UNIVERSITY OF SASKATCHEWAN
College of Engineering
DEPARTMENT OF MECHANICAL ENGINEERING

CubeSat Primary Frame Design

ME495 Industry Design Project

Group 01: Design Cubed

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Abstract

The University of Saskatchewan Space Team provided Design Cubed with a project to design, analyse, and optimize the frame of a cube satellite or CubeSat. Current commercial off the shelf units do not easily accommodate the addition of secondary structure components such as attitude determination systems, inhibit switches, or antennas. Additionally, off the shelf units are difficult to service requiring complete disassembly of the frame. Although off the shelf units are lightweight, their cost is hard to justify. With these issues in mind, the problem statement was created: a primary structure is required to maintain the structural integrity of a CubeSat, which must interface and securely retain all internal components of the CubeSat while meeting all requirements for spaceflight.

The design was optimized for six objectives, listed in order of importance: ease of serviceability, ease of assembly, reduce frame mass, ease of manufacture, reduce cost, and maximize interior envelope. The design had to adhere to the following constraints: 1) meet NanoRacks specifications, 2) meet Canadian Space Agency specifications, 3) meet client specifications, 4) follow National Aeronautics and Space Administration guidelines of material selection. Through an iterative and creative ideation process, five design alternatives were created. Three design alternatives were selected for further feasibility investigation.

The final design alternative features the client’s payload secured between two square cross members. The square cross members and payload will be enclosed by four identical side panels that integrates a rail and shear panel, which is unique compared to off the shelf units and reduces the number of fasteners required. The side panels contain locating and load transferring ribs which improve the ease of assembly and rigidity. The design also contains high customization for client secondary components such as magnets, hysteresis rods, solar panels, and antenna mounts.

The final design’s cost totals to $4,268.25 for material and manufacturing time, further units would have reduced costs from reusing fixtures. Environmental impact from raw material and launch were calculated, but no feasible mitigations strategies were identified. This design provides a solution to the client’s problem which will improve the ease of servicing, is highly customized for secondary components, and has a mass and cost competitive to off the shelf units.

Acknowledgements

The fourth-year design project presents an opportunity to display the culmination of our engineering undergraduate education and showcase the skills we have developed over our tenure at the University of Saskatchewan. In our case, it also presents an opportunity to send something we designed to space, an accomplishment that relatively few engineers can make. Over the last year, our team has taken an immense amount of pride in our journey and progress in creating a unique and custom design of a CubeSat frame. This project would not have been possible without the support and guidance of various individuals: faculty advisors, industry advisors, professors, and our clients. Specifically, we would like to especially thank the following people:

First, we would like to thank Dr. Chris Zhang, our faculty advisor, for his guidance and support provided over the last seven months. Dr. Zhang has generously facilitated weekly meetings to help us keep on schedule and provide technical feedback on design decisions.

Second, we would like to thank professors Dr. Allan Dolovich, Dr. James (J.D.) Johnston, and Dr. Reza Fotouhi for their guidance in the analysis of our project. Between mechanics of materials, bolted connections and FEA modelling, their assistance saved many hours of work.

Third, we would like to thank Chris Robson, of Wyvern Space, for his review and feedback of our design. His experience in CubeSat design allowed for improvements to be made and increased our confidence in our final design.

Fourth, we would like to thank our industry advisor, Justin Gerein (P Eng.) of SED Research Inc., for his feedback during client meetings and surrounding design selection. His feedback and suggestions were invaluable heading into the final stages of the project.

Fifth, we would like to thank our client, the USST. Specifically, we would like to thank Addi Amaya and Alexandra Hynes, the Mechanical Team Leads, for their effective communication and collaborative efforts to develop this CubeSat. We leave the project in your ever-capable hands and will always be available to provide assistance in the future. Best of luck!

Lastly, we would like to convey our gratitude to Jocelyn Peltier-Hunter and the University of Saskatchewan College of Engineering and its faculty for organizing and developing this design course.

List of Symbols and Nomenclature

Nomenclature	Definition
A	Area (m^2)
ASD	Acceleration Spectral Density (g^2/Hz)
D	Diameter (m)
E	Young's Modulus (Pa)
F	Force (N)
G	Force of gravity (9.81 m/s^2)
I	Area moment of Inertia (m^4)
L	Length (m)
m	Mass (kg)
T	Torque (Nm)
t	Thickness (m)
ρ	Density (kg/m^3)
2U	Two-unit size
ASD	Acceleration Spectral Density
ANSYS APDL	Finite Element software, Ansys Parametric Design Language
ANSYS Workbench	Finite Element software, Ansys Mechanical Workbench Additive
BoM	Bill of Materials
CCP	Canadian Cube Sat Project
CM	Center of Mass
COTS	Commercial Off-the-Shelf
CSA	Canadian Space Agency
CubeSat	Cube Satellite
CVCM	Collected Volatile Condensable Material
FEA	Finite Element Analysis
FEM	Finite Element Modelling
GSE	Ground Support Equipment
Helicoil	Threaded insert or Threaded Bushing
ISS	International Space Station
LEO	Low Earth Orbit
MEFL	Maximum Expected Flight Level
MRS	Mitigated Risk Score
NASA	National Aeronautics and Space Administration
NRCSD	NanoRacks CubeSat Deployer
PCB	Printed Circuit Board
RACI	Responsible Accountable Consulted and Informed
RBF	Remove Before Flight
TML	Total Mass Loss
USST	University of Saskatchewan Space Team

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1.0 Introduction

The following chapter will discuss key aspects of the project lifecycle undertaken by Design Cubed in the design of a two-unit (2U) Cube Satellite, or CubeSat. The problem background and clients will be introduced, followed by an evaluation of key stakeholders and associated roles and responsibilities. Next, the refined problem statement and description will be discussed in detail. Then, the key engineering principles utilized for design and analysis will be examined. Finally, the project scope will be defined, including major deliverables.

1.1 Background

Design cubed has been tasked with designing the primary structure of a 2U CubeSat, with dimensions of 10x10x20 cm, for clients Justin Gerein from SED Research and the University of Saskatchewan Space Team (USST).

CubeSat standard was developed through the collaboration between Jordi Puig-Suari, a professor at California Polytechnic State University and Bob Twiggs, a professor at Stanford University's Space Systems Development Laboratory. The two professors worked to develop more "affordable [and] hands-on" (CSA 2018) access to space exploration for universities and created a CubeSat standard as a result. Building off the CubeSat standard, the Canadian Space Agency (CSA) launched the Canadian CubeSat Project (CCP) in 2017 to advance education and space technology across Canada. The CCP aims to launch a CubeSat constructed by a post-secondary institution from each Canadian province by the year 2021. The USST has been selected to develop Saskatchewan's CubeSat.

In turn, the Design Cubed capstone group has been tasked with designing the primary structure or frame of the CubeSat for the USST. The frame is a very important piece of the CubeSat design as all components rely upon it for structural support and thermal regulation. The USST desired a robust and detailed solution tailored to the needs of their specific CubeSat. The decision to outsource to a third party ensured a thorough and detailed design was completed while reducing the USST's workload. Design Cubed was thrilled to be offered the project and agreed to take on the challenge.

1.2 Client Overview

Design Cubed has two main clients:

i.) The University of Saskatchewan Space Team Mechanical Team Leads
ii.) Justin Gerein (SED Research Inc.)

The USST is the project owner where Design Cubed will work in direct collaboration with the USST Mechanical Team Leads. The team leads and Design Cubed will work closely to ensure all internal payload mounting requirements and secondary structures are accounted for in the primary structure design. Justin Gerein has extensive CubeSat knowledge and will act as an industry consultant to Design Cubed. Justin Gerein also holds the role as project sponsor, for the purposes of the capstone class format.

1.3 Stakeholders and Roles

The USST CubeSat is a large project involving many stakeholders from a variety of fields. A responsibility assessment matrix was developed, as seen in Appendix A, to visually identify the roles and responsibilities of key stakeholders. Appendix A can be summarized as follows:

i.) USST (Primary Client)
ii.) Justin Gerein (Industry Client)
iii.) Chris Zhang (Faculty Advisor)
iv.) Jocelyn Peltier-Huntley (Course Coordinator)
v.) Professor Li Chen (Experimental Equipment Testing)
vi.) Dr. Ekaterina Dadachova (Experimental Equipment Testing)
vii.) Tim Muench (Saskatchewan Polytechnic, Manufacturer)
viii.) NanoRacks (Launch Provider)
ix.) International Space Station Personnel (Launch Preparation)
x.) CSA (Project Initiator)

It is important to note that the USST is Design Cubed’s primary client and Saskatchewan Polytechnic will be manufacturing the final product. Continuous communication was maintained between the USST Mechanical Team Leads (Primary Client), Justin Gerein (Industry Client), and Chris Zhang (Faculty Advisor) throughout the entirety of the project.

1.4 Problem Statement and Description

Design Cubed has developed the following problem statement:

A primary structure is required to maintain the structural integrity of a CubeSat, which must interface and securely retain all internal components of the CubeSat while meeting all requirements for spaceflight.

The client has identified that commercial off the shelf (COTS) units are inadequate designs. COTS designs do not provide a high degree of serviceability or customization for secondary structure components such as hysteresis rods, solar panels, antennas, or attitude control systems. By opting to have the primary frame designed custom, a few considerations and realizations need to be made. First, the frame will need to interface with a CubeSat deployer. A CubeSat deployer is a device which securely retains a CubeSat during launch from Earth to the International Space Station (ISS). From the ISS, the CubeSat deployer will gently release the CubeSat into low Earth orbit (LEO). The clients' CubeSat will have a mission length of approximately one year. To ensure a successful mission, the frame needs to adhere to the requirements specified by the launch provider and the client. Second, the primary frame will need to consider the stresses and deflections of the frame from the dynamic rocket launch and the vacuum effects of space.

1.5 Objectives, Metrics, and Constraints

Utilizing a pairwise comparison matrix, Design Cubed has outlined that the selected design should increase the ease of assembly and serviceability of the CubeSat while finding a balance between manufacturing costs and reducing the overall frame mass. It is expected that the CubeSat will be assembled and disassembled roughly 25 times before flight, meaning an easily serviceable and simple design is critical. Additionally, to allow for as much usable space as possible, Design Cubed has identified that maximizing the interior envelope of the CubeSat is a priority but of lower importance than those mentioned above. A summary of a pairwise comparison, to rank design objectives, can be found in Table 1-1.

Table 1-1. Pairwise comparison objective ranking results and metrics

Rank	Objective	Metric	Weight (%)
1	Serviceability	No. Fasteners & Frame Parts	31.25
2	Ease of Assembly	No. steps in access internals	25
3	Reduce Frame Mass	Total Frame Mass	18.75
4	Ease of Manufacture	Number of Unique Parts	12.5
5/6	Reduce Cost	Material/Fabrication Costs	6.25
5/6	Maximize Interior Envelope	Interior Volume	6.25

Major constraints include adhering to requirements outlined by the launch provider, NanoRacks. NanoRacks specifies several design driving features such as geometric tolerancing, surface hardness, and minimum strength requirements, as outlined in Appendix B. Further, the USST has outlined design interface requirements for the payload as well as secondary components such as magnets, hysteresis rods, solar panels, wiring harnesses, and antenna mounts. The design must also be compliant with the National Aeronautics and Space Administration (NASA) outgassing guidelines for selecting materials to be used in space, as per requirement 4.4.10.3 (NanoRacks 2018).

1.6 Engineering Principles

Basic engineering principals used throughout the design and analysis of the CubeSat frame included static and vibrational principals. The launch provider, NanoRacks, provided an equivalent quasi-static loading representative of the dynamic shuttle launch. Quasi-static in this context is a state of dynamic equilibrium by which a dynamic loading is occuring slowly enough to be analyzed statically. As such, static mechanics of materials can be applied to deduce stresses and deflections within the CubeSat frame. Finite Element Modelling (FEM) is then used as an isolated method of verification of results. A vibrational analysis must also be considered as the launch vehicle will impart physical and acoustic vibrations onto the CubeSat. The vibration analysis was approached in three different ways, a statically equivalent loading based on literature findings, modal analysis, and random vibration testing. Physical vibration testing will be performed by the USST to confirm the theoretical results outlined in this report. Lastly, engineering thermodynamic principles must also be considered as the CubeSat will be exposed to a range of temperatures during its mission in low earth orbit (LEO).

1.7 Scope Definition

Design Cubed is responsible for the design and manufacturing of a primary structure specifically for the USST's 2U CubeSat. Computational structural and vibrational analysis of the structure will be conducted by Design Cubed to ensure the integrity of the design during its launch and subsequent flight. Thermal analysis is not included in the scope of the project and the USST will be responsible for this evaluation after project handover. Manufacturing will be limited to a prototype model and no physical tests will be conducted. The USST will complete vibration testing outside the timeline of the project.

The USST will provide preliminary design interface documents for all components and sub-systems and it will be Design Cubed's responsibility to meet all interfacing requirements. The design and selection of the components or sub-systems will not be the responsibility of Design Cubed. No design changes will be made after the manufacturing process has begun.

1.8 Project Deliverables

Project deliverables for the design project include:

i.) Finite Element Analysis report of frame design

ii.) Vibrational analysis report of frame design

iii.) SolidWorks model and drawing package

iv.) Final report including all information required to reproduce design

v.) Prototype of frame

vi.) All working files from the project

2.0 Design Alternatives

After defining the problem and outlining the design scope, a literature review was conducted to understand the existing solutions. During an iterative ideation process, five alternative designs were created that met the requirements. Of the five design alternatives, three designs were selected using a weighted decision matrix. The top three alternatives underwent further feasibility investigation, including developing SolidWorks models. This allowed for a more comprehensive comparison to be conducted before making the final alternative selection. The three designs that were developed further for re-evaluation will be discussed in this section.

2.1 Literature Review

Five existing frame designs and two patents were identified during the literature review. The COTS options were evaluated against the objectives and proved to be inadequate for the clients' needs. To gain further understanding of existing solutions a COTS frame model was 3D printed. Many CubeSat frames are custom designed and there are numerous academic papers outlining their design and how they were incorporated into the overall CubeSat. It was determined that there was no identifiable solution existing and each frame is customizable to a unique problem.

2.2 Alternative 1: L Bracket

Alternative 1, as seen in Figure 2-1, has four unique parts consisting of four identical side panels that have one rail integrated into each shear panel. The square cross members are used to connect the side panels as well as hold the payload. The strength of this design is the low number of unique parts and fasteners, combining to make a lightweight frame. By removing the fasteners in one side panel it is possible to remove the panel and access the payload inside. Additionally, the wiring harness for the solar panels would have to be disconnected. The integrated rail and shear panel reduces the number of parts, but it is an inefficient use of the material as a flat bar must have the majority of its material removed.

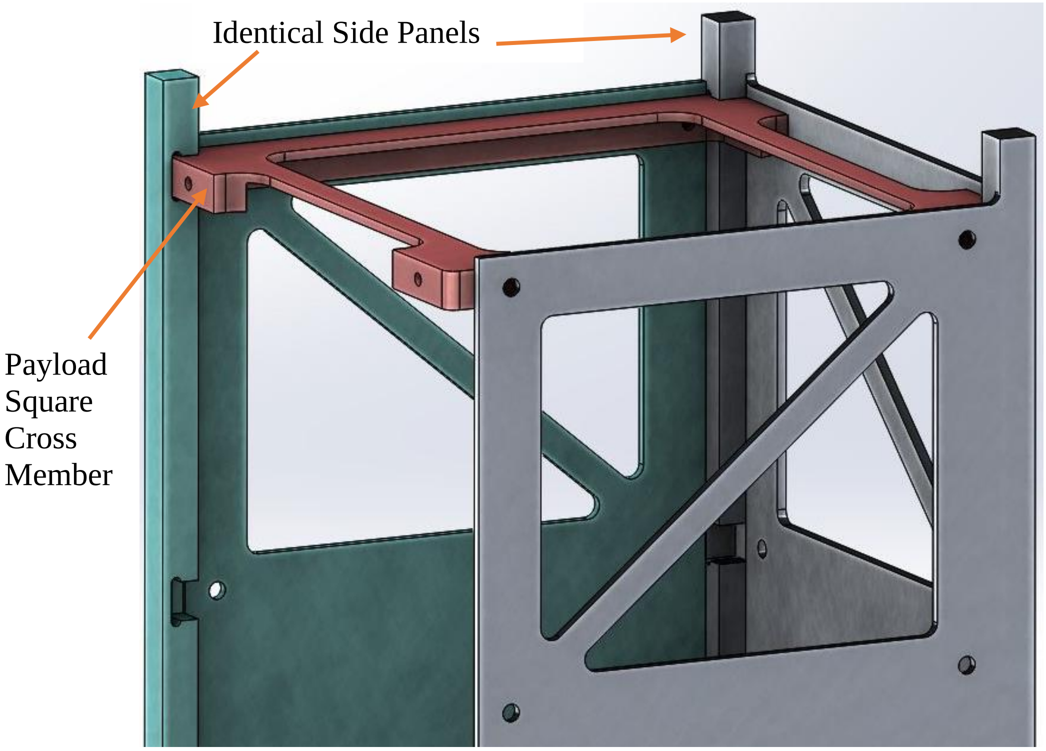


Figure 2-1. Alternative 1 with one side panel and cross member removed to show connections

2.3 Alternative 2: Hinged Side Panels

The second alternative was inspired by a hinge design patent (Judd, et al. 2015). As seen in Figure 2-2, a hinged design focuses on maximizing serviceability by having three of the external sides mounted on hinges. The payload is sandwiched between the top square cross member and an intermediate cross member. These cross members are secured to a rigid back panel that provides support. There are cut-outs in the rails of the back panel to allow for the hinging of the side panels. The hinged panels are secured with fasteners onto the square cross members. The largest strength of this design is the ease of serviceability. By removing a few fasteners from three sides, the payload is quickly exposed for servicing. The wiring harness for the solar panels would not have to be disconnected which reduces the number of steps and the risk of damaging the solar panels during servicing. The side panels consist of one rail and an integrated shear panel which reduces the number of fasteners to connect the parts. The weakness of this design is meeting the tight tolerances for the rails while allowing the side panels to rotate freely.

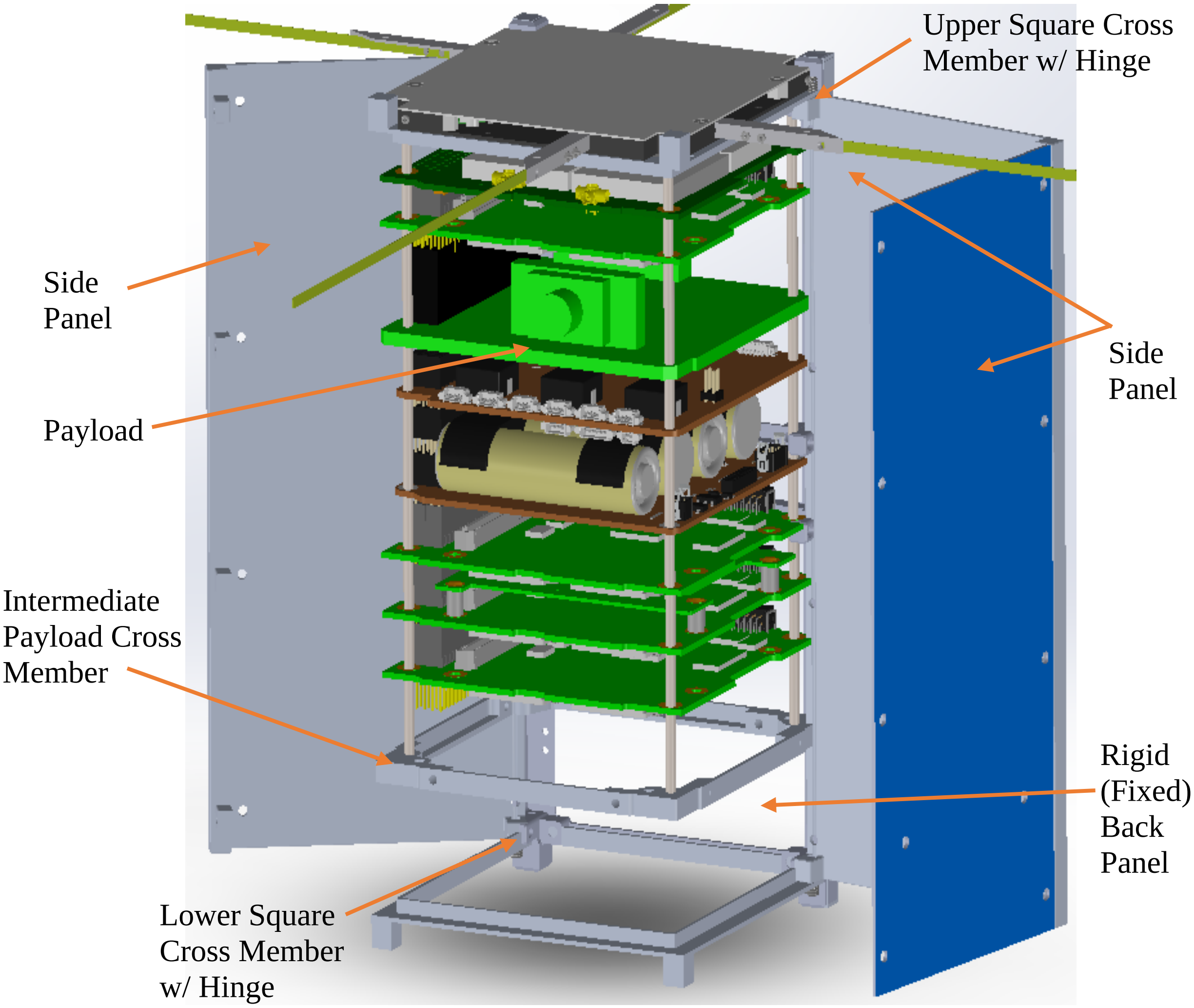


Figure 2-2. Alternative 2 with hinged side panels opened, payload included for clarity

2.4 Alternative 3: Two Faces with Shear Panels

The third alternative, as seen in Figure 2-3, has two panels, each consist of two vertical rails connected by integrated horizontal struts. The two panels are connected by shear panels made from sheet metal. All parts are held together by fasteners threaded into the two panels. The payload is secured to the two panels using threaded rods. This design had several strengths in that there are only three unique parts and the manufacturing costs are low. As there are fewer parts this results in fewer fasteners which reduces assembly weight, cost, and time. Servicing requires significant disassembly of the frame, demonstrating a weakness in the design. Another weakness is that loads are transferred through bolted connections in shear and through thin sheet metal which could create areas of high stress concentrations.

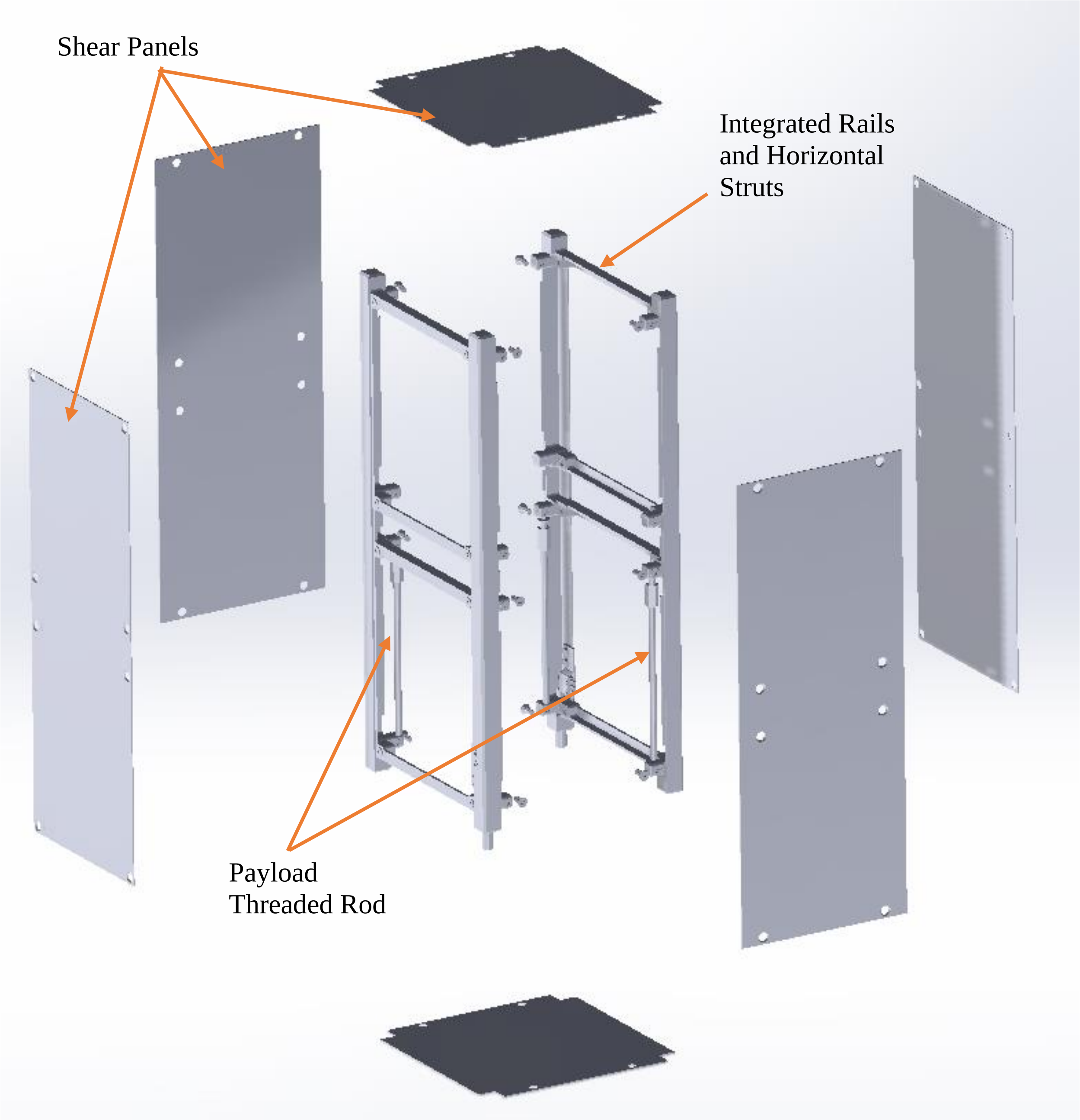


Figure 2-3. Alternative 3 with mirrored panels and connecting shear panels

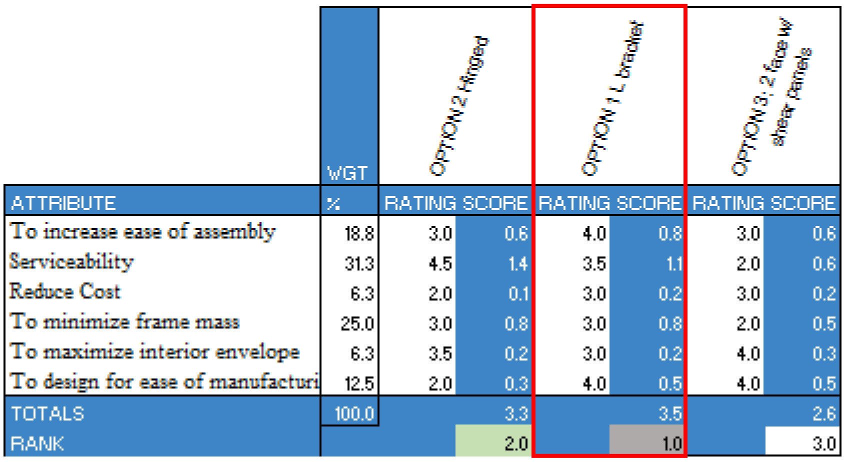
2.5 Value Analysis

To select an alternative design, a weighted decision matrix was used. A detailed account for the process by which the final design was selected can be found in Appendix C. Each design alternative was analysed to assess how well it achieved each objective. Each design attribute, such as the design mass or relative cost, was given a value between one and five based on how well it met the objective, using the metrics. This value was then multiplied by the weighting, determined by a pairwise comparison matrix, and the results summed. From an initial five design concepts, the top three alternatives with the highest score were then identified as the favoured designs. The top three designs were then further investigated for feasibility as unseen challenges were expected to arise as the design becomes more detailed.

From the initial weighted decision matrix, as seen in Appendix C, the highest-ranked design alternative was the hinged design. The hinged design allowed for the best serviceability of all the alternatives. As the detailed design progressed, concerns arose regarding the geometric tolerancing and suspected manufacturing challenges made creating a practical design difficult. After numerous iterations, it was decided that the hinge design could not meet the geometric tolerance requirements of the rails outlined by NanoRacks. Additionally, time to align the four rails would negate the ease of serviceability and repeatability was questionable.

The top three designs were reviewed again in the weighted decision matrix based on the hinged design findings. As seen in Table 2-1, after re-evaluations alternative one had the highest score and was selected as our final design.

Table 2-1. Top three alternative weighted decision matrix results



	WGT	OPTION 2 Hinged		OPTION 1 L bracket		OPTION 3: 2 face w/ shear Panels	
ATTRIBUTE	%	RATING	SCORE	RATING	SCORE	RATING	SCORE
To increase ease of assembly	18.8	3.0	0.6	4.0	0.8	3.0	0.6
Serviceability	31.3	4.5	1.4	3.5	1.1	2.0	0.6
Reduce Cost	6.3	2.0	0.1	3.0	0.2	3.0	0.2
To minimize frame mass	25.0	3.0	0.8	3.0	0.8	2.0	0.5
To maximize interior envelope	6.3	3.5	0.2	3.0	0.2	4.0	0.3
To design for ease of manufacturi	12.5	2.0	0.3	4.0	0.5	4.0	0.5
TOTALS	100.0		3.3		3.5		2.6
RANK			2.0		1.0		3.0

3.0 Final Design

The design alternative dubbed the L-Bracket was selected as the final design alternative. An annotated drawing of the selected design alternative can be seen in Figure 3-1. The design features three unique parts for the primary frame and 15 fabricated parts for the entirety of the assembly. A complete drawing package and complete bill of materials is included in Appendix D and can be referenced for additional details.

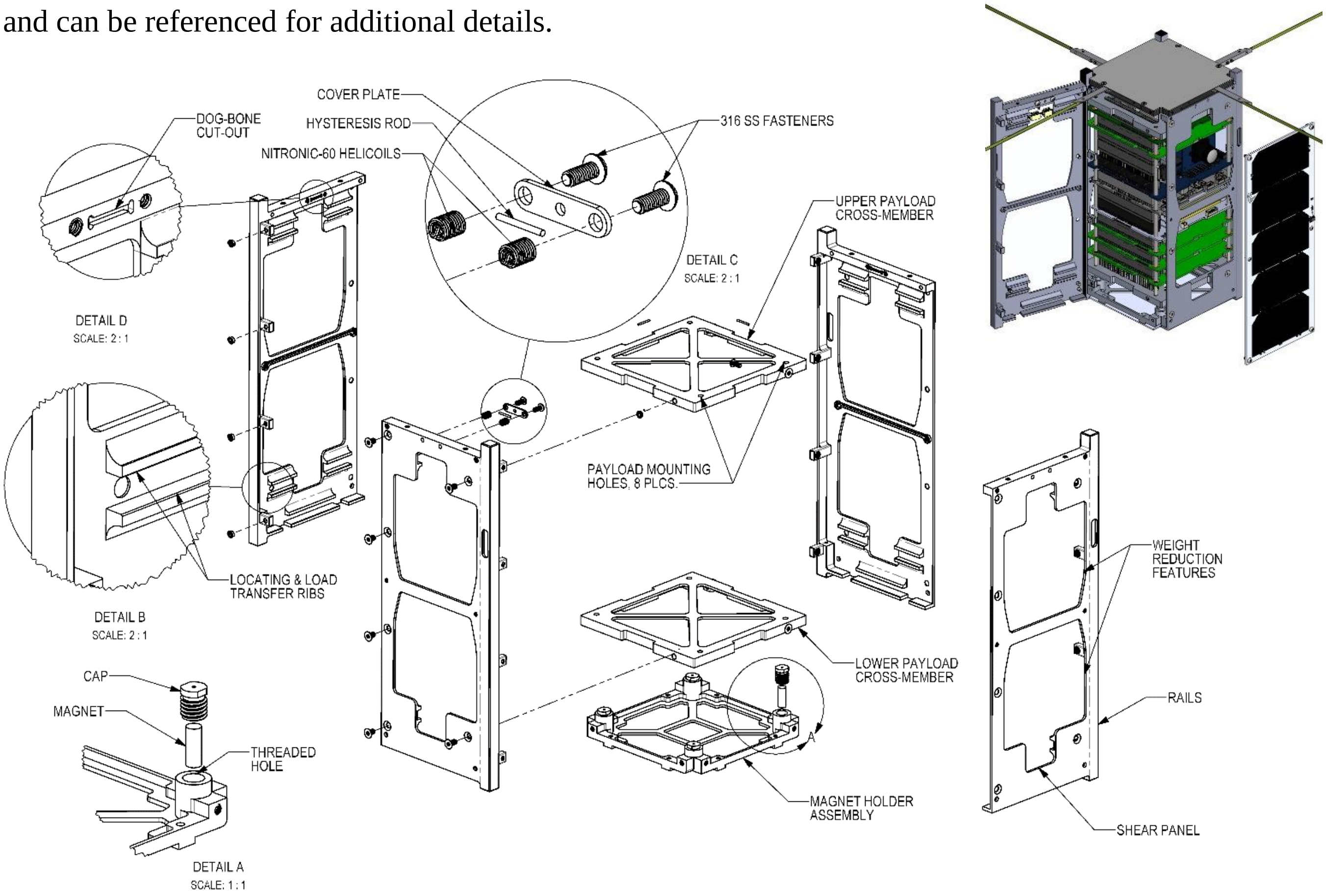


Figure 3-1. L-Bracket annotated drawing

The USST's payload will consist of a stack of printed circuit boards (PCBs) which will interface with the upper and lower payload cross members. The payload cross members will be secured to four identical side panels. A third square cross member, the magnet holder assembly, will also be secured to the four side panels. CES analysis, a material selection software, was conducted as documented in Appendix E. Results outlined that a 6000 series aluminum would be optimal. Fabricated parts will be made from 6061-T6 aluminum based on material costs, availability, commonality in other CubeSats, and machinability. Further, 6061-T6 was selected in compliance with requirement 4.4.10.3 of NanoRacks (2018) as it is on the approved NASA outgassing materials list. The client also requested the frame be developed from a metal with suitable thermal conductivity properties.

The primary structure of the frame, including fabricated parts and fasteners, has a mass of 371 g. This mass can be compared to COTS units which have a mass in the range of 280-320 g. The selected alternative has a mass 16% larger than COTS units. This increase in mass was justified by the increased functionality the design provides to the client as well as being highly customized versus the “one-size-fits-all” approach of COTS.

3.1 Side Panels

A literature review of current solutions showed that many COTS units have four identical rails with either square or individual cross members to secure the payload to the rails and four shear panels to secure the cross members. The shear panels create a mounting surface for the solar panels and add rigidity to the CubeSat. COTS units contain high part and fastener counts which is less than optimal for serviceability. The selected design alternative opts to integrate the rail and shear panel by fabricating the part from a single piece. Tolerance stacking is reduced by integrating the rail and shear panel. The final design uses four identical side panels, which can be seen in greater detail in Figure 3-2.

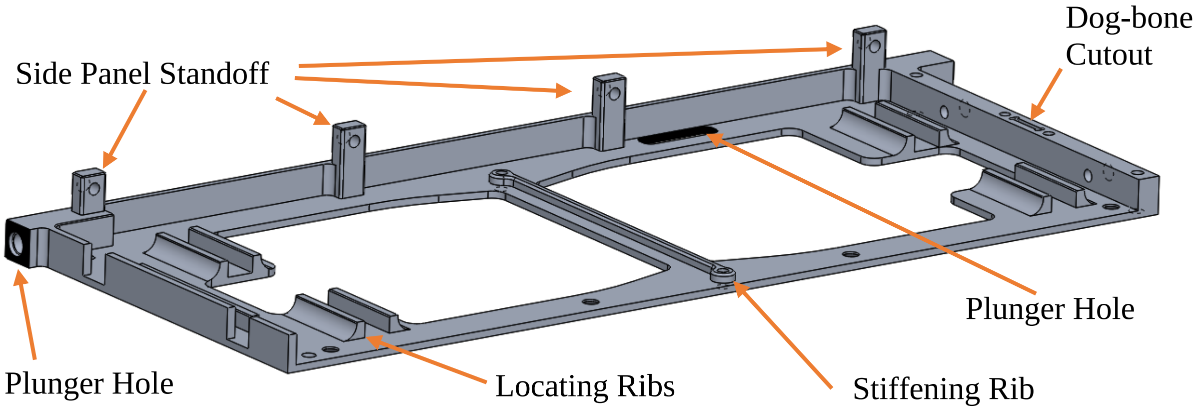


Figure 3-2. Final design side panel detail

The side panels serve two main functions. First, the side panels must interface with cross members to securely retain the client’s payload. Secondly, the rail segment of the side panel must interface with the launch deployer, NanoRacks. NanoRacks requirements are extensive and can be found in Appendix B. To summarize, NanoRacks places several geometrical tolerances on the CubeSat assembly, specifies surface hardness of the rails, and indicates further functionality to house inhibit switches into the rails of the frame. The side panels are also highly unique in that they contain locating and load distributing ribs that will interface with the square cross members of the payload and the magnet holder. The side panels display customization to the clients' needs by the addition of a dog-bone cut-out for hysteresis rods and holes for plungers, a feature unavailable in COTS units. The side panels have an individual weight of 64.2 g each and will be made from 6061-T6 aluminum. The shear panels have a thickness of 1.5 mm, which is the minimum machinable thickness before warping or machine chatter can affect dimensional accuracy. At the request of the client, bolted connections will contain a threaded insert called Helicoils (not shown). The threaded inserts aim to reduce the wear placed on the aluminum which is prone to stripping the threads after a few uses. The side panels have Helicoils added for mounting solar panels, hysteresis rod covers, and the antenna. Only through-holes are used to prevent gases from being trapped by the fasteners. Trapped gases, upon exposure to a vacuum, could potentially violently escape causing damage to the CubeSat.

3.2 Square Cross Members

A literature review showed that COTS units will often have four cross members connected to the four rails. Again, by making the cross member from a single piece, the overall part count can be reduced. A square cross member, seen in Figure 3-3, will retain the client's payload of stacked PCBs by four threaded holes. The square cross members are then secured to the side panels via four more fasteners. All threaded connections will receive a stainless steel Helicoil (not shown). The square cross members have an individual weight of 25.5 g and will be made from 6061-T6 aluminum. The square cross members feature a minimum manufacturable wall thickness of 1.5 mm to reduce part mass. Lightening holes are added to reduce mass while retaining the rigidity of the part.

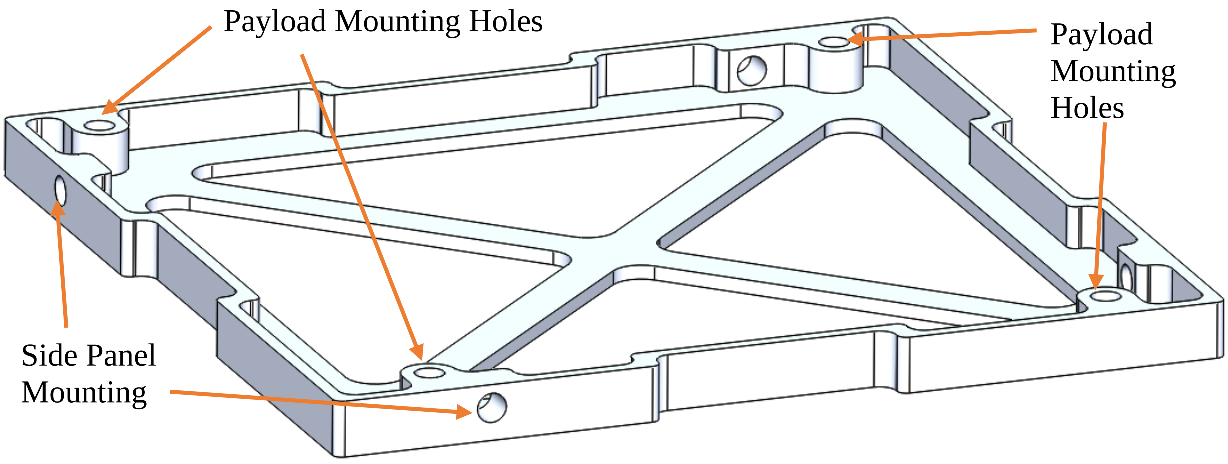


Figure 3-3. Final design cross member detail

3.3 Magnet Holder Assembly

The magnet holder assembly can be seen in Figure 3-4 whose function is to improve the rigidity of the frame as well as secure four magnets, as specified by the client. The magnets will be retained with vented caps to prevent gas from being trapped. The magnet holder square cross member will locate on the ribs of the side panels and be retained by eight fasteners. All threaded connections will receive a stainless steel Helicoil. The magnet holder assembly will also have a solar panel (not shown) mounted to the underside of the assembly. The magnet holder square cross member has an individual weight of 38.5 g and will be made from 6061-T6 aluminum. The square cross members feature a minimum manufacturable wall thickness of 1.5 mm to reduce part mass. Lightening holes are added to reduce mass while retaining the rigidity of the part.

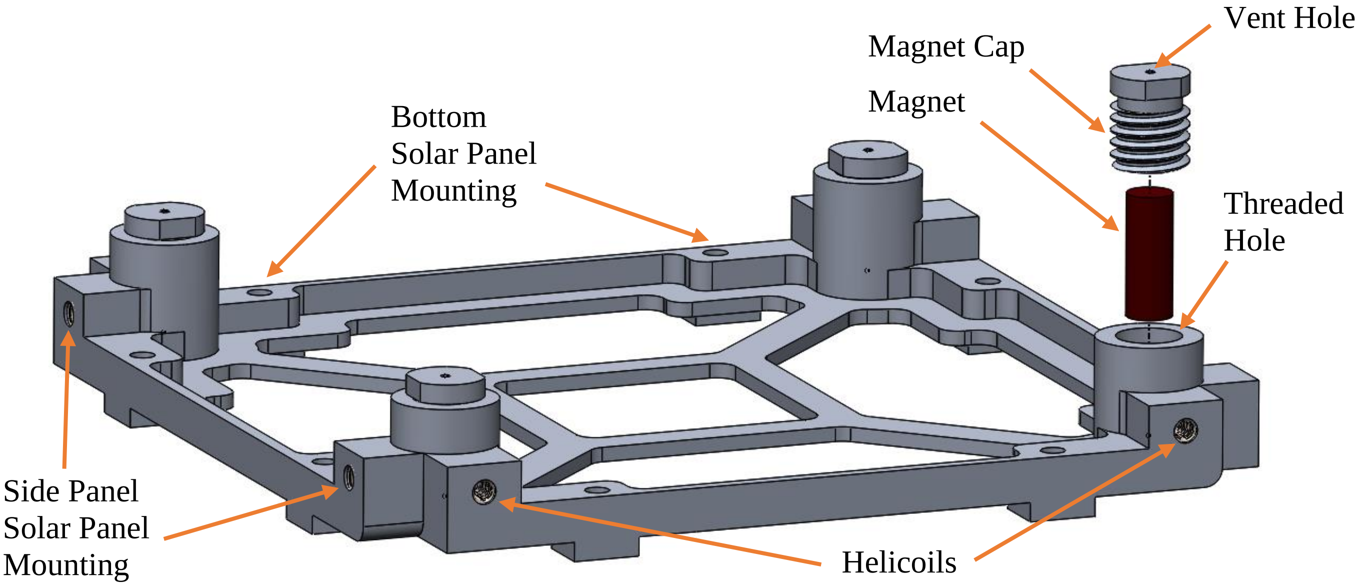


Figure 3-4. Final design magnet holder assembly detail

3.4 Design Calculations

The CubeSat and its frame will need to withstand Earth, launch, and space conditions. As previously mentioned, the CubeSat will be placed into a CubeSat deployer. Figure 3-5 displays the orientation the CubeSat will have during launch and assigns an X, Y, and Z-axis to the CubeSat to be referenced throughout the analysis.

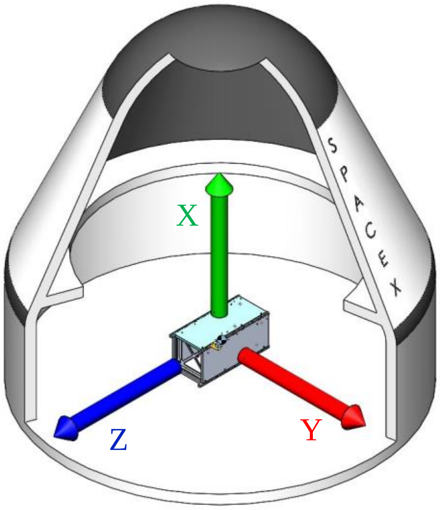


Figure 3-5. CubeSat launch orientation detail

The CubeSat deployer will secure the CubeSat using a jackscrew, imparting a force along the Z-axis of the frame. NanoRacks has outlined that the dynamic effects imparted from the launch vehicle to the CubeSat and frame ad these can be taken as an equivalent quasi-static loading of seven, four, and four times Earth's gravity in the X, Y, and Z axes respectively. The deployer, as outlined by NanoRacks in Appendix B, interfaces the CubeSat along its four rails. The CubeSat and the deployer contain a clearance such that the boundary conditions will be assumed to be sliding frictionless contacts on one X and one Y face concurrently. The Z-axis will be supported also by a sliding frictionless contact. Vibrations from the rocket engines must be considered and NanoRacks specifies a hard-mount random vibration profile that must be satisfied. From Brakeboer (2015), it can be taken that adding 47.4 G's to each axis is a convenient and conservative approach to calculating the deflections and stresses caused by random vibrations. Further, this approach was verified in consultation with field experts in static and structural analysis.

For the sake of hand calculations, the geometry was simplified to a solid and constant cross-sectional member of external dimensions 10x10x22.7 cm with a wall thickness of 1.5 mm. This sub-section will describe the method by which the frame was analysed. The simple member was analysed for forces in the Z-axis and X-axis separately. The detailed and accurate model was analysed for a combined load case and complete vibrational analysis. Bolt calculations were completed to optimize the size and material of all structural fasteners.

3.4.1 Z-Axis Load Case

As specified by NanoRacks, the CubeSat frame will experience 1,200 N of compressive force supplied by a jackscrew in the Z-axis. Body forces on the frame and payload are applied with an acceleration of four times Earth's gravity for the quasi-static loading. The deflection of the frame can be calculated using Equation (1) where F is the net force applied to the frame, L is the length of the frame, E is the Young's Modulus of aluminum, and A is the cross-sectional area of the frame.

$$\delta = \frac{FL}{EA} \tag{1}$$

Using Equation (1), the deflection of the frame due to forces in the Z-axis is 7.05 µm. From ANSYS APDL, using beam-189 elements to model the frame, the same forces were applied. The element size of the APDL model was decreased to establish the convergence on a solution. APDL yielded 6.82 µm of deflection with a 3.3% difference from mechanics of materials. The

3.3% difference shows acceptable agreeance between FEA and hand calculations providing confidence in the FEA results. With high confidence, the maximum stresses due to forces in the Z-axis are 2.17 MPa. The results from the Z-axis load case have been summarised below in Table 3-1.

Table 3-1. Z-axis load case summary of results

	Deflection [µm]	% Difference
Mechanics of Materials	7.05	-
ANSYS APDL	6.82	3.26%
ANSYS Workbench – Simplified Model	6.88	2.45%
ANSYS Workbench – Accurate Model	22.9	-

Buckling needs to be considered as the frame is slender in length compared to the wall thickness. Equation (2) is the Euler buckling equation where E is Young's Modulus of aluminum, I is the area moment of inertia, and L is the length of the frame.

$$P_{cr} = \frac{\pi^2 EI}{L^2} \tag{2}$$

It was determined that the critical buckling force, P_{cr}, is 1,280 kN. In comparison to the 1.2 kN being applied to the frame, buckling is not of concern.

3.4.2 X-Axis Load Case

The X and Y axes of the frame experience the quasi-static loading on body forces of the frame and payload using an acceleration of seven and four times Earth's gravity, respectively. Considering how the frame is physically restrained in the CubeSat deployer, the analysis shows a high degree of static indeterminacy. In consultation with an expert in static and structural analysis, a simplified case was identified to balance the accuracy of the real load case with the time and resources required to complete hand calculations. Castigliano's second theorem was exploited as the simple problem demonstrates internal static indeterminacies. Equation 3 was used to determine the deflection in one of the shear panels of the frame accounting for bending, axial, and shear effects caused by the force.

$$\delta_{W_1} = \frac{\partial U}{\partial W_1} = \int \frac{M}{EI}\frac{\partial M}{\partial W_1}\,ds + \int \frac{N}{EA}\frac{\partial N}{\partial W_1}\,ds + K\int \frac{V}{GA}\frac{\partial V}{\partial W_1}\,ds \tag{3}$$

Appendix F contains the detailed calculations completed to determine the desired deflections. Castigliano’s yields 12.9 μm of deflection and APDL, modelled using beam-189 elements, yields 12.9 μm, after increasing the number of elements to check for convergence, at the corresponding point. The two deflections agree to 0.1% which demonstrates agreeance and strong confidence in the FEA model. To verify the ANSYS Workbench model, the X-axis load case was recreated and yielded 12.4 μm, a 3.76% difference. ANSYS APDL results can be found in Appendix F. The results from the X-axis load case have been summarised below in Table 3-2.

Table 3-2. X-axis load case summary of results

	Deflection [μm]	% Difference
Mechanics of Materials	12.9	-
ANSYS APDL	12.9	0.10%
ANSYS Workbench – Simplified Model	12.4	3.76%

3.4.3 Combined Load Case

ANSYS Workbench presents itself as a useful tool to analyze complicated geometries which would be difficult to analyze by hand or model in ANSYS APDL. Inputting the accurate model and applying all the loads applied to the frame, it was determined that a maximum deflection of 22.5 μm is observed with a nominal maximum stress of 20.6 MPa. Appendix F contains thermal maps of the deflections and stresses in the detailed frame as well as anomalies in the results. The maximum deflections are acceptable as they are not large enough to cause interference with the NanoRacks launch deployer or to come into contact with the payload. The maximum stress of 20.6 MPa is significantly below the yield strength of 6061-T6 aluminum, 276 MPa. Areas of stress concentration, as seen in Appendix F, are not of concern as they present characteristics of anomalies and are still under the yield strength of aluminum. Additionally, an eigenvalue buckling analysis was conducted on the complex model within Workbench and the combined loading case. Simulations resulted in a load multiplier of roughly 40, meaning the combined loading experienced by the frame is 40 times less than the critical loading required for buckling.

