POLYSAT CPX MODULAR PICOSATELLITE STRUCTURAL SYSTEM

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In Partial Fulfillment

of the Requirements for the Degree

Aerospace Engineering

by

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TITLE: PolySat CPX Modular Picosatellite Structural System

AUTHOR: Jason William Phelan

DATE SUBMITTED: March 23rd, 2007

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ABSTRACT

TITLE: PolySat CPX Modular Picosatellite Structural System

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This thesis focuses on a systems engineering approach to designing the next generation modular Polysat pico-satellite structure. By integrating certain design aspects that have been incorporated into previous Polysat structural designs that were determined by coordinating with design parameters of payloads and electronic components set by various other engineering disciplines (ie. electrical engineering, mechanical engineering, software engineering) working on the project, the modular structures design is realized. The need for a modular structural system that can be easily adapted to future revisions in payloads or components and also have the ability to be assembled into a single, double, or triple length pico-satellite is addressed. Design considerations for the new modular structure also take into account lessons learned from the design and manufacturing of CP2 on campus, the design and off campus manufacturing of CP3/CP4 structures, benefits of solid modeling and finite element analysis, and design changes to make manufacturing less costly and time conservative.

ACKNOWLEDGMENTS

I would like to take this opportunity to thank those who have made this thesis possible. Thank you Dr. P and the PolySat crew for giving me the chance to attribute many years of time and effort put into the PolySat project. Without the interaction with various other engineering disciplines and the hands on experience gained through the pico-satellite project, I would still be scratching my head asking myself “what does an aerospace engineer do?”

Special thanks to all who I work with at Omni Design Group, Inc. for keeping me financed through the better half of my college career. As a part time employee for many years it was extremely valuable to have such a flexible work schedule that was tailored around my class schedule and numerous sick days without any complaints (a.k.a. study for tests or work on labs and projects that were overdue.) It was also a great asset to have such a great working environment and a friendly and helping staff to top it off (school can sometimes be stressful). I am thankful for the opportunity that was given to me to gain management experience working full time while finishing my thesis work.

Thank you Scott from Lansco Engineering for working with me on the manufacturing portion of this thesis. It makes a project a lot easier when you have great communication with the manufacturer and all parameters are set forth prior to start of manufacturing.

Special thanks to Phil from Suspension Concepts. Without your hard work over a four day period to start and complete all of the small pieces, I would have had to postpone my defense and finishing of this thesis. You did an excellent job and met the desired tolerances and gave an excellent price for the amount of overtime you put in to make the deadline possible. You fit in well with the PolySat and CubeSat communities need for the extra time and hard work put into projects.

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1.0 INTRODUCTION

In 1999 a combined effort between California Polytechnic State University and Stanford Universities Space Systems Development Laboratory launched the beginning of the student supported CubeSat project. This set the standards for the picosatellite deployment device. The project was coordinated with the professional aerospace community to set up actual launch dates for low earth orbit vehicles and also set the boundary conditions for the dimensions, materials, and format for the picosatellite structural configuration and orientation to fit within the launch device. Since 1999 the CubeSat program branched out to over 60 universities and private companies (both domestic and international). Numerous satellite structural designs are based around the CubeSat standards. Each cube is unique based on the design parameters of the payload of the satellite and the skill and experience of the designer and the team of engineers and scientists working on it.

Cal Poly's first project to produce its own picosatellite was a branch off of the CubeSat project and eventually became known as Polysat. When designing structures for picosatellites, factors such as weight, ease of assembly and access to internal components, external and internal printed circuit board (PCB) mounting, payload mounting, connections between components and structural integrity are considered. Cal Poly's first satellite (named CP1, see Figure 1) design of the structures did not allow for easy assembly, did not utilize solar panels on all six sides, and did not have easy access to internal circuit board components.

The flaws in the structural design of CP1 sparked a revision to the structural design. The next generation PolySat satellite CP2 (see Figure 1) structures focused on three main concepts:

1. ease of access to internal components and mounting of internal PCB’s and any payload
2. ease of assembly and disassembly
3. utilization of all external faces for PCB or payload mounting.

The next generation CP3 satellite structure was a minor modification to allow the same mounting pattern for all external PCB’s thus making a structure that could have any orientation of external PCB’s and, if needed, the same PCB for all faces (see Figure 1). PolySat’s structures were beginning to evolve into a generalized structure system “kit” that contained a standardized C&DH and power board at a specific location with room and mounting space for a multitude of payloads.

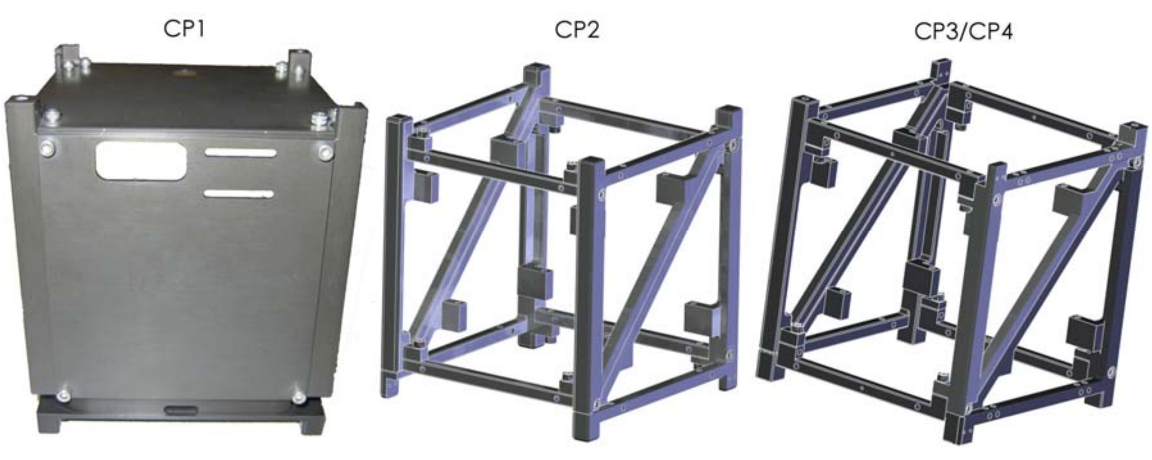

Figure 1 : CP1, CP2, and CP3 Structures

Other universities developed structures in unique structural configurations with much consideration of the specific payload or electrical components. NCUBE from the

University of Norway utilized a unique structural configuration where the internal PCB's were mounted vertically and stacked with a tethered mass payload at the center of the structures (see Figure 2). This leaves little room for modification and demonstrates the uniqueness of the structure designed around the interior components and payload. The University of Hawaii's Voyager structure consisted of primarily solid aluminum sides which gave no room for circuits on the back panels of any exterior PCB's (ie. solar panel boards) without the use of some form of standoff. This is another example of a structure that is tailored for a specific payload and allows little room for modification (see Figure 2).

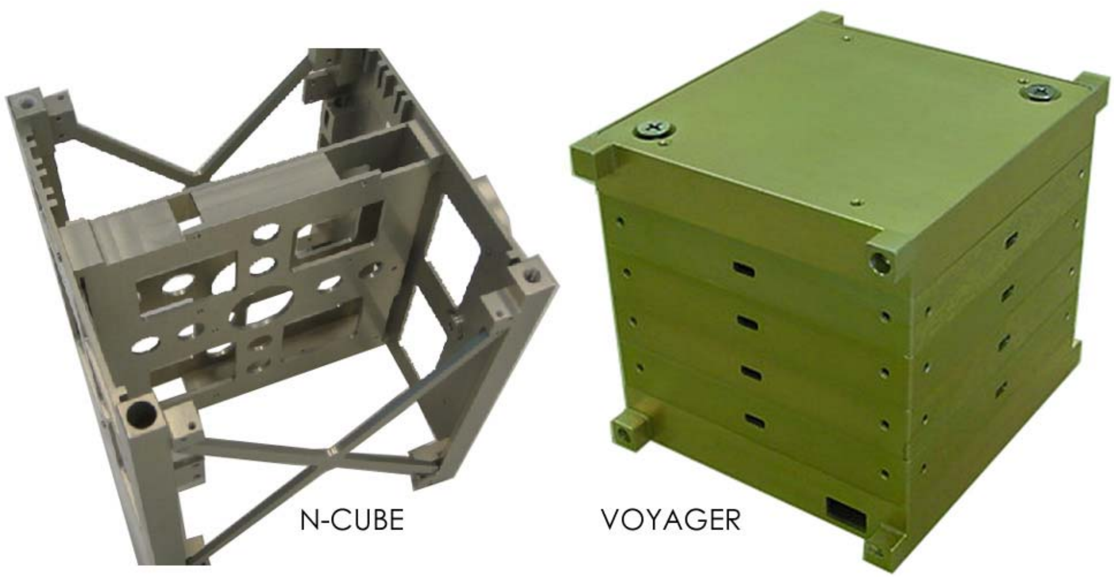

Figure 2 : University of Norway and University of Hawaii Structures

The CubeSat project's launch vehicle was named the P-POD which was restricted to a total of three single picosatellites per P-POD. For larger payloads, a double length or triple length picosatellite is needed. The University of Illinois ION Cube satellite utilized a double length structure. The structure was tailored to incorporate the payload. NASA's GeneBox triple length satellite structure was composed of solid machined panels triple in length. This is another example of a structure well tailored around the needs of the payload without much consideration of other payloads or configurations (see Figure 3).

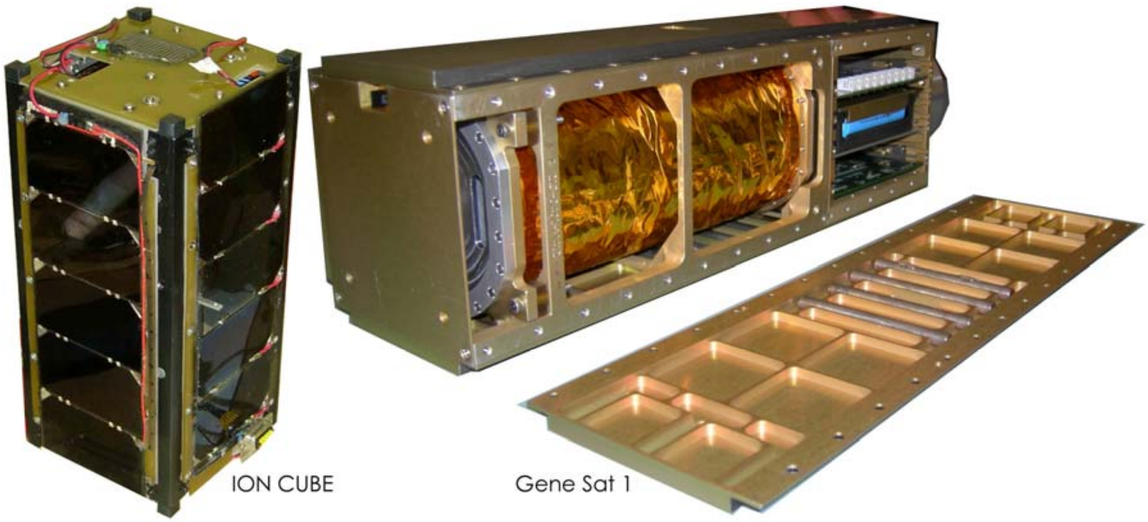

Figure 3 : University of Illinois and NASA Structures

With the CubeSat community increasing by more universities and more companies participating in picosatellite projects, the need for a generalized structure became apparent. It would require a multitude of configurations for mounting internal and external PCB's and also a wide variety of mounting locations for payloads to allow new developers in the CubeSat community to fabricate picosatellites faster without dedicating much time to structural design, fabrication, and testing. Since the introduction of double and triple length cubesats, the need for the generalized structure to be "modular" was one major evolution that the generalized structure needed to tackle[3]. This thesis addresses the need for the modular structures for picosatellites deemed CPX Structures (see Figure 4). The main focus on this next generation of PolySat structures is to be “modular”[3], meaning that the difference between a single, double, or triple assembly is simple by exchanging four end pieces with four connecting pieces is easy to assemble, and access to internal components is also simple. This structural design also focuses on the ability to retain previous PolySat CP2 and CP3 payload configurations and board layouts but also to adapt to new board configurations and payloads[4]. This design also focuses on reduction of manufacturing costs by implementing design changes to reduce the difficulty of machining and to limit the number of unique large components to manufacture[5]. Lessons learned from previous designs using solid modeling software led to the realization of the importance of designing virtual parts and assemblies on the computer to find errors in the design[6], and to run finite element analysis[7] programs to determine structural deflections and strengths with the design and to modify if necessary. Costs[8] for exporting the manufacturing of the structures are discussed along with targeted parameters for anodization compensation that were given to the manufacturer and the actual post manufactured and anodized structures tolerances and fit check within a P-POD[9]. To finish, the overall performance of the structures is tested with a vibration test to ensure the structure holds up to launch conditions[10].

Figure 4 : CPX Structures (Single, Double, Triple)

2.0 Structural Standards

2.1 CubeSat Standards

The CubeSat standard set the boundary conditions for the size, shape, and overall mass of the picosatellite structure. The structural design of all picosatellite structures is based on a 100mm by 100mm dimension to fit within the CubeSat Poly Picosatellite Orbital Deployer (P-POD) deployment device (see Figure 5).The P-POD is a rectangular shaped enclosure that has a spring in the center that is depressed as up to three single length satellites are loaded into it. When the launch vehicle is in the correct orbit it sends an electrical signal to the P-POD to release the screw that holds the door shut and the satellites contained within are expelled from the P-POD Single length structures are set at 113.5 mm in height, doubles at 227 mm, and triples at 340.5 mm. All tolerances are within ±0.1mm (±0.2mm and ±0.3mm vertically for a double and triple length.)

Figure 5 : Cubesat P-POD (Poly Picosatellite Orbital Deployer)

7075 or 6061-T6 aluminum is recommended for structures but other metals with similar thermal expansion coefficients are acceptable. These material restrictions are due to the tight tolerances (0.1mm) set on the structures and the P-POD and the possibility of temperature changes between the time of integration of satellites into the P-POD and actual deployment. If the thermal expansion coefficients of the structures materials are significantly different from those of the P-POD their rises a risk of the satellites being “stuck” in the P-POD and not deploying by satellite structures expanding more than the P-POD. The inner rails of the P-POD that are in contact with the rails of the satellites have an inner dimension of 100.7 mm which gives only a 0.7mm gap between the satellite rails and the rails of the P-POD therefore if the satellite tolerance is above 100 mm the less gap space there is for expansion, deflection, and fit.

The four edges, or rails, of the structure are to have a minimum rail dimension of 8.5x8.5mm with a minimum contact width of 6.5mm per side of rail (see Figure 6) and they must be hard anodized if made from aluminum. This will prevent cold-welding of the satellite structure to the P-POD rails during vibration and will also reduce wear and provide some electrical isolation between the satellites and the P-POD. Two spring separation mechanisms on opposite sides of the rail feet and at least one deployment switch are required.

The final restriction set on the overall satellite design is a maximum mass of one kilogram. One of the goals of the structural design of a picosatellite is to minimize the mass while keeping structural integrity to withstand vibration, gravitational forces, and all attachments to the structure. The less mass the structures occupies per the one kilogram restriction leaves more mass for various payloads and other components.

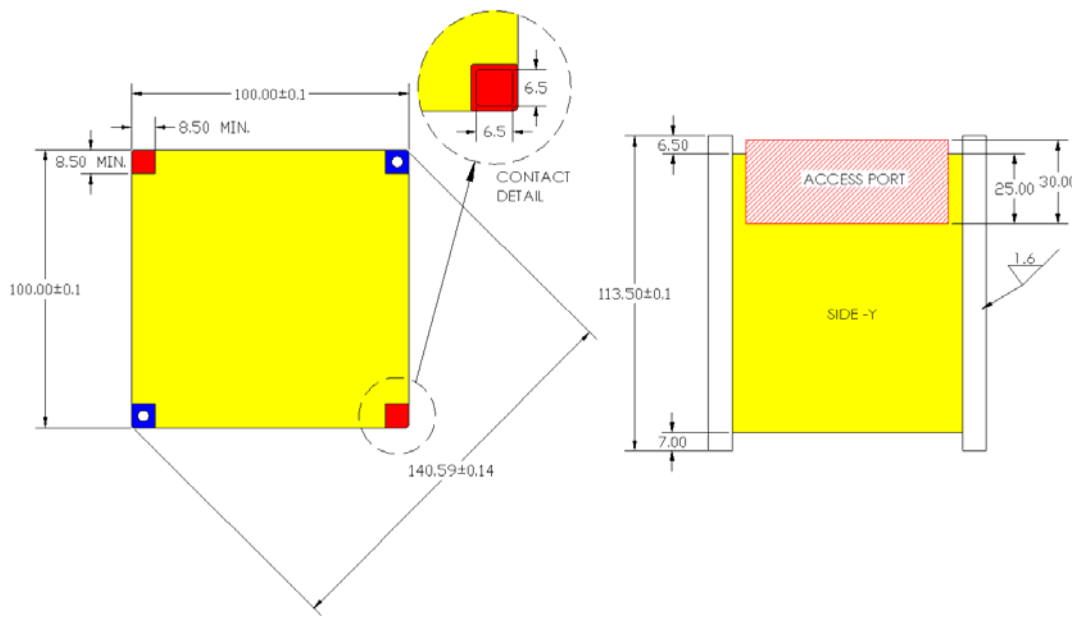

Figure 6 : Cubesat Standards for Picosatellite Structures

2.2 PolySat Standards

Part of the next generation structural design for PolySat stemmed the need for a modular design that would also be able to encompass previous boards, payloads, and clearances. Previous designs to include are:

1. C&DH (Command and Data Handling) and power board layout mounting configuration is to remain the same
2. the location of I/O (input/output) and RBF (Remove Before Flight) pin is to remain the same
3. external solar panel board hole mounting configuration is to remain the same

New changes to accomplish in design:

1. modular design (single, double, or triple assembly from modular pieces)
2. rigid in all axis while maintaining low structural mass

3. multitude of mounting options, payloads, and future modular revisions are to be easy
4. use easy to manufacture design strategy with off the shelf materials and cost efficient design

3.0 Modular Structures

3.1 Single Assembly

The first step in designing a structure that through a modular design could be a single, double, or triple length is to define the parameters for the single structure and then build off of that structure with a minimal amount of parts or changes. With design parameters discussed in section's 2.1 CubeSat Standards and 2.2 PolySat Standards taken into consideration (and discussed in later sections in detail), a single side that could be attached end to end to make the main cube structure for the satellite was designed. The Modular Side is attached to another modular side with two M3 screws, and the four sides form to make the main body of the structures (see Figure 7). Design considerations that molded the Modular Side design are discussed in sections 4.0 Evolution of Design Modifications, 5.0 Manufacturing Design Implementations, and 7.0 Finite Element Analysis.

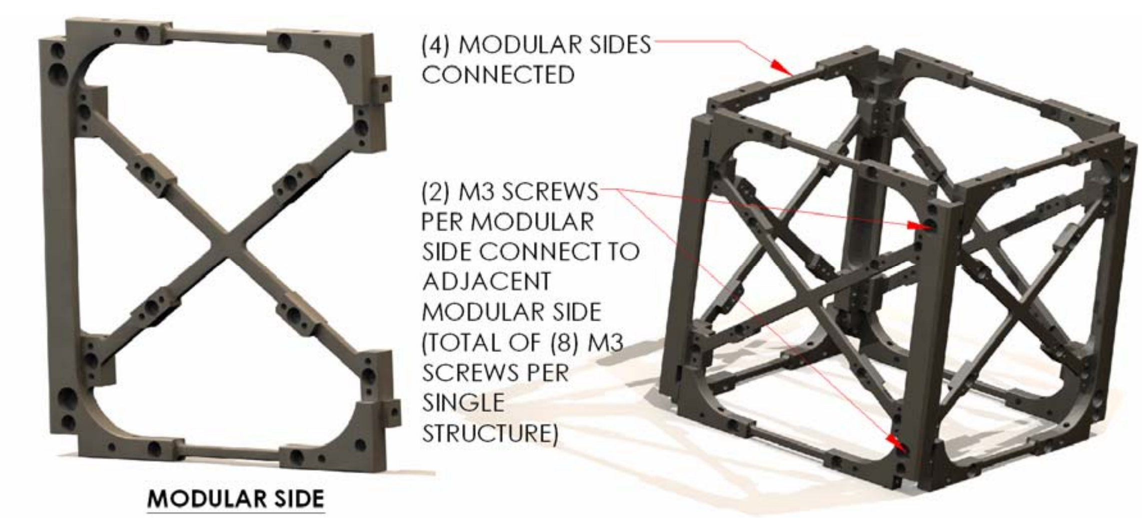

Figure 7 : Modular Side

To complete the rails of the single structure and to add modularity to the structural design, End Pieces were designed to attach to the top and bottom of the structure (a total of eight End Pieces (see Figure 8). Using the previous CP2, CP3, and CP4 specified spring plungers and deployment switches, the four top End Pieces were modified to allow the attachment of these devices. Two End Pieces have #6-32 tapped holes to allow the placement of the spring plungers while the other two End Pieces have the majority of the part milled off and two #0-80 tapped holes to allow two deployment switches per End Piece to be mounted to them. The bottom four End Pieces are mirrored versions of the top four End Pieces (non-modified top End Pieces). Each End Piece is attached to one Modular Sides with two M2 screws (see Figure 8).

Figure 8 : End Pieces (Spring Plunger, Deployment Switches, and Bottom)

To give the top and the bottom of the structures similar rigidity that the Modular Side gives the other four faces (discussed in section 7.0 Finite Element Analysis), an Upper/Lower Piece was designed to be mounted using two M2 screws mounted to each Modular Side (see Figure 9). The attachment holes to the Modular Side were positioned at the same horizontal location as the internal board mount holes to allow for the Upper/Lower Piece to be attached at these locations if needed (discussed in section 4.3 Internal Board/Payload Mounting).

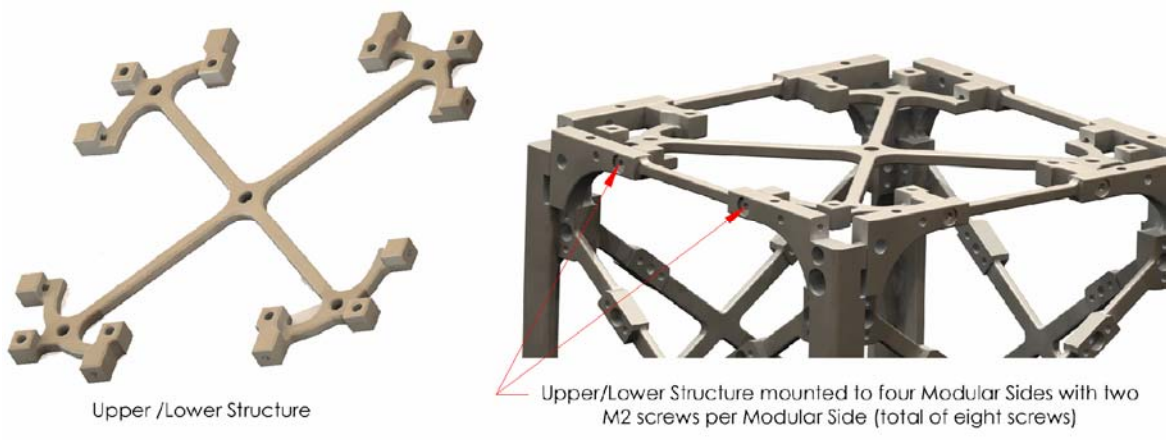

Figure 9 : Upper/Lower Structure

To keep the CP2 and CP3/CP4 internal board mounting hole configuration and location three internal board mounting structures were designed. The Internal Board Mounts are removable and allow for the end mounting holes of the internal circuit boards to be mounted in the same position as previous designs but also allows for four of these to be used in future internal circuit boards to allow symmetrical mounting holes at the end corners of a 82 mm X 82 mm board. Both the Internal Board Mount and Left and Right Internal Board Mounts are attached to the Modular Side structure with one M2 screw and two M1.5 dowel pins (the dowel pins are attached to the board mounts and aligned into holes in the Modular Side (see Figure 10).

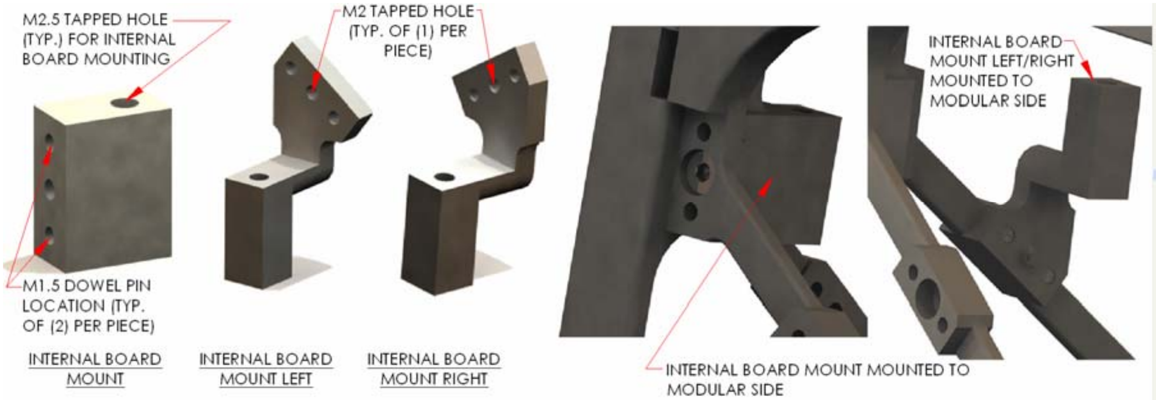

Figure 10 : Internal Board Mounting Pieces

3.2 Double and Triple Assembly

Making a double assembly (or triple) is easily accomplished by removing the bottom End Pieces of one structure and the top End Pieces of another and inserting four Interconnect Pieces as a replacement. These four Interconnect Pieces are double length End Pieces with attachment screw holes on both ends to allow two single structures (or add an additional third to make a triple assembly) to be attached to each other (see Figure 11). Since the assembly of a double or triple is accomplished by replacing four (or eight for a triple) End Pieces with Interconnect Pieces, CubeSat developers who are indecisive on the size of a payload or have plans for future double or triple length satellites now have a modular structural design that allows for expansion and progression to double or triple length structures without the need for extensive design work and manufacturing for double or triple length satellite structures.

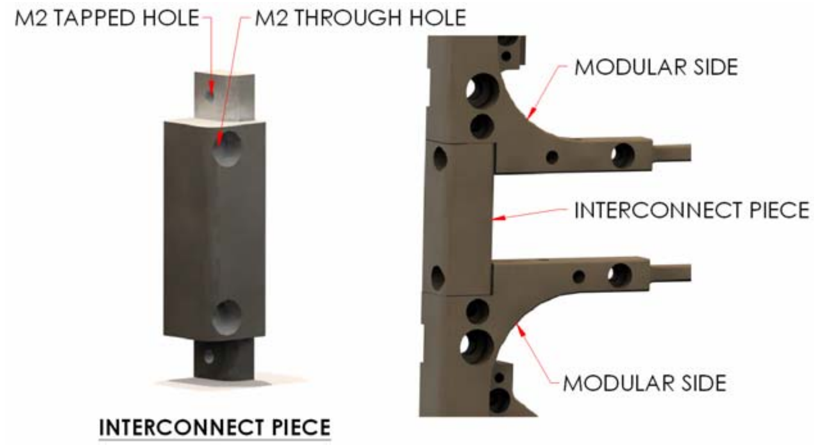

Figure 11 : Interconnect Piece

With all the pieces together it is easy to choose between assembly of a single structure up to a triple length structure by using all of the previously described part. To visualize a triple assembled satellite structure with individual parts called out see Figure 12.

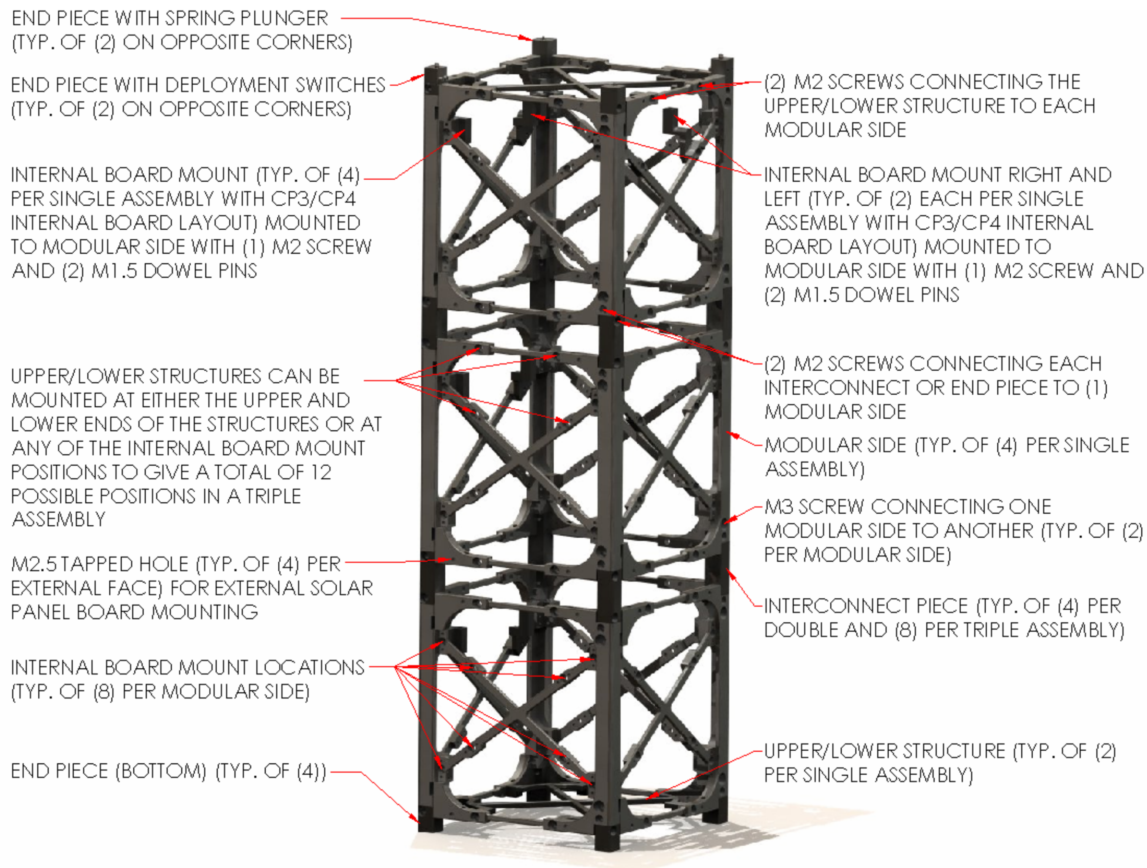

Figure 12 : Triple Assembly of CPX

4.0 Evolution of Design Modifications

4.1 Assembly and Access Evolution and Modifications

One goal in structural design for pico-satellites is to design structures that are easy to assemble and provide easy access to internal and external components. The evolution of the PolySat structures has gone from difficult to assemble and access internal components (CP1) to easier to assemble and access internal components (CP2, CP3, CP4 and CPX).

CP1 structures consisted of three different main components and five aluminum plate sides which were easy to assemble with no internal or external components mounted but difficult when assembled with the components (see Figure 13). The bottom component that housed the antenna route was attached to two side support panels via two #4-40 screws per side panel that were accessed internally. By having to place screws internally to attach the bottom antenna route structure, it was difficult to place the connection screws and tighten them especially with any internal components installed. The internal circuit boards were mounted via screws that were mounted internally to one of the side panels. When the side panel was not assembled into the entire structure it was easy to attach the circuit board but when the structure was fully assembled it was necessary to disassemble the entire structure to gain access to the internal board mounts. This would have been a workable design if internal boards did not have to be replaced or repaired after full assembly was completed, but with experimentation and implementation of design changes in circuit boards and problems that arise with circuit boards assembled and designed in the lab the need for an easier access to internal components for replacement and repairs was quickly realized.

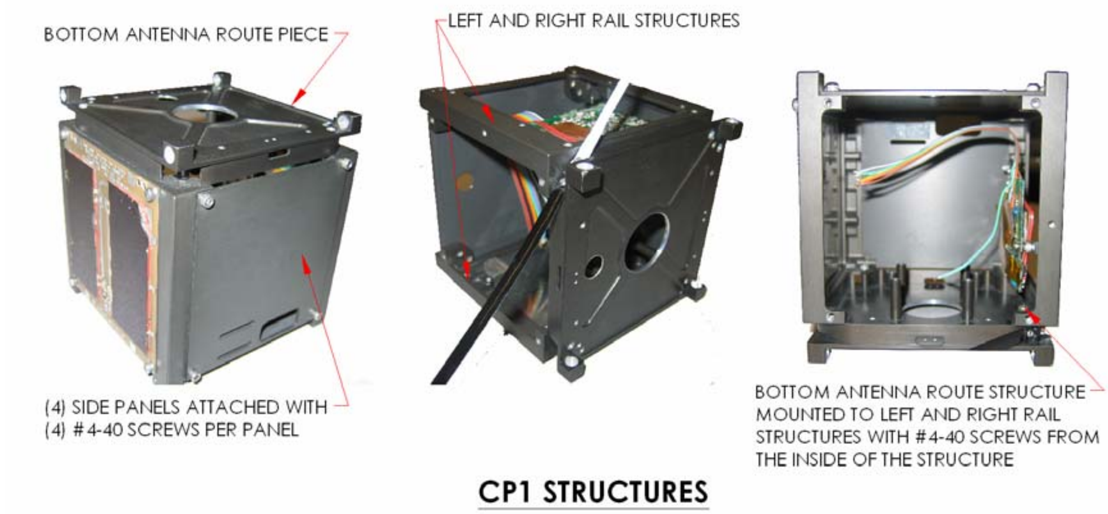

Figure 13 : CP1 Structures

The difficulties with the CP1 structural layout instigated a need for a redesign of the structures and thus the CP2 “clamshell” design concept was proposed. The new clamshell design allowed an easy assembly of the structural components by having the fastener screws accessed from the outside of the structures rather than from the inside. Access to the internal Command and Data Handling (C&DH) board and Power boards were simple by having the upper and lower clamshell halves separated. Each half consisted of two triangular side pieces with two crossmembers connecting the triangular pieces together (see Figure 14). This also allowed access to the payload on the opposite half of the structures and allowed easy routing of necessary cables and wires to solar panels and internal components. When internal boards and components needed to be accessed for replacements or repairs, the ease of disassembling the two clamshell halves proved a valuable design change.

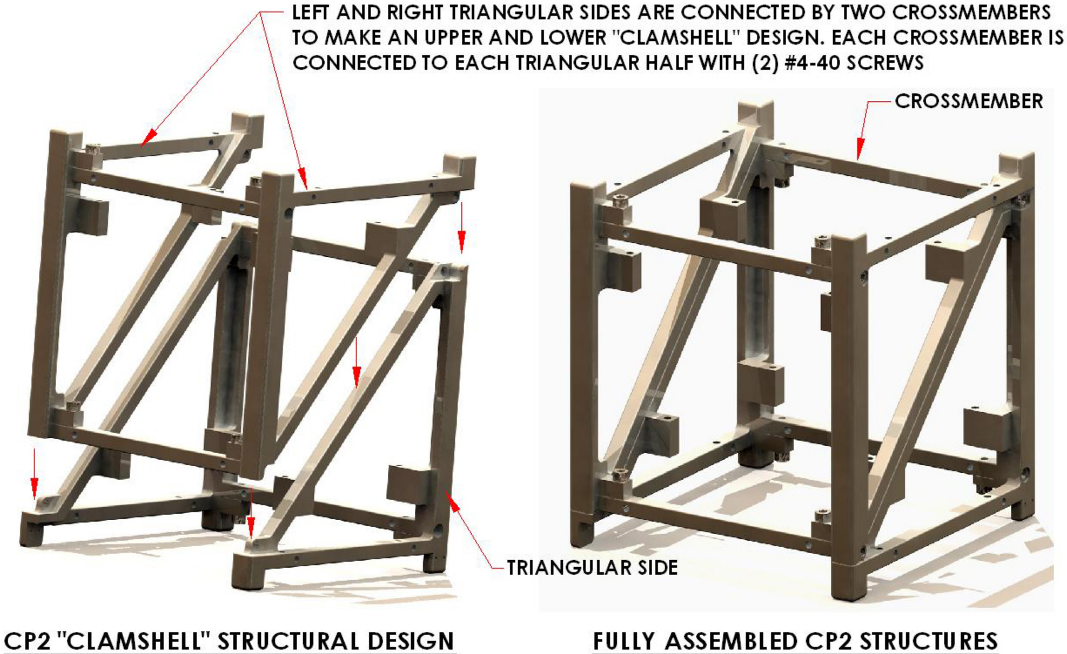

Figure 14 : CP2 Structures

The internal boards and payloads were attached via four mounting screws per board or payload in four fixed positions (see Figure 15). When the two halves were apart, the initial design used a 1/8” diameter through hole and one #4-40 screw with a nut per connection. After a vibrational test of a prototype, the nut and screw came loose. A design change to the mounting post was needed and the 1/8” diameter through holes were changed to #4-40 tapped holes. Since the C&DH and power boards were mounted back to back, it allowed easier mounting by allowing each board to be mounted separately. This mounting design change was quicker than compared to having to hold both boards in position and mounting at least two screws with nuts to hold them into place (see Figure 15).

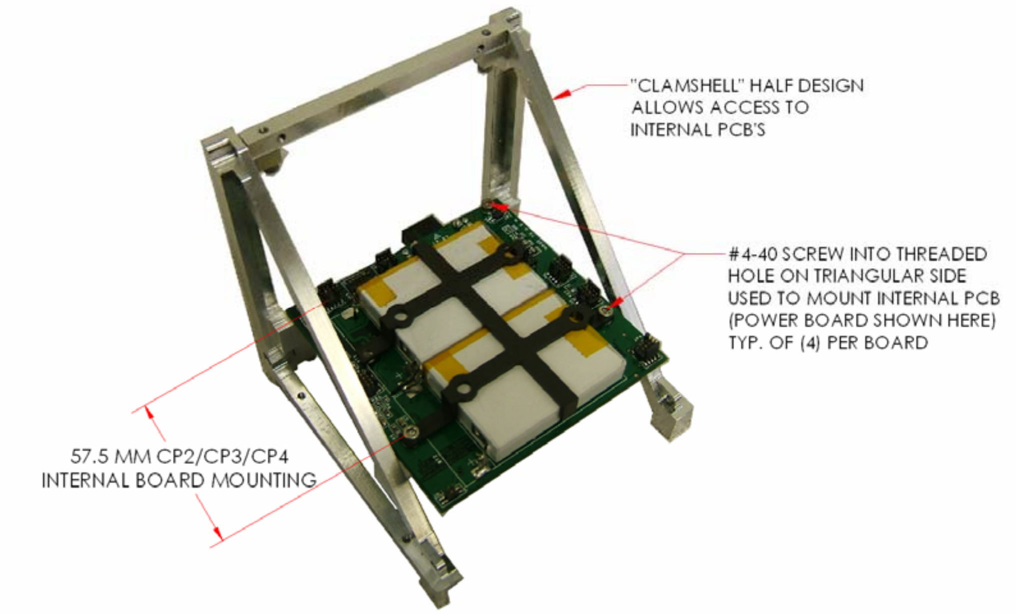

Figure 15 : CP2 "Clamshell" Design and Internal Board Mounting

With the success of the CP2 design and the need to produce a working structure for the next generation PolySat satellite, a few small modifications were made for the CP3/CP4 structural design to make the external board mounting “modular”. Previously, four external solar panels had the same hole mounting configuration while the front and back solar panels had a different hole mounting configuration. The CP3/CP4 structural redesign consisted of changing the crossmember configuration to allow the same hole mounting configuration on all six external faces of the cube (see Figure 16). This would allow the design of one external solar panel board for five faces and one external solar panel board with antenna route for the sixth face allowing any board to be placed in any one of the six sides of the cube. Access to the internal components of the structure remains the same as the CP2 clamshell design.

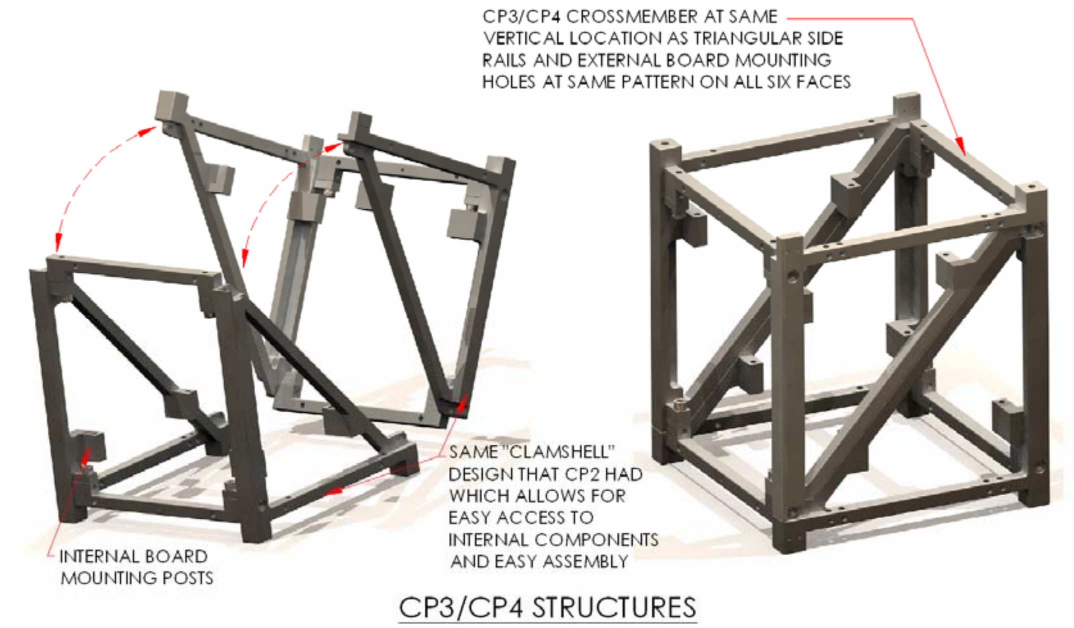

Figure 16 : CP3/CP4 Structures

This generation of structures needed to incorporate the same design changes that allowed easy access to internal components along with the same mounting configurations of the previous C&DH, power board and external solar panel boards. The CPX structures maintain a semi-clamshell design by having a variety of ways to be assembled and disassembled making access to the internal boards easy. The design changes make the structures modular, easier to manufacture, structurally rigid in all axis, and offer a multitude of payload mounting positions (all discussed in later sections). The assembly and disassembly of the new CPX structures has comparable ease of access and assembly to that of the previous CP2, CP3, and CP4 “clamshell” design (see Figure 17). Two Modular Side structures along with one Upper/Lower Support structure are assembled with four End Pieces to make up one half of the “clamshell” structure. One side of the internal board mounts are mounted to the modular side while the other side of internal board mounts can either be mounted between the internal boards (C&DH and power boards shown here) or to the other half of the structure if there is space to tighten the internal board mounting screws (slide the C&DH and power boards in to the internal board mounts and then mount to the internal board mounts with screws). The Internal Board Mount mounting screw was designed to be accessed from the exterior of the structure to allow the Internal Board Mount structures to be mounted to the internal boards and then released from the Modular Side when taking apart the structure for repairs or modifications to the internal components (see Figure 17).

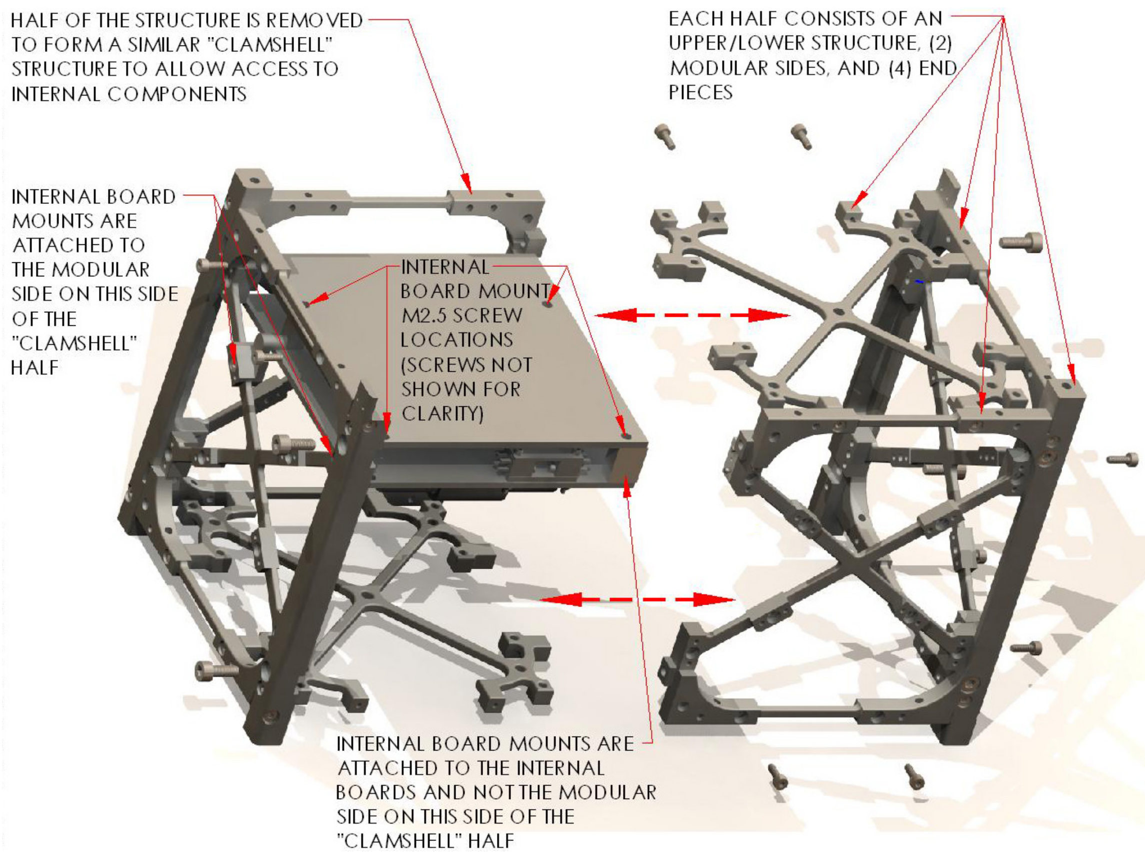

Figure 17 : CPX "Clamshell" Assembly

Any one Modular Side can be removed easily with an upper and lower End Piece attached to it due to slots in the main M3 connecting screw areas located at the rail end of the Modular Side (see Figure 18). This feature was added for any future payloads or any internal components that needed access from only one side for maintenance or connections. The C&DH and power board can be secured in place with all internal board mounts and three modular sides assembled together while leaving the fourth modular side off for payload attachment to internal mounting points. The internal boards can also be slid horizontally into the structure through the open side over the internal board mounts. This assumes there are no circuits on the internal board within 5 mm of the edge of the board and the board is carefully slid in without contacting the Internal Board Mount Pieces. These previously discussed guidelines for access and assembly also apply to double or triple assemblies.

