksites and should meet this requirement.
EVA load for design of PFR supporting structure	274 lbf force; 4200 in-lb moment	Quasi-static load applied at PFR socket to structure interface	Force in any direction; moment about any axis	All structure on which a foot restraint is External	Force and moment applied simultaneously	This would apply to AMS/ELC type payloads that require an APFR worksite.
EVA tool tether attach point	75 lbf	Concentrated load-pull (tension)	Any direction	Any structures supporting tool tether attach points		
Tool Impact	125 lbf	Concentrated load on a 0.06 inch radius circular area	Any direction	Windows and exposed glass		

Appendix B

The following table shows the accelerations that the CubeSat will experience during launch aboard a SpaceX Dragon Capsule.



Load Set	X	Y	Z	Rx	Ry	Rz
	g	*g*	*g*	*rad/s2*	*rad/s2*	*rad/s2*
1	23.8	14.8	15.8	0.0	0.0	0.0

NOTE: X-axis is launch axis

Based on these accelerations, the launch forces were determined using Newton's Second Law and a CubeSat mass of 4 kg.