3.4.4 Sensitivity Analysis

NanoRacks specifies that the CubeSat center of gravity must be within ±2 cm, ±2 cm, and ±4 cm of the center of geometry of the frame in the X, Y, and Z directions respectively. One of the assumptions made in the analysis was that the center of mass of the payload was coincident with the center of geometry. A sensitivity analysis was completed where the payload mass was moved around to the edges of the bounding box to identify the influence on the stresses and deflections of the frame. In the simple model combined loading case, the worst-case scenario adds 78% more deflection and 95% more stress to the frame. However, due to the small deflections and stresses observed in the frame under static loading, this is not a concern. At the client's request, all efforts have been made to retain the alignment of the center of mass with the center of geometry for the CubeSat. Completing the sensitivity analysis provides confidence that slight or unexpected changes in the center of mass will not be a cause for concern.

3.4.5 Design Iteration & Topological Optimization

One objective of the final design was to minimize the mass of the frame to be comparable with COTS units. In the early stages of the project, Design Cubed 3D printed a COTS unit to physically interact with the frame to aid in design alternative ideation as well as identify areas for improvement. It was noticed that the COTS unit lacked rigidity in shear and twisting loads. With tight tolerances placed on the CubeSat frame, it was decided to improve the rigidity of the frame as rough manipulation during assembly could result in the frame becoming out of tolerance. Figure 3-6a. shows the preliminary, geometrically artistic side panel design. The preliminary design was 3D printed for demonstration in presentations to faculty advisors, clients, consulted experts, and manufacturers. The integration of the shear panels and rails and adding the unique locating and load transfer ribs proved to significantly improve the torsional rigidity. To verify or optimize the geometric cut-outs of the frame, SolidWorks Topology Optimization was used to generate a computer recommended mass savings based on the combined load cases. Figure 3-6b. shows the results from the topology optimization. The results indicate that the geometric cut-outs add little to the structural integrity of the frame and further mass savings can be achieved by having one large cut-out. The buckling of the side panel rails was checked with Workbench and to improve confidence in the results, a single brace was included at the center of the panel. The final iteration of the side panel design has a mass savings of 14.5% from the original design and can be seen in Figure 3-6c.

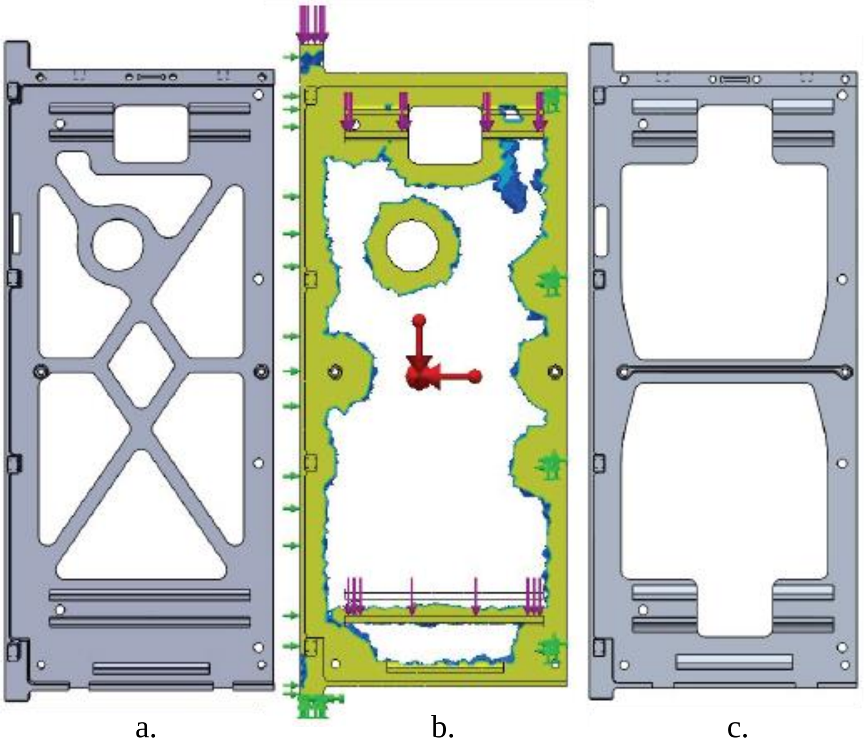


Figure 3-6. SolidWorks Topology Optimization: (a) before topology, (b) simulation results, and (c) optimized design

3.4.6 Vibration Analysis

The launch vehicle to deliver the CubeSat to LEO will impart random vibrations from the rocket, both physically and acoustically. NanoRacks, the launch provider, requires that a physical random vibration test profile must be sustained in each axis for 60 seconds before being approved for flight (NanoRacks 2018). As mentioned previously, the USST will be conducting the required physical testing after design handover, Design Cubed will be responsible for the theoretical analysis. The theoretical vibrational analysis was completed using three different methods:

i.) ANSYS Workbench modal analysis
ii.) Vibrational equivalent quasi-static loading
iii.) ANSYS Workbench random vibrational analysis

First, a modal shape analysis was conducted to gain further insight into the vibrational reactiveness of the design. It is important to note that the deflections and stresses observed within the ANSYS Workbench modal analysis software are not accurate. Workbench was used to identify mode shapes and the frequency at which they occur. The same combined loading pre-stress was applied to three alternate models with varying degrees of cut-outs, as seen in Figure 3-7.

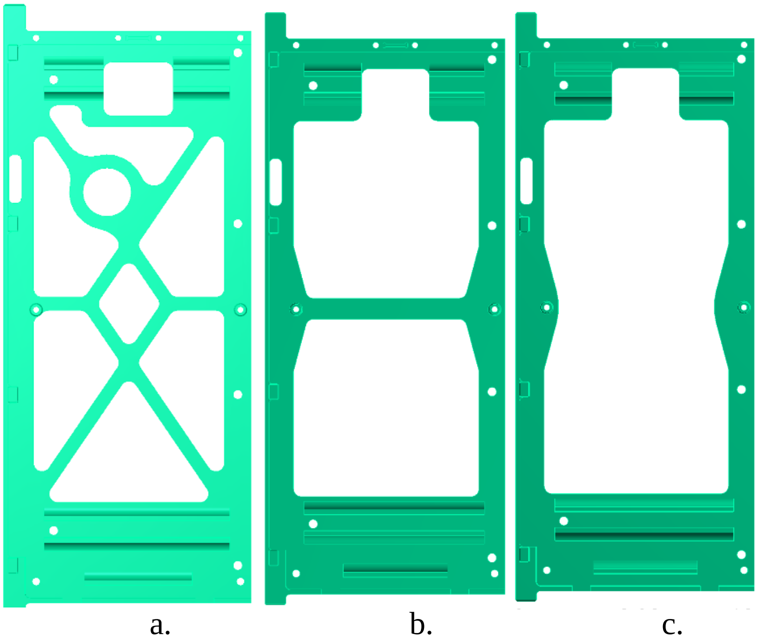

a. b. c.

Figure 3-7. Vibration analysis cut-out design alternatives: (a) Original, (b) Alternate, and (c) Fully Cut

Interestingly, the first four modes of the original cut-out design occurred within the complex cut-out geometry of the side panels. The resulting modes occurred in the 600-700 Hz range and resembled a trampoline. For this reason, the original cut-out design was not used as the risk of the side panels deforming and contacting the launch device was too great. The original cut-out design proved to have little necessity for the strength of the part. The alternate and fully cut-out designs allowed for greater mass savings and eliminated the risk of large deflections due to vibrations.

Evaluating the alternate and fully cut-out designs, the first three modes of each remained consistent with the same trampoline effect occurring previously, but instead within the thin cross member sections around 700-1000 Hz. However, both the alternate and fully cut-out designs had flaws. The next mode of the alternate cut-out design resulted in the same trampoline effect within the side panel at around 850 Hz. Additionally, the fully cut-out design resulted in a torsional mode in the rails at around 925 Hz.

Considering the results of the modal analysis a final design was selected, increasing the modal frequency of the side panel distortion to 1,100 Hz. This was achieved by adding a stiffening rib along the backside of the alternate cut-out design as shown in Figure 3-8.

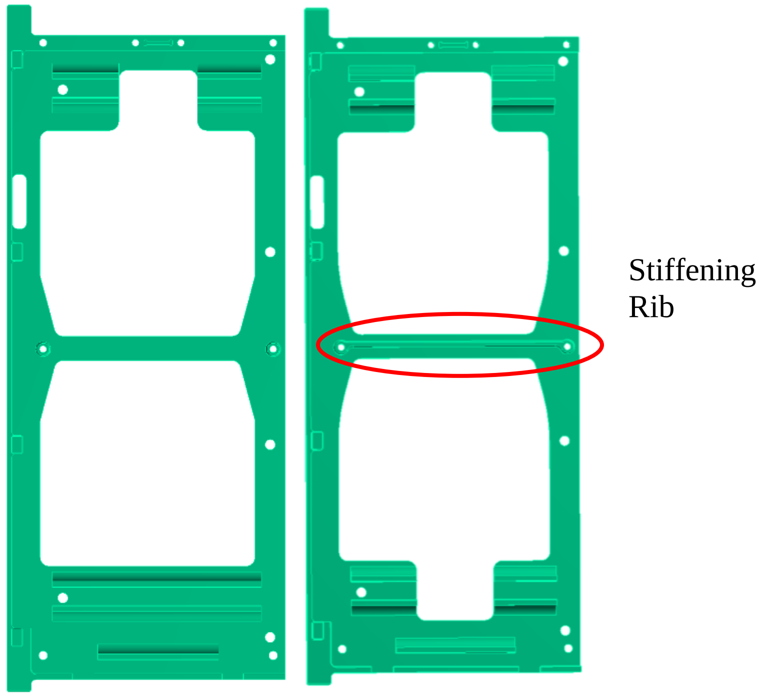


Figure 3-8. Alternative and final cut-out design comparison

Second, from literature, it was found that a root mean square method of equating a random vibration profile to a quasi-static equivalent loading (Brakeboer 2015) could be implemented. As per Appendix G, it can be taken that adding 47.4 G's to the quasi-static loads is a convenient and conservative approach to calculating the deflections and stresses caused by the NanoRacks random vibrations profile. The vibrational equivalent quasi-static loading case was evaluated in ANSYS Workbench and the resulting max stress of 64.6 MPa was observed. It is important to note that this is a conservative estimation and the stresses are well below the yield strength of 6061-T6 aluminum. Maximum total deflections were recorded at 24.4 µm within the thin cross members of the frame but are not large enough to interfere with surrounding components or the launch device.

Third, the random vibrational analysis tool of ANSYS Workbench was used to test the NanoRacks hard-mount random vibration profile. The analysis was conducted with the base or -Z end of the CubeSat fixed and the NanoRacks hard-mount random vibration test profile applied. It is important to note that a pre-stressed model was used for the random vibration testing as per the combined loading case discussed in the design calculations section of the report (Section 3.4.3). The maximum stress observed was 68.4 MPa with 99.7% certainty and maximum deflections in each of the axes (X, Y, Z) were 53.4 µm, 31.3 µm, and 309 µm respectively. The resulting stresses aligned with the quasi-static equivalent case and remain within acceptable tolerances. However, substantial Z-axis deflections of 309 µm are now introduced within the same thin cross member supports identified above. This is significantly greater deflection than the static equivalent case but is still small enough to not interfere with internal components or the launch device.

3.4.7 Bolted Connections

All fasteners shall have two locking mechanisms, as per NanoRacks 4.4.3 (2018), to ensure that at no time in the life of the CubeSat a fastener could back out and become space debris or allow for the CubeSat to disassemble or structurally fail. The primary locking mechanism is to apply sufficient torque to the fastener to elastically deform it and thus create a constant normal force on the threads that is sufficient to lock the fastener in place by friction. The secondary locking feature as chosen by the USST is a NASA outgassing approved thread locking compound, either Loctite 271 or 242. Using the procedure from Shigley’s Mechanical Engineering Design to find the required preload and the torque that needs to be applied to the substrate and fastener is then analysed to ensure the applied stresses do not exceed the limits of the material (Nisbeth and Budynas 2014). The complete bolt preload analysis can be found in Appendix H and a summary of results can be seen in Table 3-3.

Table 3-3. Bolt preload summary of results, preload, required torque, and safety factors

Nominal Thread Size (mm)	Permanent Preload (kN)	Permanent Torque (Nm)	Substrate Thread Shear SF (Von Mises)	Axial Failure SF of Fastener	Torsional Failure SF of Fastener
2.5	1.04	0.391	2.64	1.33	1.15
3	1.57	0.705	2.53	1.33	1.15
8	3.38	4.050	8.35	1.33	3.61

It is important to note that proof strength, S_p, is used in the calculations and is 85% of yield strength, this ensures that statistically the fastener will not reach the yield point. As the interface between the aluminum substrate and the 316 stainless steel fastener is lubricated by the Loctite the friction coefficient is reduced, which must be considered. The proof load and the area of the fastener are used to determine the required preload, this value is then used to find the required torque to friction lock the fastener. Lastly, a check of the substrate and the fastener's modes of failure, shear, axial, and torsion, was conducted with all values being found to be larger than one and thus acceptable. The substrate shear analysis was conducted using the dimensions of the fastener for a conservative approach as the Helicoil dimensions are larger.

To ensure that the primary locking mechanism is successful a repeatable procedure must be followed when installing fasteners and an accurate torque application tool is required. It is also critical to note that each fastener once torqued to the required permanent preload cannot be used again if removed from the substrate as permanent deformation may have occurred.

4.0 Project Plan

The project plan plays a large role in the organization and efficiency with which a project is completed. This chapter will include the project management tools, budget, schedule, and engineering hours breakdown for this project.

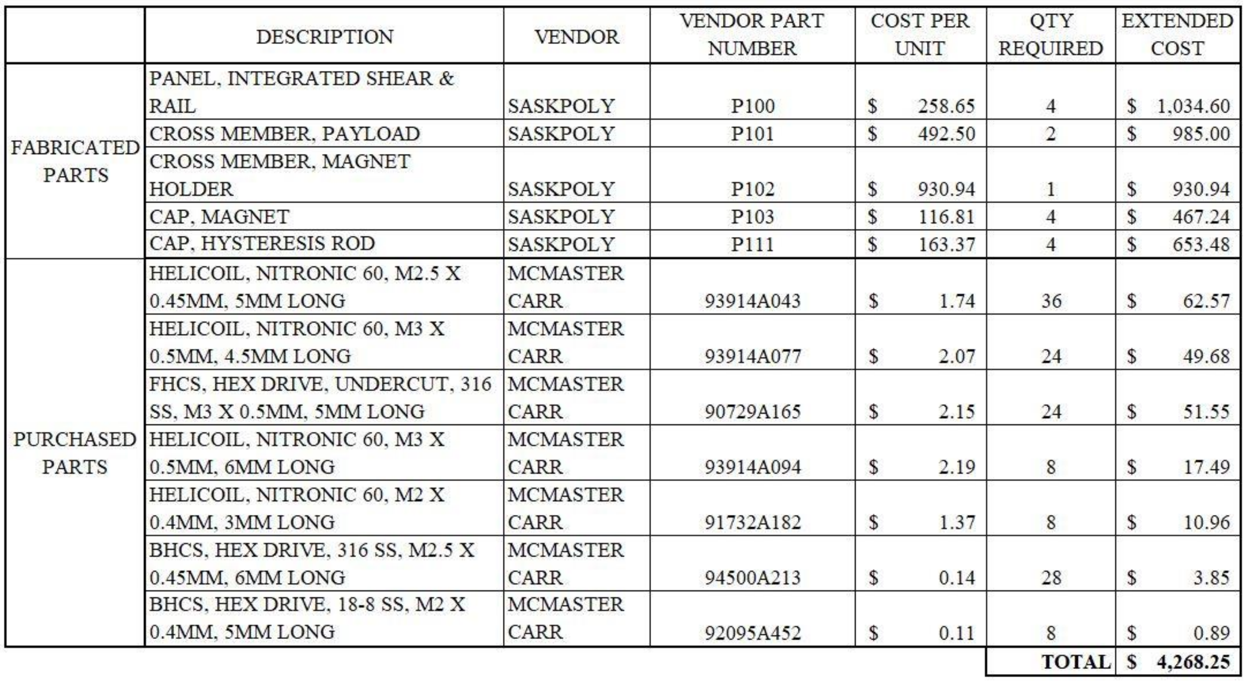
4.1 Project Management Tools

Various project management tools were employed to ensure the success of the project. Tools to handle team communication, file management, and client change requests are required. The team used a multithreaded communications application, Slack, to handle team communication and meeting scheduling. Dropbox was used to handle file management and revision control of all pertinent documents and CAD files. Finally, the team created a change request form, seen in Appendix I, to ensure that ongoing changes from the client were appropriately communicated and approved by both parties. Utilizing these tools was critical in an efficient and smooth operation of collaborative efforts over the duration of the project.

4.2 Budget

A preliminary budget for the fabrication of the CubeSat frame was established at $2,000.00. The budget accounted for materials and labour but excluded the engineering hours and assembly labour costs. A detailed cost estimation updates the project to $4,268.25. A summary of the budget breakdown can be found in Table 4-1. The large increase in price is attributed to the underestimation of manufacturing labour and the addition of a stainless-steel threaded insert for every fastener, at the request of the client. The threaded inserts were not accounted for in the preliminary budget.

Table 4-1. 2U CubeSat project cost breakdown summary



	DESCRIPTION	VENDOR	VENDOR PART NUMBER	COST PER UNIT	QTY REQUIRED	EXTENDED COST
FABRICATED PARTS	PANEL, INTEGRATED SHEAR & RAIL	SASKPOLY	P100	$ 258.65	4	$ 1,034.60
	CROSS MEMBER, PAYLOAD	SASKPOLY	P101	$ 492.50	2	$ 985.00
	CROSS MEMBER, MAGNET HOLDER	SASKPOLY	P102	$ 930.94	1	$ 930.94
	CAP, MAGNET	SASKPOLY	P103	$ 116.81	4	$ 467.24
	CAP, HYSTERESIS ROD	SASKPOLY	P111	$ 163.37	4	$ 653.48
PURCHASED PARTS	HELICOIL, NITRONIC 60, M2.5 X 0.45MM, 5MM LONG	MCMASTER CARR	93914A043	$ 1.74	36	$ 62.57
	HELICOIL, NITRONIC 60, M3 X 0.5MM, 4.5MM LONG	MCMASTER CARR	93914A077	$ 2.07	24	$ 49.68
	FHCS, HEX DRIVE, UNDERCUT, 316 SS, M3 X 0.5MM, 5MM LONG	MCMASTER CARR	90729A165	$ 2.15	24	$ 51.55
	HELICOIL, NITRONIC 60, M3 X 0.5MM, 6MM LONG	MCMASTER CARR	93914A094	$ 2.19	8	$ 17.49
	HELICOIL, NITRONIC 60, M2 X 0.4MM, 3MM LONG	MCMASTER CARR	91732A182	$ 1.37	8	$ 10.96
	BHCS, HEX DRIVE, 316 SS, M2.5 X 0.45MM, 6MM LONG	MCMASTER CARR	94500A213	$ 0.14	28	$ 3.85
	BHCS, HEX DRIVE, 18-8 SS, M2 X 0.4MM, 5MM LONG	MCMASTER CARR	92095A452	$ 0.11	8	$ 0.89
					TOTAL	**$ 4,268.25**

4.3 Project Schedule

A schedule was developed during the project initiation phase. Design Cubed was able to adhere to the project schedule, as outlined in the Gantt Chart found in Appendix J. Some of the major milestones of the project included:

i.) Kick-off meeting with client, industry advisor, and faculty advisor.

ii.) Develop a strong and clear understanding of the problem background including objectives, functions, and constraints of design alternatives.

iii.) Investigate potential design alternatives and selection of the design alternative using tools such as weighted decision matrices.

iv.) Detailed design and analysis using concepts learned in coursework and industry-standard tools, such as SolidWorks and ANSYS.

v.) Project closeout by completing the fabrication of a prototype and exit meetings with the client and industry/faculty advisors.

4.4 Engineering Hours

It was originally estimated that the project completion would require 791 engineering hours. Design Cubed completed the CubeSat project in 722.5 hours, 9.5% less than estimated. The majority of the engineering hours were spent completing presentations/reports and analysis at 236.5 and 186 hours, respectively. Team and faculty advisor meetings used 17.2% of the time, required for effective communication and refocusing of individual efforts. Research and planning accounted for 6.8% of the time, paramount for establishing a solid foundation for which future efforts will be focused. Figure 4-1 shows the engineering hour breakdown of where time was spent and on which tasks.

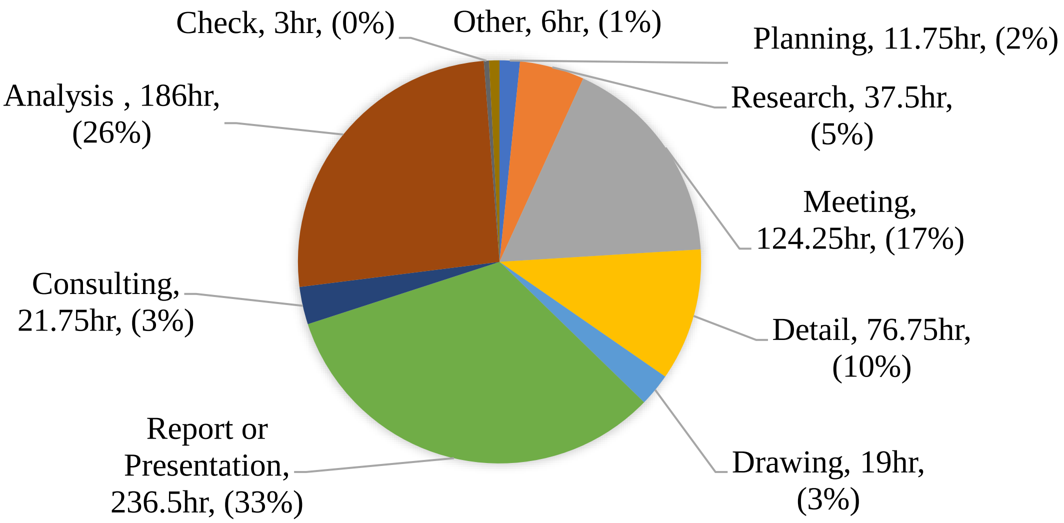


Figure 4-1. Project management engineering hour breakdown summary

5.0 Planning for Next Project Phase

At the completion of this project, the prototype frame and report will be delivered to the client and an exit meeting will occur to complete the transfer of knowledge. Project closeout will consist of creating high-level project management documents to guide the next team responsible for the CubeSat.

The frame will be utilized for testing to confirm analysis and to act as an engineering model to practice assembly of the complete CubeSat before a flight-ready frame is manufactured. The flight-ready frame will incorporate lessons learned in the manufacturing, assembly, and testing of the prototype frame. For further insights please refer to the recommendations section (Section 9.1) of the report.

5.1 Schedule

The CubeSat frame is one part of the CubeSat with many systems and groups collaborating on it, and as such the timeline for the remainder of this project is focused on the order of milestones and less on the time between milestones. For the future project schedule see the Gantt chart in Appendix K.

5.2 Future Cost

The cost of machining for future versions of the frame should be similar to the cost of the prototype as long as revisions to the design are minimal, labour savings may occur if fixtures for machining can be reused. As each frame is a custom one-off there are no economies of scale to lower the cost of manufacturing or increase the speed of manufacturing each frame. Possible additional costs will be incurred by the application of surface coatings. The client is investigating the cost of Type-3 anodizing for the flight model, which was not used on the prototype to reduce the time required for manufacturing.

Payback analysis is not applicable as there is no revenue stream from the creation or use of the CubeSat frame.

5.3 Future Project Management Uncertainties

At the completion of this report, a prototype frame design has been manufactured which gives confidence in future scheduling and budget estimates as well as the ability to analyse the accuracy of the prototype project schedule. A risk analysis has been completed for the next phase of the project and can be found in Appendix L. Cost overruns is considered a critical risk as this would limit or prevent further frames from being manufactured. To mitigate this, continuing good relations with Saskatchewan Polytechnic must be maintained and machining hours must be used only for mission-critical parts. The loss of this capstone groups report with design details and analysis has also been identified as a high risk to future phases of the project. To mitigate this cloud-based storage is used along with backup copies of all files.

6.0 Sustainability Considerations

This chapter will outline the decisions made by Design Cubed to ensure their final product addresses sustainability concerns and the environmental impact of the project. Areas of concern as well as mitigation strategies, if available, will be discussed to demonstrate Design Cubed has done its due diligence. Any concerns or areas of uncertainty will also be noted for future work and investigation.

6.1 Environmental Considerations

The design of a CubeSat frame is somewhat unique from a sustainability perspective as there are three discrete environments to consider: the Earth, the ISS, and LEO. The two latter environments are only considered within the aerospace domain and have significantly different conditions to consider.

6.1.1 Earth Environment

The frame components are manufactured from aluminum, which produces an average of 13.3 kg of carbon per kg of aluminum refined (CES 2017). Design Cubed has compiled the raw material required for manufacturing and assigned the frame a manufacturing carbon footprint. Table 6-1 shows the stock material required for each part and the total resultant emissions. The method used to calculate this footprint can be found in Appendix M.

The CubeSat will be launched into space within an ISS resupply mission propelled by a large-scale rocket, whose exhaust from burning fuel will release significant carbon emissions into Earth's atmosphere. To estimate the carbon footprint resulting from the launch, Design Cubed assigned the frame a fraction of the total emissions as part of the payload. A total of 0.845 kg of carbon dioxide will be emitted into Earth's atmosphere as a result of launching the frame to the ISS, roughly three times the weight of the frame itself. This is considered an acceptable value given the requirements to launch payloads into space are tremendous. There also exists no alternative option to launch CubeSats and as such, there is no way to mitigate this impact. The method used to determine this footprint has been included in Appendix N.

The total emissions for the frame are summarised in Table 6-1. The total emissions are 76.9 kg of carbon dioxide, which is over 200 times the mass of the frame. This is a very high number, but it is considered acceptable because there are no plans for mass production of the design; the prototype model produced in this project is the only product within scope. For a mass-produced product, this would be considered unacceptable.

Table 6-1. Summary of CubeSat frame component stock mass and emissions

Part	QTY	Stock mass (kg_{Al})	Emissions (kg_{CO_2})
P100	2	4.80	63.55
P101	2	0.36	4.71
P102	1	0.53	7.06
P103	4	0.05	0.67
P111	4	7.54E-4	0.04
Launch	▨	▨	0.85
		TOTAL	76.88

6.1.2 International Space Station Environment

Onboard the ISS, the air supply for the crew is limited and difficult to filter or replace. The frame must not release any particulates into the air that could pollute the supply and pose a threat to the astronauts. Design Cubed’s selected frame material, 6061-T6 aluminum, is not known to release particulates (ATSDR 2008) and is therefore confident the frame will not pose a threat to the crew of the ISS.

6.1.3 Low Earth Orbit Environment

Spacecraft operating within the immediate proximity of the Earth over the years have produced a vast field of debris that has essentially polluted the region with collision hazards, threatening to damage all other equipment placed in the same orbit. Known as space junk, this debris ranges from intact yet obsolete satellites to paint chips, all travelling at such high speeds that they can cause catastrophic damage in a collision. It is required to design the frame such that it will not contribute to this debris by failing in orbit, ejecting its components into space and threatening other current and future spacecraft. The frame material has been selected from NASA’s outgassing list of materials (NASA 2018) which guarantees its capability to withstand the LEO space environment without degrading. This adequately mitigates the risks of producing debris and no further steps need be taken.

In the unlikely event that a large piece of debris strikes the frame in orbit, the frame will almost undoubtedly fail, and the CubeSat will be reduced to its components, contributing to existing space junk. This risk was not considered in design as not enough information is known about a potential impact to properly design for prevention.

6.1.4 End of Life Considerations

Design Cubed’s manufactured prototype will be used primarily by its client for testing CubeSat systems and performing physical testing. Assuming the design survives all testing, it has been indicated by the USST that it will become a display piece or be given to a sponsor of the project. The final flight-ready model used for the CubeSat will be placed in a degrading orbit to burn and disintegrate in the atmosphere over a one year period. The frame has a very small relative mass to the Earth’s atmosphere and is not expected to produce any adverse effects. Neither of these end-of-life situations give rise to concerns and are considered safe, low impact results. Thus, no further action need be taken.

6.2 Social Considerations

The frame and CubeSat are not permanent installations, nor will they operate in a space where they can directly affect most individuals’ lives. However, there are a select group of stakeholders for the project, and considerations involving this group are detailed in this section.

The frame will be launched within a resupply mission to the ISS, containing expensive equipment and crucial supplies for astronauts onboard the station. It is important that the CubeSat handle launch loads appropriately and not risk the launch in any way to avoid massive collateral damage. Suitability for launch conditions is covered in Appendix B and has been shown to be acceptable. No other concerns with this environment exist.

As the USST CubeSat is tested, handled, mounted into the CubeSat deployer, and finally launched into orbit from the ISS, it will be handled by various personnel. These individuals are at risk of any safety hazards from the frame and these must be minimized. The sole concern Design

Cubed has in this regard are sharp edges or burrs remaining from machining. The final product will have all edges deburred to prevent cuts and scrapes from being a concern.

6.3 Economic Considerations

The USST CubeSat Project is a research focused, educational program that is not-for-profit and supported by sponsors and donations (USST 2018). As a result, the frame design proposed by Design Cubed is not constrained by needs to profit from the design but must still be inexpensive to be feasible for the client to produce. The manufacturing costs of the frame have been covered by a partnership between the USST and Saskatchewan Polytechnic, so the final cost of the design is not a great constraint for Design Cubed.

The final frame design is required to be functional for the full duration of testing, launch, and orbiting, approximately two years. Failure at any of these times could result in absolute mission failure. Design Cubed’s frame has been designed to sustain the worst load cases expected, the launch conditions, as shown in section 3.4, Design Calculations, of this report and is not expected to fail from minor loads during other conditions. The materials for the frame have been chosen from the NASA outgassing material list (NASA 2018) to prevent failure from factors in the space environment. The only other stress expected to be imparted on the frame is thermal cycling in orbit, which is not within the project scope. Given these design considerations, Design Cubed is confident that the frame will last for the full two-year lifecycle.

7.0 Codes and Standards

This chapter details the relevant documents that include requirements and best practices for the CubeSat frame design. Design Cubed adhered to the following documents during design to ensure the frame meets the needs of the client in the fullest capacity.

The design of a CubeSat frame is not primarily governed by traditional engineering associations such as ASME, IEEE, or others but rather by the organizations the client has partnered with. Those organizations and their standards are as follows:

7.1 NanoRacks: NRCSD Interface Definition Document (NR-NRCSD-S0003)

This document is from the client's launch provider and lists the requirements for a CubeSat to properly interface with the Nanoracks CubeSat Deployer (NRCSD, referred to as the CubeSat deployer for simplicity in this report) and be approved for flight. The details in this document are primarily focused on geometry and material specifications, but also extend to mass properties and load cases. All requirements in NR-NRCSD-S0003 are hard constraints, not best practices. Relevant sections are summarized below.

NR-NRCSD-S0003 Section 4.1: Rail Properties

This section includes requirements for the four rails of the CubeSat frame. At a high level, this section indicates the following conditions:

i.) The requirement of four rails at the edges of the payload envelope
ii.) The length along the Z-axis and the width of the rails along the X and Y faces
iii.) The surface properties of the rails, such as surface hardness and roughness

The details of these requirements were noted at the beginning of the project and incorporated into detailed design. Applicable tolerances were included in the final drawings, and the choice of materials was affected by the surface property requirements.

NR-NRCSD-S0003 Section 4.12: Mass Properties

This section includes details on the mass and location of the center of mass within the CubeSat. Details include:

i.) The total mass of the CubeSat

ii.) The permissible deviation from the geometric center of the actual center of mass

To satisfy these requirements, Design Cubed used the information provided by the client on the secondary structures and components of the CubeSat to determine acceptable parameters for the frame. An acceptable mass budget for the project was derived, and the center of mass was evaluated with all components mounted to the frame during design to ensure compliance. Design Cubed is confident the frame's mass is sufficiently low that the CubeSat will not become overweight, nor will its center of mass be out of specification.

NR-NRCSD-S0003 Section 4.3 Acceleration Loads and Vibrations

Here the load factors and random vibration expected during the launch of the CubeSat are provided. Load factors are given as accelerations and vibrations in Hertz ranges. Design Cubed has incorporated these into their structural analysis, which is detailed in the Design Calculations section of this report (Section 3.4).

7.2 ASTM Standard E595-15

Many materials commonly used on Earth fail in unexpected ways in the space environment. It is best practice to select materials for design from a list of previously flown or tested materials to prevent unexpected problems once in orbit. Materials are tested for spacecraft suitability using the ASTM standardized test E595-15. This test involves submitting a material at a prescribed temperature and humidity to a vacuum environment for 24 hours and recording two parameters; total mass loss (TML) and collected volatile condensable materials (CVCM). A result of less than 1.00 % TML and 0.10% CVCM approves the material for use in spacecraft.

To avoid testing candidate materials, Design Cubed took advantage of a publicly available record of materials known to have passed ASTM E595-15 produced by NASA (2018). Candidate materials were limited to those included on the list, ensuring that all materials used satisfied the requirements for use in spacecraft. For this reason, the NASA outgassing list was considered the constraining document instead of ASTM E595-15, as seen in section 1.5 of this report.

7.3 CSA: Canadian CubeSat Specification Requirements

The CSA has provided this document as a list of requirements that must be met for the CubeSat to be eligible for launch. Regarding details pertaining to the primary structural frame of the CubeSat, all information has been found to be derived directly from NanoRacks' NR-NRCSD-

S0003. These constraints will not be repeated in this report, as they have been acknowledged and followed as part of adhering to NanoRacks requirements, as outlined in Appendix B.

7.4 PC104 Standard

This standard governs the properties of CubeSat appropriate PCBs. Of note for this project were the dimensions specified for PCBs, which make up the payload of the CubeSat. The interface points for the interior payload of the frame were designed in order to suit a PCB stack following the PC104 standard. The space required for the PCBs was also considered when designing the frame so that adequate space was available to install the PCBs and prevent frame-to-PCB contact during the mission.

7.5 ISO 31000: 2009

ISO 3100: 2009 is a set of guidelines for risk management that can be applied to any project. Design Cubed used the following best practices from this standard to mitigate risks within the project:

i.) Avoiding the risk by deciding not to start or continue with the activity that gives rise to the risk
ii.) Accepting or increasing the risk in order to pursue an opportunity
iii.) Removing the risk source
iv.) Changing the likelihood
v.) Changing the consequences
vi.) Sharing the risk with another party or parties (including contracts and risk financing)
vii.) Retaining the risk by informed decision

The application of these practices is discussed in Chapter 7 and was used when developing the risk assessment matrix available in Appendix O. The application of these practices allowed Design Cubed to be prepared for issues as they arose and able to react quickly to maintain the project schedule. Fortunately, none of the expected risks became concerns to be addressed, so the developed mitigation strategies were never used.

8.0 Risk Management

The following chapter will describe in detail the risk management approach used by the Design Cubed team. A summary of the resulting assessment over the lifecycle of the project will be presented and key findings highlighted.

8.1 Risk Management Approach

The risk management approach involved the continuous cycle of identification, assessment, mitigation, and review of project risks. Risks were first identified through a brainstorming activity at the initiation of the project considering objectives, stakeholders, and what could possibly go wrong. Identified risks were then added to a risk assessment matrix and evaluated based on the likelihood of the event as well as the resulting severity. Additional risks identified throughout the project were then added to the matrix and evaluated accordingly. Each risk was then assigned a total score based on the likelihood and severity of the event. Risks deemed unacceptable were then mitigated according to ISO 31000:2009. This standard is discussed further in Chapter 7 (Section 7.5).

Having identified the applicable risk mitigation strategies, the residual risk was then scored once again on the risk matrix and assigned a mitigated risk score (MRS). Evaluating the MRS with Design Cubed's risk tolerance level then dictated if the mitigated risk level was acceptable. Mitigations then became assigned action items to members within Design Cubed.

8.2 Risk Assessment

Through a preliminary brainstorming session, Design Cubed identified that the risks aligned with two different categories being management risks and design risks. The highest-ranked management risks scored within the extreme risk ranking category before mitigation implying that the consequences to the project are extreme and it is advised not to proceed. The risk entailed a substantial budget reduction, effecting project deliverables. The following risk mitigation strategies were implemented:

i.) Clear documentation of material, fastener, and tool requirements and budgets to the USST client (Seamus Woodward-George + Daniel Franko + Aaron Peters)

ii.) Consistent communication with the manufacturer, Saskatchewan Polytechnic (Seamus Woodward-George) iii.) Schedule machine time and drawing handover well in advance (Seamus Woodward-George + Daniel Franko)

iv.) Preliminary agreement with the client that in the event of a substantial budget reduction Design Cubed could remove prototype manufacturing from the required scope and deliverables (All)

Through accountability and preliminary action, the extreme risk ranking was lowered to a medium risk and within Design Cubed's acceptable risk tolerance. For further detail, a complete risk matrix and risk evaluation can be referenced in Appendix O.

9.0 Conclusions

This report outlined that the client saw issues with serviceability and customization of commercial off the shelf units (COTS) for their specific CubeSat. The client requested a design for a CubeSat frame to be optimized for their specific objectives. Through an iterative and creative design process, an alternative that is unique from COTS designs was achieved. With integrated rails and shear panels, the overall number of parts was able to be reduced. By adding locating and load transferring ribs, serviceability and rigidity of the frame were improved.

An iterative design process was used where COTS units were 3D printed to find shortcomings in their design. The final design alternative was preliminarily modelled and 3D printed as well to confirm design choices and find further shortcomings. Iterating the selected design alternative, mass savings were achieved by using SolidWorks Topology Optimization. Individual part masses were reduced by roughly 14% from their original designs to meet client objectives of reducing the frame mass.

Having obtained an iterated and polished conceptual design, both analytical and finite element methods of analysis were completed of the CubeSat frame based on loads applied during launch conditions. Design tools, such as ANSYS APDL and Workbench, were used to verify that the deflections and stresses of the frame were acceptable. The final design of the frame sees a maximum deflection of 0.309 mm with a nominal maximum stress of 68.4 MPa, from quasi-static loading and random vibrations. The deflections and stresses were determined to be acceptable as the deflections do not cause interference and stresses are well below the yield strength of the material. Evaluation of mode shapes and frequencies also yields acceptable results, and the final design presented has been optimized to minimize modal effects.

The design was completed using 723 engineering hours. The final design uses raw material, purchased parts, and manufacturing labour for a total design cost of $4,268.25. The nature of the project is for a one-off product and does not present an opportunity to recover the costs, thus there is no payback period. The project closeout will consist of a client meeting to assist in knowledge transfer and working files of the project will be shared.

The CubeSat requires environmental considerations from emissions caused by the design fabrication and the transportation of the CubeSat to LEO. The fabrication and launch of the CubeSat to the ISS will release 76.0 kg and 0.845 kg, respectively, of CO_2 to the atmosphere.

The project recognized and adhered to code, standards, and requirements outlined by multiple entities. NanoRacks, the CubeSat launch provider, outlined requirements for interfacing and flight approval. NASA provided guidelines regarding the material selection of the CubeSat frame for use in a vacuum. Additionally, CSA and PC104 standard were recognized and followed.

In conclusion, Design Cubed was successfully able to deliver a unique and custom design for the client that is competitive with COTS units. The design adheres to the many requirements and specifications outlined by NanoRacks and the client. The design was optimized to improve the serviceability, ease of assembly, and ease of manufacture. Design Cubed retains high confidence in the success of the design in service from rigorous analytical and finite element analysis.

9.1 Recommendations

Over the course of the project, Design Cubed made several observations of details that were either out of scope or the strict project deadline did not allow to be investigated. A list of such observations has been provided below as recommendations to the USST for future work.

1. Complete testing to verify or obtain certification that material properties of fasteners purchased are identical to values in bolt pretension calculations.
2. Investigate the design of the magnet holder assembly and magnet cap as the design may require better venting.
3. Design modifications are necessary if mass manufacturing is required. Design is currently not economically optimized for mass production but was justified for fabricating a single unit.
4. Vibrational analysis of solar panel substrate and client payload were out of scope but will need to be completed in the future. The client may add additional material to shear panels to support the solar panel substrate or add additional cross members to support the payload.

5. In consultation with industry experts, it was recommended that less than 1 Ω of resistance exist between any two points on the frame for the grounding of electrical components. This should be verified by physical measurements.
6. Design changes to secondary structure components, for example the addition of inhibit switches, or changes to the payload should be followed up with checking that center of mass is within the acceptable range of the center of geometry. As detailed in section 3.4.4, deviation from the geometric center of mass has a significant effect on stresses in the frame.
7. Considerations should be made for jigging, fixturing, and storage of the CubeSat while in-service before flight. Work instructions for frame assembly and payload servicing should be completed as per the drawings in Appendix D.

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Appendix A: Responsibility Assessment Matrix

The following appendix will provide an in-depth view of the roles and responsibilities of key stakeholders involved in the CubeSat design project using a responsible, accountable, consulted, and informed (RACI) responsibility assessment matrix. Table A-1 displays in detail key stakeholders in the CubeSat design project and the associated roles and responsibilities.

Table A-1. CubeSat project key stakeholder RACI responsibility assessment matrix

PROJECT TASK OR DELIVERABLE	**DESIGN CUBED**	**PRIMARY CLIENT**	**INDUSTRY CLIENT**	**MANUFACTURER**	**FACULTY ADVISOR**
LITERATURE REVIEW	R/A	I	I	I	I
PROJECT PLANNING & IDEATION	R/A	I	C	I	I
ALTERNATIVE ANALYSIS	R/A	C	C	I	C
PROJECT PLAN MEMO & PRESENTATION	R/A	I	I	I	I
DESIGN SELECTION	R/A	C	C	C	C
DESIGN ANALYSIS	R/A	I	I	I	C
INTERIM TECHNICAL REVIEW	R/A	I	C	I	C
MANUFACTURING	A	I	I	R	I
FINAL REPORT	R/A	I	I	I	C
DESIGN EXPO	R/A	I	I	I	C
CLIENT EXIT MEETING	R/A	R	R	I	I

Additionally, **Error! Not a valid bookmark self-reference.** provides background context for each of the responsibility assessment matrix assignments: R, A, C, and I.

Table A-2. RACI responsibility assessment matrix legend

RESPONSIBLE**:** **R**	Party Responsible for completing the task or deliverable. Every task needs one or more Responsible parties.
ACCOUNTABLE**:** **A**	This party delegates work and is the last to review the task or deliverable before it's deemed complete. The Responsible party may also serve as the Accountable party. One Accountable party must be assigned to each task or deliverable.
CONSULTED**:** **C**	Consulted parties are typically the people who provide input based on either how it will impact their future project work or their domain of expertise on the deliverable itself.
INFORMED**:** **I**	These team members simply need to be kept in the loop on project progress, rather than roped into the details of every deliverable.

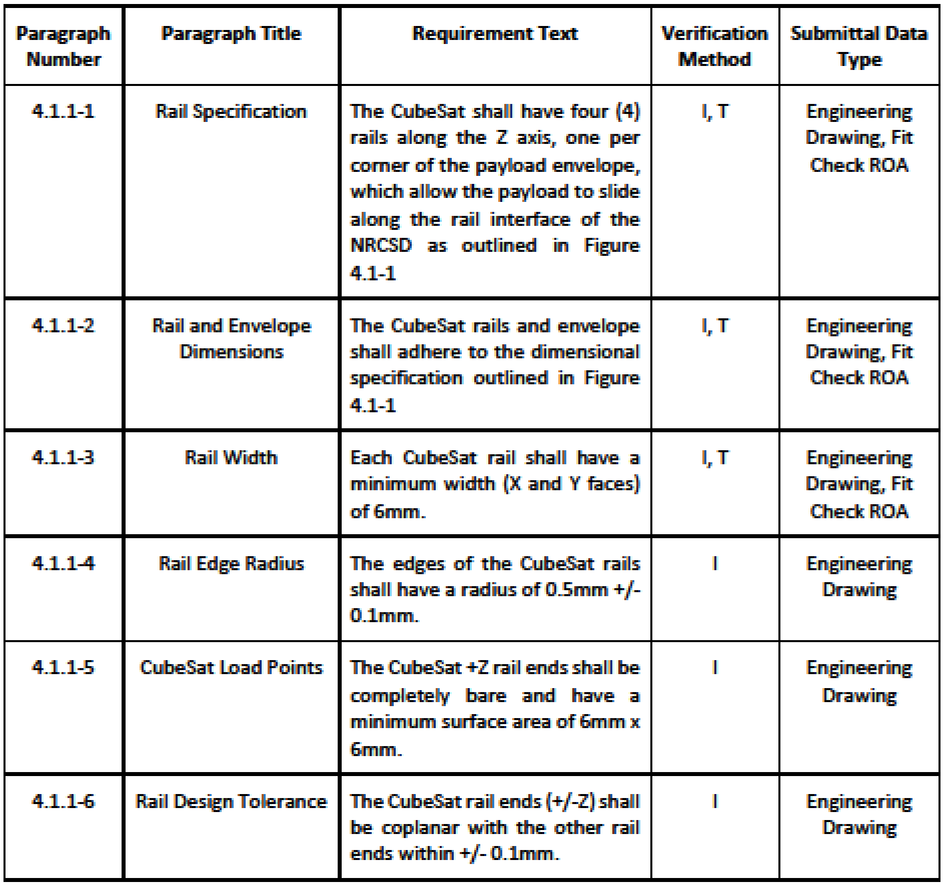
In conclusion, The Design Cubed team is dually the responsible and accountable party for the majority of tasks until handover to manufacturing. The RACI responsibility assessment matrix is an effective tool for discerning a clear and concise division of roles and responsibilities. As well, the matrix allows for clear identification of when consulting resources can/should be utilized utilizing resources effectively and efficiently.

Appendix B: Launch Requirements

The following appendix will outline the specific launch requirements as specified by the various parties involved in the CubeSat project including the launch provider NanoRacks, the CSA as well as NASA. Each of the following sections will provide a reference to full documentation and summarize the applicable requirements of each.

B.1 NanoRacks Launch Requirements

The following section will outline the specific launch requirements as specified by NanoRacks applicable to the Design Cubed CubeSat design. The excerpts represented are in reference to the NanoRacks CubeSat Deployer Interface Definition Document: NR-NRCSD-S0003. Specifically, section 5: Requirements Matrix (NanoRacks 2018).