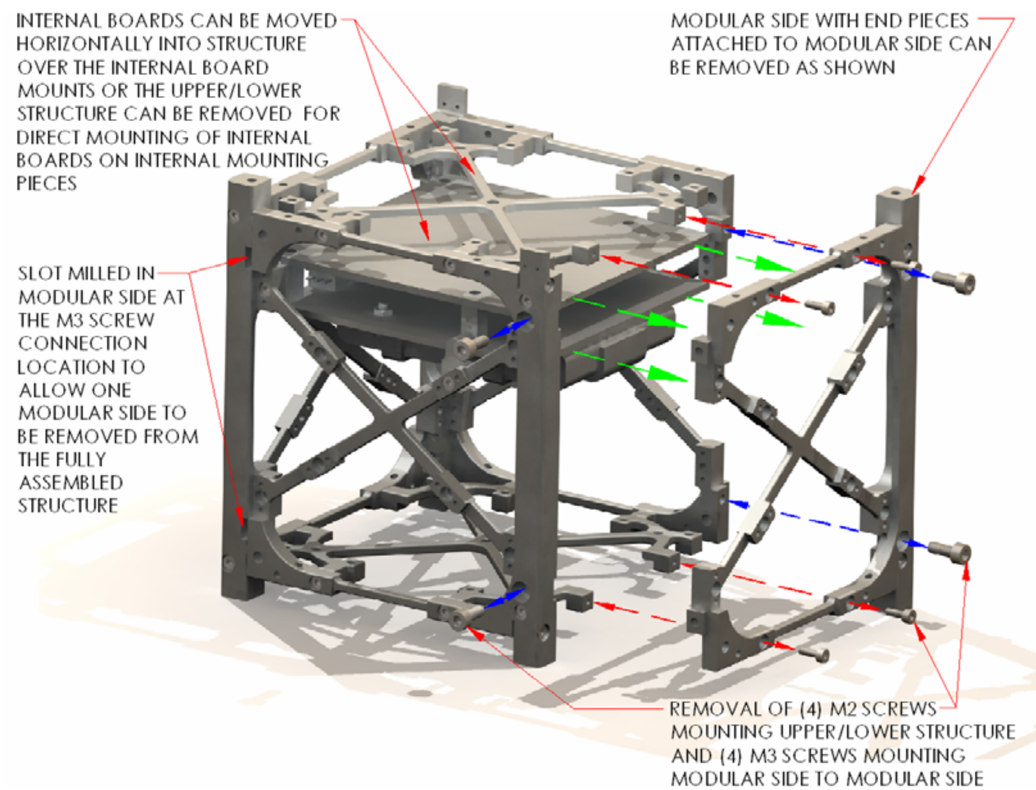

Figure 18 : CPX One Side Removal Access

4.2 External Board Mounting

Keeping the same external solar panel board mounting configuration with minimal changes in clearances on the back side of the solar panel board was one factor in external board mounting configuration for the new CPX structural design. As seen in Figure 19, the same offset hole configuration that was used in the CP3 and CP4 structural design has been implemented into the new design. All six sides incorporate the same hole mounting configuration which allows for any external board to be mounted to any side.

Slight modifications to the overall clearances on the back side of the solar panel boards from the CP3 and CP4 designs are necessary for the new CPX configuration. As seen in Figure 19, the actual direct contact between the structures and the backside of the solar panel boards has significantly been reduced by approximately 30% which gives more locations for surface mounted electrical components on the back side of the solar panel boards or any externally mounted boards. On previous PolySat structural designs, there were three different clearances associated with external solar panel boards. All had different clearances and all sides were integrated into the clearance zones. The new CPX design has two different clearances and are combined as one clearance shown in Figure 19. If all external solar panel boards and any other board or payload attached to the outside follows the clearance guidelines in Figure 19, then any board or payload can be mounted to any external surface of the structures unlike CP2 and CP3/CP4 structures which had different clearances for the front and back boards compared to the rest of the solar panel boards.

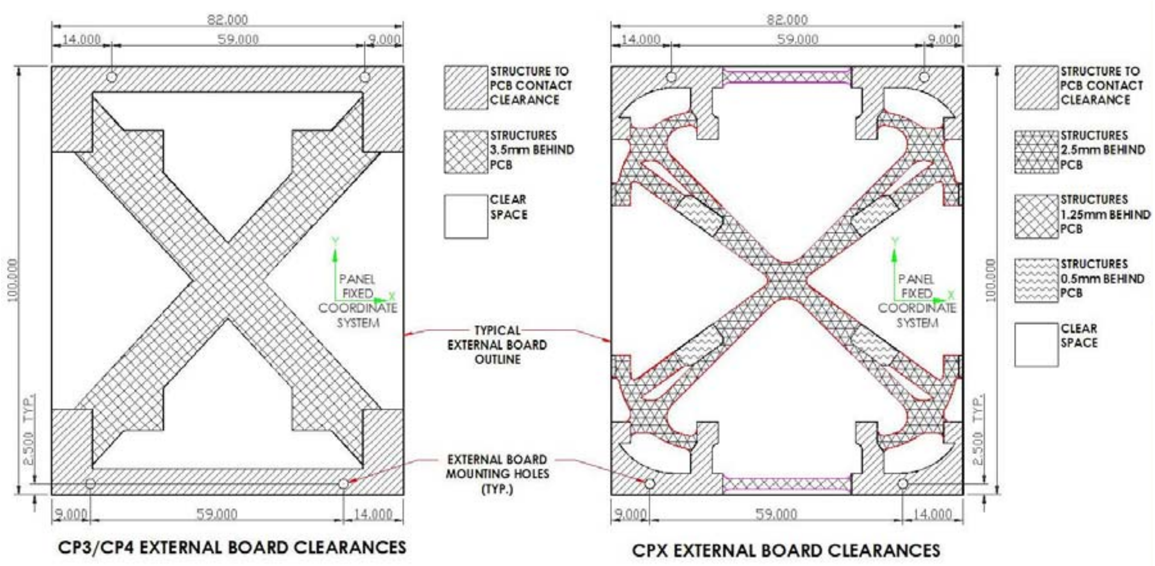

Figure 19 : External Board Structural Clearances

4.3 Internal Board/Payload Mounting

Integration of the existing C&DH and power boards at the existing CP3/CP4 mounting location was a design integrated into the new CPX structures. Because of the previous clamshell design with fixed internal board mounting locations, the internal board mounting holes were not symmetrical on the 82mm x 82mm C&DH and power boards. To keep this mounting hole configuration but also allow for future boards with symmetrical hole mounting configurations, modular internal board mounting pieces were designed (as seen in Figure 10 : Internal Board Mounting Pieces).

The internal board mounting pieces consist of three different parts. All are connected to the modular side with one M2 screw and kept from rotating with two 1.5mm stainless steel dowel pins. The dowel pins are also used to align the internal board mounts with the structure. For future modified C&DH and power boards that want to utilize a symmetrical mounting hole configuration (holes near the end corners of the board) the use of four of the rectangular mounting pieces instead of the two with left and right center mounting pieces would be used. Because of the symmetry of the internal board mounting piece hole locations on the modular side, the existing internal boards and payloads can be mounted either in their intended orientations or 180 degrees rotated facing the opposite direction (see Figure 20).

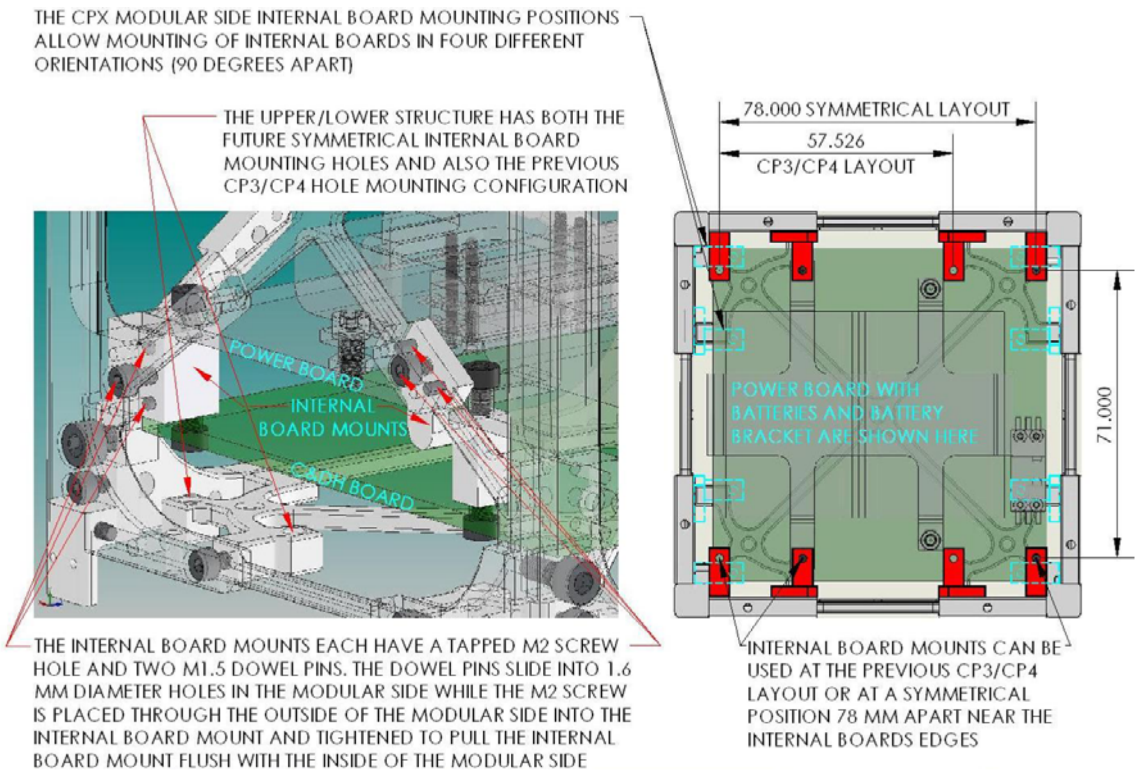

Figure 20 : Internal Board Mounting Configurations

Existing payloads that utilize the existing mounting locations from the CP3/CP4 structures can be mounted in the same location on the new CPX structures, but since the internal board mounts are removable, future payload mounting has a multitude of mounting options and locations. Since payload mounting brackets are customized to the payload, future payload mounting brackets can utilize any of the available four M2 screw holes per modular side (not counting the four at the C&DH and power board mounting locations) for a total of 16 screw mounting locations (see Figure 21).

To make future internal board mounting and future payload mounting easier, the upper/lower support structure was modified to allow the mounting of the existing internal board hole configurations along with future symmetrical mounting configurations (see Figure 21). The upper/lower support structure can also be mounted at any of the internal board mounting locations which gives it a possible four mounting locations on a single structural assembly and twelve locations on a triple assembly.

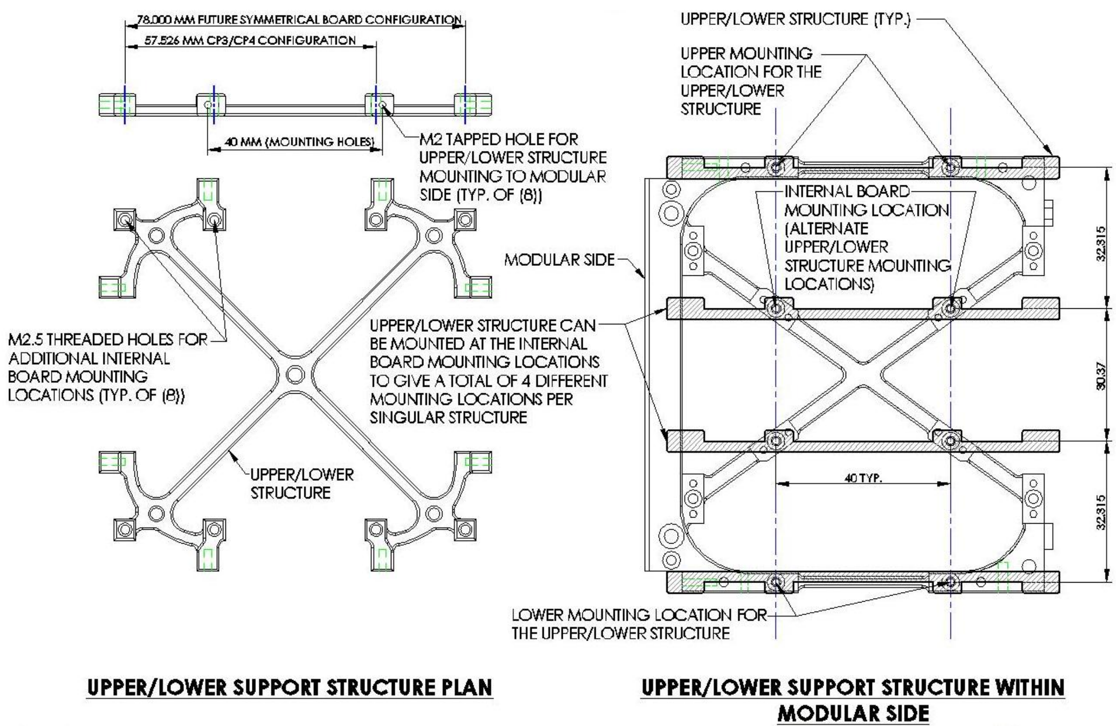

Figure 21 : Upper/Lower Structure as an Internal Board Mount Component

4.4 End and Interconnect Pieces

Initially, the End Pieces and Interconnection Pieces were designed to be made from 8.5mm x 8.5mm bar stock for ease of mass production and lower cost. On previous structural designs, any modifications to the feet of the rails (ie. a change in deployment switches or spring plungers) would call for the redesign and remanufacturing of the entire triangular side of the structure. Since the End Pieces are small and can be produced in large quantities, future modifications to allow for a multitude of mounting options (other than P-POD deployment or revisions in the P-POD) will be easy to initiate and will be cost efficient.

The Interconnect Pieces are designed the same at the bottom End Pieces but twice the length with connection screw holes and tapped holes at both ends (see Figure 22). This piece was designed not only to connect a double or triple length satellite structure together, but also to have enough area in the central portion for any payload or mission modifications necessary. The central 14mm space between the connection screw holes can be removed and/or modified and replaced with future experiments such as separation joints to make a tethered satellite with two equal sized structures at each end (a double separated) or a single structure attached to a double. The Interconnect Piece could be modified to make an extension joint for a payload that could extend the length of the satellite for more surface area. Overall, since the Interconnect Piece is small and has space to be modified, future modifications to the piece can be determined by the payload and mission of the satellite.

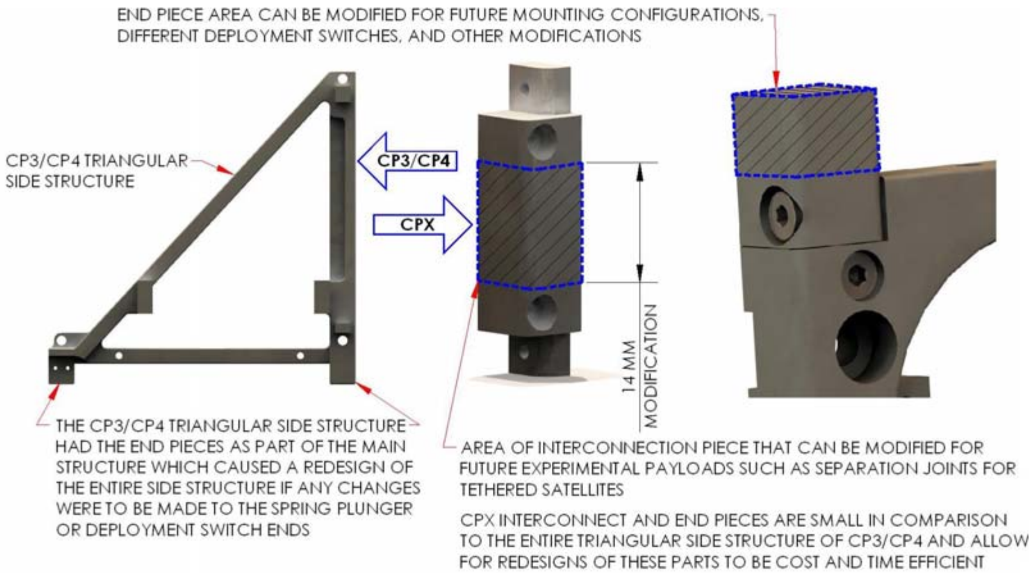

Figure 22 : Ease of Modifications to End and Interconnect Pieces

4.5 Structural Rigidity in All Axis

The CP2 and CP3/CP4 clamshell structural design partially addressed the issue of adding diagonal rigidity by having a diagonal brace along the sides where the two halves are assembled (see Figure 23). This works well in one direction of loading but lacks rigidity in others. Another flaw with this structure is seen on the front, back, top, and bottom sides that have no diagonal bracing at all. Since the triangular sides of the structure are connected with only four crossmembers, there is no diagonal bracing which can cause some of the torsional load to be translated through the internal and external circuit boards. Depending on how the P-POD is mounted within the launch vehicle, there might be a significant amount of load applied horizontally across the direction without any diagonal bracing.

To make the structures rigid in all axis to reduce any deformation due to stresses during launch, the structural design for CPX integrated diagonal cross bracing into the design (see Figure 23). As later seen in section 7.0 Finite Element Analysis, diagonal cross bracing on the Modular Side reduces significantly the amount of deflection in all directions compared to the previous CP2 and CP3/CP4 structural designs that had notable differences in stress and deflection in reference to different axis and different loading conditions.

To complete the top and bottom rigidity the Upper/Lower Support pieces were designed to mount in line with the top rails and similar to the Modular Sides. This caused a significant reduction in deflection caused by loads in the X-Y direction (See Figure 23 for clarity of directions). Refer to section 7.0 Finite Element Analysis for more details of the deflection reduction predictions using a finite element analysis program while using simplified models of the structure.

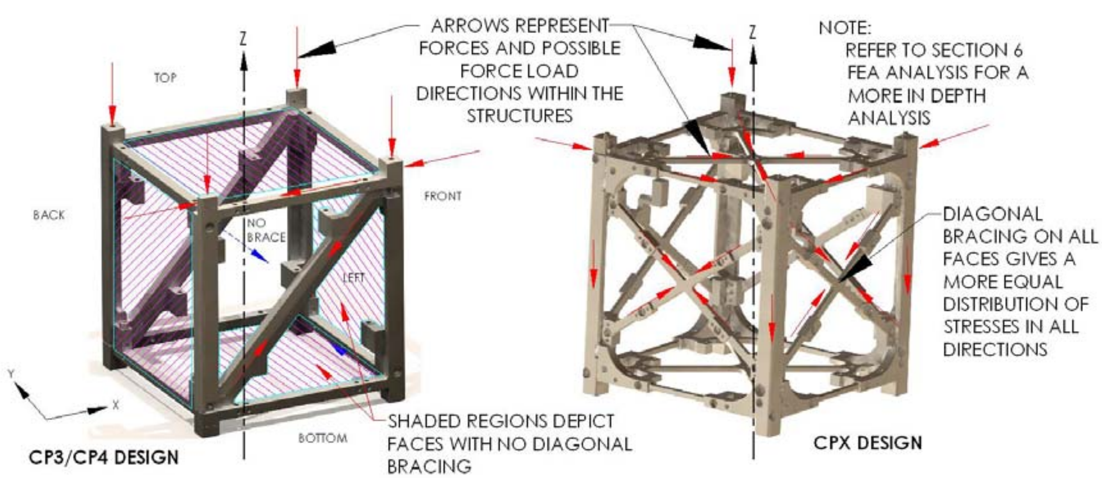

Figure 23 : Structural Rigidity in All Axis

4.6 Structural Mass

Another goal of the structures was to reduce the amount of structural mass. By reducing the structural mass, the percentage of the overall one kilogram mass restriction for a single pico-satellite is increased for payload and internal components. These structural mass comparisons were based off solid model CAD designs with mass properties per material. They do not take into account mass differences caused by defects in materials, slight differences with tolerances of machined materials, anodization, mechanical staking compound, or impurities of materials (7075 aluminum structural components and cast stainless steel for screws with properties of each material listed in Section 6.) Minor modifications were made to CP2 to reduce the amount of structural mass to approximately 178 grams (see Table 1) when assembled with all structural assembly screws. With the addition of a slightly larger crossmember to allow the same circuit board hole mounting profile on all six exterior faces, the structural mass was increased by a gram between CP2 and CP3/CP4 structures.

In order to make the CPX structure modular (removable and replaceable End Pieces) and also structurally rigid in all axis (the addition of the Upper/Lower Support Piece) the overall structural mass was increased 11.5 grams from the previous CP3/CP4 design. More than half of this difference in mass is due to a significant increase in the number of stainless steel screws used in the CPX structures (a total of 44 various metric screws including four for one set of internal board mounts) compared to the previous CP2, CP3/CP4 structures (16 #4-40 screws holding the structure together.) Without the difference in mass caused by the screws there is only a five gram difference between the previous CP3/CP4 structures and the new CPX structures. To account for an almost similar mass between CP3/CP4 and the CPX structures is seen in the previous structural designed cross bracing along the triangular halves in the CP2 and CP3/CP4 structures that used a significant amount of extra mass without addressing the issues associated with rigidity in all axis and directions. Refer to Table 1and Table 2 for structural mass comparisons between previous designs and also for the individual masses of individual parts for CPX.

Table 1: Structural Mass Differences for Single Satellite

	CP2	**CP3/CP4**	**CPX**
Mass with Screws (grams)	178.31	179.58	191.08
Mass difference between CPX	-12.77	-11.50	

Table 2: CPX Component Masses

Structural Item	**Mass (grams)**
Modular Side	31.32
Upper/Lower Structure	12.21
End Piece with Cherry Deployment Switch	1.31
End Piece with Spring Plunger	2.29
End Piece	2.39
Interconnection Piece	4.93
Mounting Bracket Base	1.15
Internal Board Mount Left/Right	1.35
M2x5 (stainless steel)	0.270
M2x6 (stainless steel)	0.291
M2x8 (stainless steel)	0.334
M3x8 (stainless steel)	0.884

5.0 Manufacturing Design Implementations

5.1 In House Manufacturing Design Lessons from CP2

Lessons learned from manufacturing CP2 on campus led to many design changes for CPX structures to minimize the cost of manufacturing and also minimize the complexity and difficulty of manufacturing multiple parts. Since the previous structural designs consisted of left and right upper and lower triangular pieces (four unique large structural pieces) and four identical crossmembers, manufacturing became costly per single structure due to the time needed for manufacturing four different large structural pieces.

Manufacturing of CP2 structures was designed to be made on campus in the Aero hanger using tools and machinery available to students and also parts and materials easily ordered over the counter (the majority from McMasterCARR.com). The majority of all manufacturing was done using a HAAS CNC machine and writing the G&M code for the machining procedures by hand. This was done at this time due to the lack of experience using code writing programs such as MasterCAM, but was also done to acquire a feel for machining first hand and understanding the basic concepts of manufacturing small parts. In an attempt to make CP2 structures simple to manufacture, the construction of a jig that was made from a large solid block of aluminum was constructed (see Figure 24). The structural triangular sides of CP2 were milled down half of the way (8.5mm) on one side then turned over using the same coordinate system origin and the other side finished. Symmetrical #8-32 screws (four per triangular piece) with two symmetrical dowel pins per triangle were used to hold the rectangular solid aluminum prepared parts down. When the back side of the structures were close to finish milling (1.5 mm of material left), #4-

40 screws were placed through the screw holes on the structure and used to secure the triangular pieces down when fully milled out.

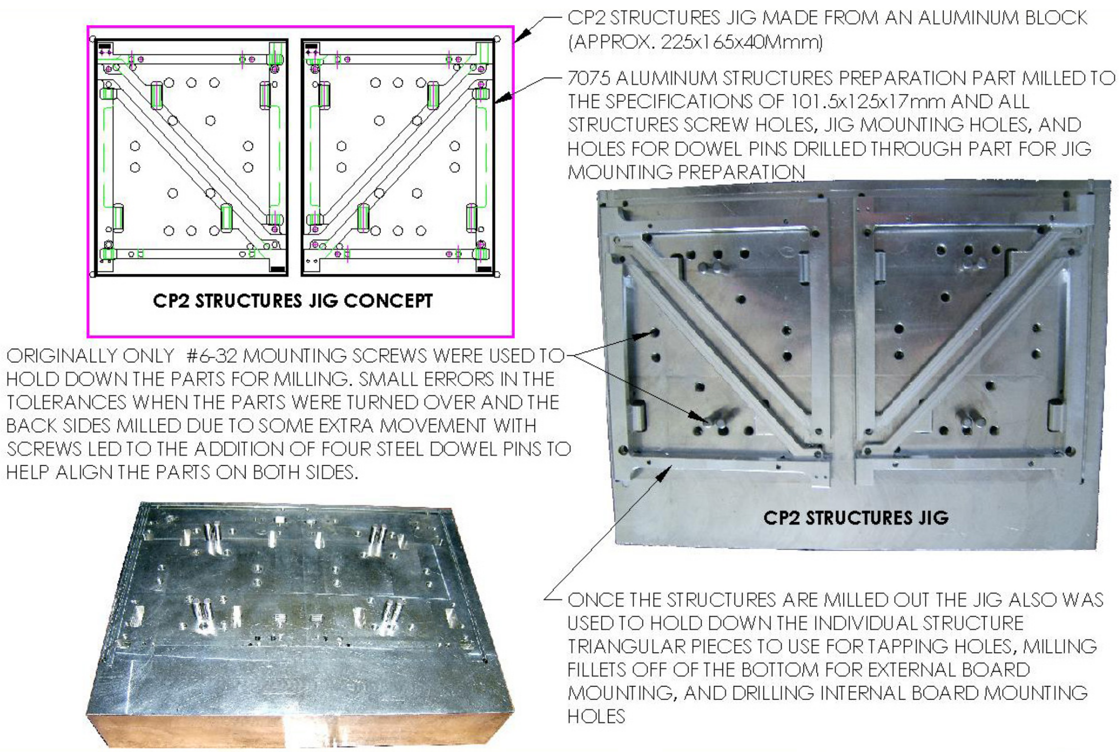

Figure 24 : CP2 Jig for Manufacturing

One main problem that occurred during manufacturing of the CP2 structures was eighth inch end mill depths in conjunction with the tools available at the aero hanger. Initially, the upper crossmember support post area had an eighth inch end mill procedure that was initially 11 mm down from the back face of the structure but positioned directly next to a 5mm x 5mm crossmember support post. A regular eighth inch end mill using the end mill collet and support chuck (supplied at the aero hanger) could not be used due to the end mill support chuck having interference from the crossmember support post. Also, the adjacent #8-32 manufacturing support screws, at depths greater than approximately 9.5 mm, would rub on the adjacent parts and not be able to proceed to the necessary cutting depth without damaging the part and the tool (see Figure 25). When the 1/8" end mill was extended to greater than 9.5 mm from the holder it would chatter (vibrate out of the cutting direction) and cause uneven milling and distorted corners. These problems led to a design change. The CP2 structure was modified to have in the area close to the upper crossmember support post only depths of 9.5 mm milling maximum (actually only 8.5 mm).

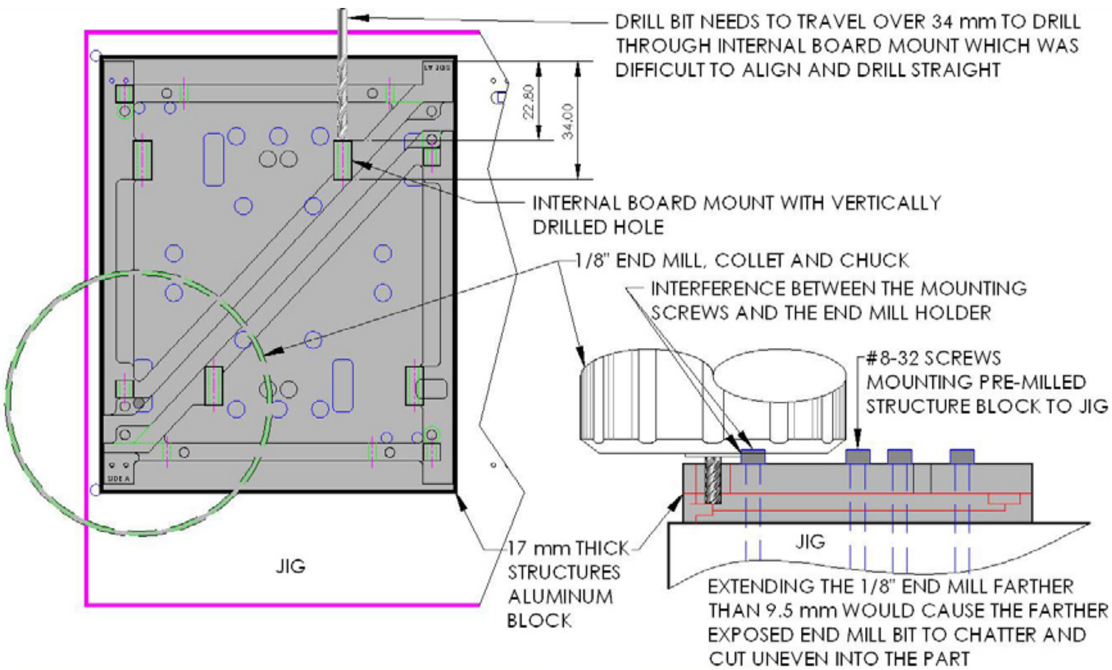

Figure 25 : CP2 Milling and Drilling Problems

One last problem with the CP2 mounting of internal boards was tolerance fitting due to the tight clearances the #4-40 screws had within the holes through the power boards and C&DH boards. Since the drill needed to travel from the bottom triangle of the structure 22.8 mm prior to reaching the internal board mounting post, it was difficult to start the drill in exactly the correct position. Also, since this hole drilling was done after the milling procedures, the internal board mount structure had a tendency to deflect slightly under the pressure of the drill bit. The holes were not always directly centered on the internal board mounting post and had to be drilled out and slotted. ¾” long #4-40 screws with nuts replaced the usual #4-40 screw with tapped holes. This introduced a problem found in previous vibration tests. Screws with nuts showed that a nut is more likely to vibrate loose during a vibration analysis test compared to a screw in a tapped hole although both were mechanically staked with mechanical staking compound. Because of some errors in the hole drilling for the tapped #4-40 holes on the internal board mounts for CP2 an elaborate scheme for applying pressure to the sides of the structures while tightening the structural screws was used to bring the overall width tolerance to within the ±0.1 mm tolerance (see Figure 26). This caused the undesirable use of the internal circuit boards as structural members and the possibility of causing damage to layers within the board and circuits on the circuit board.

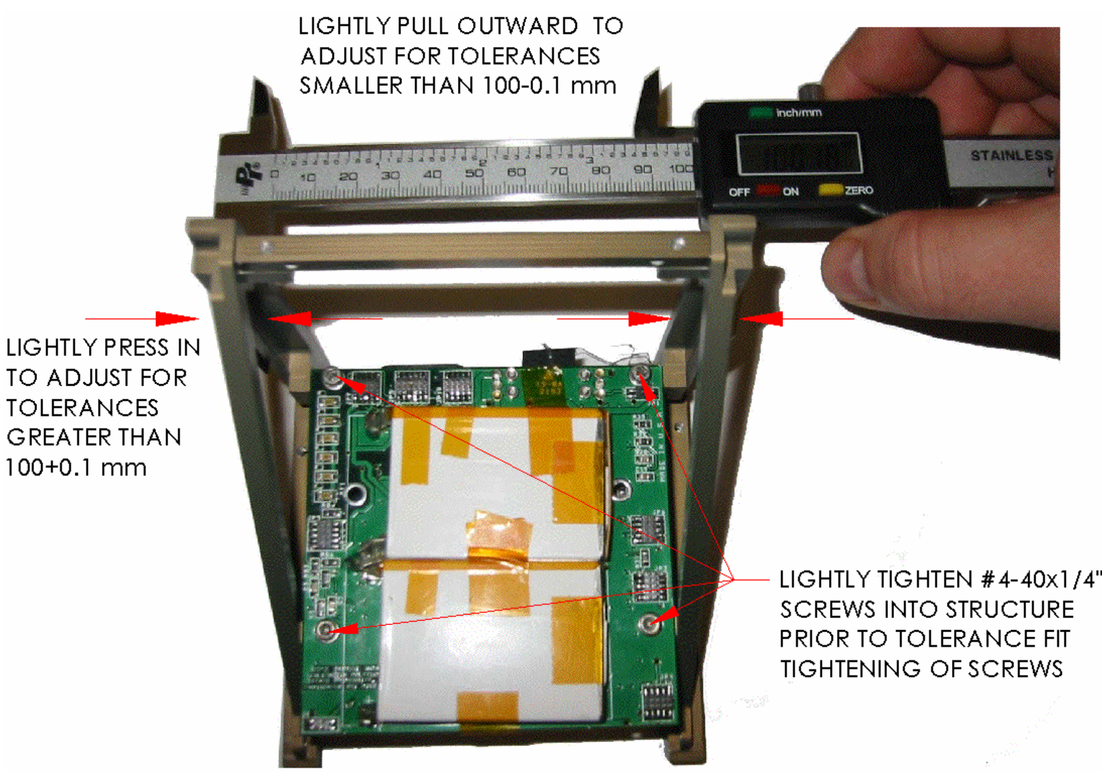

Figure 26 : CP2 Tolerance Adjustments via Internal Boards

Time and materials were wasted due to the depth and amount of material removed on the back side of the triangular structure and the 7075 T6 aluminum bar sizes that could be ordered through McMasterCarr.com. With the depth of the structure being 17mm total, the bar stock in the 7075 T6 grade aluminum came in one inch and one half inch thicknesses (25.4 and 12.7 mm). Initially 8.4 mm of material was needed to be milled from the raw piece of aluminum to acquire the starting depth of 17 mm. Then the back side of the triangular structure consisted of milling 80% of the material away for 8.5 mm depth (half of the structural depth) for only four posts (two crossmember posts and two internal board mount posts) of actual structure to remain. This caused a lot of wasted time for machining down the structure and also a lot of wasted material.

Tolerance of the overall structure when fully assembled and anodized was always slightly above tolerance (approximately 0.1 to 0.2 mm too large). Initially there were only errors in the tolerance in the width across the crossmember direction which put the width dimension from 0.1 to 0.3 mm out of tolerance. These errors were caused by slightly out of tolerance crossmember lengths, slight errors in the hole placements on the crossmembers and support posts, and slightly out of tolerance widths of side pieces. We discovered later a slight uneven milled surface on the jig caused a gradual increase of structural depth from the bottom of one rail to the top by approximately 0.15 mm. Corrections where made by sanding off excessive structure (0.1 to 0.3 mm) using a flat surface and carefully sanding the surface evenly but this method sometimes caused slight errors from uneven sanding. When fully anodized, although the structures were modified to within tolerance, the structures were again out of tolerance by approximately 0.1 to 0.15 mm in most directions. It was discovered later that the hard clear coat anodization process (part of the requirements from Cubesat) not only anodized approximately 0.025 mm into the structure but it also built up an anodized surface approximately 0.025 mm on the structure surface. When one side of the structure was assembled with two triangular halves, the triangular halves had one edge of each triangular side in contact with another triangular side and then the rails gave an extra 0.1 mm width to the already almost out of tolerance dimension which gave the overall width an over tolerance measurement of 0.15 to 0.2 mm. The width in the crossmember direction had an extra two mating surfaces and two outside surfaces for an extra 0.15 mm width which put the crossmember direction width out of tolerance more than the side width tolerance.

5.2 Export Manufacturing Lessons from CP3/CP4

Since CP3/CP4 was manufactured outside of Cal Poly through the company Next Intent, Inc. (the makers of the Mars Rover wheels), manufacturing complications followed through but with new added complications. In working with this new outside manufacturing company, problems arose with definitions of what work needed to be provided, what additional charges would be applied, and the tolerances of parts when anodized.

Communication of what charges would be made for what services was the first problem to arise with CP3/CP4. With an initial design review of the project, a quote for seven complete structures in tolerance when assembled after anodization was given for $5,291.37 ($755.91/single structure) and all Next Intent needed solid model files in either SolidWorks format or IGES format to complete this task (stated by them). When the structures were completed, additional money was charged for simple 2D CAD drawings showing the dimensions of the parts. Sections were added to show details of the milled out interior portions of the rails and the dimensions were converted to English units (decimal inches) from the originally designed metric units (millimeters). These drawings had already been completed prior to start of manufacturing for Polysat records on campus and could have been easily been provided to Next Intent if they had specified that they would require these drawings.

In the design review, the issues with CP2 and tolerances due to hard clear coat anodizing was discussed with the manufacturer. The manufacturer agreed to remove additional surface material during manufacturing to compensate for the additional 0.025 mm per surface of anodization. In error, the manufacturer initially milled the structure out of tolerance by approximately 0.15 in the width to 0.4 mm in height above tolerance prior to anodization when assembled. Part of this error was caused by Next Intents drafters conversion of metric dimensions to English units. The metric units were scaled to three decimal places while the English units were also scaled to three decimal places (0.001 mm converted to English units is 0.00004 inches which is not accounted for in a three decimal dimension and rounding errors occur). The second error was in imperfect machining. An extra charge for additional milling to remove the errors in tolerance was added to the bill. Finally, when fully assembled after anodization, the overall dimensions of the structures were above tolerance approximately 0.1 to 0.2 mm due to all mating surfaces not being accounted for when compensating for the 0.025 mm anodization increase. Refer to section 8.1 Export Manufacturing Price Comparison from CP3/CP4 for a more in depth price description of CP3/CP4 structures.

5.3 CPX Modular Side Manufacturing Design Changes

To alleviate the complexity of manufacturing with having four main structural parts, the modular CPX structure is designed to consist of one main structural component. Having only one main part lowered the complexity of the jig and narrows the error in tolerance down to only one part. Also, when manufacturing outside of Cal Poly, manufacturing one part lowers the price due to the ability to order large quantities of the same part compared to smaller quantities of four individual parts. Having one part used to make the majority of the structure, the tolerance of ±0.1 mm is easier to obtain. When assembling two modular sides and checking the 100 ±0.1mm dimension, the entire structure in the X-Y plane should be in tolerance due identical pieces. Similarly, when checking the Z plane dimension of 113.5 ±0.1mm, since all of the Modular Sides are identical and the upper and lower feet are also identical, if within tolerance the tolerance should hold for all parts. Since the Modular Sides are one piece, they can be placed back into the jig and additional material can be removed from each piece since they were all manufactured from the same jig and material.

The problem with CP2 and the deflection of the internal board mount post when drilling was corrected with the CPX internal board mount. The internal board mount posts were redesigned and made modular and removable. Having the internal board mounts as separate parts allowed for the tapped holes to be drilled directly on the internal board mount without any obstruction and therefore increased the accuracy of the hole placement and drilling. Also, the use of M2.5 screws for mounting the internal boards (and external) instead of #4-40 screws gave a slight placement adjustability to the boards with an extra 0.4 mm diameter of screw clearance room within the holes (#4-40 screw has approximately a 2.80 mm diameter compared to the approximate 2.40 mm diameter of the M2.5 screw).

Without the need for crossmember support posts and the design change to make the internal board mounts modular and removable, the total depth of the structure was reduced to 8.5 mm which gave the manufacturing process no interferences with eighth inch end mills and also reduced the amount of wasted material. Since 7075 T6 aluminum could be purchased in half inch thickness (12.7 mm), only 4.2 mm of total material was needed to be milled down to have the necessary 8.5 mm thickness (half of what CP2, CP3/CP4 needed)

5.4 CPX Export for Manufacturing Changes

Lessons learned with exporting manufacturing work from CP3/CP4 with Next Intent Inc. caused a more aggressive approach to choosing and interacting with a machinist off campus. Lansco Engineering was chosen to manufacture the CPX structures due to a very competitive price and a straightforward quote with all requirements and duties required prior to manufacturing to acquire the exact quoted price. Issues with cost per piece, cost per triple length structure, and cost for multiple triple length structures were discussed and also tolerances and tolerances fully assembled after anodization. Anodization costs, costs of materials and costs of tools were also included in the quoted price.

Communication played an important role in the correct completion of the manufactured product. As each part was manufactured the machinist in charge of the part would contact the design engineer to ensure that dimensions, tapped and untapped holes, and surface compensations for anodization were taken into account. Without this communication, some minor errors (such as not enough anodization compensation for mating surfaces) would have occurred.

6.0 Solid Modeling

6.1 Solid Modeling Lessons from CP2 and CP3/CP4

Since the majority of CP2 was designed to be manufactured using Cal Poly equipment, and because I had extensive knowledge and practice in 2-D drafting, it was initially easier to design and make changes in 2-D drafting using AutoCAD. The full potential of solid modeling was not used. Because of my inexperience with manufacturing, and only three days of training at a HAAS CNC milling class using a CNC mill machine, the use of 2-D drafting while plotting out the coordinates for the end mill (while writing G&M code) was used as the quickest approach to produce a product. I was also able to educate myself in the basic concepts of machine code and the use of CNC machines (see Figure 27). Although accurate when making revisions, changing any item in a three view mechanical drawing was very time consuming. The addition of views of all sides of the assembled structure was needed in order to see clearances for external board mounting which also took longer due to 2-D drafting.

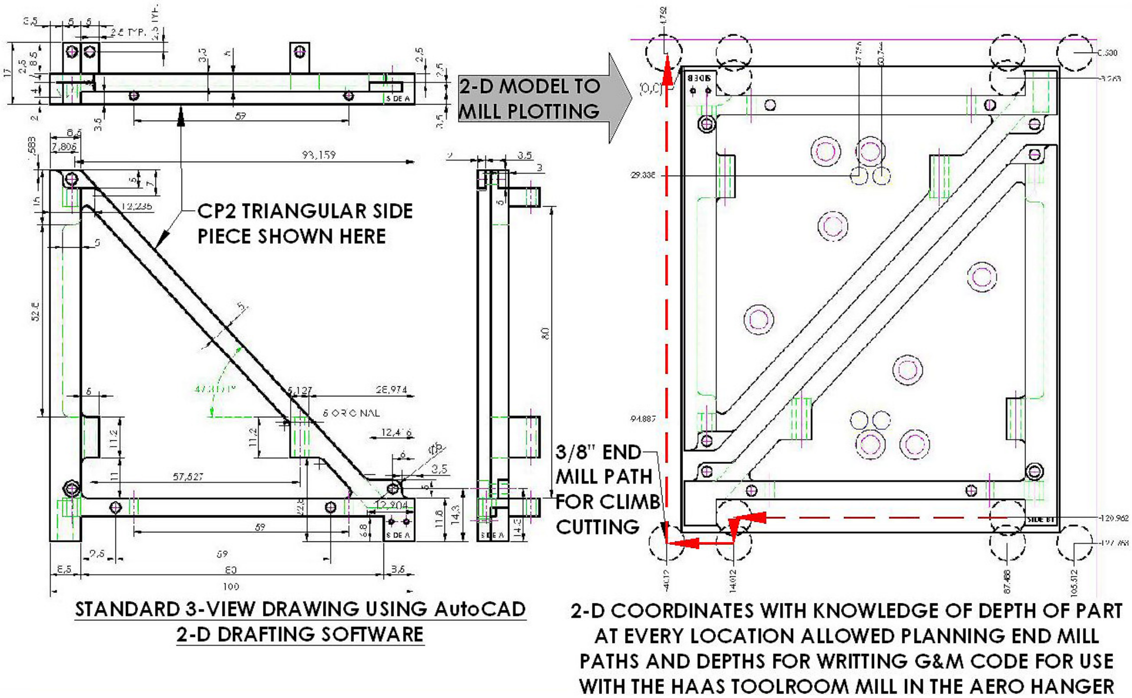

Figure 27 : CP2 Milling Procedure

When CP3/CP4 structures were designed, the use of the solid modeling program SolidWorks was used due to the ease of use and availability on campus. This proved a valuable tool to design structures and identify problems within the structure. Having the onscreen ability to design individual parts and assemble those parts gave a new perspective on the overall picture of the satellite structure. The previous time consuming 3-view mechanical drawings now took little time to make when solid models were used. Complex section views that took some imagination and time to complete could now be accomplished in seconds by identifying where on a solid model a section view was needed. As changes were made to the solid model (ie. revisions to parts, new holes, etc.), the 3-view drawings, sections, and assembled models automatically updated with the revised part. In 2-D drafting it would take a significant amount of time to make the revisions in all the other views.

To save more time with design and checking for assembly problems, and because of the use of over the counter parts, the screws and bolts that were ordered from McMasterCARR.com were available for download from the website in 3-D SolidWorks files and were used to complete structural assembly. While having a fully assembled solid model of the structure with the actual screws used in the assembly, a feature in SolidWorks allowed the detection of structural interferences between individual parts and could identify problems within an assembled structure. While using the actual tap drill size for holes that need to be tapped on the structure, SolidWorks interference detection would identify all of the screw connections between the screws and tapped holes as having interferences. This was a good way to catalog and track the interferences that are suppose to be in the structure and also structural assembly problems if an interference is not at a tapped screw hole location.

Making simplified models of all of the internal and external components (ie. external solar panels boards, internal power board with batteries and battery brackets, C&DH board with I/O port and RBF pin, payload components, etc.) and including them in the full assembly of the structures is the most valuable tool for solid modeling. This is an essential asset to the coordination and verification of mounting designs and clearances with the other engineers involved in the design of the satellite. Without the full assembly errors in both the structural design and/or the circuit boards or payloads in reference to mounting positions, holes and clearances between the structures and circuits or clearances between various circuits on boards within close proximity to each other will be missed until the actual assembly of a manufactured product. These errors can be expensive in time, redesign, and remanufacture costs if not caught prior to manufacturing. An error in the solar panel board mounting holes on the CP3/CP4 structural design was not caught until a simplified model of the solar panel board was used in a fully assembled solid model of the structures using SolidWorks. Since the left two triangular pieces of the structure were mirrored versions of the right, the left structures were modeled and then mirrored to save time from having to construct the right half. The one item that was missed was that the hole pattern position on the right half in reference to external boards is not a mirrored version of the left (holes have to be staggered to the right on the top of the board and to the left on the bottom so screws do not have the same mounting location for top and side boards). Since manufacturing of the structures had already started and half of the structures had already been completed, this error cost an extra $385.32 to drill and tap an additional four holes on each triangular half. This reinforced the need to assemble a full structure with simplified models of the entire satellite system prior to manufacturing (see Figure 28).