Paragraph Number	Paragraph Title	Requirement Text	Verification Method	Submittal Data Type
4.1.1-1	Rail Specification	The CubeSat shall have four (4) rails along the Z axis, one per corner of the payload envelope, which allow the payload to slide along the rail interface of the NRCSD as outlined in Figure 4.1-1	I, T	Engineering Drawing, Fit Check ROA
4.1.1-2	Rail and Envelope Dimensions	The CubeSat rails and envelope shall adhere to the dimensional specification outlined in Figure 4.1-1	I, T	Engineering Drawing, Fit Check ROA
4.1.1-3	Rail Width	Each CubeSat rail shall have a minimum width (X and Y faces) of 6mm.	I, T	Engineering Drawing, Fit Check ROA
4.1.1-4	Rail Edge Radius	The edges of the CubeSat rails shall have a radius of 0.5mm +/- 0.1mm.	I	Engineering Drawing
4.1.1-5	CubeSat Load Points	The CubeSat +Z rail ends shall be completely bare and have a minimum surface area of 6mm x 6mm.	I	Engineering Drawing
4.1.1-6	Rail Design Tolerance	The CubeSat rail ends (+/-Z) shall be coplanar with the other rail ends within +/- 0.1mm.	I	Engineering Drawing

4.1.1-7	Rail Length	The CubeSat rail length (Z axis) shall be the following (+/- 0.1mm): a. 1U rail length: 113.50mm b. 2U rail length: 227.00mm c. 3U rail length: 340.50mm d. 4U rail length: 454.00mm e. 5U rail length: 567.5mm f. 6U rail length: 681 to 740.00mm	I, T	Engineering Drawing, Fit Check ROA
4.1.1-8	Rail Continuity	The CubeSat rails shall be continuous. No gaps, holes, fasteners, or any other features may be present along the length of the rails (Z-axis) in regions that contact the NRCSD rails.	I	Engineering Drawing
4.1.1-9	Rail Envelope	The *minimum* extension of the +/-Z CubeSat rails from the +/-Z CubeSat faces shall be 2mm.	I	Engineering Drawing
4.1.1-10	Mechanical Interface	The CubeSat rails shall be the only mechanical interface to the NRCSD in all axes (X, Y and Z axes).	I, T	Engineering Drawing, Fit Check ROA
4.1.1-11	Rail Hardness	The CubeSat rail surfaces that contact the NRCSD guide rails shall have a hardness equal to or greater than hard-anodized aluminum (Rockwell C 65-70).	I	Materials List
4.1.1-12	Surface Roughness	The CubeSat rails and all load points shall have a surface roughness of less than or equal to 1.6 µm.	I	Materials List
4.1.2-1	Mass Limits	The CubeSat mass shall be less than the maximum allowable mass for each respective payload form factor per Table 4.1-1	T	Integration ROA
4.1.2-2	Center of Mass	The CubeSat center of mass (CM) shall be located within the following range relative to the geometric center of the payload. a. X-axis: (+/- 2cm)	I	Safety Data Template

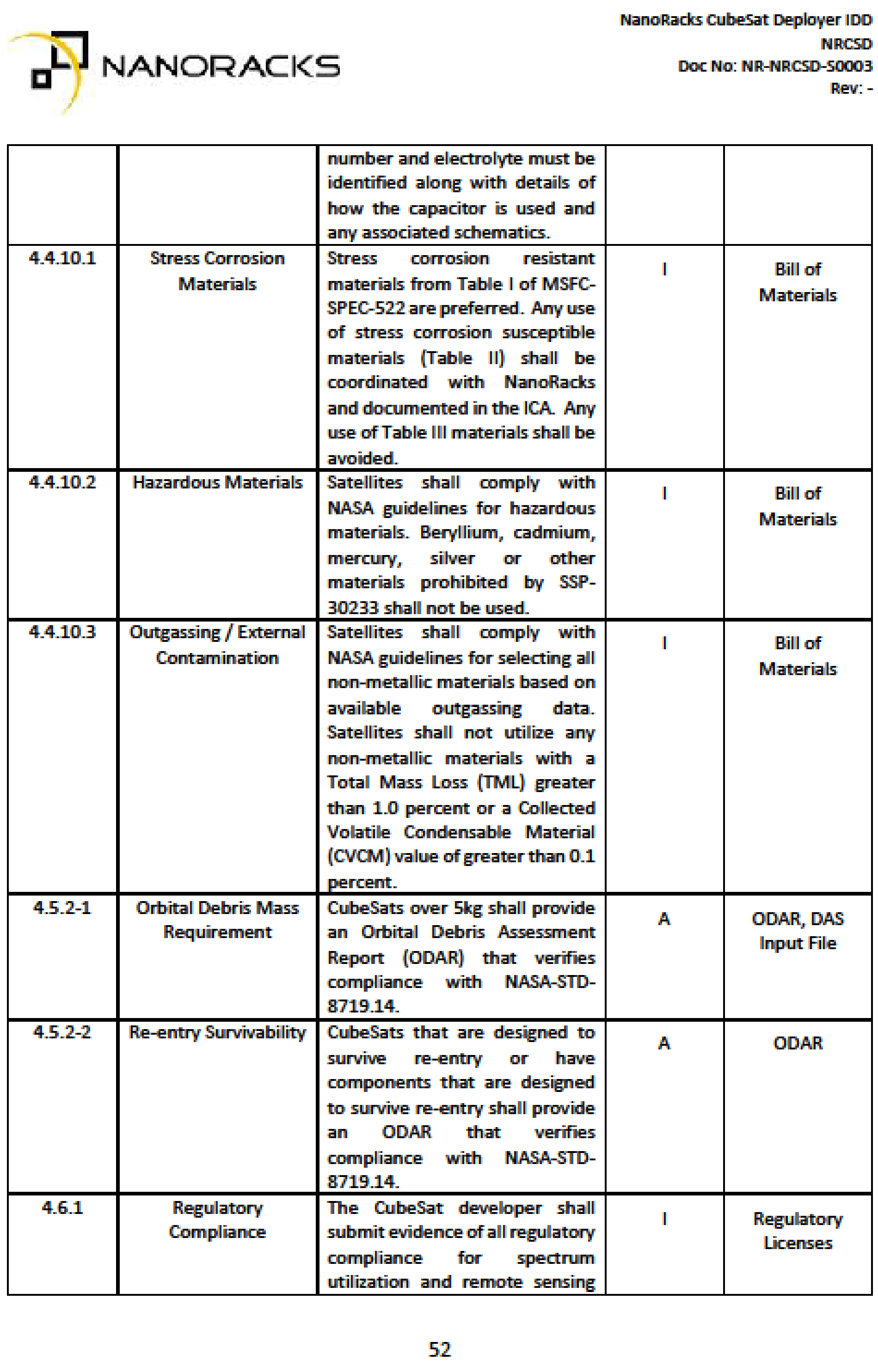
		b. Y-axis: (+/- 2cm) c. Z-axis: i. 1U: (+/- 2cm) ii. 2U (+/- 4cm) iii. 3U (+/- 6cm) iv. 4U (+/- 8cm) v. 5U (+/- 10cm) vi. 6U (+/- 12cm)		
4.1.3-1	RBF / ABF Access	The CubeSat shall have a remove before flight (RBF) feature or an apply before flight (ABF) feature that is physically accessible via the NRCSD access panels on the +Y face of the dispenser.	I, T	Engineering Drawing, Fit Check ROA
4.1.4-1	Deployment Switch Requirement	The CubeSat shall have a minimum of three (3) deployment switches that correspond to independent electrical inhibits on the main power system (see section on electrical interfaces).	I, T	Electrical Schematic, Fit Check ROA
4.1.4-2	Plunger Switch Location	Deployment switches of the pusher/plunger variety shall be located on the rail end faces of the CubeSat's -Z face.	I, T	Electrical Schematic, Fit Check ROA
4.1.4-3	Roller Switch Location	Deployment switches of the roller/lever variety shall be embedded in the CubeSat rails (+/- X or Y faces).	I, T	Electrical Schematic, Fit Check ROA
4.1.4-4	Switch Contact Surface Area	Roller/slider switches shall maintain a minimum of 75% surface area contact with the NRCSD rails (ratio of switch contact to NRCSD guide rail width) along the entire Z axis.	I	CAD
4.1.4-5	Switch Reset	The CubeSat deployment switches shall reset the payload to the pre-launch state if cycled at any time within the first 30 minutes after the switches close (including but not limited to	I	Safety Data Template

		radio frequency transmission and deployable system timers).		
4.1.4-6	Switch Captivation	The CubeSat deployment switches shall be captive.	I	Engineering Drawing
4.1.4-7	Switch Force	The force exerted by the deployment switches shall not exceed 3N.	I	Switch Datasheet
4.1.4-7	Total Switch Force	The total force of all CubeSat deployment switches shall not exceed 9N.	I	Switch Datasheet
4.1.5-1	Deployable Systems Restraint Mechanisms	CubeSat deployable systems (such as solar arrays, antennas, payload booms, etc.) shall have independent restraint mechanisms that do not rely on the NRCSD dispenser.	I, T	Safety Data Template, Fit Check ROA
4.2	Electrical System Interface Requirements	-	-	-
4.2.1	Electrical System Design	-	-	-
4.2.1-1	Power Storage Device Location	All electrical power storage devices shall be internal to the CubeSat.	I	Safety Data Template
4.2.1-2	Post-Deployment Timer	CubeSat shall not operate any system (including RF transmitters, deployment mechanisms or otherwise energize the main power system) for a minimum of 30 minutes where hazard potential exists. Satellites shall have a timer (set to a minimum of 30 minutes and require appropriate fault tolerance) before satellite operation or deployment of appendages where hazard potential exists.	I, T	Safety Data Template
4.2.1-3	Electrical Inhibits	The CubeSat electrical system design shall incorporate a minimum of three (3) independent inhibit switches	I	Electrical Schematic

		actuated by physical deployment switches as shown in Figure 4.2-1. The satellite inhibit scheme shall include a ground leg inhibit (switch D3 on Figure 4.2-1) that disconnects the batteries along the power line from the negative terminal to ground.		
4.2.1-4	Ground Circuit	The CubeSat electrical system design shall not permit the ground charge circuit to energize the satellite systems (load), including flight computer (see Figure 4.2-1). This restriction applies to all charging methods.	I	Electrical Schematic
4.2.1-5	RBF / ABF Requirement	The CubeSat shall have a remove before flight (RBF) feature or an apply before flight (ABF) feature that keeps the satellite in an unpowered state throughout the ground handling and integration process into the NRCSD.	I, T	Electrical Schematic, Fit Check ROA
4.2.1-6	RBF / ABF Functionality	The RBF /ABF feature shall preclude any power from any source operating any satellite functions except for pre-integration battery charging.	I	Electrical Schematic
4.2.1-7	Wire Requirement	The CubeSat Electronics Power System (EPS) shall have no more than six (6) inches of wire 26AWG or larger between the power source (i.e. battery pack) and the first electrical inhibit (MOSFET or equivalent).	I	Safety Data Template
4.3.2-1	Random Vibration Environment	The CubeSat shall be capable of withstanding the random vibration environment for flight with appropriate safety margin as outlined in Section 4.3.2.1.	T	Vibration Test Report
4.3.5	Integrated Loads Environment	The CubeSat shall be capable of withstanding a force 1200N across all load points equally in the Z direction.	I	Safety Data Template

4.3.8	Airlock Depressurization	The CubeSat shall be capable of withstanding the pressure extremes and depressurization / pressurization rate of the airlock as defined in Section 4.3.8	I	Safety Data Template
4.4.6-1	CubeSat Sub-Deployables	CubeSats shall not have detachable parts during launch or normal mission operations. Any exceptions will be coordinated with NanoRacks and documented in the unique payload ICA.	I	Safety Data Template
4.4.6-2	Space Debris Compliance	CubeSats shall comply with NASA space debris mitigation guidelines as documented in NASA Technical Standard NASA-STD-8719.14A.	A	ODAR
4.4.7.3	Battery Testing	All flight cells and battery packs shall be subjected to an approved set of acceptance screening tests to ensure the cells will perform in the required load and environment without leakage or failure. While the specific test procedures vary depending on the type of battery, the majority of Lithium ion or Lithium polymer cells / batteries used in CubeSats can be tested to a standard statement of work issued by NanoRacks (NR-SRD-139).	T	Battery Test Report
4.4.7.4	Internal Short Circuit	Protection circuity and safety features shall be implemented at the cell level to prevent an internal short circuit.	I	Electrical Schematic
4.4.7.5	External Short Circuit	Protection circuity and safety features shall be implemented at the cell level to prevent an external short circuit.	I	Electrical Schematic
4.4.7.6	Overvoltage & Undervoltage Protection	Protection circuitry and safety features shall be implemented at the cell level to prevent overvoltage or undervoltage conditions of the cell.	I, T	Electrical Schematic, Battery Test Report

4.4.7.7	Battery Charging	It should be verified that the battery charging equipment (if not the dedicated charger) has at least two levels of control that will prevent it from causing a hazardous condition on the battery being charged.	I	Electrical Schematic
4.4.7.8	Battery Energy Density	For battery designs greater than 80 Wh energy employing high specific energy cells (greater than 80 watt-hours/kg, for example, lithium-ion chemistries) require additional assessment by NanoRacks due to potential hazard in the event of single-cell, or cell-to-cell thermal runaway.	I, T	Electrical Schematic, Battery Test Report
4.4.7.9	Pouch Cell Expansion	Lithium Polymer Cells i.e. "pouch cells" shall be restrained at all times to prevent inadvertent swelling during storage, cycling, and low pressure or vacuum environments with pressure restraints on the wide faces of the cells to prevent damage due to pouch expansion.	I	Safety Data Template
4.4.7.10	Button Cell Batteries	Button cell or coin cell batteries are often used in COTS components to power real-time clocks (RTCs), watch-dog circuits, or secondary systems for navigation, communication, or attitude control. These batteries shall be clearly identified by part number and UL listed or equivalent.	I	Safety Data Template
4.4.7.11	Capacitors	Capacitors used as energy storage devices are treated and reviewed like batteries. Hazards associated with leaking electrolyte can be avoided by using solid state capacitors. Any wet capacitors that utilize liquid electrolyte must be reported to NASA. The capacitor part	I	Safety Data Template

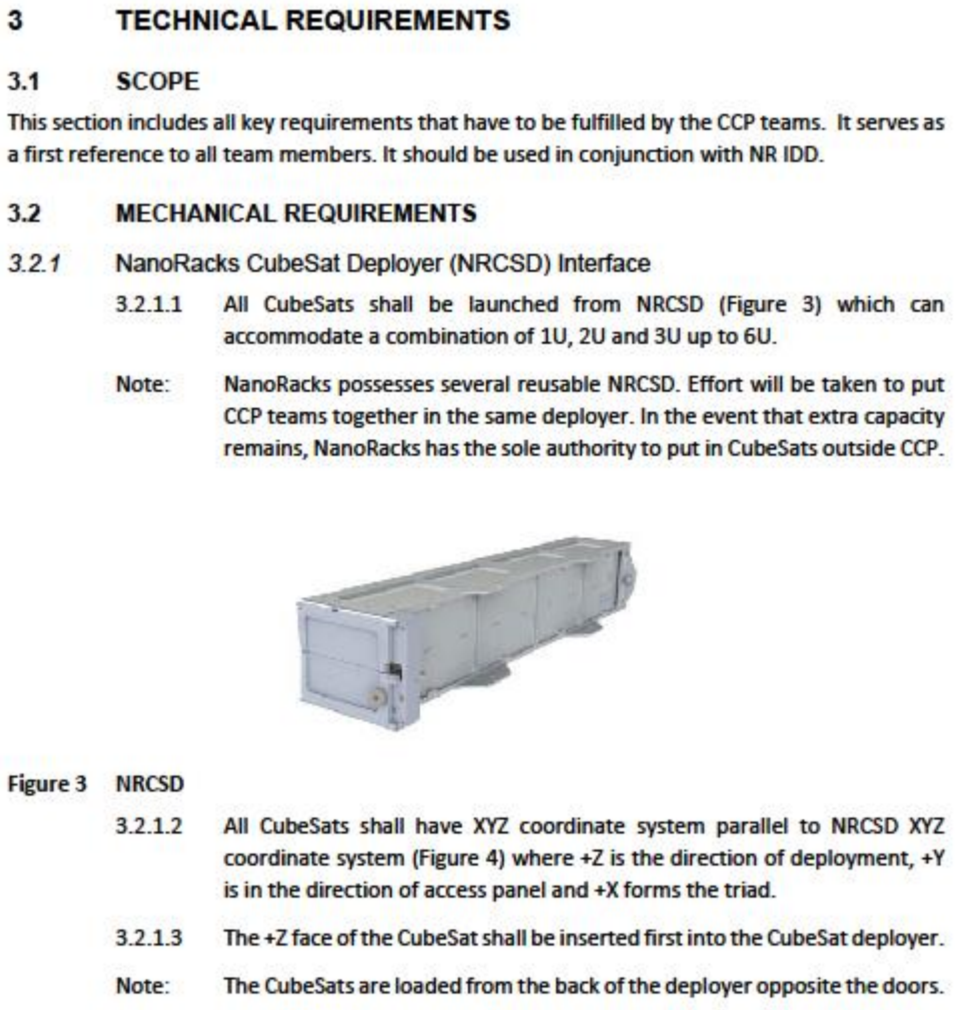


		number and electrolyte must be identified along with details of how the capacitor is used and any associated schematics.		
4.4.10.1	Stress Corrosion Materials	Stress corrosion resistant materials from Table I of MSFC-SPEC-522 are preferred. Any use of stress corrosion susceptible materials (Table II) shall be coordinated with NanoRacks and documented in the ICA. Any use of Table III materials shall be avoided.	I	Bill of Materials
4.4.10.2	Hazardous Materials	Satellites shall comply with NASA guidelines for hazardous materials. Beryllium, cadmium, mercury, silver or other materials prohibited by SSP-30233 shall not be used.	I	Bill of Materials
4.4.10.3	Outgassing / External Contamination	Satellites shall comply with NASA guidelines for selecting all non-metallic materials based on available outgassing data. Satellites shall not utilize any non-metallic materials with a Total Mass Loss (TML) greater than 1.0 percent or a Collected Volatile Condensable Material (CVCM) value of greater than 0.1 percent.	I	Bill of Materials
4.5.2-1	Orbital Debris Mass Requirement	CubeSats over 5kg shall provide an Orbital Debris Assessment Report (ODAR) that verifies compliance with NASA-STD-8719.14.	A	ODAR, DAS Input File
4.5.2-2	Re-entry Survivability	CubeSats that are designed to survive re-entry or have components that are designed to survive re-entry shall provide an ODAR that verifies compliance with NASA-STD-8719.14.	A	ODAR
4.6.1	Regulatory Compliance	The CubeSat developer shall submit evidence of all regulatory compliance for spectrum utilization and remote sensing	I	Regulatory Licenses

		platforms prior to handover of the payload. This evidence shall come in the form of the authorization or license grant issued directly from the governing body / agency (which is dependent on the country the CubeSat originates).		

B.2 CSA Requirements

The following section will outline the specific launch requirements as specified by the CSA applicable to the Design Cubed CubeSat design. The excerpts represented are in reference to the CSA Canadian CubeSat Project Design Specification document: CCP-CSA-00011-MIS-SP. Specifically, sections 3.2 Mechanical Requirements, 3.3 Launch Environment, and 3.5 Safety Requirements, (CSA, Canadian CubeSat Project Design Specification 2018).



3 TECHNICAL REQUIREMENTS

3.1 SCOPE

This section includes all key requirements that have to be fulfilled by the CCP teams. It serves as a first reference to all team members. It should be used in conjunction with NR IDD.

3.2 MECHANICAL REQUIREMENTS

3.2.1 NanoRacks CubeSat Deployer (NRCSD) Interface

3.2.1.1 All CubeSats shall be launched from NRCSD (Figure 3) which can accommodate a combination of 1U, 2U and 3U up to 6U.

Note: NanoRacks possesses several reusable NRCSD. Effort will be taken to put CCP teams together in the same deployer. In the event that extra capacity remains, NanoRacks has the sole authority to put in CubeSats outside CCP.

Figure 3 **NRCSD**

3.2.1.2 All CubeSats shall have XYZ coordinate system parallel to NRCSD XYZ coordinate system (Figure 4) where +Z is the direction of deployment, +Y is in the direction of access panel and +X forms the triad.

3.2.1.3 The +Z face of the CubeSat shall be inserted first into the CubeSat deployer.

Note: The CubeSats are loaded from the back of the deployer opposite the doors.

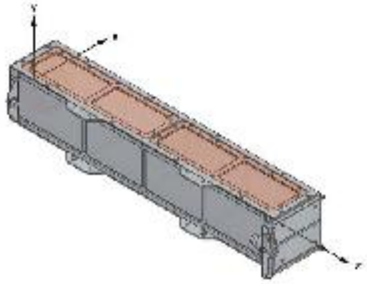


Figure 4 **NRCSD Coordinate System**

3.2.2 CubeSat Mechanical Requirements

3.2.2.1 The CubeSat shall have four (4) rails along the z-axis, one per corner of the CubeSat envelope, which allow the CubeSat to slide along the rail interface of the NRCSD (Figure 5).

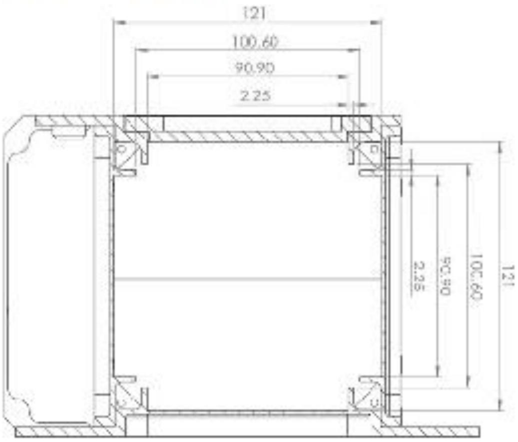


Figure 5 **NRCSD Mechanical Interface (dimensions in mm)**

3.2.2.2 CubeSat X-Y surface dimension shall adhere to the specification outlined in Figure 6.

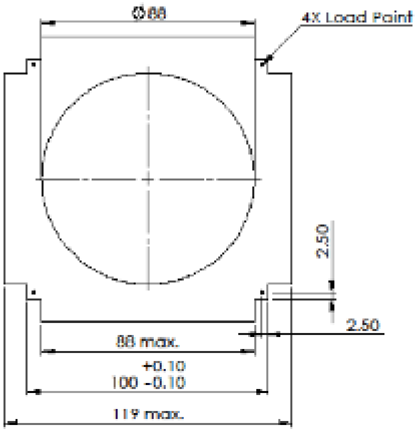


Figure 6 CubeSat XY Face Dimension (in mm)

3.2.2.3 Each CubeSat rail shall have a minimum width of 6mm.

3.2.2.4 The edges of the CubeSat rails shall have a radius of 0.5mm±0.1mm.

3.2.2.5 The CubeSat rail length (Z-axis) shall be according to Table 1.

Table 1 Rail Length for Different CubeSat Form Factors

Form Factor	Rail Length
1U	113.5±0.1mm
2U	227.0±0.1mm
3U	340.5±0.1mm

3.2.2.6 The minimum extension of the ±Z CubeSat rails from the ±Z CubeSat faces and all external features shall be 2mm.

Note: Figure 7 clarifies the requirements 3.2.2.5 and 3.2.2.6

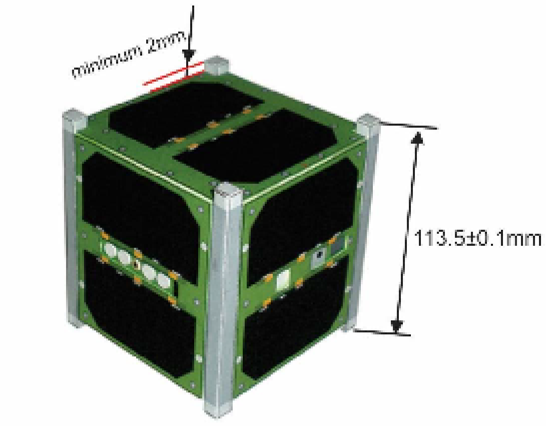


Figure 7 Distinguishing Requirements 3.2.2.5 and 3.2.2.6 using 1U

3.2.2.7 The CubeSat rails shall be the only mechanical interface to the NRCSD in all axes (X, Y and Z axes)

3.2.2.8 The CubeSat rail surfaces that contact the NRCSD guide rails shall have a hardness equal to or greater than hard-anodized aluminum (Rockwell C 65-70).

3.2.3 Mass Properties

3.2.3.1 CubeSat mass shall be less than the maximum allowable mass for each respective form factor listed in Table 2.

Table 2 **Maximum Cubesat Mass for Different Form Factors**

Form Factor	Maximum Mass (kg)
1U	2.40
2U	3.60
3U	4.80

3.2.3.2 CubeSat center of mass (CM) shall be located within the range listed in Table 3 relative to the geometric center of the CubeSat.

Table 3 **Range of CM in Each Axis for Different Form Factors**

Form Factor	X-Axis	Y-Axis	Z-Axis
1U	±2cm	±2cm	±2cm
2U	±2cm	±2cm	±4cm
3U	±2cm	±2cm	±6cm

3.2.4 Remove Before Flight (RBF)

3.2.4.1 CubeSat shall have a remove before flight (RBF) feature and it shall be physically accessible via the NRCSD access panels on the +Y face of the NRCSD.

Note: RBF pin is not the same as deployment switch described below. RBF pin disconnects the battery pack from the electrical circuit regardless of deployment switch state.

Note: Illustration of the access panels is shown in Figure 8. The RBF will be removed once the CubeSat is integrated into NRCSD and prior to the closing of access panels.

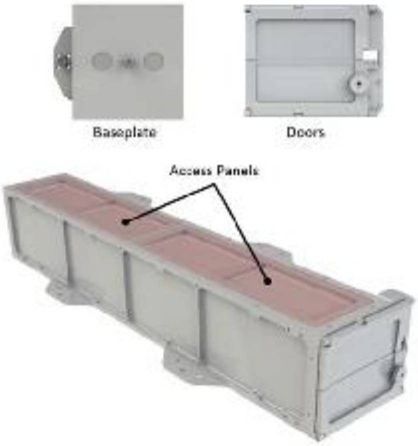
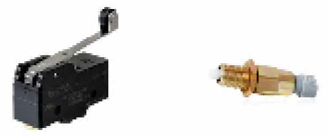


Figure 8 **NRCSD Access Panel Illustration**

3.2.5 Deployment Switches

3.2.5.1 The CubeSat shall have a minimum of three (3) deployment switches that correspond to independent electrical inhibits on the main power system.

3.2.5.2 The deployment switch shall be either plunger/pusher or roller/lever type (Figure 8)



Roller/Lever Switch Plunger/Pusher Switch

Figure 9 Example micro roller and plunger switches

Note: When the switch is described as "Open," it is not operational (in the pressed / open-circuit state). When the switch is described as "Closed", it is in operational state (close-circuit state).

3.2.5.3 The deployment switches shall remain captive to the switch housing / CubeSat assembly so that no debris is generated upon deployment.

3.2.5.4 The deployment switches shall reset the CubeSat to the pre-launch state when not all 3 switches are closed within the first 30 minutes after the first switch closes.

3.2.5.5 The deployment system timer and software timer shall reset when the condition stated in Requirement 3.2.5.4 occurs.

Note: The switches can be closed sequentially.

Note: During the integration of the CubeSat into the NRCSD or when the deployer is subjected to vibration load of the launcher , one or two of the switches can become closed temporarily. Requirements 3.2.5.4 and 3.2.5.5 aim to prevent accidental turn-on of the CubeSat.

3.2.5.6 The force exerted by each deployment switch shall not exceed 3N.

3.2.6 Deployment Velocity and Tip-Off Rate

3.2.6.1 The CubeSat shall be capable of withstanding a deployment velocity of 0.5 to 2.0 m/s at ejection from the NRCSD.

3.2.6.2 The CubeSat shall be capable of withstanding up to five (5) deg/sec/axis tip-off rate.

Note: The CubeSat attitude control system should be designed to acquire nominal attitude following the maximum deployment velocity and tip-off rate.

3.3 LAUNCH ENVIRONMENT

3.3.1 Quasi-Static Load

3.3.1.1 Cubesat shall withstand quasi-static loads of the launcher listed in Table 4.

Table 4 Quasi-Static Launch Load

Axis	Quasi-Static Acceleration (g)
X	±4
Y	±4
Z	±7

3.3.2 Random Vibration

3.3.2.1 Random vibration testing of the flight article in the soft-stow flight configuration to the Maximum Expected Flight Level (MEFL) +3dB (Table 5 and Figure 10) for a duration of 60 seconds in each axis.

Table 5 Soft-Stow Test Profile

Frequency (Hz)	ASD (g^2/Hz)	Frequency (Hz)	ASD (g^2/Hz)
20	4.000E-02	250	5.558E-02
25	4.000E-02	315	4.102E-02
31.5	4.000E-02	400	2.998E-02
40	4.000E-02	500	2.236E-02
50	4.000E-02	630	1.651E-02
63	4.490E-02	800	1.206E-02
80	5.062E-02	1000	9.000E-03
100	5.660E-02	1250	6.034E-03
125	6.200E-02	1600	3.878E-03
160	6.200E-02	2000	2.600E-03
200	6.200E-02	Grms	5.76
		Duration (sec)	60

3.3.2.2 Random vibration testing of the flight article in the hard-mount configuration (Table 6 and Figure 10) shall be done to a combined test profile that envelopes the Maximum Expected Flight Level (MEFL) +3dB and a minimum workmanship level (MWL) vibe, for a duration of 60 seconds in each axis.

Table 6 Hard-Mount Test Profiles

Frequency (Hz)	ASD (g^2/Hz)
20	5.700E-02
153	5.7E00-02
190	9.900E-02
250	9.900E-02
750	5.500E-02
2000	1.800E-02
Grms	9.47
Duration (sec)	60

Note: NanoRacks offers both Soft-Stow and Hard-Mount options for random vibration testing. Soft-Stow requires special flight approved packing materials provided by NanoRacks. Both options are available to CCP teams.

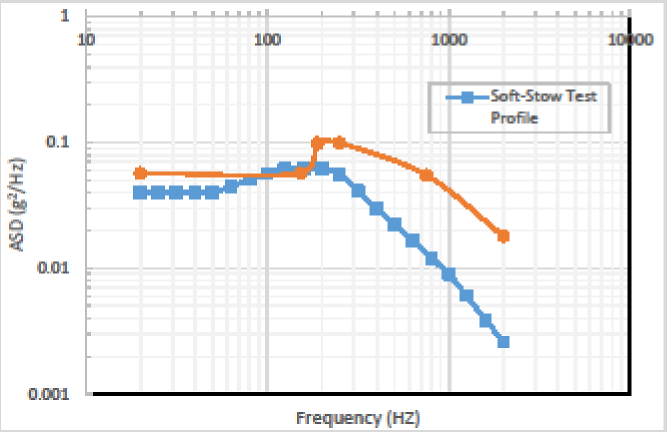


Figure 10 Random Vibration Profile for both Soft-Stow and Hard-Mount Test Profiles

3.3.3 Venting

3.3.3.1 The Maximum Effective Vent Ratio (MEVR) of the CubeSat structure an any enclosed containers internal to the CubeSat shall not exceed 5080 cm.

Note: The MEVR is calculated as follows:

$$MEVR = \left(\frac{\text{Internal Volume}\left(cm^3\right)}{\text{Effective Vent Area }\left(cm^2\right)} \right) \leq 5080cm$$

Effective vent area shall be considered as the summation of the unobstructed surface area of any vent hole locations or cross-sectional regions that air could escape the CubeSat.

3.3.4 Humidity

3.3.4.1 The CubeSat shall be capable of withstanding the relative humidity environment from 25% to 75% for all mission phases leading up to deployment.

3.3.5 Thermal Environment

3.3.5.1 The CubeSat shall be capable of withstanding the temperature range from –20ºC to 50ºC.

Note: The most extreme temperature range (–10º to 45ºC) proposed by NR IDD is based on EVR prior to deployment. This is insufficient for a satellite mission.

3.4 ELECTRICAL SYSTEM INTERFACE REQUIREMENT

3.4.1 Electrical System Design and Inhibits

3.4.1.1 CubeSat shall not operate any system (including RF transmitters, deployment mechanisms or otherwise energize the main power system) for a minimum of 30 minutes where hazard potential exists.

Note: Once the CubeSat is released from the NRCSD, the hazard potential refers to any situation that may impact on the safety and security of ISS structure and the crew. Potential hazard could be the collision between CubeSat and the ISS, the interference in RF communications, and fragmentation of CubeSat.

3.4.1.2 The CubeSat electrical system design shall incorporate a minimum of three (3) independent electrical inhibits configured in series actuated by physical deployment switches as shown in Figure 11.

3.4.1.3 The satellite inhibit scheme shall include a ground leg inhibit (switch D3 in Figure 11) that disconnects the batteries along the power line from the negative terminal to ground.

3.4.3.5 After a command to stop radio emissions has been released, automated rebooting of the CubeSat shall not lead to recommencement of radio emissions.

3.5 SAFETY REQUIREMENTS

3.5.1 Finish

3.5.1.1 The CubeSat shall not have any sharp corner or edge in the chassis and in all accessible areas.

3.5.2 Materials

3.5.2.1 Stress corrosion resistant materials from Table 1 of MSFC-SPEC_522 are preferred.

Note: Aluminum alloy 6061-T6 is the most commonly used for CubeSat

Note: The use of aluminum alloy 7075 with temper T7531 is an alternative

3.5.2.2 Satellites shall comply with JSC 27472 Rev B, JSC 63838 Rev B, JSC 66869 and applicable NASA guidelines for hazardous materials.

3.5.2.3 Satellites shall comply with NASA guidelines for selecting all non-metallic materials based on available outgassing data.

3.5.2.4 CubeSats shall not utilize any non-metallic materials with a Total Mass Loss (TML) greater than 1.0% and Collected Volatile Condensable Material (CVCM) greater than 0.1%.

3.5.2.5 A Bill of Materials (BoM) shall be provided to NanoRacks to verify all material requirements are met.

Note: The NASA website (http://outgassing.nasa.gov) is a useful source for obtaining outgassing data for materials.

Note: ESTEC maintains an outgassing database which is accessible online at http://esamat.esa.int/materialframe.html)

3.5.3 Secondary Locking Feature

3.5.3.1 The CubeSat shall have an approved secondary locking feature for any and all fasteners or subcomponents external to the CubeSat chassis and that would not be held captive by the CubeSat structure should it come loose.

Note: The measured and recorded fastener torque is considered the primary locking feature for fasteners. Mechanical or liquid locking compounds are approved as secondary locking feature. Approved thread locking compounds include Loctite® Threadlocker Red 271™ and Blue 242™.

3.5.4 Pyrotechnics

3.5.4.1 The CubeSat shall not contain any pyrotechnics.

Note: Electrically operated melt-wire system for deployables are permitted.

3.5.5 Batteries

3.5.5.1 All flight cells and battery packs shall be subjected to an approved set of acceptance screening tests issued by NanoRacks (NR-SRD-139) to ensure the cells will perform in the required load and environment without leakage or failure.

3.5.5.2 Protection circuitry and safety features shall be implemented at the battery pack level to prevent overvoltage or under-voltage conditions of the cell.

3.5.5.3 Battery designs for the CubeSat shall be less than 80 Wh.

3.5.5.4 Lithium Polymer Cells i.e. "pouch cells" shall be restrained at all times to prevent inadvertent swelling during storage, cycling, and low pressure or vacuum environments with pressure restraints on the wide faces of the cells to prevent damage due to pouch expansion.

3.5.5.5 Button cells shall be clearly identified by part number and UL listed or equivalent.

3.5.6 Pressure Vessels

3.5.6.1 CubeSat shall not have any sealed container with an internal pressure greater than 100 psia (pounds per square inch absolute).

Note: All hermetically sealed containers, even those less than 100 psia, may require additional data to support structural verification

3.5.7 Propulsion System

3.5.7.1 Cubesat shall not have any propulsion systems.

3.5.8 Magnetic Devices

3.5.8.1 The use of permanent magnets and electro-magnets shall be permitted.

3.5.8.2 The permanent magnet shall have a strength less than 3 Gauss measured at a distance of 7cm.

Note: This requirement is a flow down from the ISS requirement which states "Payloads shall not generate static (DC) magnetic flux density exceeding 170 dB above 1 pico-Tesla (3.16 Gauss) at a distance of 7 cm from the surface of the equipment while in the ISS and/or in a non-Russian transport vehicle. This applies to electromagnetic and permanent magnetic devices. This requirement is not applicable to solenoid valves, solenoid relays, and electric motors with current of less than 1 ampere."

Note: If there are more than 1 magnet, the combined magnetic field strength shall satisfy the requirement 3.5.8.2

3.6 OPERATIONAL REQUIREMENTS

3.6.1 Lifetime

3.6.1.1 The CubeSat shall be designed to have an in-orbit lifetime of at least 3 months.

Note: The lifetime of a CubeSat launched from ISS depends significantly on the solar activity. Past records indicate that some CubeSats can survive up to 2 years.

3.6.2 Two-Line Element (TLE)

3.6.2.1 The CubeSat team should register on Space-track (www.space-track.org)

3.6.2.2 CubeSat team shall be responsible for downloading and updating the CubeSat TLE from Space-track

Note: Space-track is managed by US 18th Space Control Squadron. It promotes a safe, stable, sustainable and secure space environment through SSA information sharing.

Note: TLE data can also be downloaded from www.celestrak.com. Most satellite operations software can accept TLE data as input.

3.6.3 Launch & Early Orbit Phase (LEOP)

3.6.3.1 The CubeSat shall not transmit or receive within 30 minutes after deployment from NRCSD.

3.6.3.2 The CubeSat shall not activate the deployment of any mechanical component within 30 minutes of the deployment from NRCSD.

Note: Figure 12 is an illustration of deployment switch operation and LEOP

B.3 NASA Requirements

The following section will outline the specific requirements as specified by NASA applicable to the Design Cubed CubeSat design. The excerpts represented are in reference to the NASA outgassing database. All materials used in the design of Design Cubed's project have used materials allowable by NASA's outgassing standards. As such, please reference database directory located in citations of report for full details, (NanoRacks 2018).

Appendix C: Alternative Design Selection Process

The following appendix will describe in detail the alternative selection process executed by the Design Cubed team. Critical objectives were identified, and metrics used to measure each accordingly. Next, each objective was weighted utilizing a pairwise comparison matrix. Weighted objectives were then used to evaluate five different alternatives utilizing a weighted decision matrix. The top three design alternatives were then developed in more detail through SolidWorks CAD modelling. Again, the top three alternatives were presented and evaluated utilizing the same weighted decision matrix. The final design selection was then made based on the highest-ranking alternative, in this case the Hinged CubeSat design. However, after further detailed design on the Hinged CubeSat, it was determined that key aspects of the design were overestimated, and shortcomings underestimated. The Design Cubed team revisited the weighted decision matrix with new insights and pivoted to the “L-Bracket” model. The following sections will describe in detail the process.

C.1 Objectives and Metrics

COTS units will be used as a benchmark in the comparison of design alternatives. The following objectives and metrics have been identified to be valuable to the client and by which the design alternatives will be objectively compared.

- i. To increase ease of assembly
    - a. Number of fasteners
    - b. Number of frame parts
- ii. Serviceability
    - a. Steps to fully access internal printed circuit board stack
- iii. Reduce Cost
    - a. Material costs
    - b. Fabrication costs
    - c. Total project cost
- iv. To minimize frame mass
    - a. Total frame weight
    - b. Number of fasteners

v. To maximize interior envelope
   a. Interior volume
vi. To design for ease of manufacturing
   a. Estimated number of machine setups per part
   b. Number of unique parts

C.2 Objective Pairwise Comparison Matrix

In order to compare design alternatives, a ranking must be determined of which objectives are most important in a design. The use of pairwise comparison matrix is used where two objectives are compared and the more important objective is selected. The number of “wins” is totalled for each objective and then assigned a weight out of 100%. Table C-1 shows the pairwise comparison of objectives.

Table C-1. Objective pairwise comparison matrix results

				To increase ease of assembly	Serviceability	Reduce Cost	To minimize frame mass	To maximize interior envelope	To design for ease of manufacturing
	score	weight		A	B	C	D	E	F
To increase ease of assembly	3	18.75	A	-	B	A	D	A	A
Serviceability	5	31.25	B	-	-	B	B	B	B
Reduce Cost	1	6.25	C	-	-	-	D	E	CF
To minimize frame mass	4	25	D	-	-	-	-	D	D
To maximize interior envelope	1	6.25	E	-	-	-	-	-	F
To design for ease of manufacturing	2	12.5	F	-	-	-	-	-	-

The factors that influenced decisions of which objective is more important was recorded as follows:

i.) AB: Servicing is more important as it is repetitive where assembly is a one-time activity
ii.) AC: Manufacturing is not limiting factor -> Sask poly free $$$$
iii.) AD: comparable mass to COTS options is more important
iv.) AE: Gains in volume are minimal. Ease of assembly may decrease with design efforts to increase interior volume
v.) AF: manufacturing is going to be complicated in the best-case scenario

vi.) BC: Cost is less constrained

vii.) BD: Increasing serviceability is more important than an increase in mass

viii.) BE: Serviceability will negate the increased volume

ix.) BF: Manufacturing is going to be complicated in the best-case scenario

x.) DC: Mass wins every time

xi.) CE: Volume beats cost with minimal know knowledge of volume needs and the costs associated with increasing volume

xii.) CF: Equal

xiii.) DE: Mass wins every time

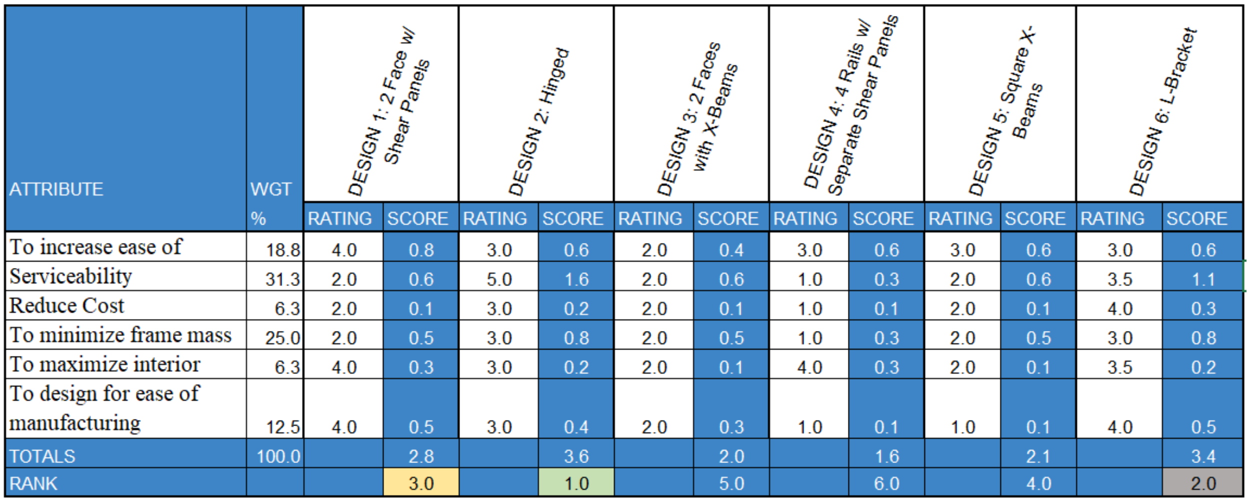
xiv.) DF: Mass wins every time

xv.) EF: Thin structure hard to make

C.3 Initial Alternatives and Ranking

Having obtained a ranking of the most important objective to least important objective, each design alternative can be rated, on a scale of one to five, how well or optimally it meets the objective. A weighted decision matrix can be used to rank the original five design alternatives. Each design will be judged on how well it meets the six design alternatives and its score will be weighted as per the pairwise comparison outcome. Table C-2 displays the weighted decision matrix for the initial five design alternatives.

Table C-2. Initial five alternative weighted decision matrix results



ATTRIBUTE	WGT %	DESIGN 1: 2 Face w/ Shear Panels		DESIGN 2: Hinged		DESIGN 3: 2 Faces with X-Beams		DESIGN 4: 4 Rails w/ Separate Shear Panels		DESIGN 5: Square X-Beams		DESIGN 6: L-Bracket	
		RATING	SCORE	RATING	SCORE	RATING	SCORE	RATING	SCORE	RATING	SCORE	RATING	SCORE
To increase ease of	18.8	4.0	0.8	3.0	0.6	2.0	0.4	3.0	0.6	3.0	0.6	3.0	0.6
Serviceability	31.3	2.0	0.6	5.0	1.6	2.0	0.6	1.0	0.3	2.0	0.6	3.5	1.1
Reduce Cost	6.3	2.0	0.1	3.0	0.2	2.0	0.1	1.0	0.1	2.0	0.1	4.0	0.3
To minimize frame mass	25.0	2.0	0.5	3.0	0.8	2.0	0.5	1.0	0.3	2.0	0.5	3.0	0.8
To maximize interior	6.3	4.0	0.3	3.0	0.2	2.0	0.1	4.0	0.3	2.0	0.1	3.5	0.2
To design for ease of manufacturing	12.5	4.0	0.5	3.0	0.4	2.0	0.3	1.0	0.1	1.0	0.1	4.0	0.5
TOTALS	100.0		2.8		3.6		2.0		1.6		2.1		3.4
RANK			3.0		1.0		5.0		6.0		4.0		2.0

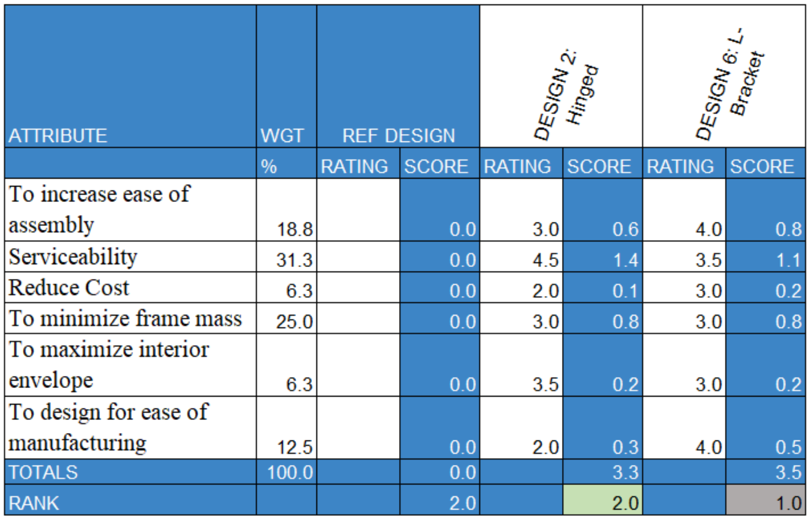
The weighted decision matrix ranked the top three design alternatives, respectively, as the hinged, L-Bracket, and the two-face with shear panel design.

C.4 Detailed Alternative Review

The top three designs from the weighted decision matrix were taken one step further past an initial conceptual design. Using SolidWorks, the three designed were modelled to a reasonable degree. The model removed interferences, accounted for fasteners, was roughly optimized to obtain a mass under 400g to create a feasible design. The details of the design were fleshed out such that the metrics of the design objectives could be given a quantifying value.

Taking the models to a more detailed level revealed that the Two-Faces with Shear Panels design was not a real contender as the number of fasteners and number of steps to service the design was too high. The remaining top two, the Hinged and L-Bracket designs, were then re-compared in another weighted decision matrix, as seen in Table C-3.

Table C-3. Final design selection weighted decision matrix results



ATTRIBUTE	WGT	REF DESIGN		DESIGN 2: Hinged		DESIGN 6: L-Bracket	
	%	RATING	SCORE	RATING	SCORE	RATING	SCORE
To increase ease of assembly	18.8		0.0	3.0	0.6	4.0	0.8
Serviceability	31.3		0.0	4.5	1.4	3.5	1.1
Reduce Cost	6.3		0.0	2.0	0.1	3.0	0.2
To minimize frame mass	25.0		0.0	3.0	0.8	3.0	0.8
To maximize interior envelope	6.3		0.0	3.5	0.2	3.0	0.2
To design for ease of manufacturing	12.5		0.0	2.0	0.3	4.0	0.5
TOTALS	100.0		0.0		3.3		3.5
RANK			2.0		2.0		1.0

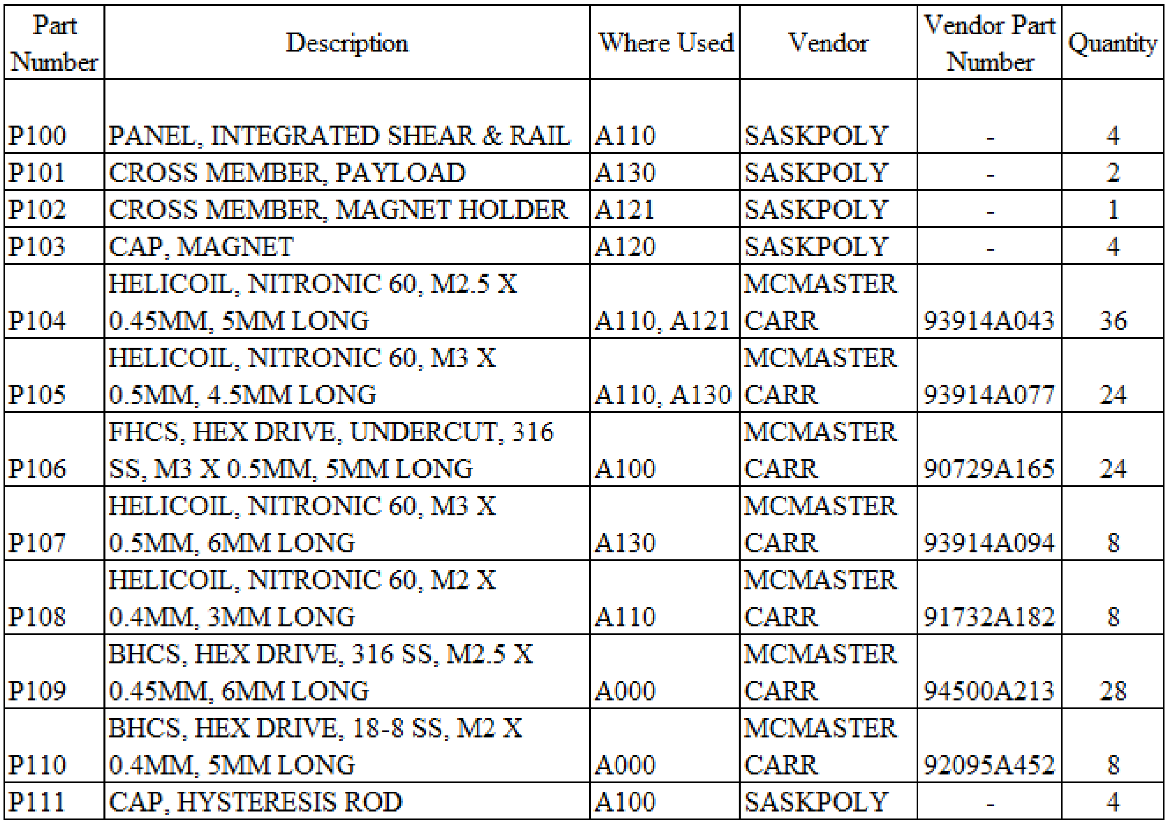
C.5 Alternative Selection

The selected design alternative was the L-Bracket design. Although the Hinged design initially won the weighted decision matrix, further investigation raised uncertainty, doubt, and risk is perusing the design. The concept of integrating a hinge into a CubeSat frame, to our knowledge, is completly unique and the first of its kind. However, the use of a hinge raised challenges in tolerancing and manufacturing as the hinge needs to operate smoothly but needs to close repeatably to meet assembly tolerances. The uncertainty of the designs' performance increased the risk, which can be mitigated by simply not pursuing the design. Further investigation into the feasibility of the hinged design revealed that the design was extremely serviceable, the highest-ranked objective. Almost at a consequence, the Hinged design consistently scored lower than the L-Bracket in other objective categories, such as cost or ease of manufacture. The L-Bracket design, although not as serviceable as the Hinged design, is a well-balanced design with room for optimization and customization to the clients' needs. The L-Bracket requires few unique parts, few fasteners, and provides quick assess to CubeSat internals. The design is still very unique compared to off the shelf units and will be the selected design alternative that Design Cubed will pursue.

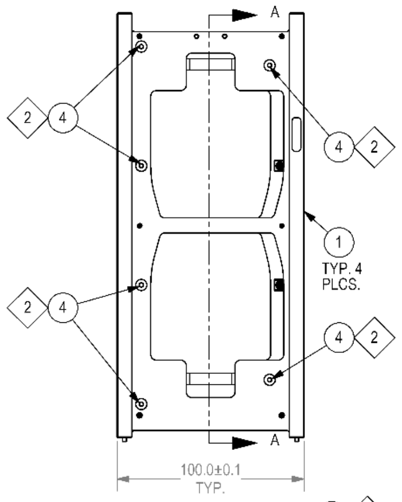
Appendix D: SolidWorks Drawings

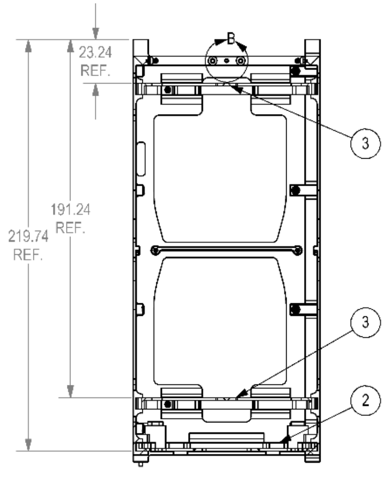
The following appendix provides detailed drawings required to fabricate and assemble Design Cubed’s CubeSat frame. It is important to note that all machined parts will be supplied in kind by Saskatchewan Polytechnic. Additional fasteners and threaded inserts will be sourced from the approved vendor, McMaster Carr. A comprehensive design package will be provided to the USST upon handover of the project including SolidWorks PDF Drawings and SolidWorks CAD model files. A bill of materials can be seen below in Table D-1.

Table D-1. 2U CubeSat frame comprehensive parts list

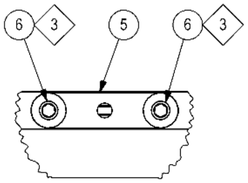


Part Number	Description	Where Used	Vendor	Vendor Part Number	Quantity
P100	PANEL, INTEGRATED SHEAR & RAIL	A110	SASKPOLY	-	4
P101	CROSS MEMBER, PAYLOAD	A130	SASKPOLY	-	2
P102	CROSS MEMBER, MAGNET HOLDER	A121	SASKPOLY	-	1
P103	CAP, MAGNET	A120	SASKPOLY	-	4
P104	HELICOIL, NITRONIC 60, M2.5 X 0.45MM, 5MM LONG	A110, A121	MCMASTER CARR	93914A043	36
P105	HELICOIL, NITRONIC 60, M3 X 0.5MM, 4.5MM LONG	A110, A130	MCMASTER CARR	93914A077	24
P106	FHCS, HEX DRIVE, UNDERCUT, 316 SS, M3 X 0.5MM, 5MM LONG	A100	MCMASTER CARR	90729A165	24
P107	HELICOIL, NITRONIC 60, M3 X 0.5MM, 6MM LONG	A130	MCMASTER CARR	93914A094	8
P108	HELICOIL, NITRONIC 60, M2 X 0.4MM, 3MM LONG	A110	MCMASTER CARR	91732A182	8
P109	BHCS, HEX DRIVE, 316 SS, M2.5 X 0.45MM, 6MM LONG	A000	MCMASTER CARR	94500A213	28
P110	BHCS, HEX DRIVE, 18-8 SS, M2 X 0.4MM, 5MM LONG	A000	MCMASTER CARR	92095A452	8
P111	CAP, HYSTERESIS ROD	A100	SASKPOLY	-	4





SECTION A-A



DETAIL B
SCALE: 2 : 1
TYP. 4 PLCS.

NOTES:

1. SEE SHEET #2 FOR EXPLODED ISOMETRIC VIEW.

◇2 FOR M3 FASTENERS:

TEMPORARY FASTENER:
- USE ONE (1) DROP OF LOCTITE 242 - MEDIUM STRENGTH BLUE
- TORQUE TO 0.705 Nm

PERMENANT FASTENER:
- USE ONE (1) DROP OF LOCTITE 271 - HIGH STRENGH RED
- TORQUE TO 0.705 Nm

KEY DO NOT REUSE FASTENERS AFTER TORQUING. REPLACE AFTER EACH USE.

◇3 FOR M2.5 FASTENERS:

TEMPORARY FASTENER:
- USE ONE (1) DROP OF LOCTITE 242 - MEDIUM STRENGTH BLUE
- TORQUE TO 0.391 Nm

PERMENANT FASTENER:
- USE ONE (1) DROP OF LOCTITE 271 - HIGH STRENGH RED
- TORQUE TO 0.391 Nm

KEY DO NOT REUSE FASTENERS AFTER TORQUING. REPLACE AFTER EACH USE.

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	A110	INSTALLATION, HELICOILS, SIDE PANEL & RAIL	4
2	A120	ASSEMBLY, MAGNET HOLDER	1
3	A130	INSTALLATION, HELICOILS, CROSS MEMBER, PAYLOAD	2
4	P106	FHCS, HEX DRIVE, UNDERCUT, 316 SS, M3 X 0.5MM, 5MM LONG	24
5	P111	CAP, HYSTERESIS ROD	4
6	P109	BHCS, HEX DRIVE, 316 SS, M2.5 X 0.45MM, 6MM LONG	8

A	FIRST ISSUE	N/A	2020 FEB 01	DF
REV	DESCRIPTION	DR	DATE	BY

REVISIONS

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UNLESS OTHERWISE SPECIFIED, DIMENSIONS ARE IN MM

TOLERANCES ARE:	FRACTIONS	DECIMALS	ANGLES
	± 1/2	.X±.3 .XX±.12 .XXX±.050	± 1°

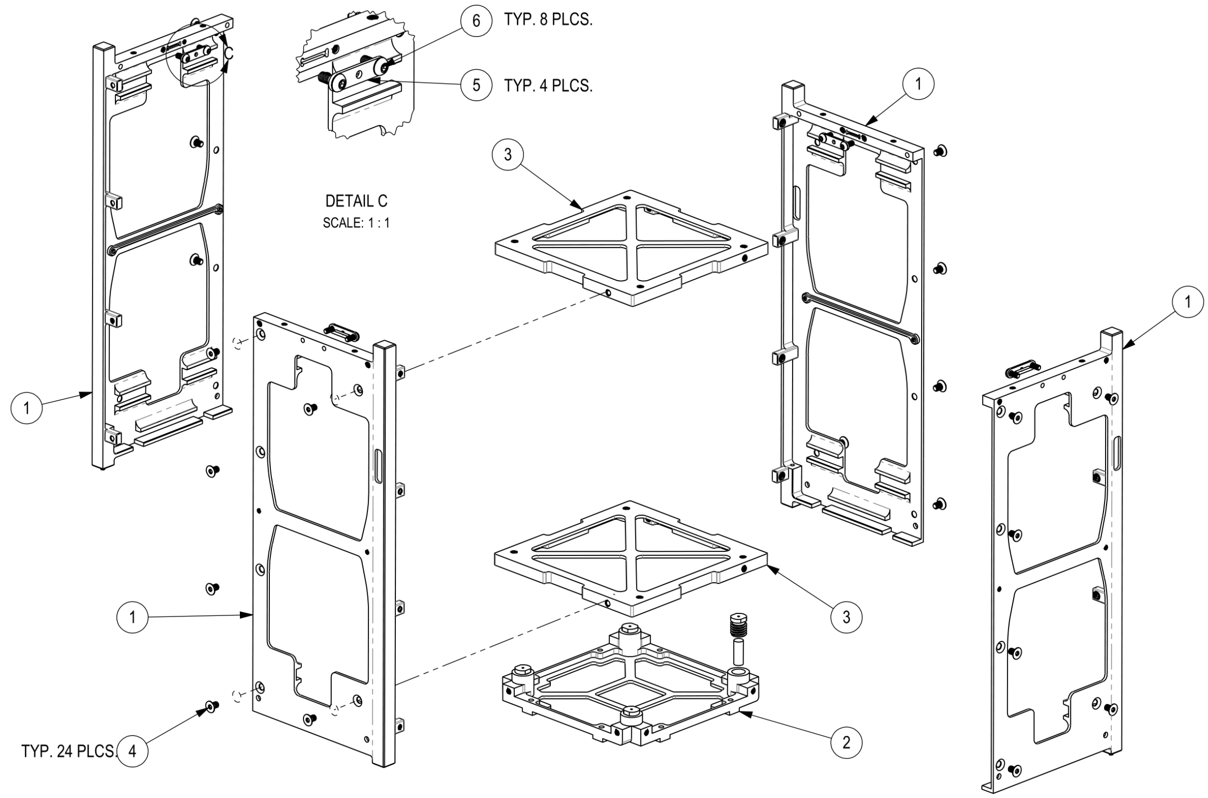
THIRD ANGLE PROJECTION

APPROVALS		DATE (YYYY-MMM-DD)
DRAWN	DANIEL F	2020 FEB 01
CHECKED	SEAMUS W G	2020 FEB 27
DXF		

MATERIAL N/A
QUANTITY 1
WEIGHT 387.27 G
AREA N/A

TITLE:
ASSEMBLY, 2U FRAME

SIZE B
DWG. NO. A100
REV. A
SCALE NTS
TYPE ASSEMBLY
SHEET 1 OF 2



A	FIRST ISSUE	N/A	2020 FEB 01	DF
REV	DESCRIPTION	DR	DATE	BY

REVISIONS

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TOLERANCES ARE:	FRACTIONS	DECIMALS	ANGLES
	± 1/2	.X ± .3 .XX ± .12 .XXX ± .050	± 1°

THIRD ANGLE PROJECTION

APPROVALS	DATE (YYYY-MMM-DD)
DRAWN DANIEL F	2020 FEB 01
CHECKED SEAMUS W G	2020 FEB 27
DXF	

MATERIAL N/A
QUANTITY 1
WEIGHT 387.27 G
AREA N/A

TITLE:
ASSEMBLY, 2U FRAME

SIZE B
DWG. NO. A100
REV. A
SCALE NTS
TYPE ASSEMBLY
SHEET 2 OF 2

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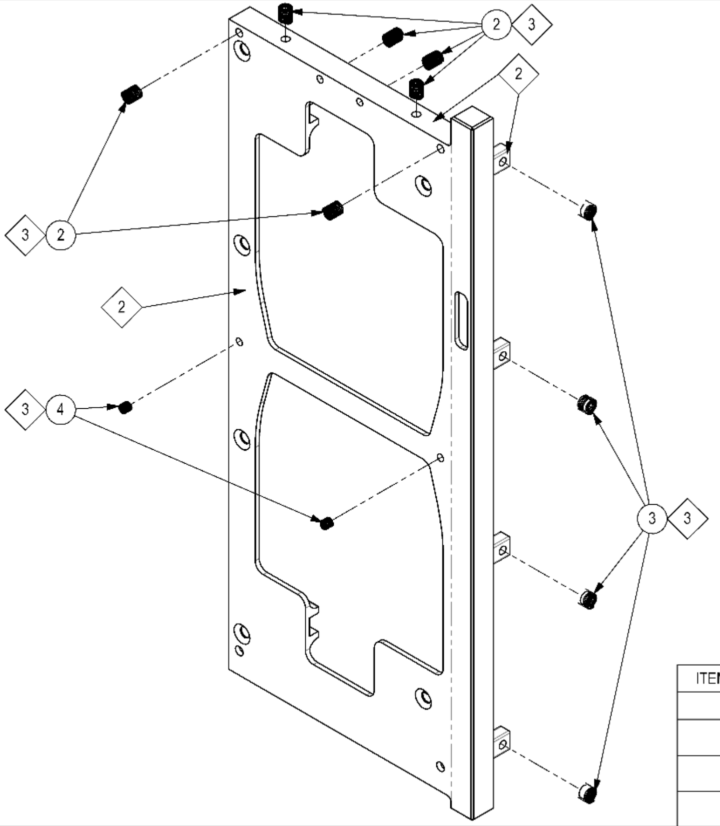


NOTES:
1. EXPLODED DIRECTION ALSO INDICATES DIRECTION OF INSTALLATION.
2. ENSURE HELICOIL IS FLUSH OR BELOW SURFACE.
3. APPLY ADEQUATE AMOUNT (2-3 DROPS) OF LOCTITE 271 - HIGH STRENGTH RED BEFORE INSTALLATION

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	P100	PANEL, INTEGRATED SHEAR & RAIL	1
2	P104	HELICOIL, NITRONIC 60, M2.5 X 0.45MM, 5MM LONG	6
3	P105	HELICOIL, NITRONIC 60, M3 X 0.5MM, 4.5MM LONG	4
4	P108	HELICOIL, NITRONIC 60, M2 X 0.4MM, 3MM LONG	2

REV	DESCRIPTION	DR	DATE	BY
A	FIRST ISSUE	N/A	2020 FEB 01	DF

REVISIONS

UNLESS OTHERWISE SPECIFIED, DIMENSIONS ARE IN MM

TOLERANCES ARE:	FRACTIONS	DECIMALS	ANGLES
	± 1/2	X ±.3 .XX ±.12 .XXX ±.050	± 1°

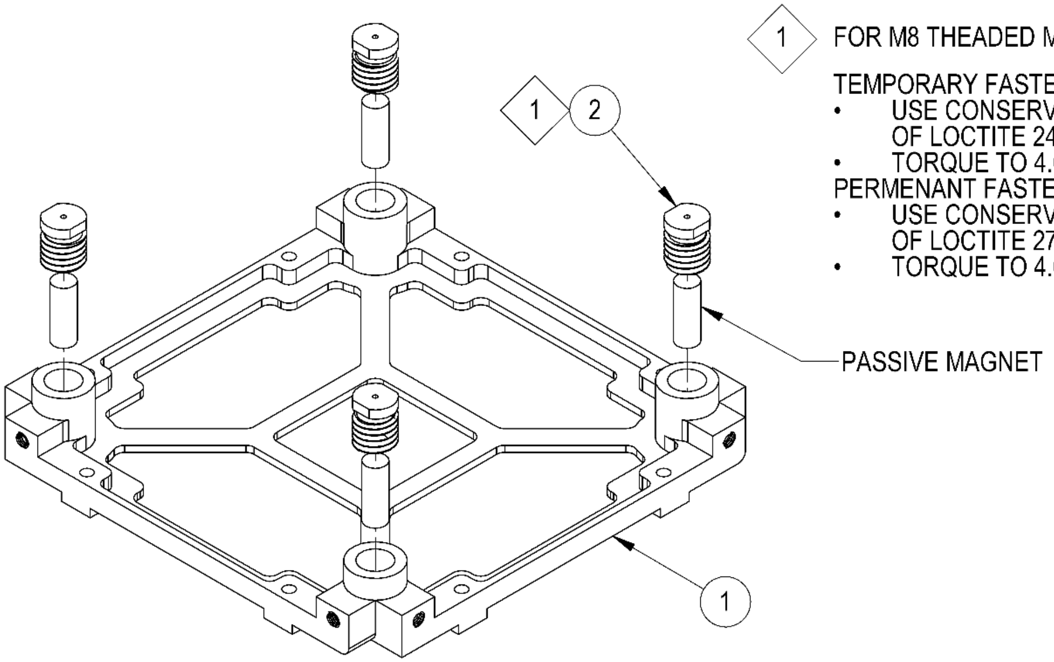
THIRD ANGLE PROJECTION

APPROVALS		DATE (YYYY-MMM-DD)
DRAWN	DANIEL F	2020 FEB 01
CHECKED	SEAMUS W G	2020 FEB 27
DXF		

MATERIAL N/A
QUANTITY 4
WEIGHT 66.28 G
AREA N/A

TITLE:
INSTALLATION, HELICOILS, SIDE PANEL & RAIL

SIZE B
DWG. NO. A110
REV. A
SCALE NTS
TYPE ASSEMBLY
SHEET 1 OF 1



NOTES:

1 FOR M8 THEADED MAGNET CAPS

TEMPORARY FASTENING:
- USE CONSERVATIVE AMOUNT (3-4 DROPS) OF LOCTITE 242 - MEDIUM STRENGTH BLUE
- TORQUE TO 4.05 Nm

PERMENANT FASTENING:
- USE CONSERVATIVE AMOUNT (3-4 DROPS) OF LOCTITE 271 - HIGH STRENGTH RED
- TORQUE TO 4.05 Nm

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	A121	INSTALLATION, HELICOILS, CROSS MEMBER, MAGNET HOLDER	1
2	P103	CAP, MAGNET	4

REV	DESCRIPTION	DR	DATE	BY
A	FIRST ISSUE	N/A	2020 FEB 04	DF

REVISIONS

D^3 design cubed

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TOLERANCES ARE:	FRACTIONS	DECIMALS	ANGLES
	± 1/2	.X±.3 .XX±.12 .XXX±.050	± 1°

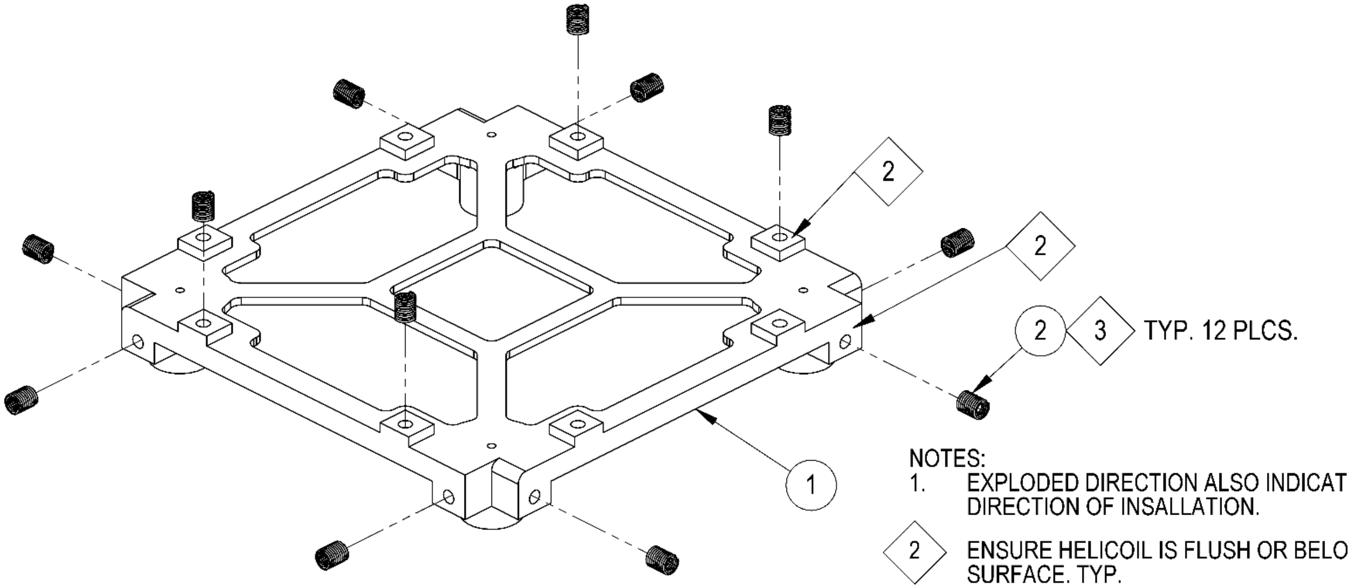
THIRD ANGLE PROJECTION

APPROVALS		DATE (YYYY-MMM-DD)
DRAWN	DANIEL F	2020 FEB 04
CHECKED	SEAMUS W G	2020 FEB 27
DXF		

MATERIAL N/A
QUANTITY 1
WEIGHT 51.4 G
AREA N/A

TITLE:
ASSEMBLY, MAGNET HOLDER

SIZE A
DWG. NO. A120
REV. A
SCALE NTS
TYPE: ASSEMBLY
SHEET 1 OF 1



NOTES:

1. EXPLODED DIRECTION ALSO INDICATES DIRECTION OF INSALLATION.

2 ENSURE HELICOIL IS FLUSH OR BELOW SURFACE. TYP.

3 APPLY ADEQUATE AMOUNT (2-3 DROPS) OF LOCTITE 271 - HIGH STRENGTH RED BEFORE INSTALLATION

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	P102	CROSS MEMBER, MAGNET HOLDER	1
2	P104	HELICOIL, NITRONIC 60, M2.5 X 0.45MM, 5MM LONG	12

A	FIRST ISSUE	N/A	2020 FEB 04	DF
REV	DESCRIPTION	DR	DATE	BY

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UNLESS SPECIFIED OTHERWISE, DIMENSIONS ARE IN MM

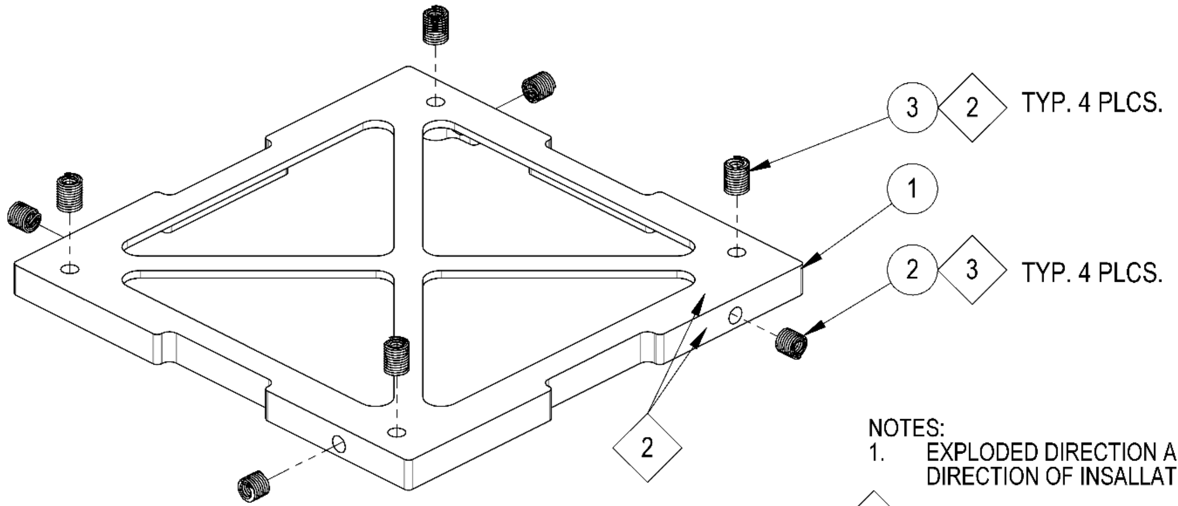
TOLERANCES ARE: FRACTIONS ± 1/2 DECIMALS .X±.3 .XX±.12 .XXX±.050 ANGLES ± 1°

THIRD ANGLE PROJECTION

APPROVALS		DATE (YYYY-MMM-DD)
DRAWN	DANIEL F	2020 FEB 04
CHECKED	SEAMUS W G	2020 FEB 27
DXF		
MATERIAL	N/A	QUANTITY 1
WEIGHT	40.7 G	AREA N/A

TITLE:
INSTALLATION, HELICOILS, CROSS MEMBER, MAGNET HOLDER

SIZE A
DWG. NO. A121
REV. A
SCALE NTS
TYPE: ASSEMBLY
SHEET 1 of 1



NOTES:

1. EXPLODED DIRECTION ALSO INDICATES DIRECTION OF INSALLATION.

2 ENSURE HELICOIL IS FLUSH OR BELOW SURFACE.

3 APPLY ADEQUATE AMOUNT (2-3 DROPS) OF LOCTITE 271 - HIGH STRENGTH RED BEFORE INSTALLATION

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	P101	CROSS MEMBER, PAYLOAD	1
2	P105	HELICOIL, NITRONIC 60, M3 X 0.5MM, 4.5MM LONG	4
3	P107	HELICOIL, NITRONIC 60, M3 X 0.5MM, 6MM LONG	4

A	FIRST ISSUE	N/A	2020 FEB 01	DF
REV	DESCRIPTION	DR	DATE	BY

REVISIONS

D3 design cubed

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TOLERANCES ARE: FRACTIONS ± 1/2 DECIMALS X±.3 .XX±.12 .XXX±.050 ANGLES ± 1°

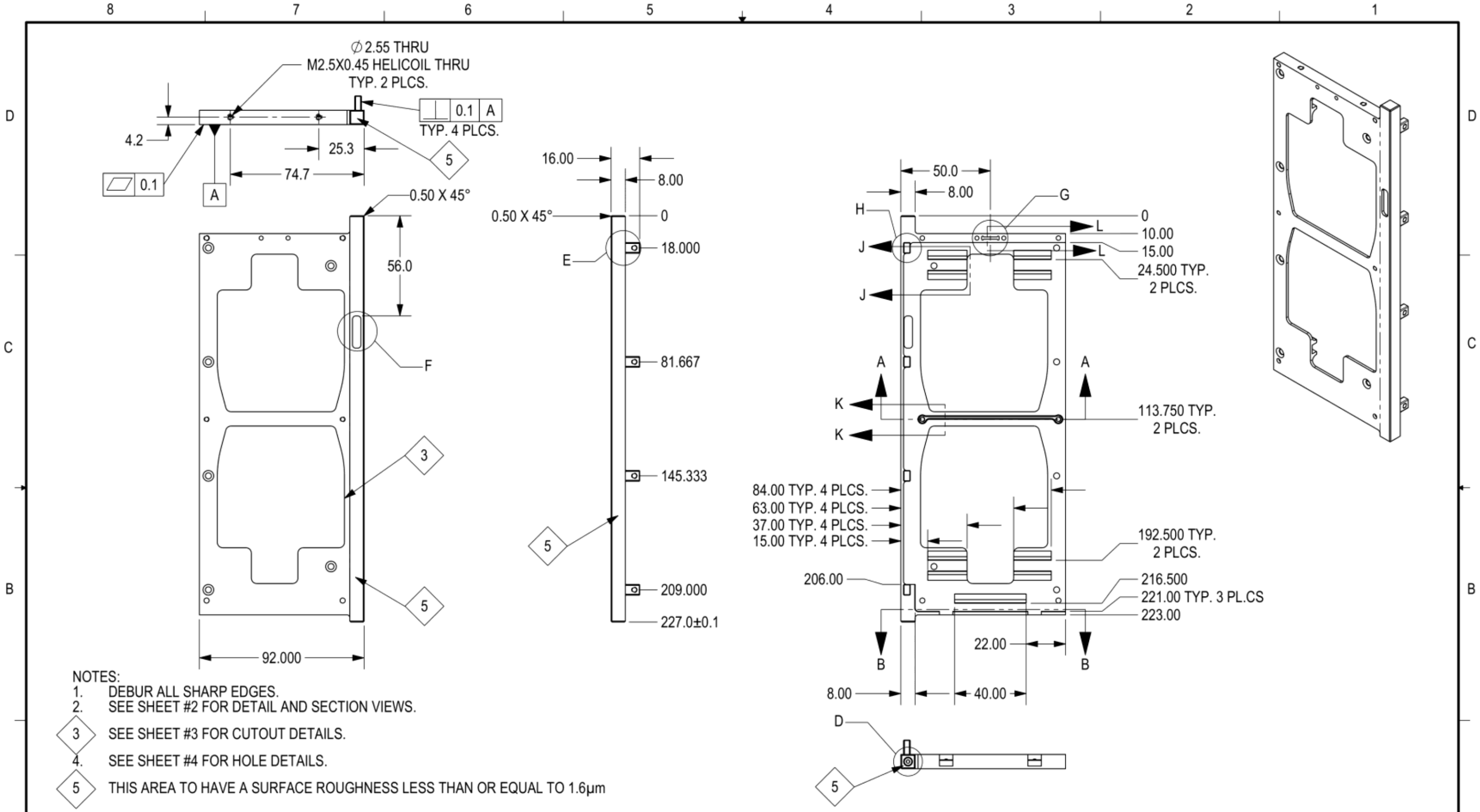
THIRD ANGLE PROJECTION

APPROVALS		DATE (YYYY-MMM-DD)
DRAWN	DANIEL F	2020 FEB 01
CHECKED	SEAMUS W G	2020 FEB 27
DXF		

MATERIAL N/A
QUANTITY 2
WEIGHT 27.59 G
AREA N/A

TITLE:
INSTALLATION, HELICOILS, CROSS MEMBER, PAYLOAD

SIZE A
DWG. NO. A130
REV. A
SCALE NTS
TYPE: ASSEMBLY
SHEET 1 OF 1



NOTES:
1. DEBUR ALL SHARP EDGES.
2. SEE SHEET #2 FOR DETAIL AND SECTION VIEWS.
3. SEE SHEET #3 FOR CUTOUT DETAILS.
4. SEE SHEET #4 FOR HOLE DETAILS.
5. THIS AREA TO HAVE A SURFACE ROUGHNESS LESS THAN OR EQUAL TO 1.6μm

REV	DESCRIPTION	DR	DATE	BY
A	FIRST ISSUE	N/A	2020 FEB 01	DF

REVISIONS

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TOLERANCES ARE: FRACTIONS ± 1/2 DECIMALS .X ±.3 .XX ±.12 .XXX ±.050 ANGLES ± 1°

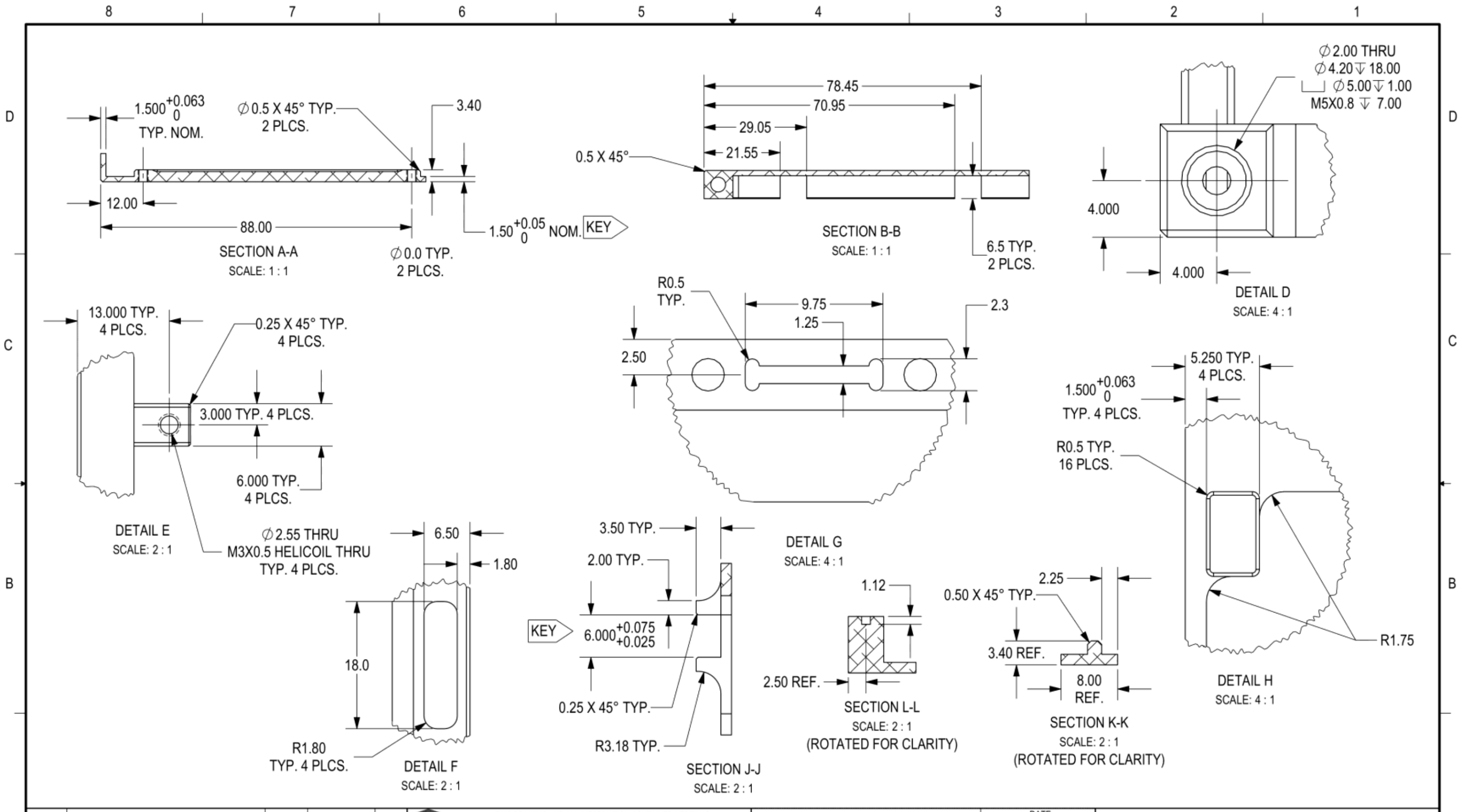
THIRD ANGLE PROJECTION

APPROVALS		DATE (YYYY-MMM-DD)
DRAWN	DANIEL F	2020 FEB 01
CHECKED	SEAMUS W G	2020 FEB 03
DXF		

MATERIAL 6061-T6 (SS)
QUANTITY 4
WEIGHT 64.2 G
AREA N/A

TITLE:
PANEL, INTEGRATED SHEAR & RAIL

SIZE B
DWG. NO. P100
REV. A
SCALE NTS
TYPE MACHINED
SHEET 1 OF 5



REV	DESCRIPTION	DR	DATE	BY
A	FIRST ISSUE	N/A	2020 FEB 01	DF

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TOLERANCES ARE:	FRACTIONS	DECIMALS	ANGLES
	± 1/2	.X ± .3 .XX ± .12 .XXX ± .050	± 1°

THIRD ANGLE PROJECTION

APPROVALS		DATE (YYYY-MMM-DD)
DRAWN	DANIEL F	2020 FEB 01
CHECKED	SEAMUS W G	2020 FEB 03
DXF		

MATERIAL 6061-T6 (SS)
QUANTITY 4
WEIGHT 64.2 G
AREA N/A

TITLE:
PANEL, INTEGRATED SHEAR & RAIL

SIZE B
DWG. NO. P100
REV. A
SCALE NTS
TYPE MACHINED
SHEET 2 OF 5

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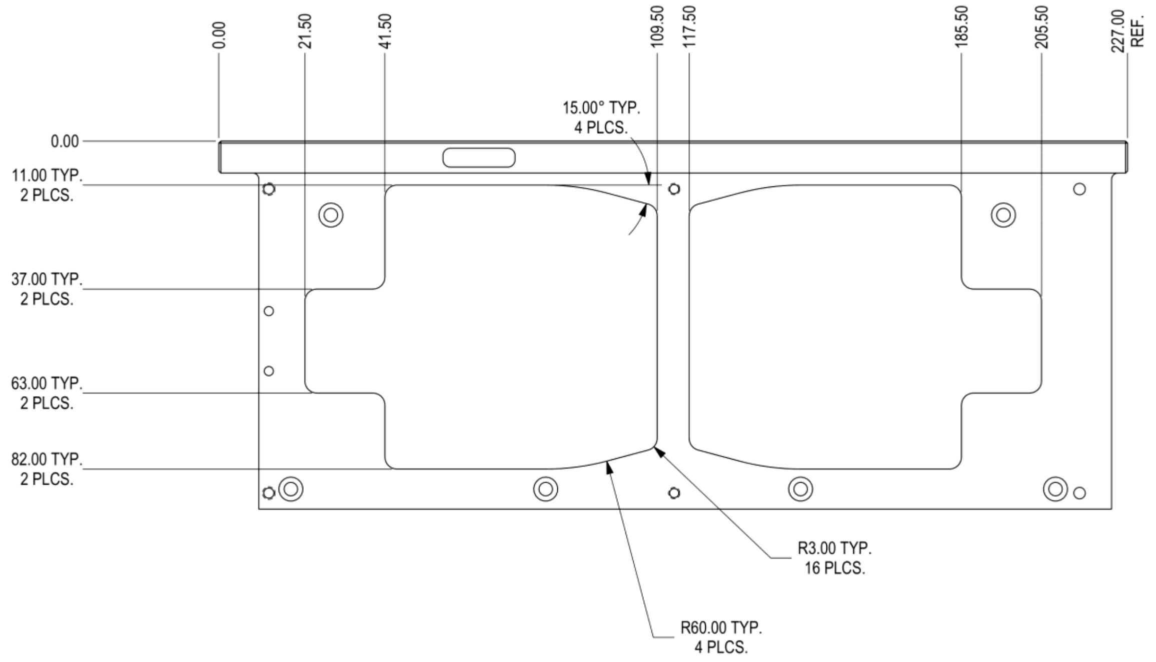

REV	DESCRIPTION	DR	DATE	BY
A	FIRST ISSUE	N/A	2020 FEB 01	DF

REVISIONS

D3 design cubed

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TOLERANCES ARE: FRACTIONS ± 1/2 DECIMALS .X ± .3 .XX ± .12 .XXX ± .050 ANGLES ± 1°

THIRD ANGLE PROJECTION

APPROVALS		DATE (YYYY-MMM-DD)
DRAWN	DANIEL F	2020 FEB 01
CHECKED	SEAMUS W G	2020 FEB 03
DXF		

MATERIAL 6061-T6 (SS)
QUANTITY 4
WEIGHT 64.2 G
AREA N/A

TITLE:
PANEL, INTEGRATED SHEAR & RAIL

SIZE B
DWG. NO. P100
REV. A
SCALE NTS
TYPE MACHINED
SHEET 3 OF 5

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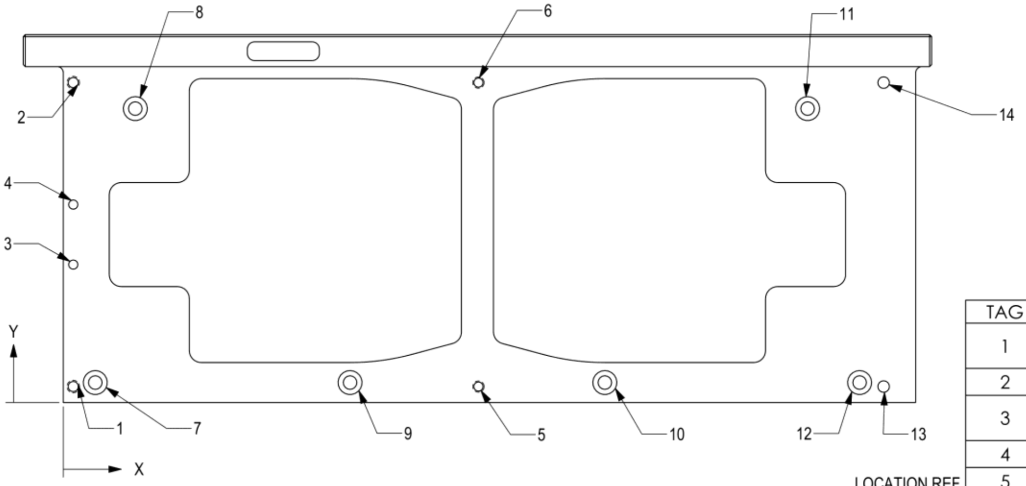


	TAG	X LOC	Y LOC	SIZE
	1	2.50	4	⌀2.55 THRU M2.5X0.45 HELICOIL THRU
	2	2.50	80	
	3	2.50	34.50	
	4	2.50	49.50	
LOCATION REF.	5	103.75	4	⌀2.30 THRU M2X0.4 HELICOIL THRU
LOCATION REF.	6	103.75	80	
	7	8	5	⌀3.40 THRU ⌵ ⌀6.00 X 100°
	8	18	73.50	
	9	71.67	5	
	10	135.33	5	
	11	186	73.50	
	12	199	5	
	13	205	4	⌀2.90 THRU
	14	205	80	

REV	DESCRIPTION	DR	DATE	BY
A	FIRST ISSUE	N/A	2020 FEB 01	DF

REVISIONS

UNLESS OTHERWISE SPECIFIED, DIMENSIONS ARE IN MM

TOLERANCES ARE: FRACTIONS ± 1/2 DECIMALS .X ± .3 .XX ± .12 .XXX ± .050 ANGLES ± 1°

THIRD ANGLE PROJECTION

APPROVALS		DATE (YYYY-MMM-DD)
DRAWN	DANIEL F	2020 FEB 01
CHECKED	SEAMUS W G	2020 FEB 03
DXF		

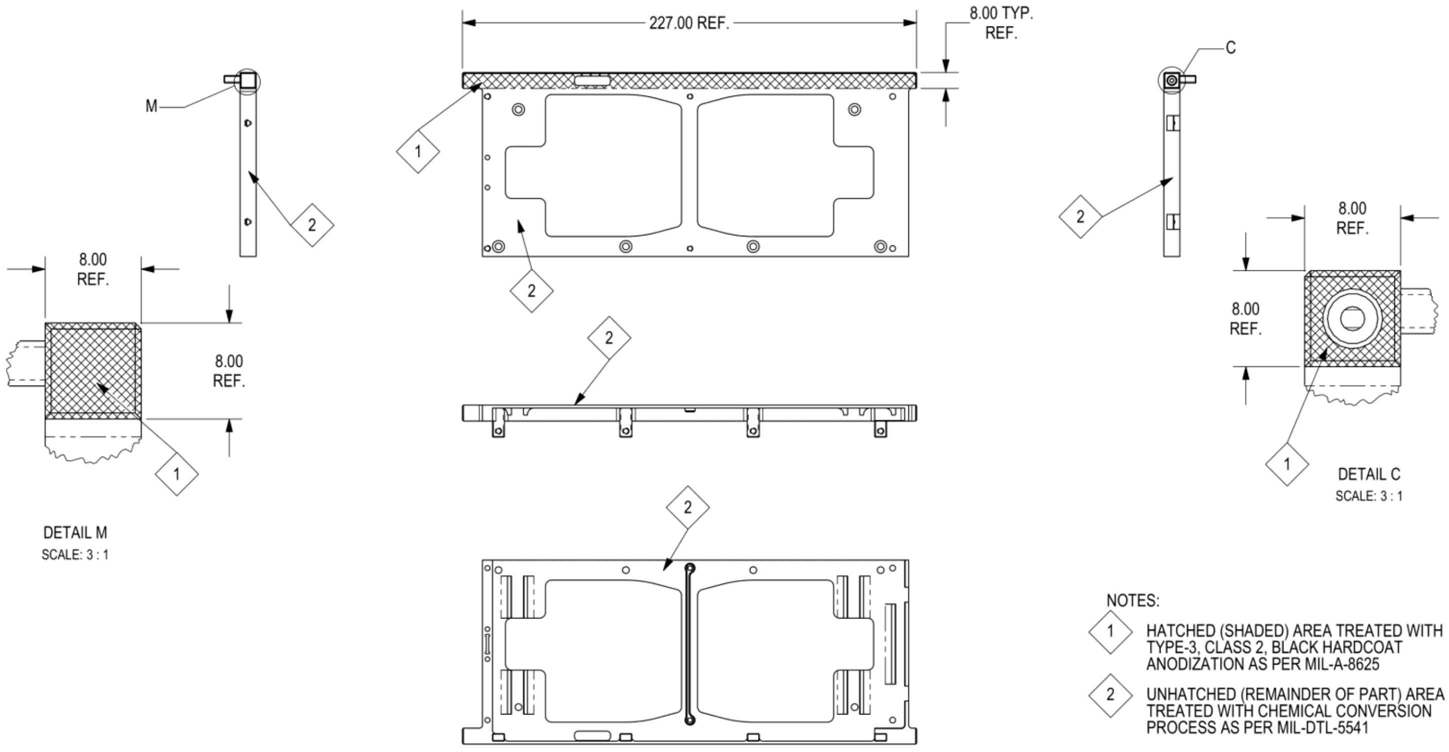
MATERIAL 6061-T6 (SS) QUANTITY 4

WEIGHT 64.2 G AREA N/A

TITLE:
PANEL, INTEGRATED SHEAR & RAIL

SIZE B DWG. NO. P100 REV. A

SCALE NTS TYPE MACHINED SHEET 4 OF 5



NOTES:

1 HATCHED (SHADED) AREA TREATED WITH TYPE-3, CLASS 2, BLACK HARDCOAT ANODIZATION AS PER MIL-A-8625

2 UNHATCHED (REMAINDER OF PART) AREA TREATED WITH CHEMICAL CONVERSION PROCESS AS PER MIL-DTL-5541

A	FIRST ISSUE	N/A	2020 FEB 01	DF
REV	DESCRIPTION	DR	DATE	BY

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TOLERANCES ARE:	FRACTIONS	DECIMALS	ANGLES
	± 1/2	.X ± .3 .XX ± .12 .XXX ± .050	± 1°

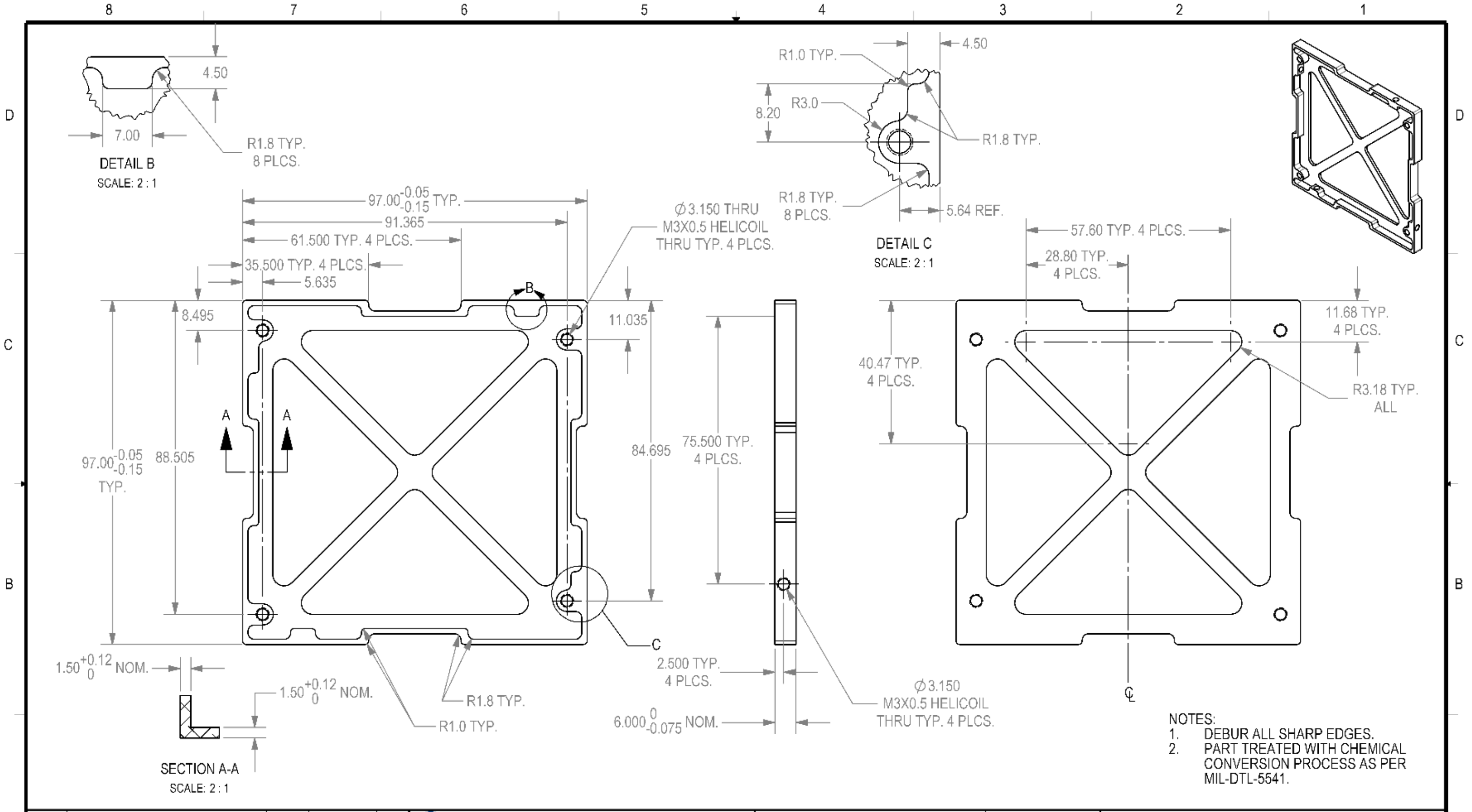
THIRD ANGLE PROJECTION

APPROVALS		DATE (YYYY-MMM-DD)
DRAWN	DANIEL F	2020 FEB 01
CHECKED	SEAMUS W G	2020 FEB 03
DXF		

MATERIAL 6061-T6 (SS)
QUANTITY 4
WEIGHT 64.2 G
AREA N/A

TITLE:
PANEL, INTEGRATED SHEAR & RAIL

SIZE B
DWG. NO. P100
REV. A
SCALE NTS
TYPE MACHINED
SHEET 5 OF 5



NOTES:
1. DEBUR ALL SHARP EDGES.
2. PART TREATED WITH CHEMICAL CONVERSION PROCESS AS PER MIL-DTL-5541.