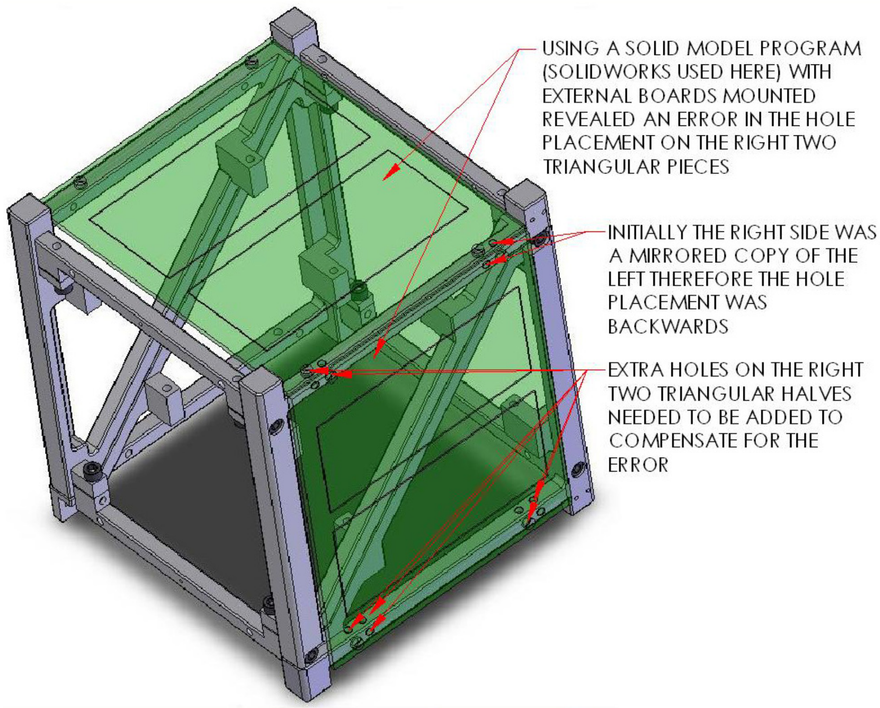

Figure 28 : Solid Modeling and the CP3/CP4 Hole Placement Error

6.2 Modular Structures Solid Modeling Revisions

With lessons learned from all previous versions of the Polysat structures, the modular structural designs of CPX went through four revisions to account for mounting issues, clearances, and problems with fully assembled structures. The Modular Side first version tackled the need for one main structural piece with End Pieces attached to it and cross diagonal cross bracing to aid in structural rigidity. When fully assembled with simplified models of internal components and external boards, a significant error in the design was discovered. The C&DH and power board have an I/O connector and the RBF pin circuit is in a fixed position and location (per Cubesat standards). The initial Modular Side's cross bracing was designed to go from the center of the corners of the modular side but with an assembly with the internal boards mounted in their fixed positions it was revealed that the cross brace blocked a portion of the I/O port location as seen through the external antenna board and also in internal C&DH and power boards (see Figure 29). Without a full assembly showing internal components and external components, this error could have been overlooked and much time could have been wasted in the future to correct the problem.

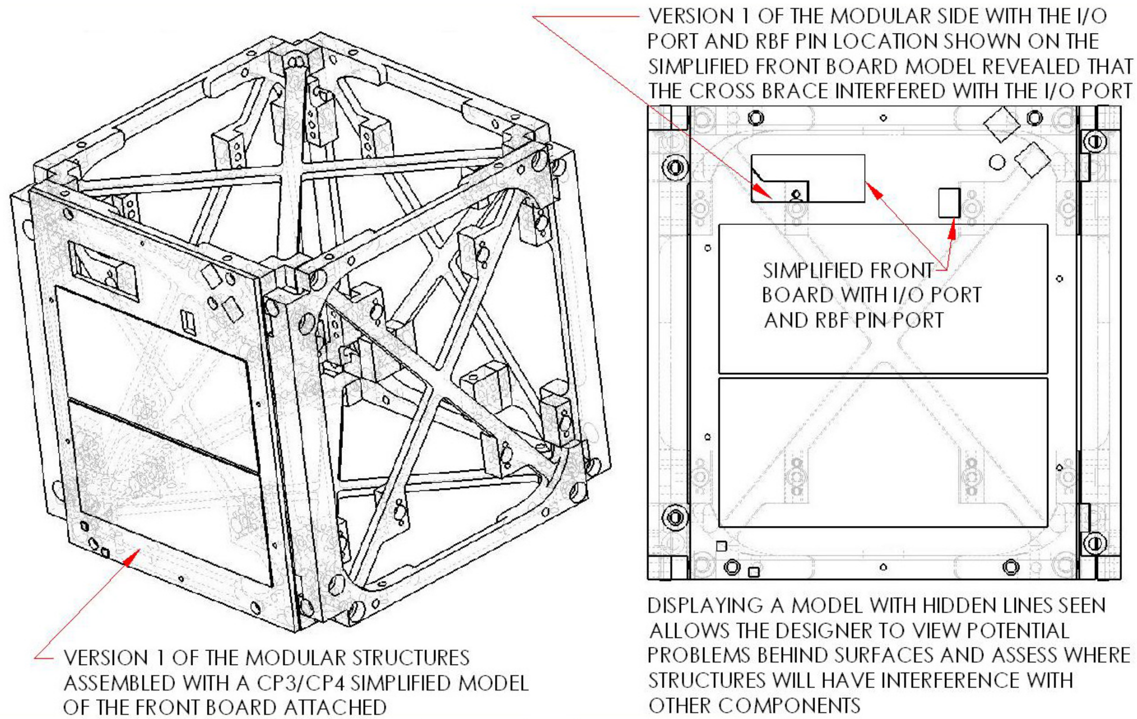

Figure 29 : CPX Modular Design Version 1 Errors

With a redesign of the location of the cross bracing on the Modular Side, the access to the internal components was addressed and a slight modification to the connection of the Modular Sides was made. The full assembly of the structures having no interference issues showed a feasible assembly but did not address the ease of access to the internal components or how to make the structures similar to the previous “clamshell” design of the previous Polysat structures. While using a fully assembled structure without the simplified internal and external components, it was discovered that the new Modular Structures were difficult to disassemble and access internal components without having to disassemble the entire structure. It was quickly realized by moving one Modular Side through another (physically impossible with real models). A simple notch milled out towards the rail where the Modular Sides M3 connecting screws were located would allow the structures to easily have one Modular Side removed for access to internal components or have two sides removed at the same time to give a similar “clamshell” access (see Figure 18 : CPX One Side Removal Access for clarification).

With a final design review with the Polysat team prior to manufacturing, a design change to the Upper/Lower piece was asked to be implemented to allow for the internal board mounting tapped holes to be added. This change also gave way to change the location of the internal board mounting pieces to allow the same mounting hole locations so the Upper/Lower structure could be then mounted at any one of the four locations as discussed in Section 2. By using solid modeling with the fully assembled structure it was quickly seen that the internal board mount designs needed to be redesigned to adjust for the mounting hole location change which once again proved the importance of solid modeling using assembled structures.

The final revision to the structure was the addition of extra holes to ease manufacturing by having extra screw mounting holes to stabilize the structure when mounted to a jig. The use of the solid modeling feature that allows for hidden lines to be seen allowed the quick placement of extra holes by showing the depth and location of existing holes and thicknesses between the new hole locations. This allowed the fast placement of the extra holes near the M3 tapped holes on the end of the Modular Side and also allowed a slight increase in rounded edges on the Upper/Lower structure in five locations.

Using rendering software in conjunction with the solid models allowed pictures of the structures with almost photographic quality to be produced. These images were hard to tell if they were images of the actual manufactured models or of computer simulated models. This feature for solid modeling allows the designer's ideas to be presented to the client (ie. the thesis advisor and the Polysat team) with a realistic look compared to the standard drafted three view drawings or solid model drawings without much detail to realistic looking views. Sometimes, when convincing the client that your design is exactly what they are looking for, it helps significantly to give a realistic view of what the product should look like post-manufactured (see Figure 30).

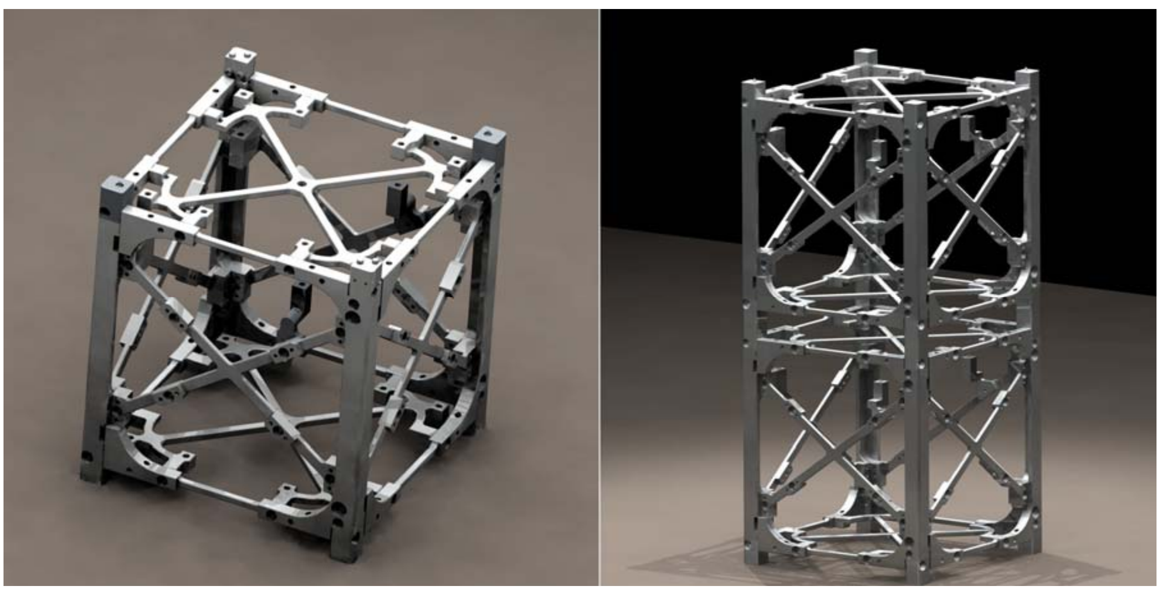

Figure 30 : Photo Renderings of CPX Structures

6.3 Rapid Prototyping

Since the introduction of solid modeling programs, a significant amount of time and money has been proven in designing parts and assemblies, but solid modeling using software still does not replace the ease of actually checking design work with an actual manufactured model. The introduction of rapid prototyping machines and fast cheap physical models of parts makes checking issues with the design easier. Similar to an ink jet printer, most rapid prototyping machines “print” a layer of a solid model design with a form of fast drying liquid plastic and then continue to build up upon each layer to produce a 3-D composite model of the computer simulated solid model.

Rapid prototypes of the CP2 and CP3/CP4 clamshell designs were made to allow the electrical engineers to check for internal board clearances and mounting issues. With the final CPX design, rapid prototypes of a single assembled structure along with individual parts to assemble a double structure were made (see figure F). The individual Modular Side pieces allowed an actual physical assembly of the model to check for assembly issues and clearances. The fully assembled model allowed for the team to physically hold and examine what the new structures would look like and how the new modular design fit together (see Figure 31).

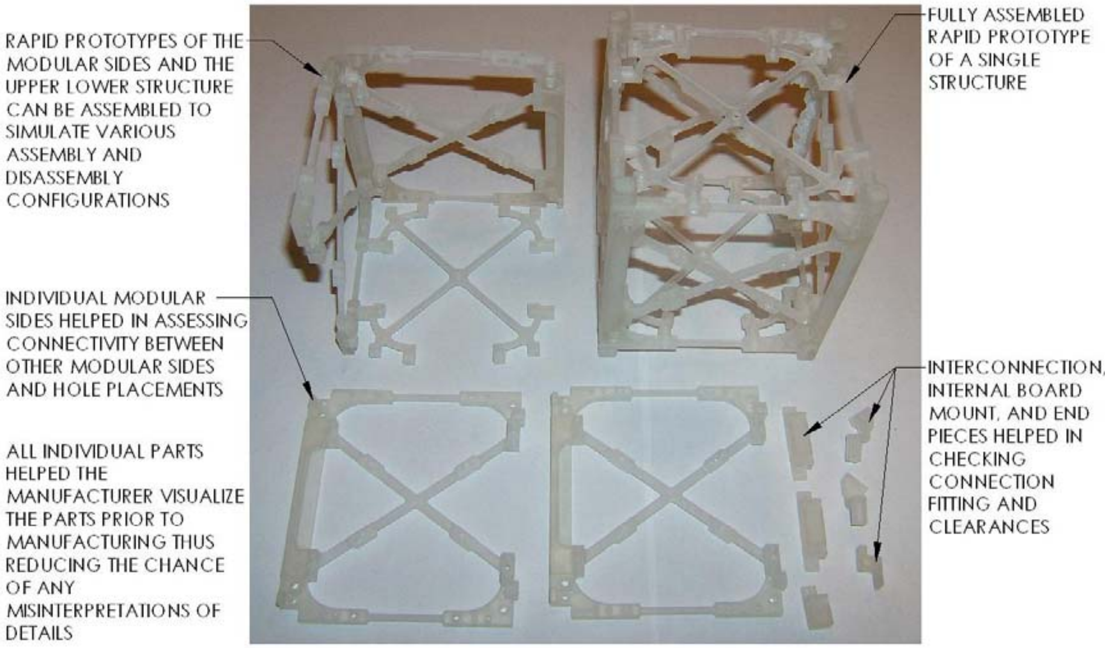

Figure 31 : Rapid Prototype of Single Assembly and Individual Parts

7.0 Finite Element Analysis

7.1 Finite Element Analysis (FEA)

Because of the complexity of shapes that are designed today, computers using finite element analysis (FEA) programs are used to predict the stresses, strains, displacements, thermal analysis, and modal analysis on models of the structures. Previously, prior to the invention of computers and programming, predicting the structural properties of materials under force, thermal or vibrational conditions could take weeks of time with hundreds of pages of mathematical calculations to predict the outcome. Now, with the ease of designing components using solid model programs such as Solid Works, IDEAS, and ProEngineer, the ability to design models with great complexity has increased significantly. This also has increased the complexity of predicting how the components will react when subjected to loading, vibration, or thermal scenarios.

7.2 Reduction of Time Running an FEA

The computer hardware being used, the type of FEA algorithm and size of the mesh, and the complexity of the model all contribute to the speed at which an FEA can be performed on a solid model of a structure. Depending on the computer processor being used, the processor speed, and the amount of RAM, the computer program FEA can easily be accomplished within minutes or as long as a day. To make a comparison, running a static load FEA on the Modular Side, using Cosmos Design Star 4.5 took 2.5 hours to complete on a 1.8GHz Pentium M processor with 1GB of RAM. Running the exact same FEA on a 2.4GHz Athlon 64 processor with 2GB of RAM took only 2.5 minutes to complete with the exact same results. Decreasing the distance between nodes in the mesh during the FEA increases the amount of time it takes to calculate the results due to the increase in the amount of computations needed to be completed but it yields a slightly more accurate result. Increasing the distance between nodes decreases the accuracy of the results but can significantly decrease the time it takes to run the computations, and also in certain circumstances with structures with complex shapes that have difficulties with meshing correctly, it makes the meshing process easier.

Finally, to make the FEA process significantly faster, depending on the complexity of the structure (ie. various different shapes, various holes, connections, etc.) and the complexity of the assembly of an entire structure system, simplified models of the structures are made that in general, model the main features of the structure but leave out features that increased the complexity of the design such as holes, multiple rounded edges, and complex shapes (see Figure 32). This allows issues and difficulties with meshing and analyzing complex shapes and the complexities of stresses around holes to be simplified down to a simple model with main features. In the case of CPX, the simplified structures contained the smallest cross sectional areas to account for the weakest spots in the structure. Holes will experience compressive deformations thus increasing the cross sectional area for a stress analysis and therefore increasing the strength at those locations. Since the simplified models are assumed to produce solutions similar to the more complex analysis but reduce the time needed to calculate results, the values gained can be used to estimate the reactions of loads. Although FEA's give good results in prediction of stresses, strains, and displacements, actual real testing of the manufactured structures are still necessary to validate designs. FEA's significantly cut down on the amount of time from design, predict, build, test, and redesign.

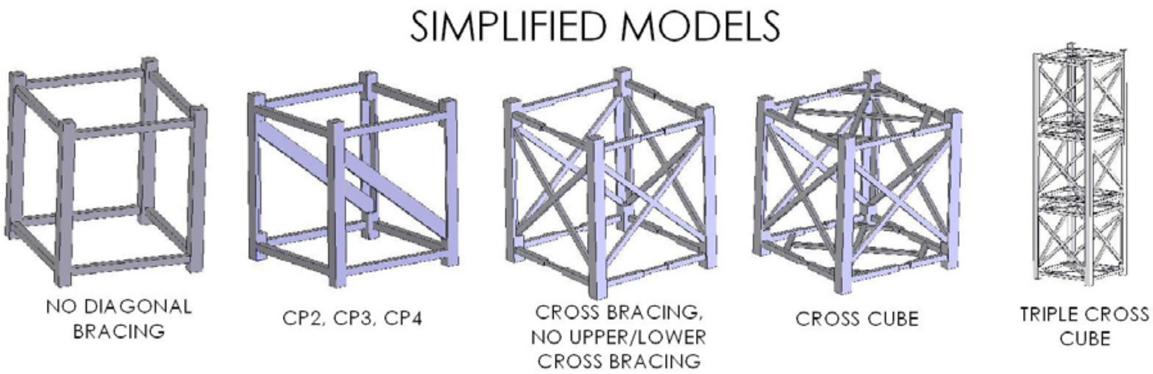

Figure 32 : Simplified Models for FEA

7.3 Parameters for Analysis

The steps in the preparation for a static load FEA are to:

- define the material being used with the material properties defined
- define the fixed locations on the structure and which areas are free to movement
- define the direction, magnitude, and location of forces to be applied including gravitational forces
- define what factor of safety the part or simplified structure needs to attain.

All of the CPX structures were manufactured out of 7075 T6 aluminum, therefore some of the properties for 7075 T6 aluminum are listed in Table 3 below. Due to the lack of data on the compressive yield strength of aluminum, the tensile yield strength was used as the compressive yield strength due to most ductile materials having similar values for both the compressive and tensile strength values.

Table 3 : Properties of 7075 T6 Aluminum

Density	2.81 g/cc
Tensile Yield Strength	503 MPa
Compressive Yield Strength	503 MPa
Shear Modulus	26.9 GPa

The bottom End Pieces were set as the fixed positions for the simplified models for Z-axis vertical loading (most force direction if loaded in the P-POD at the bottom with two satellites above). The total load for a static analysis is defined as the forces experiences from the static load plus the dynamic load. This takes into account the forces applied directly to the satellite structure from other satellites within the same P-POD, the forces caused by the acceleration of the launch vehicle, and the forces caused by vibrations created by the launch vehicle propulsion systems.

$$Force = mass * acceleration * (static + dynamic)_{forces} \qquad \textbf{Equation 1}$$

Since the dynamic loading varies with each launch vehicle, the worst case scenario of 18Gs was used and provided by a FE analysis performed by Cubesat students on the P-POD. For a single structure analysis, an additional 36N force was distributed over the four upper End Pieces to simulate two separate single satellites each with a 1 kg mass (18 Gs acceleration times 2kg mass gives 36N force which is distributed to 9N force applied normal to each End Piece to simulate the static load of the two satellites if the CPX structures were located at the bottom of the P-POD). This is worst case scenario for static force that would actually be applied to the structures. The overall design of the structure was not to minimize the structural mass to the point of only a factor of safety of two or more but to make the structure easy to manufacture while reducing the overall mass.

The next step is to set up the parameters for the mesh for the solid model FEA. COSMOS in SolidWorks allows the element size to be from course to fine and varying the element size can save time running the meshing process depending on the complexity of the part that is to be examined. The following table shows the parameters that were used in meshing.

Table 4 : Mesh Setup for FEA

Mesh Type:	Solid mesh
Mesher Used:	Standard
Automatic Transition:	On
Smooth Surface:	On
Jacobian Check:	4 Points
Element Size:	1.9854 mm
Tolerance:	0.099272 mm
Quality:	High

Once the mesh has successfully been created, algorithms used to determine the stress and strain throughout the part are run. Von Mises stress analysis was the algorithm used to find the stress distribution throughout the simplified model and subsequently strain and displacement values were also plotted based on the input materials properties. See Figure 33 for a visual step through the process of a typical FEA run using COSMOS.

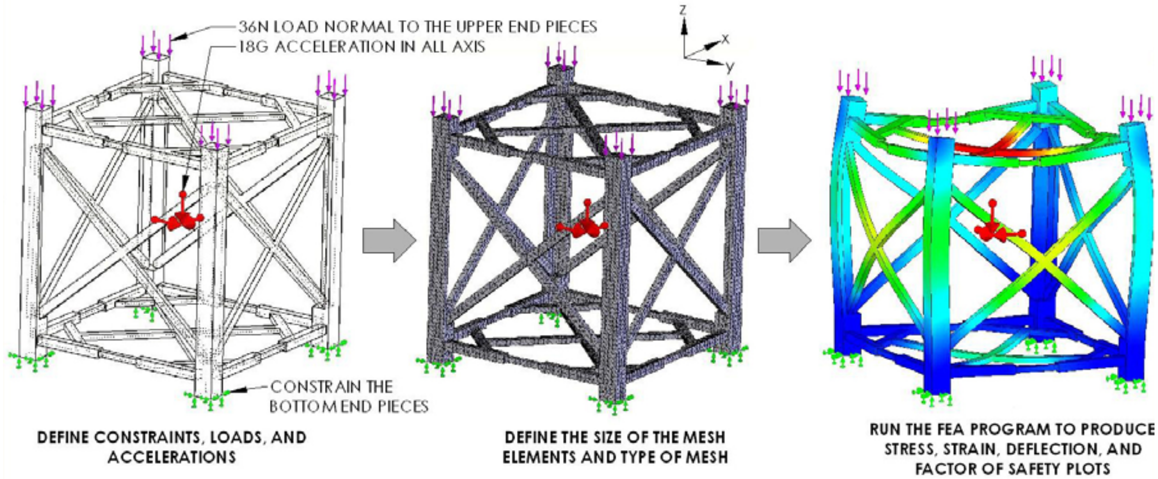

Figure 33 : Steps for FEA

7.4 Comparison of Variations in Structure

To determine the effectiveness of different designs of the structures, a multitude of varied simplified models were used with the same loading conditions to determine the feasibility of cross bracing on the sides and top compared to only side cross bracing, single side bracing on two sides (CP2, CP3, and CP4 structures), and no bracing at all. Mainly, since the overall factor of safety (FOS) on all the simplified models is greater than 19, the main focus of the FEA's are to compare displacement characteristics between previous Polysat structural designs and new cross bracing structural support (stress and strain data is also listed but not talked about in depth). Certain parameters for the shape of the structure were defined by the Cubesat pico-satellite structure guidelines, therefore no other shapes for the rails besides 8.5 mm x 8.5 mm square rails were run through a simplified model FEA.

The worst case scenario was run assuming that a single satellite structure was placed at the bottom of the P-POD and two satellites each weighing 1 kg were placed above it with the P-POD in a vertical position (vertically up). The following table shows that the maximum stress, strain, and displacement is affected by cross bracing where the majority of the load is along the Z-axis (vertical).

Table 5 : Vertical Z-Axis Loading Comparison

Simplified Model	***Maximum Stress***	***Maximum Strain***	***Maximum Displacment***	***Minimum FOS***
	N/m^2	***m***	***m***	
No diagonal bracing	6.37353E+06	5.34689E-05	4.10902E-05	79
Single diagonal bracing CP2/CP3/CP4	7.17648E+06	7.17035E-05	3.30073E-05	70
Single diagonal bracing half diagonal thickness	7.55402E+06	6.10244E-05	3.43232E-05	67
Side cross bracing	5.82758E+06	4.57389E-05	1.03561E-05	86
Cross bracing cube	6.08246E+06	4.84042E-05	1.44915E-05	83

As seen in Table 5, from no diagonal bracing to cross bracing, the stress, strain, and displacement decreases while the minimum factor of safety increases. The modular structure without the Upper/Lower support appears to have less displacement than the modular structure with the Upper/Lower support. With closer examination of the displacement plots, it is shown logically that since the bottom End Pieces are the fixed positions and the structure is under compressive forces, it would produce a buckling effect inward due to the horizontal upper and lower bars causing restriction to outward buckling. This inward buckling causes all four rails to buckle slightly inward causing the Upper/Lower structure to deflect down in the same direction as the 18G acceleration. In the case without the Upper/Lower structure, the side cross supports are attached to two rails that buckle inward causing the cross support to bow outwards in which causes less maximum displacement. Since all four corners of the rails are buckling inward the Upper/Lower structure has greater stress than the side cross bracing thus it also has greater strain (see Figure 34). With the addition of the Upper/Lower structure as seen by

Figure 34 the overall stress, strain, and displacement has been decreased in all other areas of the structure. The minimum factor of safety is governed by the maximum stress location which is located in the Upper/Lower structure.

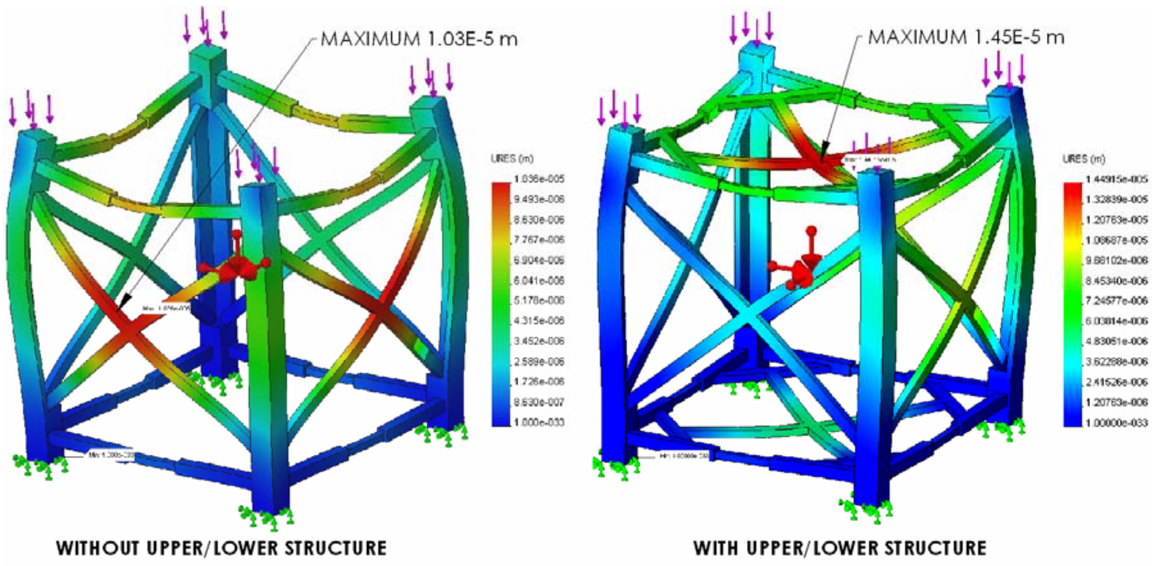

Figure 34 : CPX Z-Axis Force Displacement with/without Upper/Lower Structure

In worst case scenarios, the maximum outward deflection the rails experience is approximately between .004 to .007 mm. There is not enough deflection to cause the satellite to stick within the P-POD (100mm plus twice the most displacement is still only 100.014 mm which is considerably less than the 100.7 mm inside dimension of the P-POD.) This deflection is elastic in nature and the actual deployment environment is much less dynamic (micro-gravity environment with relatively low vibration). The worst case scenarios are to provide evidence that the structure will make it through the launch phase without possibilities of permanent deformation that would cause a failure to be expelled from the P-POD.

To provide a clear picture of the benefits of the cross bracing design with upper and lower cross bracing, FEA's were run using the simplified models. The structure is placed in a position where the load is applied to the side while the opposite side is set as the fixed position (if the P-POD were mounted in the launch vehicle sideways with either of the sides facing the launch direction and against the launch vehicle acceleration vector.)

Table 6 : Side Force and Mounting Comparison

Simplified Model	***Maximum Stress***	***Maximum Strain***	***Maximum Displacment***	***Minimum FOS***
	N/m^2	***m***	***m***	
Side mount no diagonal	2.59749E+07	2.24442E-04	1.34926E-04	19
Side mount CP2/CP3/CP4 no diagonal brace direction	1.82303E+07	1.64244E-04	7.75528E-05	28
Side mount CP2/CP3/CP4 diagonal brace direction	9.26095E+06	8.49930E-05	5.25511E-05	54
Side mount cross sides	1.55024E+07	1.36347E-04	1.16021E-04	32
Side mount cross cube	8.24213E+06	7.89143E-05	2.40263E-05	61

As seen in Table 6, the addition of the Upper/Lower structure significantly drops the maximum displacement compared to the same structure without the Upper/Lower structure. The CP2/CP3/CP4 simplified model shows the logical trend that without diagonal or cross bracing the overall stress and displacements are significantly increased. Since the upper and lower horizontal members of the CP2/CP3/CP4 simplified model are slightly larger (5mm x 5mm cross section) than the CPX simplified models (4mm x 4mm), the difference in the results would be larger if they were both equally sized. See Figure 35 for clarification of the orientation of the simplified models.

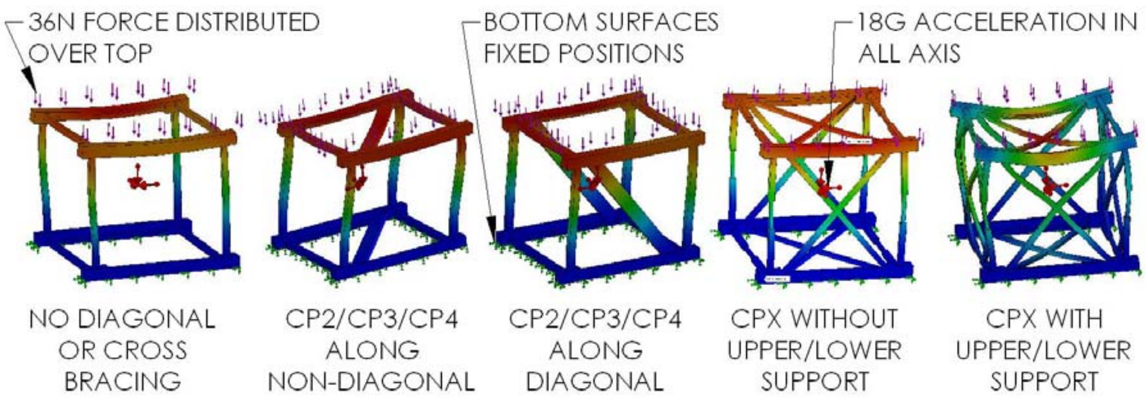

Figure 35 : Side Force and Mounting Configuration

Since the End Pieces are removable and easily modified, a FEA was run to see the effects of a side load against the rails if the bottom End Pieces were set as fixed constrained positions compared with the other simplified models (ie. if in the future the End Pieces were modified to be attached directly to a launch vehicle.) As seen in Table 7 and Figure 36, the CPX structure with the Upper/Lower structure has a significant less maximum displacement compared to all other simplified models.

Table 7 : End Piece Constrained with Side Load Comparison

Simplified Model	***Maximum Stress***	***Maximum Strain***	***Maximum Displacment***	***Minimum FOS***
	N/m^2	***m***	***m***	
Side force no diagonal	1.84644E+07	1.72614E-04	9.39329E-05	27
Side forceCP2/CP3/CP4 diagonal side	6.41014E+06	5.53765E-05	3.41017E-05	78
Side force CP2/CP3/CP4 non-diagonal side	1.63729E+07	1.62006E-04	8.32344E-05	31
Side force cross sides	9.28906E+06	7.55125E-05	2.04154E-05	54
Side force cross cube	6.69944E+06	5.92848E-05	1.71522E-05	75

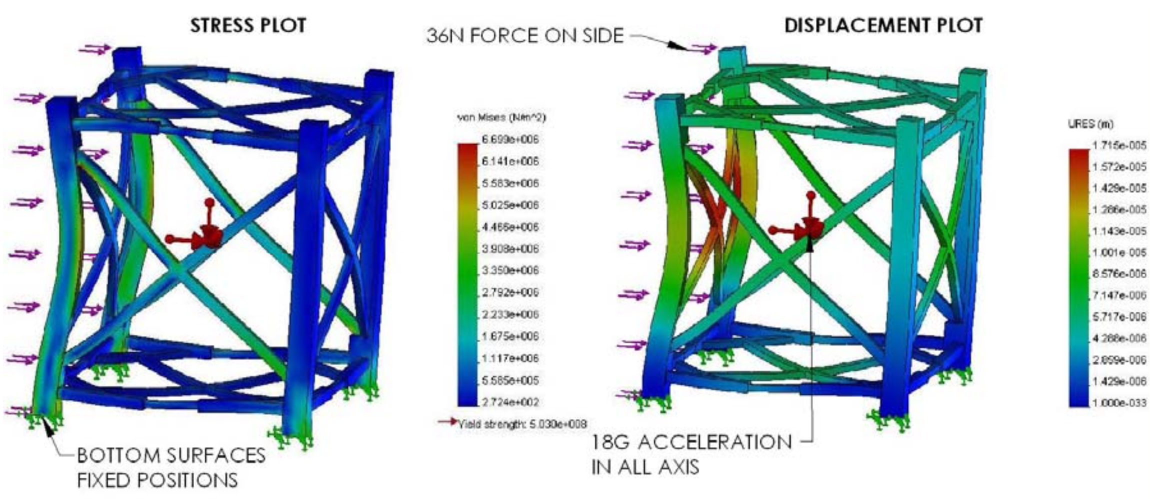

Figure 36 : End Piece Constrained with Side Force (Stress and Displacement Plots)

To finish a FEA analysis of the Modular structures, a static load was also applied to a triple length satellite. A 9N force (to account for the force caused by the spring in the P-POD) was applied to the upper End Pieces and the bottom End Pieces were set as the constrained points. As seen in Table 8 and Figure 37, the maximum displacement is approximately 0.05 mm which is well below the internal tolerance clearance of 0.7 mm for the P-POD. The triple length structure will not deflect enough to cause it to be stuck within the P-POD. Since all of these deflections are within linear elastic deformation, they are only temporary deflections and will return the structure to normal dimensions when vibration and loading are removed (expulsion from the P-POD).

Table 8 : Triple Length CPX Structures FEA

Simplified Model	*Maximum Stress*	*Maximum Strain*	*Maximum Displacment*	*Minimum FOS*
	N/m^2	*m*	*m*	
Triple Length Vertical Load	7.23690E+06	7.37685E-05	4.59458E-05	70

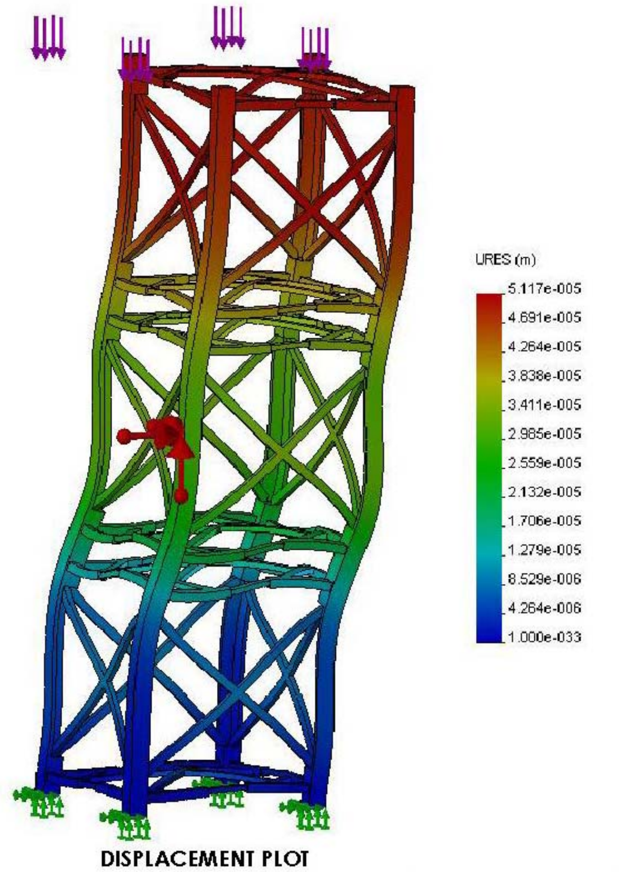

Figure 37 : Triple Length CPX Structures Displacement

8.0 Manufacturing Costs

8.1 Export Manufacturing Price Comparison from CP3/CP4

Although the manufacturing of the CP2 structures on campus was a great learning tool that helped significantly in the design of future models, payloads, and payload support brackets, it was a time consuming experience. The use of manufacturing off campus with local manufacturing firms was conceived and implemented into the design of future structures. The first steps to the manufacturing of the CP3/CP4 structures was to get competitive quotes from local companies. Cloud Co., Next Intent, and Lansco Engineering were the three companies located in San Luis Obispo County that could handle the task of small satellite structure manufacturing. All companies were asked for quotes. Each company became a candidate because of either previous CubeSat or Polysat work that was done with them, recommendations from other companies, or their reputation for aerospace manufacturing projects.

Cloud Co., the company that previously made CubeSat P-POD panels and parts, would not take on small projects anymore (projects with less than a 100 parts manufactured). They were not used but they recommended a company based in Atascadero named Lansco Engineering. Lansco was a relatively small company (less than 6 employees) that had a very competitive price for the CP3/CP4 structures. Manufacturing of the structures had a relative low price that was quoted at $2,233.00 for seven units (each unit consisting of four triangular pieces and not including the crossmembers). The low quote was partially due to the publicity that CubeSat and Polysat had gained through a one page article in the local paper (the Telegram Tribune) which sparked interest in the company owner and his interest in helping a school run project by reducing the costs. The quote was also low because it did not include the manufacturing of the crossmembers which would have added approximately \$1200.00 to the overall price. Since this was a relatively small company, the Polysat team decided that they would like to use a well known company that could make small parts within tolerances. Next Intent, Inc. was chosen.

Next Intent was chosen by the Polysat team not for the price quote (their quote was not the cheapest and was for \$5,297.37 for seven complete structures with crossmembers, \$756.77/structure) but for their reputation for being the machinists that manufactured the Mars Rover wheels, and for their reputation for manufacturing for many large aerospace companies including JPL and Lockheed Martin. As previously discussed in section 5.2 Export Manufacturing Lessons from CP3/CP4, what previously was thought to be a decent price quote from a well respected company soon became a significant overprice of the product. The final price became \$8019.26 (with taxes and anodization, \$1145.61/structure) due to charges that were not discussed as part of the scope of work and also for not making the design tolerances. An extra \$1000.00 was charged for 26 hours of creating 2-D drawings from the 3-D SolidWorks files that were supplied to them even though during the pre-manufacturing meeting and pricing they specified they only needed solid models of the structures to be used in a program to generate the machine code. Polysat had 3-view mechanical drawings of all structures that could have easily been handed to them if they would have specified that they needed the 2-D drafting to complete the manufacturing. Another \$290.48 was charged for extra milling of the rails of the structure after the structures were completed because they were not initially manufactured within the tolerances stated in the design meeting (assembled structure 100±0.1 mm *when* anodized). Part of their error in the tolerance is their conversion of the 0.1 mm tolerance (0.0039”). They stated in the scope of work after manufacturing of the parts that the tolerance was to be 0.006” (0.152 mm) which was a partial cause to the out of tolerance specification. Part of a manufacturer’s responsibilities are to make sure the parts they are making are manufactured to the customers design specifications. Tolerances with compensation for surface plating (anodization) that were discussed at the initial design review meeting should have been implemented in the manufacturing. Charging Polysat for adjustments to bring the manufactured parts to within tolerance is not a chargeable fee. The parts should have been manufactured to the tolerances specified in the initial design review meeting.

8.2 Pumpkin Structural Kits

Since many colleges and businesses are starting their own pico-satellite projects, some of them do not have the time or mechanical expertise to design and manufacture structures for their projects. Pumpkin Incorporated, a company that provides structural systems for pico-satellites in a variety of sizes from a half unit size all the way up to a triple length structure, made a market out of the rapid increase in pico-satellite construction. These structures consist of aluminum sheet metal sides that are either solid or “skeletonized” (parts of the solid aluminum sheet are punched out to form cross bracing) which does not affect the price. Since these structures are not modular and made mainly from sheet aluminum, there is little room for upgrades or mounting positions for payloads and circuit boards. The cost for a single structure is $\$750.^{\underline{00}}$ for the walls plus $\$325.^{\underline{00}}$ for the base plate (end pieces with spring plungers and a deployment switch) and $\$275.^{\underline{00}}$ for the cover plate ($\$1350.^{\underline{00}}$/single). A triple structure with top and bottom would cost $2600.00. This is a competitive price for a structure but significantly lacks support for a variety of payloads and modifications. Also, their structure is tailored to their C&DH and power boards, RBF pin, and deployment switch (only one without redundancy) which all cost extra and are not cheap (which also need their software to program and run which is also another expense). To mount solar panels, separate solar panel clips needed to be purchased (conveniently purchased through their website.) See Figure 38 for a picture of a single Pumpkin structure. This solidifies the need for a modular and upgradeable structure at a reasonable price.

Figure 38 : Pumpkin "Skeletonized" Single Structure

8.3 CPX Manufacturing Costs

The problems that were encountered with manufacturing with Next Intent led to not using them as a candidate for the CPX structures. Lansco Engineering, who had previously successfully manufactured antenna routes for Polysat and who were also recommended by Cloud Co., was chosen for the task of manufacturing the CPX structures. Because of the modularity of the CPX structures, the cost per structure was expected to be greater than those of the CP3/CP4. With Lansco Engineering, the costs and what was associated with the costs were discussed and clarified in the beginning of the project prior to manufacturing. Quotes included materials, anodization, and labor costs, and all necessary drawings were to be supplied to the manufacturer to alleviate any unseen drafting charges that were previously added to the CP3/CP4 manufacturing charges.

To help out Polysat and to obtain recognition in this thesis, two price quotes were quoted for the structures. For a triple assembly with eight End Pieces, eight Interconnection Pieces, four Upper/Lower structures and twelve Modular Sides the quoted price was \$5,289.00 which included materials, anodization, and labor. A discounted price of \$2,750.00 was given to help out with the initial build of the design for this thesis and to start a possible relationship with Lansco Engineering for future satellite structures. Ordering more kits significantly drops the price. 10 triple structures are quoted at \$20,317.00 (\$2031.70/triple structure or \$677.23/single structure). Ordering individual parts increases the price significantly due to the time it takes to set up the CNC machine and prepare the materials. It is recommended to order in quantities of parts to lower the price significantly per part. Table A shows the price of the structures and the price per individual part.

Table 9 : CPX Price Quotes from Lansco Engineering

Complete Structures	Price Each
Triple Assembly	5,289.00
10 Triple Assemblies	20,317.00

Individual Parts	Price Each
Modular Side	396.00
Upper/Lower Structure	179.50
End Piece	224.00
End Piece with Deployment Switch	172.00
End Piece with Spring Plunger	94.00
Internal Board Mount Left	172.00
Internal Board Mount Right	172.00
Internal Board Mount	94.00

After a three month waiting time between the finish manufacturing of the Modular Side and the Upper/Lower Structure and the continued waiting for the small pieces to be started and completed, time was running out. The thesis defense was a week away and the completed structure was necessary for completion of the written portion, vibration testing, and also the defense therefore a fast return on manufacturing of the rest of the structure was essential to meet the deadline. Another local manufacturing company recommended by Next Intent, Suspension Concepts, was chosen to finish the rest of the structures. This company was able to accomplish the task within four days of receipt of the order and put in more than 30 hours of work time to achieve close to an anodization compensated tolerance on all of the small parts. The cost of this scope of work was $1750. Lansco Engineering decided to deduct the cost to manufacture the rest of the structure from their quoted price therefore bringing the overall cost of the entire structure back to the original Lansco Engineering quoted price of $2,750.$^{\underline{00}}$. Although Lansco Engineering lost a significant amount of money in man hours spent on manufacturing the large structures, they saved approximately $600 by not having to anodize the structures and by having all of the raw materials and tapping tools provided to them although they were included in the initial scope of work and services.

9.0 Post-manufactured Structures

9.1 Anodization Compensations

There was a three month delay in manufacturing after the Modular Side and Upper/Lower structure were completed; therefore, there was an ample amount of time in preparation for manufacturing the rest of the structures. The Modular Side and Upper/Lower structure were checked for manufacturing tolerances before the End Pieces, Interconnecting Pieces, and Internal Board Mounts were made. It was determined that most of the anodization surface reduction compensation of 0.025 mm for mating surfaces and external surfaces for an overall complete assembled tolerance had not been completed and that some of the dimensions were above post-manufactured post-anodized tolerances. The manufacturer had been informed at a kickoff meeting prior to manufacturing about the reduction required for anodization compensation for all mating surfaces. It was also discussed the necessity to compensate for the End Pieces and Interconnection Pieces because of the tight fit into the Modular Side. If compensation is not implemented into the design, the End and Interconnect Pieces would not fit and the screw holes would not align after anodization. Somewhere between the meeting and the actual manufacturing, the majority of the information on what surfaces to be compensated was not implemented into the manufacturing. The Upper/Lower structure was on average approximately 0.031 mm wider than the targeted anodization compensation dimension. The Modular Side on average was at the actual design dimension without any anodization compensation except for the end M3 tapped connection hole protruding section heights depicted by dimensions D1 and D2 (see Table 10 and Figure 39).

Table 10: Modular Side Pre-Anodize Tolerances

Dimension	A	B	C	D1	D2	E1	E2	F	G
Average	90.029	100.002	91.508	5.959	5.968	2.028	2.023	100.011	8.483
Design Dimension	90	100	91.5	6	6	2	2	100	8.5
Anodized Compensation	89.95	99.95	91.45	5.95	5.95	1.975	1.975	99.95	8.45
Out of Tolerance by:	**0.079**	**0.052**	**0.058**	**0.009**	**0.018**	**0.053**	**0.048**	**0.061**	**0.033**

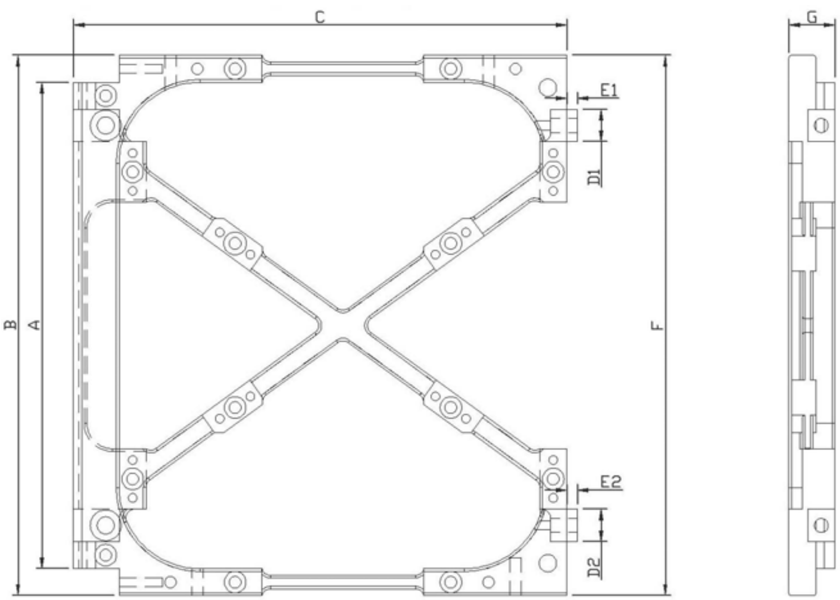

Figure 39 : Modular Side Pre-Anodized Measurements

Since the Modular Side, when fully assembled with the Upper/Lower structure, had slightly lower than 100.00 mm dimensions, and without the Upper/Lower structure attached had almost exactly 100.00 mm, it was determined that the single mating of two Modular Sides (two surfaces) with the exterior surfaces also included should be at the upper limit of the Cubesat standard set tolerance of 100.10 mm (0.025 mm per surface of anodization with four surfaces gives 0.1 mm extra). No major changes were to be made to the Modular Side and Upper/Lower structure. Since the protruding mating tapped M3 area was not compensated for in depth (design dimension of 2 mm with actual manufactured dimensional average of 0.025 mm above design dimension, approximately 0.050 mm above anodization compensated dimension (refer to Figure 39 and Table 1 dimensions E1 and E2) it was decided to file down the end approximately 0.050 mm. This would guarantee that the majority of the mating surfaces between the Modular Sides would be flush between each other without having a gap caused by the uncompensated protruding tapped M3 areas.