A	FIRST ISSUE	N/A	2020 FEB 02	DF
REV	DESCRIPTION	DR	DATE	BY

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TOLERANCES ARE FRACTIONS ± 1/2 DECIMALS X±.3 .XX±.12 .XXX±.050 ANGLES ± 1°

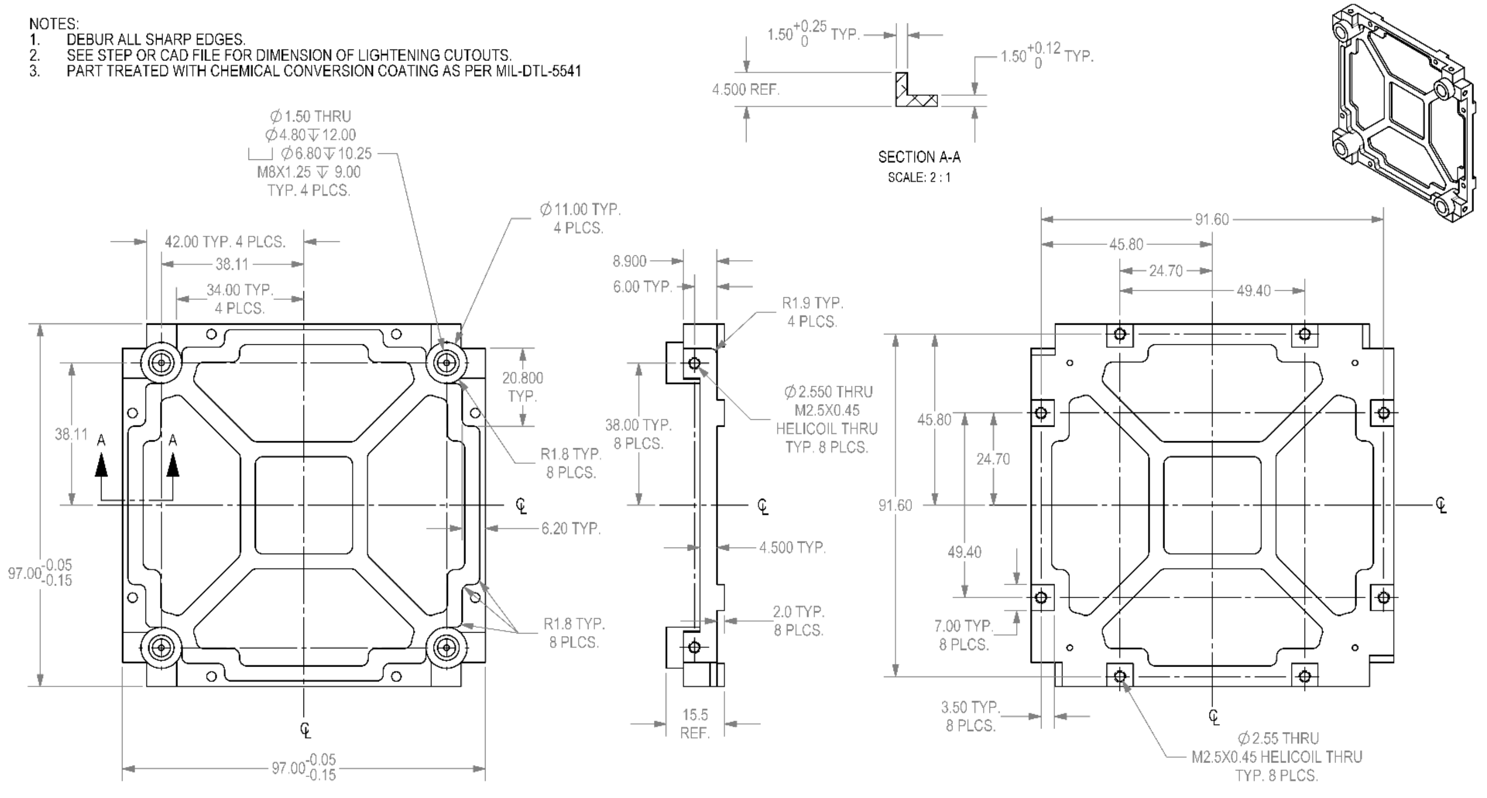
THIRD ANGLE PROJECTION

APPROVALS	DATE (YYYY-MMM-DD)
DRAWN DANIEL F	2020 FEB 02
CHECKED SEAMSUS W G	2020 FEB 04
DXF	
MATERIAL 6061-T6 (SS)	QUANTITY 2
WEIGHT 25.5 G	AREA N/A

TITLE:
CROSS MEMBER, PAYLOAD

SIZE B | DWG. NO. P101 | REV. A
SCALE NTS | TYPE MACHINED | SHEET 1 OF 1

NOTES:
1. DEBUR ALL SHARP EDGES.
2. SEE STEP OR CAD FILE FOR DIMENSION OF LIGHTENING CUTOUTS.
3. PART TREATED WITH CHEMICAL CONVERSION COATING AS PER MIL-DTL-5541



REV	DESCRIPTION	DR	DATE	BY
A	FIRST ISSUE	N/A	2020 FEB 01	DF

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TOLERANCES ARE:	FRACTIONS	DECIMALS	ANGLES
	± 1/2	.X ±.3 .XX ±.12 .XXX ±.050	± 1°

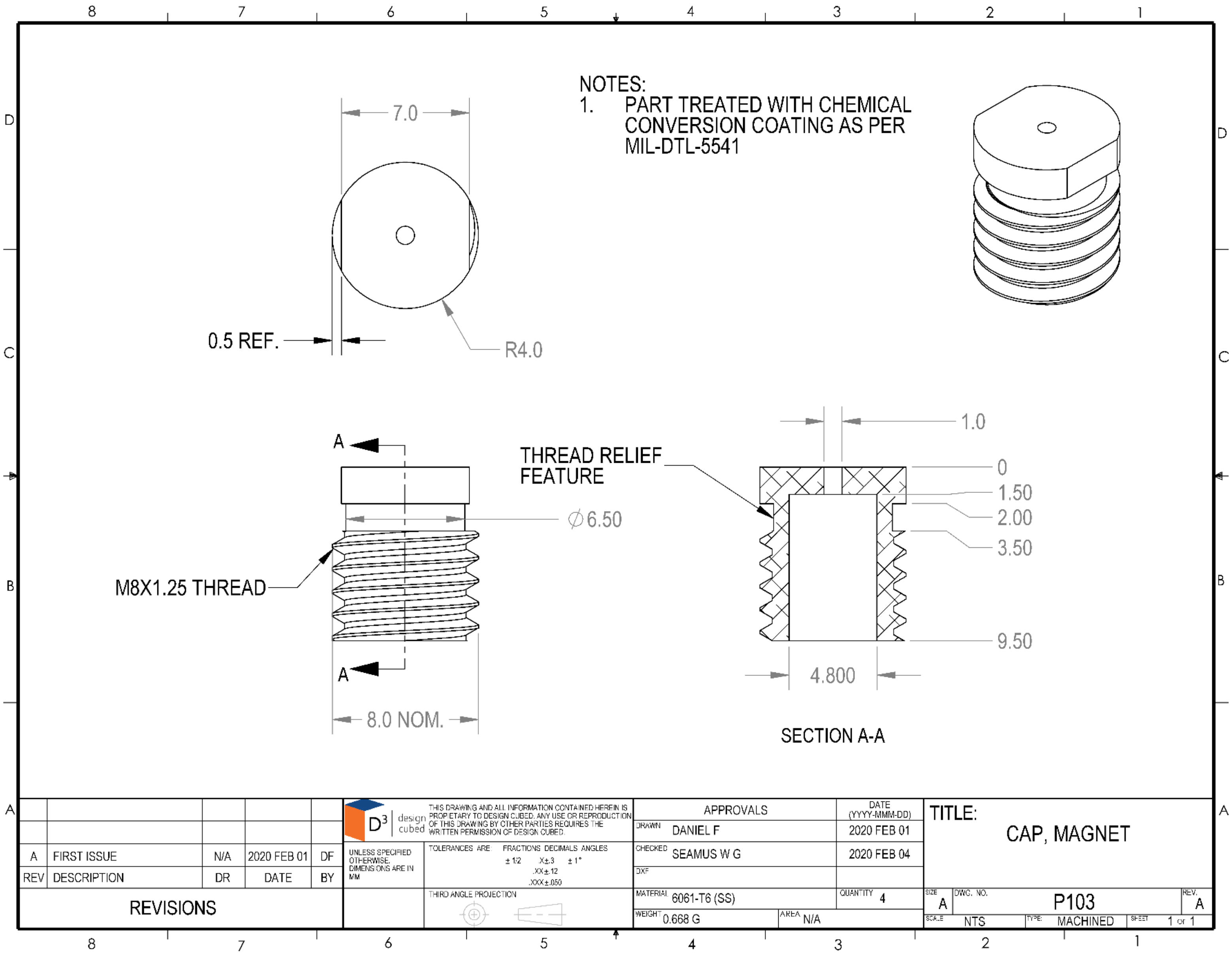
THIRD ANGLE PROJECTION

APPROVALS		DATE (YYYY-MMM-DD)
DRAWN	DANIEL F	2020 FEB 01
CHECKED	SEAMUS W G	2020 FEB 04
DXF		

MATERIAL 6061-T6 (SS)
QUANTITY 1
WEIGHT 38.5 G
AREA N/A

TITLE:
CROSS MEMBER, MAGNET HOLDER

SIZE B
DWG NO. P102
REV. A
SCALE NTS
TYPE MACHINED
SHEET 1 OF 1



NOTES:
1. PART TREATED WITH CHEMICAL CONVERSION COATING AS PER MIL-DTL-5541

REV	DESCRIPTION	DR	DATE	BY
A	FIRST ISSUE	N/A	2020 FEB 01	DF

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TOLERANCES ARE:

FRACTIONS	DECIMALS	ANGLES
± 1/2	.X±.3 .XX±.12 .XXX±.050	± 1°

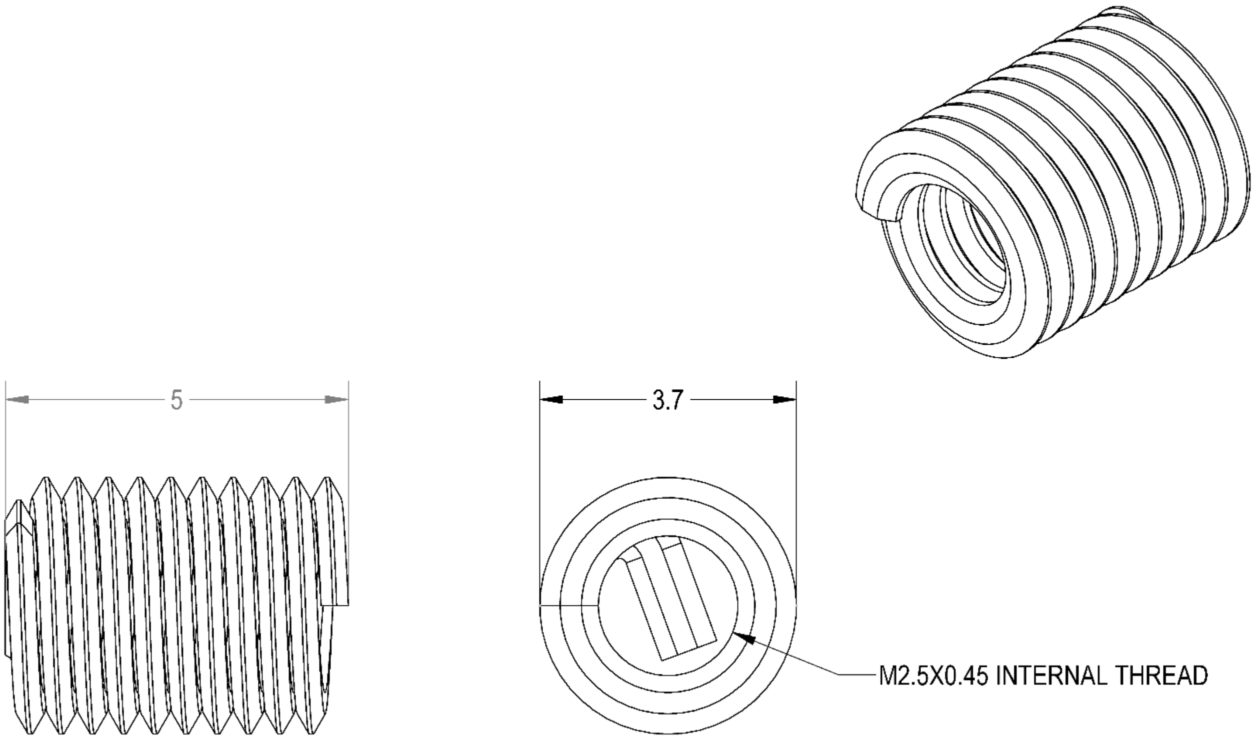
THIRD ANGLE PROJECTION

APPROVALS		DATE (YYYY-MMM-DD)
DRAWN	DANIEL F	2020 FEB 01
CHECKED	SEAMUS W G	2020 FEB 04
DXF		

MATERIAL 6061-T6 (SS)
QUANTITY 4
WEIGHT 0.668 G
AREA N/A

TITLE: CAP, MAGNET

SIZE A
DWG. NO. P103
REV. A
SCALE NTS
TYPE: MACHINED
SHEET 1 of 1



APPROVED VENDOR: MCMASTER CARR
APPROVED VENDOR PART NUMBER: 93914A043

REV	DESCRIPTION	DR	DATE	BY
A	FIRST ISSUE	N/A	2020 FEB 01	DF

REVISIONS

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TOLERANCES ARE:	FRACTIONS	DECIMALS	ANGLES
	± 1/2	.X±.3 .XX±.12 .XXX±.050	± 1°

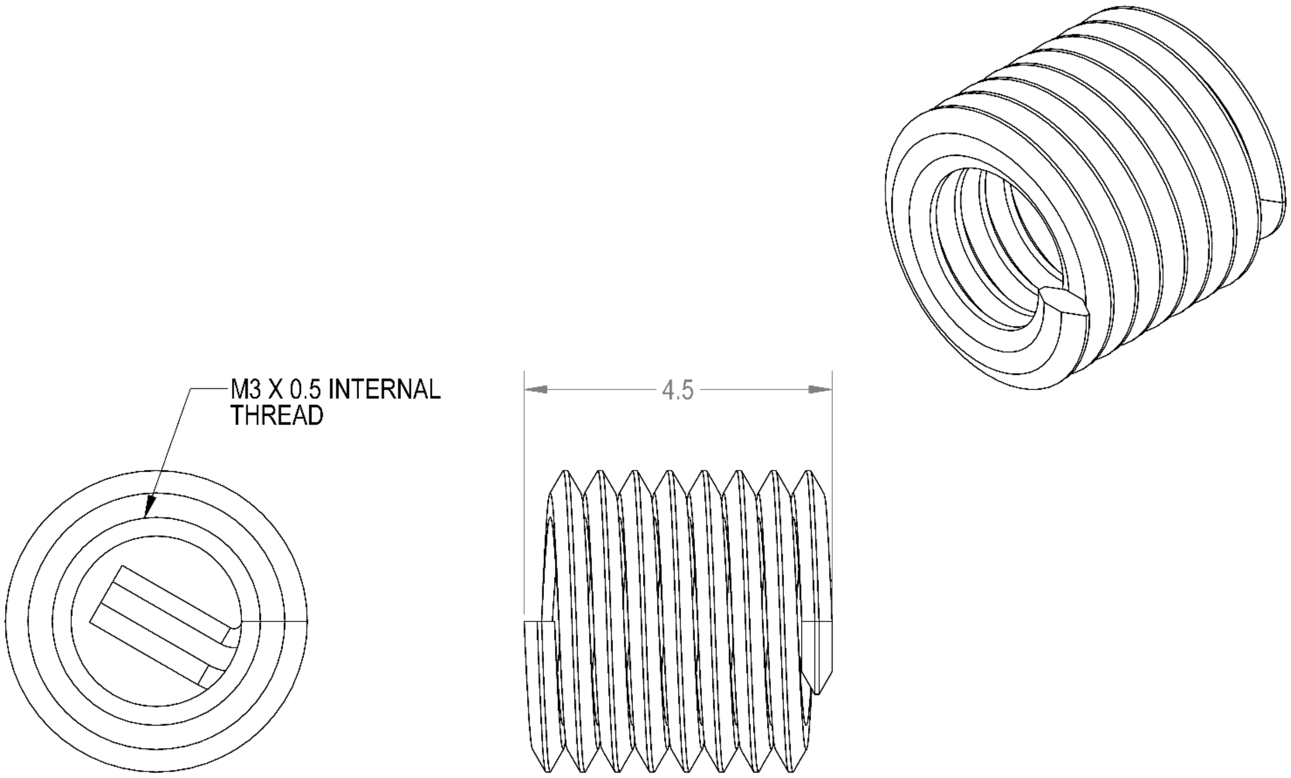
THIRD ANGLE PROJECTION

APPROVALS		DATE (YYYY-MMM-DD)
DRAWN	DANIEL F	2020 FEB 01
CHECKED	SEAMUS W G	2020 FEB 27
DXF		

MATERIAL NITRONIC 60 SS
QUANTITY 36
WEIGHT 0.18 G
AREA N/A

TITLE:
HELICOIL, NITRONIC 60, M2.5 X 0.45MM, 5MM LONG

SIZE A
DWG. NO. P104
REV. A
SCALE NTS
TYPE: PURCHASED
SHEET 1 OF 1



APPROVED VENDOR: MCMASTER CARR
APPROVED VENDOR PART NUMBER: 93914A077

A	FIRST ISSUE	N/A	2020 FEB 02	DF
REV	DESCRIPTION	DR	DATE	BY

REVISIONS

D3 design cubed

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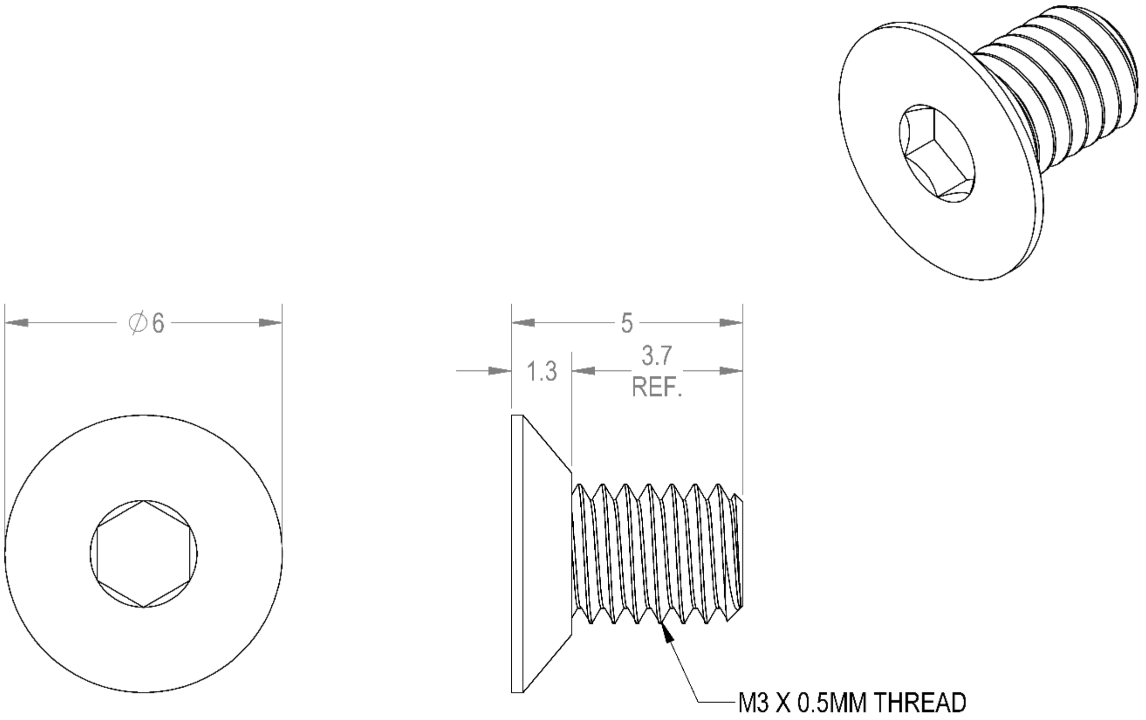
TOLERANCES ARE:	FRACTIONS	DECIMALS	ANGLES
	± 1/2	.X±.3 .XX±.12 .XXX±.050	± 1°

THIRD ANGLE PROJECTION

APPROVALS		DATE (YYYY-MMM-DD)
DRAWN	DANIEL F	2020 FEB 02
CHECKED	SEAMUS W G	2020 FEB 27
DXF		
MATERIAL	NITRONIC 60 SS	QUANTITY 24
WEIGHT 0.22 G	AREA N/A	

TITLE:
HELICOIL, NITRONIC 60, M3 X 0.5MM, 4.5MM LONG

SIZE A	DWG. NO. P105		REV. A
SCALE NTS	TYPE: PURCHASED	SHEET 1 OF 1	



APPROVED VENDOR: MCMASTER CARR
APPROVED VENDOR PART NUMBER: 90729A165

REV	DESCRIPTION	DR	DATE	BY
A	FIRST ISSUE	N/A	2020 FEB 02	DF

REVISIONS

UNLESS SPECIFIED OTHERWISE, DIMENSIONS ARE IN MM

TOLERANCES ARE: FRACTIONS ± 1/2 DECIMALS .X±.3 .XX±.12 .XXX±.050 ANGLES ± 1°

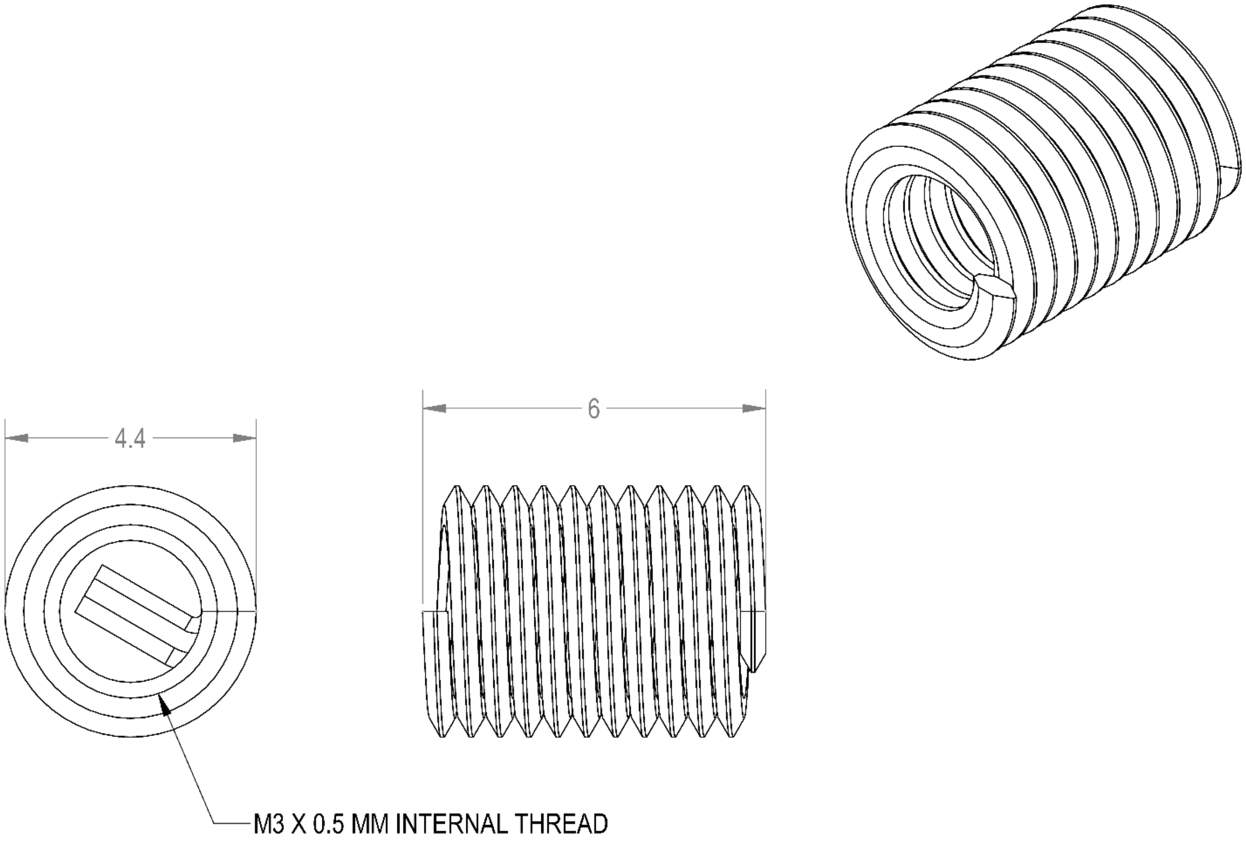
THIRD ANGLE PROJECTION

APPROVALS		DATE (YYYY-MMM-DD)
DRAWN	DANIEL F	2020 FEB 02
CHECKED	SEAMUS W G	2020 FEB 27
DXF		

MATERIAL 316 SS
QUANTITY 24
WEIGHT 0.349 G
AREA N/A

TITLE:
FHCS, HEX DRIVE, UNDERCUT, 316 SS, M3 X 0.5MM, 5MM LONG

SIZE A
DWG. NO. P106
REV. A
SCALE NTS
TYPE: PURCHASED
SHEET 1 of 1



APPROVED VENDOR: MCMASTER CARR
APPROVED VENDOR PART NUMBER: 93914A094

A	FIRST ISSUE	N/A	2020 FEB 02	DF
REV	DESCRIPTION	DR	DATE	BY

REVISIONS

D3 design cubed

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UNLESS SPECIFIED OTHERWISE, DIMENSIONS ARE IN MM

TOLERANCES ARE:	FRACTIONS	DECIMALS	ANGLES
	± 1/2	.X±.3 .XX±.12 .XXX±.050	± 1°

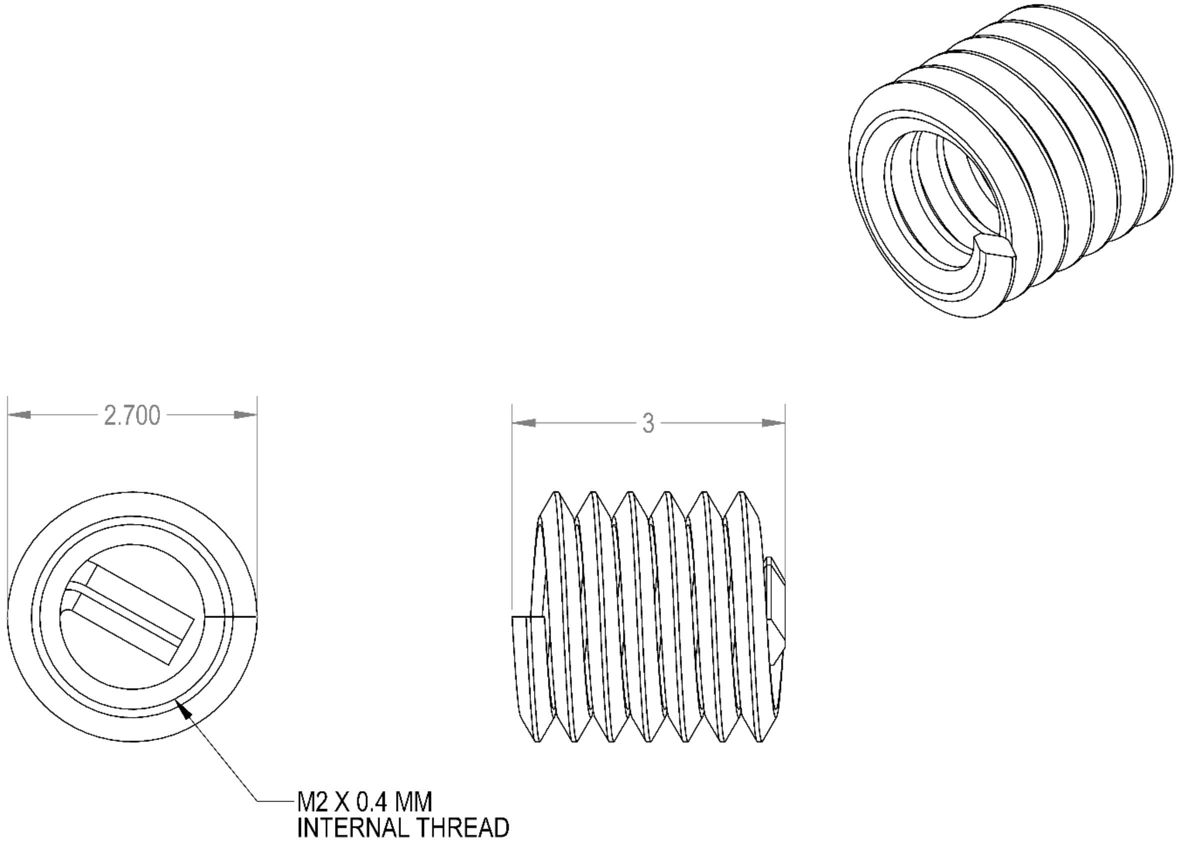
THIRD ANGLE PROJECTION

APPROVALS		DATE (YYYY-MMM-DD)
DRAWN	DANIEL F	2020 FEB 02
CHECKED	SEAMUS W G	2020 FEB 27
DXF		
MATERIAL	NITRONIC 60 SS	QUANTITY 8

WEIGHT 0.30 G
AREA N/A

TITLE:
HELICOIL, NITRONIC 60, M3 X 0.5MM, 6MM LONG

SIZE A
DWG. NO. P107
REV. A
SCALE NTS
TYPE: PURCHASED
SHEET 1 OF 1



APPROVED VENDOR: MCMASTER CARR
APPROVED VENDOR PART NUMBER: 91732A182

A	FIRST ISSUE	N/A	2020 FEB 02	DF
REV	DESCRIPTION	DR	DATE	BY

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TOLERANCES ARE:	FRACTIONS	DECIMALS	ANGLES
	± 1/2	.X±.3	± 1°
		.XX±.12	
		.XXX±.050	

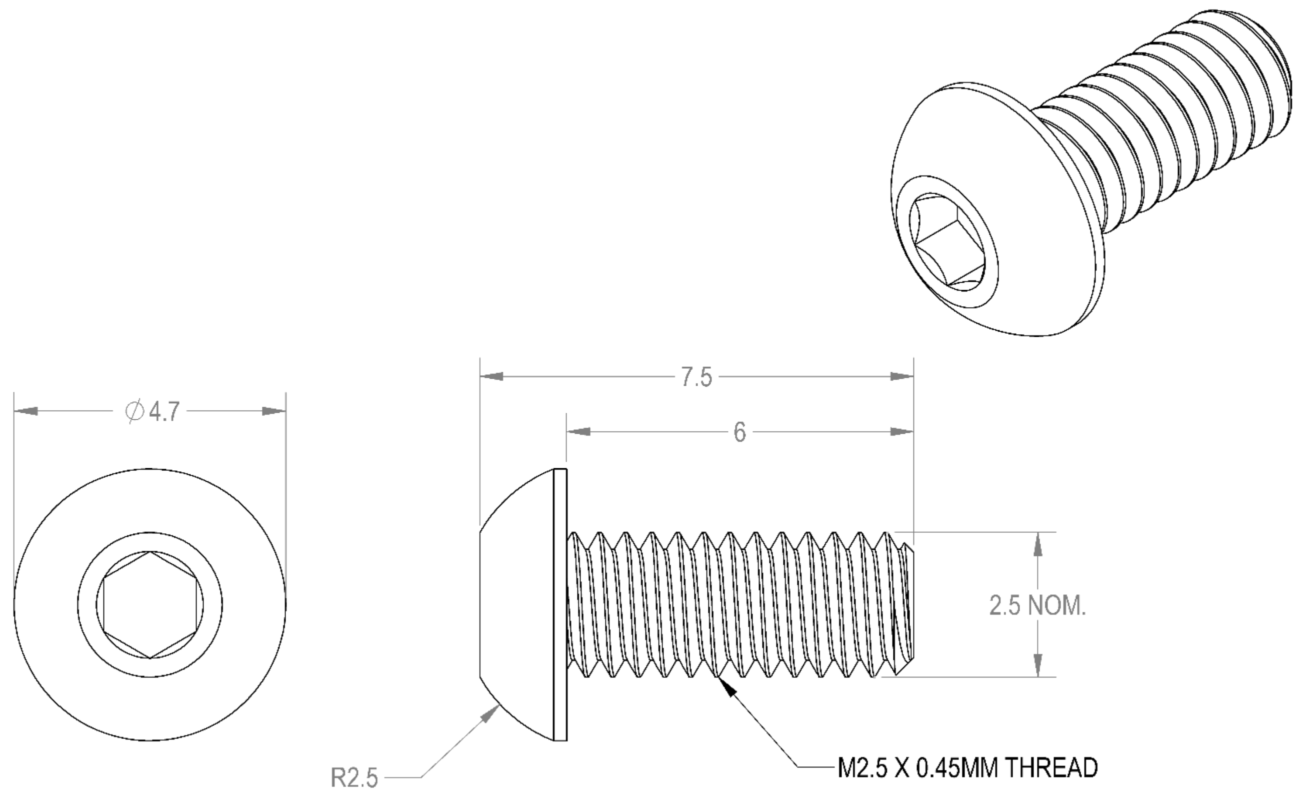
THIRD ANGLE PROJECTION

APPROVALS		DATE (YYYY-MMM-DD)
DRAWN	DANIEL F	2020 FEB 02
CHECKED	SEAMUS W G	2020 FEB 27
DXF		

MATERIAL NITRONIC 60 SS
QUANTITY 8
WEIGHT 0.05 G
AREA N/A

TITLE:
HELICOIL, NITRONIC 60, M2 X 0.4MM, 3MM LONG

SIZE A
DWG. NO. P108
REV. A
SCALE NTS
TYPE: PURCHASED
SHEET 1 of 1



APPROVED VENDOR: MCMASTER CARR
APPROVED VENDOR PART NUMBER: 94500A213

A	FIRST ISSUE	N/A	2020 FEB 02	DF
REV	DESCRIPTION	DR	DATE	BY

REVISIONS

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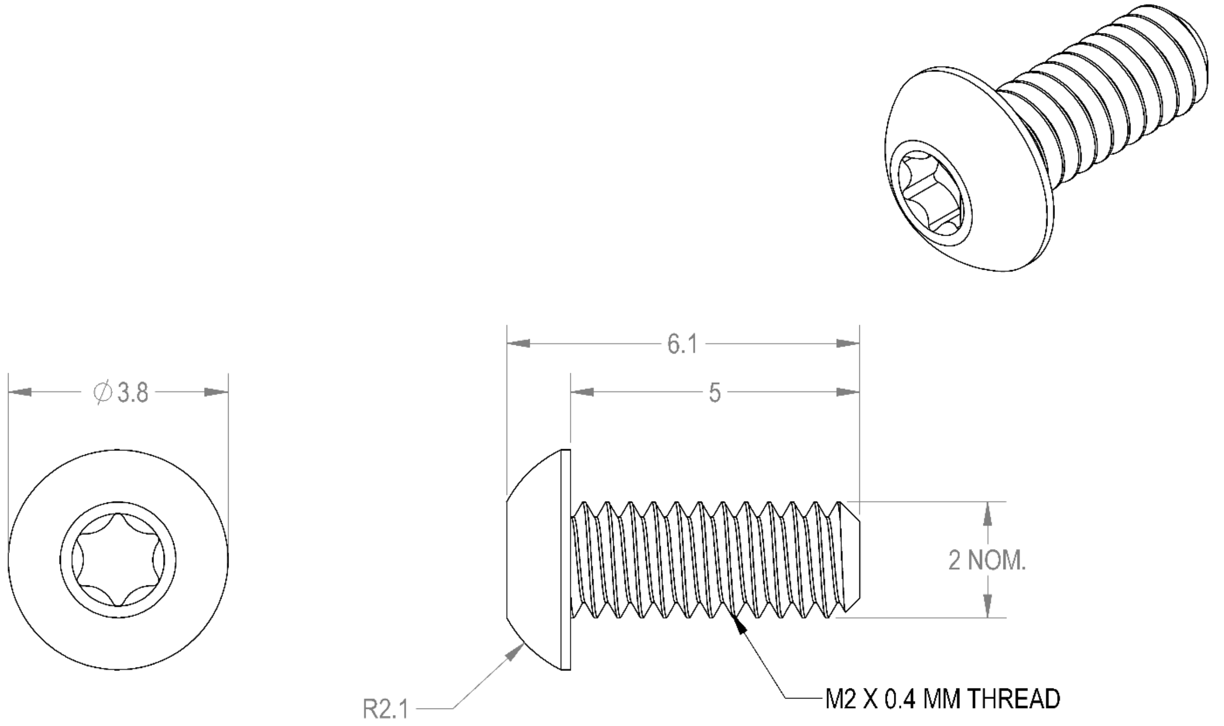
TOLERANCES ARE:	FRACTIONS	DECIMALS	ANGLES
	± 1/2	.X±.3 .XX±.12 .XXX±.050	± 1°

THIRD ANGLE PROJECTION

APPROVALS		DATE (YYYY-MMM-DD)
DRAWN	DANIEL F	2020 FEB 02
CHECKED	SEAMUS W G	2020 FEB 27
DXF		
MATERIAL	316 SS	QUANTITY 28
WEIGHT 0.319 G	AREA N/A	

TITLE:
BHCS, HEX DRIVE, 316 SS,
M2.5 X 0.45MM, 6MM LONG

SIZE A
DWG. NO. P109
REV. A
SCALE NTS
TYPE: PURCHASED
SHEET 1 OF 1



APPROVED VENDOR: MCMASTER CARR
APPROVED VENDOR PART NUMBER: 92095A452

A	FIRST ISSUE	N/A	2020 FEB 02	DF
REV	DESCRIPTION	DR	DATE	BY

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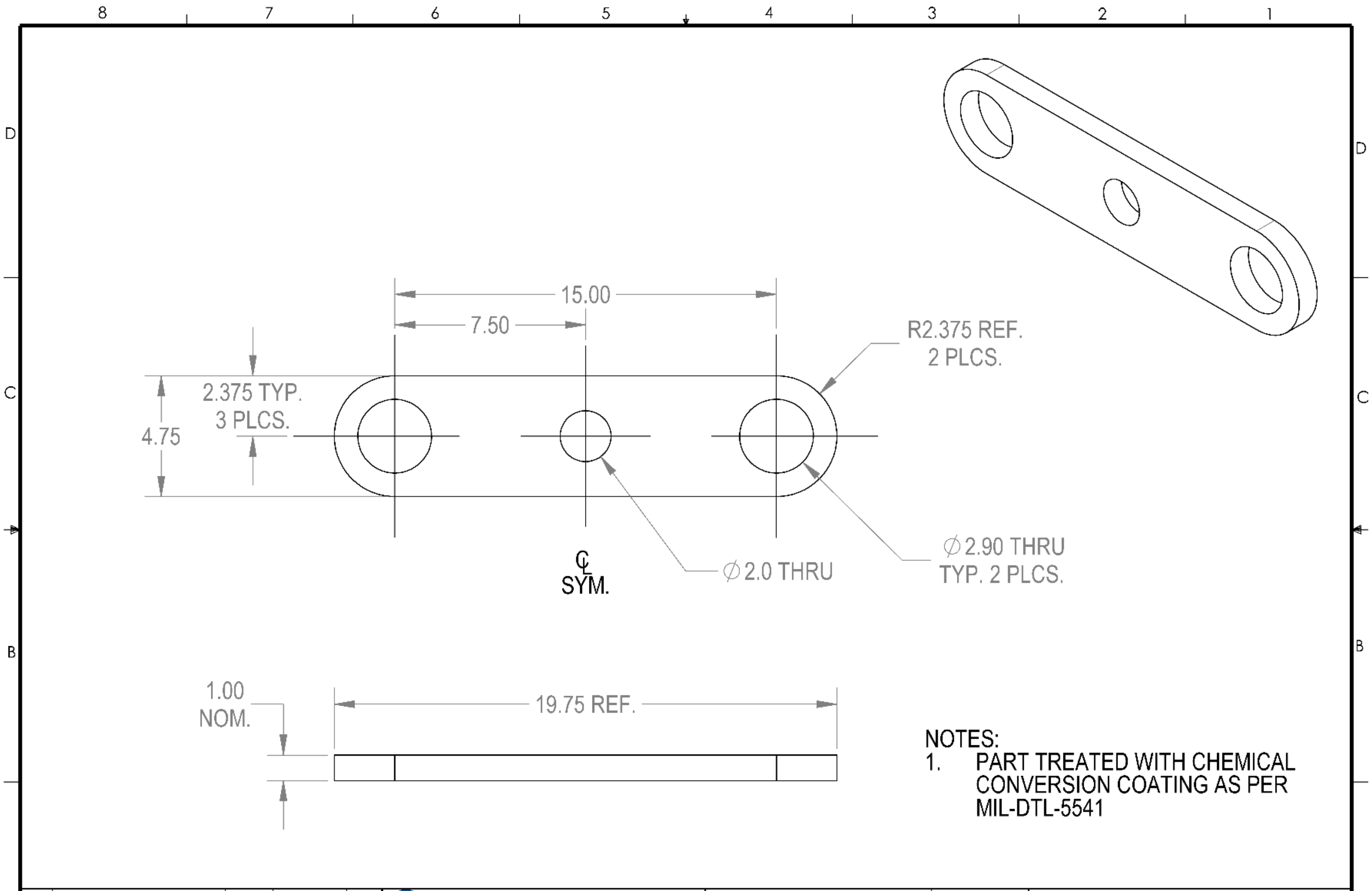
TOLERANCES ARE:	FRACTIONS	DECIMALS	ANGLES
	± 1/2	.X±.3	± 1°
		.XX±.12	
		.XXX±.050	

THIRD ANGLE PROJECTION

APPROVALS		DATE (YYYY-MMM-DD)
DRAWN	DANIEL F	2020 FEB 02
CHECKED	SEAMUS W G	2020 FEB 27
DXF		
MATERIAL	316 SS	QUANTITY 8
WEIGHT 0.16 G	AREA N/A	

TITLE:
BHCS, HEX DRIVE, 18-8 SS, M2 X 0.4MM, 5MM LONG

SIZE	DWG. NO.		REV.
A	P110		A
SCALE NTS	TYPE: PURCHASED	SHEET 1 OF 1	



NOTES:
1. PART TREATED WITH CHEMICAL CONVERSION COATING AS PER MIL-DTL-5541

REV	DESCRIPTION	DR	DATE	BY
A	FIRST ISSUE	N/A	2020 FEB 02	DF

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TOLERANCES ARE:

FRACTIONS	DECIMALS	ANGLES
± 1/2	.X±.3 .XX±.12 .XXX±.050	± 1°

THIRD ANGLE PROJECTION

APPROVALS		DATE (YYYY-MMM-DD)
DRAWN	DANIEL F	2020 FEB 02
CHECKED	SEAMUS W G	2020 FEB 04
DXF		

MATERIAL 6061-T6 (SS)
QUANTITY 4
WEIGHT 0.20 G
AREA 72.6 SQ. MM

TITLE:
CAP, HYSTERESIS ROD

SIZE A
DWG. NO. P111
REV. A
SCALE NTS
TYPE: MACHINED
SHEET 1 OF 1

In summary, the 22 drawings detailed within the appendix provide clear manufacturing instructions for CNC manufacturing by Saskatchewan Polytechnic. As well, adequate instruction has been provided for assembly of the 2U primary frame design and integration of internal components by the USST. For further detail, the comprehensive SolidWorks model provided upon project handover shall provide additional context.

Appendix E: CES Material Selection

This section will outline the materials selection process used for the CubeSat primary structure. Design Cubed implemented the Ashby system of material selection (Ashby 2017), to compile a list of candidate materials that fit the criteria of the project. To simplify selection, the software CES Edupack 2017 was used to quickly filter materials during the process. Further restrictions and criteria for candidate materials were developed to narrow down the available options and are discussed below.

Due to the strict mass budget available for the project, the material selection was driven by reducing mass as much as possible. In order to ensure the material chosen fit the mass budget, a limit of 2800 kg/m^3 was applied. The highest load experienced by the CubeSat frame, Z-axis loading, was used as the design case for material selection. The material must ensure the frame is able to sustain compressive force without failure and the loading conditions considered were compressive force and buckling.

The client has indicated the material selected must be a metal. Saskatchewan Polytechnic can perform traditional machining and additive manufacturing, so based on these requirements only metals well suited to these processes were considered. To ensure the material is affordable, Design Cubed placed a restriction of $5.00/kg on potential materials to ensure economic viability. The frame is expected to be shipped for physical testing and will be exposed to a variety of climates as a result, so corrosion resistance corrosion from salt and fresh water was considered. For sustainability reasons, materials were limited to those that were easily recyclable.

Once in orbit, the frame's material will need to be suitable for the Low Earth Orbit environment. The material will need to have a minimum and maximum service temperature of -40 °C and 60 °C respectively for safe operation. Severe UV radiation will be present, so the material must not degrade under this condition.

Materials meeting all requirements above were then evaluated on their relative strength and stiffness to density ratios to isolate the most effective candidates. Specifically, relative strength and density were evaluated first as per Figure E-1.

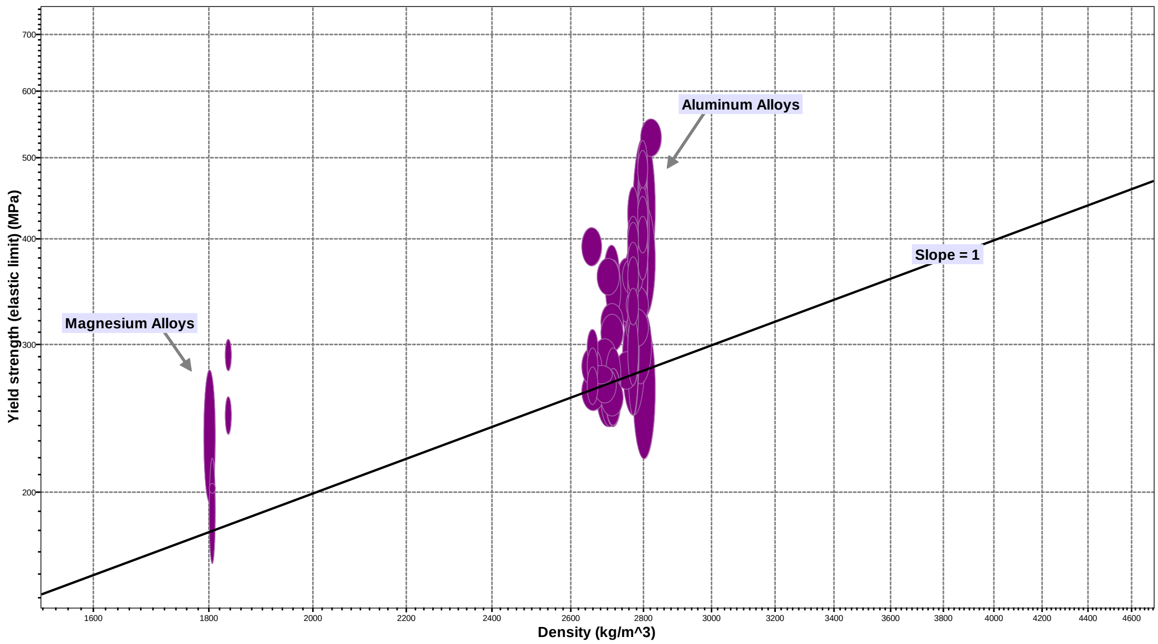

Figure E-1. Candidate materials based on relative strength and density

Additionally, young's modulus and density were also compared as per Figure E-2. The process resulted in exclusively aluminum alloys as potential materials, specifically 2000, 5000, 6000 and 7000 series aluminum.

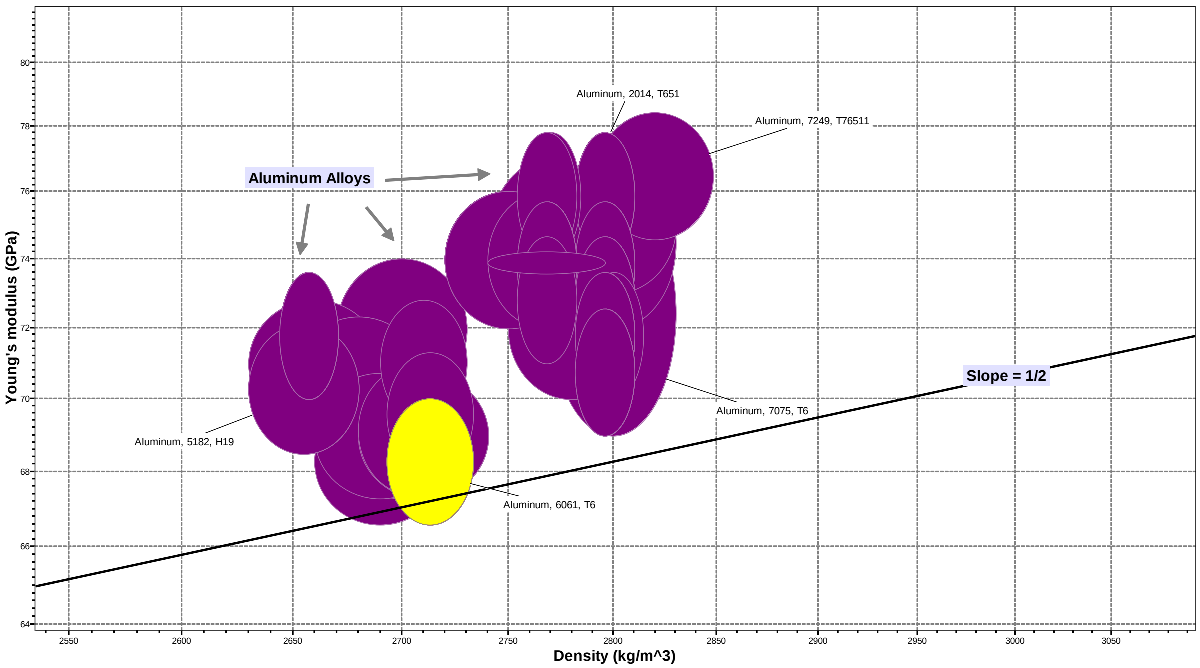

Figure E-2. Candidate Materials based on relative young's modulus and density

Reviewing the list, it was concluded that the difference in strength and stiffness was not significantly different amongst available alloys to merit one over the other. In order to satisfy the project objective of low mass, alloys with the lowest densities were considered. Materials that were readily available and commonplace in industry were then given preference. 6061-T6 is a common material in aerospace that Saskatchewan Polytechnic has in stock and has machined before. 6061-T6 is also is one of the lowest density materials on the list. For these reasons, 6061-T6 aluminum was selected as the final material for the design.

Appendix F: Detailed Calculations

This appendix will contain relevant hand calculations and finite element analysis for three load cases. The three load cases are the loading in the Z-direction, loading in the X-direction, and the combined loading effects. This appendix will demonstrate the approach used to determine the convergence of all finite element model solutions.

F.1 Analytical Analysis

The portion of the appendix will contain the mechanics of materials hand calculations used to establish a basis for the load cases as well as used to establish agreeance with finite element models. For the Z-direction, along the length of the frame, the CubeSat sees forces due to self-weight, the payload, and 1,200 N applied by a jackscrew in the NanoRacks launch deployer.

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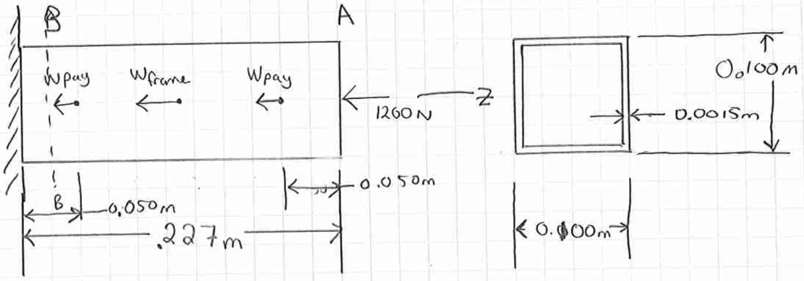


Knowns: $W_{frame} = \rho A L \cdot 4g$, $\rho = 2700\ kg/m^3$ (aluminum)

$A = (0.100)^2 - (0.097)^2 = 5.91 \times 10^{-4}\ m^2$

$L = 0.227\ m$

$W_{frame} = \left(2700\ \frac{kg}{m^3}\right)\left(5.91 \times 10^{-4}\ m^2\right)\left(0.227\ m\right) \times 4\ (9.81)$

$W_{frame} = 14.214\ N$

$E = 70 \times 10^9\ Pa$ (aluminum)

$W_{pay} = \frac{m_{payload} \cdot 4g}{2}$

$m_{payload} = 1.8\ kg$

$W_{pay} = \frac{(1.8 kg)(4)(9.81)}{2}$

$W_{pay} = 35.316\ N$

Find: Deflection @ A , δ_A

Stress at Section B-B , σ_B

Critical Buckling force, P_{CR}.

Solution:

$\Sigma F_{Z=0} = F_R - 2W_{pay} - W_{frame} - 1200$

$F_R = 2(35.316) + 14.214 + 1200$

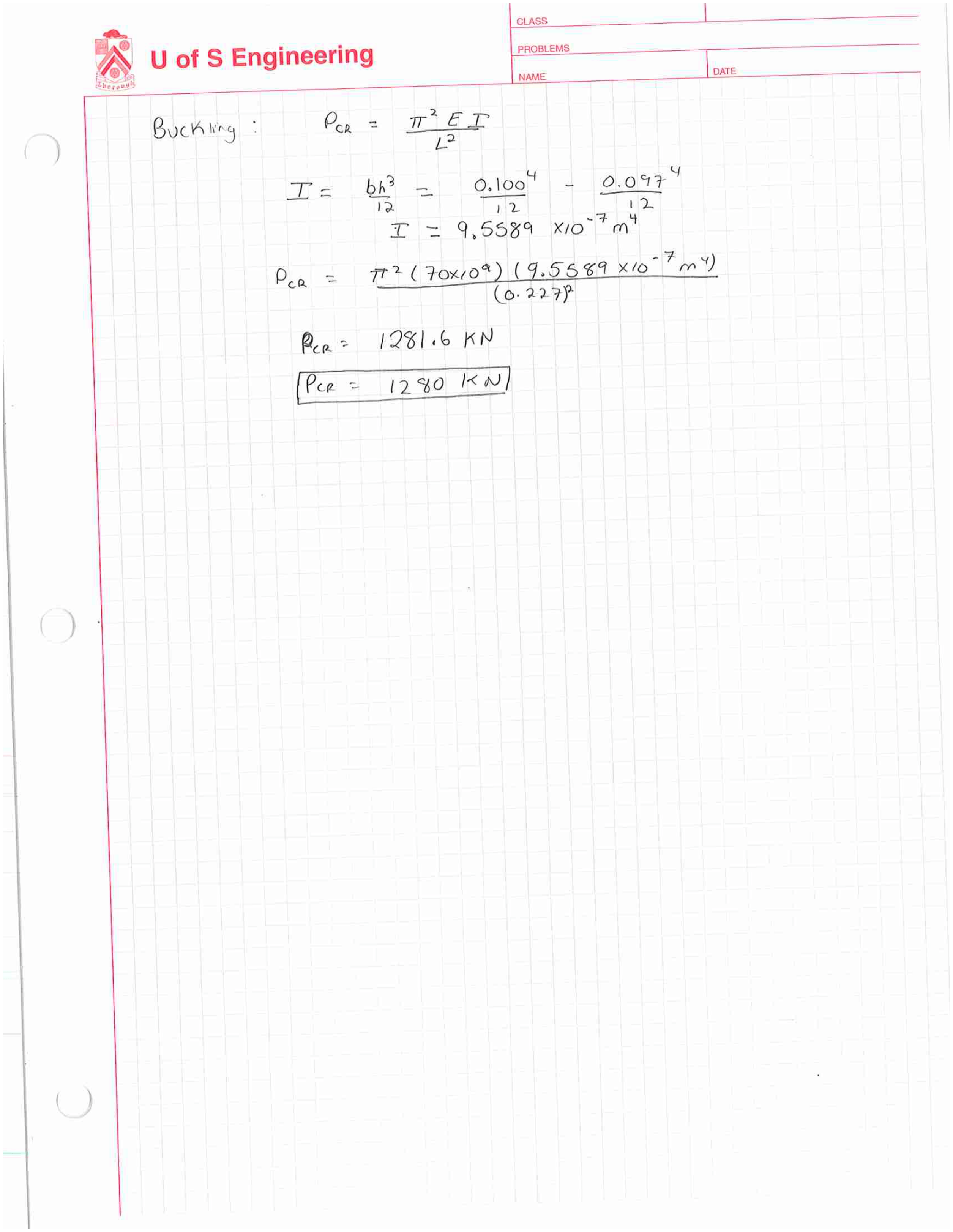
$F_R = 1284.8 N$

$\delta_A = \frac{F_R L}{EA} = \frac{(1284.8)(0.227)}{(70 \times 10^9)(5.91 \times 10^{-4})}$

$\delta_A = 7.0500 \times 10^{-6}\ m$

$\boxed{\delta_A = 0.00705\ mm}$

$\sigma_B = \frac{F_R}{A} = \frac{1284.8}{5.91 \times 10^{-4}} = 2.1740\ MPa \Rightarrow \boxed{\sigma_B = 2.17\ MPa}$



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Buckling : $P_{CR} = \frac{\pi^2 E I}{L^2}$

$I = \frac{bh^3}{12} = \frac{0.100^4}{12} - \frac{0.097^4}{12}$

$I = 9.5589 \times 10^{-7} m^4$

$P_{CR} = \frac{\pi^2 (70\times10^9)(9.5589 \times 10^{-7} m^4)}{(0.227)^2}$

$P_{CR} = 1281.6$ KN

$\boxed{P_{CR} = 1280 \text{ KN}}$

It was determined that the forces in the Z-direction, using mechanics of materials fundamentals, will cause a deflection of 7.05 µm and a maximum stress of 2.17 MPa. The critical buckling force is 1,280 kN.

For the X-direction, in the cross section of the sattelite, the frame will experience forces applied from self weight as well as the payload forces. The X-direction will have a seven times gravity quasistatic loading to conservatively approximate the dynamic effects of the rocket launch forces. Considering the forces applied and the boundary conditions of the NanoRacks launch deployer, the frame proves to be internally statically indeterminate. Using Costigliano's second theorem, deflections and stresses can be determined. However, the method by which the problem is solved, is extensive and difficult. Thus, a very simplied problem was considered where the forces due to the self weight of the top and bottom panels are applied to the frame structure. Payload forces and self weight of the two side panels will be ignored. The solution that follows aims to determine the deflection at the point where W1, the weight of the top panel, is applied.

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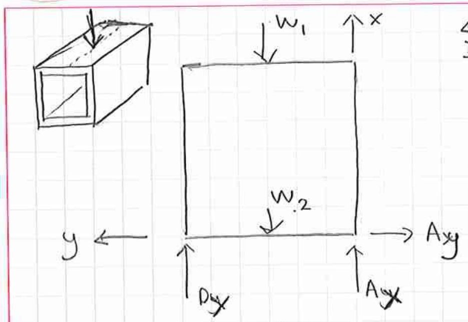


$$\circlearrowleft + \sum M_A = 0 = W_1 \frac{l}{2} + W_2 \frac{l}{2} - D_x l$$

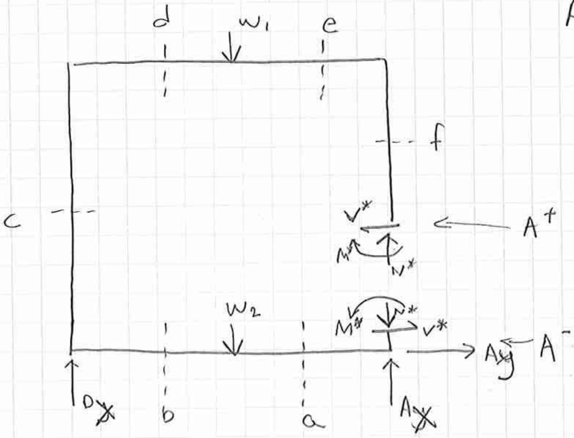
$$D_x = \frac{(W_1 + W_2)}{2}$$

$$\sum F_y = 0 = A_y \Rightarrow A_y = 0$$

$$\sum F_x = 0 = A_x + D_x - W_1 - W_2$$

$$A_x = W_1 + W_2 - \left(\frac{W_1 + W_2}{2}\right)$$

$$A_x = \frac{(W_1 + W_2)}{2}$$



$$W_1 = W_2 = \rho A L \cdot 7 g$$

$$= \left(2700 \frac{Kg}{m^3}\right)(0.095_{mm})(.227)(0.1) \times 7 \times 9.81$$

$$= 6.3131\ N$$

$A_x = D_x = 6.3131\ N$

$L = 0.1\ m$

$$I = \frac{bh^3}{12} = \frac{0.227(0.0015)^3}{12}$$

$I = 6.3843 \times 10^{-11}\ m^4$

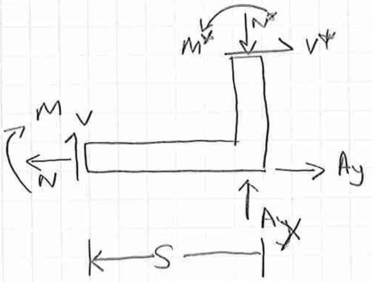
$E = 70 \times 10^9$ GPa (aluminum)

$K = 1.2$, $\nu = 0.3$ (aluminum)

$$G = \frac{E}{2(1+\nu)} = 26.923\ GPa$$

$A = 0.0015 \times 0.227 = 3.405 \times 10^{-5}\ m^2$

Member A^- to a (1)



$$\circlearrowleft + \sum M_a = 0 = M^* - M + A_x S - N^* S$$

$$M = M^* + A_x S - N^* S$$

$$\sum F_y = 0 = V^* - N + A_y$$

$$N = V^* + A_y$$

$$\sum F_x = 0 = V + A_x - N^*$$

$$\left.\begin{array}{l} V = N^* - A_x \\ V = N^* - \frac{W_1}{2} - \frac{W_2}{2} \end{array}\right\} \text{for } 0 < S < \frac{l}{2}$$

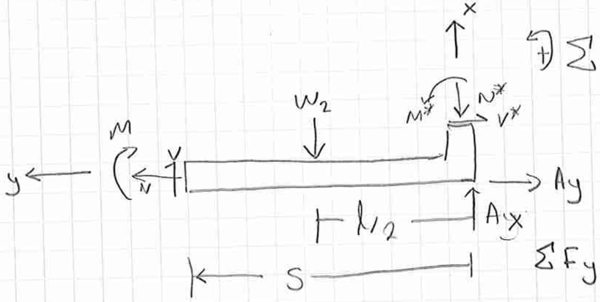
$$\frac{\partial M}{\partial M^*} = 1 \qquad \frac{\partial N}{\partial M^*} = 0 \qquad \frac{\partial V}{\partial M^*} = 0$$

$$\frac{\partial M}{\partial N^*} = -S \qquad \frac{\partial N}{\partial N^*} = 0 \qquad \frac{\partial V}{\partial N^*} = 1$$

$$\frac{\partial M}{\partial V^*} = 0 \qquad \frac{\partial N}{\partial V^*} = 1 \qquad \frac{\partial V}{\partial V^*} = 0$$

$$\frac{\partial M}{\partial W_1} = \frac{S}{2} \qquad \frac{\partial N}{\partial W_1} = 0 \qquad \frac{\partial V}{\partial W_1} = -\frac{1}{2}$$

Member A^- to b (2)



$$\circlearrowleft + \sum M_b = 0 = M^* - M - W_2\left(S - \frac{l}{2}\right) + A_x S - N^* S$$

$$M = M^* - W_2\left(S - \frac{l}{2}\right) + A_x S - N^* S$$

$$\sum F_y = 0 = V^* - N + A_y$$

$$N = V^* + A_y$$

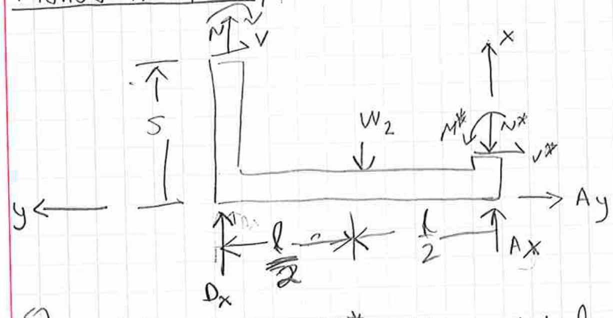
$$\sum F_x = 0 = V \mp A_x - N^* - W_2$$

$$V = N^* + W_2 - A_x$$

$$V = N^* + W_2 - \frac{W_1}{2} - \frac{W_2}{2}$$

$$\left.\begin{array}{lll} \frac{\partial M}{\partial M^*} = 1 & \frac{\partial N}{\partial M^*} = 0 & \frac{\partial V}{\partial M^*} = 0 \\ \frac{\partial M}{\partial N^*} = -S & \frac{\partial N}{\partial N^*} = 0 & \frac{\partial V}{\partial N^*} = 1 \\ \frac{\partial M}{\partial V^*} = 0 & \frac{\partial N}{\partial V^*} = 1 & \frac{\partial V}{\partial V^*} = 0 \\ \frac{\partial M}{\partial W_1} = \frac{S}{2} & \frac{\partial N}{\partial W_1} = 0 & \frac{\partial V}{\partial W_1} = -\frac{1}{2} \end{array}\right\} \text{for } \frac{l}{2} < S < l$$

Member A^- TO C: (3)



$$\sum F_y = 0 = V^* + V + A_y$$

$$V = -V^* - A_y$$

$$\sum F_x = 0 = N - N^* + A_x + D_x - W_2$$

$$N = N^* - A_x - D_x + W_2$$

$$N = N^* - \frac{W_1}{2} - \frac{W_2}{2} - D_x + W_2$$

$$\circlearrowleft + \sum M_c = 0 = M^* - M - W_2 \frac{l}{2} - N^* l + A_x l + V^* S + A_y S$$

$$M = M^* - W_2 \frac{l}{2} - N^* l + A_x l + V^* S + A_y S$$

$$\left.\begin{array}{lll} \frac{\partial M}{\partial M^*} = 1 & \frac{\partial N}{\partial M^*} = 0 & \frac{\partial V}{\partial M^*} = 0 \\ \frac{\partial M}{\partial N^*} = -l & \frac{\partial N}{\partial N^*} = 1 & \frac{\partial V}{\partial N^*} = 0 \\ \frac{\partial M}{\partial V^*} = S & \frac{\partial N}{\partial V^*} = 0 & \frac{\partial V}{\partial V^*} = -1 \\ \frac{\partial M}{\partial W_1} = \frac{l}{2} & \frac{\partial N}{\partial W_1} = -\frac{1}{2} - \frac{1}{2} = -1 & \frac{\partial V}{\partial W_1} = 0 \end{array}\right\} \text{for } 0 < S < l$$

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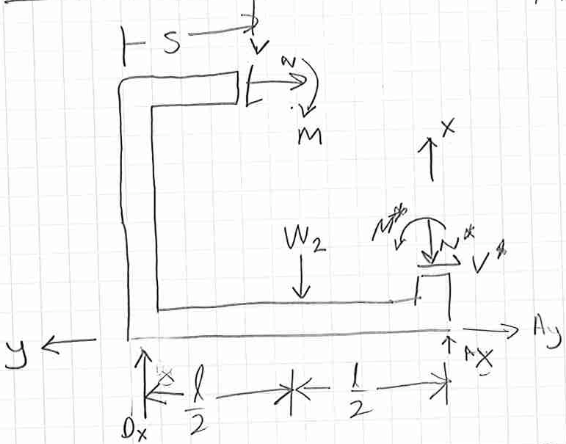
Member A⁻ to d (4)



$$\overset{+}{\circlearrowleft}\sum M_d = 0 = M^* - M - W_2\left(\frac{l}{2} - S\right)$$
$$- N^*(l-s) + A_{\cancel{x}}(l-s)$$
$$+ V^*(l) - D_{\cancel{x}}S + A_y l$$

$$M = M^* - W_2\left(l/_2 - s\right)$$
$$- N^*(l-s) + A_{\cancel{x}}(l-s) + V^* l$$
$$+ A_y l - D_{\cancel{x}}S$$

$$\sum F_y = 0 = V^* + A_y + N$$
$$N = - A_y - V^*$$

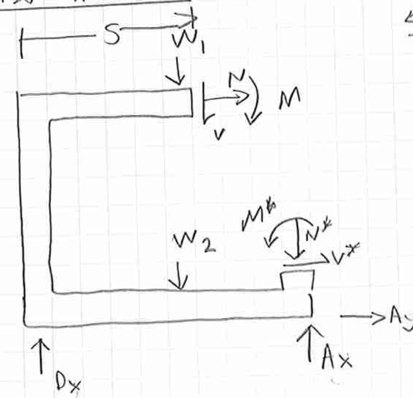
$$\sum F_x = 0 = A_x + D_x - N^* - V - W_2$$
$$V = - N^* + A_x + D_x - W_2$$

$$\frac{\partial N}{\partial M^*} = 0 \quad \frac{\partial N}{\partial N^*} = 0 \quad \frac{\partial N}{\partial V^*} = -1$$
$$\frac{\partial M}{\partial M^*} = 1 \quad \frac{\partial M}{\partial N^*} = -(l-s) \quad \frac{\partial M}{\partial V^*} = l$$
$$\frac{\partial V}{\partial M^*} = 0 \quad \frac{\partial V}{\partial N^*} = -1 \quad \frac{\partial V}{\partial V^*} = 0$$

for $0 < S < l/_2$

$$\frac{\partial M}{\partial w_1} = \left[\frac{(l-s)}{2} - \frac{S}{2}\right] \quad \frac{\partial N}{\partial w_1} = 0 \quad \frac{\partial V}{\partial w_1} = \frac{1}{2} + \frac{1}{2} =$$

Member A⁻ to e (5)



$$\overset{+}{\circlearrowleft}\sum M_e = 0 = M^* - M + W_2\left(S - \frac{l}{2}\right) + A_y l$$
$$- N^*(l-S) + A_s(l-s)$$
$$+ V^*(l) + W_1\left(S - \frac{l}{2}\right) - D_x S$$

$$M = M^* + W_2\left(S - \frac{l}{2}\right) - N^*(l-s)$$
$$+ A_x(l-s) + V^*(l) + W_1\left(S - \frac{l}{2}\right)$$
$$+ A_y l - D_x S$$

$$\sum F_y = 0 = N + V^* + A_y$$
$$N = - A_y - V^*$$
$$\frac{\partial N}{\partial A_y} = -1 \Rightarrow \frac{\partial N}{\partial V^*} = -1$$

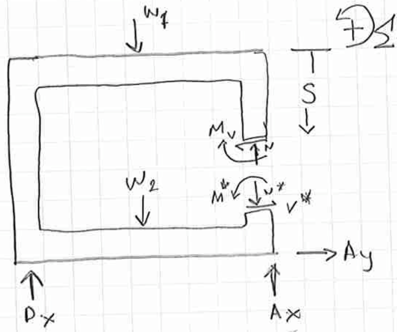
$$\sum F_x = 0 = A_x + D_x - V - N^* - W_1 - W_2$$
$$V = -N^* + D_x + A_x - W_1 - W_2$$

$$\frac{\partial M}{\partial M^*} = 1 \quad \frac{\partial N}{\partial M^*} = 0 \quad \frac{\partial V}{\partial M^*} = 0$$
$$\frac{\partial M}{\partial N^*} = -(l-s) \quad \frac{\partial N}{\partial N^*} = 0 \quad \frac{\partial N}{\partial N^*} = -1$$
$$\frac{\partial M}{\partial V^*} = l \quad \frac{\partial N}{\partial V^*} = -1 \quad \frac{\partial V}{\partial V^*} = 0$$
$$\frac{\partial M}{\partial w_1} = \left[\left(S - \frac{l}{2}\right) + \frac{(l-S)}{2} - \frac{S}{2}\right] = 0$$

for $0 < S < \frac{l}{2}$

$$\frac{\partial N}{\partial W_1} = 0$$
$$\frac{\partial V}{\partial w_1} = \left[-1 + \frac{1}{2} + \frac{1}{2}\right] = 0$$

Member A^- to f (6)



$$\circlearrowleft + \sum M_f = 0 = M^* - M + W_1(l/2) + W_2(l/2) - D_x l + V^*(l-s) + A_y(l-s)$$

$$M = M^* + W_1(l/2) + W_2(l/2) - D_x l + V^*(l-s) + A_y(l-s)$$

$$\sum F_y = 0 = V^* - V + A_y$$
$$V = A_y + V^*$$

$$\sum F_x = 0 = N - N^* + A_x + D_x - W_1 - W_2$$
$$N = N^* - A_x - D_x + W_1 + W_2$$

$$\left.\begin{matrix} \frac{\partial M}{\partial M^*} = 1 & \frac{\partial N}{\partial M^*} = 0 & \frac{\partial V}{\partial M^*} = 0 \\ \frac{\partial M}{\partial N^*} = 0 & \frac{\partial N}{\partial N^*} = 1 & \frac{\partial V}{\partial N^*} = 0 \\ \frac{\partial M}{\partial V^*} = (l-s) & \frac{\partial N}{\partial V^*} = 0 & \frac{\partial V}{\partial V^*} = 1 \end{matrix}\right\} \text{for } 0<s<l$$

$$\frac{\partial M}{\partial w_1} = \left[\frac{l}{2}\right] - \frac{l}{2} = 0 \qquad \frac{\partial N}{\partial w_1} = \left[1 - \frac{1}{2} - \frac{1}{2}\right] = 0 \qquad \frac{\partial V}{\partial w_1} = 0$$

To solve for M^*, V^*, N^* we know that the strain energy caused by internal forces/moments M^*, V^*, N^* are zero, thus we can obtain

$$\frac{\partial U}{\partial M^*} = \frac{\partial U}{\partial N^*} = \frac{\partial U}{\partial V^*} = 0$$ yields 3 equations, 3 unknowns

$$G = \frac{E}{2(1+\nu)} = \frac{70\times10^9}{2(1+0.3)} = 26.923\times10^9 \text{ Pa}$$
$$= 26.923 \text{ GPa}$$

For a rectangular section, $K = 1.2$

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$$\frac{\partial U}{\partial M^*} = \int_0^{l/2} \left[\frac{N_1}{EA} \cancel{\frac{\partial N_1}{\partial M^*}}^{\nearrow 0} + \frac{M_1}{EI} \frac{\partial M_1}{\partial M^*} + \frac{K V_1}{GA} \cancel{\frac{\partial V_1}{\partial M^*}}^{\nearrow 0} \right] ds \quad (1)$$

$$+ \int_{l/2}^{l} \left[\frac{N_2}{EA} \cancel{\frac{\partial N_2}{\partial M^*}}^{\nearrow 0} + \frac{M_2}{EI} \frac{\partial M_2}{\partial M^*} + \frac{K V_2}{GA} \cancel{\frac{\partial V_2}{\partial M^*}}^{\nearrow 0} \right] ds \quad (2)$$

$$+ \int_0^{l} \left[\frac{N_3}{EA} \cancel{\frac{\partial N_3}{\partial M^*}}^{\nearrow 0} + \frac{M_3}{EI} \frac{\partial M_3}{\partial M^*} + \frac{K V_3}{GA} \cancel{\frac{\partial V_3}{\partial M^*}}^{\nearrow 0} \right] ds \quad (3)$$

$$+ \int_0^{l/2} \left[\frac{N_4}{EA} \cancel{\frac{\partial N_4}{\partial M^*}}^{\nearrow 0} + \frac{M_4}{EI} \frac{\partial M_4}{\partial M^*} + \frac{K V_4}{GA} \cancel{\frac{\partial V_4}{\partial M^*}}^{\nearrow 0} \right] ds \quad (4)$$

$$+ \int_{l/2}^{l} \left[\frac{N_5}{EA} \cancel{\frac{\partial N_5}{\partial M^*}}^{\nearrow 0} + \frac{M_5}{EI} \frac{\partial M_5}{\partial M^*} + \frac{K V_5}{GA} \cancel{\frac{\partial V_5}{\partial M^*}}^{\nearrow 0} \right] ds \quad (5)$$

$$+ \int_0^{l} \left[\frac{N_6}{EA} \cancel{\frac{\partial N_6}{\partial M^*}}^{\nearrow 0} + \frac{M_6}{EI} \frac{\partial M_6}{\partial M^*} + \frac{K V_6}{GA} \cancel{\frac{\partial V_6}{\partial M^*}}^{\nearrow 0} \right] ds \quad (6)$$

$$= \int_0^{l/2} \left(\frac{M^* - A_x s - N^* s}{EI} \right) (1)\, ds$$

$$+ \frac{1}{EI} \int_{l/2}^{l} \left(M^* - W_2 \left(s - \frac{l}{2} \right) + A_x s - N^* s \right) (1)\, ds$$

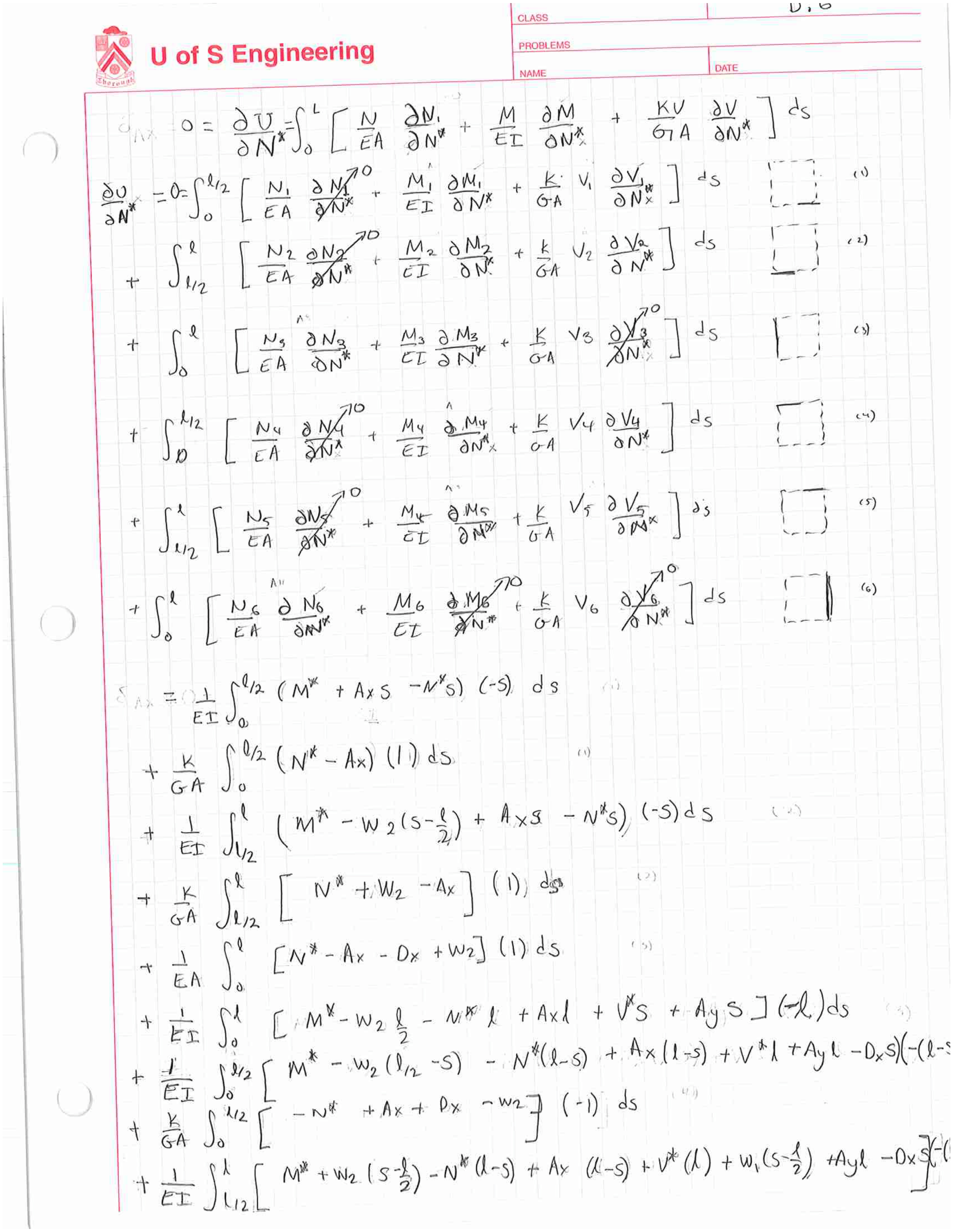
$$+ \frac{1}{EI} \int_0^{l} \left(M^* - W_2 \frac{l}{2} - N^* l + A_x l + V^* s + A_y s \right) (1)\, ds$$

$$+ \frac{1}{EI} \int_0^{l/2} \left(M^* - W_2 (l/2 - s) - N^* (l - s) + A_x (l - s) + V^* l + A_y l - D_x s \right) (1) d$$

$$+ \frac{1}{EI} \int_{l/2}^{l} \left(M^* + W_2 (s - l/2) - N^* (l - s) + A_y l - D_x s \right) (1)\, ds$$

$$+ \frac{1}{EI} \int_0^{l} \left(M^* + W_1 (l/2) + W_2 (l/2) - D_x l + V^* (l - s) + A_y (l - s) \right) (1)$$

$$0 = 0.089504\, M^* - 0.0044752\, N^* + 0.0044752\, V^* + 0.014126$$



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$$\delta_{Ax} \quad 0 = \frac{\partial U}{\partial N^*} = \int_0^L \left[\frac{N}{EA} \frac{\partial N_1}{\partial N^*} + \frac{M}{EI} \frac{\partial M}{\partial N^*_x} + \frac{KV}{GA} \frac{\partial V}{\partial N^*} \right] ds$$

$$\frac{\partial U}{\partial N^*} = 0 = \int_0^{l/2} \left[\frac{N_1}{EA} \cancelto{0}{\frac{\partial N_1}{\partial N^*}} + \frac{M_1}{EI} \frac{\partial M_1}{\partial N^*} + \frac{K}{GA} V_1 \frac{\partial V_1}{\partial N^*_x} \right] ds \qquad (1)$$

$$+ \int_{l/2}^{l} \left[\frac{N_2}{EA} \cancelto{0}{\frac{\partial N_2}{\partial N^*}} + \frac{M_2}{EI} \frac{\partial M_2}{\partial N^*} + \frac{k}{GA} V_2 \frac{\partial V_2}{\partial N^*} \right] ds \qquad (2)$$

$$+ \int_0^{l} \left[\frac{N_3}{EA} \frac{\partial N_3}{\partial N^*} + \frac{M_3}{EI} \frac{\partial M_3}{\partial N^*} + \frac{K}{GA} V_3 \cancelto{0}{\frac{\partial V_3}{\partial N^*_x}} \right] ds \qquad (3)$$

$$+ \int_0^{l/2} \left[\frac{N_4}{EA} \cancelto{0}{\frac{\partial N_4}{\partial N^*}} + \frac{M_4}{EI} \frac{\partial M_4}{\partial N^*_x} + \frac{K}{GA} V_4 \frac{\partial V_4}{\partial N^*} \right] ds \qquad (4)$$

$$+ \int_{l/2}^{l} \left[\frac{N_5}{EA} \cancelto{0}{\frac{\partial N_5}{\partial N^*}} + \frac{M_4}{EI} \frac{\partial M_5}{\partial N^*} + \frac{K}{GA} V_5 \frac{\partial V_5}{\partial N^*_x} \right] ds \qquad (5)$$

$$+ \int_0^{l} \left[\frac{N_6}{EA} \frac{\partial N_6}{\partial N^*} + \frac{M_6}{EI} \cancelto{0}{\frac{\partial M_6}{\partial N^*}} + \frac{K}{GA} V_6 \cancelto{0}{\frac{\partial V_6}{\partial N^*}} \right] ds \qquad (6)$$

$$\delta_{Ax} = 0 \; \frac{1}{EI} \int_0^{l/2} (M^* + A_x s - N^* s)(-s)\, ds \qquad (1)$$

$$+ \frac{K}{GA} \int_0^{l/2} (N^* - A_x)(1)\, ds \qquad (1)$$

$$+ \frac{1}{EI} \int_{l/2}^{l} \left(M^* - W_2 \left(s - \frac{l}{2}\right) + A_x s - N^* s \right)(-s)\, ds \qquad (2)$$

$$+ \frac{K}{GA} \int_{l/2}^{l} \left[N^* + W_2 - A_x \right] (1)\, ds \qquad (2)$$

$$+ \frac{1}{EA} \int_0^{l} \left[N^* - A_x - D_x + W_2 \right] (1)\, ds \qquad (3)$$

$$+ \frac{1}{EI} \int_0^{l} \left[M^* - W_2 \frac{l}{2} - N^* l + A_x l + V^* s + A_y s \right] (-l)\, ds \qquad (3)$$

$$+ \frac{1}{EI} \int_0^{l/2} \left[M^* - W_2 (l/2 - s) - N^*(l-s) + A_x (l-s) + V^* l + A_y l - D_x s \right] \left(-(l-\right.$$

$$+ \frac{K}{GA} \int_0^{l/2} \left[-N^* + A_x + D_x - W_2 \right] (-1)\, ds \qquad (4)$$

$$+ \frac{1}{EI} \int_{l/2}^{l} \left[M^* + W_2 \left(s - \frac{l}{2}\right) - N^*(l-s) + A_x (l-s) + V^*(l) + W_1 \left(s - \frac{l}{2}\right) + A_y l - D_x s \right] \left(-(\right.$$

$$+\frac{K}{GA}\int_{l/2}^{l}\left[-N^* + D_x + A_x - W_1 - W_2\right](-1)\,ds \qquad (5)$$

$$+\frac{1}{EA}\int_{0}^{l}\left[N^* - A_x - D_x + W_1 + W_2\right](1)\,ds \qquad (6)$$

$$0 = -0.0044752N^* + 0.00037296N^* \quad -0.00022376V^* - 0.001172$$

$$\cancel{A_y}\quad 0 = \frac{\partial U}{\partial V^*}\int_0^l\left[\frac{N}{EA}\frac{\partial N}{\partial V^*} + \frac{M}{EI}\frac{\partial M}{\partial V^*} + \frac{KV}{GA}\frac{\partial V}{\partial V^*}\right]ds$$

$$\frac{\partial U}{\partial V^*} = 0 = \int_0^{l/2}\left[\frac{N_1}{EA}\frac{\partial N_1}{\partial V^*} + \frac{M_1}{EI}\cancel{\frac{\partial M_1}{\partial V^*}}\to 0 + \frac{K}{GA}V_1\cancel{\frac{\partial V_1}{\partial V^*}}\to 0\right]ds \qquad (1)$$

$$+\int_{l/2}^{l}\left[\frac{N_2}{EA}\frac{\partial N_2}{\partial V^*} + \frac{M_2}{EI}\cancel{\frac{\partial M_2}{\partial V^*}}\to 0 + \frac{K}{GA}V_2\cancel{\frac{\partial V_2}{\partial V^*}}\to 0\right]ds \qquad (2)$$

$$+\int_0^{l}\left[\frac{N_3}{EA}\cancel{\frac{\partial N_3}{\partial V^*}}\to 0 + \frac{M_3}{EI}\frac{\partial M_3}{\partial V^*} + \frac{K}{GA}V_3\frac{\partial V_3}{\partial V^*}\right]ds \qquad (3)$$

$$+\int_0^{l/2}\left[\frac{N_4}{EA}\frac{\partial N_4}{\partial V^*} + \frac{M_4}{EI}\frac{\partial M_4}{\partial V^*} + \frac{K}{GA}V_4\cancel{\frac{\partial V_4}{\partial V^*}}\to 0\right]ds \qquad (4)$$

$$+\int_{l/2}^{l}\left[\frac{N_5}{EA}\frac{\partial N_5}{\partial V^*} + \frac{M_5}{EI}\frac{\partial M_5}{\partial V^*} + \frac{K}{GA}V_5\cancel{\frac{\partial V_5}{\partial V^*}}\to 0\right]ds \qquad (5)$$

$$+\int_0^{l}\left[\frac{N_6}{EA}\cancel{\frac{\partial N_6}{\partial V^*}}\to 0 + \frac{M_6}{EI}\frac{\partial M_6}{\partial V^*} + \frac{K}{GA}V_6\frac{\partial V_6}{\partial V^*}\right]ds \qquad (6)$$

$$\frac{\partial U}{\partial V^*} = 0 = \int_0^{l/2}\frac{1}{EA}\left[V^* + A_y\right](1)\,ds$$

$$+\frac{1}{EA}\int_{l/2}^{l}\left[V^* + A_y\right](1)\,ds$$

$$+\frac{1}{EI}\int_0^{l}\left(M^* - W_2\frac{l}{2} - N^*l + A_x l + V^*s + A_y s\right)(s)\,ds$$

$$+\frac{K}{GA}\int_0^{l}\left[-V^* - A_y\right](-1)\,ds$$

$$+\frac{1}{EA}\int_0^{l/2}\left[-A_y - V^*\right](-1)\,ds$$

$$+\frac{1}{EI}\int_0^{l/2}\left[M^* + W_2\left(l/2 - s\right) - N^*(l-s) + A_x(l-s) + V^*(l) + A_y l - D_x s\right)(l)\,d$$

$$+\frac{1}{EA}\int_{l/2}^{l}\left[-V^* - A_y\right](-1)\,ds$$

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$$+\frac{1}{EI}\int_{l/2}^{l}\left(M^* + W_2(s-l/2) - N^*(l-s) + A_x(l-s) + V^* l + W_1(s-l/2) + A_y l - D_x s\right)(l)\,ds$$

$$+\frac{1}{EI}\int_0^l \left[M^* + W_1(l/2) + W_2(l/2) - D_x l + V^*(l-s) + A_y(l-s)\right](l-s)\,ds$$

$$+\frac{K}{GA}\int_0^l \left[A_y + V^*\right](1)\,ds$$

From matlab; $0 = 0.0044752M^* - 6.00022376N^* + 0.00037296V^* + 0.00052971$

Summary of equations:

$$\begin{bmatrix} 0.089504 & -0.0044752 & 0.0044752 \\ -0.0044752 & 0.00037296 & -0.00022376 \\ 0.0044752 & -0.00022376 & 0.00037296 \end{bmatrix}\begin{bmatrix} M^* \\ N^* \\ V^* \end{bmatrix} = \begin{bmatrix} -0.014126 \\ +0.0011772 \\ -0.00052974 \end{bmatrix}$$

Solving the three equations from $\frac{\partial U}{\partial M^*} = \frac{\partial U}{\partial N^*} = \frac{\partial U}{\partial V^*} = 0$, using matlab;

$M^* = -0.059171$

$N^* = 3.1565$

$V^* = 1.1834$

Determine the deflection at the applied load W_1 via Castigliano's 2nd Theorem:

$$\delta_{W_1} = \frac{\partial U}{\partial W_1} = \int_{0\ \text{structure}}^{l}\left(\frac{N}{EA}\frac{\partial N}{\partial W_1} + \frac{M}{EI}\frac{\partial M}{\partial W_1} + \frac{KV}{GA}\frac{\partial V}{\partial W_1}\right)ds$$

$$= \int_0^{l/2}\left(\frac{N_1}{EA}\cancelto{0}{\frac{\partial N_1}{\partial W_1}} + \frac{M_1}{EI}\frac{\partial M_1}{\partial W_1} + \frac{KV_1}{GA}\frac{\partial V_1}{\partial W_1}\right)ds$$

$$+ \int_{l/2}^{l}\left(\frac{N_2}{EA}\cancelto{0}{\frac{\partial N_2}{\partial W_1}} + \frac{M_2}{EI}\frac{\partial M_2}{\partial W_1} + \frac{KV_2}{GA}\frac{\partial V_2}{\partial W_1}\right)ds$$

$$+ \int_0^{l}\left(\frac{N_3}{EA}\frac{\partial N_3}{\partial W_1} + \frac{M_3}{EI}\frac{\partial M_3}{\partial W_1} + \frac{KV_3}{GA}\cancelto{0}{\frac{\partial V_3}{\partial W_1}}\right)ds$$

$$+ \int_0^{l/2}\left(\frac{N_4}{EA}\cancelto{0}{\frac{\partial N_4}{\partial W_1}} + \frac{M_4}{EI}\frac{\partial M_4}{\partial W_1} + \frac{KV_4}{GA}\frac{\partial V_4}{\partial W_1}\right)ds$$

$$+ \int_{l/2}^{l}\left(\frac{N_5}{EA}\cancelto{0}{\frac{\partial N_5}{\partial W_1}} + \frac{M}{EI}\cancelto{0}{\frac{\partial M_5}{\partial W_1}} + \frac{KV_5}{GA}\cancelto{0}{\frac{\partial V_5}{\partial W_1}}\right)ds$$

$$+ \int_0^{l}\left(\frac{N_6}{EA}\cancelto{0}{\frac{\partial N_6}{\partial W_1}} + \frac{M}{EI}\cancelto{0}{\frac{\partial M_6}{\partial W_1}} + \frac{KV_6}{GA}\cancelto{0}{\frac{\partial V_6}{\partial W_1}}\right)ds$$

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$$\delta_{w_1} = \frac{1}{EI}\int_0^{l/2} \left(M^* + A_x s - N^* s\right)\left(\frac{s}{2}\right) ds \qquad (M_1)$$

$$+ \frac{K}{GA}\int_0^{l/2} \left(N^* - A_x\right)\left(\frac{-1}{2}\right) ds \qquad (M_1)$$

$$+ \frac{1}{EI}\int_{l/2}^{l} \left(M^* - W_2(s - l/2) + A_x s - N^* s\right)\left(\frac{s}{2}\right) ds \qquad (M_2)$$

$$+ \frac{K}{GA}\int_{l/2}^{l} \left(N^* + W_2 - A_x\right)\left(\frac{-1}{2}\right) ds \qquad (V_2)$$

$$+ \frac{1}{EA}\int_0^{l} \left(N^* - A_x - D_x + W_2\right)\left(-1\right) ds \qquad (N_3)$$

$$+ \frac{1}{EI}\int_0^{l} \left(M^* - W_2 \frac{l}{2} - N^* l + A_x l + V^* s + A_y s\right)\left(\frac{l}{2}\right) ds \qquad (M_3$$

$$+ \frac{1}{EI}\int_0^{l/2} \left(M^* - W_2(l/2 - s) - N^*(l-s) + A_x(l-s) + V^* l + A_y l - D_x s\right)\left[\left(\frac{l-s}{2}\right) - \frac{s}{2}\right] ds$$

$$+ \frac{K}{GA}\int_0^{l/2} \left(-N^* + A_x + D_x - W_2\right)\left(1\right) ds \qquad (N_4)$$

$$+ \frac{1}{EI}\int_{l/2}^{l} \left(M^* + W_2(s - l/2) - N^*(l-s) + A_x(l-s) + V^*(l) + W_1(s - l/2) + A_y l - D_x s\right)\left[\cancel{\left(s - \frac{l}{2}\right)} + \frac{(l-s)}{2} - \frac{s}{2}\right] ds \qquad (M_5)$$

$$+ \frac{K}{GA}\int_{l/2}^{l} \left(-N^* + D_x + A_x - W_1 - W_2\right)\left(0\right) ds \qquad (V_5)$$

$$+ \frac{1}{EA}\int_0^{l} \left(N^* - A_x - D_x + W_1 + W_2\right)\left(0\right) ds \qquad (N_6)$$

$$+ \frac{1}{EI}\int_0^{l} \left[M^* + W_1(l/2) + W_2(l/2) - D_x l + V^*(l-s) + A_y(l-s)\right]\left(0\right) ds$$

(M_6)

$$\delta_{w_1} = 0.0019579\, M^* - 6.00017249\, N^* + \left(8.3910 \times 10^{-5}\right) V^* + 0.00057316$$

$$\delta_{w_1} = 1.2913 \times 10^{-5}\ m$$

$$\boxed{\delta_{w_1} = 0.0129\ mm}$$

The deflection due to load w_1 is 0.0129mm.

F.2 ANSYS APDL

As hand calculations are often simplified to allow for the use of fundamental mechanics of materials equations, this introduces error from how the actual frame will deflect under the provided load cases. Physical testing is the ideal way to confirm hand calculations and with high degrees of confidence, validate the design. Physical testing, in this scenario where the cost of prototyping is high and timeline to iterate the design is short, finite element analysis can be used to verify hand calculations and optimize the design. This section of the report will display the FEA results of the three load cases: Z-direction, X-direction, combined loading. This section will also demonstrate the method by which convergence was confirmed. Using ANSYS APDL, Figure F-1shows a deflection of 6.82 µm using 10 mm element lengths.

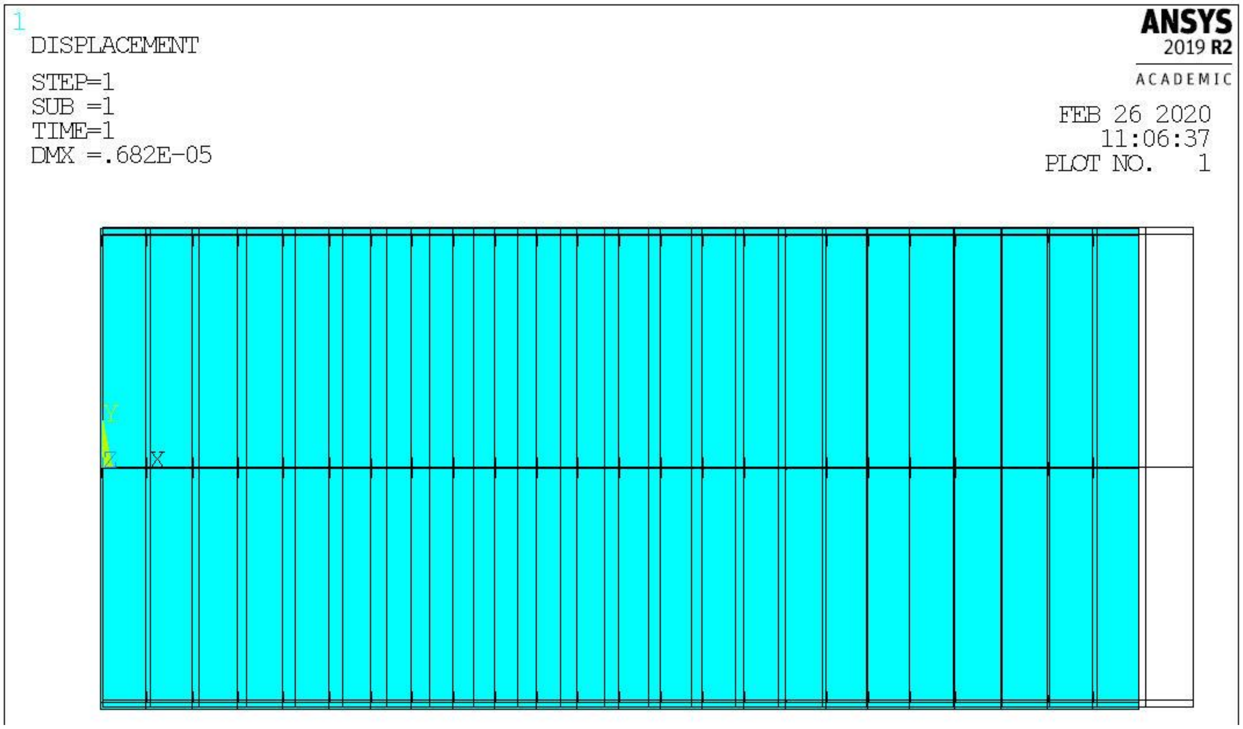


Figure F-1. ANSYS APDL X-axis loading, 10 mm element lengths

Again using ANSYS APDL, Figure F-2 shows a deflection of 6.82 µm using 5mm element lengths. As the deflection does not change as the number of elements was increased, convergence on a solution can be confirmed.

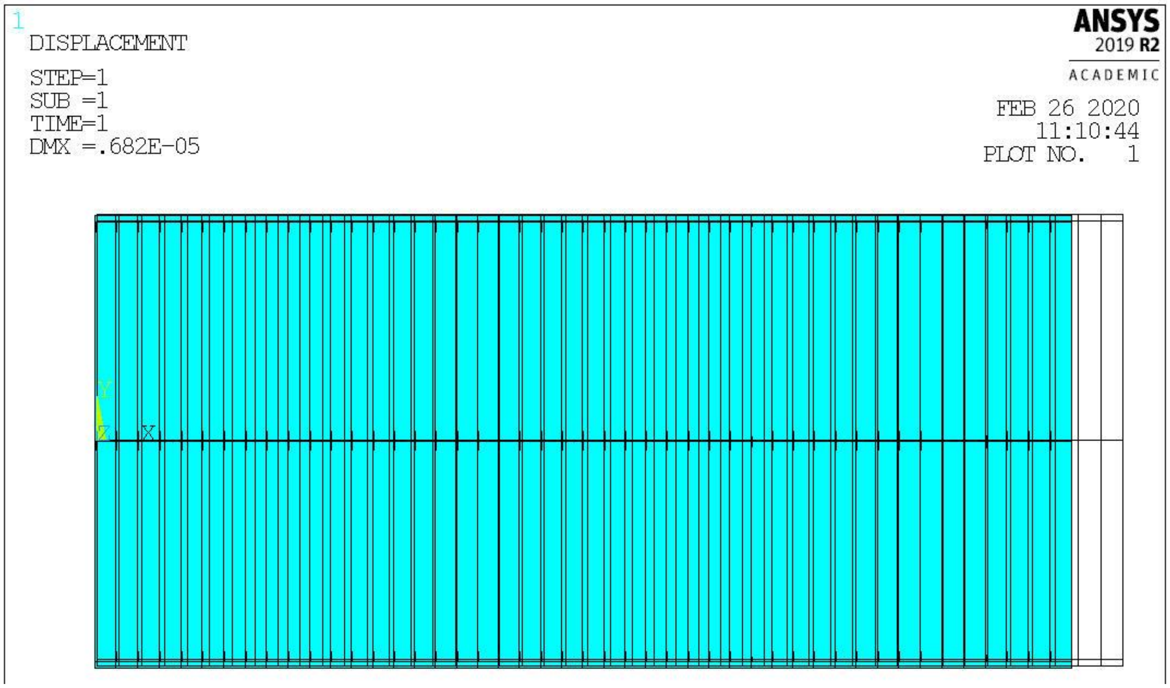


Figure F-2. ANSYS APDL simple model, X-axis loading, 5 mm element lengths

The stresses in the frame due to forces in the Z-direction can be easily determined by ANSYS APDL, as seen in Figure F-3. The stresses are 2.17 MPa and agree 100% with hand calculated stresses using mechanics of materials fundamental equations.

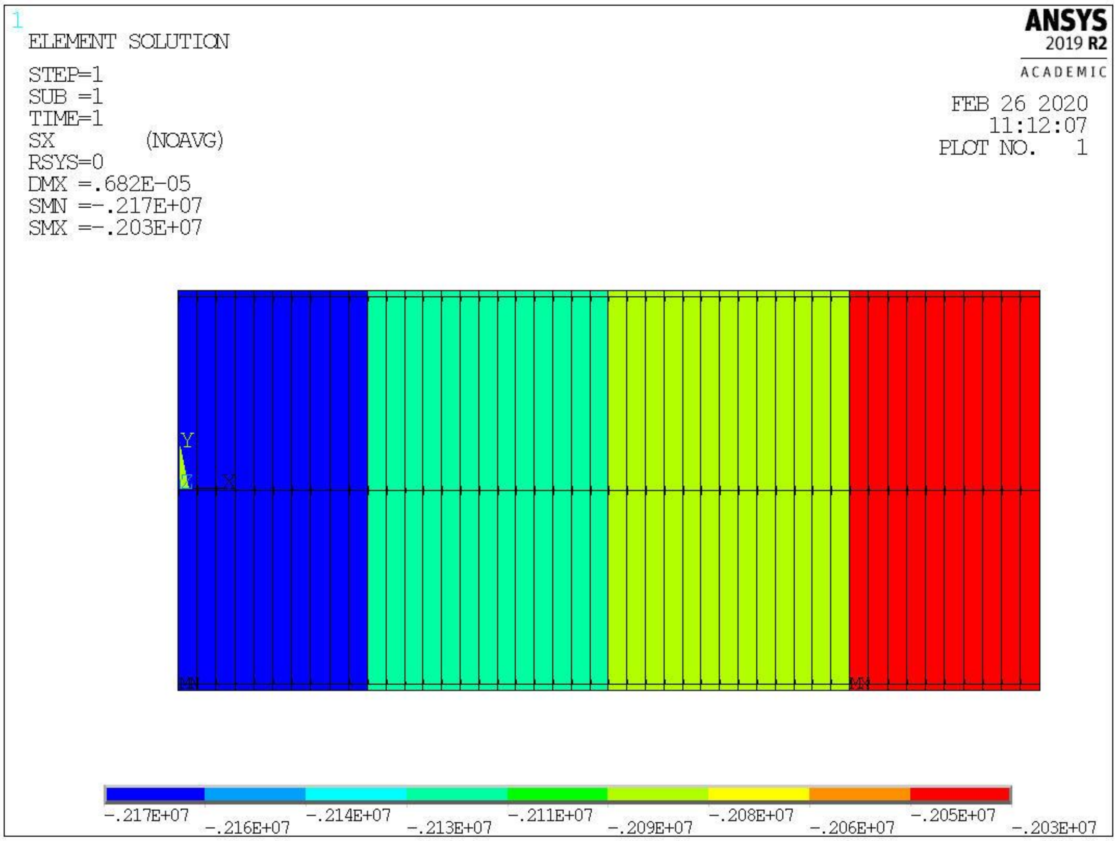


Figure F-3. ANSYS APDL, simple model, Z-axis stresses, 5 mm element lengths

The deflections obtained from ANSYS APDL demonstate convergence on a solution as well as agreement with hand calculated delfections. Turning to the X-direction load case, the deflections from ANSYS APDL can be seen in Figure F-4.