Since the small structural pieces had not been manufactured yet, the decision was made to overcompensate for the bottom and top End Pieces and Interconnect Pieces to ensure that the pieces fit within the assembled Modular Sides after anodization. They would also meet the upper tolerance of the fully assembled vertical tolerance (113.5 ±0.1 mm, with two mating surfaces and two end surfaces the anodization would add an extra 0.15 mm of length to the rail length). Since the Modular Side was not compensated for, anodization where the End Pieces mate with it gave rise to the possibility that if the End Pieces were not overcompensated, the two M2 screw holes (one tapped and one a through hole) that connect them to the Modular Side might not align properly with the Modular Side holes (one tapped and one a through hole) and also the End and Interconnect Pieces would not fit. A double compensation was also applied to the sides of the Internal Board Mount. This was done because of one side in contact with an uncompensated Modular Side surface while attached to another Modular Side might push the Internal Board mount towards the center of the structure. This raised the possibility of having the mounting screw and dowel pins on the Internal Board Mount not aligning with their respective counterparts on the Modular Side.

9.2 Small Pieces Post-Manufacturing Measurements

Due to the inability by Lansco Engineering to complete the small pieces of the structures (all End Pieces, Interconnect Pieces, and all Internal Board Mounts) within a reasonable time frame, Precision Suspension, another local manufacturing company, was hired to finish the work. From time of accepting the work to completion only took four days (compared to the three months waiting time with no results from the original manufacturer). To complete the work, 3-view drawings (8.5”x11” format) with anodization compensated measurements were supplied (refer to Appendix C for drawings) to the manufacturer and also assembled Modular Sides to help in evaluating mating locations and to check fit of parts.

Precision Suspension manufactured the small pieces to within an average of less than 0.03 mm above the anodization compensation target measurement on most parts with an exception to certain dimensions (see Table 11 for average measurements and Figure 40 for measurement locations). The only compensated dimension that was not accounted for was in the Internal Board Mounts Left and Right. The target 10.80 mm board mount location (depicted by measurement “B” in Figure 40) actually was measured to be closer to the original design dimension of 11.20 mm. This was caused by the manufacturer using the supplied solid model file of the Internal Board Mounts Left and Right to compile the G and M code for manufacturing and then overlooking the desired compensated value. The extra 0.20 mm compensation on the upper and lower board mount locations was designed to compensate for the addition of a sill pad (for vibration) and kapton tape (to hold the sill pad in place) in between the internal boards and the structure.

Table 11 : Small Pieces Post-Manufactured Measurements

	Measurement				
	A	B	C	D	E
End Piece					
Average	8.42	8.42	5.97	3.44	11.72
Design Dimension	8.5	8.5	6	3.5	11.75
Anodized Compensation	8.4	8.4	5.9	3.4	11.65
Out of Tolerance by:	**0.019**	**0.017**	**0.066**	**0.043**	**0.071**
Connection Piece					
Average	8.42	8.41	5.94	3.44	23.33
Design Dimension	8.5	8.5	6	3.5	23.5
Anodized Compensation	8.4	8.4	5.9	3.4	23.3
Out of Tolerance by:	**0.015**	**0.014**	**0.042**	**0.039**	**0.033**
End Piece with Deployment Switch					
Average	8.43	8.41	5.93	3.50	11.74
Design Dimension	8.5	8.5	6	3.5	11.75
Anodized Compensation	8.4	8.4	5.9	3.4	11.65
Out of Tolerance by:	0.027	0.013	0.028	0.102	0.085
End Piece with Spring Plunger					
Average	8.42	8.42	5.92	3.46	11.73
Design Dimension	8.5	8.5	6	3.5	11.75
Anodized Compensation	8.4	8.4	5.9	3.4	11.65
Out of Tolerance by:	0.024	0.024	0.020	0.064	0.077
Internal Board Mount					
Average	4.81	8.39	10.84		
Design Dimension	5	8.5	11.2		
Anodized Compensation	4.8	8.4	10.8		
Out of Tolerance by:	0.012	-0.015	0.041		
Internal Board Mount Left and Right					
Average	2.47	11.19	2.48	11.19	
Design Dimension	2.5	11.2	2.5	11.2	
Anodized Compensation	2.45	10.8	2.45	10.8	
Out of Tolerance by:	0.021	0.387	0.026	0.390	

Note: Internal Board Mount Left measurements are depicted by measurements A and B while measurements C and D are measurements A and B for the Internal Board Mount Right.

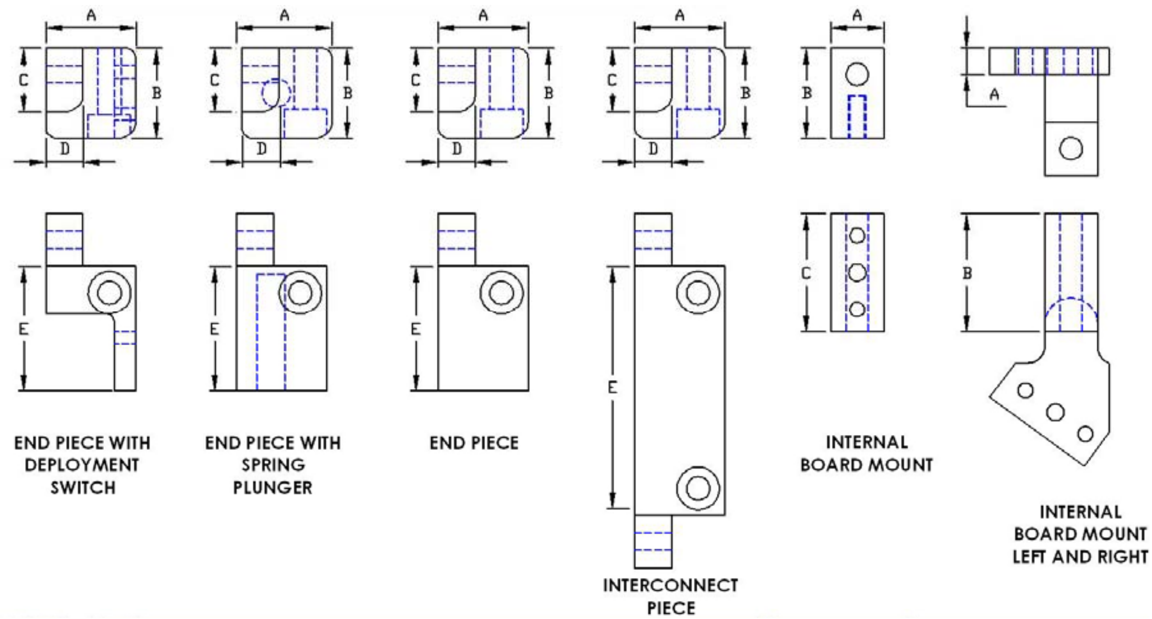

Figure 40 : Small Pieces Post-Manufacturing Measurement Locations

9.3 Assembly of Structures: No Anodization Judgment

The judgment to make this first round of structures the engineering and testing structures and to not anodize them was due to the tolerance compensated small pieces fitting tightly into the non-compensated Modular Sides. The End Pieces (including deployment switch and spring plunger types) along with the Interconnect Pieces fit with little to mild friction into assembled Modular Sides and the connection screw holes aligned correctly. The M1.5 dowel pins were easily pushed into the Internal Board Mounts and Internal Board Mounts Left and Right with the use of a manufactured alignment tool and a drill press (drill press not turned on but used as a stamping tool to apply the pressure necessary to push the pin into the part). Since the assembled structure has a tight fit and every piece aligns with their respective holes, the probability is high of the structures not fitting back together after anodization (see Figure 41 for pictures of the assembled structures).

The Modular Side was not compensated for anodization and most of the measured dimensions were above post-anodized measurements (refer to Table 10); therefore, the pin portion (protruding portion with the M2 tapped hole) of the End and Interconnect Pieces would need an additional 0.05 mm removed from all sides to be able to fit after anodization. The two sides of the End and Interconnect Pieces that mate with the Modular Side would also need an additional 0.05 mm of material removed to keep the holes aligned in the same positions that they were currently in. Because of the time constraints and costs to make such changes to the small pieces (possibly easier to create new small pieces), the judgment was made to not anodize the entire structure.

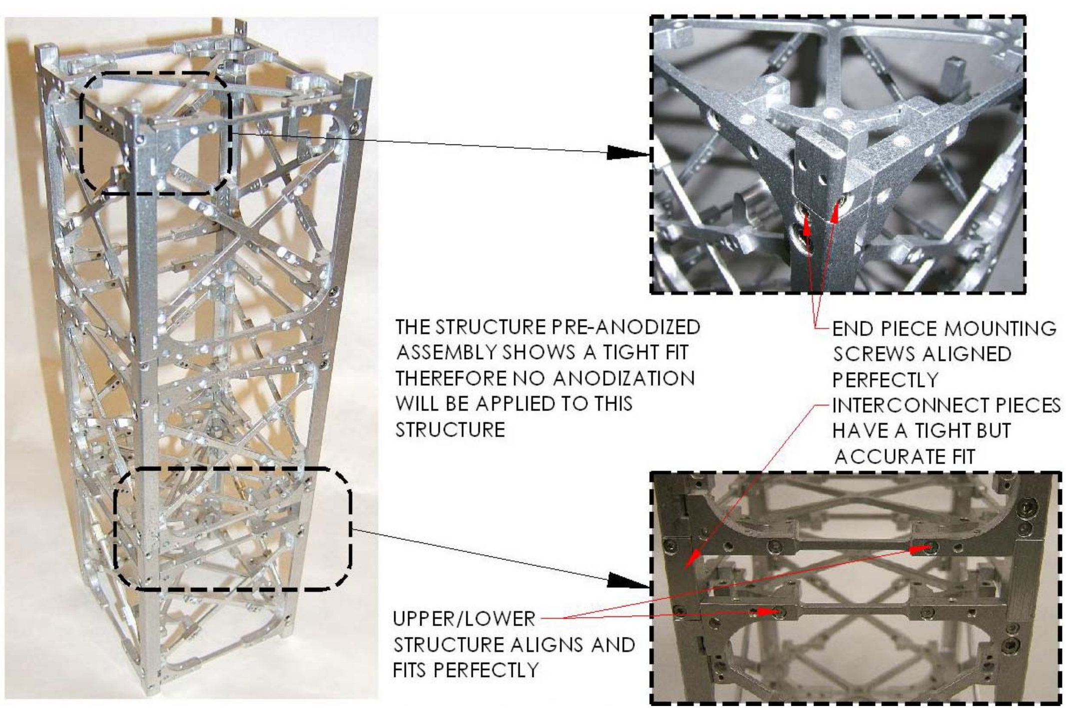

Figure 41 : Pre-anodized Assembled Structure

Since the part was not to be anodized, it was decided to smooth sharp edges and apply a surface finish to achieve a uniform surface look to all the parts. All of the parts were tumbled with small hard plastic pieces in a water/oil mixed solution for approximately an hour. This process reduced the reflectivity of the surface. It also helped to de-burr small fragments of aluminum left from manufacturing and also removed scratches created by holding clamps and vises used during the manufacturing process. Rough jagged edges where rounded edges transitioned to flat surfaces were smoothed out. See Figure 42 for a comparison of an Internal Board Mount Right that was tumbled vs. one that was not.

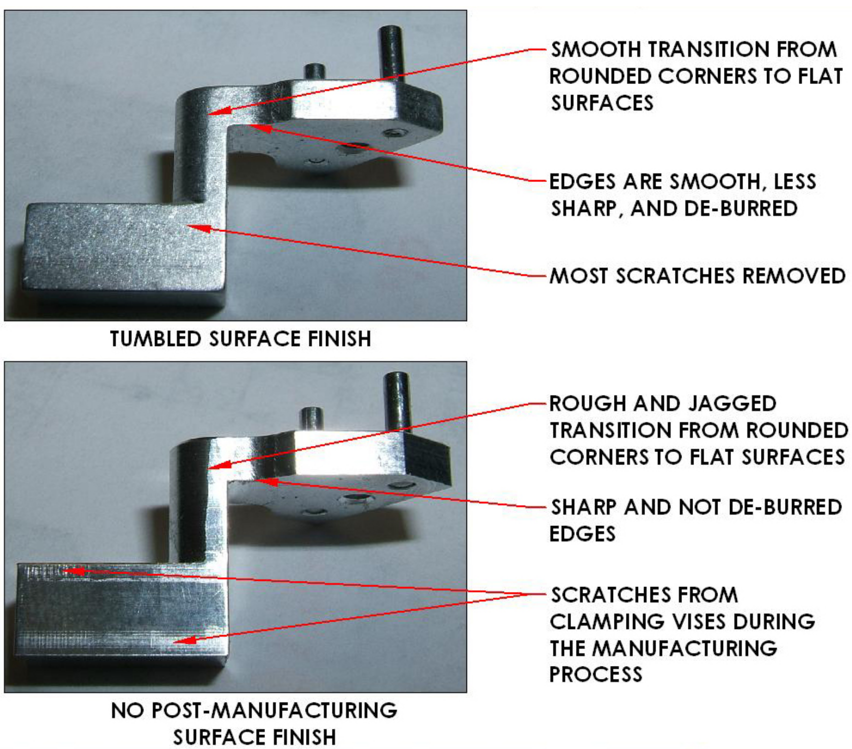

Figure 42 : Tumbled Part vs. Non-Tumbled Part

10.0 Vibration Qualification of Structures

10.1 Satellite Preparation for Vibration Qualification

To complete the design, a vibration test is needed to qualify the structures to ensure that:

- It does not fail under launch conditions
- It passes the NASA GEVS vibration standard
- All internal and external circuit boards and payloads stay intact and in working order after vibration (not part of this vibration test)
- None of the mounting screws or components vibrate loose and cause damage to the satellite, P-POD, or other satellites within the P-POD.

A triple length structure was chosen to qualify the entire modularity of the structure. If a triple length assembly passes, it is highly probable that a double or single will also pass.

To set up for a vibration test, an assembled structure with a power board, C&DH board, and various solar panel boards was constructed and prepared at least 24 hours in advanced. Thirteen various CP2 unpopulated (without circuits) solar panel boars along with a non-functioning C&DH and power board combination were used. A CP3/CP4 front board (board with antenna route mounted directly in front of the RBF pin and I/O port) was needed but not accessible in time for the vibration test therefore it was left out. Five Upper/Lower Structures were used and placed at various locations within the structure. One unpopulated internal board was mounted to one of the Upper/Lower Structures to show the usefulness of the Upper/Lower Structure as an alternate internal board mounting position. All screw heads and nuts were mechanically staked with a staking compound given to CubeSat by Raytheon and given 48 hours to dry. The properties of the compound are not known but it has proven its effectiveness in keeping screws from backing out during vibration numerous times in the past and also has been space qualified by Raytheon. See Figure 43 for a picture of the assembled and vibration test ready satellite structure.

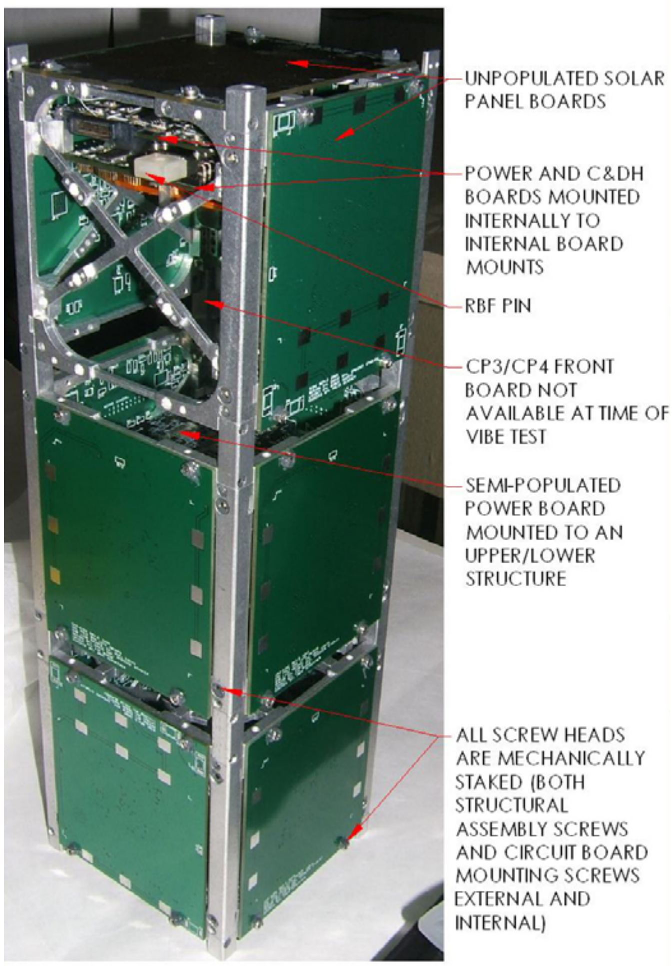

Figure 43 : Vibration Test Triple Assembly

The next step is to pass the CubeSat Acceptance Checklist (refer to **Error! Reference source not found.** for the qualification sheet.) The main purpose of the checklist is to ensure that the satellite structure tolerances and masses are within the standards set forth by CubeSat. All measurements fell within CubeSat standards except for the rail 3 vertical height of 340.91mm (needs to be 340.5±0.3mm, therefore it is 0.11 mm over tolerance). This slightly out of tolerance measurement could easily be caused by the measurement was taken with a caliper that had only a 150 mm measurement distance and the overall distance was calculated by measurements of three sections of the length with the intersections of the measurements approximated visually. Back checking the measurements with a caliper that can measure greater than the total length of the triple length structure measured all four rails at approximately 340.2 mm thus qualifying rail 3. The overall mass of the assembled structure with unpopulated solar panel boards and a populated power and C&DH board was 1187.5 grams. This is far below the 3000 gram limit. A portion of the small amount of total mass can be accounted for by the use of non-populated and non-conformal coated solar panel circuit boards and also no payload. Spring plungers and deployment switches were not included in the vibration test.

The final acceptance qualification is inserting the satellite into the P-POD, closing the lid, and adjusting the P-POD spring plungers to coordinate the fit to match the measured rail dimensions (keep the bottom plate in the P-POD as level to the satellite structures as possible.) Surprisingly, there have been instances with other universities satellites not fitting into the P-POD even when the tolerances needed are given to them and the tight tolerances that the P-POD has are explained. Since the entire acceptance checklist measurements were within standards, the assembled triple length satellite fit with little resistance due to an additional clearance between the satellite rails and the P-POD rails. See Figure 44 for a picture of the triple length CP-X satellite fitting within the P-POD.

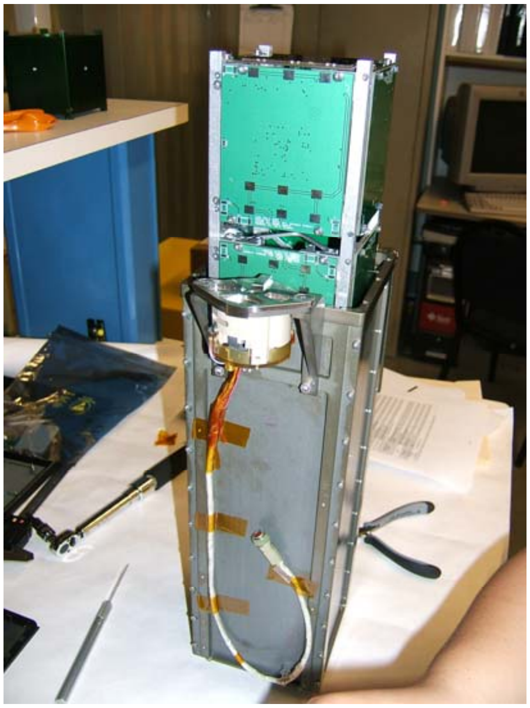

Figure 44 : Insertion of CP-X Satellite into the P-POD

10.2 Vibration Table Testing Setup

To qualify for most U.S. launch vehicles, the NASA GEVS vibration qualification is used to qualify the picosatellites. Table 12 shows the test levels for the NASA GEVS Qualification Test.

Table 12 : NASA GEVS Qualification Test Levels

Hz	G2 / Hz
20	0.026
50	0.16
800	0.16
2000	0.026

The P-POD with the test satellite within it is attached to a mounting plate (specifically made for the P-POD). This mounting plate is then attached to a larger mounting plate that is mounted to the vibration table. Since the vibration table has movement in the horizontal direction, to test all three axis the P-POD will initially be tested for Z-axis vibration and then needs to be turned 90 degrees for the X-axis vibration and then rotated 90 degrees for the Y-axis vibration. See Figure 45 for clarification of the orientation of the P-POD in reference to the axis being tested.

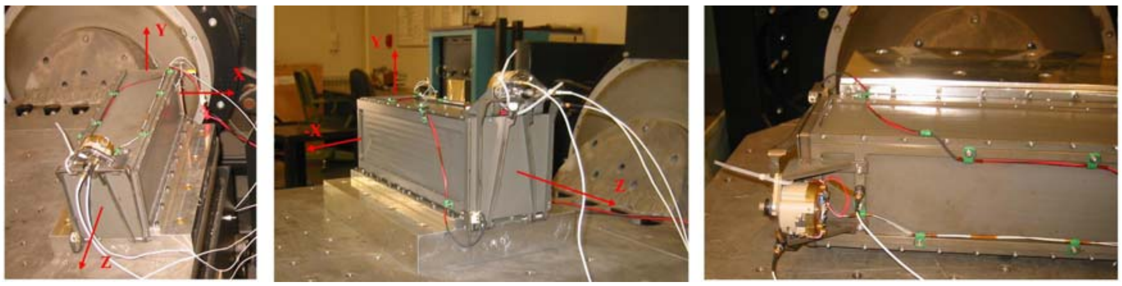

Figure 45 : Vibe Table Z-Axis, X-Axis, and Y-Axis Orientation of the P-POD

One tri-axis accelerometer was placed on the top exterior of the P-POD near the front door and held in place with a red wax compound.

10.3 Vibration Qualification Results

As predicted by FEA analysis and previous vibration tests with previous structural designs, nothing wrong happened. The vibration test was successful and no parts were damaged or came loose. All screws remained intact without any loosening of any screw. No circuit boards were damaged or showed any sign of damage. Since the triple assembled structure was successfully vibe tested, a double or single structure should also pass. The only sign of any wear was located on the ends of the End Pieces. The End Pieces during vibration rubbed against the bottom plate and the door of the P-POD and some of the Teflon impregnated anodized P-POD surface finish was transferred to the

End Pieces of the CP-X structures. See Figure 46 for a picture of the only abnormal result of the vibration qualification test.

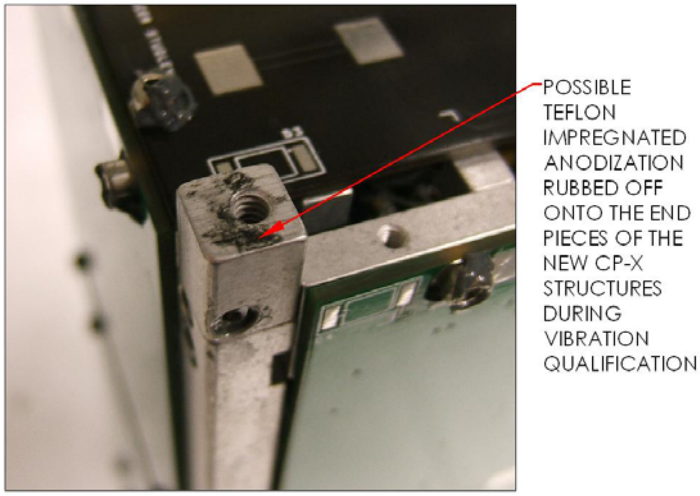

Figure 46 : Possible Teflon Impregnated Anodization Transferred to CP-X

11.0 Conclusions

11.1 Main Design Considerations

In the design of future pico-satellite structures, the importance of defining the parameters which need to be incorporated into the design and sketching various different ways to accomplish this task have been proven a valuable asset in the design phase. Understanding the specifications that need to be met set forth by the CubeSat Standards in conjunction with whatever design parameters are set by previous designs or possible future payloads will save a lot of redesign and re-manufacturing time.

The importance of creating solid models of all components, not only the structural components, is one of the most time saving design tools available. During assembly of vibration qualification triple assembly, the importance of creating assemblies in solid model software and then using a mechanical simulation to assemble the entire satellite was revealed. One item that was seen while creating a standard exploded view of the CPX structures was the necessity to remove solar side panels to gain access to the Internal Board Mount mounting screws along with the Upper/Lower Structure mounting screws. Although the internal components can be accessed in a similar “clamshell” disassembly of the structures, the complexity of the CPX structures does not allow for all of the solar panel boards to be mounted to two halves and then be able to assemble without removing them again. A mechanical simulation of the assembly procedures in a solid model program could have addressed either the acceptance of the current configuration or proposed an alternate (if possible) way to disassemble the structures while leaving the solar panel boards intact. The more precise the designs and mechanical assemblies performed prior to manufacturing can significantly reduce the number of revisions in future structural designs.

11.2 Manufacturing Considerations

The majority, if not all, of the manufacturing for PolySat structures and payloads is now being outsourced to local manufacturing companies; therefore, it is imperative to understand how to communicate your design intent and what parameters need to be met. The following tasks need to always be discussed or understood with outsourcing manufacturing tasks:

- Always have a design kickoff meeting with the manufacturer to define what parameters need to be provided to the manufacturer so there are no extra costs.
- CubeSat standards have tolerances for the “total” structure; therefore, bring it to the attention of the manufacturer that the tolerances have to be met for a fully assembled and anodized structure, not just the individual parts.
- The lowest bid price is not always the best. Sometimes the higher price actually produces the product you need in the desired time you want at the acceptable tolerances you choose.
- Provide anodization compensated drawings to the manufacturer so there are no confusions to what surfaces need anodization compensation and so the manufacturer can be held accountable for not making targeted tolerances.
- When it comes to compensated tolerances, educate the manufacturer on why certain areas need compensation. This will help them visualize the importance of making the tolerances requested.

- Make the manufacturer commit to a reasonable time line needed to complete the structures. Penalties for not completion within the stated time should be discussed and agreed upon at the initial design review. A final limit date should be set that if the work is not complete, another manufacturer can be hired to complete the unfinished work and those charges subtracted from the original quoted price.

Following these tasks will ensure time and costs of manufacturing will be decreased and fewer errors will be propagated into the manufactured structures.

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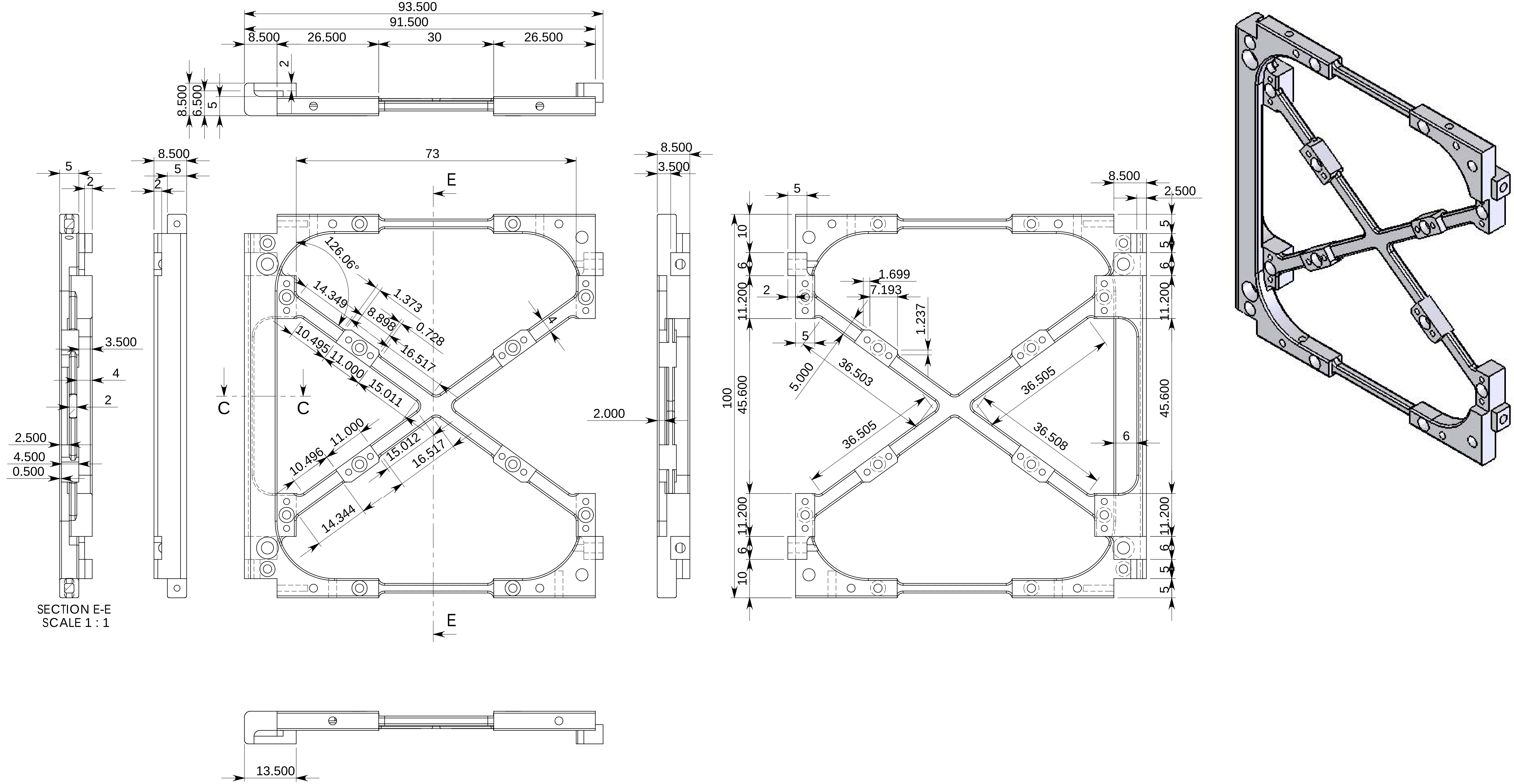
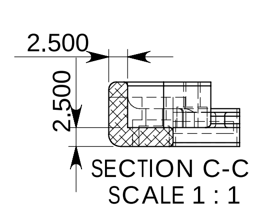
APPENDIX A: CPX Specifications

The following pages are mechanical drawings of the individual CPX structure pieces and also assembled structure drawings for single, double, and triple length structures in 11x17 paper format. Each drawing was completed using the drawing feature in SolidWorks 2006. The drawing feature simplifies the time it takes to produce standard 3-view mechanical drawings by allowing single parts or assemblies to be imported into a 2-D drafting environment. The title block surrounding each drawing is a template incorporated into the SolidWorks drawing feature and has been modified to reference CPX structures and its properties.





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DIMENSIONS ARE IN MM
TOLERANCES: ±0.1
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: 7075 AL

FINISH: ANODIZED CLEAR HARD COAT

DO NOT SCALE DRAWING

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DRAWN		
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ENG APPR.		
MFG APPR.		
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COMMENTS:

TITLE:

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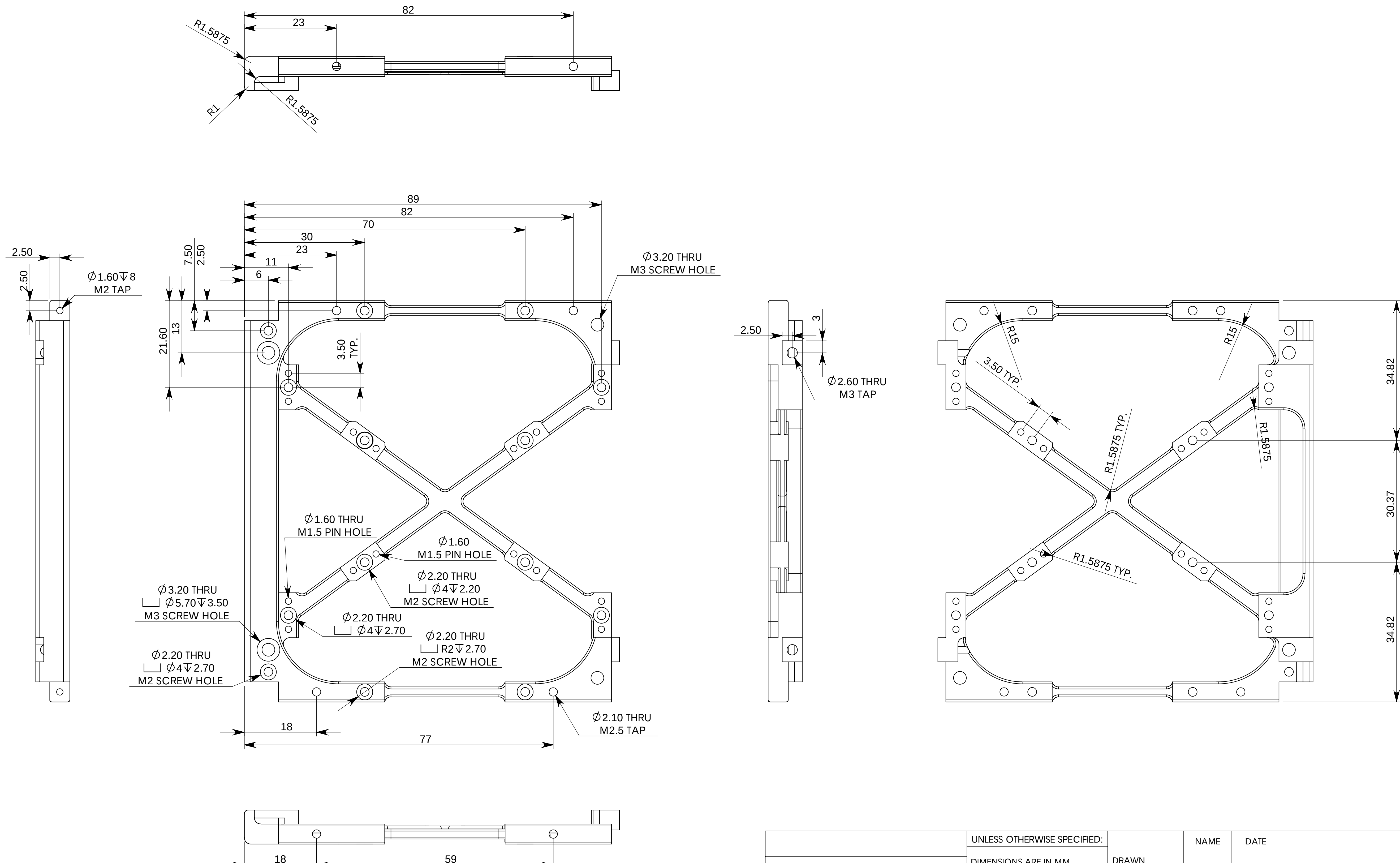

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		MATERIAL AL 7075	COMMENTS:		
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SIDE HOLES AND RADII

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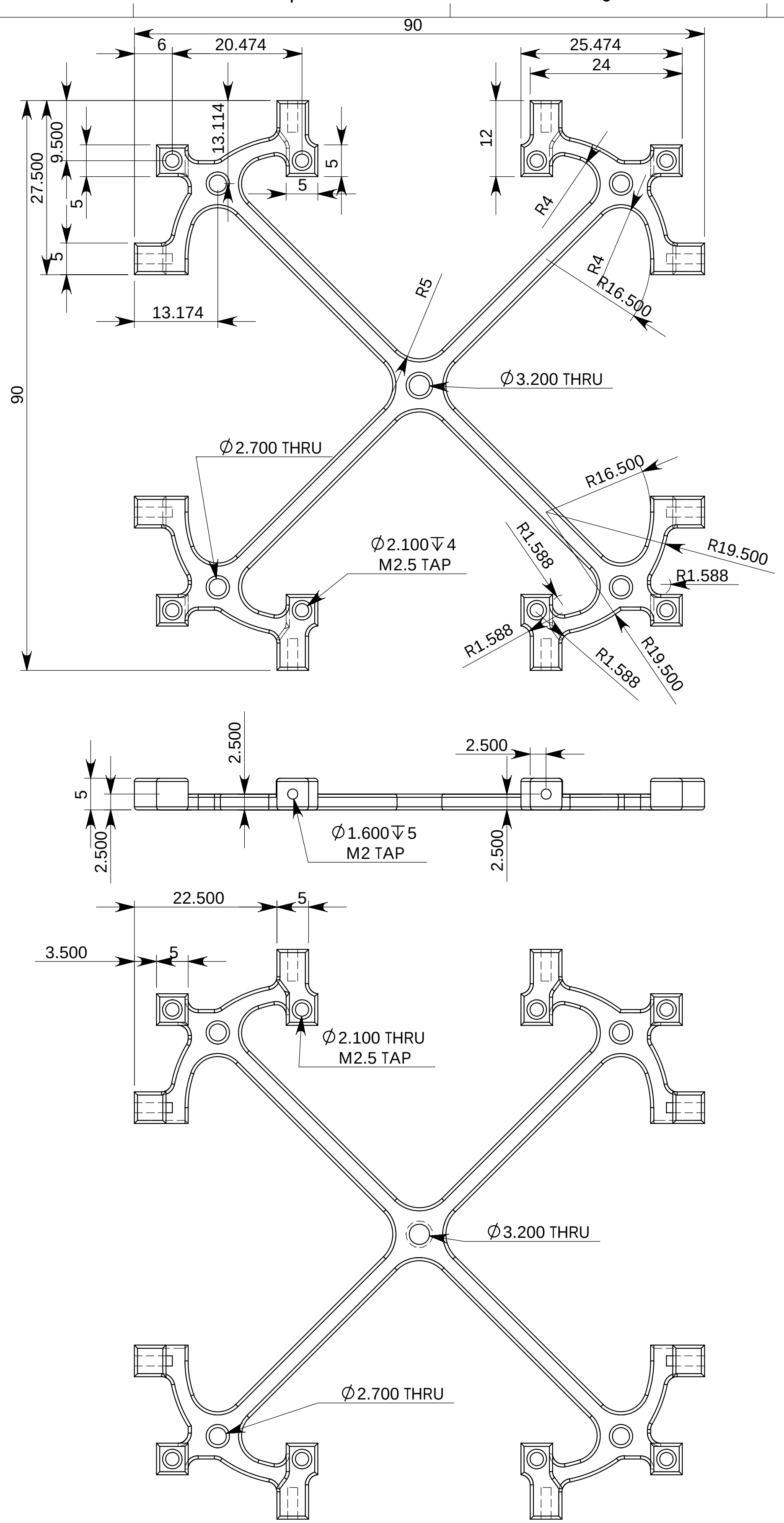

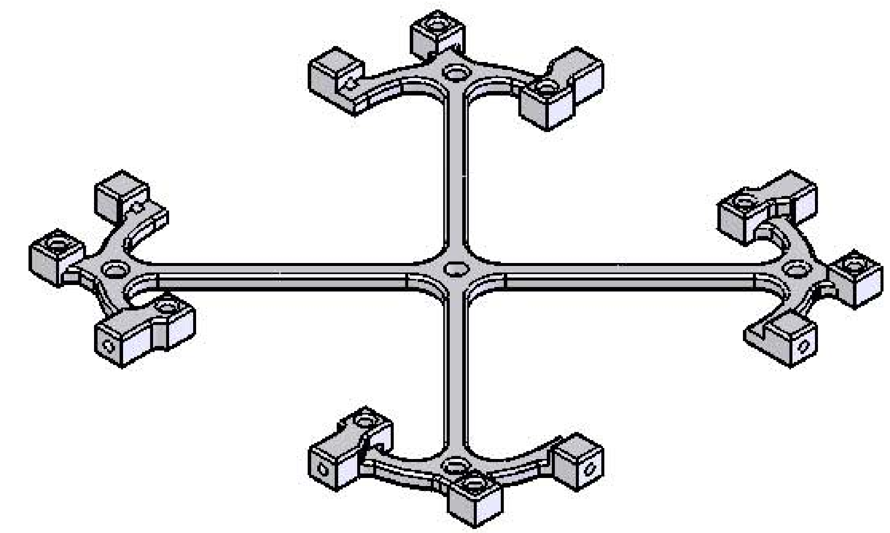

TOP/BOTTOM CROSS BRACE WITH
INTERNAL BOARD MOUNT HOLES

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INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL AL 7075

FINISH ANODIZED HARD CLEAR COAT

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TOP/BOTTOM CROSS BRACE

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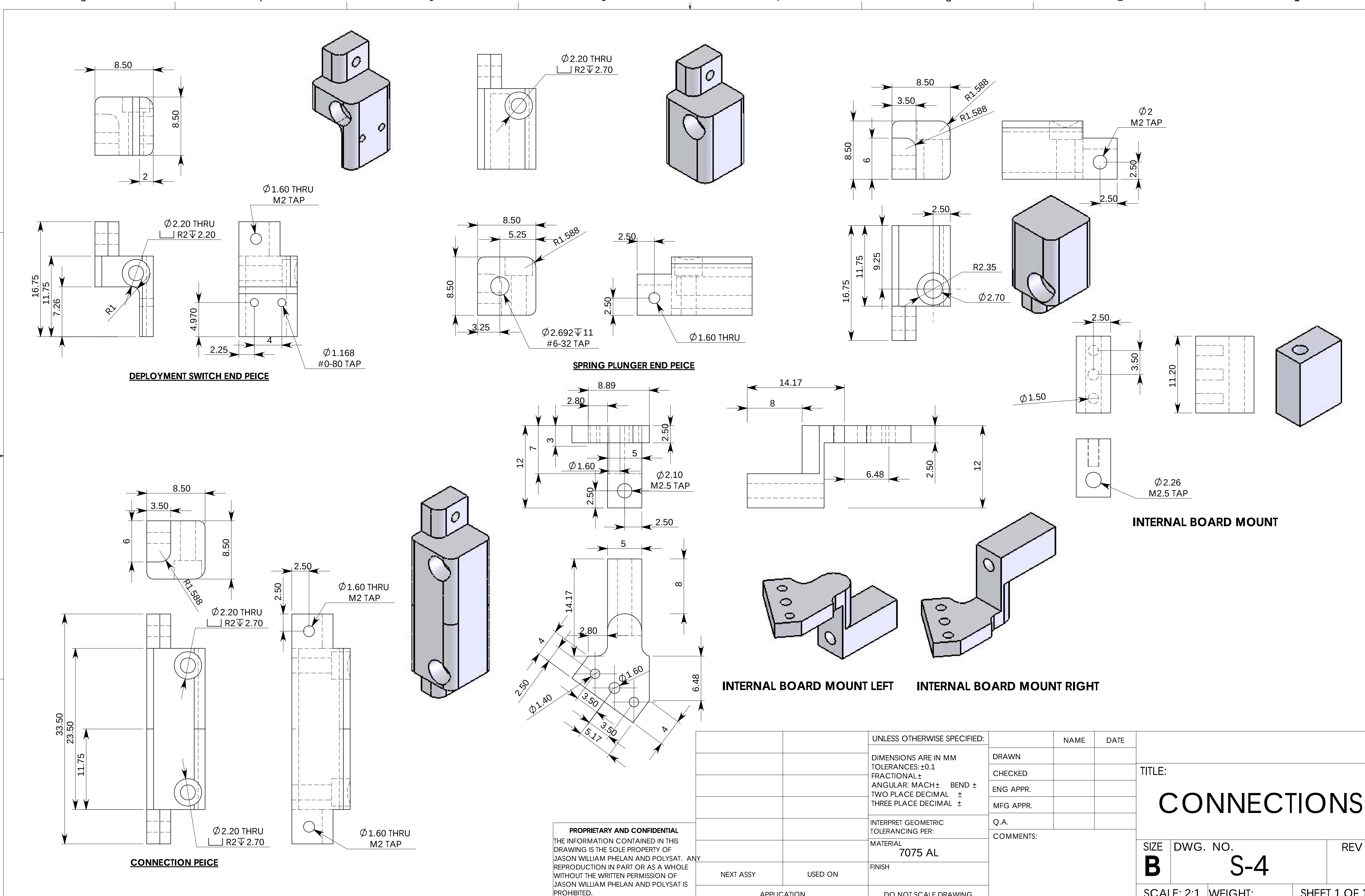
DEPLOYMENT SWITCH END PEICE
8.50
2
Ø2.20 THRU
R2 ↧ 2.20
16.75
11.75
7.26
R1
Ø1.60 THRU
M2 TAP
4.970
2.25
4
Ø1.168
#0-80 TAP
Ø2.20 THRU
R2 ↧ 2.70
SPRING PLUNGER END PEICE
5.25
R1.588
3.25
Ø2.692 ↧ 11
#6-32 TAP
2.50
Ø1.60 THRU
3.50
R1.588
6
Ø2
M2 TAP
9.25
R2.35
Ø2.70
INTERNAL BOARD MOUNT
Ø1.50
11.20
Ø2.26
M2.5 TAP
8.89
2.80
3
7
12
Ø1.60
5
Ø2.10
M2.5 TAP
14.17
8
6.48
INTERNAL BOARD MOUNT LEFT
INTERNAL BOARD MOUNT RIGHT
CONNECTION PEICE
33.50
23.50
Ø1.40
5.17
Ø1.60
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DIMENSIONS ARE IN MM
TOLERANCES: ±0.1
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MATERIAL
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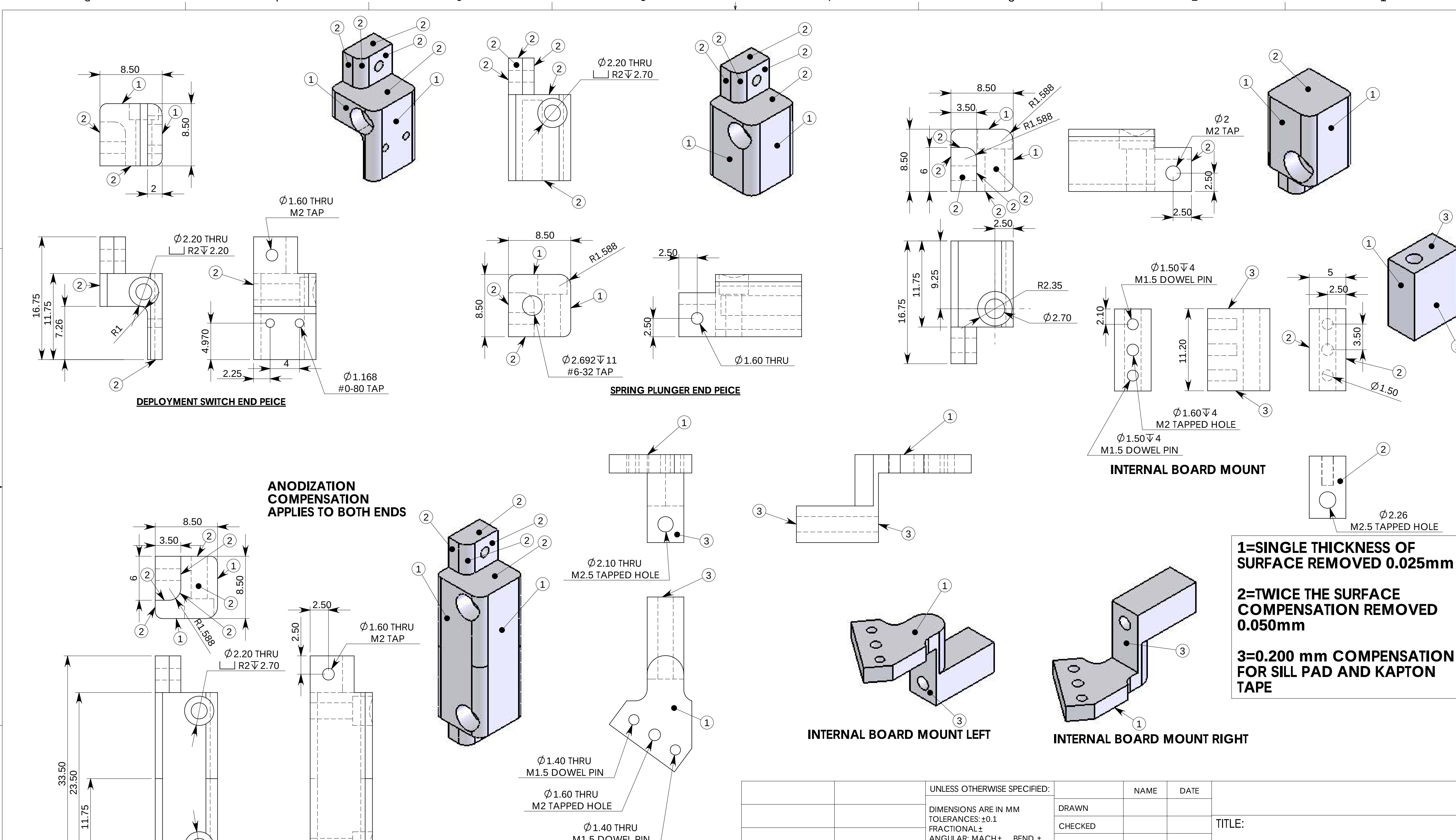

1=SINGLE THICKNESS OF SURFACE REMOVED 0.025mm

2=TWICE THE SURFACE COMPENSATION REMOVED 0.050mm

3=0.200 mm COMPENSATION FOR SILL PAD AND KAPTON TAPE

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APPLICATION		

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DIMENSIONS ARE IN MM
TOLERANCES: ±0.1
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL 7075 AL

FINISH

DO NOT SCALE DRAWING

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ENG APPR.		
MFG APPR.		
Q.A.		