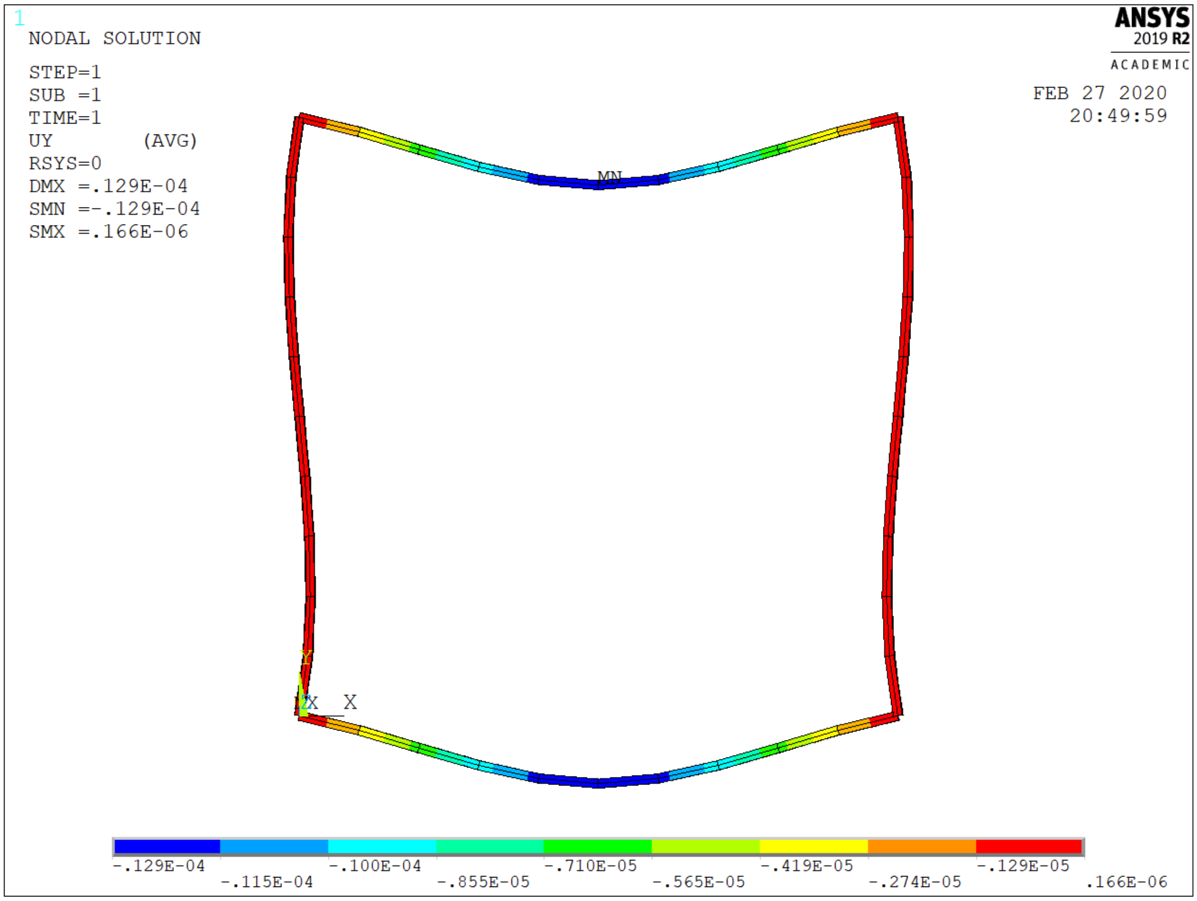


Figure F-4. ANSYS APDL, simple model, X-axis deflections, 5 mm element length

F.3 ANSYS Workbench

ANSYS Workbench is another tool that can be used to complete finite element analysis on more complex geometries that would be difficult to model in ANSYS APDL. Assumptions and simplifications to the model were made in order to make hand calculations feasible. To verify that the model is set up correctly in ANSYS Workbench, the x-direction load case was modelled as seen in Figure F-5. Workbench yields a deflection of 12.9 µm, in agreeance with deflections obtained by hand calculations and APDL.

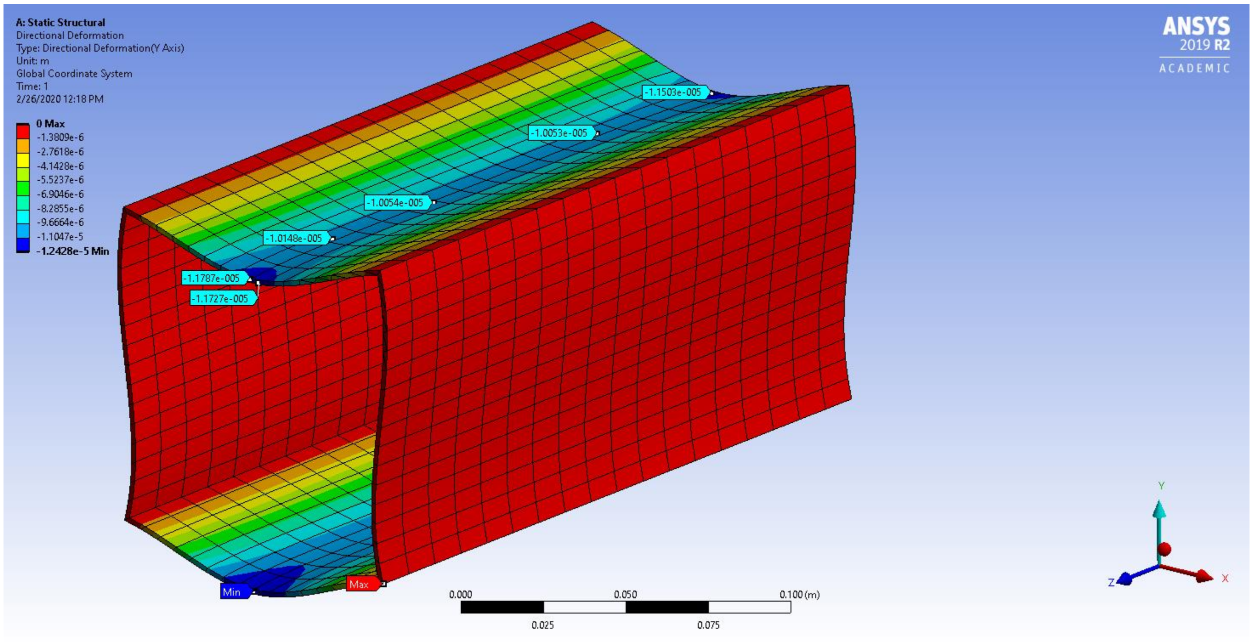


Figure F-5. ANSYS Workbench, simple model, X-axis deflections (Workbench Y-axis)

The complex, accurate, and detailed model of the selected design alternative was imported to Workbench and the combined load case and boundary conditions were applied to the model. Figure F-6 shows a thermal map of the total deflections in the frame, the largest deflection being 22.5 µm. This deflection is not of concern as the deflection is not large enough to cause interference with the NanoRacks Launch Deployer or to come into contact with the USST PCB payload.

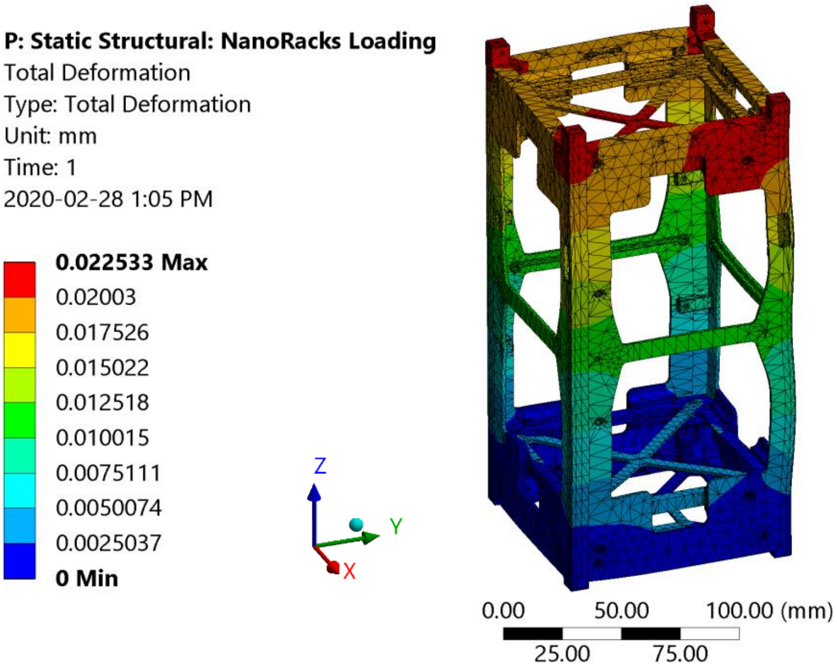


Figure F-6. ANSYS Workbench, complex model, complex loading, total deformation

Looking at the von Mises, or equivalent, stresses in the frame from Figure F-7 it can be seen that the nominal stresses in the frame range from 12.71 – 19.09 MPa, well below the yield strength of 6061-T6 aluminum, 276MPa.

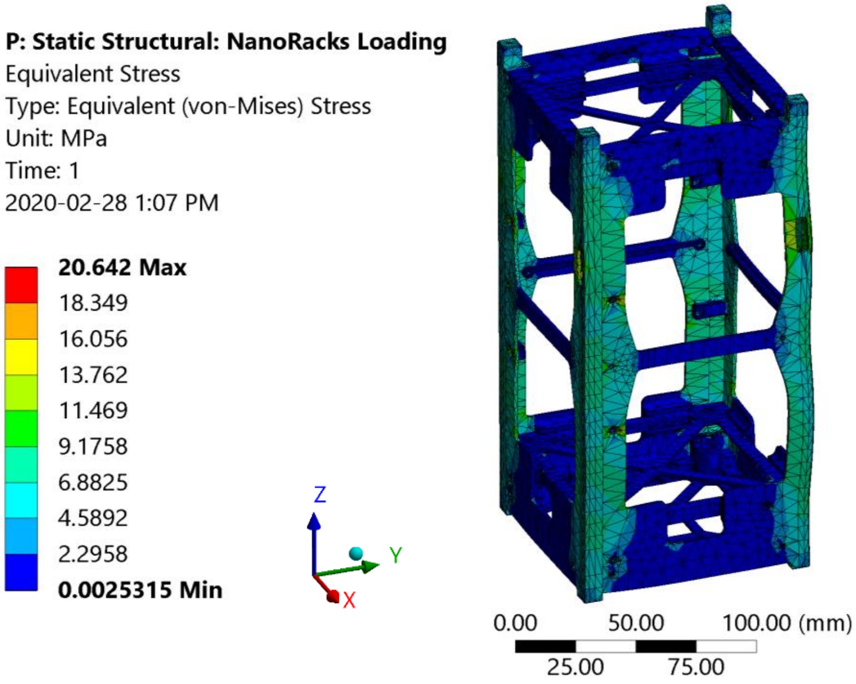


Figure F-7. ANSYS Workbench, complex model, complex loading, Equivalent stress

Additional detail is shown in Figure F-8 showing areas of increased stress in thinner members along the rails.

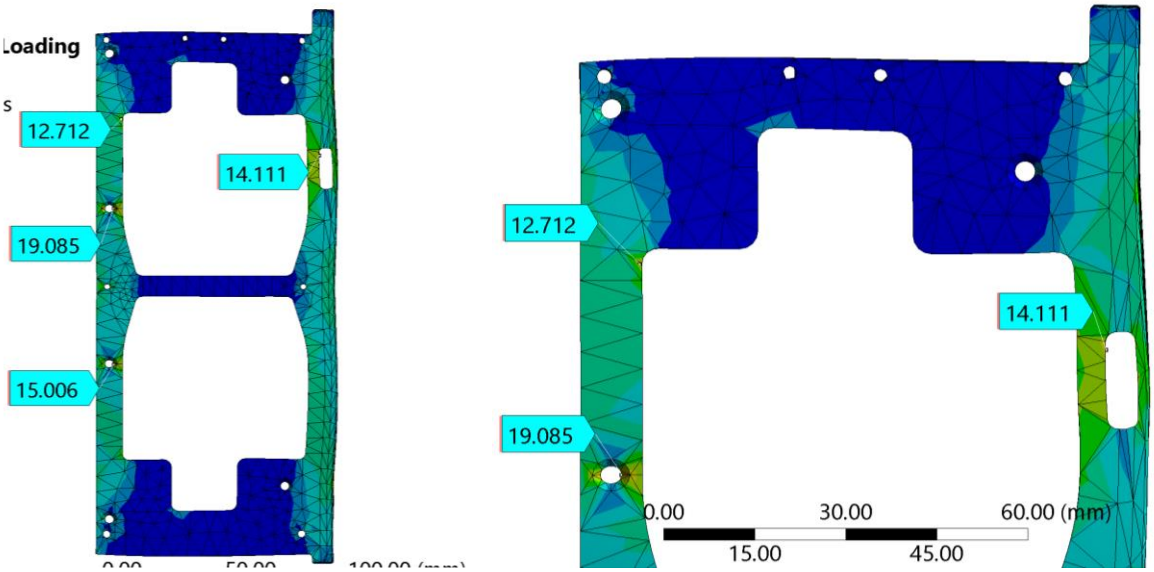


Figure F-8. ANSYS Workbench, complex model, complex loading, Equivalent stress detail

The largest stress in the frame was determined to be 20.6 MPa, as seen in Figure F-9, however, this is an anomaly of the FEA software. This stress concentration is regarded as a stress concentration as the maximum stress is significantly larger than the nominal stress of the immediate area. Secondly, the gradient at which the stress increase is very sharp, indicating the likelihood of an anomaly. Further mesh refinement would be necessary in the location of interest to derive a more realistic result. However, due to the magnitude of stresses observed, this is not required.

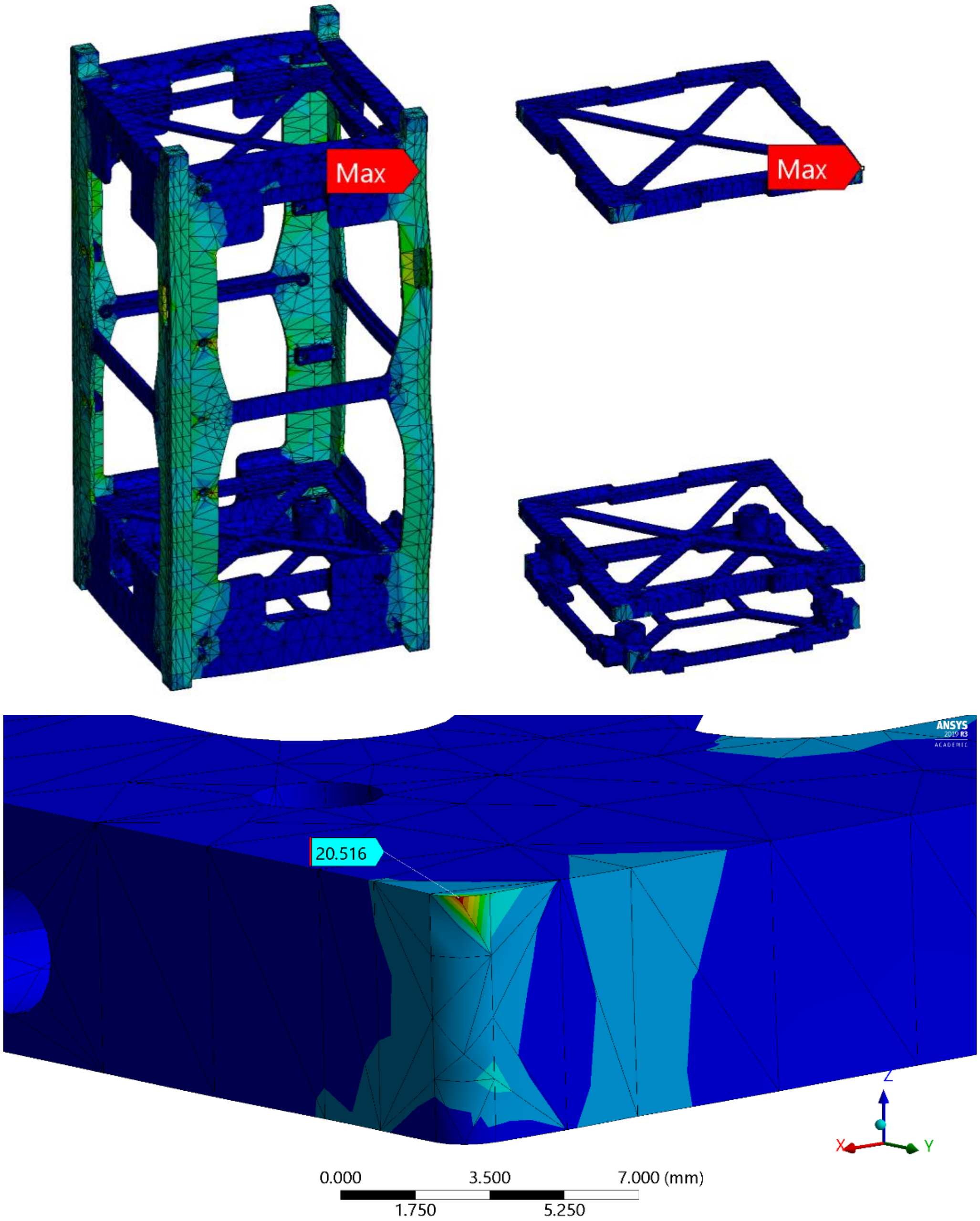


Figure F-9. ANSYS Workbench, complex model, complex loading, Equivalent stress anomalies

Appendix G: Vibration Analysis

The following appendix will discuss in detail the vibration requirements of the project as well as detail the literature and analysis referenced within the report. It is important to note the USST will be conducting the required physical testing as per NanoRacks requirements after design handover. However, Design Cubed will be responsible for the theoretical analysis. Additionally, all ANSYS Workbench files referenced within the appendix will be included within the handover documentation to the USST upon project completion.

G.1 NanoRacks Requirements

NanoRacks requires that the CubeSat withstand a random vibration environment as specified by Figure G-1. NanoRacks specifies that the design must be tested using the hard-mount configurations profile that envelopes the MEFL +3dB and a minimum workmanship level (MWL) vibe for a duration of 60 seconds in each axis.

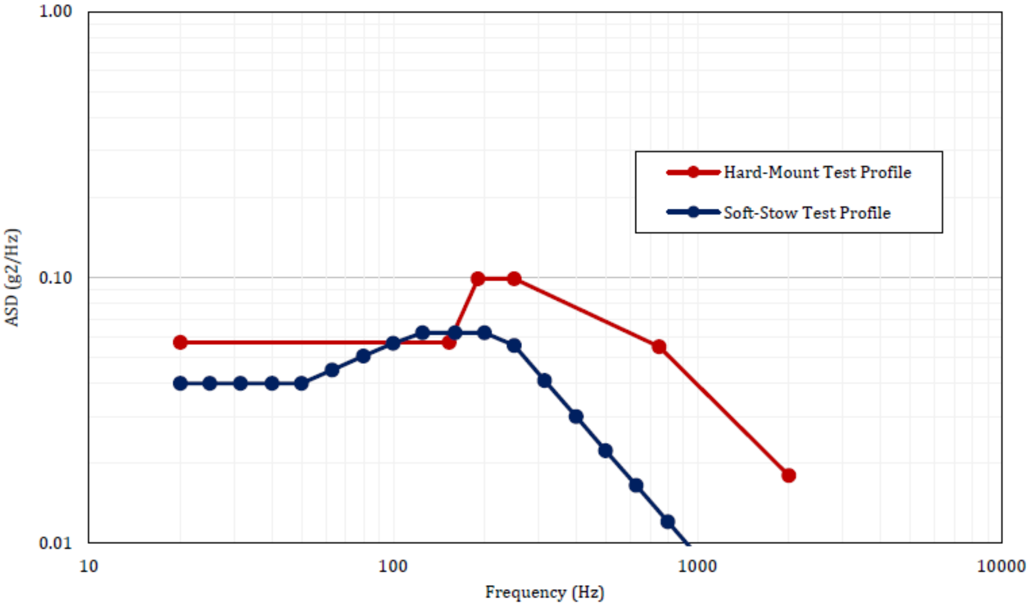
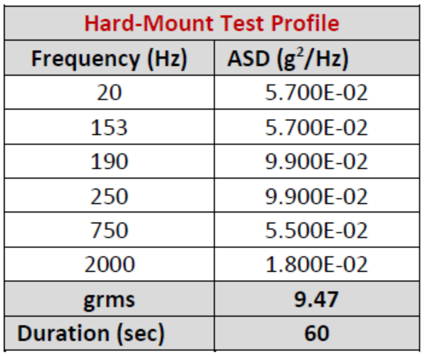


Figure G-1. NanoRacks random vibration test profile (NanoRacks 2018)

Additionally, the data for the hard-mount random vibration test profile graphed in Figure G-1 is provided in Figure G-2 below.



Hard-Mount Test Profile

Frequency (Hz)	ASD (g^2/Hz)
20	5.700E-02
153	5.700E-02
190	9.900E-02
250	9.900E-02
750	5.500E-02
2000	1.800E-02
grms	**9.47**
Duration (sec)	**60**

Figure G-2. NanoRacks hard-mount test profile data table

G.2 Vibration Analysis Methods

The following sections will outline the various vibration analysis methods conducted by Design Cubed. Three different methods of vibrational analysis were utilized including modal analysis, Vibration equivalent quasi-static loading, and random vibration profile testing. Important to note, all simulations from ANSYS Workbench have undergone mesh refinement to determine solution convergence.

G.2.1 Modal Vibration Analysis

A modal shape analysis was conducted to gain further insight into the vibrational reactiveness of the design and to evaluate possible cut-out designs of the side panels. It is important to note that the deflections and stresses observed within the ANSYS Workbench modal analysis software are not accurate. As such, all figures of deformations referenced will be using an adapted scale to effectively show mode shapes. This tool was used to identify mode shapes and the frequency at which they occur.

The combined loading case referenced of the Design Calculations section (Section 3.4) of the report was used as a static structural pre-stress. Adding a pre-stress to the structure stiffens the structure and improves the accuracy of the modal analysis. Each alternate design depicted in Figure G-3 was analysed.

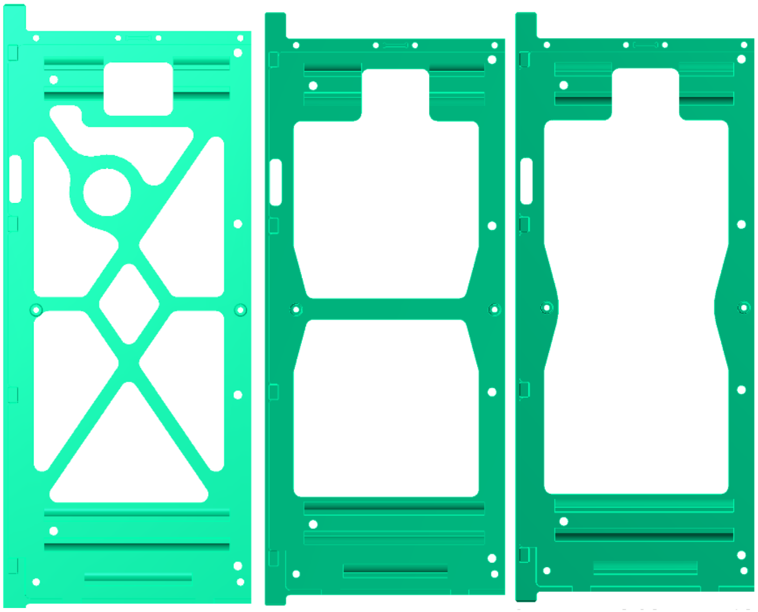
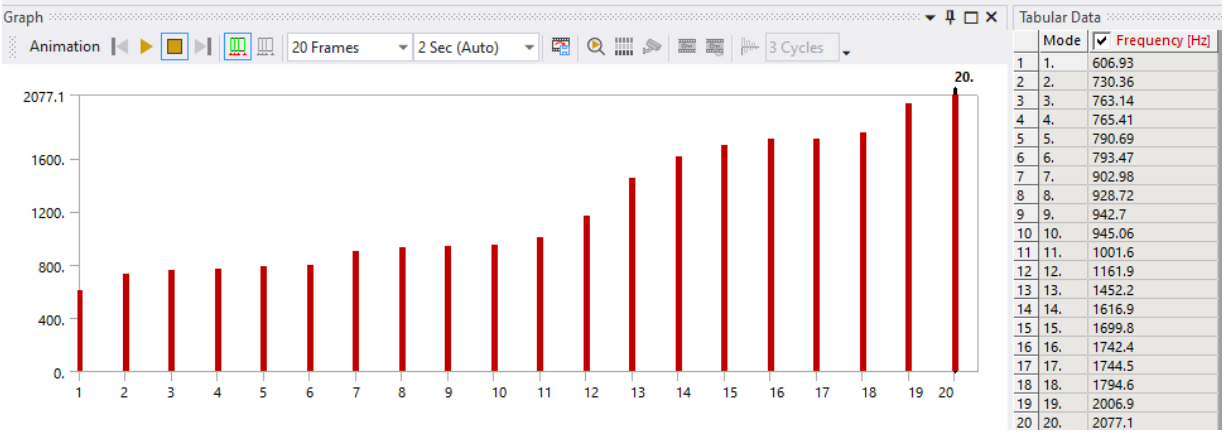


Figure G-3. Vibration analysis cut-out design alternatives

Mode frequencies, shapes, and locations were identified, and cut-out design changes made accordingly.

G.2.1.1 Original Cut-out Design

The original cut-out design, as it sounds, was the originally proposed cut-out design base upon Design Cubed's mechanical intuition and expertise. The resulting modal profile can be referenced in Figure G-4.



	Mode	☑ Frequency [Hz]
1	1.	606.93
2	2.	730.36
3	3.	763.14
4	4.	765.41
5	5.	790.69
6	6.	793.47
7	7.	902.98
8	8.	928.72
9	9.	942.7
10	10.	945.06
11	11.	1001.6
12	12.	1161.9
13	13.	1452.2
14	14.	1616.9
15	15.	1699.8
16	16.	1742.4
17	17.	1744.5
18	18.	1794.6
19	19.	2006.9
20	20.	2077.1

Figure G-4. Original Cut-out design mode frequencies

It was observed that the first four modes (607Hz -765Hz) occurred within the side panel cut-outs causing large trampoline-like deformations similar to that displayed in Figure G-5a. Modes five and six (791Hz -793Hz) yielded results similar to that of the side panels with the recognizable trampoline effect but within the thin cross member sections as depicted in Figure G-5b. Interestingly, the side panel cut-outs and the thin cross member sections were effected in modes seven through eleven (902Hz – 1002Hz). However, modes seven through eleven resembled “S” shaped deformations instead of the classic trampoline, Figure G-5c. It was not till mode twelve (1162Hz) that the rail began to be affected as seen in Figure G-5d. Considering the rails are the main interference between the CubeSat and the launching mechanism it is considered a mission-critical member. It can be observed that much of the rail deformation seems to be a function of the side cut-out design and as such alternate cut-out designs were considered to reduce the effect.

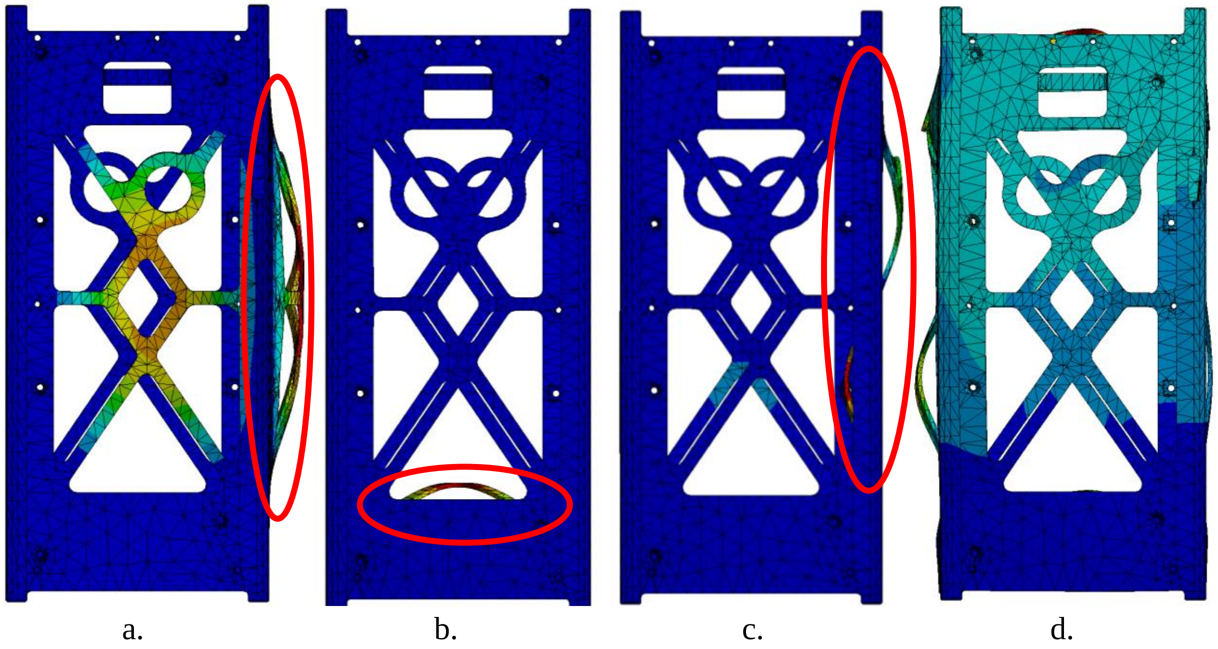


Figure G-5. ANSYS Workbench Original Cut-out design modal analysis mode shapes

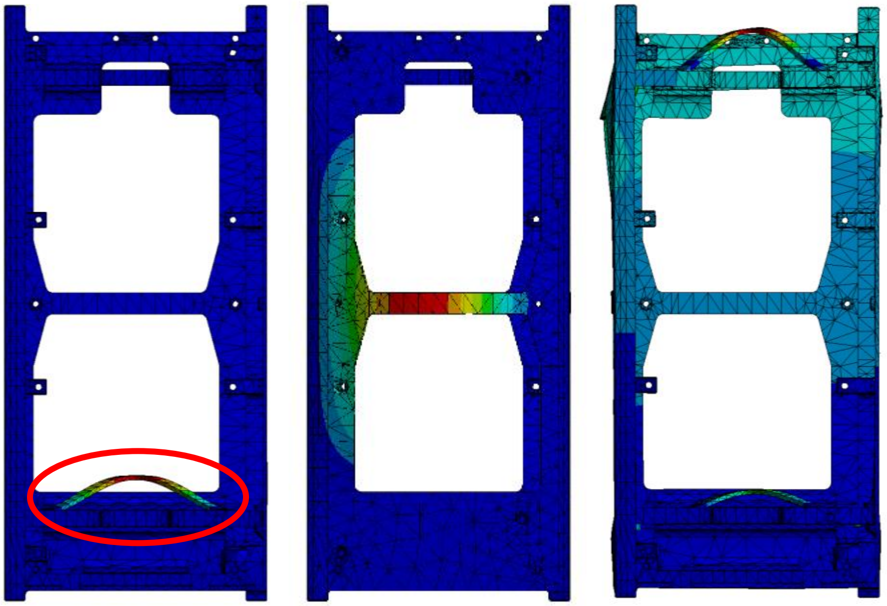
G.2.1.2 Alternate Cut-out Design

The alternate cut-out design was a first attempt in reducing the low mode frequencies and rain influencing distortions caused by the original cut-out design. Although the topology optimization analysis concluded that a fully cut design was optimal as per the design iteration and topology optimization section of the report (Section 3.4.5) and the intermediate alternative was tested. The resulting modal profile can be referenced in Figure G-6.

	Mode	☑ Frequency [Hz]
1	1.	787.34
2	2.	792.71
3	3.	852.46
4	4.	1001.
5	5.	1124.9
6	6.	1330.3
7	7.	1471.1
8	8.	1475.8
9	9.	1673.3
10	10.	1866.7
11	11.	2113.5
12	12.	2138.5
13	13.	2140.3
14	14.	2165.5
15	15.	2177.1

Figure G-6. Alternate Cut-out design mode frequencies

It was observed that the lowest modes were no longer dominated by the side panel cut-outs. The first two modes resembled the same trampoline effects within the thin cross members as seen previously (787-792Hz). It can be noted that the thin cross member section mode frequencies are affected little by cut-out alternations as seen in Figure G-7a. Additionally, the alternate side panel design deformations appeared in mode 3 (855Hz) and again interfered with the rails as per Figure G-7b. Lastly, it was observed that the same overall compressive structural mode occurred at roughly the same frequency (1125Hz) and changes to the side panel cut-outs had little effect as per Figure G-7c.

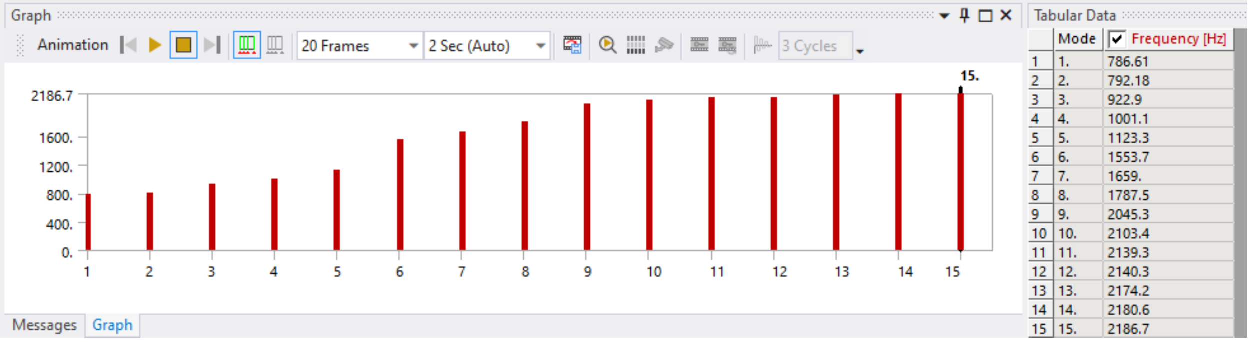


a. b. c.

Figure G-7. ANSYS Workbench Alternate Cut-out design modal analysis mode shapes

G.2.1.3 Fully Cut-out Design

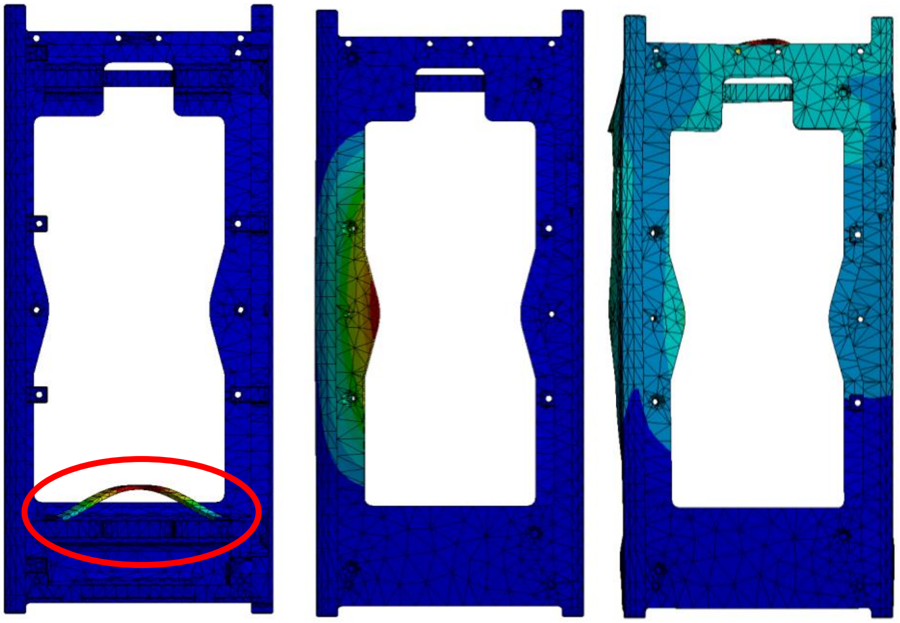
Based on the findings of the alternate cut-out design, a fully cut-out design as recommended by topology optimization was analysed. The resulting modal profile can be referenced in Figure G-8.



	Mode	☑ Frequency [Hz]
1	1.	786.61
2	2.	792.18
3	3.	922.9
4	4.	1001.1
5	5.	1123.3
6	6.	1553.7
7	7.	1659.
8	8.	1787.5
9	9.	2045.3
10	10.	2103.4
11	11.	2139.3
12	12.	2140.3
13	13.	2174.2
14	14.	2180.6
15	15.	2186.7

Figure G-8. Fully Cut-out design mode frequencies

Results were nearly identical to that of the alternate cut-out design. The first two modes were dominated by trampoline effects in the thin cross member sections (787-792) as expected, Figure G-9a. Unexpectedly, removing the new cut-out design did little to change the third mode (923Hz) having a torsional/bending shape affecting the rail member more than observed in the alternate cut-out design, Figure G-9b. Lastly, as expected from the previous two results, the frame sustained a compressive mode at roughly the same frequency (1123Hz), Figure G-9c.



a. b. c.

Figure G-9. ANSYS Workbench Fully Cut-out design modal analysis mode shapes

G.2.1.4 Final Design

Following the modal analysis results, a final side panel design was tested. This model was selected as the top-performing frame. The final design added a stiffening rib along the back of the alternate cut-out design as per Figure G-10.

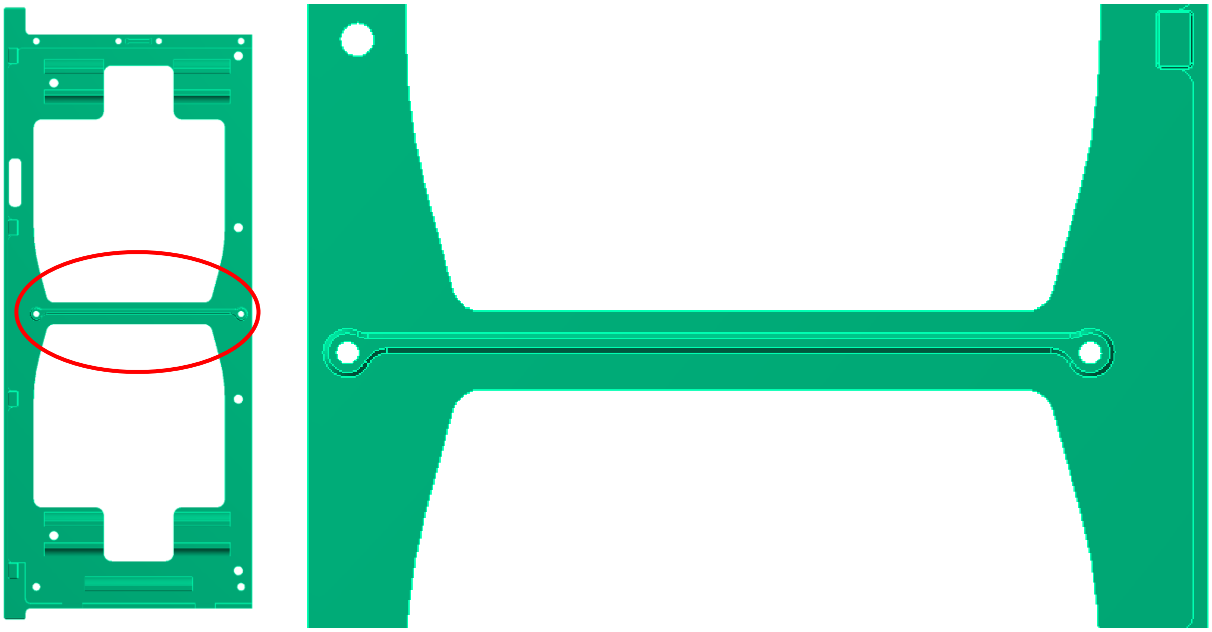
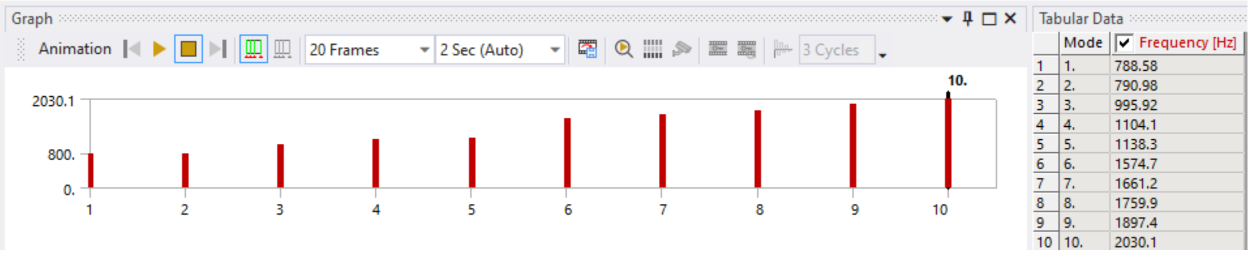


Figure G-10. Final cut-out design detail

The resulting modal analysis yielding the following results, Figure G-11.



	Mode	☑ Frequency [Hz]
1	1.	788.58
2	2.	790.98
3	3.	995.92
4	4.	1104.1
5	5.	1138.3
6	6.	1574.7
7	7.	1661.2
8	8.	1759.9
9	9.	1897.4
10	10.	2030.1

Figure G-11. Final Cut-out design mode frequencies

As expected, the first three modes (789-996Hz) were identical to the three previous tests having the trampoline-like resemblance as per Figure G-12a. However, by adding the stiffening rib the first mode affecting the rail member was increased from 923Hz to 1104Hz and the effected rail area reduced as per Figure G-12b. Additionally, the same compressive/torsional mode affecting the whole frame was present as seen in Figure G-12c. and at the expected frequency of 1138Hz.

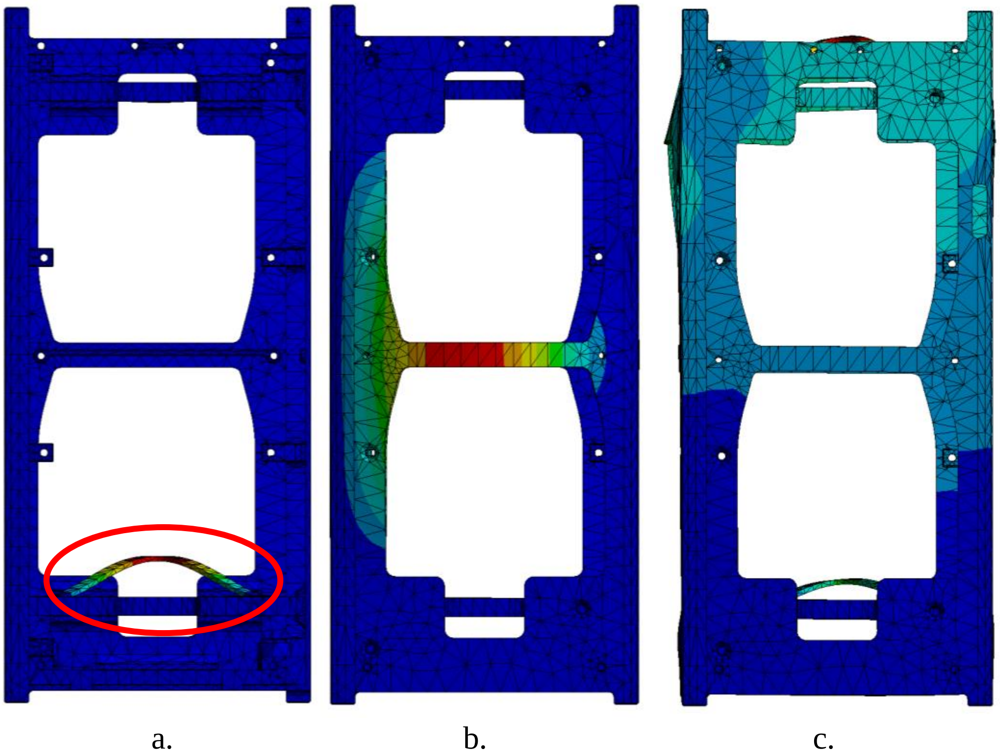

a. b. c.

Figure G-12. ANSYS Workbench Final Cut-out design modal analysis mode shapes

It is important to note at this point that Design Cubed as not concerned about the modes affecting the thin cross member sections due to the deflections observed in the following vibration analysis.

G.2.2 Random Vibration Equivalent Quasi-Static Loading

During the literature review, a graduate thesis from the University of Toronto's GHGSat was identified that outlined a procedure to obtain a quasi-static loading from the provided random vibration profile (Brakeboer 2015). This procedure applies a root mean square to the profile as seen in Table H-1, to find this value the slope of each section of the profile must be found using

$$m = 3.01\frac{\log(P_H/P_L)}{\log(f_H/f_L)}$$

where 10log(2)=3.01, P is the spectral density at the frequency, f, above and below each area of interest. The area under the curve is then found using

$$A = 3.01\frac{P_H}{3.01+m}\left(f_H - f_L\left(\frac{f_L}{f_H}\right)^{m/3.01}\right).$$

All of the areas found are then summed and the square root is taken to find the G_{rms} using

$$G_{rms} = g\sqrt{A_1 + A_2 + ... + A_n}$$

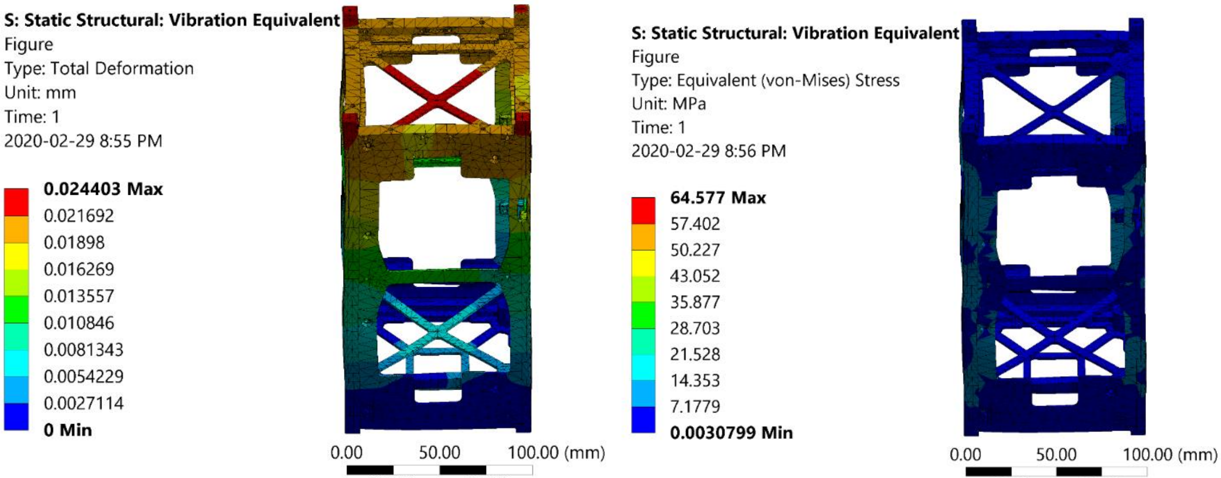
This represents the one sigma standard deviation value where the acceleration experienced by the CubeSat is less than or equal to G_{rms} 68% if the time. To ensure that all loads are accounted for in the analysis the value is multiplied by five to give a confidence of 99.9994%, or 5-sigma, that the acceleration does not exceed 47.35 m/s^2. Table G-1 summarizes the values obtained including the 5-sigma values used for testing.

Table G-1. NanoRacks random vibration profile and the root mean square values

NanoRacks hard stow test profile				
Frequency (Hz)	**ASD (g^2/Hz)**	**Slope**	**Area**	
20	0.0570	0.0000	7.5810	
153	0.0570	7.6731	2.8428	
190	0.0990	0.0000	5.9400	
250	0.0990	-1.6106	35.4859	
750	0.0550	-3.4281	37.8261	
2000	0.0180			
grms	9.4700	grms 1sigma	9.47	m/s^2
Duration (s)	60.0000	grms 5 sigma	47.35	m/s^2

This procedure allows the random vibration conditions provided by NanoRacks to be viewed as a quasi-static acceleration so that dynamic analysis is not required. The author of this paper considered this a conservative technique, and this was confirmed by consultation.

ANSYS Workbench was then used to statically analyze the complex geometry of the satellite with the addition of 47.35 G's in each axis to the combined loading case outlined in the Design Calculations section of the report (Section 3.4.3). Figure G-13a. details the total deflections and Figure G-13b. the equivalent stresses within the frame design. Maximum deflections and stresses are observed as 24 µm and 65MPa respectively.



a. b.

Figure G-13. ANSYS Workbench vibration equivalent static analysis total deformation (a) and equivalent stress (b)

However, FEM based anomalies are present within the model. As shown in **Error! Reference source not found.**, a significant stress gradient is present within the same element on the structure, thus resulting in an unrealistic stress reading. Due to the magnitude of the stress, it is of no concern and as such a simplified method of averaging surrounding node, stresses is an adequate approximation.

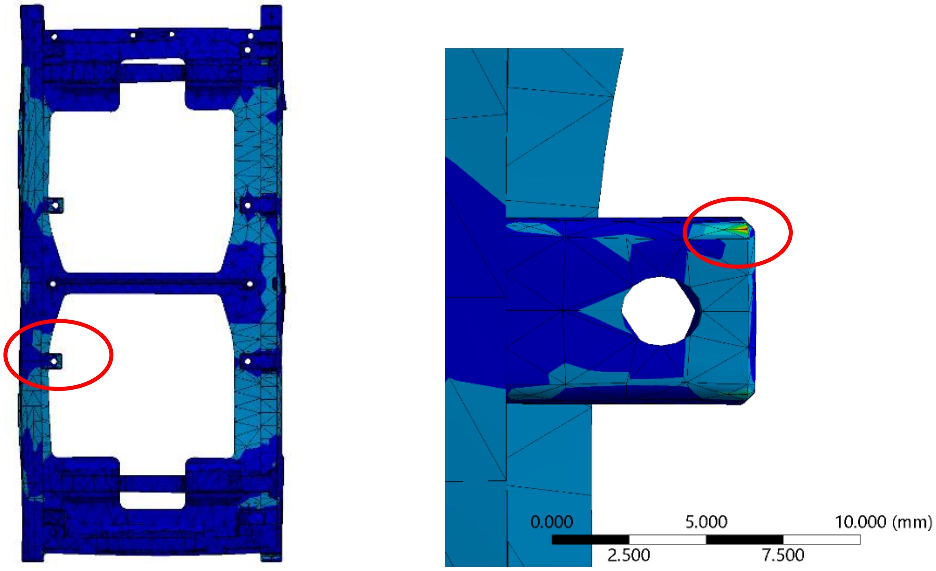


Figure G-14. ANSYS Workbench vibration equivalent static analysis equivalent stress anomalies

G.2.3 Random Vibration Profile Analysis

Lastly, ANSYS Workbench was used to analyze random vibrations according to the NanoRacks hard-mount test profile. It is important to note that the modal analysis is an input to the random vibration analysis tool and allows the analysis to account for modal frequencies. Results included stresses reaching a maximum of 68.4MPa at stress concentrations with nominal frame stresses around 30MPa, Figure G-15.