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CONNECTIONS ANODIZE COMP.

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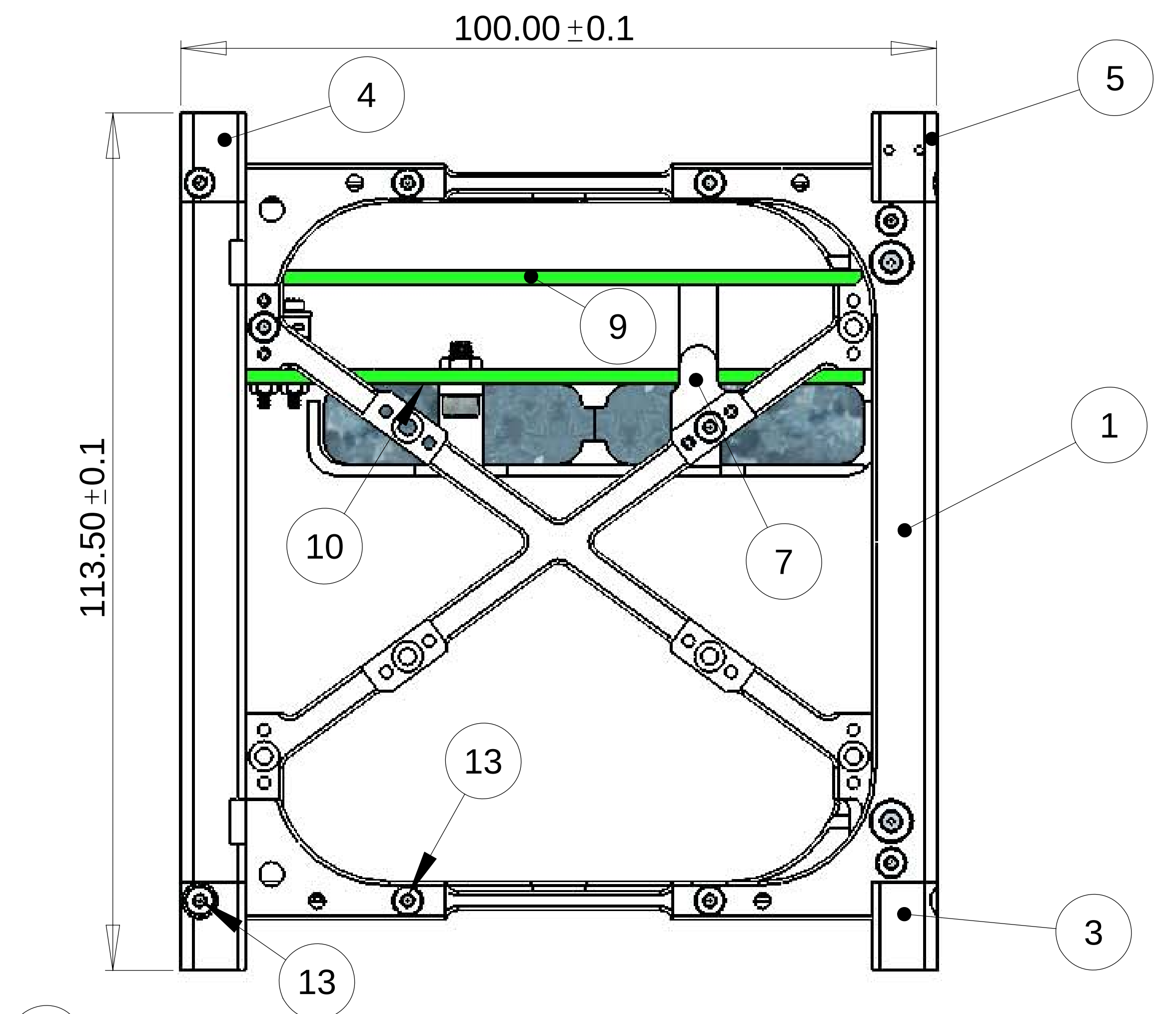
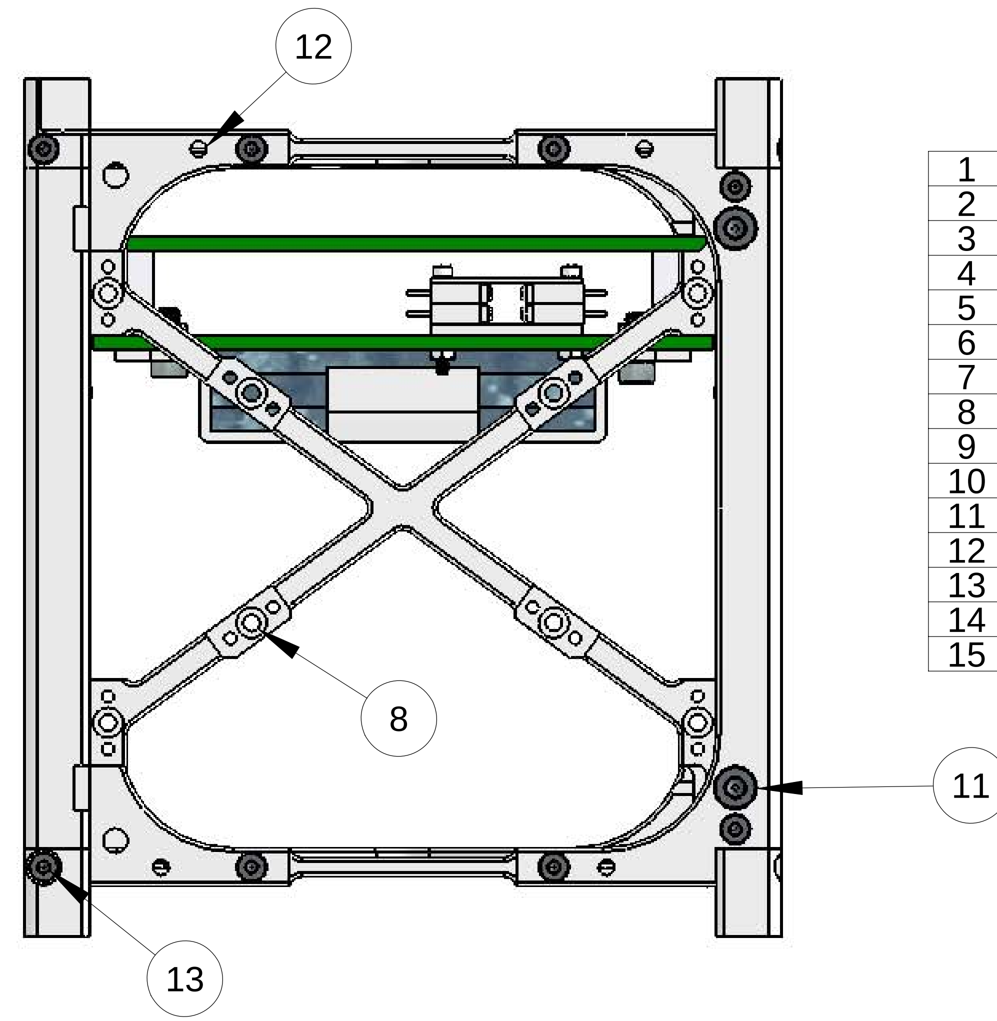
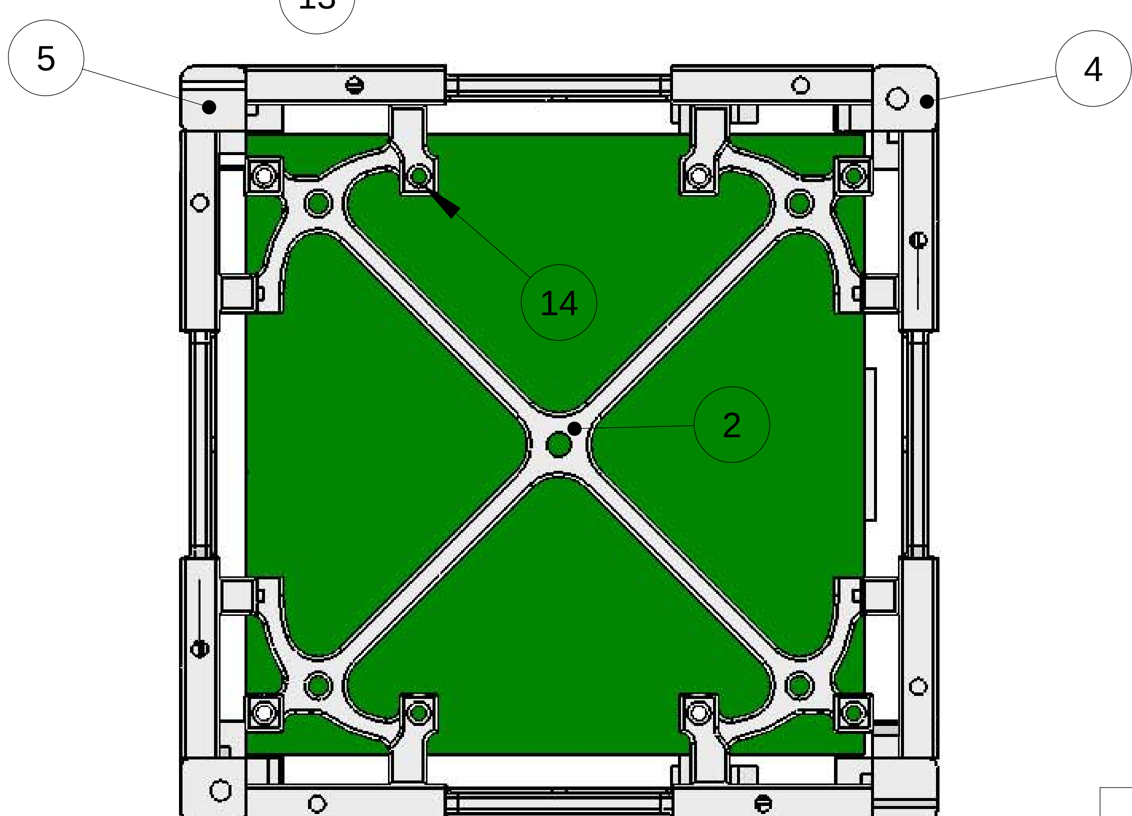




1	MODULAR SIDE
2	UPPER/LOWER STRUCTURE
3	END PIECE
4	END PIECE WITH SPRING PLUNGER
5	END PIECE WITH DEPLOYMENT SWITCH
6	INTERNAL BOARD MOUNT
7	INTERNAL BOARD MOUNT LEFT
8	MOUNTING HOLE LOCATIONS
9	C&DH BOARD
10	POWER BOARD
11	M3 SCREW
12	M2.5 TAPPED HOLE
13	M2 SCREW
14	
15	



NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN MM
TOLERANCES: ±0.1
FRACTIONAL ±0.1
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
7075 T6 ALUMINUM

FINISH
ANODIZED: HARD CLEAR COAT

DO NOT SCALE DRAWING

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ENG APPR.		
MFG APPR.		
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COMMENTS:		

TITLE:

SINGLE ASSEMBLY WITH C&DH/POWER BOARDS

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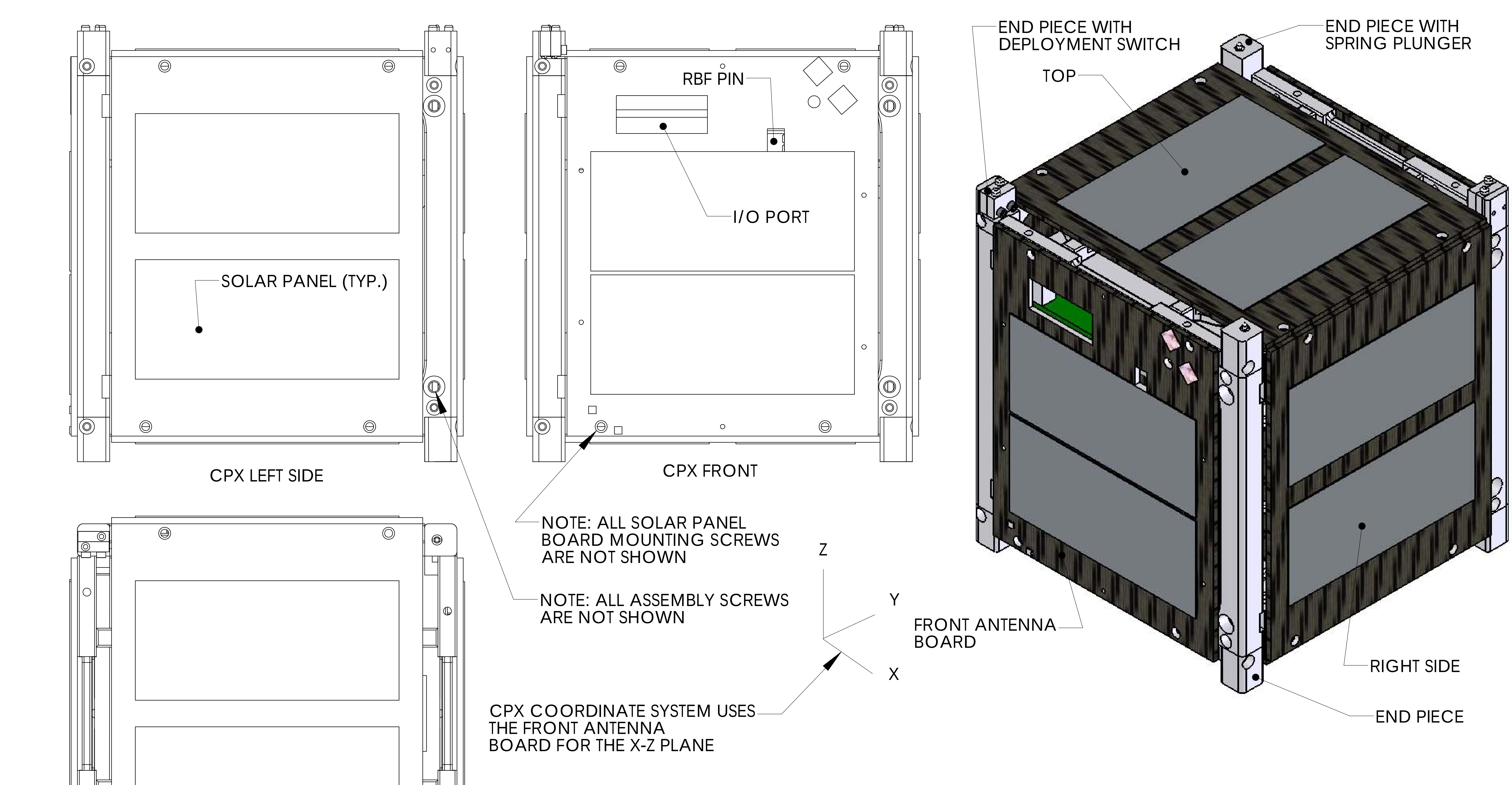

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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN MM
TOLERANCES±0.1
FRACTIONAL±0.1
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: 7075 T6 ALUMINUM

FINISH: ANODIZED: CLEAR HARD

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

SINGLE ASSEMBLY ORIENTATION

SIZE	DWG. NO.	REV
B	S-7	

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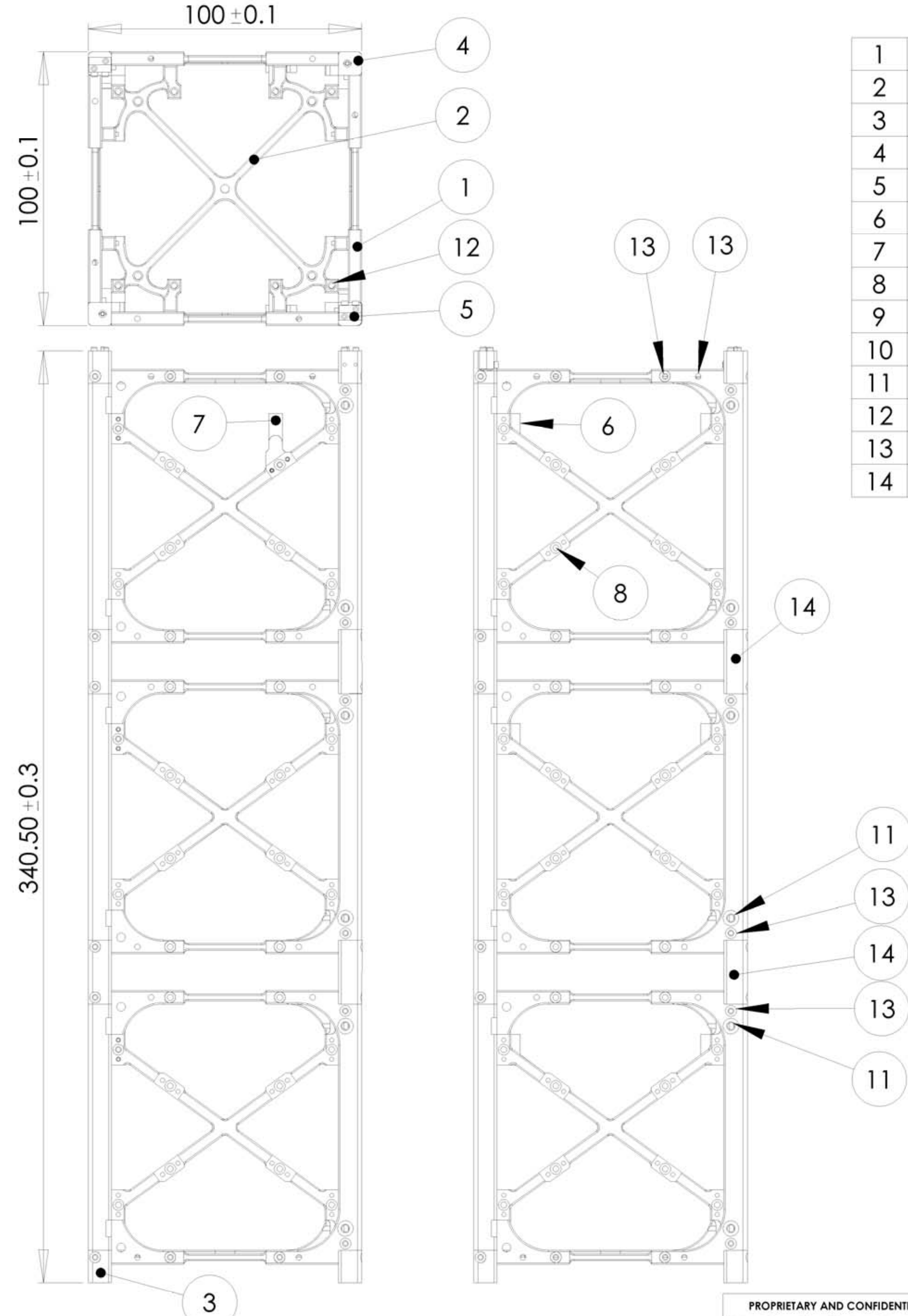
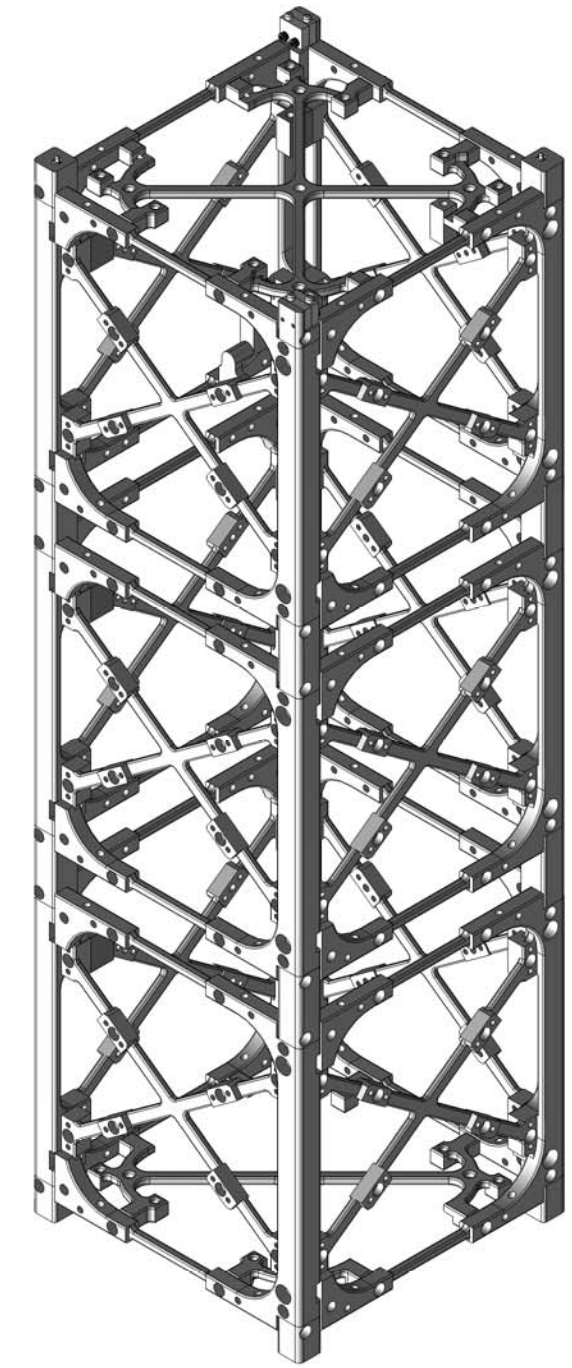


1	MODULAR SIDE
2	UPPER/LOWER STRUCTURE
3	END PIECE
4	END PIECE WITH SPRING PLUNGER
5	END PIECE WITH DEPLOYMENT SWITCH
6	INTERNAL BOARD MOUNT
7	INTERNAL BOARD MOUNT RIGHT
8	MOUNTING HOLE LOCATIONS
9	C&DH BOARD (NOT SHOWN)
10	POWER BOARD (NOT SHOWN)
11	M3 SCREW LOCATION
12	M2.5 TAPPED HOLE
13	M2 SCREW LOCATION
14	INTERCONNECTION PIECE

NOTE:
CONNECTION SCREWS ARE NOT SHOWN ON THIS ASSEMBLY TO CLARIFY ASSEMBLY OF TRIPLE STRUCTURES AND SMALL STRUCTURAL PIECES



NEXT ASSY | USED ON
APPLICATION

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES: ±0.1
FRACTIONAL ±0.1
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
ALUMINUM 7075 T6
FINISH
ANODIZED: HARD CLEAR
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
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MFG APPR.		
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TRIPLE ASSEMBLY STRUCTURES

SIZE B | DWG. NO. S-8 | REV
SCALE: 1:2 | WEIGHT: | SHEET 1 OF 1

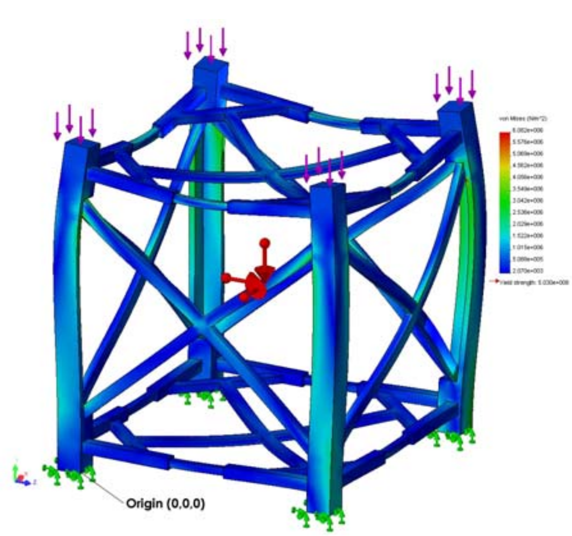
APPENDIX B: FEA Results

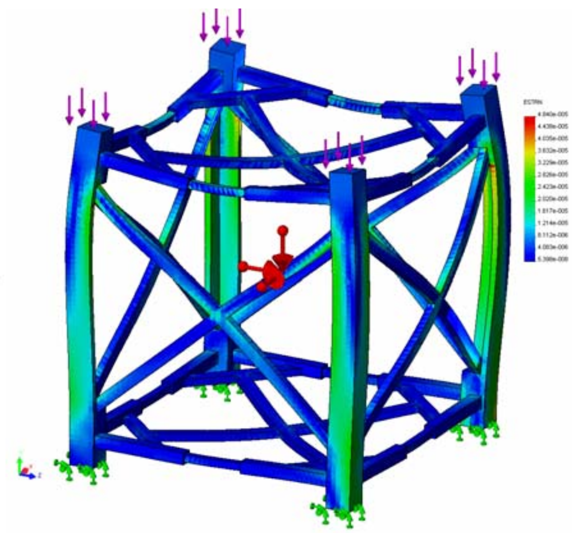
Finite Element Analysis was obtained using COSMOSWorks 2005 SP1.0 with the following parameters for aluminum 7075 T6:

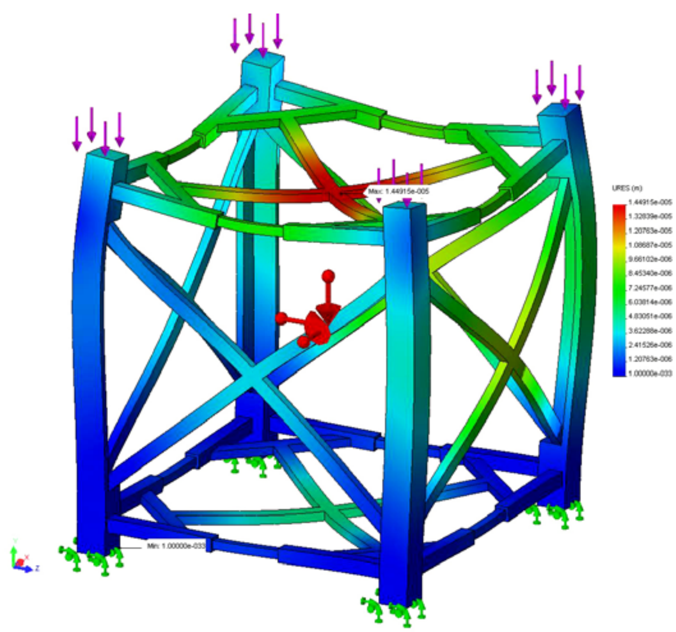
Aluminum 7075 T6 Properties for FEA			
Property Name	**Value**	**Units**	**Value Type**
Elastic modulus	7.20E+10	N/m^2	Constant
Poisson's ratio	0.33	NA	Constant
Shear modulus	2.69E+10	N/m^2	Constant
Mass density	2810	kg/m^3	Constant
Tensile strength	5.05E+08	N/m^2	Constant
Compressive strength	5.03E+08	N/m^2	Constant
Yield strength	5.03E+08	5.03E+08	Constant
Thermal expansion coefficient	2.40E-05	/Kelvin	Constant
Thermal conductivity	130	W/(m.K)	Constant
Specific heat	960	J/(kg.K)	Constant

Each individual study is listed with a picture of the plots and the pertaining stress, strain, and displacement data associated with the plots (in that order with the data located below the three plots). The origin (X=0, Y=0, and Z=0) is located on the inside of the bottom of the rail closest to the displayed axis (refer to first stress plot for CPX Cross Cube origin location which applies to all CPX plots).

The following plots and data are for a simplified CPX Cross Cube with vertical Z-axis force of 36N and 18G's in all axis:

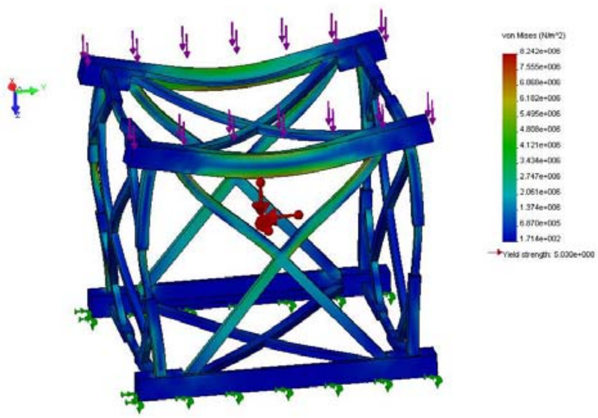


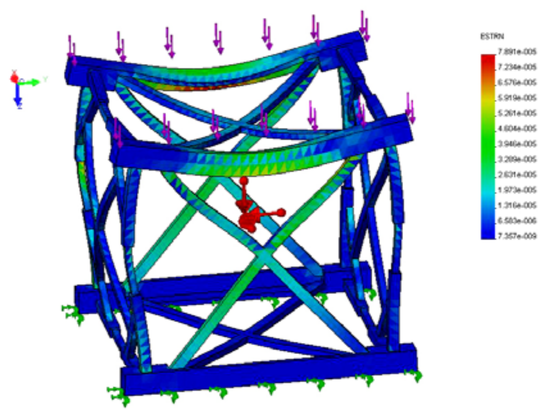


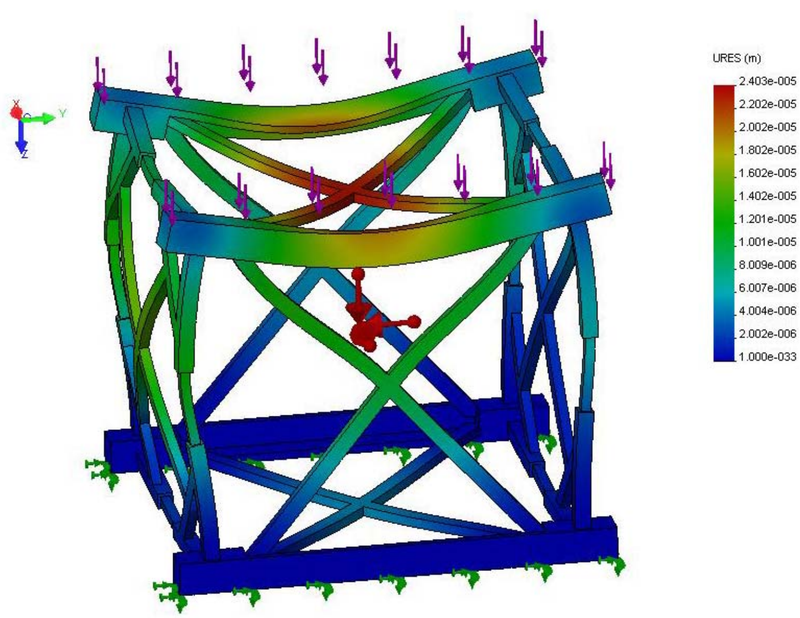


CPX Cross Cube Bottom Mount Vertical Load 18G's 36N: Minimum FOS = 83								
Analysis Type	**Minimum**	**Units**	**Node/Element**	**Location (X,Y,Z) in mm**	**Maximum**	**Units**	**Node/Element**	**Location (X,Y,Z) in mm**
VON: Von Mises Stress	2069.92	N/m^2	Node: 9406	34.75, 10.75, 88.5	6.08246E+06	N/m^2	Node: 66379	91.5, 89.3213, -6.5
ESTRN: Equivalent Strain	5.40E-08	m	Element: 18222	4.875, 7.25, 27.9571	4.84042E-05	m	Element: 15389	98.5, 89.0378, 83.4063
URES: Resultant Displacement	0	m	Node: 5217	8.5, 2.77556E-14, 0	1.44915E-05	m	Node: 92248	51.3162, 105.5, 42.8855

The following plots and data are for a simplified CPX Cross Cube side mounted with a side force of 36N and 18G's in all axis:

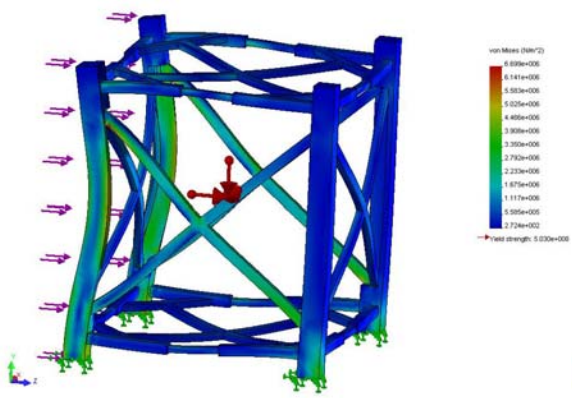


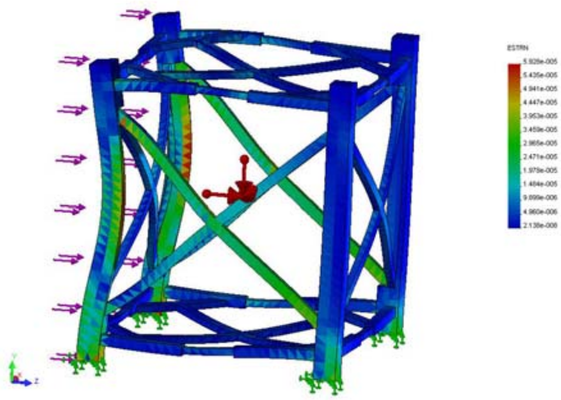


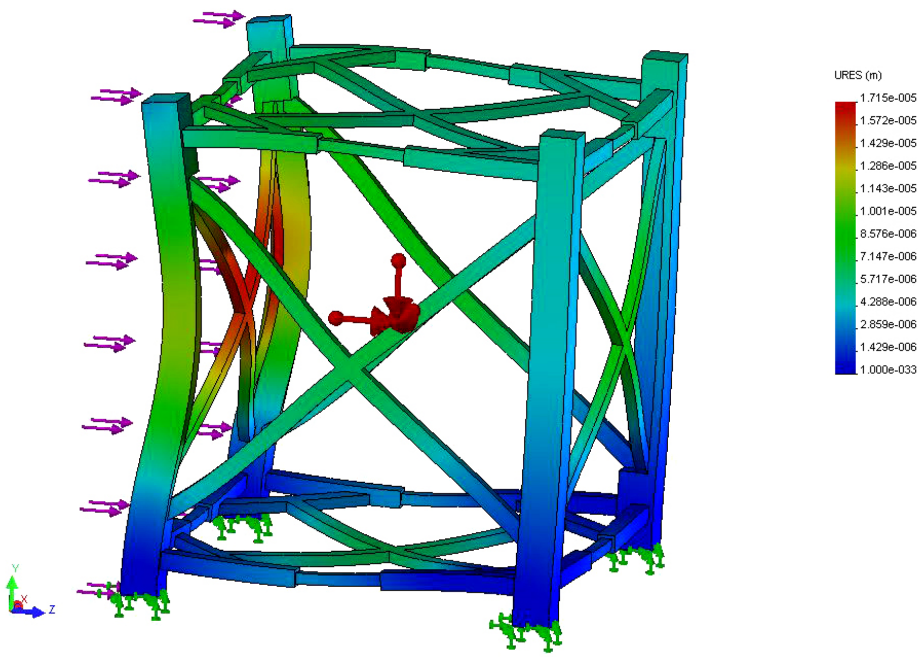


CPX Cross Cube Side Mount Side Load 18G's 36N: Minimum FOS = 61								
Analysis Type	**Minimum**	**Units**	**Node/Element**	**Location (X,Y,Z) in mm**	**Maximum**	**Units**	**Node/Element**	**Location (X,Y,Z) in mm**
VON: Von Mises Stress	171.401	N/m^2	Node: 16317	6.875, 64.6743, 89.5	8.24213E+06	N/m^2	Node: 6291	95.75, 10, 33.1667
ESTRN: Equivalent Strain	7.36E-09	m	Element: 7320	93.375, 84.0019, 91	7.89143E-05	m	Element: 9065	1.5, 56.3201, -0.8125
URES: Resultant Displacement	0	m	Node: 2817	8.5, 2.77556E-14, 91.5	2.40263E-05	m	Node: 2002	8.5, 55.0303, -8.5

The following plots and data are for a simplified CPX Cross Cube vertical mounted with a side force of 36N and 18G's in all axis:

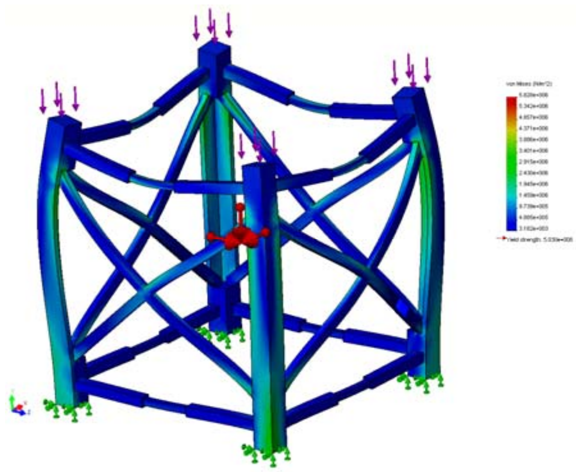


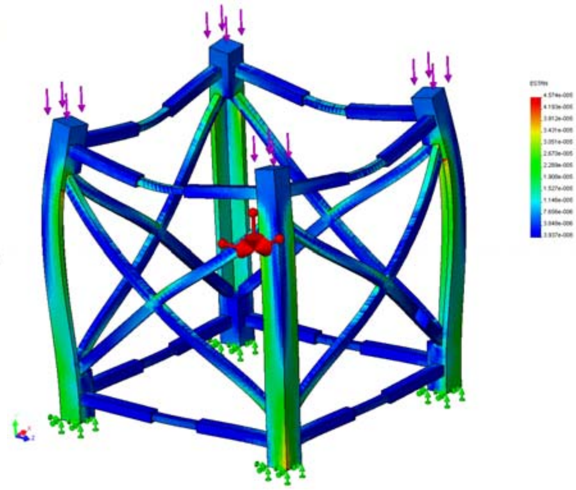


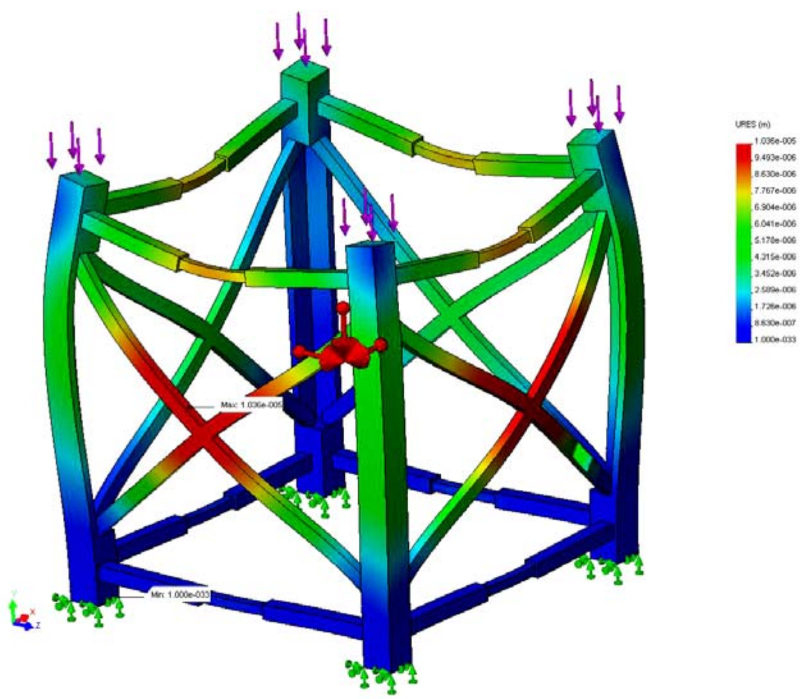


CPX Cross Cube Bottom Mount Side Load 18G's 36N: Minimum FOS = 75								
Analysis Type	Minimum	Units	Node/Element	Location (X,Y,Z) in mm	Maximum	Units	Node/Element	Location (X,Y,Z) in mm
VON: Von Mises Stress	272.368	N/m^2	Node: 3060	91.5, 113.5, 83	6.69944E+06	N/m^2	Node: 18110	2, 89.0866, 1.28183
ESTRN: Equivalent Strain	2.14E-08	m	Element: 5463	7.447, 110.552, 83.4959	5.92848E-05	m	Element: 1436	92.8059, 1.29121, -0.509425
URES: Resultant Displacement	0	m	Node: 1906	8.5, 2.77556E-14, 0	1.71522E-05	m	Node: 2593	91.5, 61.9091, -8.5

The following plots and data are for a simplified CPX Cross Cube with no Upper/Lower Structure with a vertical Z-axis force of 36N and 18G's in all axis:

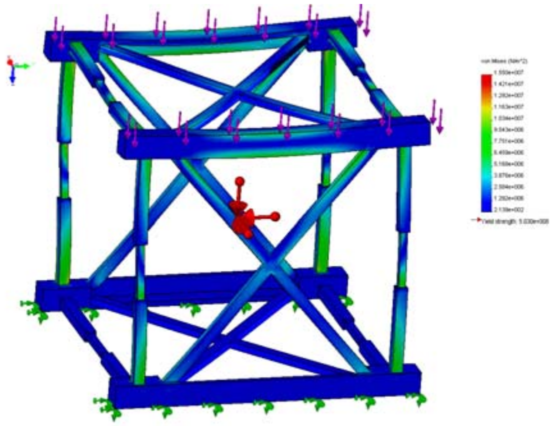


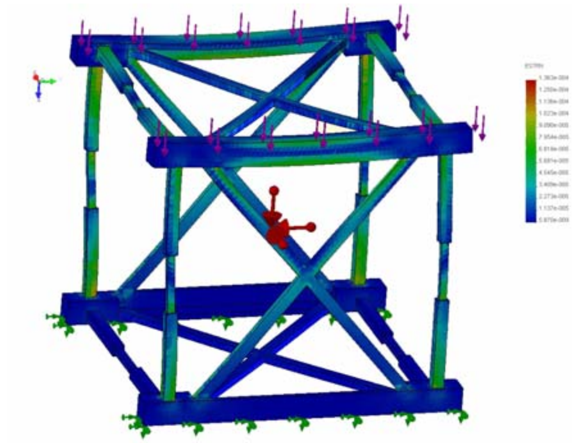


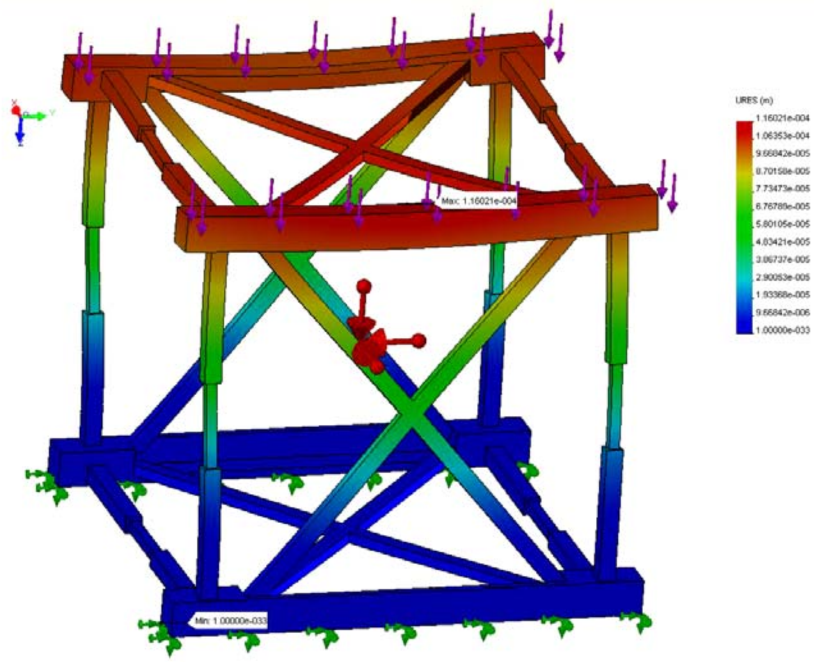


CPX Cross Sides (No Upper/Lower Structure) Bottom Mount Vertical Load 18G's 36N: Minimum FOS = 110								
Analysis Type	**Minimum**	**Units**	**Node/Element**	**Location (X,Y,Z) in mm**	**Maximum**	**Units**	**Node/Element**	**Location (X,Y,Z) in mm**
VON: Von Mises Stress	6301.09	N/m^2	Node: 925	2, 52.5685, 49.3522	4.74693E+06	N/m^2	Node: 18738	8.5, 88.529, 89.5
ESTRN: Equivalent Strain	6.51E-08	m	Element: 8316	39.2125, 10.0625, -7.3125	4.07648E-05	m	Element: 8832	7.7896, 88.0414, 90
URES: Resultant Displacement	0	m	Node: 1478	8.5, 2.77556E-14, 0	1.01171E-05	m	Node: 19384	3.25, 63.6463, 36.6176

The following plots and data are for a simplified CPX Cross Cube with no Upper/Lower Structure side mounted with a side force of 36N and 18G's in all axis:

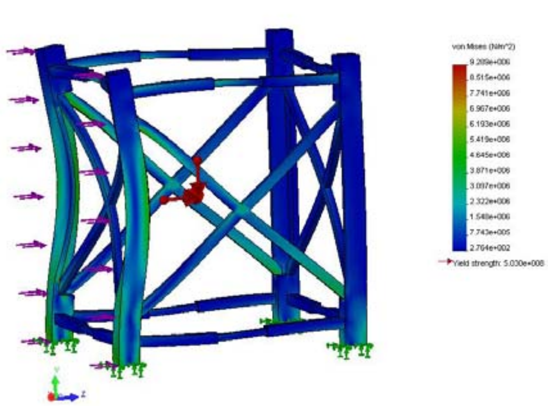


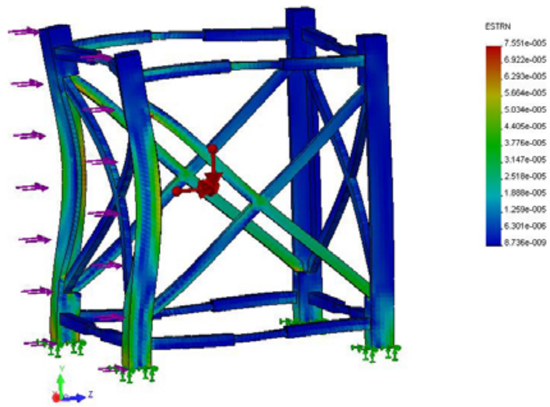


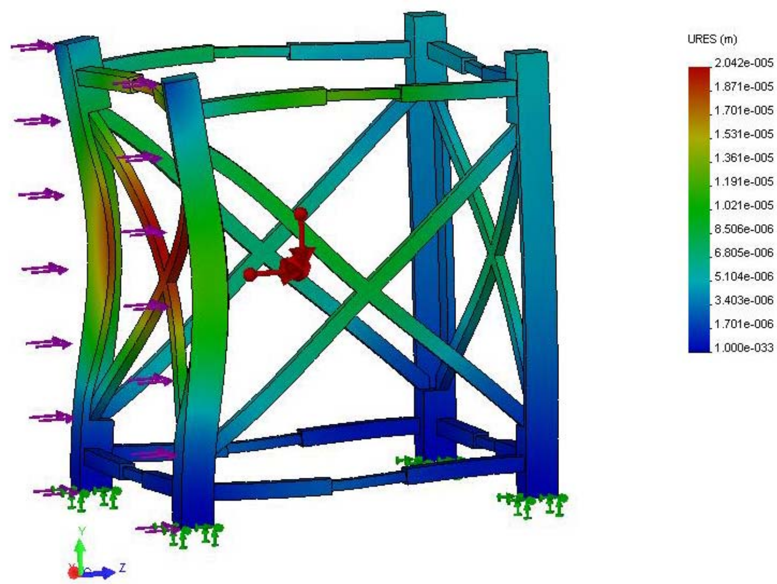


CPX Cross Sides (No Upper/Lower Structure) Side Mount Side Load 18G's 36N: Minimum FOS = 32								
Analysis Type	**Minimum**	**Units**	**Node/Element**	**Location (X,Y,Z) in mm**	**Maximum**	**Units**	**Node/Element**	**Location (X,Y,Z) in mm**
VON: Von Mises Stress	213.871	N/m^2	Node: 68150	6.875, 45.2074, 89.5	1.55024E+07	N/m^2	Node: 87121	99, 6.75, 82.171
ESTRN: Equivalent Strain	5.87E-09	m	Element: 38455	91.9062, 77.3639, 90	1.36347E-04	m	Element: 15278	98.6667, 7.08333, 82.5855
URES: Resultant Displacement	0	m	Node: 7287	8.5, 2.77556E-14, 91.5	1.16021E-04	m	Node: 60697	8.5, 55.9155, -8.5

The following plots and data are for a simplified CPX Cross Cube with no Upper/Lower Structure with a side force of 36N and 18G's in all axis:

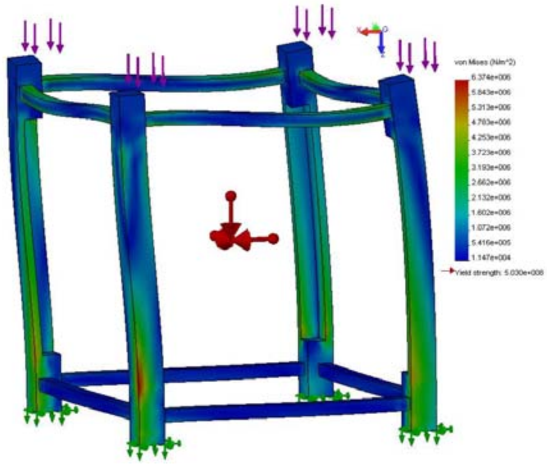


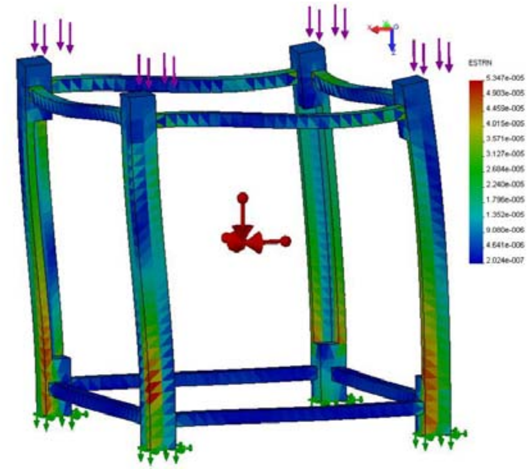


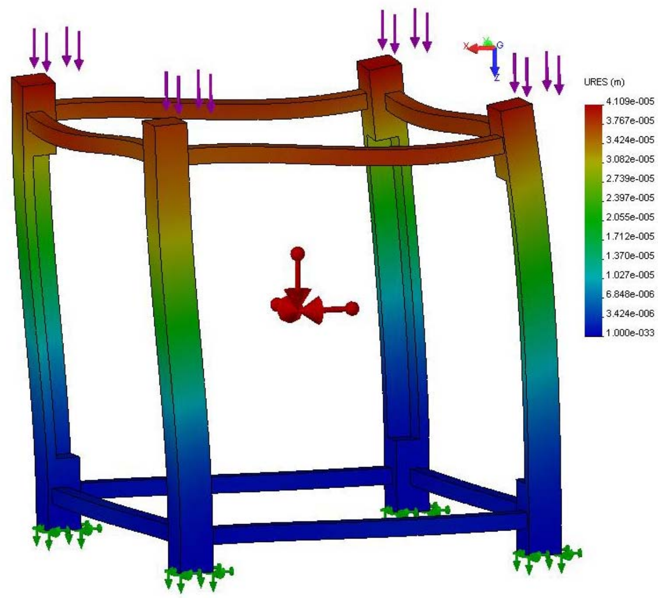


CPX Cross Sides (No Upper/Lower Structure) Bottom Mount Vertical Load 18G's 36N: Minimum FOS = 54								
Analysis Type	**Minimum**	**Units**	**Node/Element**	**Location (X,Y,Z) in mm**	**Maximum**	**Units**	**Node/Element**	**Location (X,Y,Z) in mm**
VON: Von Mises Stress	276.37	N/m^2	Node: 7133	4.04596E-13, 113.5, 83	9.28906E+06	N/m^2	Node: 73997	2, 89.6621, 0.620242
ESTRN: Equivalent Strain	8.74E-09	m	Element: 39430	91.8542, 113.091, 83.3542	7.55125E-05	m	Element: 31015	2.27225, 90.087, 0.912253
URES: Resultant Displacement	0	m	Node: 4129	8.5, 2.7756E-14, 0	2.04154E-05	m	Node: 64698	41.197, 67.0569, -5.25

The following plots and data are for a simplified cube with no diagonal support with a vertical Z-axis force of 36N and 18G's in all axis:

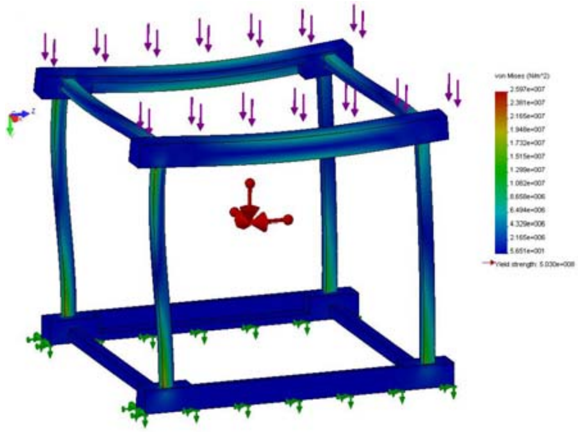


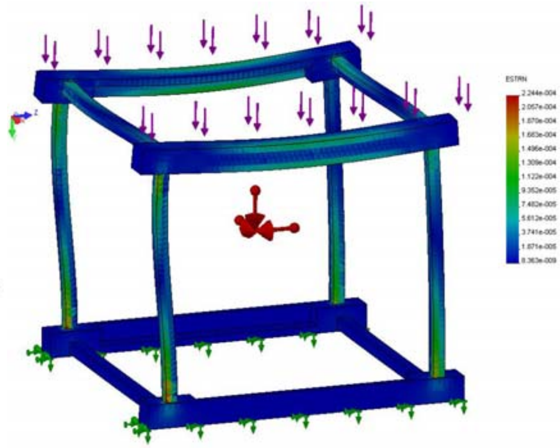


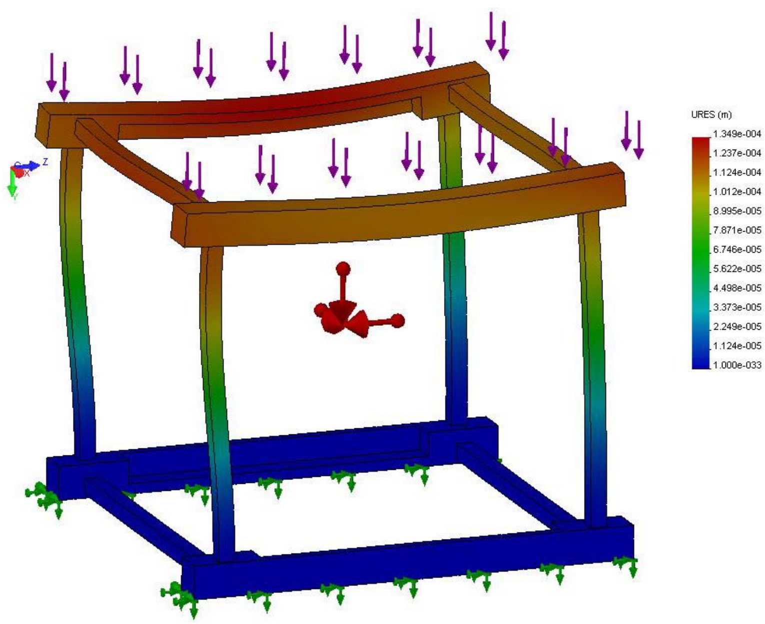


Cube with No Diagonal Bracing Bottom Mount Vertical Load 18G's 36N : Minimum FOS = 94								
Analysis Type	**Minimum**	**Units**	**Node/Element**	**Location (X,Y,Z) in mm**	**Maximum**	**Units**	**Node/Element**	**Location (X,Y,Z) in mm**
VON: Von Mises Stress	16499.3	N/m^2	Node: 175	10.2788, 96.7225, 29.2903	5.33550E+06	N/m^2	Node: 919	101.779, 5.22251, 109.839
ESTRN: Equivalent Strain	1.90E-07	m	Element: 4854	7.57649, 79.8204, 104.508	5.63581E-05	m	Element: 4732	101.216, 97.4308, 111.815
URES: Resultant Displacement	0	m	Node: 32	93.2788, 105.223, 113.5	3.25134E-05	m	Node: 341	10.2788, 13.7225, 1.388E-14

The following plots and data are for a simplified cube with no diagonal support side mounted with a side force of 36N and 18G's in all axis:

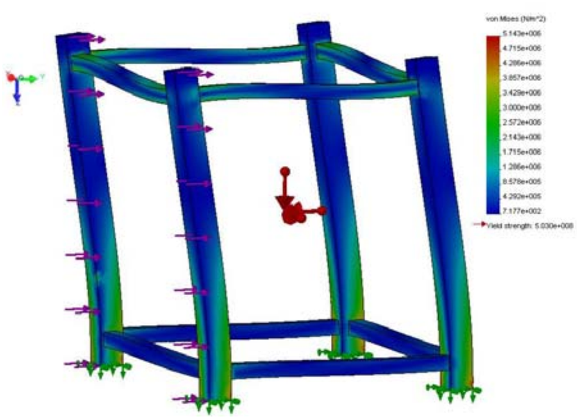


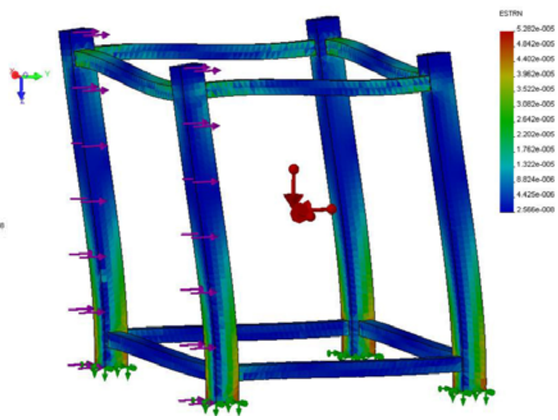


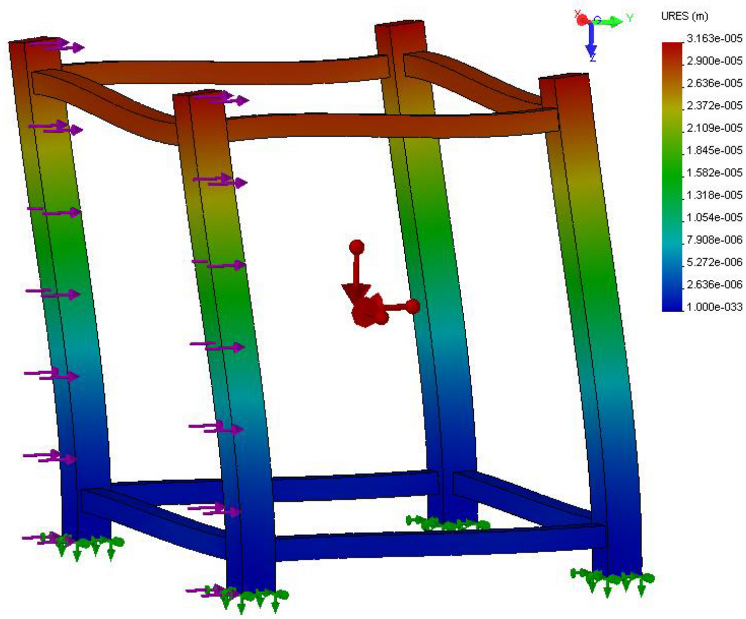


Cube with No Diagonal Bracing Side Mount Side Load 18G's 36N : Minimum FOS = 19								
Analysis Type	**Minimum**	**Units**	**Node/Element**	**Location (X,Y,Z) in mm**	**Maximum**	**Units**	**Node/Element**	**Location (X,Y,Z) in mm**
VON: Von Mises Stress	56.5104	N/m^2	Node: 245	4.27884, 96.7225, 69.0366	2.59749E+07	N/m^2	Node: 30420	100.779, 95.7793, 6.75
ESTRN: Equivalent Strain	8.36E-09	m	Element: 16912	93.7788, 103.348, 37.6077	2.24442E-04	m	Element: 6853	97.1123, 14.1941, 10.4392
URES: Resultant Displacement	0	m	Node: 61	10.2788, 105.223, 2.7755E-14	1.34926E-04	m	Node: 1263	10.2788, 5.22251, 58.6417

The following plots and data are for a simplified cube with no diagonal support with a side force of 36N and 18G's in all axis:

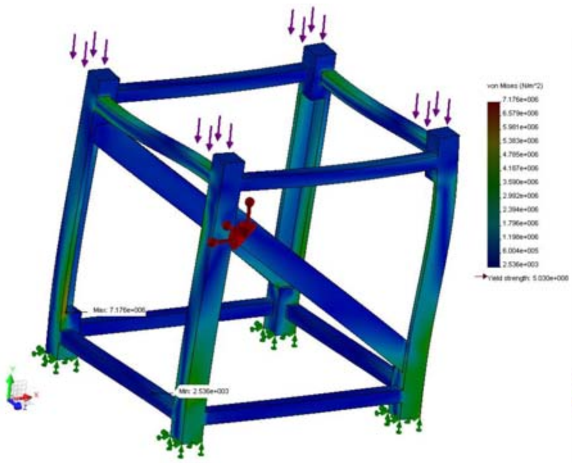


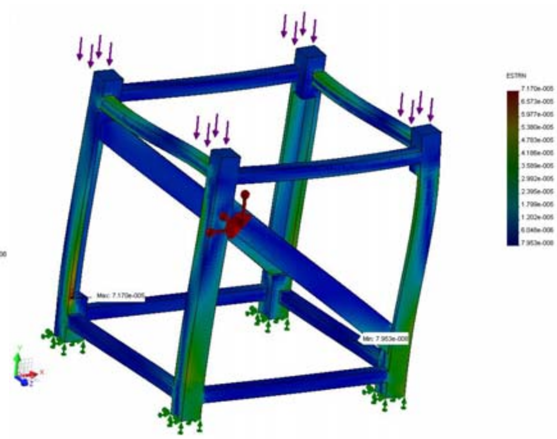


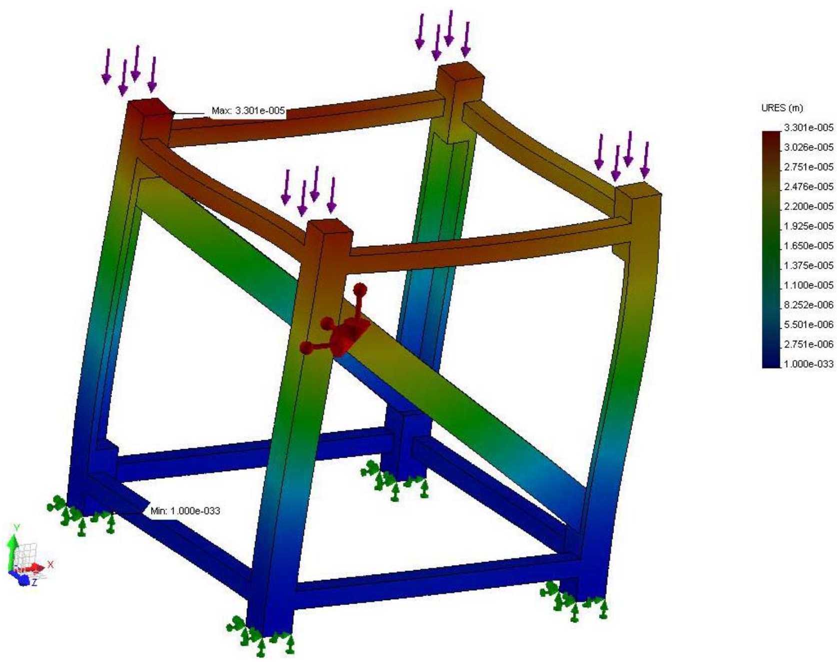


Cube with No Diagonal Bracing Bottom Mount Side Load 18G's 36N : Minimum FOS = 27								
Analysis Type	**Minimum**	**Units**	**Node/Element**	**Location (X,Y,Z) in mm**	**Maximum**	**Units**	**Node/Element**	**Location (X,Y,Z) in mm**
VON: Von Mises Stress	2097.43	N/m^2	Node: 682	93.2788, 105.223, 2.7755E-14	1.84644E+07	N/m^2	Node: 39151	4.27884, 13.7225, 94.4803
ESTRN: Equivalent Strain	5.92E-08	m	Element: 15722	93.7038, 97.1475, 0.5	1.72614E-04	m	Element: 9817	3.65384, 13.2225, 94.8469
URES: Resultant Displacement	0	m	Node: 111	10.2788, 105.223, 113.5	9.39329E-05	m	Node: 282	1.77884, 96.7225, 1.388E-14

The following plots and data are for a simplified CP2/CP3/CP4 structure with a vertical Y-axis force of 36N and 18G's in all axis (orientation changed Z-axis to Y-axis):

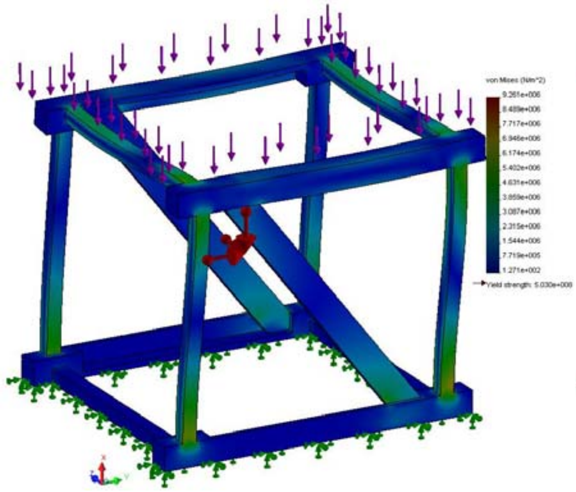


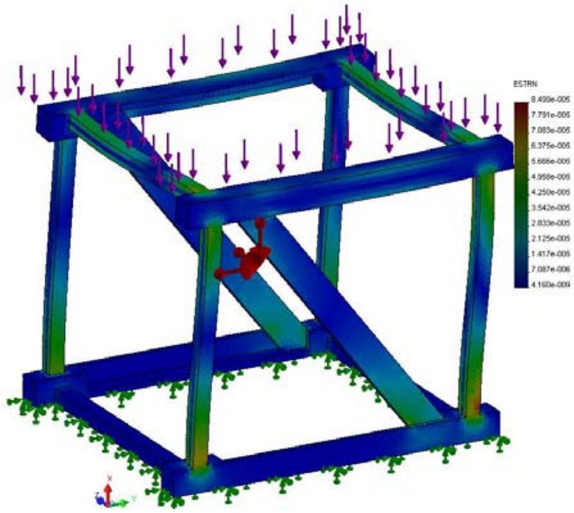


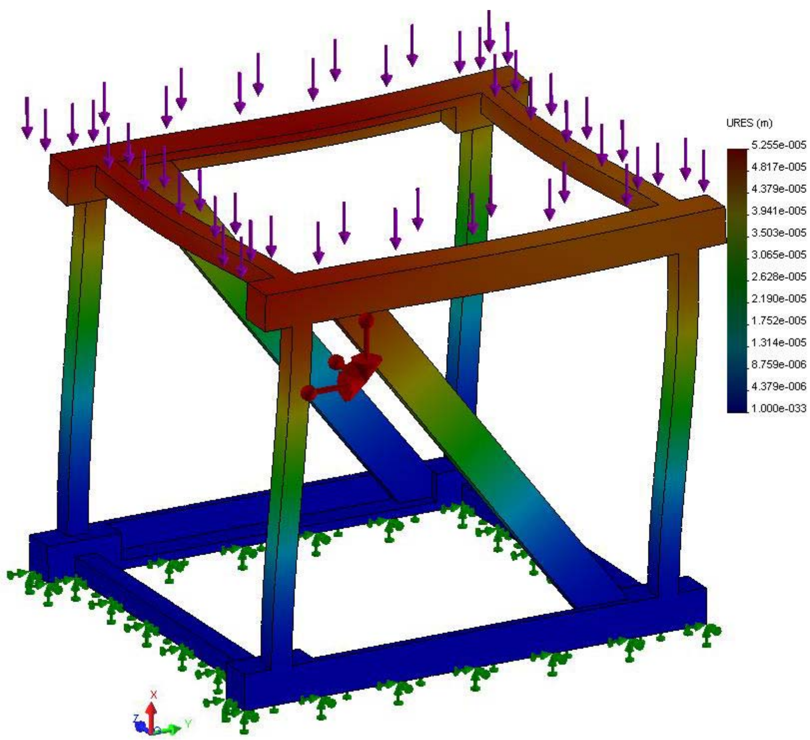


CP2/CP3/CP4 FEA Bottom Mount Vertical Load 18G's 36N: Minimum FOS = 70								
Analysis Type	**Minimum**	**Units**	**Node/Element**	**Location (X,Y,Z) in mm**	**Maximum**	**Units**	**Node/Element**	**Location (X,Y,Z) in mm**
VON: Von Mises Stress	2536.05	N/m^2	Node: 72328	5, 7.58333, 59.1596	7.17648E+06	N/m^2	Node: 89675	2, 18.8807, 0
ESTRN: Equivalent Strain	7.95E-08	m	Element: 25595	95.4167, 7.16667, 45.4734	7.17035E-05	m	Element: 48230	1.5, 18.6426, -0.40625
URES: Resultant Displacement	0	m	Node: 611	8.5, 2.77556E-14, 0	3.30073E-05	m	Node: 698	8.5, 113.5, 0

The following plots and data are for a simplified CP2/CP3/CP4 structure side mounted along diagonal brace side with a side force of 36N and 18G's in all axis (orientation changed Z-axis to Y-axis):

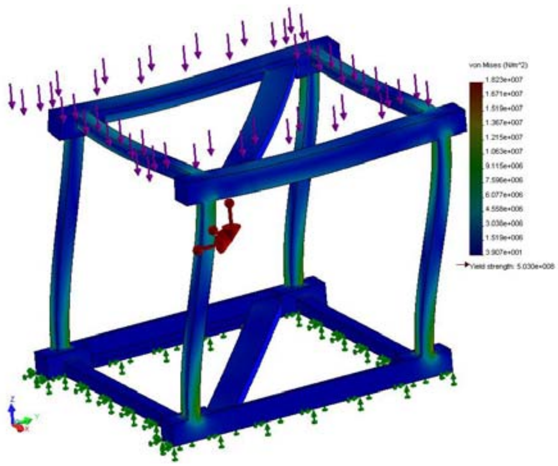


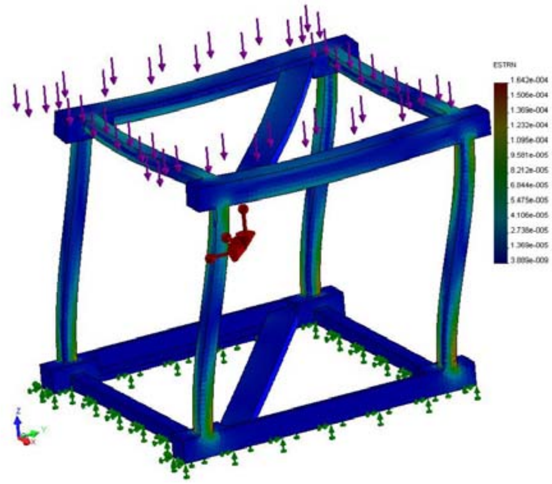


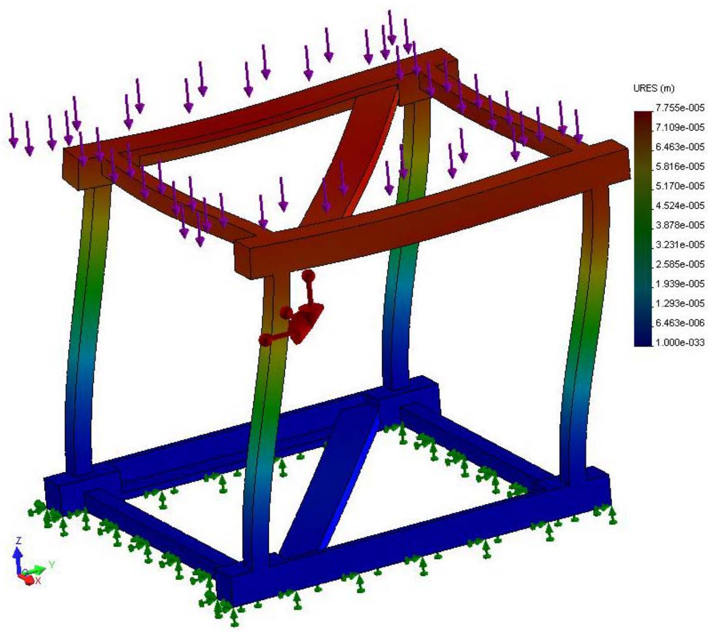


CP2/CP3/CP4 FEA Side Mount Side Load Diagonal Side 18G's 36N: Minimum FOS = 54								
Analysis Type	**Minimum**	**Units**	**Node/Element**	**Location (X,Y,Z) in mm**	**Maximum**	**Units**	**Node/Element**	**Location (X,Y,Z) in mm**
VON: Von Mises Stress	127.112	N/m^2	Node: 89715	2, 35.6136, -0.8125	9.26095E+06	N/m^2	Node: 75856	90.617, 101.75, -3.5
ESTRN: Equivalent Strain	4.16E-09	m	Element: 28668	8.075, 42.5877, 91	8.49930E-05	m	Element: 23752	90.617, 102.167, -3.91667
URES: Resultant Displacement	0	m	Node: 616	1.73472E-15, 2.77556E-14, 0	5.25511E-05	m	Node: 5304	100, 55.8676, 83

The following plots and data are for a simplified CP2/CP3/CP4 structure side mounted along non-diagonal brace side with a side force of 36N and 18G's in all axis (orientation changed Z-axis to Y-axis):

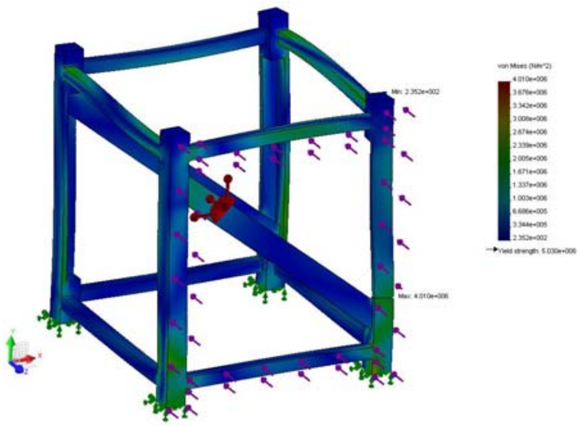


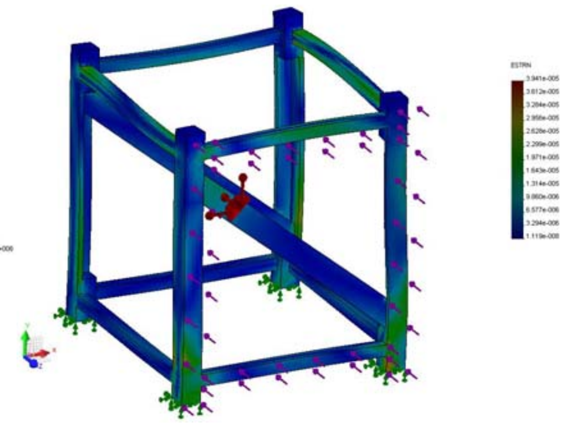


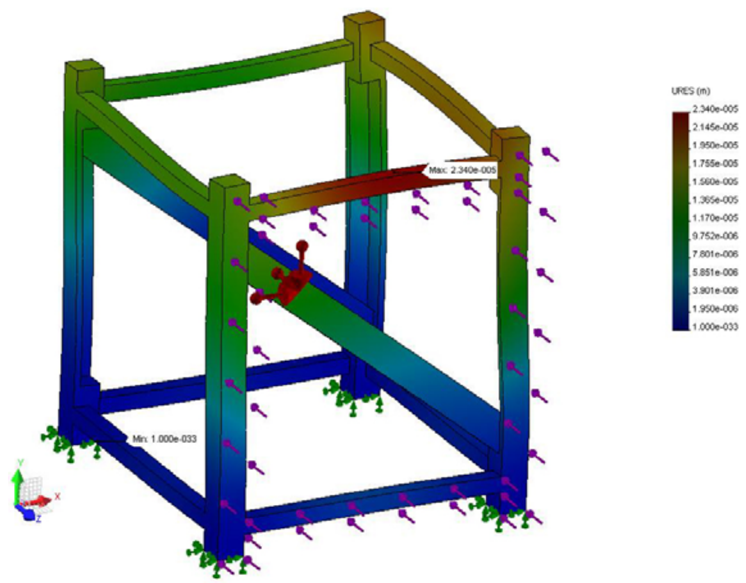


CP2/CP3/CP4 FEA Side Mount Side Load Non-Diagonal Side 18G's 36N: Minimum FOS = 28								
Analysis Type	**Minimum**	**Units**	**Node/Element**	**Location (X,Y,Z) in mm**	**Maximum**	**Units**	**Node/Element**	**Location (X,Y,Z) in mm**
VON: Von Mises Stress	39.0665	N/m^2	Node: 89744	2, 50.5852, 0	1.82303E+07	N/m^2	Node: 67643	95, 101.75, 0.882939
ESTRN: Equivalent Strain	3.89E-09	m	Element: 9034	7.89369, 42.9627, -6.75095	1.64244E-04	m	Element: 43116	95.4167, 102.167, 82.117
URES: Resultant Displacement	0	m	Node: 833	8.5, 113.5, -8.5	7.75528E-05	m	Node: 6995	8.5, 47.0441, 91.5

The following plots and data are for a simplified CP2/CP3/CP4 structure with a side force of 36N along non-diagonal brace side and 18G's in all axis (orientation changed Z-axis to Y-axis):

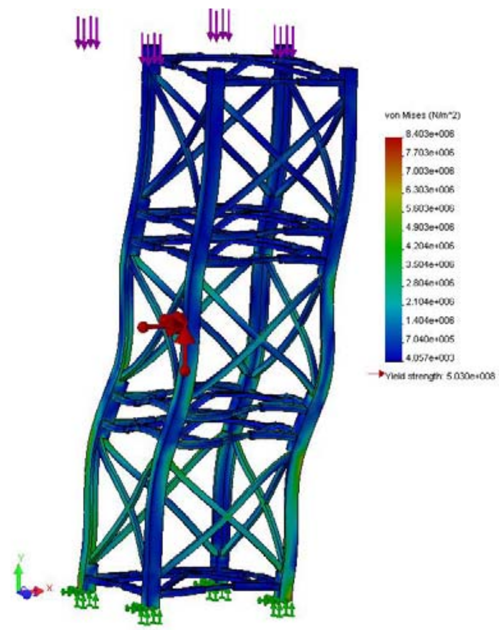


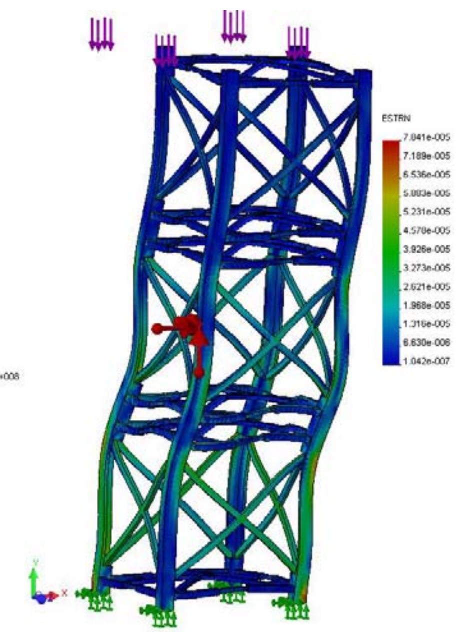


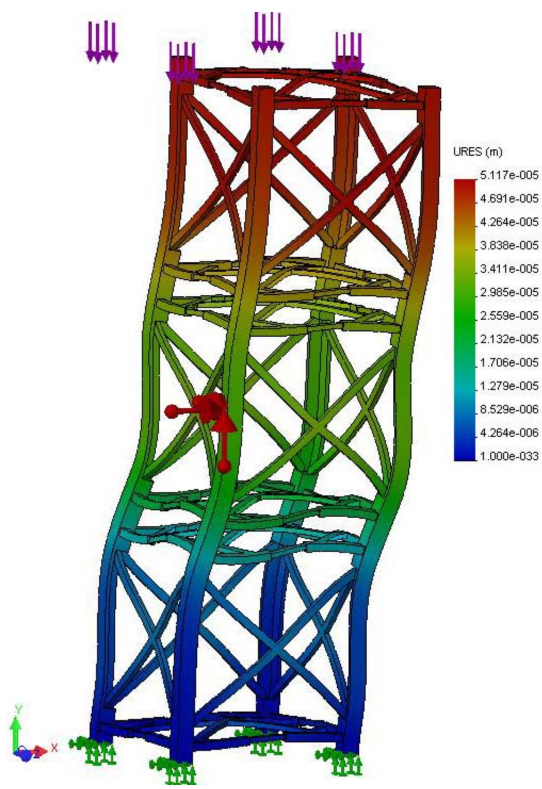


CP2/CP3/CP4 FEA Bottom Mount Side Load Non-Diagonal Side 18G's 36N: Minimum FOS = 31								
Analysis Type	**Minimum**	**Units**	**Node/Element**	**Location (X,Y,Z) in mm**	**Maximum**	**Units**	**Node/Element**	**Location (X,Y,Z) in mm**
VON: Von Mises Stress	1813.89	N/m^2	Node: 7352	84.4362, 11.75, 91.5	1.63729E+07	N/m^2	Node: 89675	2, 18.8807, 0
ESTRN: Equivalent Strain	5.31E-08	m	Element: 34575	4.58946, 9.1505, 42.899	1.62006E-04	m	Element: 48230	1.5, 18.6426, -0.40625
URES: Resultant Displacement	0	m	Node: 611	8.5, 2.77556E-14, 0	8.32344E-05	m	Node: 2214	49.117, 106.75, -8.5

The following plots and data are for a simplified CPX Cross Cube triple assembly with a Y-axis force of 36N and 18G’s in all axis (orientation changed from Z-axis to Y-axis)::



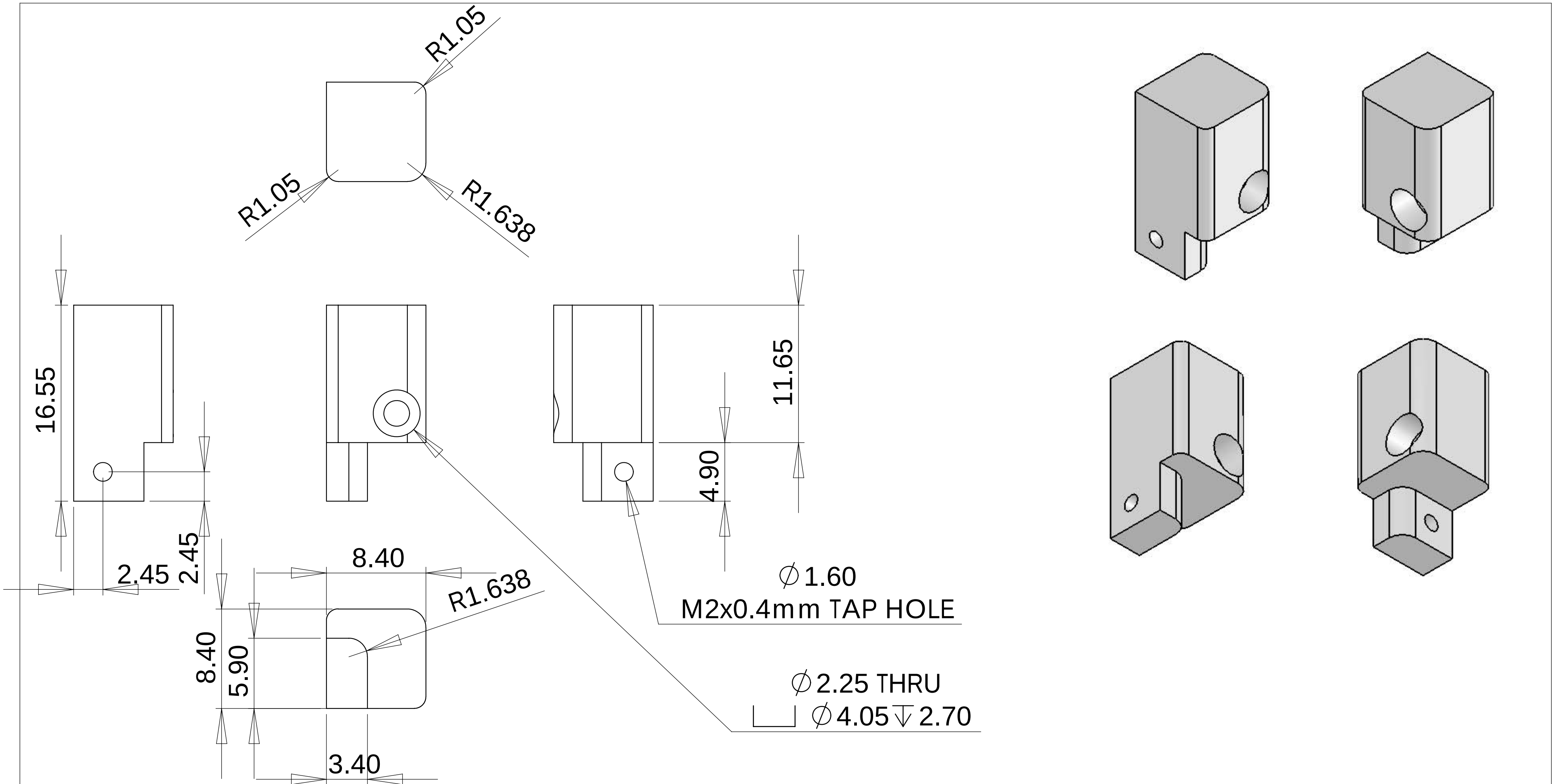




CPX Triple Length Vertical Load 18G's 9N : Minimum FOS = 60								
Analysis Type	**Minimum**	**Units**	**Node/Element**	**Location (X,Y,Z) in mm**	**Maximum**	**Units**	**Node/Element**	**Location (X,Y,Z) in mm**
VON: Von Mises Stress	4057.31	N/m^2	Node: 15828	5, 329.75, 31.5	8.40306E+06	N/m^2	Node: 107863	.-3.469E-15, 114.993, -8.5
ESTRN: Equivalent Strain	1.04E-07	m	Element: 32178	34.0075, 443.743, 88.9942	7.84109E-05	m	Element: 42726	0.7083, 114.247, -7.79167
URES: Resultant Displacement	0	m	Node: 1	1.734E-15, 113.5, 0	5.11722E-05	m	Node: 11228	58.7368, 407.499, 89.5

APPENDIX C: Small Pieces Pre-anodization Adjustments

The following pages contain 3-view mechanical drawings of the End Pieces, Interconnect Pieces, and Internal Board Mounts (all grouped as the “small pieces”). The initial 11”x17” drawing labeled S-5 was prepared for Lansco Engineering in an attempt to compensate for their errors in manufacturing of the Modular Side. When they failed to produce the small pieces in a timely manner, the company Precision Suspension was chosen to accomplish the task and was given the following seven sheets labeled SP-1 through SP-7. These sheets contain the targeted pre-anodization measurements.



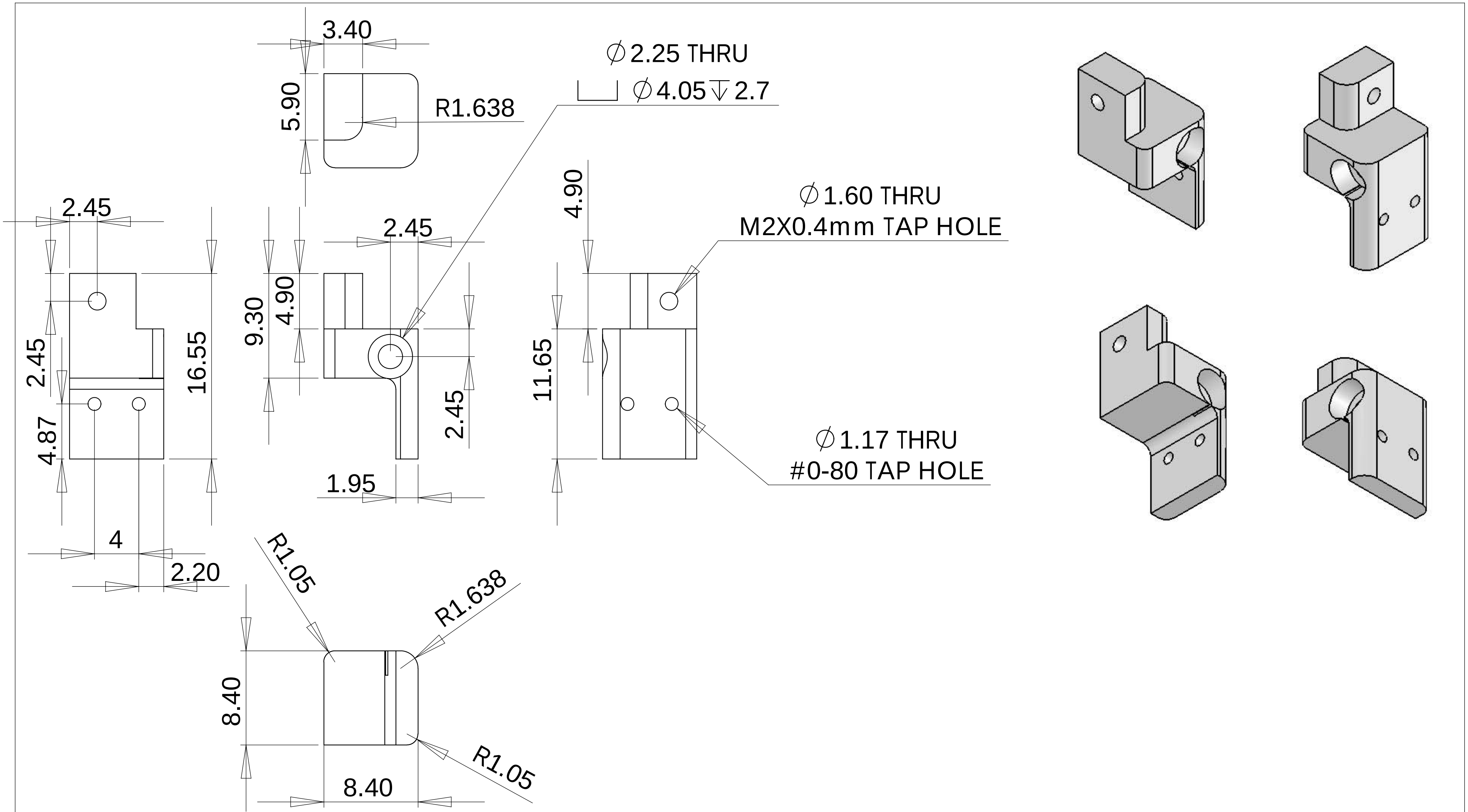
		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN MM TOLERANCES: 0.05MM FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN		
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL AL 7075 T6	COMMENTS:		
NEXT ASSY	USED ON	FINISH HARD CLEAR ANODIZE			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:

END PIECE

SIZE	DWG. NO.	REV
A	SP-1	
SCALE: 2:1	WEIGHT:	SHEET 1 OF 1

5 4 3 2 1



		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN MM TOLERANCES: 0.05 FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN		
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL AL 7075 T6	COMMENTS:		
NEXT ASSY	USED ON	FINISH HARD CLEAR ANODIZE			
APPLICATION		DO NOT SCALE DRAWING			

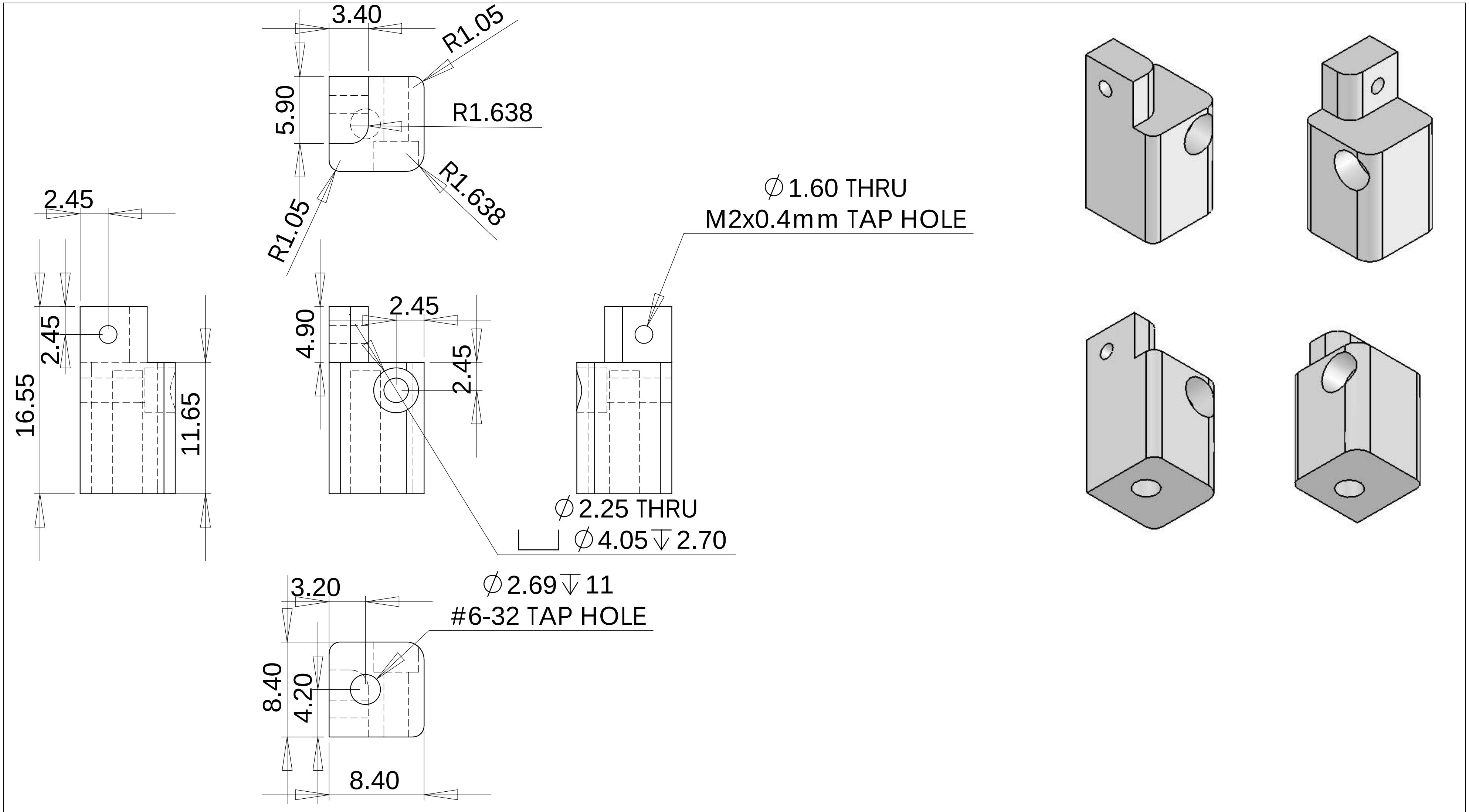
PROPRIETARY AND CONFIDENTIAL

TITLE:

END PIECE WITH DEPLOYMENT SWITCH

SIZE	DWG. NO.	REV
A	SP-2	
SCALE: 2:1	WEIGHT:	SHEET 1 OF 1

5 4 3 2 1



NEXT ASSY	USED ON	
APPLICATION		

PROPRIETARY AND CONFIDENTIAL

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UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN MM
TOLERANCES: 0.05
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
AL 7075 T6

FINISH
HARD CLEAR ANODIZE

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

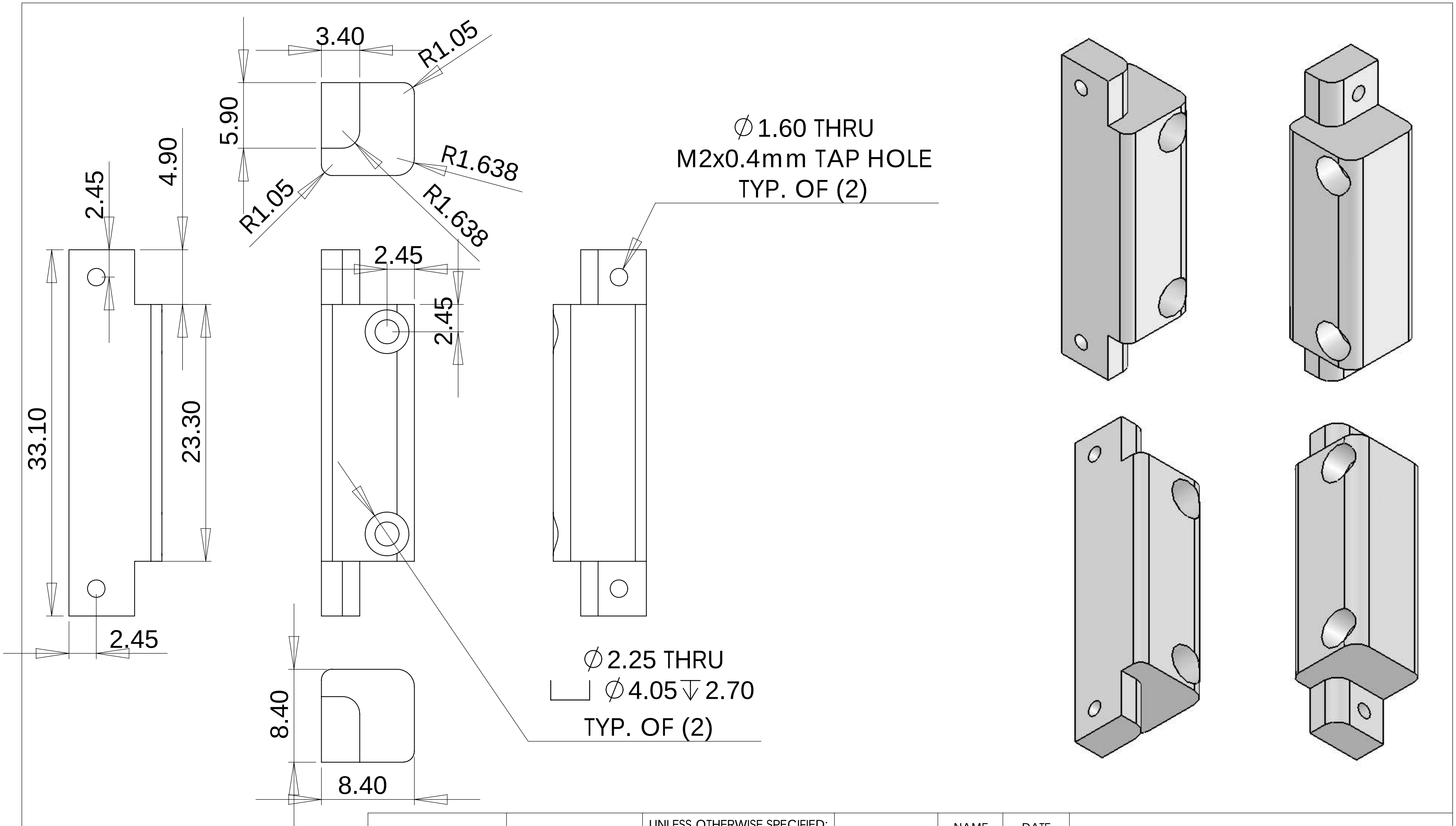
TITLE:

END PIECE WITH SPRING PLUNGER

SIZE	DWG. NO.	REV
A	SP-3	

SCALE: 2:1 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN MM
TOLERANCES: 0.05
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
AL 7075 T6

FINISH
HARD CLEAR ANODIZE

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

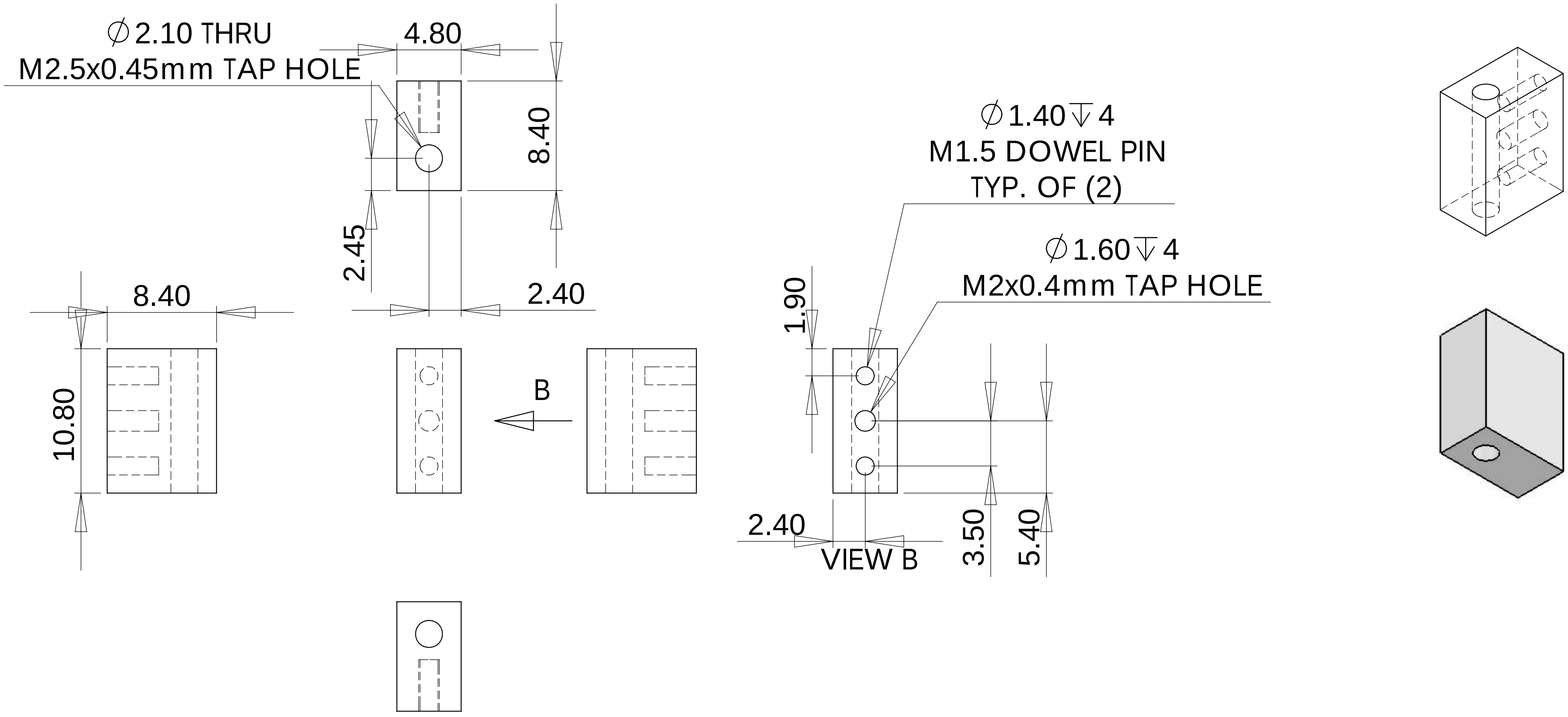
TITLE:

CONNECTION PIECE

SIZE A | DWG. NO. SP-4 | REV

SCALE: 2:1 | WEIGHT: | SHEET 1 OF 1

5 4 3 2 1



		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN MM TOLERANCES: 0.05 FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN		
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL AL 7075 T6	COMMENTS:		
NEXT ASSY	USED ON	FINISH HARD CLEAR ANODIZE			
APPLICATION		DO NOT SCALE DRAWING			

PROPRIETARY AND CONFIDENTIAL

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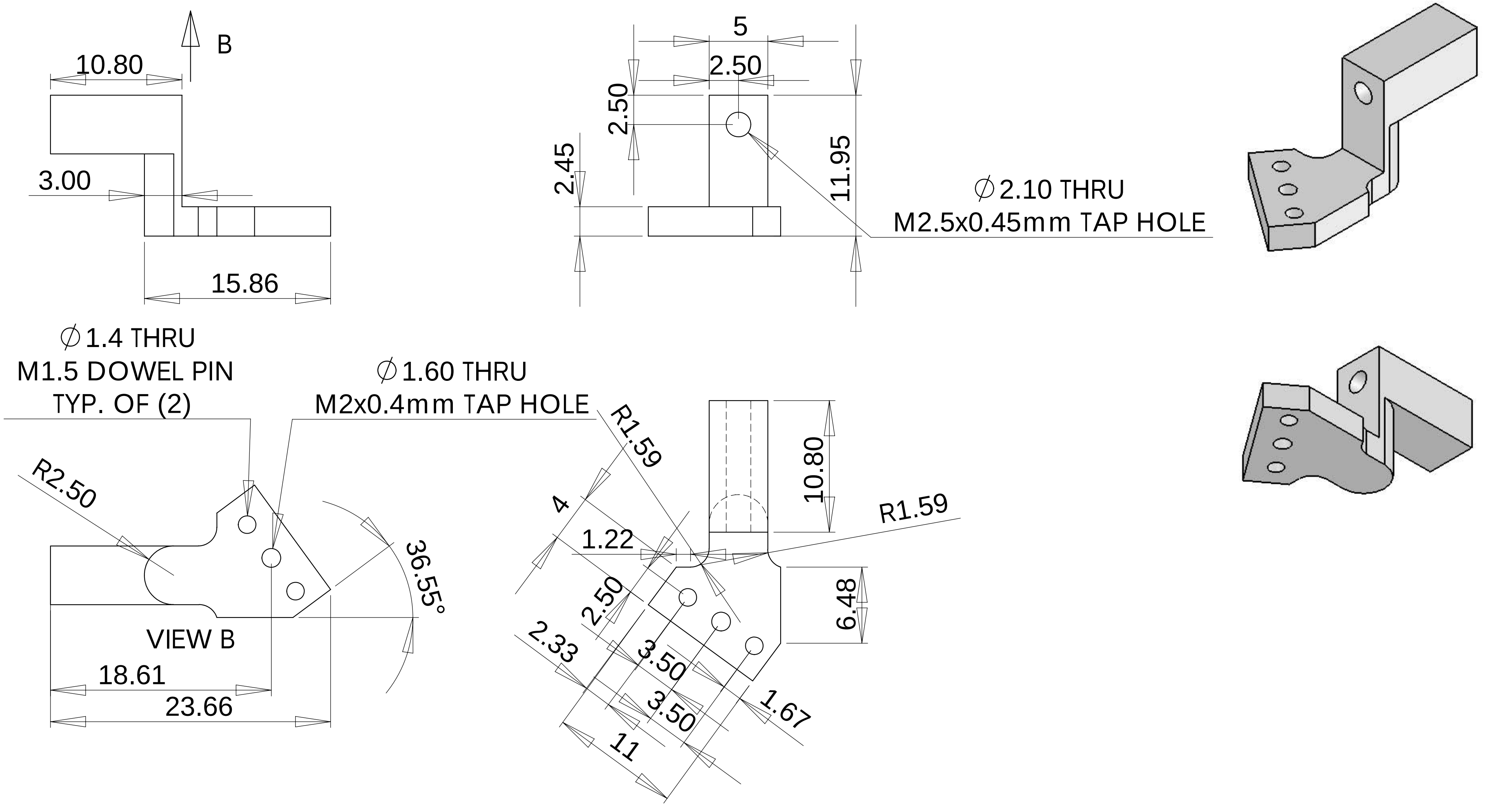
TITLE:

INTERNAL BOARD MOUNT

SIZE	DWG. NO.	REV
A	SP-5	

SCALE: 2:1 | WEIGHT: | SHEET 1 OF 1

5 4 3 2 1



SCALE 4:1

NEXT ASSY	USED ON
APPLICATION	

PROPRIETARY AND CONFIDENTIAL

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UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN MM
TOLERANCES: 0.05
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
AL 7075 T6

FINISH
HARD CLEAR ANODIZE

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

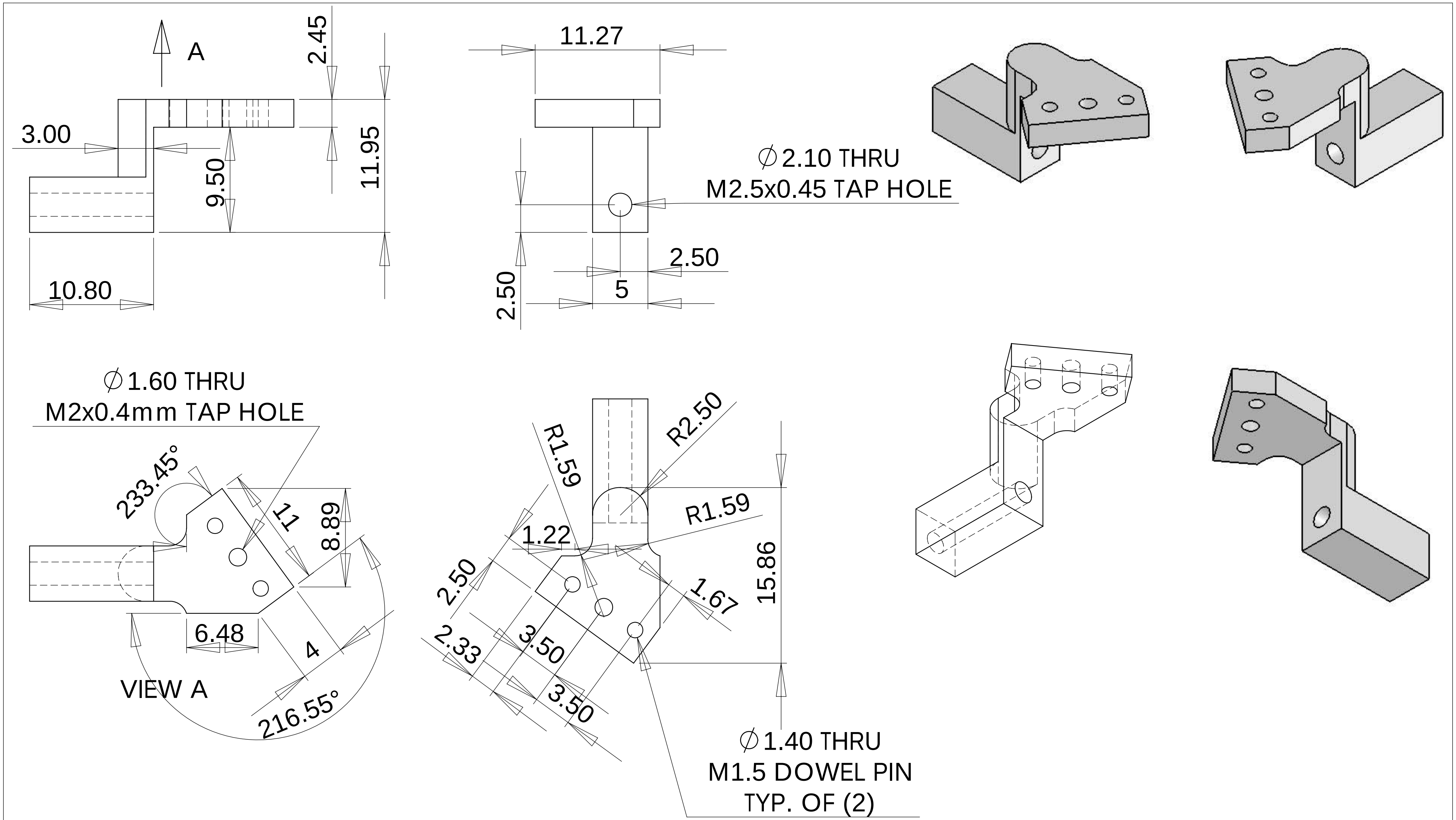
TITLE:

INTERNAL BOARD MOUNT RIGHT

SIZE	DWG. NO.	REV
A	SP-6	

SCALE: 2:1	WEIGHT:	SHEET 1 OF 1

5 4 3 2 1



		UNLESS OTHERWISE SPECIFIED:
		DIMENSIONS ARE IN MM TOLERANCES: 0.05 FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±
		INTERPRET GEOMETRIC TOLERANCING PER:
		MATERIAL AL 7075 T6
NEXT ASSY	USED ON	FINISH HARD CLEAR ANODIZE
APPLICATION		DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

TITLE:

INTERNAL BOARD MOUNT LEFT

SIZE	DWG. NO.	REV
A	SP-7	
SCALE: 2:1	WEIGHT:	SHEET 1 OF 1

5 4 3 2 1

APPENDIX D: Post Manufacturing Data

The following tables show the post manufactured pre-anodization measurements.

Modular Side V3
Post Manufacturing/Pre-anodizing measurements in mm

Part No.	A	B	C	D1	D2	E1	E2	F	G
1	90.05	100.02	91.55	5.93	5.95	2.03	2.03	100.08	8.47
2	90.02	100	91.55	5.93	5.95	2.02	2.02	100	8.45
3	90.07	100	91.5	5.97	5.97	2.01	2	100	8.49
4	90.03	100.01	91.5	5.96	5.96	2.08	2.01	99.98	8.47
5	90.01	99.99	91.5	5.95	5.98	2.03	2.02	99.97	8.49
6	90.02	100.01	91.51	5.94	5.96	2.03	2.02	100.03	8.47
7	90	100.01	91.49	5.96	5.97	2.03	2.05	100.01	8.46
8	90.04	100	91.49	5.97	5.97	2.02	2.03	100.03	8.48
9	90.02	100.01	91.5	5.94	5.97	2.05	2.03	100	8.5
10	90.04	99.98	91.5	5.98	5.98	2.02	2.03	99.99	8.5
11	90.03	99.99	91.5	5.98	5.95	2.02	2.02	100.03	8.51
12	90.02	100	91.5	6	6.01	2	2.02	100.01	8.51
Average	90.02917	100.0017	91.5075	5.959167	5.968333	2.028333	2.023333	100.0108	8.483333
Design Dimension	90	100	91.5	6	6	2	2	100	8.5
Anodized Compensation	89.95	99.95	91.45	5.95	5.95	1.975	1.975	99.95	8.45
Out of Tolerance by:	**0.079167**	**0.051667**	**0.0575**	**0.009167**	**0.018333**	**0.053333**	**0.048333**	**0.060833**	**0.033333**

Upper/Lower Structure
Post Manufacturing/Pre-anodizing measurements in mm

Part No.	A	B	C	Mounting Tapped Holes	PCB Tapped Holes
1	89.97	89.98	5.01	No	Yes
2	89.98	89.98	5.02	Yes	Yes
3	90	89.99	5.02	No	Yes
4	89.98	89.98	5.03	Yes	Yes
5	89.97	89.97	5.02	No	Yes
6	89.96	90.01	5.01	Yes	Yes
Average	89.97667	89.985	5.018333		
Design Dimension	90	90	5		
Anodized Compensation	89.95	89.95	4.95		
Out of Tolerance by:	**0.026667**	**0.035**	**0.068333**		

Three sets did not have the M2 holes tapped for mounting to the Modular Side V3. All M2.5 holes were tapped.

Assembled Structures (No End Pieces)
Post Manufacturing/Pre-anodizing measurements in mm

Assembly No.	upper	lower	upper	lower	upper	lower	upper	lower	Top	Bottom
1	99.95	99.98	99.97	99.96	99.99	100	99.99	100	100	100.02
2	99.96	99.98	99.96	99.96	99.98	99.99	99.97	100.01	99.91	99.98
3	100.01	99.96	100	100.05	99.99	99.99	100.02	99.98	99.96	99.95
	The shaded in cells depict upper measurement without upper/lower structure in assembly									

The following tables show the pre-anodization measurements of the small pieces that were double compensated for.

End Piece Post Manufacturing/Pre-anodizing measurements in mm					
Part No.	**A**	**B**	**C**	**D**	**E**
1	8.41	8.4	5.93	3.45	11.71
2	8.42	8.42	5.96	3.43	11.73
3	8.42	8.42	5.97	3.44	11.73
4	8.41	8.42	6.09	3.47	11.73
5	8.43	8.41	5.96	3.43	11.72
6	8.42	8.42	5.94	3.43	11.72
7	8.42	8.42	5.96	3.43	11.72
8	8.42	8.42	5.95	3.43	11.73
9	8.42	8.42	5.93	3.47	11.71
10	8.42	8.43	5.94	3.45	11.71
11	8.42	8.41	5.96	3.44	11.72
12	8.42	8.41	6	3.45	11.72
Average	8.419167	8.416667	5.965833	3.443333	11.72083
Design Dimension	8.5	8.5	6	3.5	11.75
Anodized Compensation	8.4	8.4	5.9	3.4	11.65
Out of Tolerance by:	0.019167	0.016667	0.065833	0.043333	0.070833

Connection Piece Post Manufacturing/Pre-anodizing measurements in mm					
Part No.	**A**	**B**	**C**	**D**	**E**
1	8.41	8.41	5.94	3.43	23.33
2	8.41	8.42	5.92	3.43	23.33
3	8.41	8.4	5.97	3.47	23.34
4	8.41	8.41	5.97	3.45	23.33
5	8.42	8.42	5.94	3.42	23.33
6	8.42	8.41	5.93	3.42	23.33
7	8.41	8.41	5.95	3.43	23.33
8	8.42	8.42	5.93	3.44	23.34
9	8.42	8.42	5.92	3.44	23.34
10	8.42	8.42	5.95	3.46	23.33
Average	8.415	8.414	5.942	3.439	23.333
Design Dimension	8.5	8.5	6	3.5	23.5
Anodized Compensation	8.4	8.4	5.9	3.4	23.3
Out of Tolerance by:	0.015	0.014	0.042	0.039	0.033

End Piece with Deployment Switch Post Manufacturing/Pre-anodizing measurements in mm					
Part No.	A	B	C	D	E
1	8.44	8.42	5.92	3.5	11.74
2	8.42	8.41	5.93	3.53	11.72
3	8.42	8.41	5.93	3.49	11.74
4	8.42	8.41	5.93	3.5	11.72
5	8.43	8.42	5.92	3.52	11.74
6	8.43	8.41	5.94	3.47	11.75
Average	8.426667	8.413333	5.928333	3.501667	11.735
Design Dimension	8.5	8.5	6	3.5	11.75
Anodized Compensation	8.4	8.4	5.9	3.4	11.65
Out of Tolerance by:	0.026667	0.013333	0.028333	0.101667	0.085

End Piece with Spring Plunger Post Manufacturing/Pre-anodizing measurements in mm					
Part No.	A	B	C	D	E
1	8.42	8.41	5.93	3.45	11.72
2	8.45	8.45	5.93	3.46	11.74
3	8.42	8.43	5.92	3.48	11.72
4	8.42	8.41	5.91	3.47	11.72
5	8.42	8.42	5.92	3.46	11.73
6	8.42	8.42	5.91	3.47	11.73
7	8.42	8.43	5.92	3.46	11.73
Average	8.424286	8.424286	5.92	3.464286	11.72714
Design Dimension	8.5	8.5	6	3.5	11.75
Anodized Compensation	8.4	8.4	5.9	3.4	11.65
Out of Tolerance by:	0.024286	0.024286	0.02	0.064286	0.077143

Internal Board Mount Post Manufacturing/Pre-anodizing measurements in mm					
Part No.	A	B	C		
1	4.81	8.39	10.83		
2	4.81	8.38	10.87		
3	4.81	8.37	10.84		
4	4.81	8.4	10.82		
5	4.81	8.38	10.86		
6	4.81	8.38	10.86		
7	4.81	8.38	10.87		
8	4.81	8.4	10.86		
9	4.81	8.4	10.86		
10	4.82	8.38	10.81		
11	4.82	8.38	10.83		
12	4.81	8.39	10.81		
13	4.82	8.38	10.81		
Average	4.812308	8.385385	10.84077		
Design Dimension	5	8.5	11.2		
Anodized Compensation	4.8	8.4	10.8		
Out of Tolerance by:	0.012308	-0.014615	0.040769		

Internal Board Mount Left and Right Post Manufacturing/Pre-anodizing measurements in mm					
Part No.	**A**	**B**	**A**	**B**	
1 Left/ 1 Right	2.46	11.17	2.47	11.18	
2 Left/ 2 Right	2.47	11.19	2.49	11.19	
3 Left/ 3 Right	2.47	11.19	2.47	11.19	
4 Left/ 4 Right	2.47	11.19	2.47	11.2	
5 Left/ 5 Right	2.47	11.19	2.47	11.19	
6 Left/ 6 Right	2.48	11.19	2.48	11.19	
7 Left/ 7 Right	2.48	11.19	2.48	11.19	
Average	2.47	11.19	2.48	11.19	
Design Dimension	2.5	11.2	2.5	11.2	
Anodized Compensation	2.45	10.8	2.45	10.8	
Out of Tolerance by:	0.021	0.387	0.026	0.390	

APPENDIX E: Vibration Qualification Data

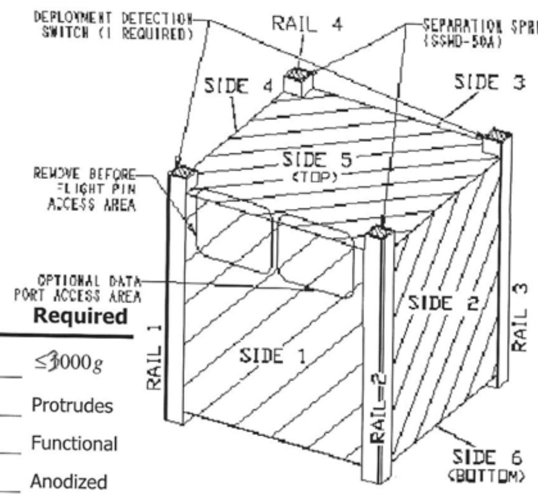
The following is the CubeSat Acceptance Checklist:

CPX Structure (Triple)

Cubesat Acceptance Checklist

Revision Date: April 4, 2004
Author: Armen Toorian

This document is intended to be used concurrently with the Cubesat Integration Procedure (CIP)



List Item	Actual	Required
Mass (1187.5g)	2.618 #	$\leq 3000g$
Remove Before Flight	0 mm	Protrudes
Spring Plungers	N/A	Functional
Rails	N/A	Anodized
Deployment Switches	N/A	Functional
Width [x-y]	TOP MID BOT	
Side 1	100.00 99.97 100.01	$100.0 \pm 0.1mm$
Side 2	99.96 99.98 99.96	$100.0 \pm 0.1mm$
Side 3	99.97 99.95 99.93	$100.0 \pm 0.1mm$
Side 4	99.95 99.93 99.97	$100.0 \pm 0.1mm$
Height [z]		340.5 ± 0.3 mm
Rail 1	120.41 + 112.7 + 107.24	~~$113.5 \pm 0.1mm$~~ = 340.35
Rail 2	120.36 + 112.68 + 107.24	~~$113.5 \pm 0.1mm$~~ = 340.28
Rail 3	119.75 + 114.15 + 107.01	~~$113.5 \pm 0.1mm$~~ = 340.91 ← double check
Rail 4	119.63 + 114.12 + 106.98	~~$113.5 \pm 0.1mm$~~ = 340.73
Diagonal [x-y]		
Top 1&3	140.3	$141.2^{+0}_{-1.5}mm$
Top 2&4	140.00	$141.2^{+0}_{-1.5}mm$
Bottom 1&3	140.28	$141.2^{+0}_{-1.5}mm$
Bottom 2&4	140.19	$141.2^{+0}_{-1.5}mm$

4.41mm protrusion (Solar Panel Board Screws)

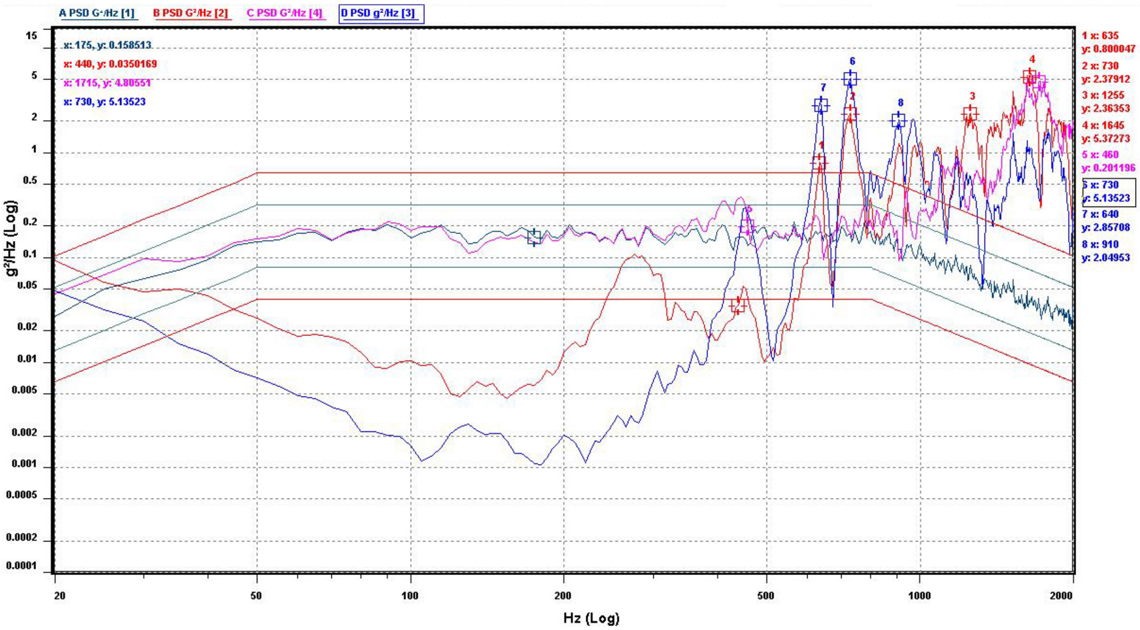
Authorized By:
IT #1: WENSCHEL LAN
IT #2: JASON PHELAN

Testing Info:
Date: 3/20/07
Passed: Y / N

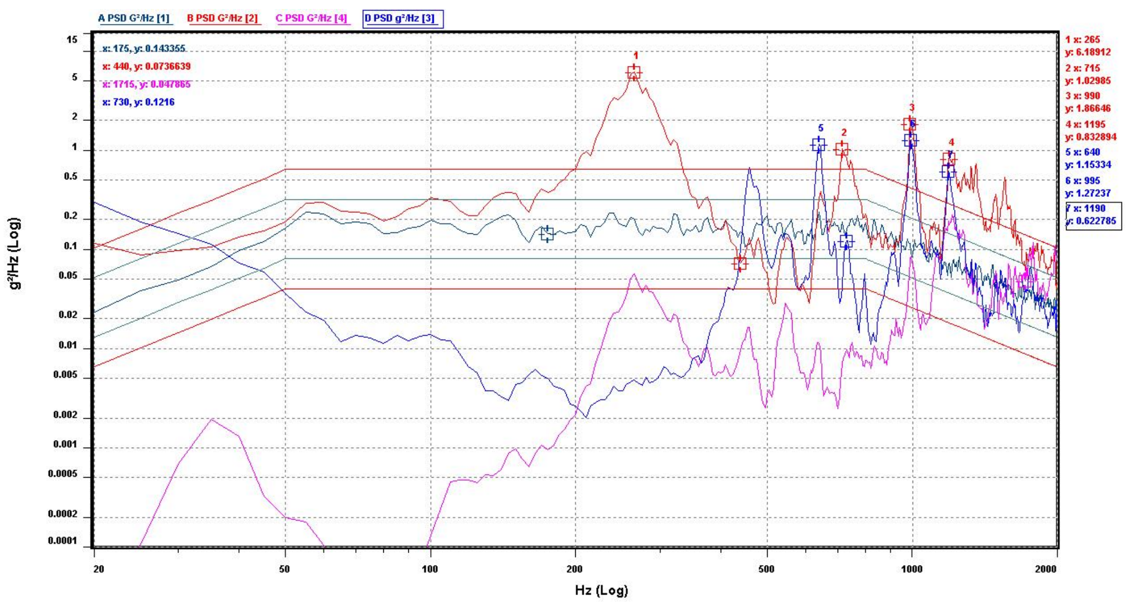
The following is a list of the equipment used in the vibration qualification testing:

- 6”x15”x1.5” Aluminum P-POD mounting head plate
    - (6) M6 Nylock screws to mount P-POD to mounting head plate
- 10”x15”x2” vibe table head plate
    - (16) 10-32 x 1 ¾” stainless steel (18-8SS) plain finish screws to mount mounting head plate to vibe table head plate
- 6”x15”x6” vibe table head plate
    - (8) 2.5”-long gold screws to mount vibe table head plate to vibe table
- 16 10-24 x 1 ¾” steel black oxide finish screws
- 8 6.5”-long steel screws
- Standard hex-wrench set
- Masking tape for accelerometer wire anchoring to side of vibe table
- Signal box and power supply (PCB Piezotronics model no. 482A22, S/N: 2242)
- 4 blue cables (on wall)
- Short black connector for closed loop (on wall)
- Tri-axis accelerometer and connecting black wires (Endevco model 63B-100, S/N:11140).
- Red wax for tri-axis accelerometer
- Control Accelerometer (S/N 10035) with connecting white wire
- Vibe table (Ling Electronics Model No. A395, S/N:142)
- Computer (Spectral Dynamics S/N:1568, Report No. SI004214)

The following are the plots of the vibration testing. The first plot is the Z-axis direction.



The following plot is for the X-axis direction:



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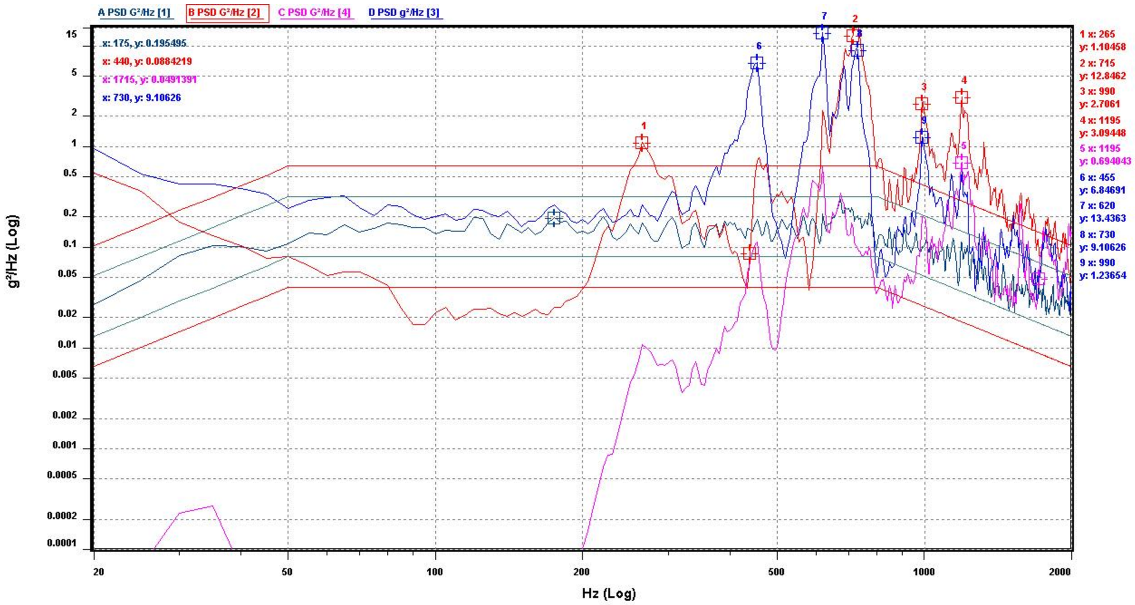
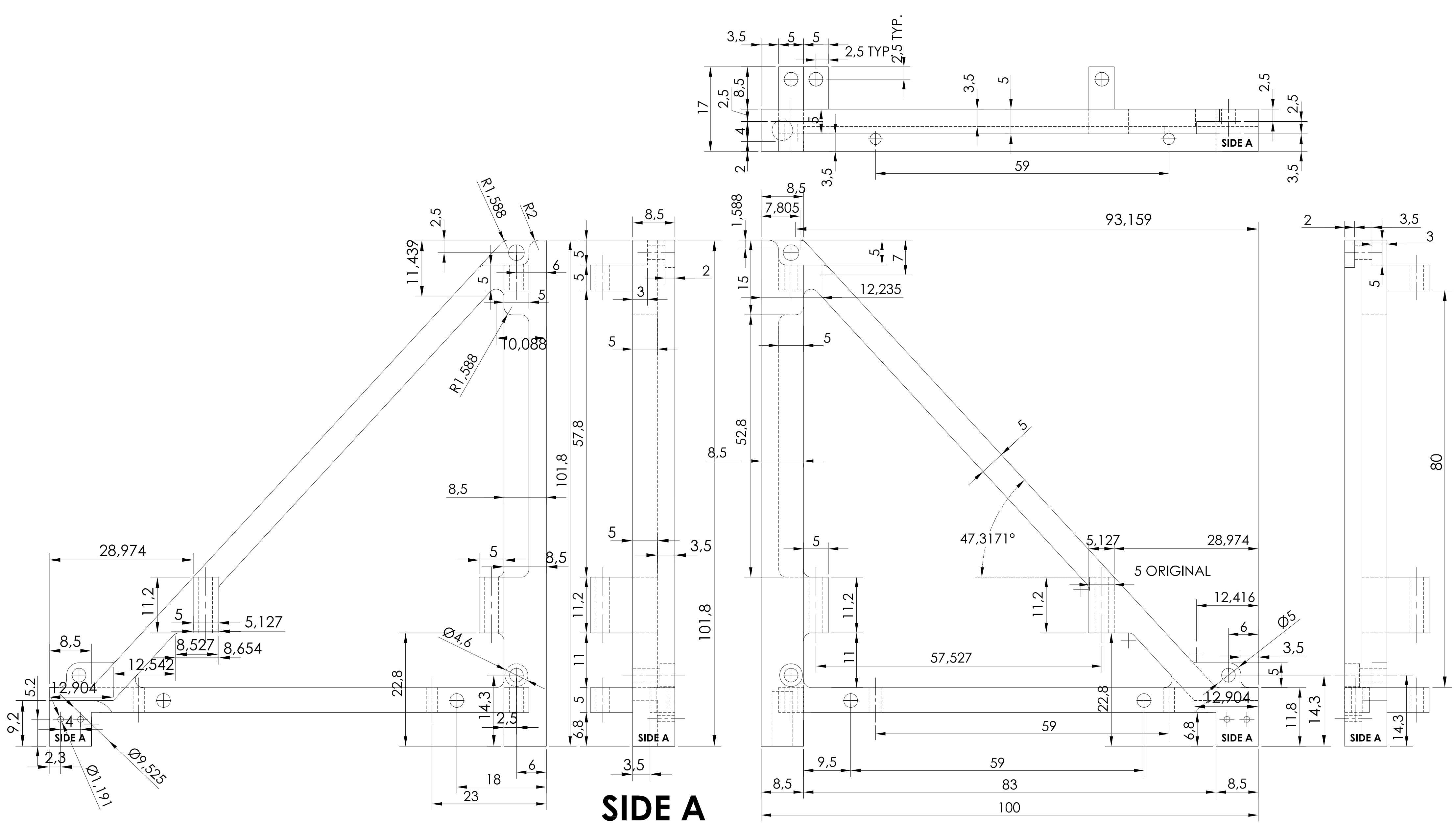


APPENDIX F: CP2, CP3, and CP4 Structures

The following pages are mechanical drawings of the CP2 and CP3/CP4 structure pieces and also assembled structure drawings in 11x17 paper format. These drawings were completed with AutoCAD 2004 in a 2-D environment. The title block was specifically made for PolySat drafting projects for CP2 and CP3/CP4 structures.