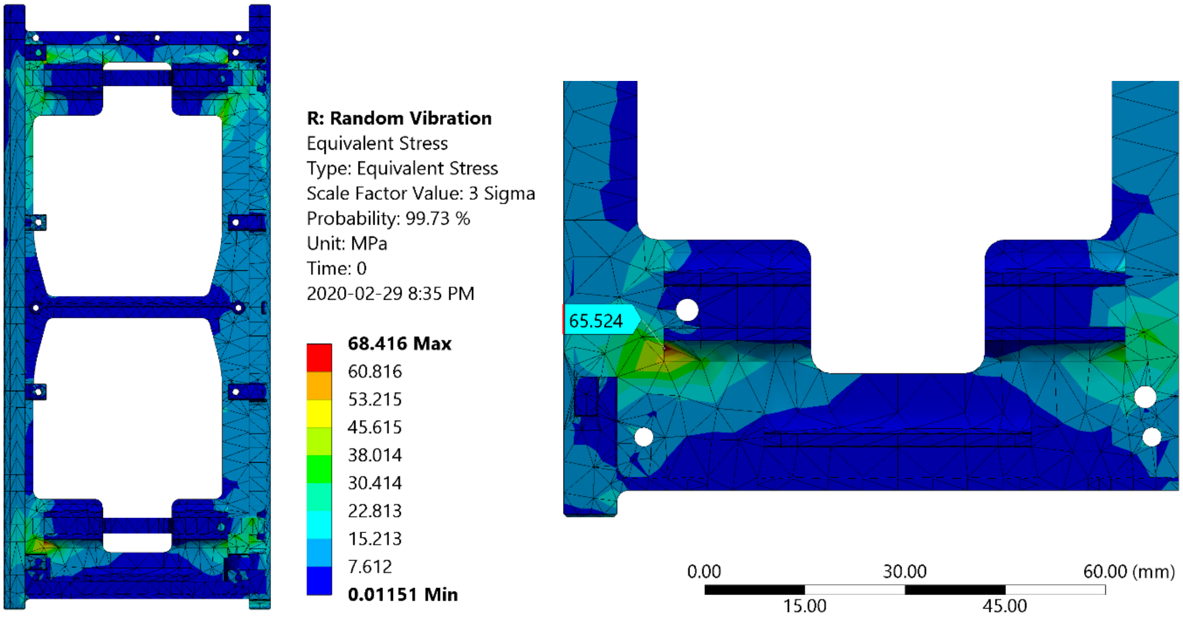


Figure G-15. ANSYS Workbench random vibration analysis equivalent stress, stress risers

It is important to note that increased stresses are observed where the payload (PCB stack) is connected to the frame via the cross members, Figure G-16. This is an expected result as all 1.9 kg of the payload is only mounted to the frame in four bolted locations.

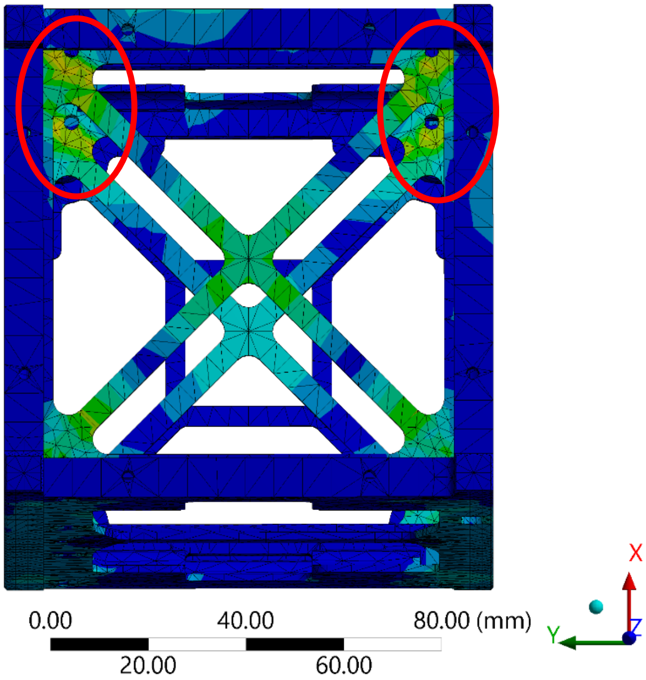


Figure G-16. ANSYS Workbench random vibration analysis equivalent stress, PCB stack mounting point stresses

Directional deformations induced by the hard-mount random vibration profile were then investigated. Results aligned with what was expected from the modal analysis. Maximum deflections in the X-axis occurred at the largely un-supported section of the frame resulting in roughly 0.05mm of deflection as per Figure G-17. The deflections are well within tolerance of the CubeSat.

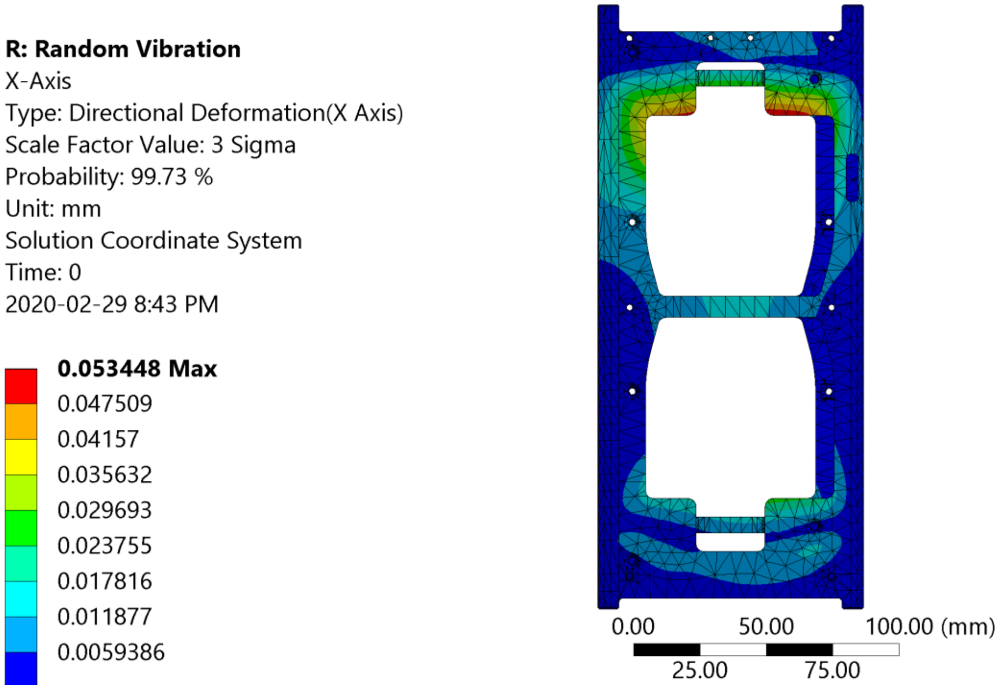


Figure G-17. ANSYS Workbench random vibration analysis X-axis deformations

In the Y-axis, very similar deformation patters to what was observed within modal analysis were observed as per Figure G-18. It is important to note that the maximum deflection is of 0.03mm and is within tolerance.

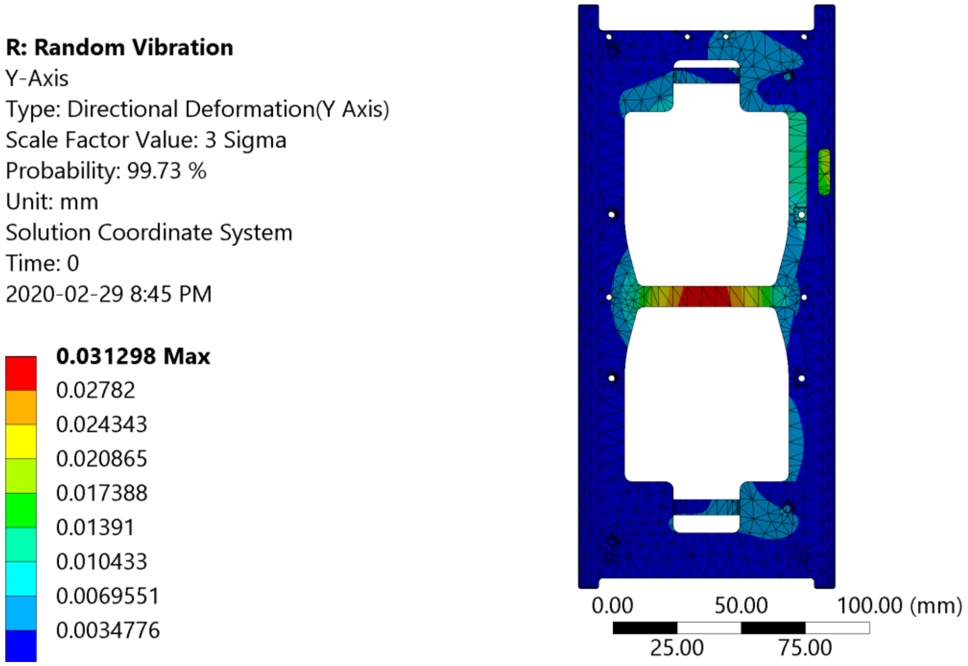


Figure G-18. ANSYS Workbench random vibration analysis Y-axis deformations

Lastly, deflections in the Z-axis were analyzed. Again, as expected from modal analysis the thin sections of the cross members deflected the most as per Figure G-19. Maximum deflections in the Z-axis were the largest of the three axes at 0.31mm. The deflection is of no concern as it will not be interfering with CubeSat internal components or with the NanoRacks deployer.

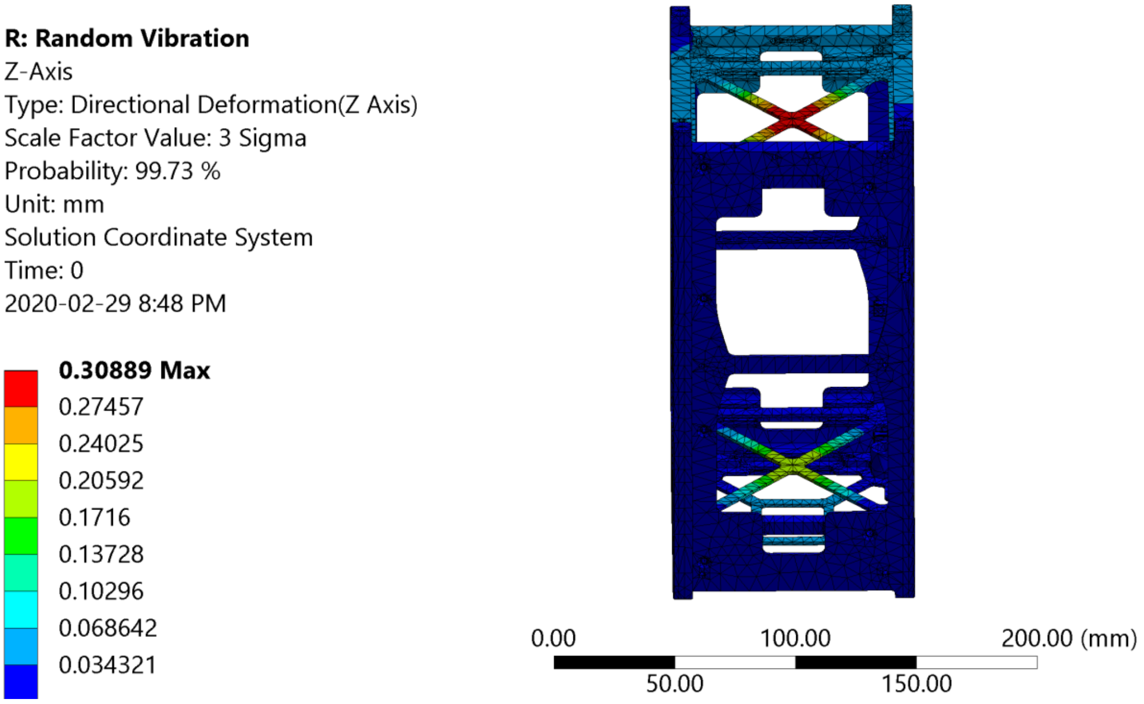
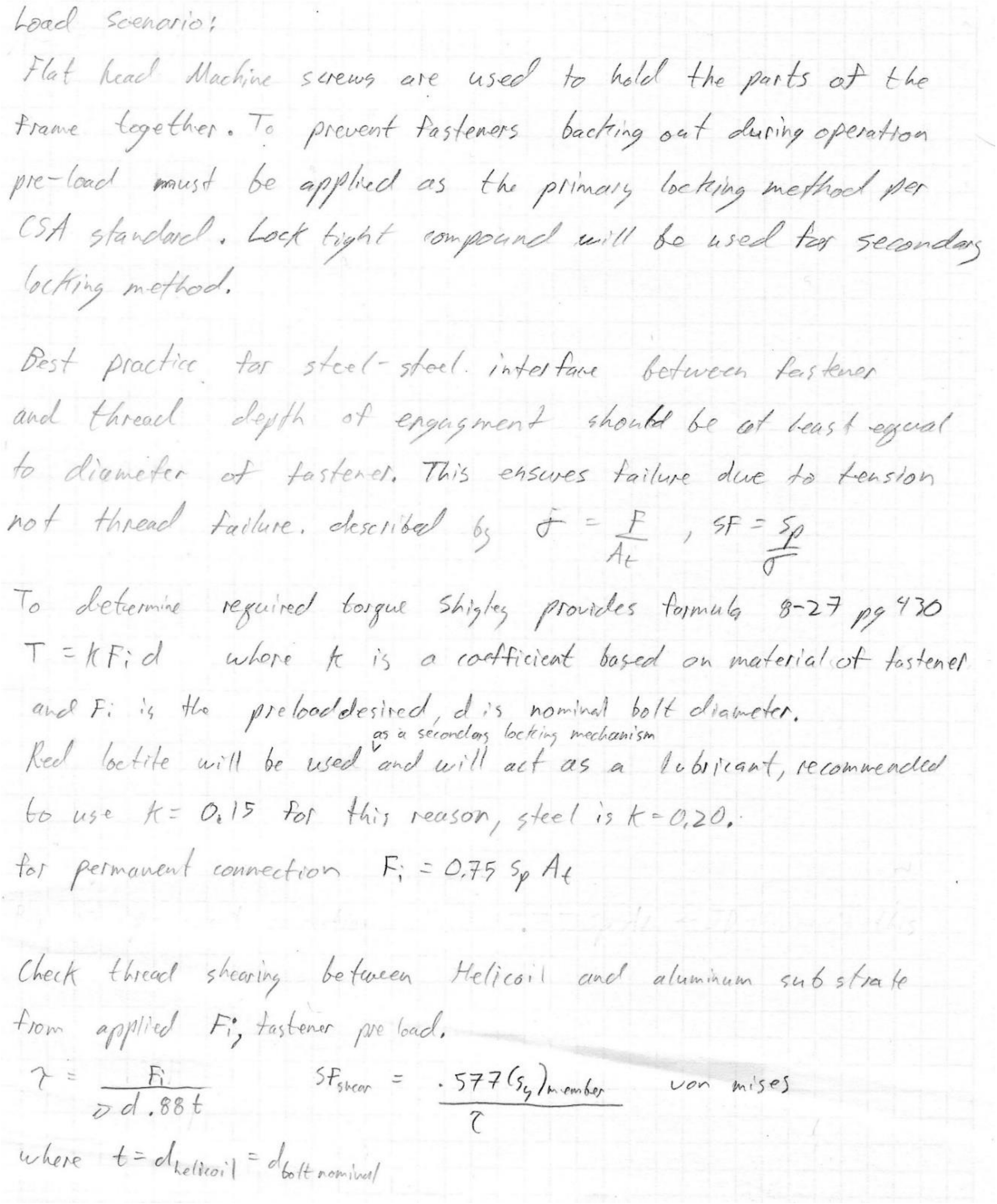


Figure G-19. ANSYS Workbench random vibration analysis Z-axis deformations

In conclusion, based on the three methods of vibration analysis and verification presented here the Design Cubed team is confident the chosen CubeSat design will meet all NanoRacks vibration requirements. Further physical testing of the CubeSat by the USST is still recommended by Design Cubed and required by NanoRacks.

Appendix H: Bolted Connections

The following appendix will provide detail for the bolted connection analysis conducted by Design Cubed. The pretension of bolted connections is a primary locking mechanism and as such a bolt analysis was performed to determine the safety factor of the stainless-steel bolt within the aluminum frame.



Load Scenario:

Flat head Machine screws are used to hold the parts of the frame together. To prevent fasteners backing out during operation pre-load must be applied as the primary locking method per CSA standard. Lock tight compound will be used for secondary locking method.

Best practice for steel-steel interface between fastener and thread depth of engagment should be at least equal to diameter of fastener. This ensures failure due to tension not thread failure. described by $\sigma = \frac{F}{A_t}$, $SF = \frac{S_p}{\sigma}$

To determine required torque Shigley provides formula 8-27 pg 430

$T = KF_i d$ where k is a coefficient based on material of fastener and F_i is the preloaddesired, d is nominal bolt diameter.

Red loctite will be used as a secondary locking mechanism and will act as a lubricant, recommended to use $k = 0.15$ for this reason, steel is $k = 0.20$.

for permanent connection $F_i = 0.75\, S_p A_t$

Check thread shearing between Helicoil and aluminum substrate from applied F_i, fastener pre load.

$$\tau = \frac{F_i}{\pi d\, .88 t} \qquad SF_{shear} = \frac{.577 (S_y)_{member}}{\tau} \quad \text{von mises}$$

where $t = d_{helicoil} = d_{bolt\ nominal}$

Permanent preload required for 3mm 316SS Machine screw

$S_p = .85 S_y = .85(482 MPa) \dot{=} 409.7\ MPa$

$A_t = 5.03 mm^2$

$F_i = 0.75\ S_p\ A_t$

$= 0.75\,(409.7 e^6)\left(\frac{5.03 mm^2}{1e^6}\right)$

$F_i = 1545.6 N$ ——— (1)

$T = k F_i d$ where $k = 0.15$

$= (0.15)(1545.6)(.003)$ $d = 3mm$

$T = 0.696\ Nm$

Pull out of helicoil in Aluminum 6061-T6 substrate

$$\tau = \frac{F_i}{\pi d^2 .88} = \frac{1545.6}{\pi (.003m)^2 .88}$$

$\tau = 62.12 MPa$

$$SF_{vm} = \frac{.577 (S_y)_{member}}{\tau}$$

$$= \frac{.577\ (276 e^6)}{62.12 e^6}$$

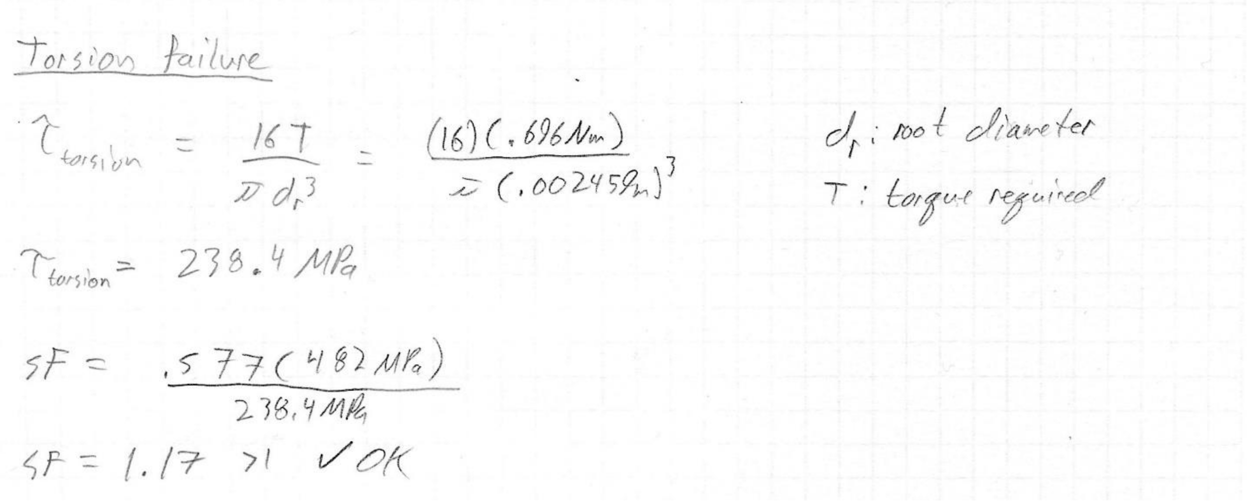
$SF_{vm} = 2.56 > 1.1 \therefore OK$

Axial stress in fastener

$$\sigma = \frac{F_i}{A_t} = \frac{1545.6}{5.09 e^{-6}} = 303.65\ MPa$$

$$SF = \frac{S_p}{\sigma} = \frac{409.7}{303.65} = 1.35 > 1 \therefore OK$$

Note: Safety factor appears small but proof load was used in the calculations giving a very high confidence in accuracy of results.



Torsion failure

$$\tau_{torsion} = \frac{16T}{\pi d_r^3} = \frac{(16)(.696 Nm)}{\pi(.002459 m)^3}$$

d_r : root diameter

T : torque required

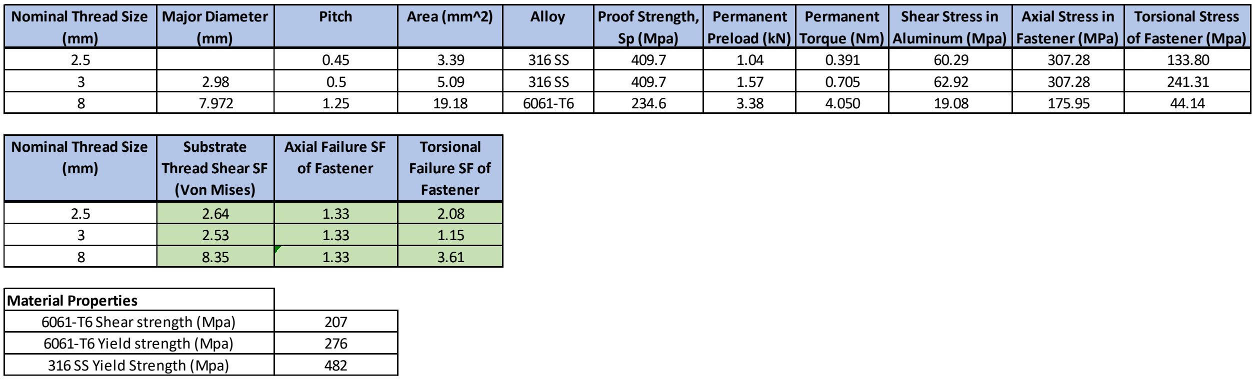
$$\tau_{torsion} = 238.4 MPa$$

$$SF = \frac{.577(482 MPa)}{238.4 MPa}$$

$$SF = 1.17 > 1 \checkmark OK$$

Results were tabulated in Excel as seen in Table H-1 for the two sizes of fasteners that are required for the frame. The safety factors highlighted in green can be seen to be above. This means that the preloads applied will not result in failure of the threaded aluminum substrate, axial failure of the fastener, or torsional failure of the fastener.

Table H-1. Bolted connection tabulated data for 3 mm and 8 mm stainless-steel fasteners



Nominal Thread Size (mm)	Major Diameter (mm)	Pitch	Area (mm^2)	Alloy	Proof Strength, Sp (Mpa)	Permanent Preload (kN)	Permanent Torque (Nm)	Shear Stress in Aluminum (Mpa)	Axial Stress in Fastener (MPa)	Torsional Stress of Fastener (Mpa)
2.5		0.45	3.39	316 SS	409.7	1.04	0.391	60.29	307.28	133.80
3	2.98	0.5	5.09	316 SS	409.7	1.57	0.705	62.92	307.28	241.31
8	7.972	1.25	19.18	6061-T6	234.6	3.38	4.050	19.08	175.95	44.14

Nominal Thread Size (mm)	Substrate Thread Shear SF (Von Mises)	Axial Failure SF of Fastener	Torsional Failure SF of Fastener
2.5	2.64	1.33	2.08
3	2.53	1.33	1.15
8	8.35	1.33	3.61

Material Properties	
6061-T6 Shear strength (Mpa)	207
6061-T6 Yield strength (Mpa)	276
316 SS Yield Strength (Mpa)	482

Appendix I: Change Request Form

Maintaining change requests and obtaining change approval from appropriate parties is an important aspect of any project. Designed Cubed has recognized that the CubeSat project will be taking place in parallel with efforts from the client to complete the project on schedule. As a result, changes to the design may need to occur in certain circumstances. As a method of tracking and obtaining approval for design changes, Design Cubed created and implemented the use of the following change order form.

Change Order Form

Date : ____/____/________

Summary of Design Change:

Reason for Change Order:

Additional supporting documents to be attached beneath this document

On behalf of the CubeSat mechanical team & management, the following changes to the design have been proposed by ________________________________. These changes are confirmed to be necessary for the project's success & as a result should be implemented by Design Cubed if possible, despite a complete set of requirements intended to be unaltered after submission having been already provided.

Signed,

________________________________	________________________________
Mechanical Lead	Proponent
________________________________	________________________________
Technical Project Manager	Proponent

Design Cubed will respond to all change orders within 3 business days of receipt. Please note due to the time constraints of Design Cubed's schedule, they reserve the right to reject any design changes submitted.

Response:

On behalf of Design Cubed, I hereby ACCEPT/REJECT this change order

Comments:

Signed,

____

Design Cubed Representative

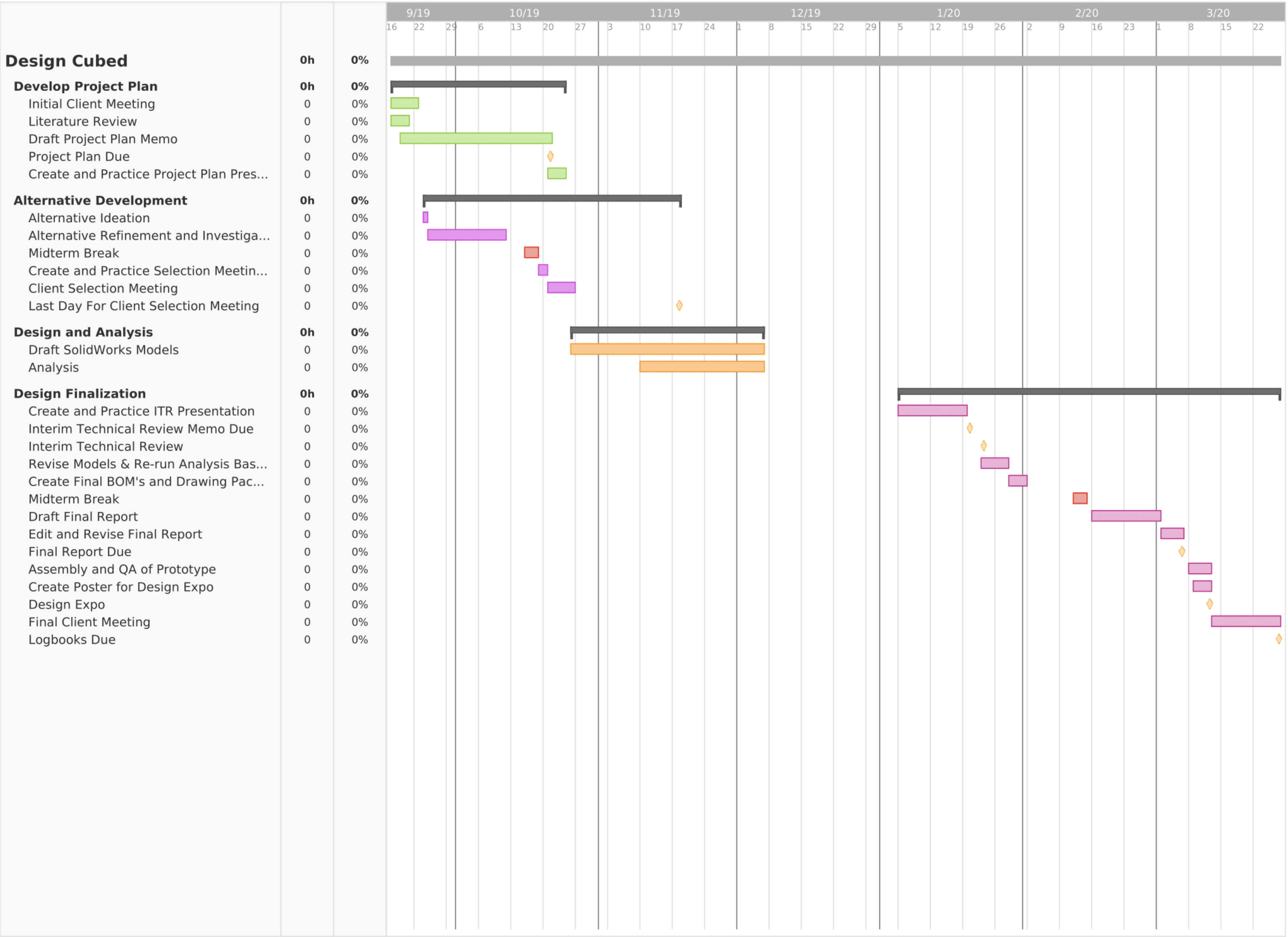
Appendix J: Gantt Chart

Establishing a clear project schedule is an important aspect of any design project. Predicting future conflicts and determining the critical path of sequential events can improve project efficiency. Table J-1 outlines the critical project milestones and their duration.

Table J-1. CubeSat frame project internal project milestones and schedule

Description	Start Date	End Date
Literature Review	2019 Sep 10	2019 Sep 20
Project Planning and Ideation	2019 Sep 20	2019 Sep 24
Finalize Alternative and Check Feasibility	2019 Sep 24	2019 Oct 11
Project Plan and Presentation Due	2019 Oct 21	
Selection Meeting with Clients	2019 Oct 21	2019 Oct 26
Interim Technical Review Memo Due	2019 Jan 20	
Interim Technical Design Review	2019 Jan 21	2019 Jan 23
Final Report Due	2019 Mar 6	
Design Expo	2019 Mar 12	
Client Exit Meeting	2019 Mar 12	2019 Mar 27

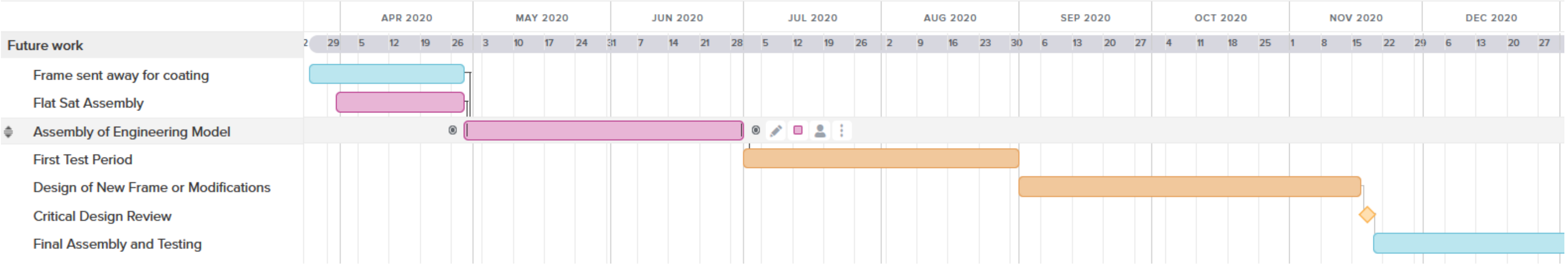
These deadlines can be implemented into the Gantt Chart, below, along with high-level project tasks such as analysis or detailed design. The Gantt Chart proved to be a vital tool for reflecting on progress and upcoming milestones. The Gantt Chart was updated as internal deadlines shifted.

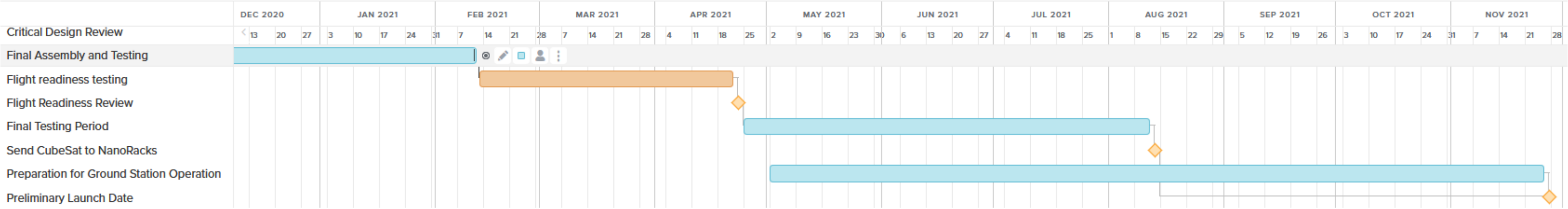


Design Cubed	**0h**	**0%**
Develop Project Plan	**0h**	**0%**
Initial Client Meeting	0	0%
Literature Review	0	0%
Draft Project Plan Memo	0	0%
Project Plan Due	0	0%
Create and Practice Project Plan Pres...	0	0%
Alternative Development	**0h**	**0%**
Alternative Ideation	0	0%
Alternative Refinement and Investiga...	0	0%
Midterm Break	0	0%
Create and Practice Selection Meetin...	0	0%
Client Selection Meeting	0	0%
Last Day For Client Selection Meeting	0	0%
Design and Analysis	**0h**	**0%**
Draft SolidWorks Models	0	0%
Analysis	0	0%
Design Finalization	**0h**	**0%**
Create and Practice ITR Presentation	0	0%
Interim Technical Review Memo Due	0	0%
Interim Technical Review	0	0%
Revise Models & Re-run Analysis Bas...	0	0%
Create Final BOM's and Drawing Pac...	0	0%
Midterm Break	0	0%
Draft Final Report	0	0%
Edit and Revise Final Report	0	0%
Final Report Due	0	0%
Assembly and QA of Prototype	0	0%
Create Poster for Design Expo	0	0%
Design Expo	0	0%
Final Client Meeting	0	0%
Logbooks Due	0	0%

Appendix K: Look Forward

The following schedule was created based on major milestones provided by the USST that starts at the exit meeting and goes till the launch of the CubeSat into orbit. Depending on the results of testing one or more alternative frames may be created from this project's design. The testing will consist of physical verification of vibration simulations and complete integration with all other components for further vibration and thermal vacuum testing.


APR 2020
MAY 2020
JUN 2020
JUL 2020
AUG 2020
SEP 2020
OCT 2020
NOV 2020
DEC 2020
Future work
2 29 5 12 19 26 3 10 17 24 31 7 14 21 28 5 12 19 26 2 9 16 23 30 6 13 20 27 4 11 18 25 1 8 15 22 29 6 13 20 27
Frame sent away for coating
Flat Sat Assembly
Assembly of Engineering Model
First Test Period
Design of New Frame or Modifications
Critical Design Review
Final Assembly and Testing


DEC 2020
JAN 2021
FEB 2021
MAR 2021
APR 2021
MAY 2021
JUN 2021
JUL 2021
AUG 2021
SEP 2021
OCT 2021
NOV 2021
13 20 27 3 10 17 24 31 7 14 21 28 7 14 21 28 4 11 18 25 2 9 16 23 30 6 13 20 27 4 11 18 25 1 8 15 22 29 5 12 19 26 3 10 17 24 31 7 14 21 28
Critical Design Review
Final Assembly and Testing
Flight readiness testing
Flight Readiness Review
Final Testing Period
Send CubeSat to NanoRacks
Preparation for Ground Station Operation
Preliminary Launch Date

Appendix L: Future Risk Matrix

This risk assessment is for the future continuation of this project after this capstone group has completed this report and transferred all knowledge to our client. Risks were identified and evaluated according to probability and impact severity. Each risk was then assigned an initial Risk Score as per the Design Cube's team risk matrix. Risks scoring at or above a medium Risk Score were then assigned mitigation steps to reduce the severity and/or probability of occurrence and thereafter assigned a Mitigated Risk Score. Lastly, it was decided that a project freeze would be required in the event risks scored in the extreme category (11-12). The design project would be frozen until subject matter experts are consulted, and additional risk mitigations or re-evaluations implemented. Please reference below for the Design Cube Risk Assessment Matrix.

		Severity			
		NEGLIGIBLE small/unimportant; not likely to have a major effect / no bodily injury to requiring minor first aid injury	**MARGINAL** minimal importance; influences the project but will not affect the project outcome / requires medical treatment	**CRITICAL** serious/important; will affect the project outcome in a negative way / suffers serious injuries or medical treatment	**CATASTROPHIC** maximum importance; could result in disaster/death; WILL affect the project in a negative way / death, dismemberment or serious injury
Probability	**HIGH** This risk WILL occur in this project, possibly multiple times, and/or has occurred in the past	**MEDIUM (3)**	**HIGH (7)**	**HIGH (9)**	**EXTREME (12)**
	MEDIUM This risk will MOST LIKELY occur during this project	**LOW (2)**	**MEDIUM (5)**	**HIGH (8)**	**EXTREME (11)**
	LOW This risk has rarely been a problem and almost never occurs in projects of this nature	**LOW (1)**	**MEDIUM (4)**	**MEDIUM (6)**	**HIGH (10)**

<table>
<tr><th colspan="3">Explanation of Risk Ranking</th></tr>
<tr><td colspan="2">EXTREME</td><td>If the consequences to the project are EXTREME, it is advised Not To Proceed.</td></tr>
<tr><td colspan="2">HIGH</td><td>If the consequences to the project are HIGH, it is advised that additional planning, support, and risk mitigation is needed.</td></tr>
<tr><td>LOW</td><td>MEDIUM</td><td>If the consequences to the project are LOW / MEDIUM, OK to proceed with project. It is advised that if the activity is MEDIUM, risk mitigation efforts should be made.</td></tr>
</table>

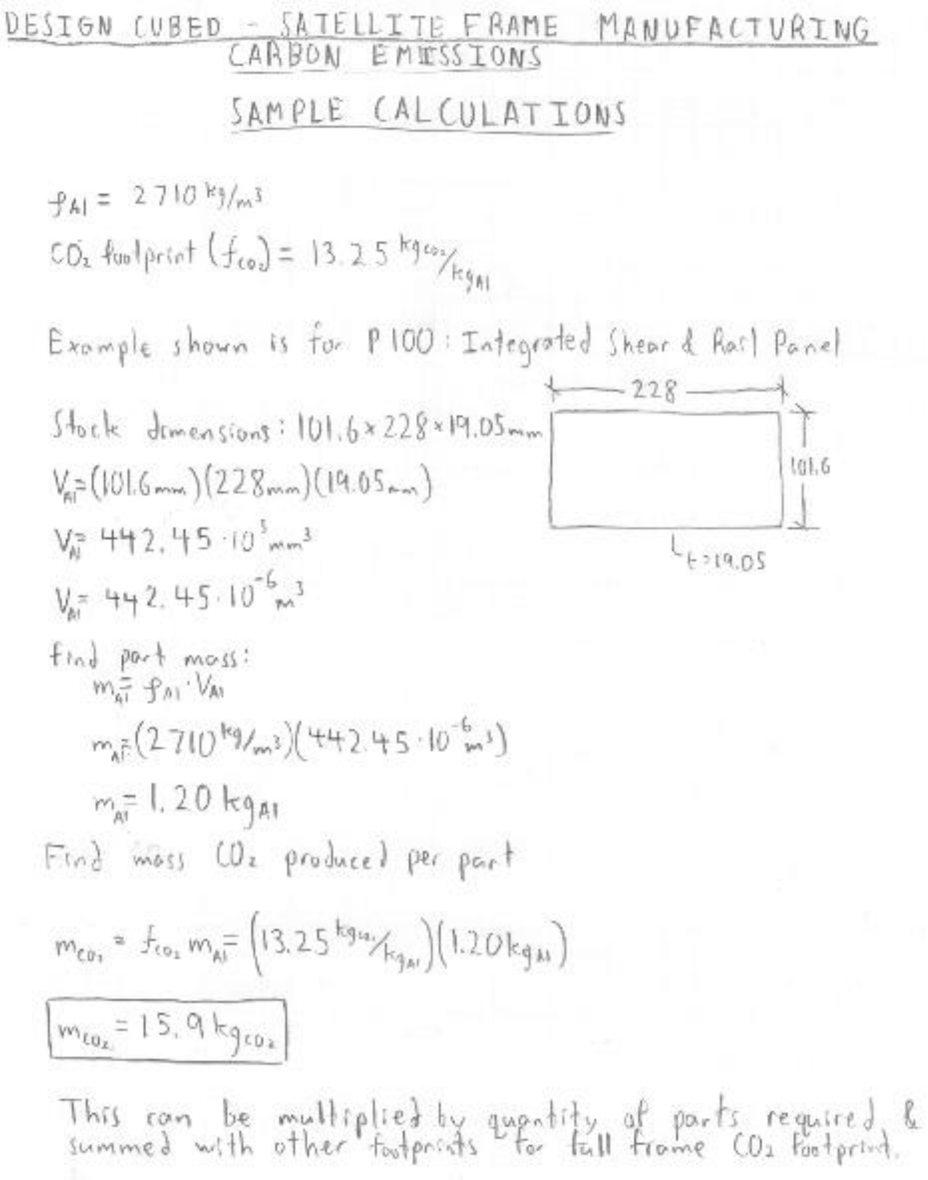
List Risks	**Probability** *The chances of that risk happening*	**Severity** *Level of impact of the risk happening*	**Risk Matrix Score** *Risk score, on the risk matrix*	**Risk Mitigation Method(s)** *A list of methods used to minimize the chances of the risk happening and/or the resulting damages of the risk*	**Mitigated Risk Score** *Risk score, after applying mitigation method(s)*
Management Risks					
Health & Safety	Low	Marginal - Risks associated with fabrication of frame	Medium (4)	1. Correct safety procedures will be followed where applicable 2. Appropriate PPE will be used where applicable 3. Implement lessons learned from first frame	Medium (4)
Budget Reduction/ loss of sponsorship	Low	Catastrophic - Reduction in available machine hours - Material/labor pricing fluctuations	High (10)	1. Maintain relationship with Saskatchewan Polytechnic as primary manufacturer 2. Schedule machine time with sponsors well in advance 3. Reduce or eliminate the number of future frames manufactured	Medium (6)
Loss of knowledge	Low	Critical - Capstone results and analysis lost	Medium (6)	1. Create hardcopy of report 2. All files saved in a cloud accessible by all members 3. Backup cloud files on external hard drive 4. Remain in contact with Capstone group	Low (1)

List Risks	**Probability** *The chances of that risk happening*	**Severity** *Level of impact of the risk happening*	**Risk Matrix Score** *Risk score, on the risk matrix*	**Risk Mitigation Method(s)** *A list of methods used to minimize the chances of the risk happening and/or the resulting damages of the risk*	**Mitigated Risk Score** *Risk score, after applying mitigation method(s)*
Design Risks					
Major Component Change	Medium	Critical - Major change to Frame - Increased workload lost time and budget - Analysis all or partially repeated	High (8)	1. Ensure sufficient lead times for components 2. Consider alternative component(s) in design to make changes easier 3. Use components with standard interface	Medium (6)

Appendix M: Raw Material Emissions

This appendix provides calculations for the method used to calculate the carbon emissions for the refinement of the raw materials used in manufacturing. The volume of each section of the stock material required was calculated and the mass found using the density of 6061 T6 aluminum. This mass was then combined with the average emissions per kilogram of aluminum produced.

Material properties in the following calculations were taken from CES Edupack (2017)



DESIGN CUBED - SATELLITE FRAME MANUFACTURING
CARBON EMISSIONS

SAMPLE CALCULATIONS

$\rho_{Al} = 2710\ kg/m^3$

CO_2 footprint $(f_{CO_2}) = 13.25\ kg_{CO_2}/kg_{Al}$

Example shown is for P100: Integrated Shear & Rail Panel

Stock dimensions: 101.6 × 228 × 19.05 mm

$V_{Al} = (101.6mm)(228mm)(19.05mm)$

$V_{Al} = 442.45 \cdot 10^3 mm^3$

$V_{Al} = 442.45 \cdot 10^{-6} m^3$

Find part mass:

$m_{Al} = \rho_{Al} \cdot V_{Al}$

$m_{Al} = (2710\ kg/m^3)(442.45 \cdot 10^{-6} m^3)$

$m_{Al} = 1.20\ kg_{Al}$

Find mass CO_2 produced per part

$m_{CO_2} = f_{CO_2} m_{Al} = \left(13.25\ kg_{CO_2}/kg_{Al}\right)(1.20 kg_{Al})$

$$\boxed{m_{CO_2} = 15.9\ kg_{CO_2}}$$

This can be multiplied by quantity of parts required & summed with other footprints for full frame CO_2 footprint.

In total Design Cubed estimates that 76.02 kg of carbon dioxide are produced to refine the aluminum required for the frame. The majority of this comes from the stock for P100s at 4.8 kg each. Table M-1 shows the results for carbon emission for each part.

Table M-1. CubeSat frame carbon emissions from refining stock material $_{CO_2}$

Part	QTY	Stock mass (kg_{AL})	Emissions (kg_{CO_2})
P100	4	4.80	63.55
P101	2	0.36	4.71
P102	1	0.53	7.06
P103	4	0.05	0.67
P111	4	754E-6	0.04

Appendix N: Rocket Launch Carbon Emissions

The following is an estimate of the carbon footprint of the frame resulting from launch into space via rocket. For this evaluation, a SpaceX Falcon 9 rocket was used, given that SpaceX currently holds a contract with NASA to resupply the ISS (NASA 2016). The total carbon emission of this rocket was estimated, and the weight fraction the CubeSat in a typical payload was calculated. A portion of the carbon emissions of the Falcon 9 was assigned to the CubeSat according to this weight fraction.

To find the Falcon 9 rocket's carbon emissions, use equation (1),

$$\mathrm{E_{F9}} = \mathrm{m_{fuel}} * \mathrm{r_c} \tag{1}$$

where E_{F9} is the carbon emissions of the Falcon 9, m_{fuel} is the rocket fuel mass, and r is the rate at which kerosene is converted into carbon. Once this is determined, the mass fraction of the CubeSat with respect to the rocket payload is determined as follows,

$$\mathrm{c} = \frac{\mathrm{m_{CubeSat}}}{\mathrm{m_{payload}}} \tag{2}$$

where c is the mass fraction of the CubeSat. Finally, the CubeSat's carbon footprint is calculated as a fraction of the rocket's emissions,

$$\mathrm{E_{CubeSat}} = \mathrm{E_{F9}} * c \tag{3}$$

The Falcon 9 rocket uses a form of Kerosene (SpaceX 2019), which produces 3 grams of carbon dioxide per gram of fuel (Engineering Toolbox 2009). The rocket uses approximately 518,500 kg of fuel (SpaceFlight101 2017) launching to orbit, so the emissions are,

$$\mathrm{E_{F9}} = 518{,}500\ \mathrm{kg_{kerosene}} * 10^{-3} \frac{\mathrm{kg_{CO_2}}}{\mathrm{kg_{Kerosene}}}$$

$$\mathrm{E_{F9}} = 5{,}185\ \mathrm{kg_{CO2}}$$

A recent resupply mission to the ISS had a mass of 2,250 kg (NASA 2019), this value will be assumed to represent the average mass for such a mission and used for this analysis. The CubeSat frame has a mass of 0.371 kg so the mass fraction is,

$$c = \frac{0.371\ \text{kg}}{2{,}250\ \text{kg}}$$

$$c = 165\text{e-}6$$

So, the following amount of emissions can be assigned to the CubeSat,

$$E_{\text{CubeSat}} = (5{,}185\ \text{kg}_{CO_2})(165\text{e-}6)$$

$$E_{\text{CubeSat}} = 0.854\ \text{kg}_{\text{Carbon}}$$

Therefore, the CubeSat will produce 0.854 kg of carbon dioxide in emissions as a portion of the payload onboard a SpaceX ISS resupply mission.

Appendix O: Risk Assessment Matrix

The following appendix will evaluate in detail all management and design risks identified through the capstone project. All efforts have been made to reduce risk levels to acceptable levels. Please reference Appendix L for detailed probability versus severity matrix and associated risk ranking explanations in addition to the following risk assessment matrix.

List Risks	**Probability** *The chances of that risk happening*	**Severity** *Level of impact of the risk happening*	**Risk Matrix Score** *Risk score, on the risk matrix*	**Risk Mitigation Method(s)** *A list of methods used to minimize the chances of the risk happening and/or the resulting damages of the risk*	**Mitigated Risk Score** *Risk score, after applying mitigation method(s)*
Management Risks					
Health & Safety	Low	Marginal - Risks associated with fabrication of frame	Medium (4)	4. Correct safety procedures will be followed where applicable 5. Appropriate PPE will be used where applicable	Medium (4)
Budget Reduction	Medium	Catastrophic - Reduction in available machine hours - Change in material selection - Material/labor pricing fluctuations	Extreme (11)	4. Document and confirm budget with client 5. Document and confirm budgeted machine hours with sponsor 6. Schedule machine time with sponsors well in advance 7. Agreement with client to remove prototype from scope if schedule or resources do not permit.	Medium (4)
Loss of Personnel	Low	Critical - Increase workload for remaining members - Loss of technical skill	Medium (6)	5. Consistent group communication 6. All files saved in a cloud accessible by all members	Medium (4)
Schedule Changes	Low	Critical - Increased workload Moving of deadlines (internal/external)	Medium (6)	1. Well defined project schedule early 2. Work proactively allowing for contingency time	Medium (3)

Design Risks					
Late Design Flaw	Low	Catastrophic - Complete redesign - Additional analysis and simulation lost time and budget	High (10)	1. Internal design freeze 2. Clear communication with client, sponsor, and within team 3. Early design selection and in-depth design review	Medium (6)
Scope Change	Medium	Critical - Design pivot - Increased workload lost time and budget	High (8)	4. Clearly defining initial scope 5. Design Freeze from client agreed upon prior to design work starting 6. Pre-arranged release of requirement to accept design changes after Sept 30th design freeze 7. Scope review with client, sponsor, and subject matter expert	Medium (6)
Environmental	Low	Negligible - Use cases after project hand off are out of scope - Environmental impacts of manufacturing prototype	Low (1)	1. Consider low environmental impact manufacturing methods/materials	Low (1)