05/13/05	
DESIGN DRAFTSMAN:	
JASON PHELAN	
DESIGN ENGINEER:	
JASON PHELAN	

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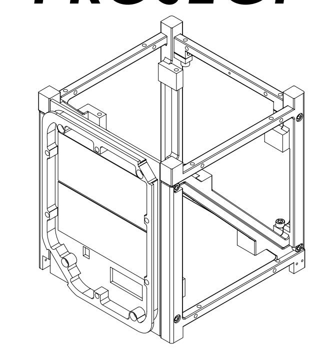


PROJECT TITLE:

STRUCTURE

UNITS: MM
TOLERANCE: ±0.1
SURFACE FINISH:

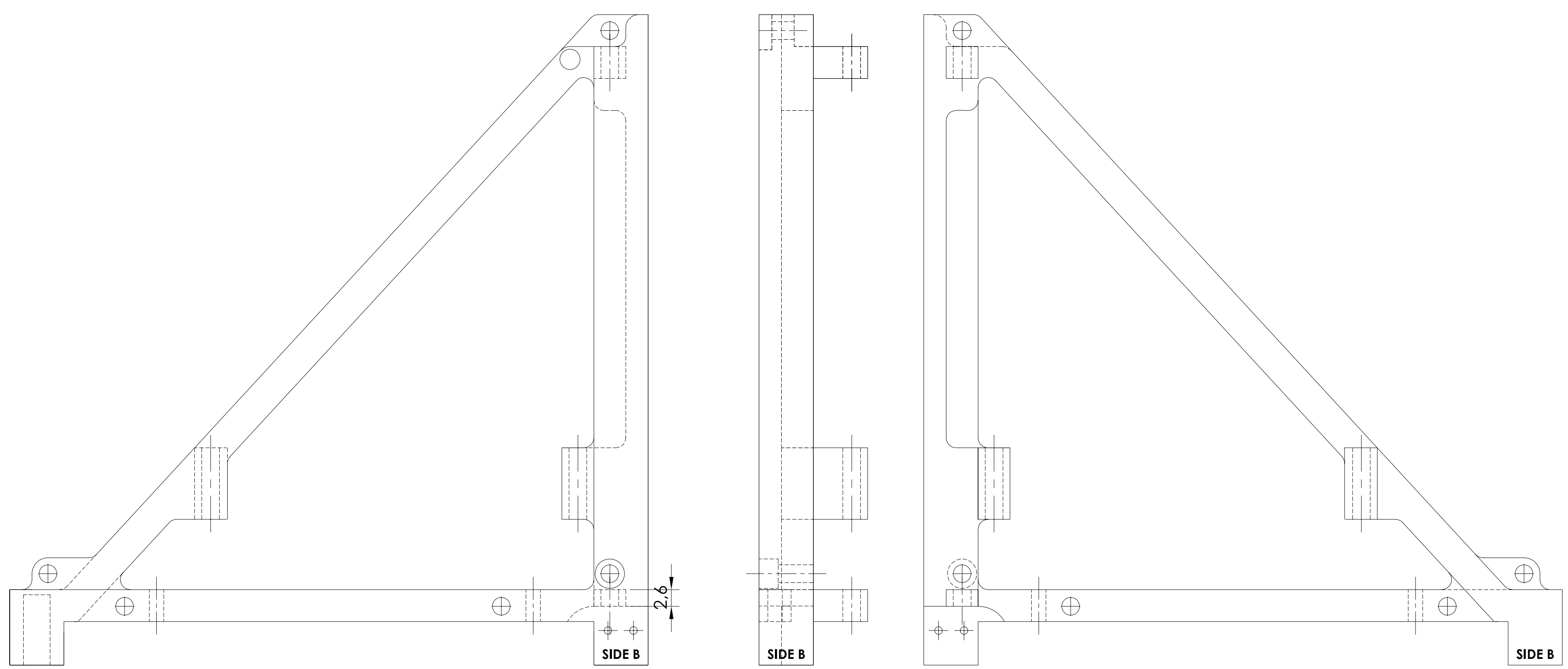
SIDE A DRAWINGS

SHEET PAGE:

S-1

1 CP2 SIDE A MEASUREMENTS

SCALE: 1:1



SIDE B

1 CP2 SIDE B

SCALE: 1:1

05/13/05

DESIGN DRAFTSMAN:

JASON PHELAN

DESIGN ENGINEER:

JASON PHELAN

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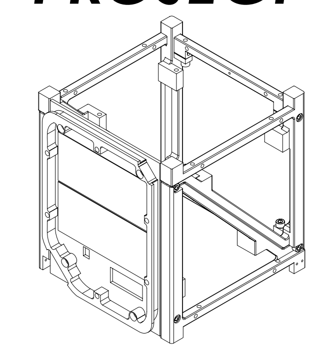


PROJECT TITLE:

STRUCTURE

UNITS: MM
TOLERANCE: ±0.1
SURFACE FINISH:

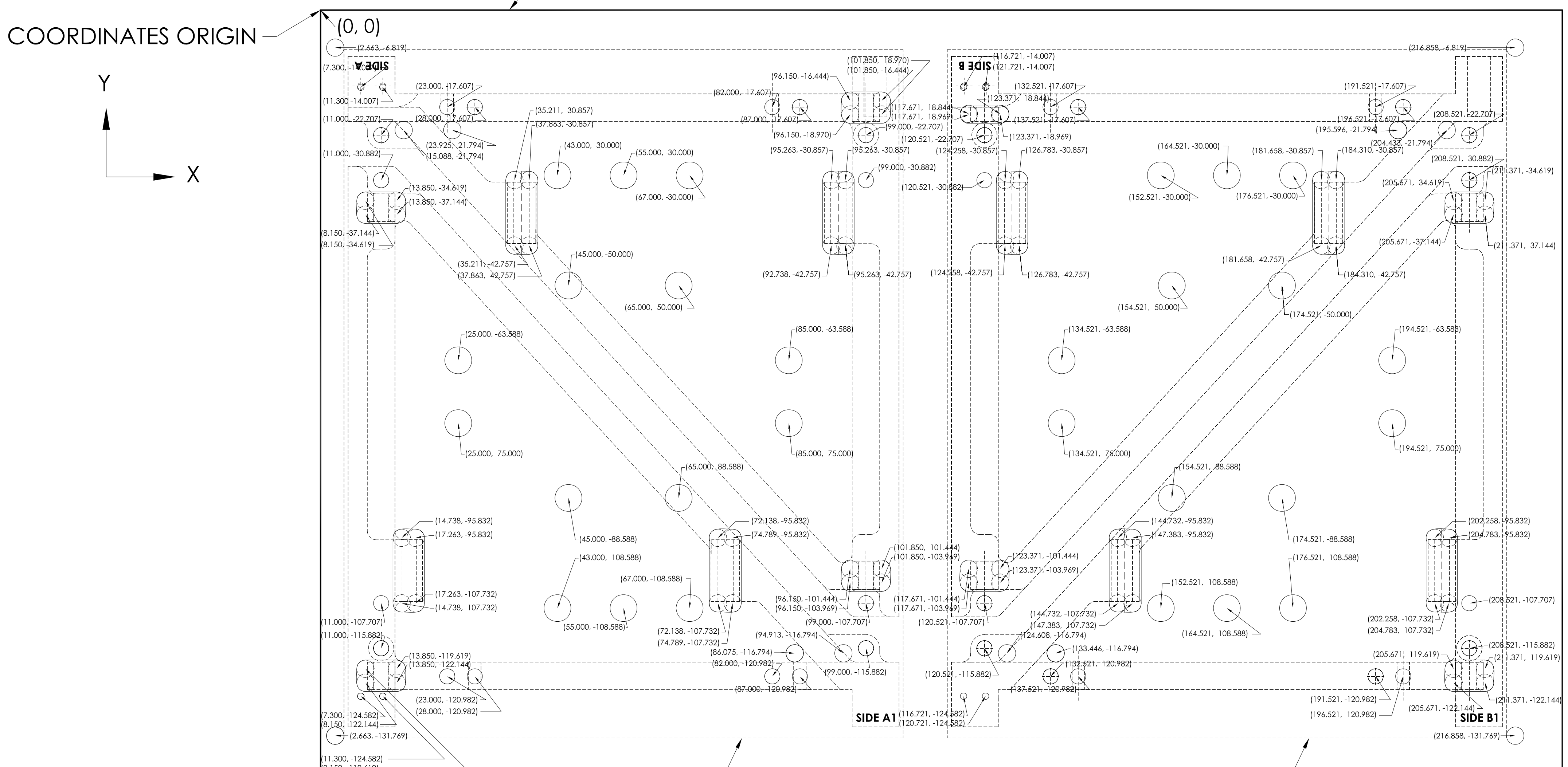
SIDE B DRAWING, DIMENSIONS ARE SIMILAR TO SIDE A

SHEET PAGE:

S-2

CP2 STRUCTURES JIG FOR MANUFACTURING

COORDINATES ORIGIN



SIDE A AND A1 SOLID PIECE

SIDE B AND B1 SOLID PIECE

05/13/05

DESIGN DRAFTSMAN:

JASON PHELAN

DESIGN ENGINEER:

JASON PHELAN

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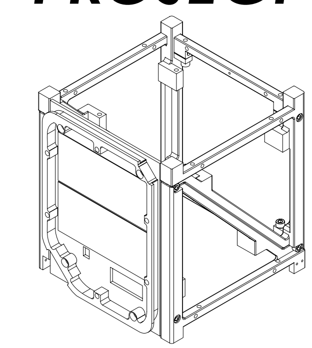
POLYSAT PROJECT



PROJECT TITLE:

STRUCTURE

UNITS: MM
TOLERANCE: ±0.1
SURFACE FINISH:

MILLING INSTRUCTIONS FOR STRUCTURES JIG

SHEET PAGE:

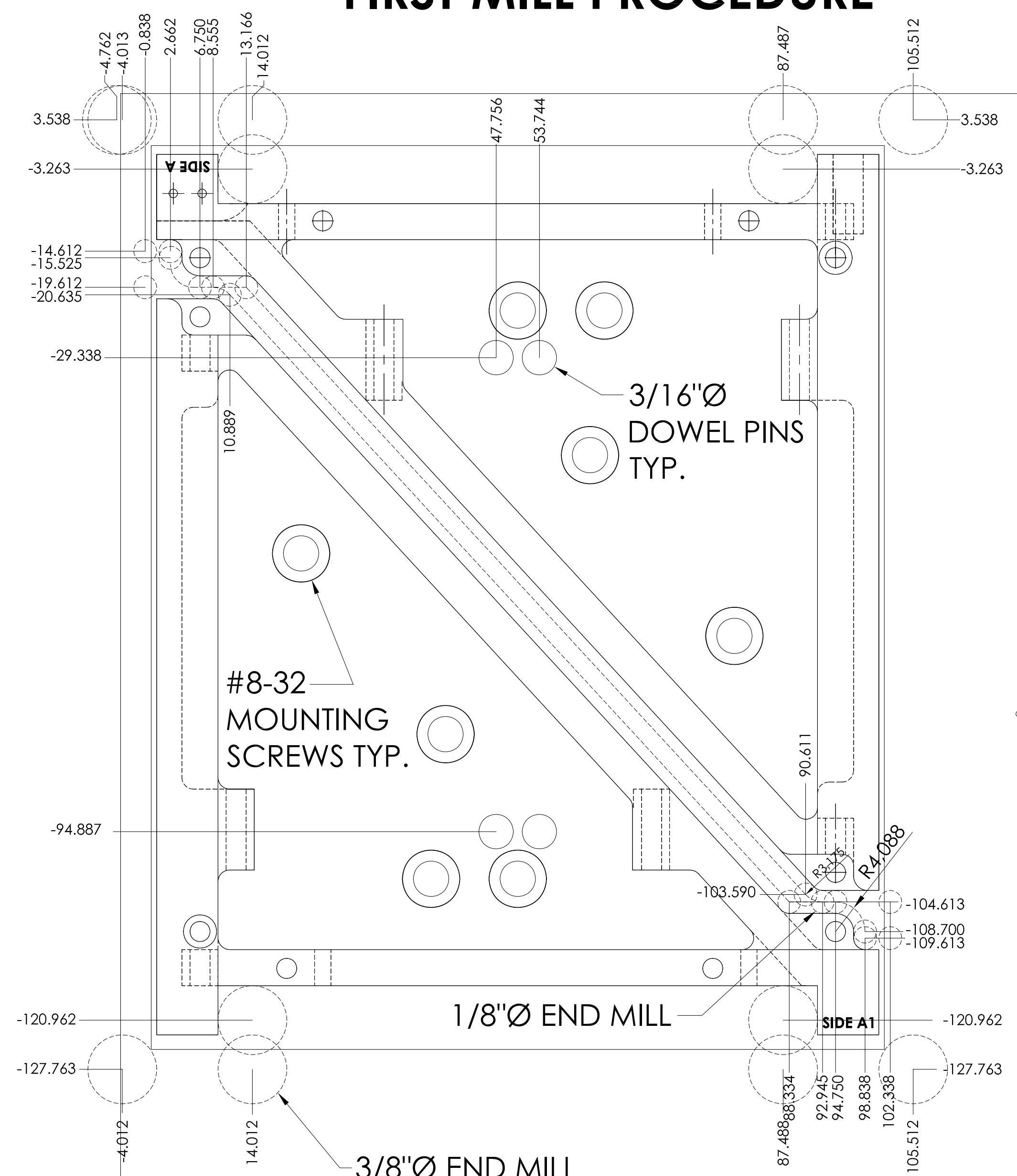
S-3

1 CP2 DRILL AND MILL LOCATIONS FOR STRUCTURES JIG

SCALE: 1:1

G&M CODE FOR SIDE A AND A1 FIRST MILLING PROCEDURE

FIRST MILL PROCEDURE




```
%
O00001 (SIDES A MILL OUTSIDE 1)
G21 (SET METRIC CODE)
T2 M06 (TOOL 2 3/8 END MILL)
G90 G54 G00 X-4.762 Y3.538  (ABSOLUTE POSITION, WORK
OFFSET, RAPID TO COORDINATES)
S3000 M03 (SPINDLE ON AT 2500RPM CLOCKWISE)
G43 H02 Z10. M08(TOOL LENGTH COMP, TOOL 2 MOVE TO 10MM
ABOVE PART)
G01 Z-1.0 F76.2  (FEED DEPTH)
X14.012 F250.0
Y-3.263
X87.488
Y3.538
X105.512
Y-127.763
X87.488
Y-120.962
X14.012
Y-127.763
X-4.013
Y3.538
X-4.762
Z-2.0 F76.2
X14.012 F250.0
Y-3.263
X87.488
Y3.538
X105.512
Y-127.763
X87.488
Y-120.962
X14.012
Y-127.763
X-4.013
Y3.538
X-4.762
Z-3.0 F76.2
X14.012 F250.0
Y-3.263
X87.488
Y3.538
X105.512
Y-127.763
X87.488
Y-120.962
X14.012
Y-127.763
X-4.013
Y3.538
X-4.762
Z-4.0 F76.2
X14.012 F250.0
Y-3.263
X87.488
Y3.538
X105.512
Y-127.763
X87.488
Y-120.962
X14.012
Y-127.763
X-4.013
Y3.538
X-4.762
Z-5.0 F76.2
X14.012 F250.0
Y-3.263
X87.488
Y3.538
X105.512
Y-127.763
X87.488
Y-120.962
X14.012
Y-127.763
X-4.013
Y3.538
X-4.762
Z-6.0 F76.2
X14.012 F250.0
Y-3.263
X87.488
Y3.538
X105.512
Y-127.763
X87.488
Y-120.962
X14.012
Y-127.763
X-4.013
Y3.538
X-4.762
Z-7.0 F76.2
X14.012 F250.0
Y-3.263
X87.488
Y3.538
X105.512
Y-127.763
X87.488
Y-120.962
X14.012
Y-127.763
X-4.013
Y3.538
X-4.762
Z-8.0 F76.2
X14.012 F250.0
Y-3.263
X87.488
Y3.538
X105.512
Y-127.763
X87.488
Y-120.962
X14.012
Y-127.763
X-4.013
Y3.538
X-4.762
Z-9.0 F76.2
X14.012 F250.0
Y-3.263
X87.488
Y3.538
X105.512
Y-127.763
X87.488
Y-120.962
X14.012
Y-127.763
X-4.013
Y3.538
X-4.762
Z10.0 F1500.0 M09
M05
G28 G91 G0.
T1 M06 (TOOL 1 EIGHTH INCH END MILL)
G90 G54 G00 X-0.838 Y-19.612 (ABSOLUTE POSITION, WORK OFFSET, RAPID TO COORDINATES)
S3000 M03 (SPINDLE ON AT 2500RPM CLOCKWISE)
G43 H01 Z10. M08(TOOL LENGTH COMP, TOOL 2 MOVE TO 10MM ABOVE PART)
G01 Z-1.0 F76.2  ( FEED TO DEPTH OF -9MM )
X8.555 F100.0
G02 X10.889 Y-20.635 R3.588
G01 X88.334 Y-104.613
X94.750
G02 X98.838 Y-108.700 R4.088
G01 Y-109.613
X100.0
Y-105.0
Y-109.613
X102.338
Y-104.613
X92.945
G02 X90.611 Y-103.590 R3.588
G01 X13.166 Y-19.613
X6.750
G02 X2.662 Y-15.525 R4.088
G01 Y-14.612
X1.0
Y-18.500
Y-14.612
X-0.838
Y-19.612
Z-2.0 F76.2
X8.555 F100.0
G02 X10.889 Y-20.635 R3.588
G01 X88.334 Y-104.613
X94.750
G02 X98.838 Y-108.700 R4.088
G01 Y-109.613
X100.0
Y-105.0
Y-109.613
X102.338
Y-104.613
X92.945
G02 X90.611 Y-103.590 R3.588
G01 X13.166 Y-19.613
X6.750
G02 X2.662 Y-15.525 R4.088
G01 Y-14.612
X1.0
Y-18.500
Y-14.612
X-0.838
Y-19.612
Z-3.0 F76.2
X8.555 F100.0
G02 X10.889 Y-20.635 R3.588
G01 X88.334 Y-104.613
X94.750
G02 X98.838 Y-108.700 R4.088
G01 Y-109.613
X100.0
Y-105.0
Y-109.613
X102.338
Y-104.613
X92.945
G02 X90.611 Y-103.590 R3.588
G01 X13.166 Y-19.613
X6.750
G02 X2.662 Y-15.525 R4.088
G01 Y-14.612
X1.0
Y-18.500
Y-14.612
X-0.838
Y-19.612
Z-4.0 F76.2
X8.555 F100.0
G02 X10.889 Y-20.635 R3.588
G01 X88.334 Y-104.613
X94.750
G02 X98.838 Y-108.700 R4.088
G01 Y-109.613
X100.0
Y-105.0
Y-109.613
X102.338
Y-104.613
X92.945
G02 X90.611 Y-103.590 R3.588
G01 X13.166 Y-19.613
X6.750
G02 X2.662 Y-15.525 R4.088
G01 Y-14.612
X1.0
Y-18.500
Y-14.612
X-0.838
Y-19.612
Z-5.0 F76.2
X8.555 F100.0
G02 X10.889 Y-20.635 R3.588
G01 X88.334 Y-104.613
X94.750
G02 X98.838 Y-108.700 R4.088
G01 Y-109.613
X100.0
Y-105.0
Y-109.613
X102.338
Y-104.613
X92.945
G02 X90.611 Y-103.590 R3.588
G01 X13.166 Y-19.613
X6.750
G02 X2.662 Y-15.525 R4.088
G01 Y-14.612
X1.0
Y-18.500
Y-14.612
X-0.838
Y-19.612
Z-6.0 F76.2
X8.555 F100.0
G02 X10.889 Y-20.635 R3.588
G01 X88.334 Y-104.613
X94.750
G02 X98.838 Y-108.700 R4.088
G01 Y-109.613
X100.0
Y-105.0
Y-109.613
X102.338
Y-104.613
X92.945
G02 X90.611 Y-103.590 R3.588
G01 X13.166 Y-19.613
X6.750
G02 X2.662 Y-15.525 R4.088
G01 Y-14.612
X1.0
Y-18.500
Y-14.612
X-0.838
Y-19.612
Z-7.0 F76.2
X8.555 F100.0
G02 X10.889 Y-20.635 R3.588
G01 X88.334 Y-104.613
X94.750
G02 X98.838 Y-108.700 R4.088
G01 Y-109.613
X100.0
Y-105.0
Y-109.613
X102.338
Y-104.613
X92.945
G02 X90.611 Y-103.590 R3.588
G01 X13.166 Y-19.613
X6.750
G02 X2.662 Y-15.525 R4.088
G01 Y-14.612
X1.0
Y-18.500
Y-14.612
X-0.838
Y-19.612
Z-8.0 F76.2
X8.555 F100.0
G02 X10.889 Y-20.635 R3.588
G01 X88.334 Y-104.613
X94.750
G02 X98.838 Y-108.700 R4.088
G01 Y-109.613
X100.0
Y-105.0
Y-109.613
X102.338
Y-104.613
X92.945
G02 X90.611 Y-103.590 R3.588
G01 X13.166 Y-19.613
X6.750
G02 X2.662 Y-15.525 R4.088
G01 Y-14.612
X1.0
Y-18.500
Y-14.612
X-0.838
Y-19.612
Z-9.0 F76.2
X8.555 F100.0
G02 X10.889 Y-20.635 R3.588
G01 X88.334 Y-104.613
X94.750
G02 X98.838 Y-108.700 R4.088
G01 Y-109.613
X100.0
Y-105.0
Y-109.613
X102.338
Y-104.613
X92.945
G02 X90.611 Y-103.590 R3.588
G01 X13.166 Y-19.613
X6.750
G02 X2.662 Y-15.525 R4.088
G01 Y-14.612
X1.0
Y-18.500
Y-14.612
X-0.838
Y-19.612
Z10.0 F1250.0 M09
M05
G28 G91 Z0. (SEND Z AXIS HOME FIRST, TURN SPINDLE OFF)
M30 (END PROGRAM)
%
```

1 SAMPLE MILLING PROCEDURE WITH G&M CODE, SIDE A AND A1

SCALE: 1:1

05/13/05

DESIGN DRAFTSMAN: JASON PHELAN

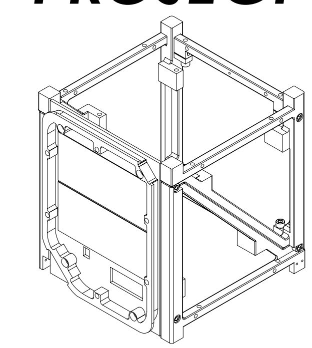
DESIGN ENGINEER: JASON PHELAN

REVISIONS

REV. #	DESCRIPTION	DATE

CALIFORNIA POLYTECHNIC STATE UNIVERSITY

POLYSAT PROJECT



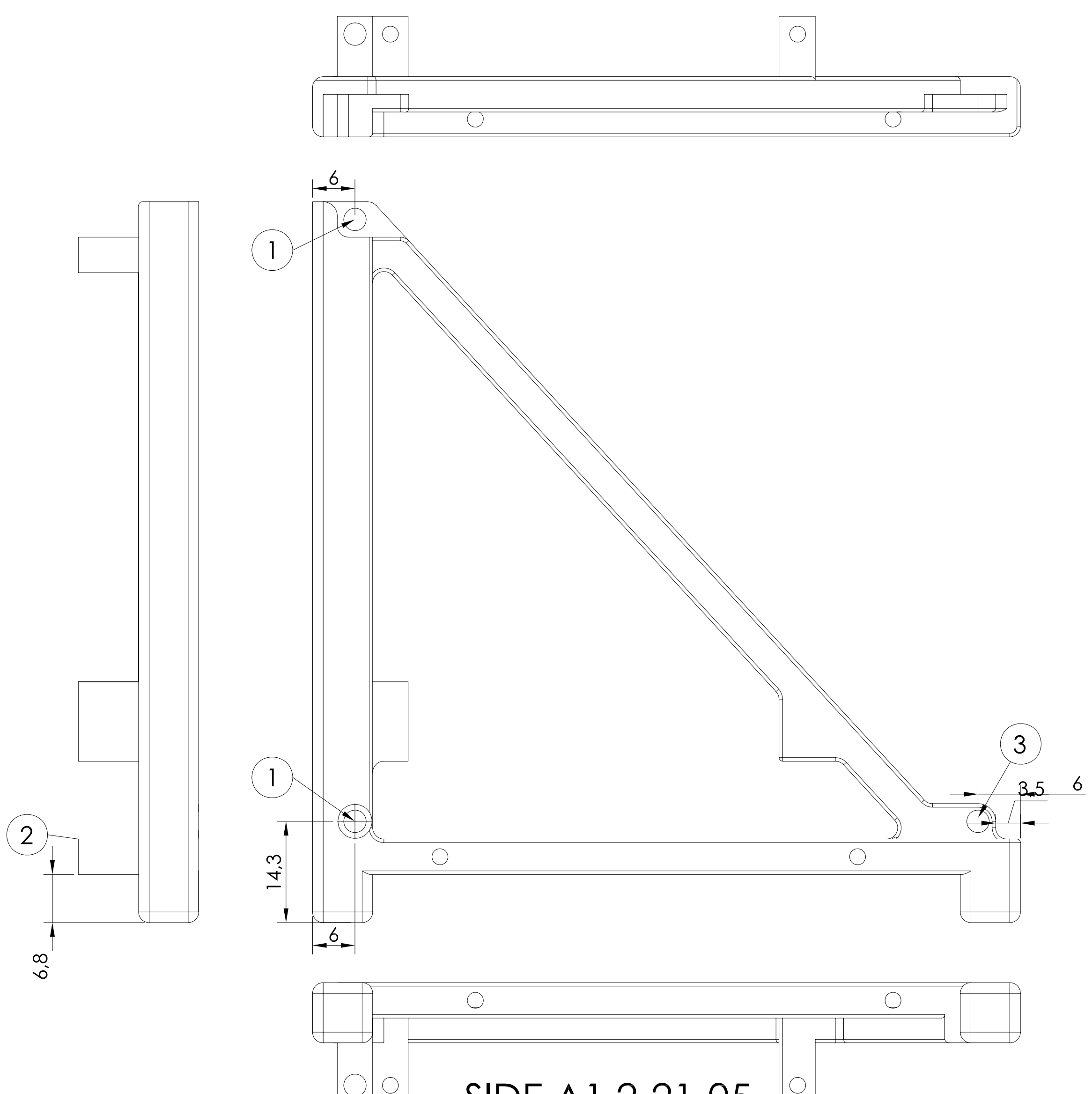
PROJECT TITLE: STRUCTURE

UNITS: MM
TOLERANCE: ±0.1
SURFACE FINISH:

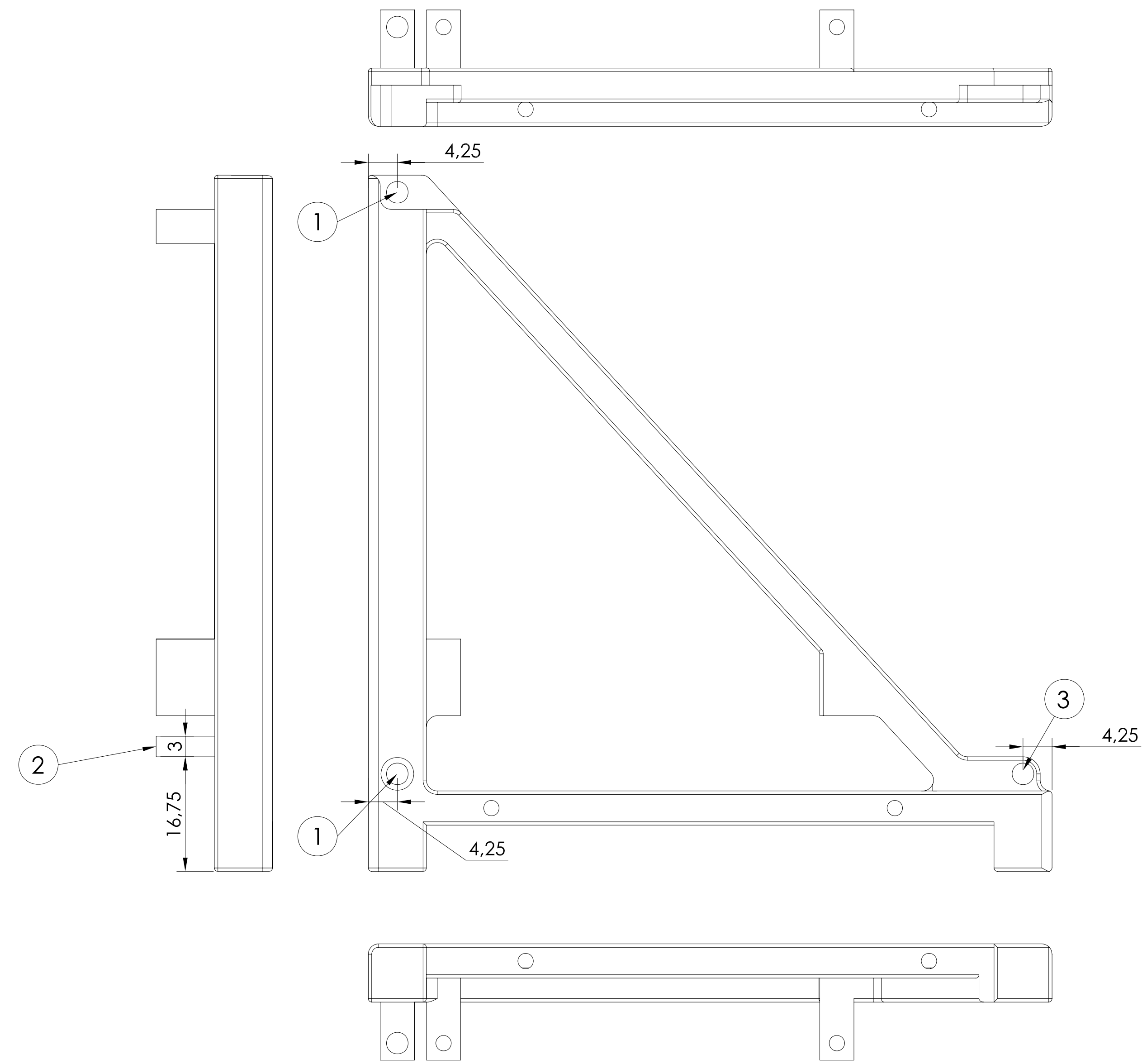
MILLING INSTRUCTIONS FOR STRUCTURES JIG

SHEET PAGE: S-4

CP2.5 SIDE A1 MODIFICATIONS (SIDE B1 SIMILAR)
1. HOLE PLACEMENT FOR TOP AND BOTTOM 1/8" HOLE FOR CROSSMEMBER CONNECTION MOVED TO THE CENTER OF THE VERTICAL RAIL TO ALLOW SYMMETRIC PLACEMENT ON THE WIDTH OF THE SIDE RAIL AND ALSO TO MOVE IT AWAY FROM THE PREVIOUS TOO CLOSE TO THE INSIDE OF THE RAIL LOCATION
2, BOTTOM PEG CONNECTION FOR CROSSMEMBER VERTICAL SUPPORT WAS MOVED ABOVE THE HORIZONTAL HOLE LOCATON AND SHORTENED TO 3MM THICK. THE RELOCATION WAS DONE TO ALLOW THE NEW CROSSMEMBER SHAPE TO HAVE THE SAME VERTICAL LOCATION FOR THE CONNECTING BAR PORTION AT THE SAME VERTICAL LOCATIONS ON THE TRIANGULAR SIDES.
3. THE BOTTOM CONNECTION HOLE WAS MOVED TO MATE WITH THE NEW LOCATION OF THE RAIL CROSSMEMBER CONNECTION HOLES (AS SHOWN IN #1)



SIDE A1 2-21-05
CP2 FLIGHT DESIGN
LEFT BOTTOM/RIGHT BOTTOM



SIDE A1 5-12-05
CP3/CP4 MODIFIED DESIGN

1 CP2 TO CP3/CP4 SIDE A1 DESIGN CHANGES

SCALE: 1:1

05/13/05

DESIGN DRAFTSMAN:
JASON PHELAN

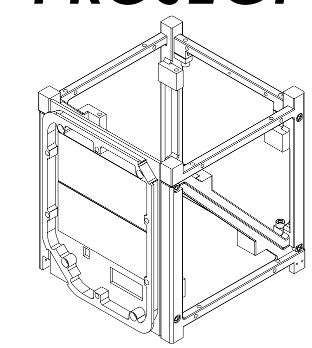
DESIGN ENGINEER:
JASON PHELAN

REVISIONS

REV. #	DESCRIPTION	DATE

CALIFORNIA POLYTECHNIC STATE UNIVERSITY

POLYSAT PROJECT



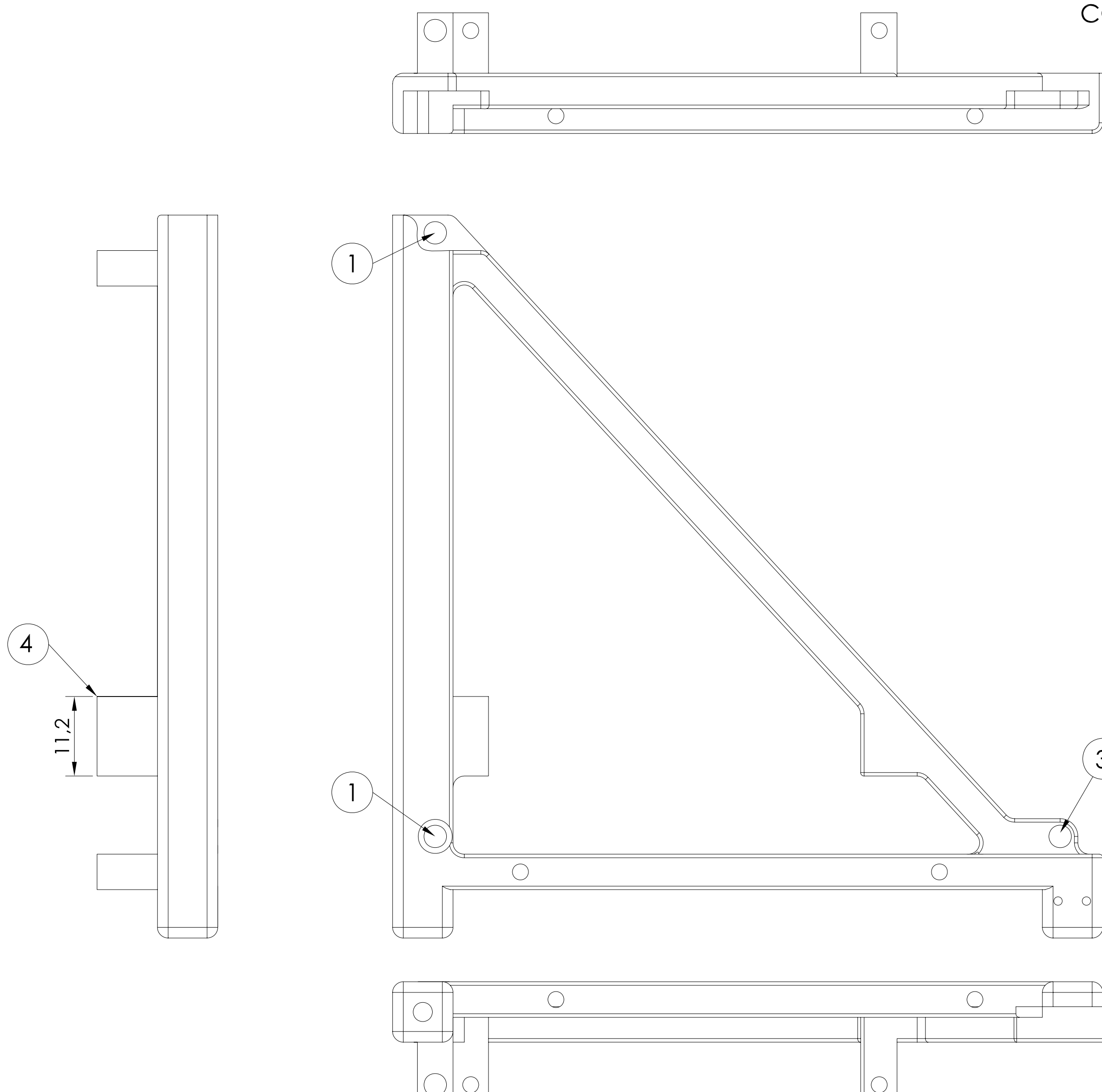
PROJECT TITLE:
STRUCTURE

UNITS: MM
TOLERANCE: ±0.1
SURFACE FINISH:

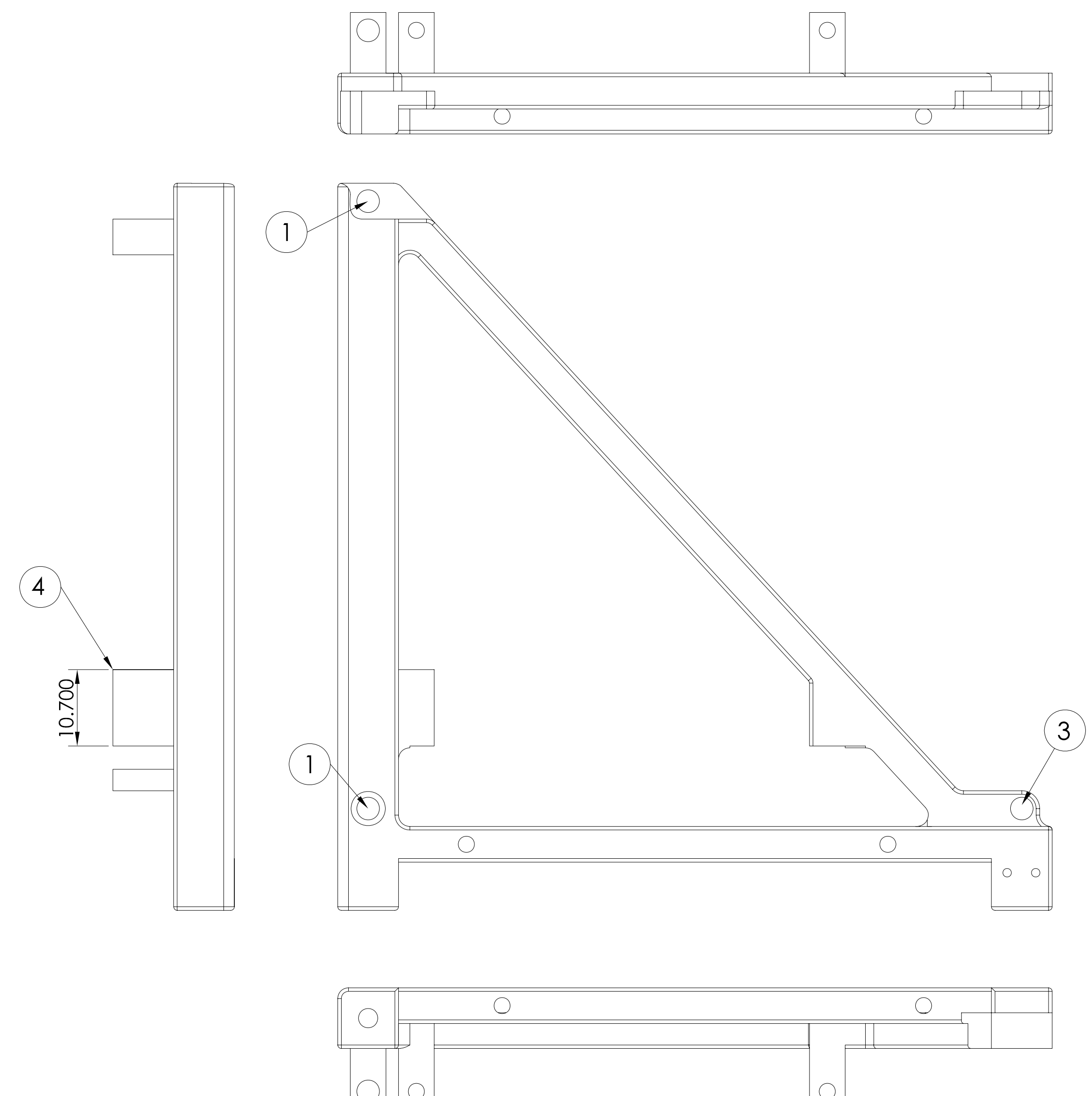
CP2 TO CP3/CP4 DESIGN CHANGES

SHEET PAGE:
S-5

CP2.5 SIDE A MODIFICATIONS (SIDE B SIMILAR)
1. HOLE PLACEMENT FOR TOP AND BOTTOM 1/8" HOLE FOR CROSSMEMBER CONNECTION MOVED TO THE CENTER OF THE VERTICAL RAIL TO ALLOW SYMMETRIC PLACEMENT ON THE WIDTH OF THE SIDE RAIL AND ALSO TO MOVE IT AWAY FROM THE PREVIOUS TOO CLOSE TO THE INSIDE OF THE RAIL LOCATION
2, BOTTOM PEG CONNECTION FOR CROSSMEMBER VERTICAL SUPPORT WAS MOVED ABOVE THE HORIZONTAL HOLE LOCATON AND SHORTENED TO 3MM THICK. THE RELOCATION WAS DONE TO ALLOW THE NEW CROSSMEMBER SHAPE TO HAVE THE SAME VERTICAL LOCATION FOR THE CONNECTING BAR PORTION AT THE SAME VERTICAL LOCATIONS ON THE TRIANGULAR SIDES.
3. THE BOTTOM CONNECTION HOLE WAS MOVED TO MATE WITH THE NEW LOCATION OF THE RAIL CROSSMEMBER CONNECTION HOLES (AS SHOWN IN #1)
4. THE HEIGHT OF THE INTERNAL PCB SUPPORT STRUCTURE FOR SIDE A AND SIDE B WAS DECREASED BY 0.25mm ON EACH SIDE TO ACCOUNT FOR THE SIL PAD AND KAPTON TAPE APPLIED TO THE STRUCTURE BETWEEN THE C&DH AND POWER BOARDS. THIS SHOULD MINIMIZE THE AMOUNT OF CONNECT/DISCONNECT BETWEEN THE MATING CONNECTION BETWEEN THE TWO PCB'S DURING VIBRATIONAL TESTING.



SIDE A 2-21-05
CP2 FLIGHT DESIGN



SIDE A 5-12-05
CP3/CP4 MODIFIED STRUCTURE

1 CP2 TO CP3/CP4 SIDE A DESIGN CHANGES

SCALE: 1:1

05/13/05

DESIGN DRAFTSMAN:
JASON PHELAN

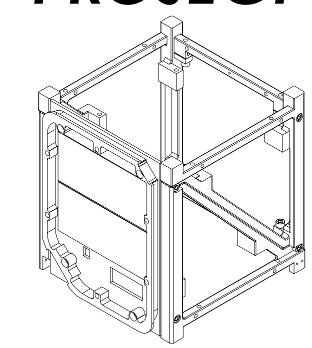
DESIGN ENGINEER:
JASON PHELAN

REVISIONS

REV. #	DESCRIPTION	DATE

CALIFORNIA POLYTECHNIC STATE UNIVERSITY

POLYSAT PROJECT



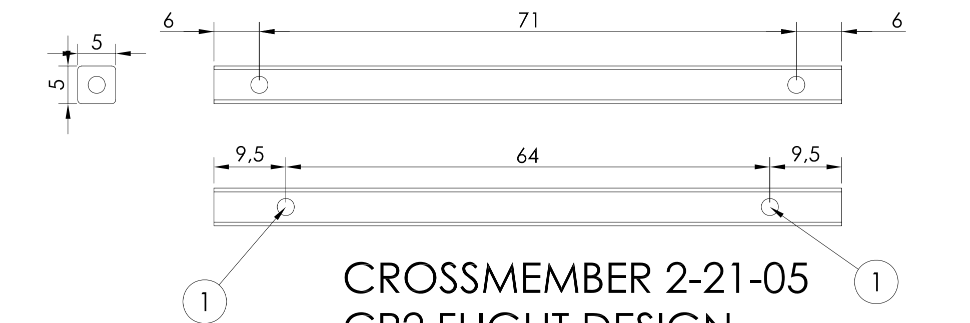
PROJECT TITLE:
STRUCTURE

UNITS: MM
TOLERANCE: ±0.1
SURFACE FINISH:

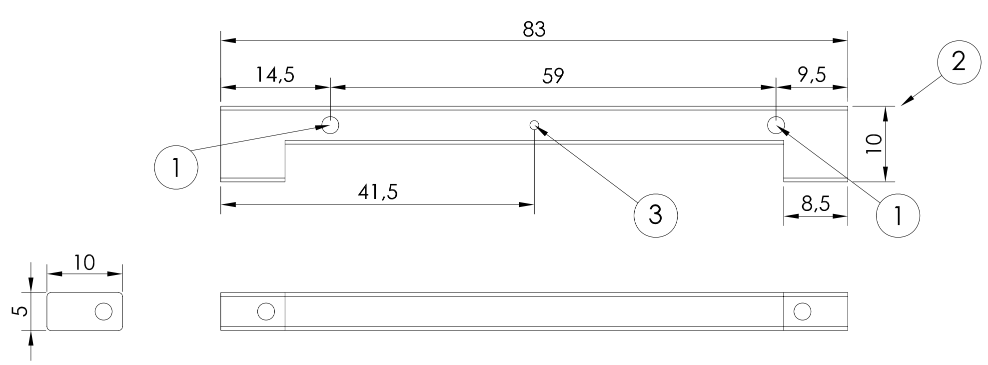
CP2 TO CP3/CP4 DESIGN CHANGES

SHEET PAGE:
S-6

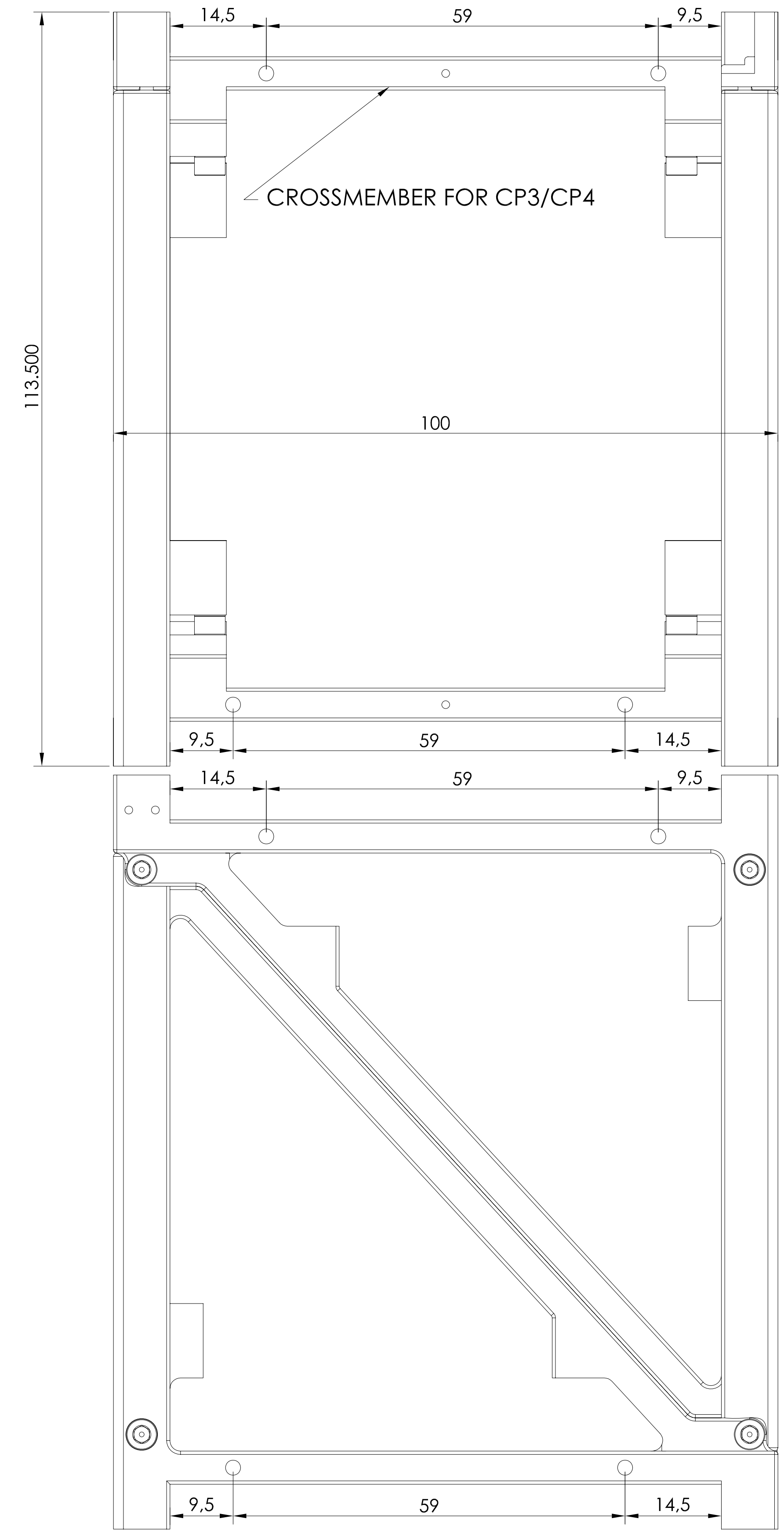
CP2.5 CROSSMEMBER MODIFICATIONS
1. HOLE PLACEMENT HAS CHANGED ON THE MODIFIED STRUCTURE TO BE IDENTICAL TO THE 4 SIDE PANELS (SOLAR PANEL BOARDS LEFT, RIGHT, TOP, AND BOTTOM).
2. CROSSMEMBER THICKNESS DOUBLED FROM 5mm TO 10mm TO ALLOW THE BAR PORTION TO BE IN LINE WITH THE TRIANGULAR MEMBERS BAR PORTION (THEREFORE ALL SIX SIDES ARE IDENTICAL IN HOLE PLACEMENT AND ANY BOARD COULD BE PLACED ON ANY SIDE.)
3. A THREADED #0-80 HOLE IS PLACED AT THE CENTER TO GIVE THE NEW FRONT BOARD/ANTENNA ROUTE DESIGN AN EXTRA MOUNTING HOLE FOR THE ANTENNA ROUTE TO USE.



CROSSMEMBER 2-21-05
CP2 FLIGHT DESIGN



CROSSMEMBER 5-12-05
CP3/CP4 MODIFIED STRUCTURE



1 CP2 TO CP3/CP4 CROSSMEMBER DESIGN CHANGES

SCALE: 1:1

05/13/05

DESIGN DRAFTSMAN:

JASON PHELAN

DESIGN ENGINEER:

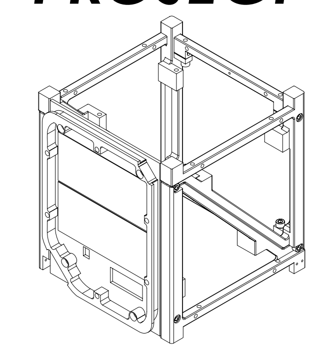
JASON PHELAN

REVISIONS

REV. #	DESCRIPTION	DATE

CALIFORNIA POLYTECHNIC STATE UNIVERSITY

POLYSAT PROJECT



PROJECT TITLE:

STRUCTURE

UNITS: MM
TOLERANCE: ±0.1
SURFACE FINISH:

CP2 TO CP3/CP4 DESIGN CHANGES

SHEET PAGE:

S-7